David H. Allen

How Mechanics Shaped the Modern World

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David H. Allen
Civil Engineering Department
Texas A&M University
College Station, TX
USA

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To my wife Claudia, who, despite the fact that she is neither a scientist nor an engineer, read this entire manuscript repeatedly, providing valuable insight and much-needed encouragement

Preface

This book was born from my lifetime of study of the scientific field of mechanics. I feel fortunate to have had a fulfilling career in such a challenging and enlightening field of study.

I was born in 1950 in the United States, the son of a World War II Army Air Corps veteran. My father was educated in Engineering at Cal Tech, and he was in every sense of the word an “engineering nerd.” I was somehow endowed by him with sufficient talents to follow in his footsteps, thus I subsequently enrolled in Engineering in college, and over a 12-year span of time that included three and a half years in the U. S. Air Force, I obtained degrees in Aerospace Engineering (B.S.), Civil Engineering (M.E.), and Aerospace Engineering (Ph.D., focus on Engineering Mechanics) at Texas A&M University. Somewhat serendipitously, I also studied meteorology for a year in graduate school in preparation for my time in the Air Force as a weather forecaster. I would not realize until much later how important that experience would be to my understanding of mechanics. I have subsequently spent my entire career as a Professor (until recently), teaching at a number of universities both in the U.S. and abroad.

Now, as I look backwards in time, I find myself to have been exceedingly fulfilled by my professional career. Nonetheless, I feel the need to impart my take on the history of my discipline. I say “my take,” because it would not be appropriate to call this text a history book. It is rather my own peculiar view of the universe, one predicated upon my experiences, which are admittedly biased by my long and somewhat narrowly focused view of my own field of study and its impact on the world. I must therefore apologize in advance to those who find error with, or worse, are offended by “my take.” In some cases there are clearly enormous gaps in the history of mechanics found within the pages of this text. In other cases, I have chosen to discuss details that may seem insignificant to some readers. Such is the nature of each person’s view of what is important to this subject. In that sense “my take” is surely highly idiosyncratic, but hopefully not offensive. For those who seek a more technical and in-depth coverage of the history of mechanics, I refer you to the excellent book entitled *A History of Mechanics*, by René Degas (Dover 1988).

I’m a big fan of Carl Sagan. I won’t go into his life or his achievements, since through one of the miracles of modern science and technology you can simply Google his name and find out everything you ever wanted to know and more. But suffice it to say this—at the time that he was writing, Dr. Sagan brought the wonders of science to more people than anyone else in the history of this planet. Yes, he was a brilliant scientist as well as a prolific author. And yes, he was taken from us far too soon (at the age of 62). But as far as I am concerned, it is his skill at making science accessible to so many that is his enduring legacy.

You may ask why I choose to elevate “showmanship” to such a lofty pedestal. No one can doubt that Carl Sagan was a showman, and a brilliant one at that. His New York accented way of saying “billions and billions” became a trademark phrase for a generation of Americans. It has even been whispered that Dr. Sagan was passed over for election to the National Academy of Science because his showmanship crossed over the boundaries of science. I will not dispute this conjecture.

What impresses me is what Dr. Sagan clearly knew, and what he was trying to do with that knowledge. I have learned so much from him. And this is what I learned—I learned the importance of education. I learned that education of our species is the driving force behind our success on this planet. I do not believe that I would have ever completely understood that fact had it not been for Carl Sagan. He not only understood it, he “put his money where his mouth was,” so to speak. To be sure, he never stopped doing important scientific work during his lifetime, but he devoted a substantial part of his time here on Earth to imparting that wisdom to the rest of his fellow humans. He understood that without education we are nothing. Without education we would still be foraging for food along with the other species. Without education, almost everyone alive on this planet today would never have been born. And so he devoted his life to education. As I said, I’m a big fan of Carl Sagan.

In this book my intention is to explain how the science of classical mechanics has affected our world in ways that are commonplace and accessible to the average person as opposed to scientists and engineers. As such, it should be considered non-technical in content. Nonetheless, I hope that these two latter groups will find pleasure in my somewhat purposefully simplified exposition of the subject.

Satisfying all of these disparate groups simultaneously is a difficult challenge, and it is at least in part for this reason that I have chosen to restrict my views to classical mechanics. This term is intended to imply that field of mechanics that developed prior to the advent of quantum mechanics, thus encompassing the pervasive field of Newtonian mechanics. Furthermore, I will not delve deeply into the subject of either special or general relativity in this book. Similarly, because it does not fall under the cognomen of classical mechanics, I will eschew the subject of quantum mechanics. These all-important subjects are amply explained in a number of exemplary volumes published in recent times, so much so that I fear my coverage of these developments would fail to measure up. Thus, as I said, I will confine my coverage to the subject of classical mechanics and henceforth in this book when I utilize the term mechanics, it is implied to be synonymous with the term classical mechanics.

The perceptive reader may ask exactly what is meant by the title of this book. This is indeed an excellent question. I have purposefully chosen a duplicitous title, and for good reason. There are in fact two objectives that I have set for myself herein, and the title of this text bridges both. First, it is my aim to explain in layman's terms how mechanics played a role in the development of so many achievements throughout the history of the universe as we know it. In some cases we do not really know how this happened, but as the reader will soon discover, this will in no way hinder me from conjecture. Second, and perhaps more importantly, it is also my intention to describe the more obvious meaning within the title—how specific developments that involved mechanics actually served to *shape* our modern world. This latter goal is indeed a lofty ambition. With this in mind, I hope that "my take" does not disappoint.

I may be reaching high, but it is my desire that the admittedly unusual perspective contained within this book will somehow accomplish the same thing for mechanics that Dr. Sagan did for Astronomy, Astrophysics, and whatever else he chose to write about—to enlighten not only those familiar with my discipline, but also those who may not be well-versed in the subject and are simply curious to know more about mechanics. If so, then my aim is indeed not too high, but has squarely struck my intended mark. And so, dear reader, I wish you both an enlightening and enjoyable read.

David H. Allen

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Contents

1 **Mechanics and Our Ancestors** 1
Early Developments 1
The Egyptians 7
  Pyramids 9
  Mummies 18
Obelisks 26
The Seven Ancient Wonders of the World 31

2 **The Greeks** 35
The Dawn of Mechanics 35
  Thales of Miletus (c. 624–546 BCE) 38
  Pythagoras of Samos (c. 570–495 BCE) 38
  Democritus (c. 460–370 BCE) 39
  Aristotle (384–322 BCE) 40
  Euclid of Alexandria (3??–2?? BCE) 41
  Aristarchus of Samos (310–230 BCE) 42
  Archimedes (287–212 BCE) 42
  Eratosthenes of Cyrene (276–195 BCE) 49
  Hipparchus of Nicaea (190–120 BCE) 51
  Claudius Ptolemy (c. 90–168 AD) 51
Other Greek Mechanists 52
Archeology of Greece 53

3 **The Romans** 59
The Roman Arch 59
Roman Roads 60
Massive Roman Structures 61

4 **Mechanics in the Middle Ages** 79
Economic and Cultural Collapse 79
Gothic Cathedrals 84
Universities 93
Language 99
Torture 101

5 The Artistic Renaissance 105
Giotto 105
Clock Towers 107
Brunelleschi 108
Da Vinci 120
Michelangelo 122
Bernini 123

6 Finding Our Way 125
The Calendar 125
The Explorers 139
  The Wasa 139
  Pythéas 139
  The Americas 140
  Marco Polo 141
  Christopher Columbus 141
  Ferdinand Magellan 141
  Francis Drake 142
  Captain James Cooke 142

7 Mechanics Reborn 145
The Astronomers 145
  Copernicus 145
  Brahe and Kepler 148
  Galileo 148
Mathematics After the Renaissance 154
  Chasing Pi 155
  Descartes 158
  Mechanical Calculators 159
  Parallel Mathematical Universes 163
  Counting 165
Rigid Body Dynamics 167
  Galileo 167
  Newton 169
  Lagrange 174
Deformable Body Mechanics 175
  Galileo 175
  Beam Theory 178
  Constitutive Models 180

8 Music and Measuring 185
Music 185
  The Pipe Organ 186
  The Harpsichord 187

The Piano 189
The Violin 198
Measuring Things 201
Time 202
Distance 206

9 Continuum Mechanics, Art and Structures 207
Continuum Mechanics 207
Impressionist Art 222
Structural Mechanics 230

10 Weather 243

11 Life Cycles 267
The Big Bang 267
Meteors 271
Tectonic Plates 277
Volcanoes 279
Glaciers 292

12 The Quality of Our Lives 299
Transportation 299
Sports 312
Warfare 316

13 Mechanics Today 323
Time-Space 323
Computational Mechanics 328
Mechanics of Materials 332
Massive Construction Projects 335
The Suez Canal 335
The Corinth Canal 337
The Panama Canal 337
The Hoover Dam 340
The Relocation of Abu Simbel 344
The Venice MOSE Project 346
The Chunnel 347
Modern Failure Mechanics 347
Tacoma Narrows Bridge Collapse 350
Sinking of the Titanic 352
The Failure of the Space Shuttle Challenger 353
1988 Aloha Airlines Disaster 354
I-35 Minneapolis Bridge Collapse 354
The UA Flight 232 Crash 355

    The Chernobyl Reactor Meltdown . . . 356
    The Tōhoku Earthquake and Tsunami . . . 356
    The Leaning Tower of Pisa . . . 357

14 The Future of Mechanics . . . 363
  Biomechanics . . . 363
  Mechanics and Extraterrestrials . . . 369
  The Mechanics of Our Destruction . . . 373
    Destruction by the Sun . . . 373
    Meteor Impact . . . 374
    Interstellar Radiation Event . . . 375
    Pandemic . . . 375
    Climate Change . . . 376
    Human Initiated Extinction . . . 376
  Mechanics and Toilet Paper . . . 377

Errata to: How Mechanics Shaped the Modern World . . . E1

About the Author . . . 381

References . . . 383

Author Index . . . 387

Subject Index . . . 391

Introduction

Those who educate children well are more to be honored than they who produce them; for these only gave them life, those the art of living well.

Aristotle

Webster's Dictionary tells us that mechanics is "the branch of physics that deals with the motion of material bodies and the phenomena of the action of forces on bodies" [1]. Note that this definition implies that there need not be human intervention for mechanics to occur. There are several different fields of physics, and many more within the domain of what we call science. This book is concerned with the physics of mechanics, but as the reader will discover in this book, mechanics is so ubiquitous as to pervade virtually every other field of scientific endeavor, and ultimately, the fabric of both the universe and all humankind.

Science is defined to be "knowledge gained through experience" [1], thus implying that principles are postulated that can be experimentally disproven. Science is therefore inextricably related to experiments, and virtually all experiments involve the measurement of the motions of bodies. It can therefore be inferred that mechanics is essential to every field of science. As will also be seen herein, mechanics may arguably also be the oldest of the sciences. These are some of the underlying reasons that mechanics is ubiquitous in our world today.

When I was a young man, the world was in the early stages of a technological revolution, one that I confess I did not completely perceive at the time. I remember going on a tour of a research facility with a group of my fellow high school students when I was about sixteen. The tour guide showed us a computer, something that was a relative oddity at the time. Communication with the computer by humans was accomplished by using a tape that was encoded with information. Within a couple of years this antiquated method of human–machine communication was replaced by a much more expedient deck of cards that was punched with holes, thus resulting in the now extinct term "keypunch." This essentially mechanical means of communication remained the primary means of interfacing humans with computers for more than a decade, a span of time that included most of my undergraduate and graduate studies.

I grew up using a slide rule, perhaps the ultimate purely mechanical device for performing computations with deceptive simplicity. During my senior year as an undergraduate in college (1971–1972), the world was introduced to Hewlett-Packard (HP) pocket calculators, and a short time thereafter, Texas Instruments (TI) pocket calculators came on the market. That was perhaps my most vivid evidence that the world was changing. Some called it “the computer age,” but in my mind, as I look back now, 40 years later, I realize that it was much more than that. The world was in the early stages of transforming from a primarily mechanical one to a world that is now both mechanical and electromagnetic.

I honestly had no comprehension as to the magnitude of the revolution that was germinating during that period of time. I thought that computers were like slide rules—just another tool for calculating faster. Had I understood, I might have chosen a different career field within the broad discipline of engineering, but I confess that I did not.

Thus, I chose to study mechanics, a field that has become quite mature over the past 40 years. In fact, I would go so far as to say that the world has been revolutionized by the science of electromagnetics within the span of my lifetime. We are now well into “the computer age,” just one of many offspring of the science of electromagnetics.

Some may trace the science of electromagnetics to the experiments of Michael Faraday, or even further back to those of Benjamin Franklin, but for my part, I consider the true father of electromagnetics to be James Clerk Maxwell, the Scottish scientist who published his theories regarding electromagnetism beginning in 1861, while he was on the faculty at Cambridge University.

Unfortunately, he died young (in 1879 at the age of 48, from abdominal cancer), but his contributions cannot be overestimated. They are truly monumental to our world today. In fact, one could go so far as to say, prior to the year 1861, the world as we know it was essentially mechanical, and since that time, the world has become increasingly electromagnetic, and most of the resulting technological changes have only become apparent to society as a whole since the fading days of World War II, when two atomic bombs were exploded in Japan, in part due to Maxwell’s discoveries.

Let us now begin our journey with a short overview of history. Our estimate as to the age of the universe keeps increasing. For the past half century, scientists have developed a consensus that The Big Bang, that enormous conflagration that initiated the spread of matter throughout the universe, occurred sometime around 13.7 billion years ago.

Similarly, scientists now believe that our Solar System, including our planet, is about 4.5 billion years old, when gravitational forces agglomerated enough mass for our Sun to undergo sufficient pressures for nuclear reactions to be initiated. As recently as 150 years ago, this span of time seemed not just unlikely, but impossible to most humans. But geologic as well as astrophysical data now seem to agree on this estimate. Think about it—4,500,000,000 years—that is a lot of zeroes!

Now let’s consider that enormous span of time in relation to the species of Homo sapiens. There seem to be three intrinsic time constants in relation to our species: the span of a heartbeat; the time for gestation; and the span of a human lifetime. All of these are much less than either the time span of our universe or our Solar System. Thus, in case it is not obvious, it can be said that—compared to the astrophysical timescale—*we humans are relatively short-lived*.

Of course, these can all be related to time constants for our planet: the span of a revolution of the Earth on its axis (a day); the span of a revolution of the moon about the Earth (about 29.5 days); and the span of a revolution of the Earth about the Sun (a year). Note that all of these time spans are measured via mechanics. As Isaac Newton so aptly put it in his book, *The Principia,* "...common time, is some sensible and external measure of duration by the means of motion..." [2].

As we delve deeper into the time span of our species, we are struck even more so by the incongruity of our evolution with respect to the evolution of the universe. As recently as about 15,000 years ago (that is only 3 zeroes!), our species appears from the archeological record to have been doing what virtually every other species of animal was doing on this planet—hunting and gathering—in order to survive from day to day [3]. Thus, it seems likely that not too very long ago, the end of each human life was not unlike the end of life that we observe in most other species today—within the stomach of another animal! Thus, we are unlikely to ever unexpectedly find any large ancient cemeteries containing the remains of humans on Earth.

To put it concisely—something very significant happened within the last 15,000 years on this planet, because we are not doing what we did as a species 15,000 years ago, and virtually every other species on this planet is functioning just the way they were then, despite the fact that most of their gestation times are significantly shorter than ours (meaning they could have evolved genetically more rapidly than we humans).

What happened? How could it have happened so quickly, a mere blink of an eye on the astronomical timescale? Had visitors to our planet passed by 15,000 years ago, they would have concluded that there was no intelligent life on this planet. How did a species (our very own) take over a planet in such a short span of time, a development that is so far as we know unprecedented in the history of the universe?

The answer to this question is one of the greatest achievements by humans. Sometime around 13,000 years ago (we do not know exactly when because carbon dating is not perfect), a person or persons, somewhere in the area of modern day Iraq, where the Tigress and Euphrates Rivers flow, attempted to use the river for irrigation purposes, perhaps designing and employing an implement for digging trenches and diverting water from the river for the purposes of nourishing plants to produce food for the village [4].

Until that point in time it was simply not possible to support villages with populations greater than about 400 humans via hunting and gathering. There just wasn't enough game within the radius that a human could walk in a day to support a larger population. But with the advent of farming, cities of perhaps 5,000 people sprang up within a single century.

Organized farming had created civilization. And that person or persons, whoever they were, we may regard today as the first engineers on Earth. While it is certainly true that there were ingenious (from whence the word engineer comes) humans before then, there was no civilization, so that there were no ingenious people creating on behalf of civilization—the definition of an engineer. So that is how it all started. Civilization on our planet was initiated by agricultural engineers.

Archeologists and anthropologists have determined that the invention of farming moved humans rapidly away from hunter-gatherer behaviors, and this produced a population explosion at places such as Uruk and Ur. Apparently, within a few short centuries there were cities of more than ten thousand persons in the Mideast. Population growth allowed for specialization of professions in these cities, and this led the way to the development of new technologies as more people specialized in the development of new ideas. In turn, the development of new ideas required some training, and the ability to transmit these developments throughout society necessitated the development of sophisticated language, both spoken and written, and mathematics.

Events thereafter began to occur at an ever increasing pace, as if time were continually being compressed. Inventions were spewed out with increasing frequency as the demands of humans for more and more life sustaining technology drove the needs of an exponentially increasing populace.

Yes, it is true that there were missteps and regressions along the way, such as the period we call the Middle Ages, but by and large, the rise of the human species is the most admirable example of *Darwin's Universal Law of Natural Selection* that can be conjured up anywhere in the universe, so far as we are aware. To wit, the number of life altering inventions just within the last century dwarfs all of the inventions within the previous 4.5 billion years on this planet. Indeed, the average life span of humans has nearly doubled in little more than a century, and advancing technology has played an enormous role in this achievement. There is no way to avoid the profundity of the world we live in today. It is little short of miraculous.

And yet, Anthropologists tell us that due to the statistical nature of microbiology, the gestation period of humans, and the complexity of our DNA, we are a species that requires around 10,000 years to undergo significant physical evolution. In other words, those people 13,000 years ago who were hunting and gathering were essentially genetically equivalent to us. Their brains were the same size as ours! They were smart; they were most likely just as intelligent as we their descendants are.

So why didn't they just invent everything on the spot, as soon as they had sufficient food? Why did it take 13,000 years? For one thing, there were only about 1 million humans on the planet 13,000 years ago. Today there are more than 7 billion humans on Earth. We can safely say that there has been a population explosion, and in many parts of the world, it is still underway. This population explosion has encouraged and supported specialization, thereby increasing the rate of growth of technology.

So what is going on here? Why has the way we humans live changed so dramatically, while other species have not? We have not evolved significantly genetically, and yet, here we are, the undisputed masters of this planet, far more so than any other species that archeologists have yet discovered.

The answer is of course—*education! Our species is the first species, so far as* we are aware, that has outrun our own physiological evolution, and we have accomplished this astounding feat via education [5].

Certainly, Darwin's law [6] played a significant role in our quest to educate ourselves, despite the fact that it was not even espoused until the mid-nineteenth century. And you thought that Darwin's law only applied to genetics. Nope, it applies to any means of evolution, and in the case of our species, we have trounced the genetic clock by applying Darwin's law to education. The fact is, we have been living our lives (and educating ourselves) according to Darwin's law, whether we have been aware of it or not. In fact, a new field of research called genetic programming has recently begun to result in many new technological developments.

Inventions led inexorably to the rise of education—a necessity for humans to survive. We used to have to compete with other species to survive. Today, each and every one of us humans must compete with other members of our own species to survive. While the higher education complexes on our planet are less than a 1,000 years old (The University of Bologna issued the first diplomas around 1088), our educational infrastructure goes back thousands of years. *It may be argued that* education is indeed the single most important invention in the history of humankind.

As I previously indicated, I chose to study mechanics. Thus, I rode the crest of a wave that, though it has now matured and one could even say—crashed upon the shore—it has nonetheless been an exciting ride in that I was there for the peak of the wave that is mechanics, one that is perhaps the most important wave of technology to ever affect humans and our world. And although it is perhaps premature to assume that mechanics is now receding, it is nonetheless instructive to trace the history of such an enormous development in the history of mankind. After all, I lived on the crest of that wave, and I of all people hope that the power of such a wave shall never be forgotten. Thus, if you will bear with me through the telling of this story, I hope that you will agree with me by the end of it that mechanics is by far the most important fundamental discipline of science that shaped our modern world.

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Mechanics and Our Ancestors

1

Yes, wonderful things.
Howard Carter (1874–1939), answering the query regarding what he saw on opening King Tut's tomb

Early Developments

As I mentioned in the Introduction, mechanics does not require human intervention. Nevertheless, an interesting question comes to mind—when did humans begin utilizing and/or studying mechanics? Unfortunately, no one is quite sure when this occurred. It would seem self-evident that humans have been using mechanics since our inception as a species, but where is the evidence? If we study our biological cousins such as chimpanzees, it would appear that they are pretty good mechanists. All one need to do is to watch them swinging through the trees, and it is obvious that they have an innate understanding of both momentum and gravitational forces. They are also known to understand mechanics sufficiently to utilize stone implements to break open objects such as nuts. But this is not really scientific evidence regarding the use of mechanics by humans.

Stone clubs are the first human mechanical inventions to appear in the archeological record. In 2010, an international team led by Shannon McPherron discovered animal bones in the Lower Awash Valley of Ethiopia that show markings from stone weapons [1]. These have been dated to 3.4 million years ago, and assuming that it was indeed humans that made these weapons, they comprise the oldest evidence on Earth of humans using mechanics. There are several other extant examples of stone weapons dating back to about 5,00,000 BCE.

Evidence seems to indicate that quite a long period of time elapsed before humans developed more sophisticated tools. Archaeologist Lyn Wadley of Wits University in South Africa recently discovered evidence in Sibudu Cave on the east coast of South Africa that Stone Age people were using arrowheads as a part of bows and arrows as long ago as 60,000 BCE [2]. Unfortunately, this technique appears not to have caught on, having disappeared and not reappeared until 20,000 years later. Nonetheless, shaping stones using mechanics was a significant step forward for humankind. And if you want to know how hard this is to accomplish, try taking a piece of flint and banging it with another rock into anything with a sharp edge. Thus, while we don't know exactly what techniques

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they used to shape arrowheads, we have evidence that humans were practicing what we would call today ‘experimental’ mechanics at least 60,000 years ago.

Another example of humans using mechanics is in cave paintings, such as those in the Cave of El Castillo in northern Spain, which date to 40,000 years ago, and those in Chauvet, France, which date to about 35,000 years ago [3]. It would seem that the painters of these fabulous pieces of artwork must have used mechanical tools to make their dyes, perhaps by grinding them into powder with stone implements. However, we cannot be certain of this.

The first evidence that humans were using mechanics for purposes other than making tools or weapons appears a short time later. Alexander Marshack discovered bones from the Aurignacian culture in France dating to about 32,000 BCE that show clear evidence of a lunar calendar [4]. In addition, Dr. Michael Rappenglueck of the University of Munich has identified markings on the walls of the famous cave paintings at Lascaux, France, that appear to be lunar calendars (Fig. 1.1) [5]. These calendars date to about 13,000 BCE. Here is much better evidence of humans *studying* mechanics. In order to make a calendar, it was most likely necessary to study the motions of heavenly bodies, ergo mechanics. Thus, we may conclude that humans were studying mechanics quite a long time ago.

Incidentally, Lascaux is quite an interesting cave. It was discovered in South Central France on September 12, 1940 by four teenagers. The cave contains nearly two thousand paintings, some estimated to be as old as 17,300 years. The cave was opened to the public in 1948, but by 1963 it had to be closed due to damage caused by carbon dioxide emissions from the visitors.

In a bizarre twist of events, the locals decided to build an exact replica of two of the caves. This turned out to be a quite challenging construction project, but it was nevertheless accomplished and Lascaux II was opened to the public in 1983. Unfortunately, the original cave has continued to deteriorate, but Lascaux II continues in operation.

At the beginning of the tour within the replica cave, visitors are treated to a description of the methodology that was used to build Lascaux II, which was in and of itself a quite interesting exercise in structural mechanics (see Chap. 9). So today visitors cannot actually enter Lascaux, but the tour of the duplicate is nonetheless quite impressive. Think of it as the archeological equivalent of EPCOT Center at Disney World.

Archeological digs that began in the mid-nineteenth century in modern-day Iraq have produced tantalizing evidence that the Mesopotamians were producing astronomical observations as early as the eighteenth century BCE. As of this writing, there have been no less than 500,000 cuneiform tablets discovered at places like Sippar, just southwest of Baghdad, and a fair number of these were used to measure celestial motions [6]. These discoveries indicate that the Mesopotamians were quite possibly the first civilization on Earth to perform systematic scientific studies, and their astronomical observations were clearly rooted in mechanics.

By the end of the Pleistocene era (10,000 BCE) humans were probably systematically studying and applying mechanics [7]. There are in fact a few extant carvings that illustrate attempts to create solar calendars around the time that the

Fig. 1.1 Painting of a Giant Deer from Lascaux. *Note* dots representing lunar calendar

last ice age ended. This is noteworthy both because solar calendars are more accurate than lunar calendars, and also because they require more advanced mechanics. Thus, the evidence proves that mechanics is a very old and rich subject within the realm of human endeavor.

One could argue that mechanics is in fact the oldest of the true sciences, going back to the earliest efforts by man to study the motions of heavenly bodies. As we know from ancient stone structures such as Stonehenge, Avebury, and Beltany, as well as numerous other megalithic structures found across Western Europe that are aligned with the motions of the Earth with respect to the Sun, people were studying not just the motion of the Moon, but also the motion of the Earth at least 5,000 years ago. Thus, at Stonehenge, on the Salisbury plain in southern England, the Sun shines directly down the main axis of the henge on the summer solstice. And not only were they building stone calendars, they were verifying their accuracy, a clear reflection that they were utilizing mechanics as a means of employing the scientific method (Fig. 1.2).

Stonehenge is apparently a very old site, dating back possibly as far as 8,000 BCE. Carbon dating of wooden fragments found inside the dirt berm suggests that the structure may have originally been wooden. It is likely that early engineers realized that in order to build structures that would stand the test of time, a more durable material was needed—stone. And indeed, almost all structures remaining

Fig. 1.2 Photograph of Stonehenge on the Salisbury plain in Southern England. *Note* the dirt berm in the foreground

today from antiquity are stone. Unfortunately, as demonstrated by the relatively small spacing between the large vertical stones, the low tensile strength of stone limits its use as a horizontal beam of substantial length. This is in fact another problem in mechanics, thus perhaps demonstrating that our ancestors understood at least empirically the nature of beams, a problem that was not solved scientifically until the eighteenth century (see Chap. 7). As we know today, a horizontal beam subjected to gravitational loading will undergo tensile stress in the horizontal direction at the bottom of the beam, and since stone will fracture when subjected to even small tensile stresses, it is not possible to use stone for horizontal beams of significant length.

There is another interesting problem in mechanics associated with Stonehenge—no one knows quite how the builders managed to transport the stones to where they stand today. There are no bluestones similar to the ones used at the site within 240 km of the Salisbury plain today, suggesting a monumental human effort was perhaps needed to transport them. However, some archeologists believe that the Irish glacier may have deposited these large stones nearby during the last ice age.

The mystery of exactly how Stonehenge was built is a very rich and interesting subject, as anyone who has watched episodes about Stonehenge on the History Channel will know. Unfortunately, there is no extant evidence describing how these ancient engineers accomplished this astounding feat, thus we are limited to conjecture.

Regardless of where they came from, the transport and subsequent raising of the stones must have presented an enormous challenge in ancient mechanics. Indeed, it has been suggested that construction involved some sort of technological skills that included the principle of the lever, and the use of transport devices such as the boat and the wheel, or rolling assembly, many of which were most likely used in various cultures well before the development of megalithic calendars. However, there is not yet a consensus regarding what techniques were employed, thus giving me ample reason to stray away from this subject. However, what we can be sure of is that mechanics was a necessary component of the construction techniques used.

Avebury, in Southwest England, contains the largest stone circle in Europe. The site dates to about 2,600 BCE, making it one of the oldest star-based calendars on Earth. There are more than a thousand stone circles that dot the countryside in the British Isles. Most were seemingly abandoned with the advent of the Iron Age, which began around 800 BCE in the British Isles. This may well be related to the fact the Celts invaded Western Europe around this time and displaced the indigenous people with their superior weapons, armaments made using mechanics.

Evidence suggests that these stone structures were predated by much older but less durable structures that may well date to before the beginning of the Holocene, which commenced when the ice receded more than 12,000 years ago. Still, on the time scale of the Earth's existence, we have little hard evidence to suggest that humans actually studied mechanics longer than a few tens of thousands of years ago. And the extant evidence that we have suggests that they were studying mechanics not just for the sake of curiosity, but more so as a means of survival. After all, both predicting seasonal changes via the motions of the heavenly bodies and making weapons are necessary for survival in harsh climates.

By the beginning of the third millennium BCE, the archeological record indicates that calendric stone structures were relatively commonplace in Western Europe, as evidenced by the numerous examples extant today. Still, there is little existing evidence as to just exactly what mechanics were employed to affect these enduring testaments to the ingenuity of our ancestors. A recent episode on the History Channel [8] demonstrated just how massive a challenge these ancient builders must have faced. Several hundred volunteers used devices known to have existed around 3,000 BCE, managing to move stones of similar size to those at Stonehenge no more than a few feet in a day.

Dick Teresi's book *Lost Discoveries* [6] catalogs numerous developments from Babylonia, Arabia, India, and even the Americas in the period after the Sumerians invented language. I will not go into detail regarding the developments in the Americas, for the simple reason that these appear to have had little impact on the modern world (see the title of this book).

On the other hand, the developments by those in the Middle East and India, and perhaps even somewhat from China, seem to have been far more profound than the traditional history books would lead us to believe.

The Sumerians, for example, seem to have invented the sexigesimal numbering system about 5,000 years ago. This system pervades our world even today. For example, we divide an hour into 60 min, and we further divide a minute into 60 s. In addition, we divide the number of degrees in a circle into 360. Why on Earth (pun intended) would we choose to do such a thing when we have 10 fingers and 10 toes?

As laid out by Ernest Zebrowski, Jr. in *A History of the Circle* [9], it comes down to a matter of expedience. No one is quite sure why the Sumerians, and later the Babylonians used the sexigesimal system, but once this decision is made, much about our current system follows naturally. In fact, the number 360 is the smallest number that is divisible by 2 through 10. It is also divisible by 24, the number of hours (chosen by humans) in a day. We also do not know the origin of this choice (it might have been related to the number of constellations—12—another human invention), but we do know that it has been around a long time, since there is a reference to a 24 hour day in the tomb of the Egyptian pharaoh Amenhotep I dating to 1500 BCE.

The choice of a 24 hour day is probably not a coincidence, resulting in the Earth spinning 15° on its axis each hour of the day. Another likely reason for the choice of 360° is that the Moon orbits the Earth approximately once every 29.5 days. In ancient calendars, this was often rounded off to 30 days, and the number of months in the year was set at 12 (perhaps also to match the number of constellations), making the calendar year approximately 360 days. This has significance for navigation by using celestial observations, and it should go without saying that all of this is related to mechanics.

In his book entitled *The Nothing That Is: A Natural History of* Zero, Robert Kaplan has made an exhaustive search for the inventor of zero [10]. Unfortunately, he is unable to determine conclusively who invented this all-important number. Although the Egyptians were using a base-ten hieroglyphic numeric system as early as 1740 BCE, the evidence of its purpose is not compelling. In the end, Kaplan argues that while the Babylonians may have had knowledge of zero, the Greeks were most likely the inventors of zero. Unfortunately, they seem to have declined to use it, thereby inadvertently donating it to the Indians.

According to Dick Teresi, “Unlike the Greeks, who abhorred them, the Babylonians dealt routinely and comfortably with irrational numbers [6].” For example, the Pythagoreans applied the Pythagorean Theorem to a triangle with equal sides of length one. Their theorem produced the disconcerting number $\sqrt{2}$ for the hypotenuse of the triangle. Although they were able to show that this number is an irrational one, they apparently were not happy with this result [6]. On the other hand, the Babylonians dealt with such mysteries without unsettling difficulty, simply rounding off for practical purposes. An understanding of such mathematical issues is important to the science of mechanics for the simple reason that in order to measure motion it is necessary to measure distance.

The Babylonians and their forerunners the Sumerians were also apparently no slouches at building construction. There is a ziggurat built in Ur around 2,500 BCE that had weep holes that allowed for proper drainage, and two levels of this temple remain today which contain arches, two millennia before the Romans began using the arch ubiquitously (See Chap. 3) [6].

Scientists and mathematicians in India appear to have been studying the heavens around the same period of time. Archeologists believe that India was one of the first places inhabited by modern man after the migration of humans out of Africa. Thus, it is perhaps not surprising that Indians were among those first scientists studying mechanics.

It is difficult to assess exactly how early developments in mechanics shaped our world. What we do know is that the archeological record seems to indicate that perhaps as much as 95 % of all early inventions were lost in antiquity due to poor communications. Stone weapons, including sharpened ones, may therefore have been invented and reinvented recursively, and at a number of different locations on Earth. Still, eventually this technology took hold and became universally deployed throughout humankind. Other inventions involving mechanics undoubtedly suffered similar spatial and temporal discontinuities in application across the Earth. Thus, while the early record is sparse, and the information we have is inconclusive, it seems likely that mechanics had a profound effect on the development of early humans.

Still later, these developments surely affected the first cultures on Earth, and this technology began to be disseminated by pictorial and written records. It would remain for the Greeks (as we will see in Chap. 2) to assemble some of this information, expand upon it, and create the first systematized scientific theories on Earth, including mechanics. But before exploring the accomplishments of the Greeks, we should pay proper respect to the Egyptians, who were perhaps not so scientifically accomplished as their neighbors to the north, but they were certainly no slouches, as we will see in the next section.

The Egyptians

Why are we so fascinated with Egypt? There are several reasons to my way of thinking. First, the Egyptian Empire lasted the longest of any culture from antiquity, from about 3,800 BCE to 31 BCE, when Cleopatra, the last pharaoh, committed suicide. Second, there is much more remaining from the oldest part of the Egyptian civilization than from any other culture from that long ago. Third, the Egyptians mummified and entombed their emperors, giving us a window into the past. And fourth, the Egyptians wrote their history on the walls of their temples, so that when the Egyptian hieroglyphic language was decoded in the nineteenth century, the previously hidden tale of their mighty empire was there for all to see and read (See Chap. 9).

Until the nineteenth century, after Napoleon's failed conquest of Egypt (more on this later), the land of Egypt was essentially cut off from the West. It was a mysterious place that was far too perilous for most Westerners to visit, mostly due to the danger of life-threatening diseases. Like as not the visitor to Egypt would never see his or her homeland again [11].

But all of that changed after Napoleon's scientists visited Egypt for 3 years (beginning in 1798) and reported on their findings [12]. The published results astounded the Western World, and so began the steady flow of visitors into Egypt, accompanied by the steady flow of her treasures out of Egypt. These days, the former continues (when civil disruptions abate), but the latter has thankfully slowed to a trickle due to strict controls put in place by the Egyptian government.

So you can and should visit Egypt today. I cannot overemphasize the importance of a pilgrimage to Egypt for the purpose of studying mechanics. You may even find yourself interested in a few others things as well.

Now, for the sake of expedience let me digress at this point with just a tiny bit of the history of Egypt. Archeologists know that there used to be a big lake in the middle of the Sahara. And it wasn't too long ago that the lake dried up, perhaps about seven or eight thousand years ago. This is due in part to climate change, but it is also due to the fact that there are two tectonic plates of the Earth's crust that are butting up against each other, and one is riding over the other in the Mediterranean Sea (See Chap. 11). This effect also produces the Alps, and it is the main reason that ancient Alexandria has slipped beneath the surface of the Mediterranean and now rests on the sea floor in modern day Alexandria's harbor. Perhaps most obviously, it is also indirectly the cause for the subsidence of Venice, and all of this is due to the mechanics of tectonic plates (to be discussed further in Chap. 11).

When the lake in the central Sahara dried up, the indigenous people who lived there were forced to migrate elsewhere. Many of them ended up moving eastward along the coast of the Mediterranean to the fertile Nile delta, creating a population explosion around 7,000 years ago. This caused a clash of two cultures—the upper Nile, and the lower Nile—which were finally united, perhaps by a King named Narmer around 3,800 BCE. You can see the evidence of Narmer's conquest, a small sculpture called Narmer's palette, just inside the entrance to the Egyptian Museum in Cairo today. It is one of the oldest and most important man-made archeological finds of all time [13].

Thus, Narmer is considered to have possibly been the first pharaoh, that is, a king of both the upper and lower Nile. We know that he was indeed a pharaoh because he is depicted on the front and back of the palette wearing the crowns representing both kingdoms (see Fig. 1.3). His reign perhaps began what is called The Old Kingdom.

Fig. 1.3 *Front* and *back* views of Narmer's Palette. *Note* depiction of Narmer with head-dress as the king of both the upper and lower Nile

The Egyptians believed in life after death, and they went to great lengths to ensure that their pharaohs would live in splendor after their deaths, thus they built elaborate funerary tombs for them. Some citizens were also entombed, but the style and size of their tombs depended on their wealth and influence. Since the pharaoh was the wealthiest and most important citizen, he/she was afforded the most impressive funerary tomb.

There was just one problem—the tombs were made from the only readily available building material of the time in Egypt—mud—which was used to make bricks. Unfortunately, after a few hundred years it became obvious to one and all (especially the succeeding pharaohs!) that this building material would not do because the desert climate eroded the bricks and consequently also the brick tombs away, thereby severely diminishing the after-death lifestyle of the old pharaohs. Thus, the mechanics of mud bricks proved to be unworthy of the lofty ambitions of the pharaohs.

Pyramids

No one is really sure when the Egyptians began to quarry stone, or indeed who was the first to do so anywhere in the world, but we do know that the Egyptians began making large sculpted statues several thousand years ago. They had access to both very hard granite (notably at Swenet, modern day Aswan, as well as elsewhere), and soft limestone at several locations along the Nile. They also had access to stones of intermediary hardness such as marble.

It wasn't long before they began to adorn monuments with stone statuary, and it was a short leap to building structures from stone. Eventually, they hatched the idea of building the Pharaoh's mastaba tomb from stone. This was a single layer structure built over an underground funerary complex. By that time the Egyptians were all too aware that their own citizens were robbing the tombs of the Pharaohs. Thus, stone was utilized because the tombs needed to be robbery—as well as weather-proofed.

Around 2,630 BCE the Pharaoh Djoser (still from the Old Kingdom) somehow had the idea to build a second level on his mastaba, and then a third, and then a fourth, and finally a fifth (perhaps he lived longer than anticipated). Thus was born the first Egyptian pyramid in history (there are some older unworked stone pyramids in Caral, Peru). Today we call it a step pyramid, because the layers are successively stepped smaller and smaller (Fig. 1.4).

This pyramid was built by an engineer named Imhotep, and he is the first engineer that history records by name. The pyramid apparently created quite a stir in ancient times, because Imhotep was later deified by the Egyptian people and worshipped as a god for thousands of years. That's pretty good for an engineer! I certainly do not know of another engineer that became a god.

Djoser's pyramid is still around today, although it is somewhat dilapidated. Engineers are currently attempting to do some restoration so that it will be around

Fig. 1.4 Djoser's step pyramid. *Note* formwork on the right

for another 5,000 years. But you don't have to wait—you can see it out in the desert on the west bank south of Giza at a place called Saqqara.

There are plenty of other exciting things to see at Saqqara. In fact, Saqqara is the site of the oldest stone-hewn building complex in the world. There are also 16 additional mastabas on the site. Saqqara is still being excavated, so stay tuned for further discoveries, such as perhaps the tomb of Imhotep, whose tomb is as yet undiscovered.

Back to our story, we are now in the third dynasty of the Old Kingdom of Egypt. Djoser's tomb was apparently quite impressive at the time, and there was a lot of wealth in Egypt around this period, thus successive pharaohs possessed the means to build their own funerary tombs in splendor. In less than 100 years the great pyramid building period had begun.

During the fifth dynasty of the Old Kingdom, the greatest pyramid builder in history became the pharaoh. His name was Snefru, and he built no less than three great pyramids (and some people think he built as many as six!). The three that still exist today are in various physical states. There is one way out in the desert at Meidum that is aptly called the Meidum pyramid. It has essentially collapsed, apparently due to poor mechanics used in the structural design. This may sound like a failure, but I would be remiss if I didn't point out that even though it has collapsed, it's *still there*! How many of us can say we've built anything at all that will still be around in 5,000 years? (Fig. 1.5).

Snefru apparently thought that he could do better, thus he started a second pyramid at Dashur, a few miles south of Saqqara. This second one also developed structural problems (presumably), and the slope of the pyramid was changed *in mid-construction* (presumably to decrease the loads on the structure)! Thus, it is today called The Bent pyramid. Of all of the pyramids I have seen (on four continents), this one is my favorite. It is just amazing to me. Much of the limestone covering still coats the pyramid today, so you can see how the other ones must have looked long ago. But more than this, it is the sheer starkness of this proud

Fig. 1.5 Snefru's failed meidum pyramid. *Note* the rubble pile in the foreground

structure standing solemnly in the desert that strikes the visitor. And it has been sitting there for nearly 5,000 years. The next time you decide to make something, see if you can design it to last 5,000 years. Because if you succeed, people will quite possibly know you by name 5,000 years from now (Fig. 1.6)!

Snefru must not have liked The Bent pyramid as much as I do, because he built a third one. This one is only about a kilometer north of the Bent pyramid. Today it is called The Red pyramid because of some red markings found on the inside walls. This pyramid is truly magnificent! It is in fact the third largest pyramid ever built, and you can actually go inside it (without even having to wait in a long line of tourists, as one does at the Great pyramid of Khufu). It is enormous (Fig. 1.7).

So Snefru finally got it right. This haphazard approach to pyramid building must have been the largest and most costly example of structural design by trial and error in history, the gothic cathedral period notwithstanding (See Chap. 4). The thought of building such massive structures by trial and error today would

Fig. 1.6 Snefru's Bent pyramid. *Note* the limestone coating

Fig. 1.7 Snefru's Red pyramid. *Note* the third largest pyramid ever built

never enter into the minds of engineers. For one thing, their companies would go bankrupt by the second iteration. But such was the lack of understanding of mechanics by humankind less than 5,000 years ago.

There is one other thing worth mentioning regarding these pyramids. Snefru's engineers had no way of knowing how to build an arch in that day and time. Thus, they employed another ingenious method for making chambers inside the Red pyramid. Today we call it a corbelled arch, which consists of nothing more than quarrying long granite stones (Fig. 1.8) and successively canting the edges over one another as you go up. Using this construction technique they were able to build chambers more than 12 m in height inside the pyramids. This is an example of a quite ingenious application of mechanics. I'll bet a lot of workers came home with sore backs at the end of a work day, too.

The Eiffel Tower was built in 1889 (see Chap. 9). It is about 320 m (1,050 ft) tall. In more than 100 years since it was completed there have been in excess of 100 taller structures built on Earth. To live in our time is to live when it is expected that humans will build both larger and taller structures at an ever increasing rate. But the world was not always that way. Until Lincoln Cathedral was built in 1300, the tallest human-made structure on Earth was the Great Pyramid of Khufu at Giza (at about 150 m, or roughly half the height of the Eiffel Tower), which was built around 2,550 BCE.

According to Greek scientists from antiquity, the story goes that the first great scientist in history was a Greek named Thales (see Chap. 2). He lived in the sixth century BCE. Once in his lifetime he traveled from his home in Miletos to see the pyramids. Such was his fame that the Pharaoh invited him for a personal visit to the palace. During that visit the Pharaoh asked Thales if he could determine how tall this great structure *from antiquity* might be. That is how old the Great Pyramid is. It is so old that the pharaohs of the late Egyptian period in antiquity considered it to be from antiquity!

Thales solved the problem by using mathematics. He placed a pole called a gnomon (the forerunner of a sundial) in the ground and measured the height of the

Fig. 1.8 Corbelled arch inside the Red Pyramid. *Note* granite beams

gnomon and the length of its shadow. He then measured the length of the shadow cast by the Great Pyramid and by employing the principle of similar triangles he calculated the height of the Great Pyramid. This may be one of the first extant example of the use of trigonometry on Earth, a field of mathematics that is essential to mechanics.

From Thales' measurements, it is possible to calculate the volume of the Great Pyramid of Khufu, and given the volume of a typical stone used in construction, it has been estimated that approximately 2.3 million stone blocks (each weighing about 2,500 kg) were needed to complete the project. However, the means by which this mammoth structure was constructed remains a mystery to this day (Fig. 1.9).

Although archeologists have not been able to determine exactly how mechanics was used to construct the Great Pyramids, there are nevertheless some tantalizing clues. For example, there is some archeological evidence at the Temple of Karnak in Luxor that suggests that mud brick ramps may have been employed for raising at least some of the stones (Fig. 1.10). Furthermore, evidence suggests that stones may have been pulled on wooden sledges, and that they may have pushed them up the ramps on rollers. However, rollers are fraught with problems, especially on inclined planes, as the rollers continuously feed out the lower or back side, and this

Fig. 1.9 The Great pyramids of Giza

can be dangerous to the workers lower down the incline. Furthermore, rollers that are not both prismatic (constant cross-section shape and diameter from one end to the other), as well as all of the same size, present additional problems that can cause further danger to workers.

Several potential construction methods have been proposed by modern engineers, one of which may just be what actually was used. For example, it has been suggested that the stones were mounted with a disk on each end and rolled up ramps [9] (Fig. 1.11). A serendipitous benefit of this method is that because the rope is wrapped around the stones rather than the disks, depending on the relative size of the disk compared to the stones, the rope plays out slightly faster than the disks rotate, thereby giving a mechanical advantage to the persons pulling the disk. This is a nice problem in mechanics.

Another proposal, put forth by French architect Jean-Pierre Houdin (1951–), posits that a system of internal spiral ramps was first constructed, and the remaining blocks were hauled up within this complex. The structure of the Great Pyramid seems to be in agreement with this theory. But in reality, the construction techniques used to fabricate the Egyptian pyramids remain a great mystery to this day.

Several studies have been performed in recent years that assume one or more of the above construction techniques were utilized, and these studies have all concluded that the Great pyramid could have been completed in 10–20 years with a work force of between 10,000 and 40,000 workers. These manpower estimates are consistent with findings from recent archeological digs at the site that uncovered the staging area and living quarters of the workers.

As a first approximation of the human power required, consider a pyramid with square base of width, b, and height, h, as shown in Fig. 1.12.

Now consider the rectangular box shown in Fig. 1.13 of height, $2h$, and base, b. It can be seen from the figure that the volume, V_B, of the box is given by

$$V_B = 2h \times b \times b = 2hb^2$$

Fig. 1.10 Photo of the entrance gate of the temple of Karnak. *Note* remnants of the mud brick ramp

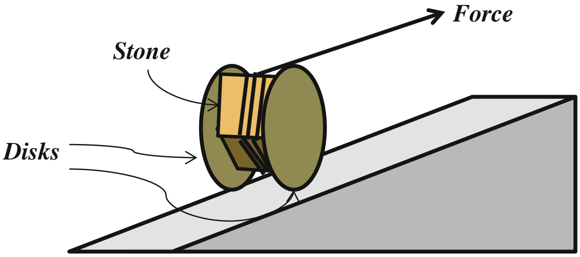


Fig. 1.11 A proposed technique for raising pyramid stones. *Note* the disks attached to the stone block

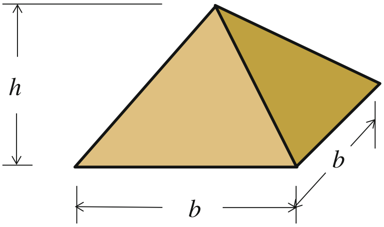


Fig. 1.12 Dimensions of a pyramid

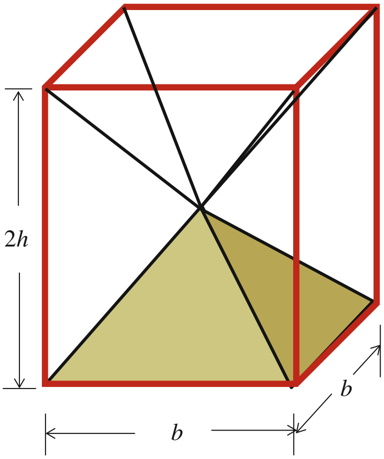


Fig. 1.13 A parallelepiped containing a pyramid

But it can also be seen from the figure that the box contains six pyramids of approximately the same size, so that the volume, V_P, of the pyramid can be approximated by

$$V_P = \frac{1}{6} V_B = \frac{1}{3} hb^2$$

The dimensions of the Great Pyramid of Khufu are approximately $h = 150$ m and $b = 230$ m. Thus, the volume of the Great Pyramid is approximately

$$V_P = \frac{1}{3} \times 150 \times 230 \times 230\,\mathrm{m} = 2,645,000\,\mathrm{m}^3$$

Now, we also know that the average volume, V_S, of the stone blocks is about $127 \times 127 \times 71\,\mathrm{cm} = 1.15\,\mathrm{m}^3$. Thus, if we assume for the moment that the pyramid is solid (no hollow chambers inside), the number of stones, N_S, in the Great Pyramid is approximately given by

$$N_S = \frac{V_P}{V_S} = \frac{2,645,000\,\mathrm{m}^3}{1.15\,\mathrm{m}^3/\mathrm{stone}} = 2,300,000\,\mathrm{stones}$$

We also know that the approximate density, ρ_S, of the stones is $2,500\,\mathrm{kg}/\mathrm{m}^3$. Therefore, each stone weighs about 2,900 kg.

Now, let's calculate the average height that a stone must be raised in the Great Pyramid. In order to do this, we need to calculate the height, $\overline{h}$, at which exactly half of the volume of the pyramid is above this plane, and half is below this plane, as shown in Fig. 1.14.

This height can therefore be determined by calculating the volume of the smaller pyramid as follows:

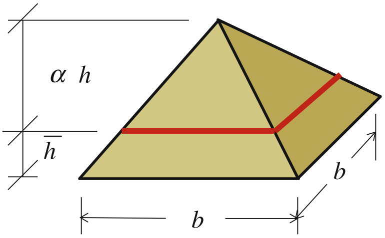


Fig. 1.14 Average height that blocks are raised within a pyramid

$$V = \frac{1}{2}V_P = \frac{1}{6}hb^2 = \frac{1}{3}\alpha h \times \alpha b \times \alpha b \Rightarrow \alpha^3 = \frac{1}{2} \Rightarrow \alpha \cong 0.7937$$

where it should be clear that the average height that a stone must be raised is given by

$$\bar{h} = (1 - \alpha)h = (1 - 0.7937) \times 150\,\mathrm{m} = 30.95\,\mathrm{m}$$

Thus, the average vertical work, W_S, required to move a stone into place is given by

$$W_S = \frac{9.8\mathrm{N}}{\mathrm{kg}} \times 2{,}900\,\mathrm{kg/stone} \times 30.95\,\mathrm{m} = 8.80 \times 10^5\,\mathrm{N{-}m/stone}$$

Extant archeological information seems to indicate that human power (as opposed to animal power) was used for most of the construction of the pyramids. Now the average person can raise a mass of 18 kg about 1,000 m in a single day (try carrying a 40 pound pack from the valley floor to Glacier Point in Yosemite National Park in a single day!). That's about 175,000 N–m/day. Thus, the number of days, N_D, that it will take the average person to raise a single stone 43.9 m is given by

$$N_D = \frac{880{,}000\,\mathrm{N{-}m/stone}}{175{,}000\,\mathrm{N{-}m/man{-}days}} = 5.03\,\mathrm{man{-}days/stone}$$

Multiplying the number of stones, N_S, by the number of days, N_D, required to raise that stone gives a total number of man days, N_T, of

$$N_T = 2{,}300{,}000\,\mathrm{stones} \times 5.03\,\mathrm{man{-}days/stone} = 11{,}600{,}000\,\mathrm{man{-}days}$$

Assuming that the workers put in about 90 days per year (recent excavations on the Giza plateau suggest that the laborers worked on the pyramids only during the period of the year after the crops had been brought in), this turns out to be about 128,000 man-years. Thus, a crew of 10,000 workers should be able to raise the stones into place in about 12.8 years. The above number needs to be amplified to account for quarrying and transporting the stones. In addition, there needs to be support staff to provide food and other services for the workers. Assuming that each of these three efforts require about the same human power as does the raising of the stones, we can see that the total estimate needs to be increased by a factor of four, giving a final estimate of about 51.2 years if a total of 10,000 workers are deployed for the project. Alternatively, a workforce of 20,000 could complete the project in about 25.6 years, and a workforce of 40,000 could complete the project in about 12.8 years. This gives a rough approximation of the building requirements for the Great Pyramid of Khufu that is consistent with more detailed estimates that have been reported in recent years. Several more accurate estimates have been made by researchers using the above approach, and all are fairly close to the approximation obtained herein.

While we do not know exactly what techniques were used to construct the Great Pyramid, this exercise in mechanics shows that the construction project is at least plausible with little more than a large labor force using the technology available at the time of Khufu's reign.

By about 2,500 BCE, the great pyramid building experiment had come to an end. The main reason for this appears to be that the economy declined, and there were not enough resources for succeeding pharaohs to pay 40,000 people for 13 years to build more of these massive structures. But there was another more philosophical reason why they stopped—the pyramids did not work. No matter how massively they were built, no matter how secretly they were designed, grave robbers broke in within a few short years and made off with the opulent furnishings. Thus, the pharaohs were forced to seek other ways of ensuring comfort in their life after death.

Nonetheless, the Great Pyramid of Khufu remained the tallest structure on Earth until 1,300 AD, and even today it remains the most massive structure ever built on our planet (excepting the Great Wall of China, which is really not a single structure anyway). As a result, it was accorded the honor of one of the Seven Ancient Wonders of the World (see below). As such, its impact on the modern world is truly incalculable.

Mummies

A thousand years passed, times of turmoil, and dissolution of the Kingdom of Egypt. Finally, in the middle part of the second millennium BCE, in a period called the New Kingdom (there was also a Middle Kingdom before that), a new funerary style of monument was conceived. A Pharaoh named Thutmose I (or possibly Amenhotep I) noticed a mountain on the west bank of the Nile that seemed to look a lot like a pyramid, only bigger, a whole lot bigger! This was promising, as everyone knew that you had to build your tomb on the west bank where the sun set, ergo life ended (Fig. 1.15).

Thus, Thutmose I decided to have a tomb carved out of the rock beneath the mountain. Instead of carting the stone out into the desert and building a mountain, why not go to the mountain and carve out the tomb right there? They built old

Fig. 1.15 Photo of King Tut's Tomb *.Note* the mountain dominating the Valley of the Kings in the background

Thutmose I this great tomb, and thus began the period of funerary construction in what has come to be called The Valley of the Kings. Archeologists have now uncovered 64 tombs in the Valley of the Kings. It is massive! (Fig. 1.16).

Fig. 1.16 Sketch Map of East Valley of the Kings

Now, one could write an entire book about the Valley of the Kings, and this has in fact been done, but we want to get to the heart of the issue—mechanics—herein as simply as possible. So here are the essential features of the valley. First, it is limestone, so it was relatively easy to quarry. The stonemasons simply dug shafts straight into the mountainside, and any old haphazard direction would do (probably suggested by the current pharaoh). Once they had built a nice large cavern suitable for a sumptuous life after death (note that the room size was limited by the strength of the limestone, a problem in deformable body mechanics—see Chaps. 7 and 13), they spruced them up with statuary and wall paintings. All of these tombs were built using mechanical devices. Given the tools available at that time, it was nevertheless quite labor intensive.

Unfortunately, just as in the case of the pyramids, robbers eventually broke in and stole the contents. In most cases, the robbery occurred within a few short years after interment of the pharaoh, and the robbers were most likely the very same persons who built the tombs. The moral of this story is: if you build a large enough tomb to live in comfort in the afterlife, the number of workers required to build it exceeds the number that you can get away with "eliminating" to preserve confidentiality. So the tombs got robbed more than 3,000 years ago*, at least all but a precious few!*

This brings us to the story of Tut-Ankh-*Amen*. Today we often call him The Boy King, because he died young, perhaps around the age of 19. We know this because we have his body, or perhaps more properly, his mummy.

In the case of the pharaohs, only they were allowed to be mummified with their arms crossed. *Voila* (French meaning literally—see there)! Any mummy found today with crossed arms is a pharaoh. And surprisingly, a fair number exist and have been identified (usually by items placed in the wrappings by the embalmers).

Back to King Tut. During the early nineteenth century (shortly after Napoleon's departure) treasure hunters, drifters, robbers, and even a few bona fide archeologists converged on the Valley of the Kings. Probably the first of these to do any systematic excavation was the Italian Giovanni Battista Belzoni (1778–1823) (Fig. 1.17). He was perhaps the first to study the tomb of Ramses VII, which had been open since ancient times. Thus, today it is called KV 1 (meaning King's Valley, number one excavation). And so it went, right up to number KV 62-Tut. Today there are a couple more that were discovered after King Tut's tomb, so that the current count is KV 64. They were almost all empty, having been broken into by robbers (a notable exception is the tomb of Seti I-KV-17, discovered by Belzoni, some of whose furnishings are now in the Cairo museum).

By the late nineteenth century, archeologists had a clear idea of the chronology of the pharaohs because of Champollion's deciphering of the Rosetta stone (more on this in Chap. 9). There was a conspicuous problem after the reign of the heretic pharaoh Akhenaten. He had attempted to change the official state religion from polytheism to worship of a single god—Aten. And he had moved the capital from Thebes (modern day Luxor) to Amarna. He was apparently so physically peculiar that a few theorists have even suggested that he came from outer space! (Fig. 1.18).

Fig. 1.17 Giovanni Battista Belzoni

Fig. 1.18 Bust of Akhenaten from the Cairo Museum. *Note* his elongated face

Extant records seemed to indicate that after Akhenaten's death his son Tut-Ankh-*Aten* had succeeded to the throne at the age of nine. But in some places, Tut's name had been erased from the record. It's pretty difficult to construct a history when all you have is a bunch of carvings on stone walls, many of which were subsequently defaced. But eventually archeologists were able to establish that Tut had actually lived, and that after Akhenaten had died, the state religion had reverted to the old polytheistic one.

Tut was apparently persuaded by his advisors to change his name to Tut-Ankh-*Amen*, meaning spirit of Amen, rather than spirit of Aten. Now here is the most interesting part—when they began searching for the tombs of the pharaohs from the New Kingdom in the nineteenth century, there seemed to be no tomb for King Tut. The pharaohs after Tut were all discovered in the Valley of the Kings. There was no sign of Akhenaten's tomb. Presumably, his tomb was in the ill-fated city of Amarna, today almost totally destroyed by the winds and sands of time, another problem in mechanics. But there was also no sign of Tut's tomb.

Had Tut been buried at Amarna? If so, his tomb would have been destroyed by now. Archeologists doubted this possibility due to the simple fact that Amarna had been abandoned shortly after Akhenaten's death. So they reasoned that there should be a tomb for Tut in the Valley of the Kings. All the others had been found, and all had been robbed. But if Tut had been buried there, it might just be possible that his tomb had not been robbed because he had died young enough that his tomb might have been rather simple by the standards of the others in the valley. Thus went the reasoning of those searching for Tut's tomb less than a century ago.

Quite a few people were looking for Tut's tomb in the Valley of the Kings at the turn of the twentieth century. It may be hard to believe given today's technology, but the only way at their disposal was to simply dig by hand. This was backbreaking work, and the climate was extremely harsh. Many Western Europeans died of exposure or from disease. Belzoni himself had succumbed to dysentery earlier.

Enter George Herbert, 5th Earl of Carnarvon (1866–1923), a wealthy Englishman. He bankrolled an effort to find Tut's tomb, and he employed one Howard Carter, a sort of soldier of fortune turned amateur archeologist (there was really no such thing as an archeology "profession" at the time. See Chap. 2).

Since most reasonable locations in the Valley had already been excavated, Carter chose a rather inconspicuous spot just downhill from the site of the burial tomb of Ramses V, who came to the throne after Tut. Carter reasoned that Tut might have been buried not too long *before* another far more famous Pharaoh, whose tomb diggers might have actually covered over the entrance to Tut's tomb with rubble from their excavations. Thus, Carter dug at a spot where there was a large mound of discarded rocks, presumably from Ramses V's tomb.

We all know the story—Carter turned out to be correct, and in 1922 he discovered the tomb of King Tut-Ankh-*Amen*. Many archeologists today consider this to be the greatest archeological discovery of all time. There are lots of reasons why, but if you want to see one (or rather more accurately 5,000) reason(s), stop in at the Cairo Museum when you visit Egypt. There you will find almost everything that was taken from Tut's small tomb (that is, assuming that you can outmaneuver the enormous crowds!). There is just no way to describe it all. You just have to see it to believe it. You will also discover from this treasure trove that the Egyptians were employing plenty of sophisticated *mechanical* tools nearly 4,000 years ago (Fig. 1.19).

Fig. 1.19 Howard Carter examining King Tut's Sarcophogus

One other thing—when you go to the Valley of the Kings, aside from the general entry fee, the only tomb you have to pay to get into see is that of King Tut, and it's not cheap! I made the mistake of heeding my guide's advice to avoid Tut's tomb the first time I went there, and I did not go inside. Because of subsequent unrest in Egypt, it would be 10 long years before my second chance occurred.

Do not miss your opportunity to go inside the tomb of King Tut! True—it is small compared to the other tombs—but there are at least two reasons to go inside. The first reason is that Tut himself is now displayed therein (Fig. 1.20). He is really worth seeing, at least in part because of the ballyhoo that has surrounded his supposed cause of death in recent years. The second reason is that the tomb is really quite small. In fact, after observing the myriad of artifacts taken from his tomb it is hard to imagine how they all fit within such a tiny space. Thus, upon seeing the rather sumptuous quarters for the other pharaohs, one can do some mind boggling extrapolation, thereby guessing how much opulence must have been carried into the other tombs to accompany the pharaohs into the afterlife. And this will in turn explain why they were all robbed! And now you have a better idea of why King Tut is so important to our history. Hopefully, you also understand the multiple roles that mechanics played in his life, death, after-life, and subsequent re-discovery.

It turns out that quite a few of the mummies of the pharaohs are still extant today, and that is a story in itself. It seems that several times during the history of Egypt there were periods of strife and turmoil, oftentimes associated with famines resulting from low flooding of the Nile (a problem related to mechanics—see Chap. 10). During one of these periods the clerical order apparently became concerned that the mummies of the pharaohs might be disturbed. They had kept watch over the mummies in the Valley of the Kings, and in many cases, despite the fact that the tombs had been robbed, the mummies therein had remained intact. Thus, on one of these occasions, the clerics decided to remove the mummies to a place of safety. For reasons that are obscure today, they chose to place many of

Fig. 1.20 Mummy of King Tut

them in tomb DB320 at Deir el-Bahri, above Hatshepsut's mortuary temple (discussed below). This happens to be over the crest of the mountain, in a valley adjacent to the Valley of the Kings.

In 1881, these were rediscovered, fittingly by a family of "professional" grave robbers. So the mummies of these pharaohs have now been restored to the Egyptian people, and you can see them at the Cairo museum. I highly recommend that you pay the rather small additional fee to visit the two rooms containing the mummies in the museum. There you can see such pharaohs as Ramses II (1303–1213 BCE), who may have been the pharaoh when Moses led his people from Egypt to the Promised Land (Fig. 1.21).

I do not know how you would feel to have your corpse on public view, but if I had been a pharaoh more than 3,000 years ago, I would be proud to have people come and see me in my splendor today. And this is the only place that I know of on earth where you can see so many royals from ancient times.

How in heck are we able to even examine a body 3,500 years old? The reason is technology: the Egyptians discovered how to preserve the body of the deceased so well that we have lots of mummies still in existence today. It is a long story, but basically, they appear to have discovered more or less by accident that bodies buried in natron, a salty natural geologic material found in the western desert, would naturally dry out without decomposing the skin and tissue (Fig. 1.22).

Fig. 1.21 The Mummy of Ramses II

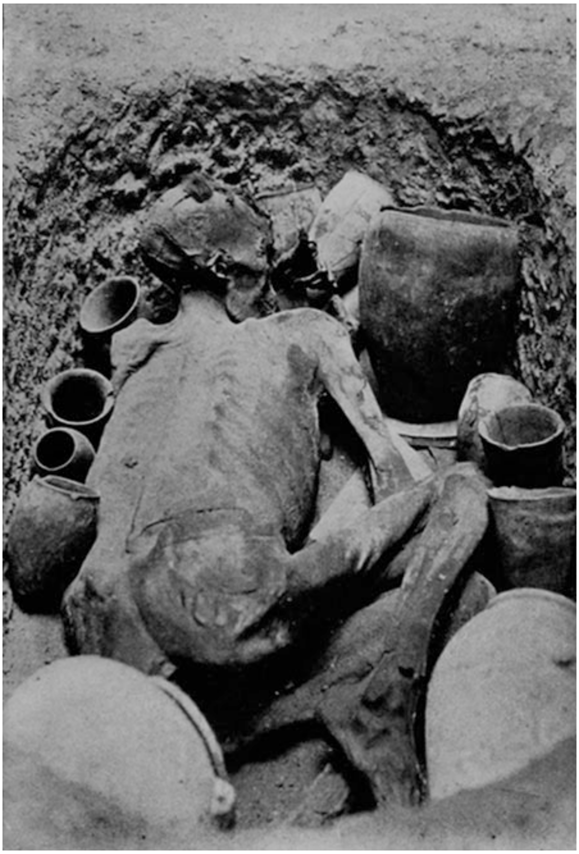


Fig. 1.22 Ginger—a naturally mummified body

There were of course complications; the internal organs had to be extracted carefully, and the remaining tissue after the drying process had to be properly protected against decay. But they figured all the details out through careful experimentation that is not unlike the scientific method of today, and once they had perfected it, they were able to "mummify" any corpse for a price.

Before leaving the entrancing subject of mummies, I suppose I'd better give you a reason why it is found in a book on mechanics. The real reason is that I just find it a very interesting subject, but I can also give a technical reason that bears some merit. As I mentioned earlier, mummification is quite an art in and of itself. Indeed, there are few other extant cases of bodies being preserved so well for thousands of years. Part of the problem is chemistry. Biologic tissue is prone to decay fairly rapidly with time. Furthermore, other biologic entities like to consume biologic tissue for sustenance. This part is not related to mechanics.

But at least a part of mummification is linked to mechanics, and this part is related to the mechanics of deformable solids, a subject that will be discussed at length in Chaps. 7 and 9. Suffice it to say that unless a body is mummified properly the skin will eventually undergo sufficient stretching and drying that it will crack into small remnants, thus destroying the integrity of the mummy. This part of mummification is related to the mechanics of fracture (see Chap. 13). I know, it is a bit of a stretch (once again, pun intended), but this is my reason for including mummies in this book on mechanics!

Still, the question remains—exactly how did Egyptian mummies shape the modern world? Well, for one thing, the search for these mummies employed quite a few archeologists and anthropologists. Without the discoveries of these incredibly devoted scientists, we would not have unlocked many of the now well-understood discoveries regarding our ancestors. Thus, I for one believe that the mechanics of mummies have indeed had a profound impact on our modern world.

Obelisks

As I mentioned earlier, the Egyptians began quarrying granite a long time ago. No one is quite sure when they began doing this, but we do have extant granite corbelled arches, as well as granite statues depicting pharaohs from the New Kingdom, so we know that they were quarrying granite more than 4,000 years ago. Perhaps the most prolific of the statue builders was none other than Ramses II, who seems to have understood better than any other pharaoh that granite statues would stand the test of time, thereby ensuring his own immortality (Figs. 1.23 and 1.24).

All of the extant Egyptian obelisks today came from the quarries along the Nile. The oldest one was constructed for Senusret I (ruled 1971–1926 BCE) of the twelfth dynasty. The remaining ones were all quarried before about 1,300 BCE (Try finding something that old in the U.S., or anywhere else, for that matter!). They became very highly prized items during the Roman period, and for obvious reasons—they were made of one of the hardest materials known to man at the time, and they were massive.

By the way, there are 29 extant Egyptian obelisks in the world today. Nine are in Egypt, and eleven in Italy (eight of which are in Rome, having been pilfered by the Romans after Augustus defeated Antony and Cleopatra in 31 BCE, thereby conquering Egypt). Others are scattered across the world. There is one in Paris, one in London, and even one in New York City. No one knows how many were

Fig. 1.23 Collage of photos of colossal granite statue of Ramses II at Memphis. *Note* relative dimensions of people in the background

Fig. 1.24 Granite head of statue of Amenhotep III (1370 BCE) discovered at the Temple of Mut in Karnak by Giovanni Belzoni and Henry Beechey in 1817, now in the British Museum

lost, but you can bet there weren't many. An obelisk is pretty hard to lose, which is one reason why everyone wanted to have one in ancient times (and still do!).

Aside from the unfinished obelisk (see below), the tallest obelisk in the world (32 m) is at the Lateran Basilica in Rome. The most interesting to me are the two (22 m) that were originally at the Temple of Luxor in Egypt. The one on the right side of the entrance was given by Egypt to France in 1829, thus it now resides in the Place de la Concorde in Paris (where the prisoners were mechanically guillotined during the French Revolution). There is a plaque at the base that shows how it was transported from Egypt to Paris by barge, which is not a simple feat. It is in fact a very complicated problem involving mechanics (Figs. 1.25 and 1.26).

Another one of my favorites is the Obelisk of Hatshepsut (1508–1458 BCE), who appears to have been the most successful and longest reigning female pharaoh. It is located within the massive temple of Karnak. Apparently, Hatshepsut was not well liked by her successors Thutmose II and Amenhotep II, for they attempted half-heartedly to expunge her name from the pharaonic record. One of their failed attempts included an effort to wall up Hatshepsut's obelisk. Fortunately for us today, that attempt was unsuccessful (Fig. 1.27).

Fig. 1.25 Luxor Temple with Granite Obelisk. *Note* that the obelisk on the right side is missing

Fig. 1.26 Luxor Temple's Twin Obelisk in Paris Place de la Concorde. *Note* the plaque at the base describing the method of transport

Hatshepsut built many monuments during her reign, including Hatshepsut's temple, which was ingeniously carved from a mountainside in Luxor near the Valley of the Kings, another great challenge in mechanics (Fig. 1.28).

All of these fabulous achievements of the Egyptians became known throughout the ancient world as a result of the interactions of traders and migrants. Suffice it to say that once the Egyptians made these amazing advances using mechanics, other civilizations followed suit.

Today we know how the obelisks were quarried. If you go to the quarry at Aswan, you can actually see the largest granite obelisk in the world, called the unfinished obelisk, because it is still in the Shellal northern quarry (Fig. 1.29). It was apparently fractured during construction and was thus never completed. Off to one side of the quarry you can see a spot where the technique of construction is elucidated. Ancient stone workers either hammered wooden wedges into the stone,

Fig. 1.27 Queen Hathsepsut's Obelisk at the Temple of Karnak

Fig. 1.28 Hatshepsut's Temple

or they used a turning tool with a stone on the tip, typically made of dolomite, together with sand to grind a shaft into the granite stone, and they did this at carefully planned spatial intervals. Once the shaft was completed a wooden dowel was placed into the shaft and it was immersed in water. The resulting swelling of

Fig. 1.29 The Unfinished Obelisk, still laying in the quarry at Aswan after more than 3,000 Years. *Note* the evidence of excavation around the obelisk

the dowels caused the granite to crack, thereby allowing the quarrying process to move forward. This is clearly quite labor-intensive! Furthermore, once the obelisk was quarried it had to be polished, which was accomplished with fine sand, a commodity that was available in abundance because most of it blew in from the western desert. All of this involved rather ingenious applications of mechanics, which is the main reason that Egyptian obelisks made their way into this book.

As you might imagine, the transport and righting of obelisks was also a massive project involving mechanics. The key to the transport of obelisks in ancient times was the annual flood of the Nile. The trick was to find a quarry that was very close in elevation to the river. Thus, when the obelisk was ready for transport, it was a simple matter to attach barges to each side of the obelisk. When the river rose during the annual flood the barges lifted the obelisk so that it could be floated down the Nile. We now know that the Egyptians built a multitude of enormous barges for purposes such as the transport of obelisks. These barges were necessarily massive construction projects that were accomplished with the aide of mechanics.

Once the obelisk arrived at its intended destination, it was erected by (supposedly) sliding it into a sand pit, from whence the sand was slowly removed, righting the obelisk in the process. This is another impressive project involving mechanics.

Anyone who has traveled to one of any number of major cities across the world has seen one of the original Egyptian obelisks. Still more obvious, there are enormous copies of these monoliths almost everywhere one turns (such as the Washington Monument, which at 169 m is the tallest obelisk in the world). There is even one outside my window on my own college campus. More importantly, however, the Egyptians served notice to the world by their inventive quarrying techniques that even the hardest of stones could be made into beautiful structures and artworks. And as we know today, these are among the most enduring man-made objects on Earth, thus ensuring their impact on our modern world.

The Seven Ancient Wonders of the World

Perhaps no symbols from antiquity better emphasize the use of mechanics than structures. Of these, perhaps the most famous were the seven Ancient Wonders of the World. With the exception of the Great Pyramids, the Ancient Wonders of the World were built during the period we call Classical Antiquity [1]. The seven ancient wonders are in chronological order, as follows: the Great Pyramid of Khufu (2,550 BCE); the Hanging Gardens of Babylon (600 BCE); the Temple of Artemis at Ephesus (550 BCE); the Statue of Zeus at Olympia (435 BCE); the Mausoleum at Halicarnassus (351 BCE); the Colossus of Rhodes (292 BCE); and the Lighthouse at Alexandria (280 BCE). Of these, only the first survives today.

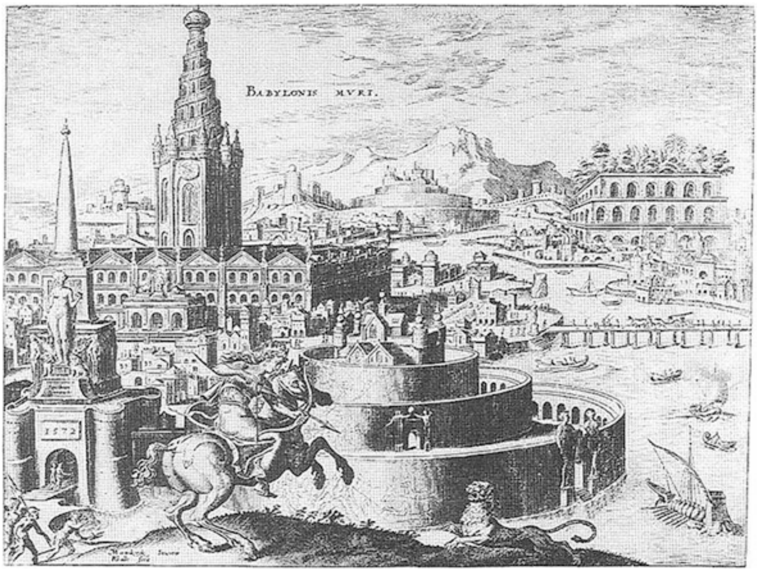


Fig. 1.30 Sixteenth century engraving of the Hanging Gardens of Babylon by Maarten van Heemskerck

Fig. 1.31 Sixteenth century image of the Temple of Artemis by Maarten van Heemskerck

Fig. 1.32 Sixteenth century rendition of the statue of Zeus at Olympia by Maarten van Heemskerck

Fig. 1.33 Mausoleum of Halicarnassus today

Fig. 1.34 1880 depiction of the Colossus of Rhodes

Fig. 1.35 1909 drawing of the Lighthouse of Alexandria by H. Thiersch

The remaining structures were all destroyed in antiquity (Figs. 1.30, 1.31, 1.32, 1.33, 1.34 and 1.35).

I will not go into detail regarding these wonders, since you can simply search for them on the Internet and find out whatever you need to know about each of them. Suffice it to say that each one was accomplished using mechanics. Exactly how they were built is another matter. The fact is we do not know precisely how any of these ancient wonders were built. There has been much speculation on this subject, but until someone uncovers a definitive archeological record, speculation is as far as we can go. However, one thing is certain: because these structures were well-known and highly regarded in ancient times, they were emulated by others, thus spurring the development of numerous additional construction projects that employed mechanics.

Thus, as we have seen in this chapter, mechanics has been used by humans for a very long time. And these early developments, though in many cases haphazard in their approach, served as beacons for the first culture to study mechanics systematically—the Greeks.

The Greeks

2

If thou art able, O stranger, to find out all these things and gather them together in your mind, giving all the relations, thou shalt depart crowned with glory and knowing that thou hast been adjudged perfect in this species of wisdom.

Archimedes (c. 287–212 BCE)

The Dawn of Mechanics

As we have seen in Chap. 1, the Greeks were not the first to achieve scientific discoveries on Earth. Still, they are the first culture to assemble a significant body of scientific developments that has stood the test of time. Indeed, their impact on the world cannot be overestimated. At least a part of their achievements may be attributed to a societal taste for the written word. Indeed, the Greeks appear to be the very first culture on Earth to employ the written word ubiquitously, and although their language is certainly not the oldest on Earth, it is the first to employ vowels, thus making it more versatile than its predecessors. This thirst for the written word takes its roots in the works such as the Iliad and the Odyssey, by Homer, and written sometime in the eighth century BCE in an early version of Greek. Shortly thereafter numerous schools of belief began to develop, such as the Ionian School, the Atomistic School, the Stoic School, the Socratic School, the Aristotelian School, and the Pythagorean School. As such, the Greeks may be said to have developed the first systematic approach to education on Earth.

By the fifth century BCE, many works were written for public consumption. Perhaps the most important writer in Greek history was Herodotus (484–425 BCE), who wrote *The Histories*, for which he is considered to be the father of history (Fig. 2.1) [15]. While his oeuvre bears no direct relation to mechanics, *The Histories* influenced the subsequent development of the use of Greek, thus allowing scientists a means of recording their achievements and inventions both for posterity and the education of their progeny. Within a short period of time several other authors appeared, such as Thucydides, Xenophon, and Polybius. And while many of these were subsequently lost in time, quite a few survived, and as we will see below, a few are still being rediscovered today. Thus, it is apparent that the Greeks were the first culture on Earth to practice science systematically, and to utilize it for educational purposes.

D. H. Allen, *How Mechanics Shaped the Modern World*,
DOI: 10.1007/978-3-319-01701-3_2,

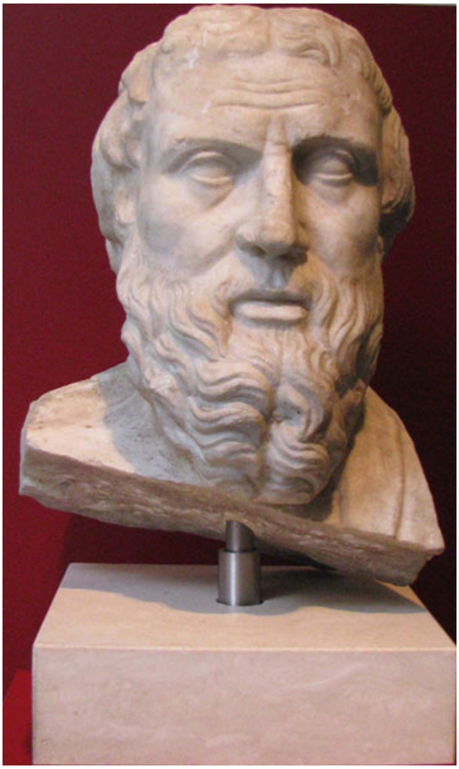


Fig. 2.1 Bust of Herodotus, National Museum of Rome

I suppose that the high point for the Greeks was the fifth century BCE, when Pericles (c. 495–429 BCE) and his colleagues built the Parthenon on the Acropolis in Athens (Fig. 2.2). The Parthenon was begun in 447 BCE and completed in 436. It was during that period that the Greeks established the first successful democracy on Earth (Fig. 2.3).

Interestingly, the Parthenon was partially destroyed when the Venetians bombed it on September 26, 1687, accidentally setting off an ammunition dump within. Today, the Greek government is engaged in a long-term effort to restore the structure to its original look. During the process, they have discovered that essentially every single piece of stone within the great structure was cut in place to fit a specific location, thus making it what some have described as the largest jigsaw puzzle on Earth. Indeed, the reconstruction of the Parthenon is an interesting challenge in mechanics.

More importantly, the Greeks became the first society on Earth to develop an advanced body of science. Apparently, their democratic form of government encouraged an explosion of scientific inquiry that produced discoveries that in many cases are still valid today. Numerous Greek scientists made advances in the field of mechanics during this period of history. The most remarkable of these are recounted briefly below in chronological order.

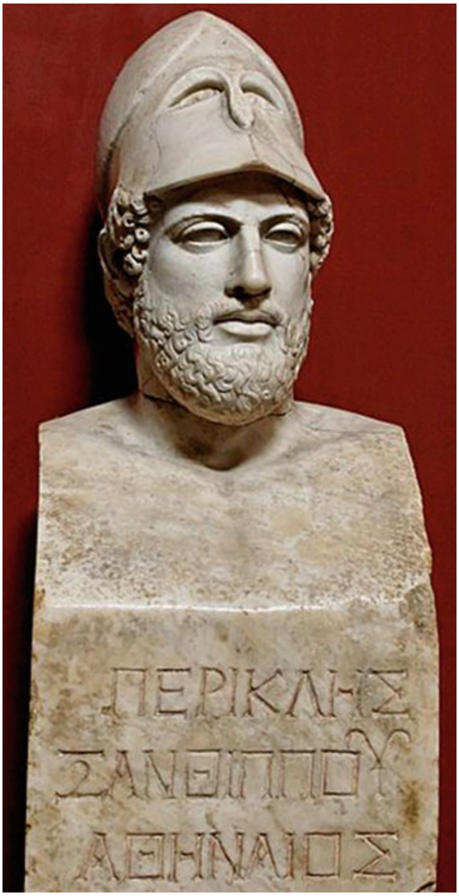


Fig. 2.2 Bust of Pericles, Vatican Museum

Fig. 2.3 Photograph of the Parthenon. *Note* the renovations underway

Thales of Miletus (c. 624–546 BCE)

Thales may be the first scientist known to us by name. Not much of Thales' works survive today. Thus, our primary means of determining his importance is via the numerous references to him by later philosophers and scientists. It seems that he was one of the first, if not the very first, to propose a scientific method based in logic rather than mythology. As such, his role in the evolution of science is self-evident.

As described in Chap. 1, there is a story that Thales visited Egypt once in his lifetime, and that the pharaoh asked him to measure the height of the ancient pyramid of Cheops. Thales did so by placing a gnomon in the ground and comparing the length of the shadow it cast to the length of the shadow cast by the great pyramid. This story demonstrates the ingenuity of Thales. Thales also is thought to have believed that the Earth is spherical, and he is known to have predicted a solar eclipse. There is little additional direct evidence of his accomplishments, but the universal reference to him by all those who followed is ample reason for his inclusion herein (Fig. 2.4).

Pythagoras of Samos (c. 570–495 BCE)

It is believed that Pythagoras, a student of Anaximander (c. 610–546 BCE), visited Thales early in his life, and that Thales affected him profoundly (Fig. 2.5). We know little about Pythagoras himself, but we do know that the Pythagorean School was all-important in the development of mathematics. For example, the theorem

Fig. 2.4 Depiction of Thales of Miletus

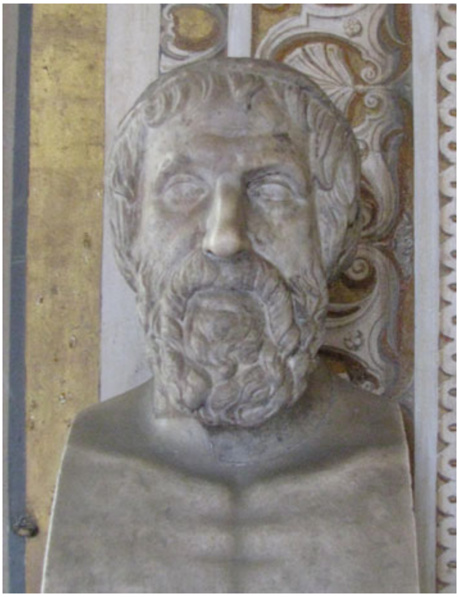


Fig. 2.5 Bust of Pythagoras in the Vatican Museum

that bears his name, called the *Pythagorean Theorem*, is one of the most important concepts in all of mechanics, providing a mathematical means of calculating the distance between any two points in space. Without this theorem, mechanics would not be a science.

Although there are no surviving documents proving that Pythagoras is responsible for the theorem that bears his name, the fact that this theorem does indeed bear his name suggests emphatically that the theorem was at least developed by someone within the Pythagorean School, if not Pythagoras himself.

Pythagoras is also known to have studied the nature of vibrating strings. This may have been related to the fact that he was an accomplished musician with the lyre. At any rate, he is known to have discovered that strings produce harmonious sound when the ratios of the lengths of the strings are whole numbers (more on this subject in Chap. 8).

Democritus (c. 460–370 BCE)

Democritus is considered by many to be the father of modern science. He formulated a complex theory of the universe that postulated the existence of atoms, the first reference in history to atoms. From the standpoint of mechanics, he may be considered to be the first person in Western culture to espouse a mechanistic view of the world, based on postulates that are rooted in experimental observation.

Democritus is sometimes called ‘‘the laughing philosopher” due to his apparent penchant for scoffing at propositions with little or no logical basis (Fig. 2.6).

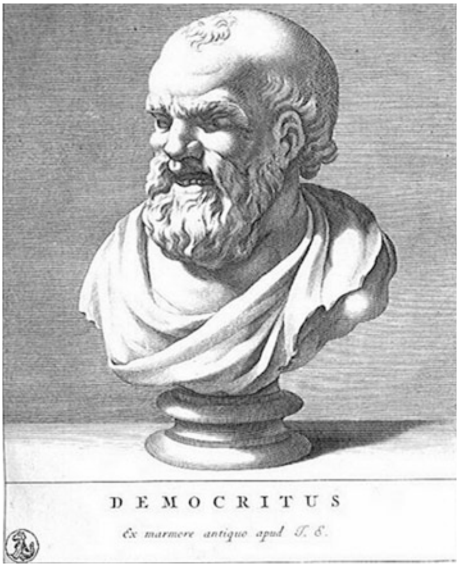


Fig. 2.6 Depiction of Democritus

Aristotle (384–322 BCE)

Aristotle was perhaps the most multi-disciplined of all of the Ancients (Fig. 2.7). His contributions span philosophy, mathematics, and most importantly to the current text—mechanics. He was clearly brilliant, as evidenced by his place as tutor to Alexander the Great, as well as his writings on philosophy. As a result, he is considered to be the father of modern logic. More than any other Greek, his works have remained relevant today.

Aristotelian mechanics remained the predominant theoretical framework until the seventeenth century, when it was supplanted by Galileo, Kepler, and Newton (see Chap. 7). Unfortunately, some of his views on mechanics proved to be incorrect, and these errors later caused serious upheaval between the Roman Catholic Church and the scientific community, resulting in quite a few unfortunate disagreements, such as those involving Giordano Bruno (executed by the Inquisition in 1600, see Chap. 7) and Galileo (convicted by the Inquisition in 1633, see Chap. 7).

For example, we have from Aristotle the following: the Moon is a perfect sphere; the Sun orbits the Earth; and heavy bodies fall faster than light ones. Although these were later proven to be incorrect, the fact remains that Aristotelian mechanics prevailed for two millennia, making Aristotle one of the preeminent practitioners of mechanics.

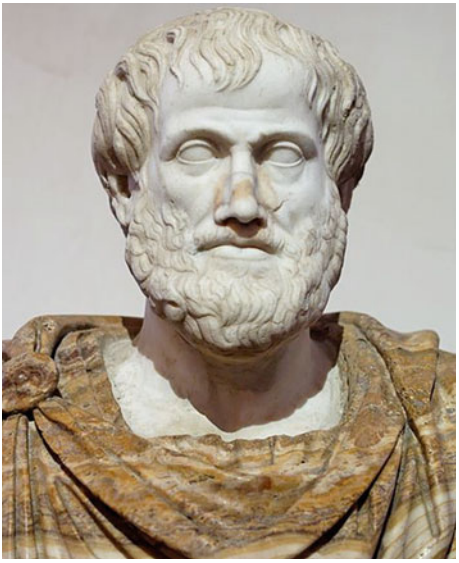


Fig. 2.7 Bust of Aristotle, National Museum of Rome

Euclid of Alexandria (3??–2?? BCE)

Little is known of the life of Euclid of Alexandria, although it is known that he predates Archimedes, who referred to him in his own works. The purists among you may wonder what Euclid is doing in a book on mechanics, since his achievements were in mathematics. To be honest, I have encountered this very problem with a host of Greek scientists—whether or not to include them in this text despite the fact that their contributions were not technically in the field of mechanics. In all other cases I have drawn the line on the conservative side (leaving quite a few deserving scientists out), but in the case of Euclid, I simply could not bring myself to do so. I have only one excuse—this man profoundly affected me personally, and had he not done so, I might not have become a student of mechanics.

I studied Euclidean geometry in high school. Its impact on me was immediate and life-long. And though the mathematics was intriguing, I can honestly say that Euclid's system of logic was what enraptured me so thoroughly. Here is one of the great scientific achievements of antiquity, and I for one believe that much of mechanics derives directly from his logical approach to geometry. Thus, I felt honor-bound to include him in this text.

In his text *Elements,* Euclid deduced the principles of geometry from a small set of fundamental principles called axioms. And amazingly, this approach to geometry (as well as many other fields of science) has endured right down to this day. I felt fortunate to have been taught Euclidean geometry in school. I am

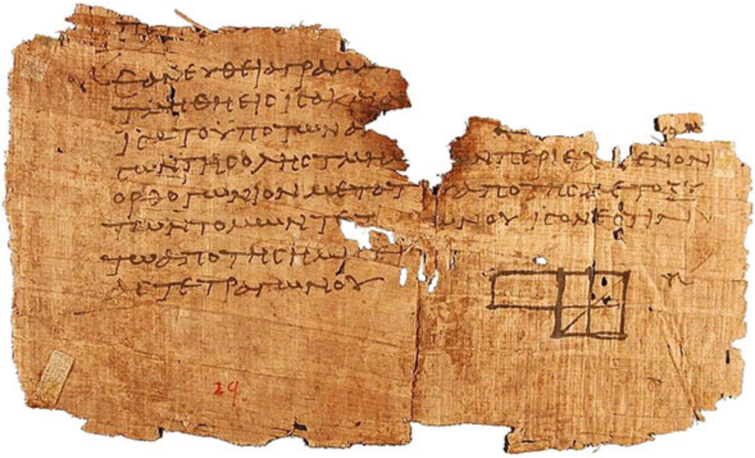


Fig. 2.8 Photograph of one of the oldest surviving fragments of Euclid's *elements*

distraught to learn that the teaching of Euclidean geometry appears to be in rapid decline today. This does not bode well for the future of mechanics, indeed for all of science (Fig. 2.8).

Aristarchus of Samos (310–230 BCE)

Aristarchus was the first person known to have proposed a Sun-centered universe (Fig. 2.9). Once he made the assumption that the solar system is Sun-centered, he was able to predict the order of the planets by observing their motions, a problem in mechanics. He thus placed the planets in correct order within his Sun-centered universe. Unfortunately, his views were not widely accepted until the time of Isaac Newton, as most humans accepted the geocentric theory of Aristotle.

Archimedes (287–212 BCE)

Certainly, there were many Greek scientists before and during the Hellenistic period who studied the motion of bodies, and while Aristotle is known to have expounded the principle of the lever, the historical record must surely point to Archimedes as the most important mechanist from antiquity (Fig. 2.10).

Archimedes gave a detailed account of the principles associated with the lever, and although slightly flawed, they can be said to contain the essential components of modern statics as embodied in Newton's First Law. They may also be viewed as a forerunner of the principle of virtual work.

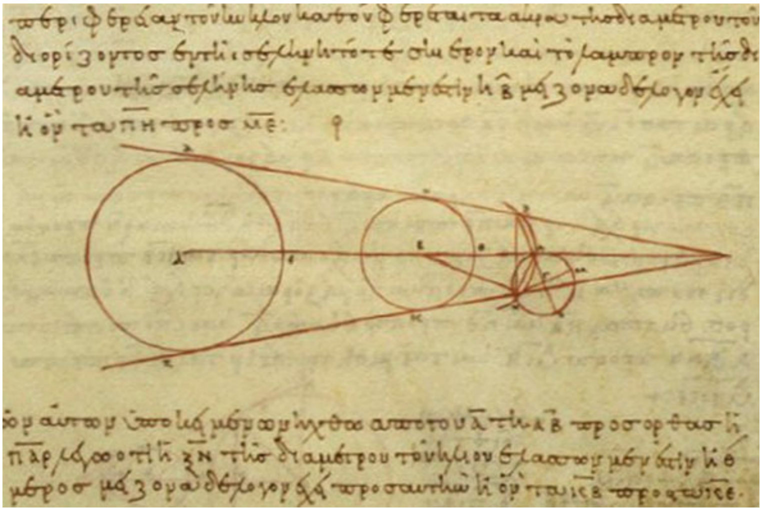


Fig. 2.9 Tenth century AD Greek copy of Aristarchus' second century BCE calculations of the relative sizes of the Sun, Moon, and the Earth, Library of Congress Vatican exhibit

Fig. 2.10 Modern Portrait of Archimedes by Domenico Fetti, Gëmaldegalerie Alte Meister, Dresden

Archimedes' Principles of the Lever are summarized as follows [16]:

Proposition 1 Equal weights at equal distances are in equilibrium, and equal weights at unequal distances are not in equilibrium but incline toward the weight which is at the greater distance.

Proposition 2 If, when weights at certain distances are in equilibrium, something is added to one of the weights, they are not in equilibrium but incline toward that weight to which the addition was made.

Proposition 3 Similarly, if anything is taken away from one of the weights, they are not in equilibrium but incline toward the weight from which nothing was taken.

Proposition 4 When equal and similar plane figures coincide if applied to one another, their centers of gravity similarly coincide.

The Law of the Lever: Two weights balance distances reciprocally proportional to their magnitudes.

The law of the lever may be stated mathematically as follows:

$$M_1 \times L_1 = M_2 \times L_2$$

where the quantities in the above equation are as shown in the figure below. It can be seen that the above formula is a simple application of summation of moments for a body at rest (Fig. 2.11).

While Archimedes' achievements with the lever alone would certainly ensure his place in the history of mechanics, there was much more to come from this great scientist. He also expounded the principle of buoyancy in great detail, thus recording the first significant results on deformable bodies and their properties [17]. He is said to have accomplished this in response to a request by the King of Syracuse. Apparently, the king suspected the goldsmith who had crafted his golden crown to have used some lesser quality metals within the crown. Thus, he charged Archimedes with the responsibility of proving this to be the case.

Archimedes is said to have been bathing at the public bath when he suddenly realized that he needed only to be able to accurately measure the volume of the crown in order to also be able to determine its density (by dividing by its weight, which could be obtained from the above-elucidated principle of the lever). Since he himself had displaced his volume of water when he had stepped into the bathing pool, he realized in a flash that the same technique could be used to measure the volume of the crown (which did in fact turn out to be partly made of lighter metals). It is recorded that in his haste to expostulate this new-found result, he raced through the street naked shouting, "Eureka (I found it!)!"

Archimedes is also known to have proven the relationship between the circumference of a circle and the area, in the process estimating the value of pi

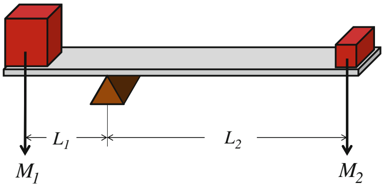


Fig. 2.11 Depiction of terms used in Archimedes' principle of the lever

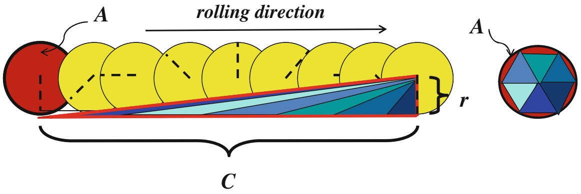


Fig. 2.12 How Archimedes related the circumference of a circle to its area. *Note* that the sum of the bases of the inscribed triangles, each with height r, equals C, the circumference of the corresponding circle

(denoted by the Greek symbol π) quite accurately (see Chap. 7) [18]. To see how Archimedes accomplished this amazing mathematical feat first recall that pi is defined to be the ratio of the circumference, C, divided by the diameter, D, which is also equal to twice the radius, r, so that

$$\pi \equiv \frac{C}{D} = \frac{C}{2r} \Rightarrow C = 2\pi r$$

where the symbol $\equiv$ implies "is defined to be". Archimedes recognized that when he rolled a circle on its edge one complete revolution (C), it plotted out a secession of triangles whose area fit neatly within the area of the circle, as shown above in (Fig. 2.12).

Given that the area of a circle is exactly half of the product of the two perpendicular sides, he was able to calculate the area of the triangle constructed by aligning the triangles:

$$A = Cr/2 \Rightarrow C = 2A/r$$

Archimedes then made his most important step in the proof. By recognizing that the larger the number of triangles that he embedded within the circle, the closer the aligned edges of the triangles approached the circumference of the circle, he concluded that the value of C in the above equation approached the value of the circumference of the circle. He thus equated the two above formulas, giving the following result

$$2\pi r = 2A/r \Rightarrow A = \pi r^2$$

The above is one of the great geometric theorems which come from antiquity. Archimedes went on to utilize the above theorem to prove that both the surface area and the volume of a sphere inscribed within a cylinder of the same radius are exactly two-thirds of the surface area and volume of the cylinder, another important geometric theorem.

Archimedes is also known to have produced a mechanical device for measuring the movements of the known planets, the Sun, and the Moon—an astronomical

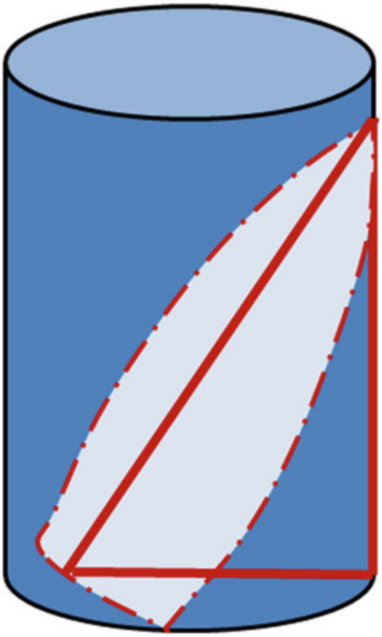
Fig. 2.13 Front and rear view photo of the Antikythera clock, Athens Museum

clock if you will. A device called the Antikythera clock was discovered in the Mediterranean in 1901, and it is believed to be a copy (or perhaps the original?) of the device constructed by Archimedes more than 2000 years ago. Today it is considered to be the first *computer* in history (Fig. 2.13).

But there is still more that came from the mind of Archimedes. His home city of Syracuse came under attack by the Romans during the Second Punic War (218–201 BCE) between the Romans and the Carthaginians. Once again the King of Syracuse came to him for help in defending the city against the Romans. Archimedes devised a giant lever that was to be used to swing out over the harbor walls. The lever had a grappling hook attached which was to be used to grasp the Roman triremes and pull the bow out of the water, thus hopefully sinking the ship in the process.

Archimedes apparently wanted to estimate the volume of water that would be necessary for his lever to flood a trireme with in order to sink it. He then reasoned that he could utilize his principle of buoyancy to determine if the trireme could be sunk by this method. He thus produced perhaps the most remarkable theorem from antiquity, calculating the center of gravity of a parabolic cylinder formed by passing a cutting plane through a cylinder at an angle. He determined the volume of the shape produced by first inscribing a triangle within the shape, as shown below. He then used the known area of this triangle, together with the areas of adjacent but smaller triangles to calculate the volume of the irregular shaped object. In so doing, by assuming that there were an infinite number of triangles contained within the object, he used the method of exhaustion (attributed to Eudoxos (410–355 BCE)) in such a way as to introduce the concept of infinity,

Fig. 2.14 Archimedes' Parabolic Cylinder. *Note* the right triangle inscribed within the volume shown



thereby pointing the way toward the theory of modern calculus, which is a necessary component in any cogent theory of mechanics (Fig. 2.14).

Interestingly, the last of the above developments attributed to Archimedes, although referred to in other literary sources, was not fully verified until a palimpsest was sold at auction at Christie's in 1998 [19]. The palimpsest was discovered during the early twentieth century to have been written over by monks during the Middle Ages with other text. The newly invented technique of x-raying was used to expose the underlying theorem by Archimedes, as shown below. This palimpsest is now under the protection of the Walters Art Museum in Baltimore, Maryland. The proof, found in this palimpsest, has amplified Archimedes' importance to the history of both mathematics and mechanics (Fig. 2.15).

In case it is not obvious, I am a big fan of Archimedes. Although the above discoveries by Archimedes are by no means his only scientific contributions, they are more than sufficient to rank him as the greatest of the ancient mechanists.

There is a story that Archimedes was so proud of his theorem proving that both the surface area and the volume of a sphere inscribed within a cylinder of the same radius are exactly two-thirds of the surface area and volume of the cylinder that he requested that a cylinder and a sphere be placed on his tomb after his death. He was subsequently put to death by a Roman soldier who entered his laboratory during the Siege of Syracuse in 212 BCE. His tomb was apparently constructed according to his wish shortly thereafter.

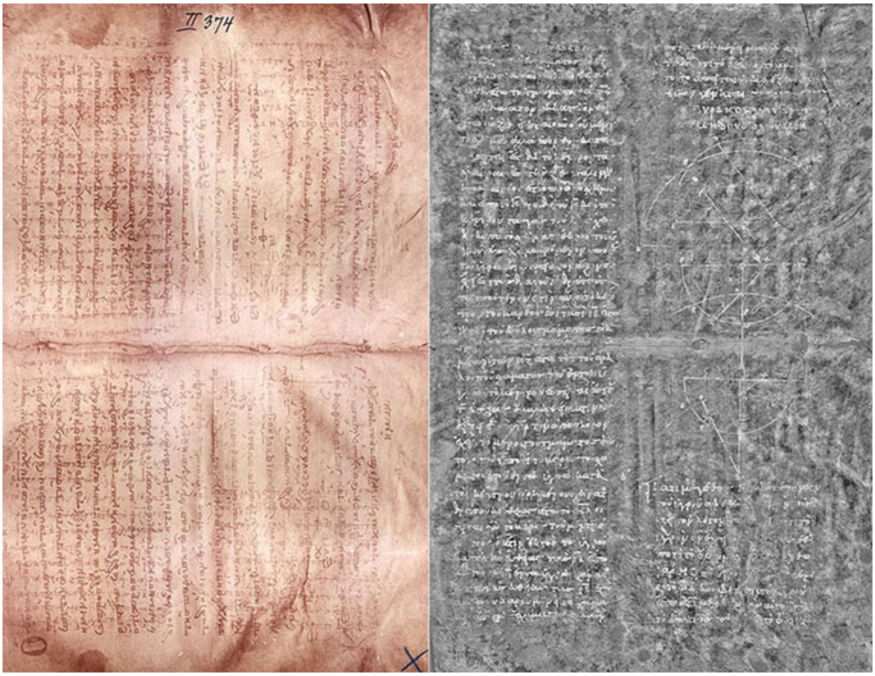


Fig. 2.15 The Archimedes Palimpsest, showing the original text of Archimedes on the *right*, and the overwritten text on the *left*

After his death Archimedes' astronomical clock was spirited away by the Romans and placed in the Roman Forum, where it remained for more than two centuries, thus ensuring that Archimedes' fame would not diminish with time.

Around 70 BCE, the well-known Roman lawyer Cicero (106–43 BCE) was appointed Quaestor on the island of Sicily by the Roman government. During one of his holidays he decided to go in search of the tomb of the famed Archimedes. Cicero described his quest as follows:

> When I was a Quaestor, I tracked down his grave; the Syracusans not only had no idea where it was; they denied it even existed. I found it surrounded and covered by brambles and thickets. I remembered that some lines of doggerel I had heard were inscribed on his tomb to the effect that a sphere and a cylinder had been placed on its top. So I took a good look around (for there are a lot of graves at the Agrigentine Gate cemetery) and noticed a small column rising a little way above some bushes, on which stood a sphere and a cylinder. I immediately told the Syracusans (some of their leading men were with me) that I thought I had found what I was looking for. Slaves were sent in with scythes to clear the ground and once a path had been opened up we approached the pedestal. About half the lines of the epigram were still legible although the rest had worn away. So, you see, one of the most celebrated cities of Greece, once upon a time a great seat of learning too, would have been ignorant of the grave of one of the most intellectually gifted citizens—had it not been for a man from Arpinum who pointed it out to them [20] (Fig. 2.16).

Fig. 2.16 Painting depicting Cicero discovering Archimedes' tomb by Benjamin West (1797)

Today there are several purported sites for Archimedes' tomb, but unfortunately none of them can be authenticated because the identifying sphere and cylinder, as well as the inscription, have long since vanished. This is a great loss in my view. We all need heroes to worship, and what better place to worship them than at their tomb? Try it next time you visit Florence. You will find Galileo's tomb in the Santa Croce Cathedral, with Michelangelo's tomb nearby. You can also see Isaac Newton's tomb in Westminster Abbey, with James Clerk Maxwell nearby.

Eratosthenes of Cyrene (276–195 BCE)

Eratosthenes was apparently the first person to calculate the circumference of the Earth. He also invented a system for determining latitude and longitude, as well as espousing many other important achievements in mechanics (Fig. 2.17).

Eratosthenes, who lived in Alexandria, met a visitor to Alexandria who lived in Swenet (modern day Aswan), at the first cataract of the Nile. Eratosthenes' visitor noted that on the summer solstice the Sun failed to cast a shadow in a water well in Swenet (because it lies on the Tropic of Cancer). Eratosthenes therefore determined the angle, α, that the Sun's shadow cast within a well in Alexandria on the summer solstice, realizing that he could determine the radius of the Earth, r, using this measurement and the distance, d, between Alexandria and Swenet. The distance between these two cities was well known at the time, but just to be safe

Fig. 2.17 Depiction of Eratosthenes

Eratosthenes convinced a friend to journey to Swenet for the purpose of verifying this estimate. The friend returned with the distance measured in stadia (plural of stadion), and from this Eratosthenes was able to calculate the radius of the Earth as follows (using modern notation, where csc is the cosecant):

$$r = \frac{d}{2}\csc\left(\frac{\alpha}{2}\right)$$

From the above it was a simple matter to calculate the circumference of the Earth using Archimedes' formula relating the circumference of a circle to the radius (see the previous section). Although we cannot be certain today of what he meant by the unit of distance called a stadion (the height of a stadium), it is believed by some that his estimated value was within two percent of the actual circumference of the Earth (Fig. 2.18).

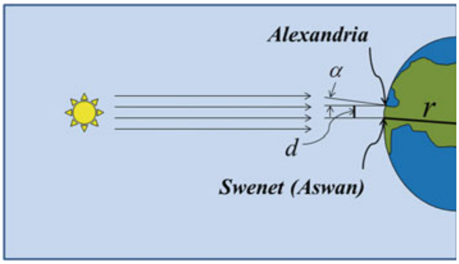


Fig. 2.18 How Eratosthenes calculated the Earth's circumference. *Note* that the sun is so far away from Earth that its rays may be assumed to be approximately parallel

Eratosthenes is also believed to have calculated the distance from the Earth to the Sun, as well as the angle of tilt of the Earth's axis. Furthermore, he is believed to have created the first map of the Earth that used latitude and longitude, and he is credited with the invention of the leap day. All of these achievements are related to mechanics, thereby securing his place as one of the greatest mechanists of antiquity.

Hipparchus of Nicaea (190–120 BCE)

Hipparchus was one of the great mechanists from antiquity. Prior to Ptolemy (see below) he is considered to be the greatest of astronomers among the ancients. His careful measurements of stellar and planetary motions led to his invention of the essential elements of modern trigonometry. Although much of his work survives only indirectly through the published works of Ptolemy (see below), it is known that he was somehow able to predict solar eclipses.

Hipparchus is remembered most importantly for the discovery of the precession of the equinoxes. He apparently wrote two books on this subject, both of which have been lost but are mentioned in Ptolemy's *Almagest*. Ptolemy recounts that Hipparchus measured the longitude of several stars, including Spica and Regulus. He then compared these measurements to those made much earlier by Timocharis and Aristillus. Using these measurements he determined that Spica had moved by two degrees relative to the autumnal equinox. Armed with this result Hipparchus went still further, measuring the length of both the solar and the sidereal years (see Chap. 10). From these comparisons he was able to discern that the equinoxes were precessing through the zodiac at a rate of about one degree per century, thus proving the precession of the equinoxes (see Chap. 10). This is one of the great mechanics achievements from antiquity.

Claudius Ptolemy (c. 90–168 AD)

Ptolemy, perhaps the last of the great Greek mechanists, was a Greek citizen living in Egypt (Fig. 2.19). He wrote the *Almagest* [21], the most widely accepted description of the solar system up until the publication of Nicolaus Copernicus' book in the sixteenth century. Although Ptolemy's epicycle-based methods for calculating the motions of the planets in an Earth centered solar system are essentially mathematically correct, they do not satisfy Ockham's razor (to be discussed in Chap. 4). The *Almagest* was therefore eventually supplanted by Nicolaus Copernicus' book *De Revolutionobus Orbium Coelestium* [22] (see Chap. 7).

There are literally dozens of ancient Greek scientists and philosophers known to us by name today. I have mentioned only a few here, those who in my view made the most significant contributions to mechanics (Fig. 2.20).

Fig. 2.19 Image of Claudius Ptolemy

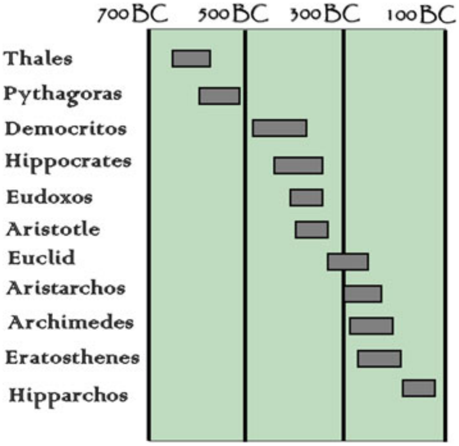
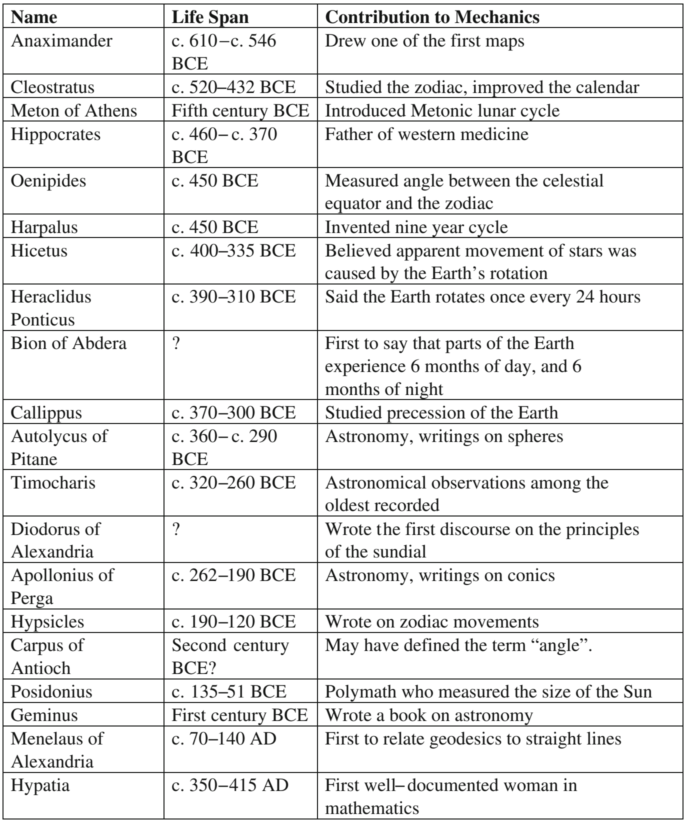


Fig. 2.20 Chronology of greek scientists

Other Greek Mechanists

There were indeed too many Greek scientists who contributed to the field of mechanics to consider in detail in this text. Nonetheless, I have attempted to provide a list below that will give the interested reader a place to start when studying this period of history (Fig. 2.21).



Name	Life Span	Contribution to Mechanics
Anaximander	c. 610–c. 546 BCE	Drew one of the first maps
Cleostratus	c. 520–432 BCE	Studied the zodiac, improved the calendar
Meton of Athens	Fifth century BCE	Introduced Metonic lunar cycle
Hippocrates	c. 460– c. 370 BCE	Father of western medicine
Oenipides	c. 450 BCE	Measured angle between the celestial equator and the zodiac
Harpalus	c. 450 BCE	Invented nine year cycle
Hicetus	c. 400–335 BCE	Believed apparent movement of stars was caused by the Earth's rotation
Heraclidus Ponticus	c. 390–310 BCE	Said the Earth rotates once every 24 hours
Bion of Abdera	?	First to say that parts of the Earth experience 6 months of day, and 6 months of night
Callippus	c. 370–300 BCE	Studied precession of the Earth
Autolycus of Pitane	c. 360– c. 290 BCE	Astronomy, writings on spheres
Timocharis	c. 320–260 BCE	Astronomical observations among the oldest recorded
Diodorus of Alexandria	?	Wrote the first discourse on the principles of the sundial
Apollonius of Perga	c. 262–190 BCE	Astronomy, writings on conics
Hypsicles	c. 190–120 BCE	Wrote on zodiac movements
Carpus of Antioch	Second century BCE?	May have defined the term "angle".
Posidonius	c. 135–51 BCE	Polymath who measured the size of the Sun
Geminus	First century BCE	Wrote a book on astronomy
Menelaus of Alexandria	c. 70–140 AD	First to relate geodesics to straight lines
Hypatia	c. 350–415 AD	First well–documented woman in mathematics

Fig. 2.21 Contributions of selected Greeks to mechanics

Archeology of Greece

Around 800 BCE Homer wrote a tale called *The Iliad*, depicting an account of a 10-year war between the Greeks and the Trojans sometime during the twelth century BCE. The story goes that the war reached its climactic end when the Greeks built the Trojan horse, thereby gaining entrance to Troy by stealth. This fabulous tale, along with its sequel *The Odyssey*, became a significant underpinning of the enormously influential culture of Greece that arose shortly thereafter (Fig. 2.22).

This epic tale became so important in the ancient world that the Romans created their own legend based on *The Iliad*. Around 20 BCE Virgil wrote the epic tale *The Aeneid*, in which he amplified the tale of one Aeneus, a character described in *The Iliad.* In the story, Aeneus wanders for many years, finally settling in Italy, and

Fig. 2.22 Depiction of the story of the Trojan horse in the art of ancient Gandhara, British Museum

becomes the ancestor of the Roman Republic. The Romans used this epic tale to give their own mythical history legitimacy.

Time passed, and with it, the influence of both the Greeks and Romans, as well as their tales of the Trojan Wars waned. By the time of the Renaissance Homer's classic tales had become revered as the greatest fictional tales from antiquity. But were they indeed fiction, or was there a possibility that they were in fact based on reality? One person, a wealthy haberdasher by trade, decided in the middle of the nineteenth century that these tales were in fact founded in truth. His name was Heinrich Schliemann (1822–1890), and although he is not the first person to address this mystery his persistence has made him (arguably) one of the founders of modern archeology [23].

Schliemann decided to go to Western Turkey, where the Trojan Wars were described to have taken place in *The Iliad*. Using the description of the site of the wars described in the Iliad, Schliemann picked a spot at Hisarlik (meaning "place of fortresses"), approximately 6.5 km equidistant from both the Aegean Sea and the Dardanelles. This spot had been previously picked out as the site of Troy in the fifteenth century by Pedro Tafur (c. 1410–1484). Still later, in the nineteenth century Frank Calvert (1828–1908) began studying the site (Fig. 2.23).

It was at this point that Schliemann arrived and took over excavation of the site. Possessed of significant financial resources, Schliemann was able to make rapid progress with the excavations (some say too rapid), and in the process going a long way toward restoring the myth of Troy to the status of history (Fig. 2.24).

Schliemann eventually uncovered multiple layers of the ancient city, as shown below. However, the legitimacy of Hisarlik as the actual site of the Trojan Wars remains in considerable doubt today (Fig. 2.25).

Not content with this feat, Schliemann then took on the site of Mycenae in the Peloponnesian peninsula of Greece, supposedly founded by Perseus, the slayer of the mythical Medusa. Mycenae was also the supposed home of Agamemnon, the Greek King from the Trojan Wars. The site had already been partially excavated in 1841 by Greek archeologist Kyriakos Pittakis (1798–1863) (Fig. 2.26). Although Pittakis excavated the famous Lion's Gate, his excavation was incomplete (Fig. 2.27).

Fig. 2.23 Photograph of Frank Calvert

Fig. 2.24 Photograph of Heinrich Schliemann

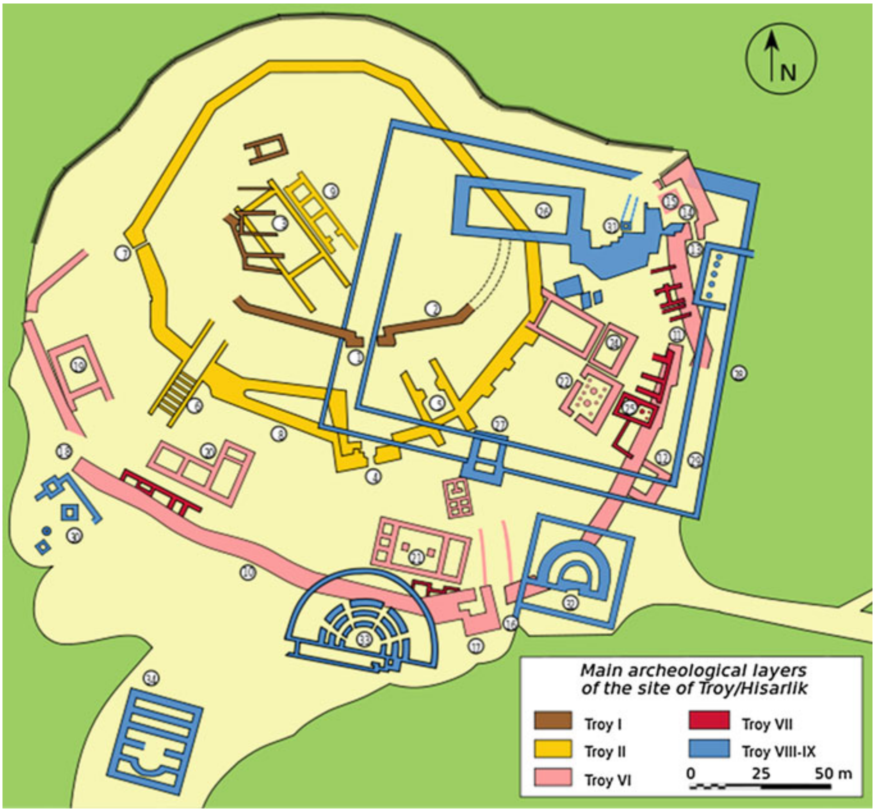


Fig. 2.25 Plan of ancient Troy

Fig. 2.26 Photograph of Kyriakos Pittakis

Fig. 2.27 Photograph taken circa 1884 of the Lion's Gate at ancient Mycenae

Fig. 2.28 Photograph of the Mask of Agamemnon, Athens Museum

Fig. 2.29 The Tomb of Clytemnestra

Schliemann arrived at Mycenae in 1876, and he undertook a much more detailed excavation of the site. In doing so, he discovered thousands of relics from the past, including the famous “Mask of Agamemnon” (Fig. 2.28). He also discovered several tombs, including the tomb of Clytemnestra, the wayward wife of Agamemnon (Fig. 2.29).

All of these discoveries showed signs of advanced mechanics being used by humans as far back as the thirteenth century BCE. Construction of large stone structures apparently became ubiquitous throughout the ancient world. In addition, the working of precious metals was clearly accomplished with advanced tools designed for more precise uses.

The Greeks established a style of construction that has endured right down to this very day. The columnar design used in the Parthenon was adopted by the Romans, and they propagated this style with little variation across the Roman Empire, which had grown by the first century AD to mammoth proportions.

More importantly, the Greeks laid the groundwork for all of modern mechanics via their scientific revelations, as described above. Thus, there was enough to build on when Western Europe awakened from the Middle Ages, as we will see in Chap. 7.

The Romans eventually appropriated Greece as a part of their empire, and when they did, they came in contact with Greek science and technology. As we will see in the next chapter, they learned a great deal from the Greeks.

The Romans

3

> *The ancient Romans had a tradition: whenever one of their engineers constructed an arch, as the capstone was hoisted into place, the engineer assumed accountability for his work in the most profound way possible: he stood under the arch.*
>
> Michael Armstrong (1944-)

According to modern historians, the Romans were not the greatest practitioners of science. This is evidenced by the paucity of Roman scientists known to us by name today, such as Gaius Sulpicius Gallus (second century BCE) and Lucilius Junior (first century AD). The Romans were apparently much better at building things, including ships, buildings, mills, and aqueducts [24]. My own personal view is that the Romans were pragmatic engineers rather than scientists and educators, as were the Greeks. Nonetheless, their achievements are so amazing that their period of supremacy is sometimes referred to as the golden age of mechanical engineering. Perhaps it was in large measure due to their means of proliferation of their culture (by military conquest) that made them create so many structures that remain today, but their mechanical achievements are nonetheless undeniably impressive.

The Roman Arch

The greatest technological advance attributed to the Romans is the arch (this is disputed, as discussed in Chap. 1), but they are also known to have utilized many additional innovations to build massive arenas, enormous water wheels, towering aqueducts, coliseums to rival those of today, a far-reaching web of paved roadways, fabulous barges, amphitheaters too numerous to count, and even indoor plumbing. In actuality nearly every one of these technological advances was introduced by the Greeks, but the Romans may be said to have been disseminators of these devices. Amazing as all of this is, it was nothing when compared to their military structures. Without Roman military engineering, it is doubtful that their republic and subsequent empire could have persisted for more than a millennium.

The Roman arch is constructed using false work, a semi-circular wooden structure that is placed at the top of the columns where the arch is to be constructed. The arch stones are then stacked sequentially on top of the false work, and the center stone, called the keystone, is then tapped or pounded into place, thereby driving the stones within the arch into compression. This is a necessary

D. H. Allen, *How Mechanics Shaped the Modern World*,
DOI: 10.1007/978-3-319-01701-3_3,

step since stones (and their joints!) cannot carry large loads in tension. As shown below, the compressive forces that arise at the interfaces of the stones once the keystone is pounded into place provide a component of vertical force that balances the weight of the stones, thereby providing a durable opening that will withstand the ravages of time.

Roman Roads

There appears to have been a bit of jealousy of the Greeks' heritage on the part of the Romans. Thus, the Romans created for themselves a mythical history going back to 753 BCE, when it was said that the twin babies Romulus and Remus were deposited on the banks of the Tiber River, where they were supposedly suckled by a she-wolf. Their history records that the seven hills along the Tiber would evolve into Rome, named after Romulus, who supposedly killed his brother Remus in a filial spat.

The historical record becomes somewhat more believable a couple of 100 years later, when the Romans ousted the last Tarquin King in 509 BCE, thereby establishing a democracy. Livy mentions in his *Ab Urbe Condita Libri (Books from the Foundation of the City)* [25] that the Romans were building roads as far back as 500 BCE.

The following was written in the *Itinerary of Antoninus* [26]:

> With the exception of some outlying portions, such as Britain north of the Wall, Dacia, and certain provinces east of the Euphrates, the whole Empire was penetrated by these *itinera* (plural of *iter*). There is hardly a district to which we might expect a Roman official to be sent, on service either civil or military, where we do not find roads. They reach the Wall in Britain; run along the Rhine, the Danube, and the Euphrates; and cover, as with a network, the interior provinces of the Empire.

The Roman roads were marvels of mechanics. They were composed of several layers, the top layer being of large paving stones. Where there was a supply of iron nearby, small iron filings were spread over the surface, whereupon they rusted and bonded together, forming a fine patina on the surface. The roads were normally built either by military engineers or by slaves. In either case, the paving materials were located as near to the construction site as possible.

It is a testament to the Romans that some of these roads still exist today. My favorite is the Via Appia (begun in 312 BCE), which stretches eastward from Rome, connecting it to Brindisi (the port of embarkation to Greece in ancient times), on the Southeast coast of Italy. It has recently been discovered that the part of the Appian Way that lies directly east of Rome is built on top of an old lava flow field, thus providing further reinforcement for the roadway.

To see the Via Appia today, take a taxi to the Catacombs of San Callisto (worth seeing in their own right). The Via Appia is right in front of the catacombs. Simply start walking east and you will shortly be transported back 2,000 years in time. If your legs will hold out, walk far enough to see the stretch of aqueduct toward the

Fig. 3.1 Ancient Roman Arches in the Hypogeum of the Coliseum

north, also a remnant of ancient times. You will also be treated to quite a few tombs along the way. Since Romans did not allow funerary tombs within the city walls, many tombs lined the roads leading from the city (Figs. 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, 3.10, 3.11, 3.12, 3.13, 3.14, 3.15, 3.16, 3.17, 3.18, 3.19, 3.20, 3.21, 3.22).

Massive Roman Structures

By the third century BCE, the Romans had begun to establish supremacy on the Italian peninsula, at which point they stumbled into the hornet's nest called the Carthaginians of North Africa. The struggle for supremacy in the western Mediterranean between these two superpowers resulted in the three Punic Wars that spanned from 264 to 146 BCE. Greece also fell under Roman rule at this time, as Rome gradually developed into the most powerful entity in the Mediterranean. It was also during this period that Archimedes was killed in the Roman siege of Syracuse, an unfortunate by-product of the Punic Wars (see Chap. 2).

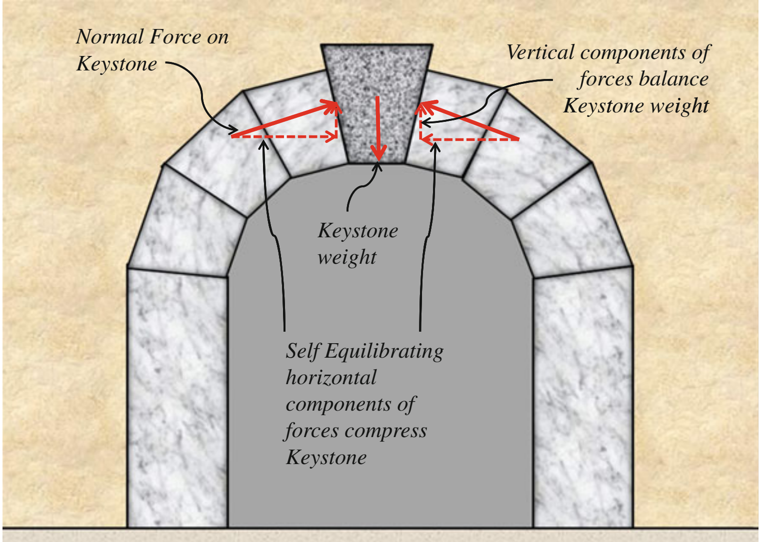


Fig. 3.2 Mechanics of the Roman Arch

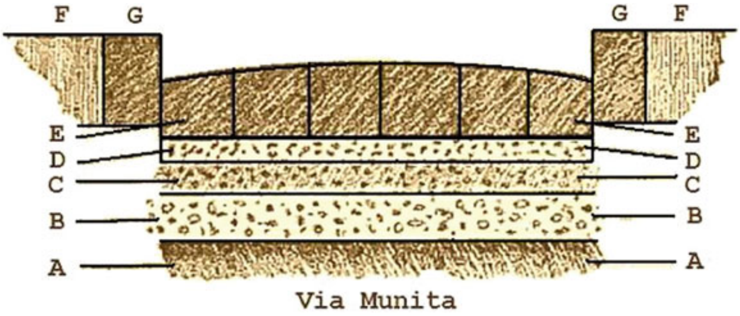
Fig. 3.3 The She-Wolf suckled by Romulus and Remus, Capitoline Museum in Rome

By the end of the second century BCE, the great Roman general Gaius Marius was the First Man in Rome, and from this time forward the Romans were embarked on the greatest building program in the history of the world up to that

Green: Via Aurelia -> Via Aumelia Scaura -> Via Julia Augusta
Bright green: Via Clodia
Yellow: Via Cassia
Blue: Via Flaminia
Grey: Via Salaria
Dark purple -> purple: Via Tiburtina -> Via Valeria
Carrot red: Via Latina
Bright red: Via Appia
Dark blue: Via Ostiensis

Additional major roads specified on the map:
Via Popilia, going to southern Italy (Rhegium) from Via Latina and Via Appia crossroads. (cyan)
Via Traiana, branching from Via Appia and also going to Brundisium. (dark red)
Via Aemilia, starting from the end of Via Flaminia at Ariminum and going to Placentia. (orange)
Via Postumia, going from Genua (Genoa) on the northwest of Italy to Aquileia on the northeast. (dark green)

Fig. 3.4 Depiction of the Roman roads in Italy by Agamemnus



(A). Native earth, levelled and, if necessary, rammed tight.
(B). Statumen: stones of a size to fill the hand.
(C). Audits: rubble or concrete of broken stones and lime.
(D). Nucleus: kernel or bedding of fine cement made of pounded potshards and lime.
(E). Dorsum or agger viae: the elliptical surface or crown of the road (media stratae eminentia) made of polygonal blocks of silex (basaltic lava) or rectangular blocks of saxum qitadratum (travertine, peperino, or other stone of the country). The upper surface was designed to cast off rain or water like the shell of a tortoise. The lower surfaces of the separate stones, here shown as flat, were sometimes cut to a point or edge in order to grasp the nucleus, or next layer, more firmly.
(F). Crepido, margo or semita: raised footway, or sidewalk, on each side of the via.
(G). Umbones or edge-stones.

Fig. 3.5 A Depiction of a Roman road

Fig. 3.6 Via Appia today. *Note* the crowning of the roadway

Fig. 3.7 Nineteenth century depiction of the temple of Jupiter Optimus Maximus in Roman times

Fig. 3.8 Photograph of the Roman Forum today as viewed from the Capitoline hill

time. The construction of massive structures necessitated the development of many new mechanical devices during this period.

In the middle of the first century BCE, Gaius Marius' nephew Gaius Julius Caesar came to power. By that point in time Rome had grown into one of the most impressive cities on Earth, with the Romans' answer to the Greek Parthenon called

Fig. 3.9 1873 depiction of the Roman Coliseum

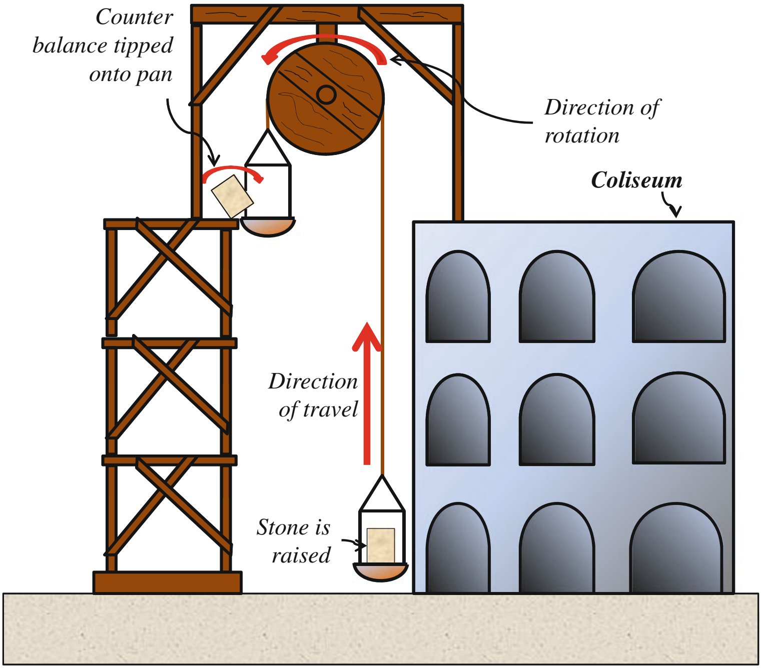


Fig. 3.10 Counterbalance and pulley system used to construct Coliseum

Fig. 3.11 Coliseum interior showing the Hypogeum

the Temple of Jupiter Optimus Maximus dominating the Capitoline Hill of Rome's Forum, the center of Roman life. Tourists can still visit the foundation of the temple, housed within the Capitoline Museum on the Campidoglio in downtown Rome.

Julius Caesar seems to have come along just at the right point in history to accomplish much, and he was up to the task. After spending a year as one of the two consuls of Rome (in 59 BCE), he became the Governor of Nearer Gaul, and it was at this point that he began his military career in earnest (although he had previously served in the military as a young man). From 58 to 50 BCE, Caesar rampaged across Further Gaul (modern day France) defeating the Celtic tribes wherever he led his legionnaires. Along the way, his legions built fabulous roads, some of which are still in existence today.

His army of 50,000 soldiers generally had two legions (of 5,000 each) that were engineers. These well-trained troops would surge ahead of the combat forces and build roads that were able to transport an army 80 km a day even in the harshest of weather conditions. And when they arrived at the battlefield, sometimes weeks earlier than the Celts expected, they immediately went to work building massive siege towers, breastworks, fortified walls, and most impressive of all—enormous weapons such as trebuchets and arrow launchers (see Chap. 12). All of these achievements were accomplished by the deployment of mechanics principles.

Everywhere they went, the Romans conquered their enemies and enslaved them. The conquering soldiers were awarded land, from whence cities emerged. The conquered slaves built these cities, and these cities required infrastructure.

Fig. 3.12 Trajan's column. *Note* the spiral sculpture on the exterior

Fig. 3.13 Photograph of Hadrian's wall

Fig. 3.14 The Pantheon. *Note* the Egyptian obelisk in front

Fig. 3.15 The Oculus in the Dome of the Pantheon. *Note* the inlaid pattern in the concrete ceiling

Thus, they built forums, city baths, aqueducts, canals, and fortresses throughout the Roman provinces.

After Caesar was assassinated in the Theatre of Pompeii on March 15, 44 BCE, the Republic gradually evolved into an Empire. Caesar's nephew Octavian shared power with Mark Antony for several years, but he eventually defeated Antony and Cleopatra at the Battle of Actium in 31 BCE, thus consolidating his power. Thereafter he was called Augustus, the first Emperor of Rome. Under his

Fig. 3.16 Neoclassical sculpture by Laurent Marqueste (1848–1920) in the Tuileries. *Note* the truncated appendages

leadership, the building program was stepped up still more so across the Roman provinces.

Augustus' friend and commanding general at the Battle of Actium was Marcus Agrippa. Agrippa came home from the wars and became Augustus' director of public works. He lit into his charge with boundless energy, and the results were impressive. Beginning in 27 BCE, during his third consulship, Agrippa constructed the Pantheon on the edge of the ancient city. Unfortunately, little of what can still be seen in Rome today dates to this period of construction. However, as we will see later, the Pantheon would later grow into one of the most amazing structures on Earth.

In the late first century, the Romans completed perhaps their most revered structure—the Coliseum. This massive arena was begun under the reign of Vespasian and completed during the reign of his son, Titus, in 82 AD. The Coliseum was essentially an extension of the previous concept of an amphitheater, now composed of two amphitheaters joined together face-to-face. The shear scope of this project is in itself an amazing feat in mechanics.

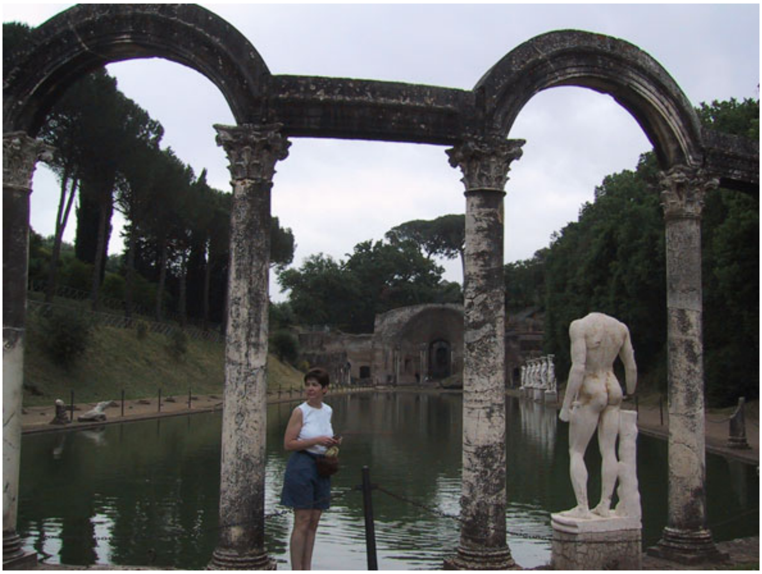


Fig. 3.17 Photo of the Canopus at Hadrian's Villa. *Note* the alternating stone beams and arches

Fig. 3.18 Photo of the Pont du Gard. *Note* the relatives size of the people standing on the lower deck

Archeologists, architects, and engineers continue to study the Coliseum in modern times, and revelations continue right up to this day. It was capable of holding between fifty and sixty thousand people at one time, and the amazing

Fig. 3.19 The Roman Aqueduct in Segovia

Fig. 3.20 Ruins of the Roman watermill at Barbegal

arched structure was designed so efficiently that it is estimated that the entire Coliseum could be emptied of spectators in less than 10 minutes.

Fig. 3.21 Arch of Constantine. *Note* the Palatine Hill in the background

Fig. 3.22 Arc de Triomphe, Paris

Extant records indicate that the structure was built primarily with the use of the mechanical advantage provided by pulley assemblies in combination with huge levers. In addition, the Romans developed assembly line techniques for creating such complex substructures as arches. A team of workers (usually slaves) would raise a wooden false work into place where the arch was to be assembled. Stones for the arch were subsequently raised using counterbalanced pulleys and placed over the false work. Visitors to the Coliseum today can see models vividly demonstrating how construction progressed.

In addition, huge wooden structures were built to raise the stones necessary to assemble the superstructure, and one possible scenario is that the stones were raised using pulleys with counterbalances, as shown below. Of course, the stones used as counterbalances had to be themselves raised, but one simple way was to require a continuous progression of slaves to mount the stairs to the offloading platform and step onto the balance, thereby returning the balance stone to the upper level so that the next stone could be raised. While this method did not provide any particular advantage in terms of the work required, it was less cumbersome than winching stones upwards by hand.

Since the Coliseum contains perhaps a thousand arches, it is amazing that this labor-intensive process was repeated to completion in just over 10 years. It can be said that the Coliseum was built with nothing more than engineering ingenuity, mechanical advantage, human power, and lots of sweat.

We know that the Coliseum was originally built in a low-lying area that had formerly been Nero’s gardens. For the first 3 years after it opened, there were several occasions when the Romans flooded the arena and held mock sea battles within. Thereafter, they felt the need for a more impressive means of providing entertainment, thus they built a complex of basements within the arena called the Hypogeum.

Once the Hypogeum was completed it was possible to create all sorts of amazing visual effects, such as lions and tigers popping from the ground within. For those who have seen the movie *The Gladiator*, the scenes within the Coliseum are apparently historically accurate. The means whereby the Romans accomplished these amazing feats was a series of elevators that were controlled using pulleys and counterbalances similar to that shown above. In other words, they used principles of mechanics previously invented by the Greeks.

Another interesting feature of the Coliseum was the cover. History records that there were awnings connected with enormous cloth covers that could be winched out over the stands by naval soldiers. Thus, the Coliseum was the model for today’s domed stadiums, predating the Astrodome (the first domed stadium in modern times, which has been closed and at this writing is apparently being scheduled for renovation) by nearly 2,000 years.

Unfortunately, the Coliseum has begun to decay rapidly since World War II. Just recently, the exterior has had to be structurally reinforced. So if you were pondering a trip to Rome to see this most famous of ancient structures, better not put it off too much longer.

By the second century AD, under the reign of Trajan the Roman Empire reached its largest extent. His defeat of the Dacians is commemorated by Trajan's column in downtown Rome. This massive column must be seen to be believed. Not only does it contain a spiral staircase within, the exterior is faced with a helical mural of the conquest of Dacia, thus making its construction a combination of both art and mechanics.

Trajan's successor Hadrian initiated the *Pax Romana*, a period of peace that lasted for a century. Hadrian was perhaps the last great builder in the Roman Empire. During his reign he visited all of the Roman provinces (the first emperor to do so). During his visit to Britannica, he commissioned Hadrian's Wall, which when completed spanned the entire island of Britain from East to West. This amazing fortress would keep the Northern invaders at bay for nearly 300 years. Unfortunately, much later during the Middle Ages the locals did not understand the importance of the wall, and much of it was carted off. However, you can still see some very interesting ruins at places such as Vindolanda. This is one of my favorite examples of the Romans' use of mechanics.

During Hadrian's reign the Pantheon was rebuilt (it had been destroyed by fire). And in what is perhaps the most amazing feat of all of the mechanics employed by the Romans, the roof of the Pantheon was rebuilt using concrete (apparently by an engineer named Neri). This was the first structure of its type on Earth. In the center of the dome is the oculus, as shown below, and this is today the last completely intact Roman structure on Earth.

No one knows how the Romans accomplished this amazing feat, but one thing we do know is that concrete was not used again in modern times until the nineteenth century (Englishman John Smeaton made the first modern concrete in 1756 by mixing aggregate with cement. The first reinforced concrete was developed by Frenchman Joseph Monier, who was granted a patent in 1867). Surely they employed mechanical pulley and counterbalance systems similar to those used in the Coliseum to raise the concrete to the height of the dome, but what happened next is anyone's guess. The intricate inlaid pattern on the interior surface of the dome suggests that a massive wooden falsework structure must have been constructed to span from opposite edges to the center of the dome, much like an arch is constructed. The workers would then have raised the concrete in powder form, mixed the concrete at elevation, and then poured the wet concrete for two opposing lobes of the dome at a time (there are a total of thirty lobes within the dome). The falsework would then have been partially disassembled and shifted to the next set of lobes, and in so doing slowly completing the circle of the dome.

Interestingly, it is believed that the coffered pattern in the ceiling was constructed for more than artistic purposes. It seems that the Romans understood all too well that the dome needed to be both structurally sound and lightweight. Modern structural mechanics models have confirmed that their solution was both ingenious and near optimal. Given the level of technology of that time, it must surely have been one of the greatest achievements in mechanics from antiquity.

Visitors to the Pantheon can also see the most massive set of twenty granite columns that I am aware of from antiquity (as well as an Egyptian obelisk in the square in front). These columns were quarried in Egypt and shipped across the Mediterranean to their present location in the portico of the Pantheon (which can be seen to still bear Marcus Agrippa's name). Here was another amazing feat of mechanics. I seriously doubt that anyone will attempt to cart these enormous columns off any time soon.

When Hadrian finally came home to Rome from his long journey throughout the Empire, he decided to build a fabulous villa outside Rome at a place called Tibur (modern day Tivoli) [27]. Since the Roman quarries were nearby, the site in the hills above Rome was ideal. There Hadrian commissioned a sumptuous recreation of the places he had visited during his travels. Much of his villa disappeared in time, but in the sixteenth century Cardinal Ippolito built the Villa D'Este just up the hillside from the Hadrian's Villa, and he removed many of the statues from the ancient site to decorate his own villa (both of these sites are worth a journey). In part due to Cardinal Ippolito's pilfering, much of Hadrian's villa was excavated over the succeeding century, producing more than two hundred sculptures from ancient times. These revelations were partially responsible for the so-called Neo-classical age in art, in which modern statuary was produced (often with missing appendages) in order to mimic ancient art. You can see examples across France today in almost any major park from that time period (try the Tuileries in Paris, or the Parc de Sceaux).

One example from Hadrian's Villa is the Canopus, shown below. It is intended to reproduce the canals of the Northern Nile, a place that was near and dear to Hadrian's heart, since his favorite Antinous had been swept away and drowned in the Nile.

The Romans utilized the arch in order to provide larger spans for stone structures, and this invention allowed the Romans to create many of the most famous structures still standing today from that time period. A telling example is the portico from the Canopus at Hadrian's villa. The portico has both flat (beams) and curved (arches) stone members between the columns, and the discerning reader will recognize that the span between the arches is slightly larger than that between the beams, attesting to the fact that arches can span larger dimensions than beams made of stone because they carry loads strictly in compression, whereas beams necessarily undergo tensile loading on the bottom edge due to their own weight, a circumstance that precludes the use of stone beams for large spans. This is an example of the mechanics of deformable bodies (see Chap. 7), and while the Romans had no theory to explain this phenomenon, they (or perhaps their forerunners the Greeks) apparently determined rules for limiting the length of stone beams via careful experimentation, a forerunner of the scientific method.

Despite their proven ability to construct both massive and impressive structures, ancient engineers did not possess rigorous design methodologies. Their was an experimental and therefore necessarily expensive discipline. For example, it is known that the Pont du Gard, built in the first century AD, was constructed at a cost that would have bankrupted a small nation today. This absolutely massive aqueduct that spans the Gardon River in Southern France is approximately 49 m in height and 275 m in length. It is part of a 50 km long aqueduct system that was built to transport water to the city of Nemausus (modern day Nimes).

Amazingly, the total elevation change from the spring to the city is only 17 m! This is indeed an amazing testament to the Romans' ingenuity with mechanics. Roman engineers possessed a number of leveling tools that worked on the same principle as the modern water bubble level. It is noteworthy that this massive aqueduct in the South of France still stands today, so that the cost may not sound so astronomical if amortized over two millennia.

Another fabulous Roman aqueduct that is still standing today is the one in the center of Segovia in Spain, as shown below. There are numerous examples of these aqueducts scattered across the remnants of the Roman Empire. They stand as silent testaments to the Romans' ingenious deployment of the principles of mechanics.

During the height of the Roman Empire aqueducts stretched throughout the provinces. In Rome itself, there were no less than eleven aqueducts, the longest of which was the Aqua Marcia, built in 144-140 BCE. It spanned 91 km, and supplied the Palatine Hill with approximately 190,000 m^3 of water each day. Wealthy Romans were able to divert running water to the interior of their homes, whereas everyone else received free water at selected locations throughout the city of more than a million inhabitants. It is believed that this is a primary reason that Rome never experienced a major plague.

The Romans were apparently quite adept at making use of the energy stored within descending water, another problem in mechanics. The watermill at Barbegal in Southern France is believed to have been the largest one in the Roman World. This watermill was apparently connected to an aqueduct that carried water to Arelate (modern day Arles). Arles lies just south of the beginning of the Camargue; the alluvial plain caused by the Rhone River.

On a steep hill 11 km north of Arelate, the aqueduct fed water to a system of sixteen waterwheels that drove a flour mill for about 200 years from the end of the first century AD. It is estimated that the mill was capable of producing 4,000 kg of flour per day, a sufficient supply for the entire population (40,000 persons) of Arelate, making it the largest producer of flour known from antiquity. Although a few mills of this type have already been discovered from Roman times, archeologists believe that there are several additional mills of this type yet to be discovered.

The Romans seem to have been enamored with triumphal arches, which were little more than monuments to their heroes. Nonetheless, they built plenty of them. The grandest of these appears to have been built to honor perhaps Rome's last great emperor, Constantine, in the fourth century AD. This arch, along with several others, was placed along the route where triumphal parades were held for conquering generals.

By the end of that century there were no less than 36 triumphal arches in Rome, not to mention the myriad of others stretching throughout the Roman Empire. As a testament to the enormous impact of so many monumental achievements, it is noteworthy that they have been emulated across the Earth in modern times, including the largest one—the Arc de Triomphe, built in Paris in the nineteenth century.

One need only go to the capital cities of London, Paris, and Washington in order to see the influence of the Greeks and the Romans on the modern world. It can be said that whereas the Greeks were the creators of mechanics, the Romans were the consummate constructors utilizing the mechanics invented by the Greeks.

As we will see in later chapters, the monumental temples, amphitheaters, roadways, aqueducts, forums, fortresses, and villas built by the Romans throughout Western Europe outlasted the Roman Empire, and these remnants and ruins served as silent sentinels to those who came after them that such structures erected using the principles of mechanics could be duplicated. And once civilization was reborn, that is exactly what occurred. The Greeks developed the science of mechanics, and the Romans left physical evidence that mechanics could be utilized to shape our modern world.

Unfortunately, after the fall of the Western Roman Empire in 476 AD, civilization in the West declined measurably, and it continued to decline for more than 800 years. Although there were clearly developments in mechanics in the Middle Ages, it would be a long time before civilization would attempt to match the magnificent mechanics accomplishments of the Greeks and the Romans.

Mechanics in the Middle Ages

4

Entities should not be multiplied beyond necessity.
William of Ockham (c. 1288-c. 1348)

Economic and Cultural Collapse

By the middle of the third century AD the Roman Empire had begun to collapse. A succession of poorly chosen emperors could do little to stave off the approaching maelstrom. But then, early in the fourth century, there came forward a unique person who would provide such leadership as to right the Empire for nearly two more centuries. His name was Constantinus, but he is known to us today as Constantine. After defeating Maxentius in battle and consolidating the Roman Empire in 312, Constantine issued the Edict of Milan in 313, thereby converting the Empire to Christianity. Perhaps more than any other event, this edict would shape Western Europe over the succeeding millennium.

Within a few years Constantine had altered the calendar substantially, and this alteration would change society enormously. Although he kept the Julian calendar intact (See Chap. 6), he first instituted a 7 day week, with the Sabbath on the seventh day. Next, he initiated the holidays of Christmas and Easter. Christianity came to the forefront of life in Western Europe.

I will not presume to delve into the religious and political ramifications of Christianity. Instead, I will concentrate on the impact that Christianity had on mechanics (as well as vice versa). For example, the imposition of a 7 day week was new to Romans. Prior to this most Romans had observed an 8 day week. But imposing a 7 day week was well received due in part to the seven heavenly bodies in the night sky, and accordingly, the days of the week were named after them, from whence we have Sunday (after the Sun), Monday (after the Moon), and so on, ending in Saturday (after Saturn). Of course, this is all related to mechanics, because these seven bodies were the only ones in the night sky that transited the heavens in a curved line (the plane of the ecliptic) over time (all other stars appeared to move in circles about the North Star).

The imposition of Christmas and Easter holidays was another matter altogether. Christmas was easy; they simply picked a date of the year arbitrarily and followed the Julian calendar (called an immovable feast). But Easter was another matter, one that would play heavily into the subject of mechanics for more than a 1,000 years.

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This is due to the fact that the First Council of Nicaea (convened by Constantine in 325 AD) set the date for Easter as the first Sunday following the full Moon immediately after the vernal equinox (a movable feast) [28].

This means of picking the date for Easter might have been a poor choice from the standpoint of accurately determining what day Easter fell upon, but from the standpoint of mechanics, it turned out to be a big plus. That is because during the Middle Ages very few people were interested in science. They were for the most part busy trying to stay alive, and toward this end they believed that the worship of God would assure them of doing so [29]. Thus, establishing the proper date for Easter came to be a very important problem in mechanics.

Suppose that you have no modern equipment, just exactly how would you establish the date for Easter? Of course, in 325 AD it was not yet known that the Julian calendar was not quite correct. That would take a few more centuries before there was general agreement among clerics that something had to be done to correct the calendar (see Chap. 6). But by the time they did, it became clear that in order to pick the right day for Easter it would be necessary to figure out exactly when the vernal equinox occurred. Therein lies the mechanics problem, and the solution to this problem would eventually come to the forefront in the Middle Ages.

The Roman Empire is regarded by historians to have come to an end in 476 AD. This of course applies only to the Western Empire. The Eastern Empire persisted in Constantinople until 1453, when it was defeated by the Ottomans. But in Western Europe, after 476 a number of invading peoples, including Huns, Vandals, and Visigoths overran the remnants of society. By the beginning of the sixth century, the resulting pandemonium across the land had resulted in the loss of the ability to read or write by the vast majority of the populace. This unfortunate societal failure plunged Western Europe into economic collapse, thus resulting in a loss of communication and the ability to transport technology via the written word.

The unhappy survivors retreated into mountaintop fortresses wherever possible, and where hills were not available to provide natural protection, they relocated to coastal islands such as the newly founded Venice. Western Europe became a backwater of little or no wealth whatsoever. As a result, the few who survived were spending so much of their time simply eking out a living that technology took a back seat, gradually declining, and in some places nearly disappearing altogether. With time, most massive Roman structures were decimated by earthquakes, floods, and, worst of all, vandalism (by the Vandals, among others).

By the early sixth century only the Eastern portion of the Roman Empire remained. The Emperor Justinian commissioned a reconstruction of the Agia Sophia (also called the Hagia Sophia—Church of the Holy Wisdom) in Constantinople (modern day Istanbul) in 532. Completed in 537, this massive domed orthodox Byzantine cathedral is considered by some to be the most important structure on Earth. Elsewhere, the octagonally domed Basilica of San Vitale was completed in 546 in the old capital of the Western Empire by the Bishop of Ravenna, Maximian during the Byzantine Exarchate of Ravenna. Both of these structures would significantly impact the design and construction of later domed structures (Figs. 4.1 and 4.2).

Fig. 4.1 Photograph of the Agia Sophia in Istanbul

Fig. 4.2 Photograph of the Basilica of San Vitale in Ravenna. *Note* the octagonal shape

Time passed with little advance in the sciences. In the early eighth century a monk in Northumbria named Bede wrote a book called *De Temporum Ratione* (On the Reckoning of Time) [30]. This is one of the very few extant scientific books

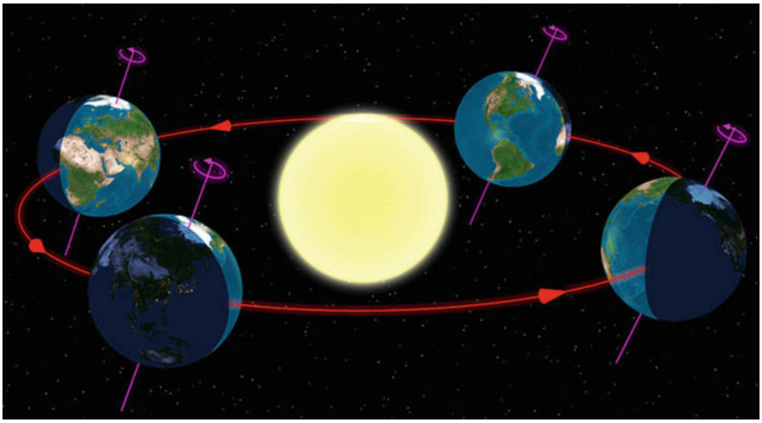


Fig. 4.3 Depiction of the relation between the Sun and Earth drawn by Tau'olunga, showing the solstices (at the extremities) and the equinoxes of the Earth

from the Middle Ages. In fact, Bede is most remembered for his many historical works detailing the history of the English people, but his scientific work stands out. In this book Bede discussed numerous scientific issues, not the least of which was the subject of the determination of the vernal equinox for the purpose of setting the date for Easter, a problem in mechanics.

Just exactly how did Bede determine the date for the vernal equinox? This of course is a problem in mechanics. There are two parts to the solution to this problem. First, one needs to measure the moment at which the equinox occurs. Bede understood that the equinox occurs when the normal to the Earth's plane of spin is precisely aligned perpendicular to the plane of the ecliptic. He solved this part of the problem by patiently plotting the location of the Sun's shadow on his own sundial numerous times each and every day over many years. Eventually, he was able to determine that the Sun's shadow always shone at the same spot on his wall when the vernal equinox occurred each year. This part of the problem was indeed rather simple, requiring nothing more than a lifetime of enormous patience (Fig. 4.3).

The second part of the problem involves the determination of exactly what time of day the equinox occurred. Unfortunately, Bede was not aware in Northumbria of the most exact means of measuring time during the period in which he lived—a clepsydra, or water clock. He was therefore forced to estimate the time of day at which the equinox occurred by interpolating the locations of the Sun's shadow on his sundial. His method was not completely accurate, as the location of the Sun's shadow on a sundial is nonlinear in time. Thus, his technique, though it was based in mechanics, left something to be desired. Still, his scientifically conceived treatise left an indelible mark on the world of his time (Fig. 4.4).

Elsewhere in the Middle and Far East, technology continued to progress. The death of the prophet Muhammad (570–632) in the early seventh century led to a period of conquest and expansion of the Islamic Faith. Islamists crossed North Africa

Fig. 4.4 Depiction of Bede on the *left*, His Tomb on the *right*

and arrived in Spain within a century, and wherever they went they saved as many of the old Greek scientific documents as they could. They also continued to explore and develop science, especially in Saudi Arabia. They were turned back by French forces under the French King Charles Martel (686–741) in 732 at The Battle of Tours (also called The Battle of Poitiers) in modern day central France, thus ending the progression of the Islamists (as well as their more advanced science) into Western Europe (Fig. 4.5).

Fig. 4.5 Painting by Charles de Steuben depicting the Battle of Tours, Palace of Versailles

Around 800 AD the illiterate Charlemagne established a far-reaching empire for a short period of time in Western Europe. During his reign he attempted to reinitiate science, but the burgeoning illiteracy of the populace was impossible to overcome. Europe plunged still further into chaos.

A notable exception in the West seems to have occurred in Venice, where enterprising individuals sought refuge on a few small islands off the coast, in the Northern end of the Adriatic Sea. This appears to have been a matter of expedience, as her nearby mainland parent city of Padova was repeatedly sacked by invading hordes during the Middle Ages. Thus, the islands off the coast offered protection in the Po Valley, the only part of Italy where there were no hills to offer natural protection from invaders.

The Venetians realized that these islands not only offered a safe haven, they also provided perhaps the most expedient access in Western Europe for ships to voyage to the Eastern Mediterranean, thereby giving Venice a trading edge over the rest of Western Europe. By the middle of the ninth century, Venice had evolved into a shipping empire.

In the year 828 the Venetians somehow managed to steal the relics of St. Mark from Alexandria. The Doge (The head of Venetian government) subsequently began construction of a great cathedral adjacent to his palace in 832. This cathedral, today called the Basilica of San Marco, evolved into one of the great Byzantine Christian cathedrals on Earth, as shown below. With its five golden domes, the construction of such a fabulous structure on an island is one of the great structural accomplishments utilizing mechanics during the Middle Ages.

Unfortunately, we have very little information today describing how the basilica was constructed. What we do know is that the design for the basilica was influenced greatly by the Agia Sophia and the San Vitale, both mentioned above. The Venetians became the consummate transporters of goods by sea, and essentially every piece of stone, every adornment, and even the artisans themselves were transported to the island by sea. The next time you visit this amazing basilica, remember this fact (Fig. 4.6).

Gothic Cathedrals

The Greeks and Romans are known to have utilized rules of thumb (principles that are not scientifically verified) for the purposes of designing structural components, and at least some of these rules were used well into the Middle Ages. However, by the beginning of the twelfth century, these rules of thumb had become outdated. Although there was as yet no sound theory for the structural design of buildings, significant new efforts were undertaken to improve building design, and the methodology used was essentially trial and error experimentation. During this period many new ideas were developed, and most of them were applied to Christian cathedrals. The clergy were obsessed with constructing places of worship that were worthy of their image of God. Invariably, they sought structures that

Fig. 4.6 Basilica of San Marco, Venice

were large, received significant sunlight inside, and most importantly, *contained a very high central vault*. Since there was no reliable construction theory for tall structures at the time, perhaps the grandest experimentally based construction period in the history of our planet began, and the most important challenge was to build the highest vault.

These Gothic cathedrals are clearly the most prominent examples of experimental mechanics during the Middle Ages. This period of fervent construction is regarded by historians to have begun in 1137, when Abbott Suger (c. 1081–1151) began reconstruction of the Cathedral at St. Denis, as shown in Fig. 4.7.

The story of St. Denis is in itself a bit strange. Denis was the first bishop of Paris (then called Lutetia) in the third century AD, during Roman times. Unfortunately, Constantine had not yet issued his Edict of Milan, converting the Roman Empire to Christianity. Thus, Denis was inevitably captured and executed (at Montmartre, the mountain of the martyrs, now an *arrondissement* on the north side of Paris). Poor Denis had his head severed, whereupon he purportedly picked it up, walked 10 km northward, all the while preaching a sermon, whence he at last expired. Thus, a basilica was built on the spot where he died, eventually evolving into the Basilica of St. Denis, since Denis was eventually canonized by the Pope.

Over time the basilica became the resting place of the Kings of France, progressing all the way from the first French king, Clovis, to the last, Louis XVI, who was himself beheaded during the French Revolution. And to this day, St. Denis is venerated as the patron saint of Paris. I know, this diversion has nothing whatsoever to do with mechanics, but I find it to be interesting nonetheless (Fig. 4.8).

Let's get back to our story—the mechanics of Gothic cathedrals. Over a period of nearly a century and a half the Gothic cathedrals were the most significant construction projects in Western Europe, as clerics and their parishioners all over

Fig. 4.7 Photo of the Gothic Cathedral of St. Denis. *Note* the slightly pointed arches in the porticos

the region attempted to find ways to elevate the height of the central vault of the cathedrals higher and higher.

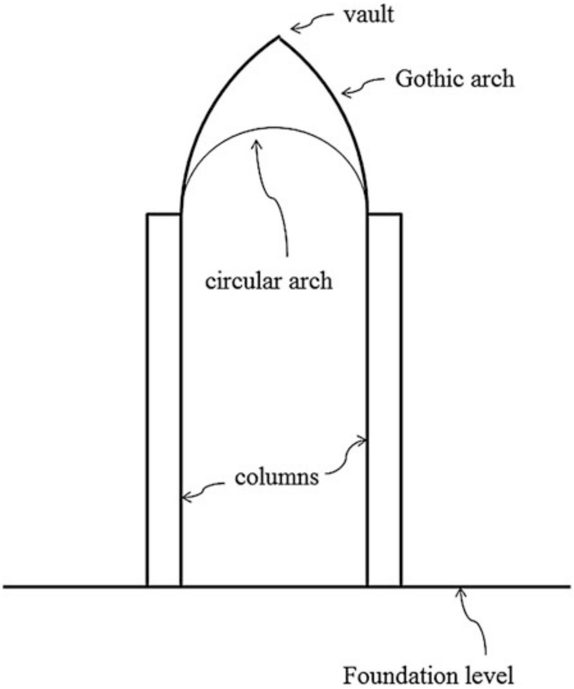
The initiation of the period of Gothic cathedral construction was characterized by the development of the so-called Gothic arch. The Romans had previously utilized the arch, but during their heyday, the arch was constructed in the shape of a half circle, and later, as a portion of a circle. Sometime in the first half of the twelfth century, an idea was born that allowed builders to construct a vault that was much higher than previously possible simply by joining two symmetric portions of the arc of a circle, as shown in Fig. 4.9.

Construction began with the building of the foundation, followed by the placing of the cathedral columns. These two parts of the construction would span perhaps 20 years, during which time the cathedral was often used for services even though there was no roof. Unfortunately, in many cases, when the roof was added, the lateral loads imparted to the tops of the columns caused quite a few vaults to collapse, often injuring or even killing construction workers.

As described in Jacques Heyman's text entitled *The Stone Skeleton* [31], if cracks appear on the inner surface of the arch parallel to the plane of the arch, this usually does not endanger the structural integrity of the arch. On the other hand, if cracks appear on the inner surface of the arch *perpendicular* to the plane of the arch, it can be shown that the stresses on the inner surface are tensile. Since arches

Fig. 4.8 Sculpture of St. Denis at the left portico of Notre Dame Cathedral, Paris

Fig. 4.9 Depiction of a Gothic Cathedral



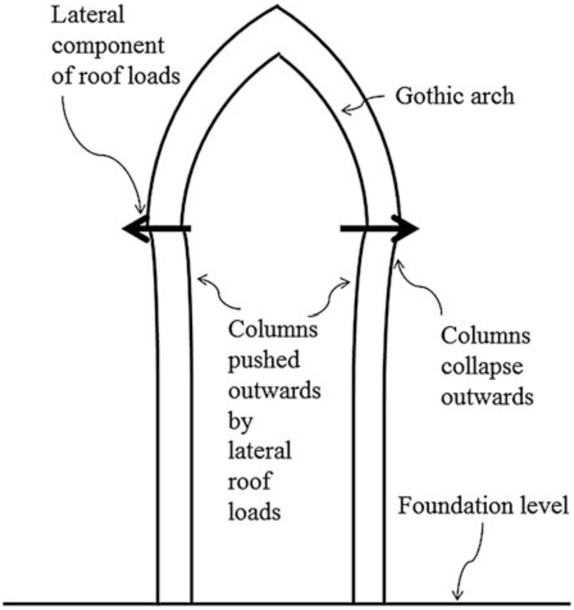


Fig. 4.10 Lateral roof loads lead to collapse of columns

cannot withstand tensile stresses in this direction, cracks running in this direction will likely lead to collapse of the arch (Fig. 4.10).

In order to provide the necessary structural integrity to incrementally increase the height of the vault, experimentation revealed that secondary naves provided lateral loadings sufficient to increase the height of the central vault. When the demand for even higher vaults persisted, mammoth bell towers were added to provide even more lateral strength to the cathedrals. By the end of the twelfth century, an additional experimental design innovation called flying buttresses was in use for providing further lateral structural integrity (Figs. 4.11 and 4.12).

Perhaps the most impressive example of multi-tiered flying buttresses in a Gothic cathedral can be found at Bourges, as shown in Fig. 4.13.

Notre Dame Cathedral in Paris is one of the first Gothic cathedrals to be constructed with flying buttresses. Interestingly, Parisians were not taken with this addition to their cathedral. Eventually, Notre Dame fell into disrepair, and it was not until the publication in 1831 of Victor Hugo's classic novel *The Hunchback of Notre Dame* [32] that the cathedral was renovated and accorded her proper place in history (Fig. 4.14).

Unfortunately, as Newton's laws would later demonstrate (see Chap. 7), all structures on Earth are ultimately limited by the magnitude of Earth's gravitational field (as well as the mass density and fracture toughness of the stone used in construction). Thus, despite the best efforts of engineers in the Middle Ages, there was a limit to the height of the nave that could be attained using stone as a building material, and this limit seems to have been reached at Beauvais, which at 48 m is the highest vault from the Gothic period, as shown below. Sadly, the cathedral partially collapsed in 1287, and construction was never completed.

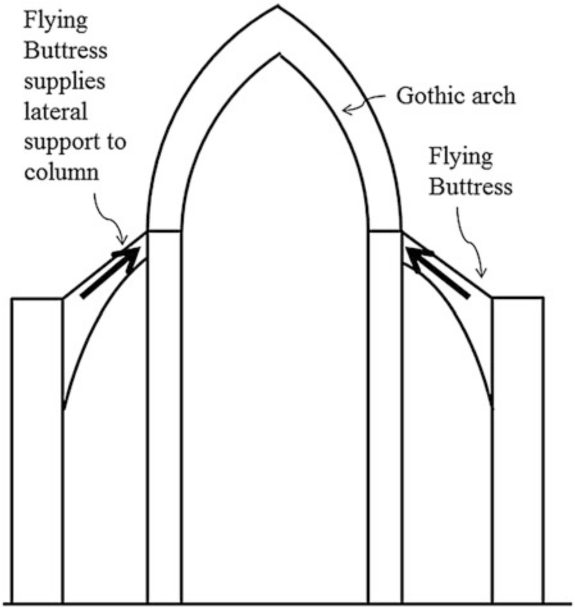


Fig. 4.11 Flying Buttresses supply lateral support to columns

Efforts to build further cathedrals were eventually forestalled by war and plague, both of which swept across Europe in the fourteenth century. Nevertheless, the construction of Gothic cathedrals is perhaps the most ambitious example of experimental mechanics and design on Earth, as more than a 100 Gothic cathedrals were built during this period in Western Europe. Although the mechanics employed at the time was largely experimental in nature, it was nonetheless mechanics on a grand scale, as these magnificent structures became over time the center of existence in much of the Christian world.

After the Gothic period of construction had ended, the countryside was dotted with enormous structures for all the world to see. Future generations therefore had visual evidence that such mammoth projects were possible even in the Middle Ages. Thus, when opportunities arose for further construction projects, the Gothic cathedrals presented iconic models for those who would dare to employ mechanics to build still more elaborate structures (Fig. 4.15).

There is a *denouement* to the story of the Gothic cathedrals. It happened in the late nineteenth and early twentieth century. A Spanish architect named Antoni Gaudi (1852–1926) embarked on an ambitious quest to build a massive cathedral in Barcelona. That cathedral would come to be known as the Basilica de la Sagrada Familia, and although Gaudi has long since passed on, and the cathedral remains unfinished, Gaudi solved the problem of the collapse of stone cathedrals in a most ingenious way (Fig. 4.16).

Using an impressive prescience with mechanics, Gaudi constructed a model *upside down* that can be seen in the basement of the basilica today. The reason that he chose this method is quite incredible. He understood that wires are not capable

Fig. 4.12 Early Flying Buttress (c. 1170) attached to the Choir of the Cathedral of St. Remi in Reims

Fig. 4.13 Multi-tiered Flying Buttresses attached to Bourges Cathedral. *Note* the massive bell tower at the far end of the cathedral

of carrying *tensile* loads in bending. That fact was most propitious, as columns made of segmented stones are not capable of carrying large *compressive* loads in bending, as described above. However, columns, unlike wires, are capable of

Fig. 4.14 Photo of Notre Dame Cathedral in Paris. *Note* the flying buttresses deployed along the nave and the choir, as well as the bell tower, all constructed for structural purposes

Fig. 4.15 Photo of Beauvais Cathedral

carrying axial loads in compression. Thus, Gaudi inverted the experiment using wires, constructing his model of the basilica upside down so that the gravitational loads would cause the wires to be loaded axially (without bending) in tension. This ingenious experiment allowed him to determine the angles from vertical that the wires would self-align themselves along so as to carry the loadings axially (without bending).

Fig. 4.16 Photograph of the Basilica de la Sagrada Familia in Barcelona

This experimental approach (when inverted) enabled him to accurately predict the angle at which the columns in the cathedral should be canted from the vertical in order to ensure that there was little or no bending load applied to them, thus allowing a much higher vault to be constructed without the columns collapsing (since there would be no bending load applied to them). Sure enough, Gaudi's design proved resistant to collapse despite the extraordinary height of the Sagrada Familia.

Unfortunately, Gaudi was killed in a streetcar accident in 1926 and his design was not completed according to his vision. When construction was finally recommenced, the new design technique of employing steel-reinforced concrete columns that are capable of withstanding bending loads was deployed in much of the remainder of the structure, so that although Gaudi had solved the mechanics problem in a most ingenious way, new technology obviated the necessity for using segmented stones.

Of course, nowadays we have finite element computer codes that can model the mechanical response of structures accurately (see Chap. 13), so that experimentation is in most cases minimized or even unnecessary. Nevertheless, Gaudi's ingenuity just over a century ago is undeniably impressive.

Perhaps the most impressive structure other than a Gothic cathedral that was built in Western Europe during the Middle Ages was the Pont St. Bénezet (also called the Pont d'Avignon), built across the Rhône River in Avignon between 1171 and 1185. As a result, the city of Avignon grew into an important point of commerce, to the point that the Popes moved there in 1309, where they remained until 1377. This is an amazing example of mechanics driving both religion and politics.

The bridge was built by St. Bénezet, who was told by angels to build the bridge. The bridge originally was composed of 22 elliptical arches, each spanning 35 m. Thus completed, the bridge spanned a total of 900 m, making it the longest bridge in the world at the time. The use of elliptical arches was a mechanical innovation for the time, as was the deployment of cutwaters, built to resist the sometimes massive flow of the Rhône. Unfortunately, repeated floods caused several arches to collapse over time, necessitating numerous rebuilding efforts. The bridge was finally destroyed in an enormous flood in 1668. Today, only four of the original arches remain (Fig. 4.17).

Universities

Perhaps it was proximity to the East that caused citizens in Italy to begin to thirst for some form of organized education in the eleventh century. Thus, The University of Bologna began granting degrees in 1088, making it the oldest institution of higher education on Earth. Within a little more than a century other educational institutions had begun in Paris (1150), Oxford (1167), Cambridge (1209), Salamanca (1218), and Padova (spun off from Bologna in 1222). Of course, all of these dates are disputed, because records from that period of time are sparse.

Fig. 4.17 Remains of the Pont St. Bénezet in Avignon

In addition, everyone has their own definition of what is a ‘university.’ The point of the present discussion is not to pick a winner, but more importantly, to point out that both education and the written word were beginning to make their way back into Western Europe around this period of time.

Much of what was studied during this period was recovered from ancient records, and some of it came from the East. The Venetians had by this time become the most powerful seafaring nation in the Mediterranean, and they bought printed matter wherever they could from the Middle East. In addition, the remnants of the Ottoman Empire still remained in Southern Spain, principally in Sevilla, where many of the ancient manuscripts were restored to the West. Suddenly, there was a treasure trove of writings on mechanics that scholars began pouring over. Principal among these were the writings of Aristotle, although many others were studied by scholars at the rapidly sprouting institutions across Western Europe. Whatever was going on, it was working, because a number of scholars appeared on the scene, and some of them even accounted for advances in mechanics.

In the ninth century the Arabic scholar Muhamed ibn MūsāAl-Kwārizmī (c. 780–850) wrote the book called *Aljebr* (ergo algebra) [33]. It was a compilation of the works of many other Arabian scientists, and this book became a very important resource on the way back to the world of technology. The book used symbols to label numbers that came from the Hindu portion of Northwest India (Figs. 4.18 and 4.19).

Much later, a young merchant named Leonardo do Pisa (c. 1170–1250) travelled with his father to Spain and North Africa and in due course he read the book *Aljebr* (among others) and eventually he wrote his own books on the subject in Latin, which was more accessible to Westerners, thus making these symbols available to the learned in the West [34]. Today we sometimes call these numbers Arabic numbers, but they are actually Hindu numbers (Fig. 4.20).

Leonardo do Pisa was subsequently forgotten for several centuries, but in the nineteenth century his importance once again came to light, and one of his biographers called him fils Bonacci, meaning son of Bonacci, which subsequently was contracted to Fibonacci, from whence mathematicians have dubbed these numbers Fibonacci numbers. But the mathematicians are incorrect, because the numbers are actually Hindu numbers. As described in Leonardo do Pisa’s book *Liber Abaci* [35], these are the numerals that we use in our base ten numbering system today over most of the world. Without these numbers we would find it very difficult to do any mechanics whatsoever, so although these numbers are not in themselves “mechanics” *per se*, the science of mechanics was encouraged by this development (Fig. 4.21).

A contemporary of Leonardo do Pisa was Robert Grosseteste (c. 1175–1253), who was born in Lincoln. He is known today for many things, but for the purpose of the present text, he has a special place. He appears to have been the first person in modern times to appreciate the writings of Aristotle sufficiently to postulate that science should proceed from specific observations to general or ‘universal’ laws, and then back to specific experiments as a means of verification. And while most

Fig. 4.18 Image of Muhamed ibn MūsāAl-Kwārizmī on a Russian stamp

of his scientific work dealt with optics rather than mechanics, it can be said that his approach to science makes him the forerunner to Galileo (Fig. 4.22).

Roger Bacon (c. 1214–1294) became the most accomplished student of Robert Grosseteste at Oxford, perhaps even eclipsing him in his own accomplishments (Fig. 4.23). He seems to have been the first scientist in modern times to treat science methodically, according to the concepts of Grosseteste. He is known to have studied the celestial bodies, and he appears to be the first person to forewarn the clergy that the Julian calendar was badly out of time with the Earth's progression about the Sun. He did this by using Bede's approach to measuring both the equinoxes and the solstices (see more on Roger Bacon in Chap. 6).

William of Ockham (c. 1288–1348) produced major philosophical and scientific works, but none measures up to the import of his razor, quoted at the beginning of this chapter. This pithy remark is most likely paraphrased, but it nonetheless hits the mark. It would be restated and used by none other than Galileo Galilei, Isaac Newton, and Albert Einstein, perhaps the three greatest mechanists in history, thus supplying ample reason for his reference in the current book on mechanics (Fig. 4.24).

Fig. 4.19 A page from *Aljebr*

Fig. 4.20 Portrait of Leonardo do Pisa by an unknown artist

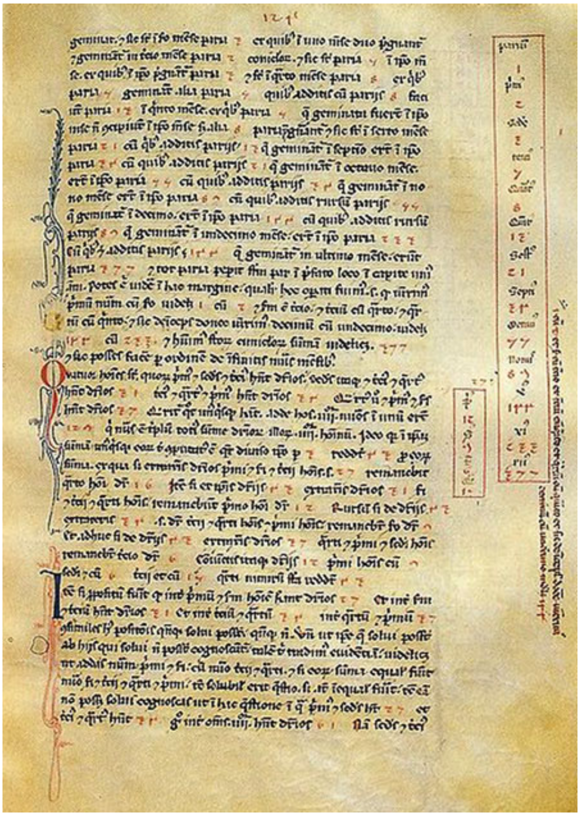


Fig. 4.21 A page from Leonardo do Pisa's book *Liber Abaci*. *Note* the Fibonacci numbers in the *right-hand* column

Fig. 4.22 The Tomb of Robert Grosseteste in Lincoln Cathedral

Fig. 4.23 Sketch of Roger Bacon

Fig. 4.24 Sketch of William of Ockham from a 1341 Manuscript

Language

The great medieval painter Cimabue (c. 1240–1302) was the last of the great old style Pre-Renaissance painters, and some of his masterpieces may be seen at the Basilica of San Francesco in Assisi. Cimabue had a student named Giotto, whom we shall speak more of in the next chapter. Interestingly, Giotto painted the oldest known painting of another artist named Dante Alighieri (c. 1265–1321). We shall see shortly that both of these icons played enormous roles in the Renaissance (Fig. 4.25).

I had an interesting conversation with a linguist one time who contended that the world would be messed up if we all spoke the same language. I am an engineer: engineers are always trying to find ways to simplify the world and make things better, ergo views such as this seem patently absurd to me. The contention was that without different languages cultural identity would be lost. I do not agree with this. While I do agree that language contributes to culture, I believe that cultural identity is significantly larger than language.

Historically, language developed as a means of transporting knowledge. One could argue that without technology there is no need for language. Imagine living in a world where the only technology is building fires. Language will necessarily be quite limited. So as technology developed over the past several 1,000 years, language became more complex. Thus, intricate language is necessary to the transport of the science of mechanics.

While we are still inventing words to describe things all the time (we even have a word for words with no name—*sniglet*), the Latin based languages essentially reached structural maturity 2,000 years ago, when the last verb tense in Latin was

Fig. 4.25 Portrait of Dante by Giotto

implemented by the Roman government. Since that time Latin based languages have waxed and waned, largely depending on communications. In Italy, for example, when the Roman Empire collapsed in the fifth century AD the incursions by all sorts of invaders over the next few centuries caused society to compress into miniscule hilltop fortresses for the sake of survival.

Because communications were largely cut off between the communities, language in each of the cities evolved more or less independently. Many of those differences persist right down to today: there are literally dozens of dialects in Italy. But in the fourteenth century, the invention of the monetary unit called the florin in Florence caused a miniature economic boom in central Italy. One needs to keep in mind that Italy was not a country until the late nineteenth century.

This economic boom allowed the ruling class in Florence (the *Signoria*) to invest in many artistic activities. From their perspective, they were just advertising their own self-importance, but from the perspective of the rest of the world, there were lots of job opportunities to be had. So there was a mass migration of artists into central Italy.

While most artists around the beginning of the fourteenth century were focused on painting and sculpture, one artist chose the written word for his canvas. That person was Dante Alighieri. His subject was Christianity, and his “paintbrush” was the local dialect of Latin that the Florentines had adopted over the 800 year period since the fall of the Roman Empire. Ejected from his home city of Florence for political reasons that were unrelated to his writings, Dante used the old Latin alphabet, but he nevertheless used the words that Florentines used every day. The book (actually an allegorical poem), called *La Divina Commedia (The Divine Comedy)* [36], was a huge success. It was so popular that the masses outside Florence began to read it. But in each of the hilltop fortress cities, the Latin language had evolved differently over the centuries so that, depending on how far the local language had strayed from Latin, there was either a little bit or a lot of translating to be done. Thus, some education was necessary in order to read the book. Readers became aware that there were communication barriers to overcome.

Why not just adopt the Florentine dialect? *Voila*, just like that, the Italian language was born. In a sense, the Italian language was created from economic necessity, yet another demonstration of Darwin’s law of survival of the fittest. So Dante, revered as a literary artist, is one of my technological superheroes. Why? Because he not only wrote the first treatise of any significance in modern times, he re-introduced the written language to the masses, thereby allowing technology (including mechanics) to have a means of transport. Thus, that transport or education took off during the Renaissance. And it was this education more so even than the art that changed the world.

The Divine Comedy was extremely controversial in Dante’s lifetime. When he passed away he was laid to rest in a small chapel in downtown Ravenna. Eventually, the tide turned in favor of *The Divine Comedy.* The mayor of Florence went on a trip to Ravenna and asked for Ravenna to give back to Florence the body of one of her greatest heroes (everyone needed bones of the revered back then). The mayor of Ravenna refused (Fig. 4.26).

Fig. 4.26 Dante's Tomb in Ravenna

The Florentines built a great tomb for Dante in the Santa Croce, near Michelangelo's final resting place. Still, the Ravennans demurred. The Florentine's cajoled and demanded, they claimed that Dante's tomb in Ravenna was not worthy, but nothing worked. The Ravennans built a better tomb (which is still there today). And each year the mayor of Florence went to Ravenna on Dante's birthday and asked the Ravennans to return the body of Dante to Florence. And each year the Ravennans refused. And each year a party broke out. So it took a very long time, but another of my heroes has his just reward. And more importantly, Dante resurrected language as a means of transporting knowledge, thus laying the foundation for a new wave of mechanics to come forth.

Torture

I seriously doubt that those of us living today could in any way comprehend the quality of life in the Middle Ages. For example, the plague that swept across Western Europe in the middle of the fourteenth century reduced the population by some estimates by two-thirds (to perhaps one million). Thus, the value of life sank to historically low proportions. Fear of death in turn gained such enormous momentum that people were actually killing their fellow humans in the vain hope that this process would gain their own salvation. As I said, we could not possibly know what it was like to live in that time.

As I am sometimes heard to remark, mechanics has no soul. It is simply a tool for the use of humankind, sometimes for the better, but sometimes also for the worse. In the case of the Middle Ages (as well as before and after), mechanics was an unwitting pawn in the deployment of torture. I am not going to go into the gory details herein, because readers would quickly abandon their perusal of this tale, but I would be remiss if I did not at least mention the invention of torture devices that utilized all sorts of extremely ingenious mechanics (Figs. 4.27, 4.28, and 4.29).

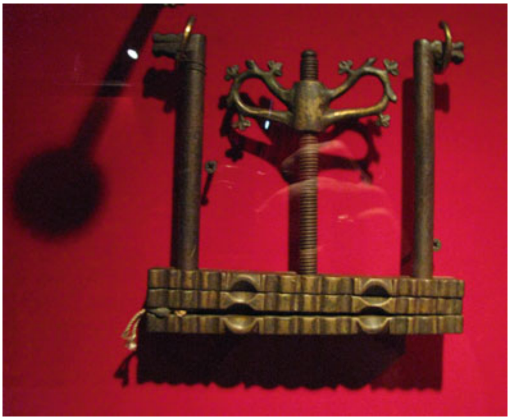


Fig. 4.27 Thumbscrew (Torture Museum, San Gimignano)

Fig. 4.28 Devices for cutting off the tongue (Torture Museum, San Gimignano)

Fig. 4.29 Depiction of torture rack

For those who are possessed of iron constitutions, I highly recommend a visit to one of the many torture museums across Europe today (my favorite is in San Gimignano, Italy). These museums not only portray the rather incomprehensible behavior of our recent ancestors, they also give ample evidence of the use of mechanics in the not-too-distant past.

Thus, we have seen in this chapter that although the pursuit of mechanics slowed considerably during the Middle Ages, it certainly did not cease entirely, and while mechanics continued to advance in some cases, the means whereby mechanics shaped the world was not always what could be termed progress.

The Artistic Renaissance

5

Every block of stone has a statue inside it and it is the task of the sculptor to discover it.

Michelangelo Buonarotti (1475–1564)

I could write a thousand pages on this chapter alone. But the history of art is not the subject of this book. Therefore, I will restrict my discussion to developments by those artists whom I think contributed substantially to the science of mechanics. The subject of Renaissance Art is such a well-researched and robust subject that I fear I shall be castigated by plenty of detractors. Nonetheless, to avoid this topic altogether would be even more remiss. Thus, here are my views on the Renaissance artists who helped to advance the science of mechanics (Figs. 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8, 5.9, 5.10, 5.11, 5.12, 5.13, 5.14, 5.15, 5.16, 5.17, 5.18, 5.19, 5.20, 5.21 and 5.22).

Sometime around the beginning of the fourteenth century there was a rapid growth in economic affluence on the Italian peninsula. As is often the case, when there is wealth, there is also a proclivity to show off. The new-found wealthy in Italy wanted to demonstrate their importance, thus they hired marketers, which at the time were actually artists, usually painters, but also often sculptors.

Giotto

I consider Giotto di Bondone (1266–1337) to be the father of the Artistic Renaissance. Sometime shortly after the turn of the fourteenth century, when no one was aware that the Renaissance was poised to burst onto the Italian landscape, Giotto began painting in a new-found style that was possessed of so much more realism than that of his immediate predecessors that there is a clear dividing line between pre-Giotto and post-Giotto art in Western Europe. His teacher, Cimabue (c. 1240–1302), the last of the great medieval artists, had attempted to open this door, but had fallen just short.

It was left for Giotto to open this door full wide, and so he did. Giotto's masterpiece is the Scrovegni Chapel in Padova, completed in 1305 (make your reservations to see the chapel well in advance!). Giotto is also believed to have painted many of the frescoes in the Basilica of San Francesco in Assisi, but we

D. H. Allen, *How Mechanics Shaped the Modern World*,
DOI: 10.1007/978-3-319-01701-3_5,

Fig. 5.1 A possible self-portrait of Giotto, Basilica of Santa Croce, Florence

cannot be sure of this. His departure from the old Byzantine style, thus depicting scenes with realism, is a milestone in the history of art. In so doing, Giotto also paved the way for more the more precise treatment of mechanics. Within a few short years it became possible to utilize the techniques deployed by Giotto in his artwork to depict the motions of bodies much more accurately than had been heretofore possible.

One thing we can be sure of is that Giotto designed the Campanile for the Santa Maria del Fiore in Florence. This harmonious edifice is a masterpiece of structural mechanics. But far more importantly, the bell tower was a means of transporting time to the masses. Toward the beginning of the fourteenth century this ingenious means of denoting the time of day had just sprung upon the western world. And it should go without saying that a ringing bell is an application of the science of mechanics.

When a bell is struck by a hammer the bell vibrates in resonance, producing a tone that depends on the dimensions and material properties of the bell (see Chladni's experiment in Chap. 9). Typically, the larger the bell, the more energy it takes to produce a sonorous tone. Thus, mechanical devices are often constructed that rotate the bell with a mechanical pulley assembly so that the striker hits the bell with enormous energy. The motions of the surface of the bell in turn jostle the molecules in the surrounding air, thus producing a mechanical acoustic wave that is capable of propagating over very long distances (although it tends to be mitigated by wind and moisture in the air), thus making it possible to transmit the time

Fig. 5.2 Cimabue's Maestà, Uffizi Gallery, Florence

of day to the entire population of a town, thereby allowing for significantly more efficient utilization of time. Thus, we find that the use of mechanics once again drives the advance of technology.

Clock Towers

This seems to be a good point for an interesting diversion. I am speaking of clock towers, which seem to have arisen in full force around the time of Giotto. Actually, clock towers go all the way back to ancient times, when sundials were displayed on the Tower of the Winds in Athens. However, I am speaking here of clock towers that contained mechanical devices for measuring time. These seem to have sprung up in the latter part of the thirteenth century [37].

Perhaps the first such device was utilized on the tower at Westminster in London in 1288. Unfortunately, the devices used at that time supplied energy to the mechanism via hanging weights, and for this reason they kept such poor time that they had to be adjusted several times a day in order to remain accurate (they were usually compared to a more accurate clepsydra). Nevertheless, these large towers

Fig. 5.3 Giotto's Lamentation (The Mourning of Christ), Scrovegni Chapel

became the primary means for townships to keep time during the Renaissance. Finally, in the mid-seventeenth century Christiaan Huygens (1629–1695) expanded on Galileo's concept of the pendulum to design clocks that kept excellent time (except on ships, see Chap. 8). Huygens would go on to make great advances in a variety of scientific fields, many of them dealing with mechanics.

Thus, we see mechanics once again driving technology through the ever improving measurement of time, and by the middle of the seventeenth century pendulum mechanisms were being used in clock towers across Europe.

Brunelleschi

Let's get back to our story of the Renaissance. One surely singular event toward the middle of this period that hastened the rebirth of science was the construction of the dome of the Santa Maria del Fiore in Florence in 1420–1434 by Filippo Brunelleschi (1377–1446) [38, 39].

There is a story that Brunelleschi was so distraught at having lost the competition for the doors of the Baptistery in 1401 to Lorenzo Ghiberti (1378–1455) that he took a long trip to Rome with his young friend Donatello (c. 1386–1466). There the pair undertook to study the Roman ruins in great detail. Some even say that they were the first in modern times to study the ancient Roman ruins in any scientific way.

Fig. 5.4 Giotto's Campanile adjacent to the Santa Maria del Fiore in Florence

Fig. 5.5 The tower of the winds in Athens. *Note* the Acropolis in the background

At any rate, history records that Brunelleschi studied the Pantheon in particular because he was aware that the *Signoria* in Florence would eventually be forced to deal with the gaping hole in the center of the Santa Maria del Fiore. You see, the

Fig. 5.6 Portrait of Christiaan Huygens

plans had been created with the thought of building a dome above the altar, but no one had yet figured out how to construct it. Arnolfo de Cambio had actually constructed a model in 1296 for an octagonal dome, and it stood for more than a century in the side aisle of the great cathedral, but as yet no one had come forth with an executable plan of construction.

Thus armed with his understanding of the Pantheon, Brunelleschi was ready when the contract for the dome was advertised many years later. Amazingly, he proposed that he could build the octagonal dome using masonry and without the necessity of using falsework, something that had never even been considered. Everyone at the time thought that a dome was like an arch, and arches required that falsework be placed beneath the arch, only to be removed after placement of the keystone in the center of the arch.

Somehow, Brunelleschi had gleaned from his study of the Pantheon that no such falsework would be necessary when building a dome. Brunelleschi apparently posited that building falsework would necessarily require cutting down all of the available timber in Lombardia. At least in part on the basis of this, the contract was

Fig. 5.7 Photograph of the Clock Tower in the Piazza San Marco, Venice

awarded to Brunelleschi, and he was subsequently proven correct. This feat was an amazing demonstration of the power of mechanics.

The development of mathematical models for elastic bodies 400 years later (see Chap. 10) would confirm Brunelleschi's prescience. We now know that the stones do not collapse in a dome during construction due to a component of stress called hoop stress. Furthermore, the hoop stress can be broken down into two components, one of which is lateral to the alignment of the stones. This component of hoop stress keeps the stones from collapsing inwards, somewhat similar to the concept of an arch except that in this case the arch is turned on its side (see Chap. 3). Unfortunately, this component of the hoop stress also forces the structure radially outwards. Brunelleschi dealt with this problem by building a double dome—a dome within a dome, as it were, and he constructed several stone and wooden tension rings at ascending levels within the dome so that the dome would not collapse outwards. His octagonal double dome design also spanned the shape of a circle, thus ensuring that it would be structurally sound.

Brunelleschi also designed and constructed massive and complex mechanical devices for both raising the stones and bricks used to build the dome to their lofty positions, and these were powered by oxen. Some of these amazing mechanical devices are considered today to be Brunelleschi's greatest contribution to the

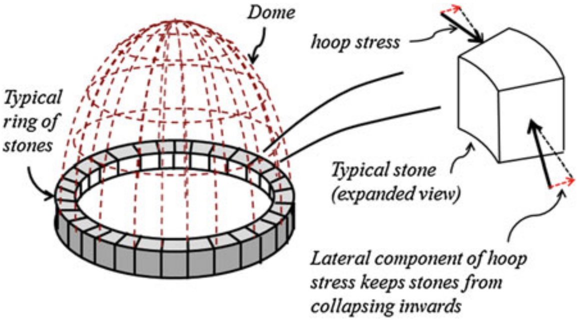


Fig. 5.8 Depiction of a Dome. *Note* the lateral component of hoop stress that keeps the stones from falling inwards

Fig. 5.9 The Brunelleschi Dome in Florence. *Note* the *octagonal shape*

Fig. 5.10 Bust of Brunelleschi in the Santa Maria del Fiore

Fig. 5.11 Da Vinci self portrait

Fig. 5.12 Da Vinci's last home, the Clos Lucé, in Amboise, France

advance of technology. By conceiving of this design and demonstrating experimentally that it would allow construction of the dome without false work, Brunelleschi advanced the science of mechanics significantly.

Fig. 5.13 Painting by Jean Auguste Dominique Ingres depicting Leonardo Da Vinci on his death bed at the close Lucé, Held in the arms of the French King François I. *Note* that this is the first room entered by visitors to the Clos Lucé

Fig. 5.14 Photo of Chambord, the largest Chateau on earth

Brunelleschi is also known to have constructed two complex paintings designed to demonstrate the concept of linear perspective, which was in infancy at that period of time. He constructed a painting of the Florence Baptistry and cut a tiny hole within it at the point of perspective. The viewer was then entreated to face the baptistery and look through the tiny hole from the backside of the painting. A mirror was then held up beyond the painting, and the viewer was able to see the painting through the mirror. When the painting and the mirror were removed, the viewer saw exactly the same view (the actual baptistry) before him/her, thus demonstrating the concept of linear perspective. Although these two panels have

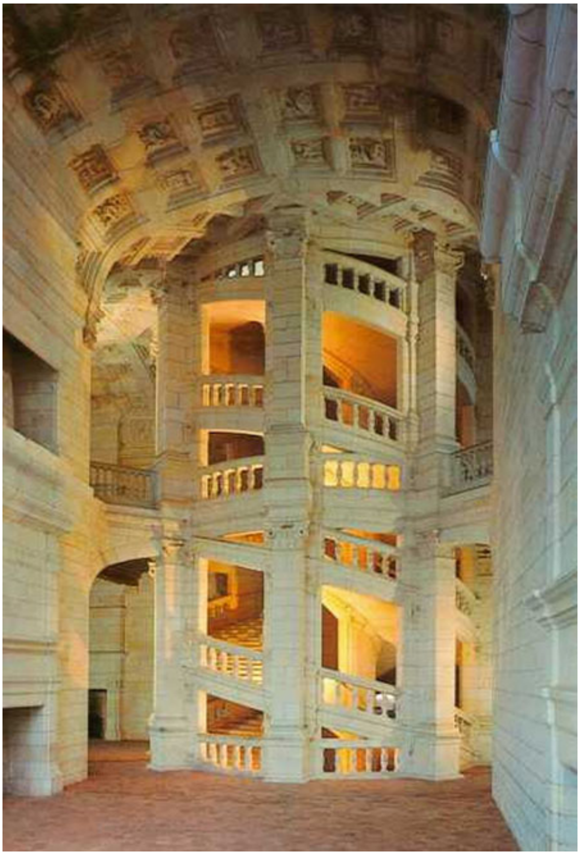


Fig. 5.15 Leonardo's double helix staircase at Chambord

been lost, Brunelleschi is therefore claimed by some to have invented the principle of modern perspective (although Ambrogio Lorenzetti (1290–1348) is known to have previously painted the Annunciation in 1344 with proper perspective), a necessary tool in mechanics. Subsequent deployment of this technique proved invaluable to the science of mechanics.

There is a story that the *Signoria* did not believe Brunelleschi when he claimed that he could build the dome without the use of false work, so he purchased a wagon load of turnips (or maybe it was rutabagas) and constructed a scale model that was large enough to walk inside in downtown Florence. If this story is true, I will bet this little dome must have become quite rancid after a few days. But the truth is, this story is almost surely a hoax, since Brunelleschi constructed a scale model from wood and bricks that was placed in the Museo dell'Opera del Duomo just behind the Dome. Sadly, this model is no longer available for viewing today. Incidentally, you can also see Michelangelo's *Florence Pietà* therein, perhaps Michelangelo's last great work of art, as well as Donatello's *Magdalene Penitent*, perhaps one of the most significant forerunners of the Impressionist Era.

Fig. 5.16 Portrait of Michelangelo by Jacopinto del Conte (c. 1535)

Fig. 5.17 Michelangelo's Dome above St. Peter's Basilica. *Note* the Egyptian obelisk in the foreground

As a reward for his grand accomplishments, Brunelleschi was buried in the basement of the Santa Maria del Fiore Cathedral, where one can visit his tomb today and see his likeness on the wall, as shown below.

Fig. 5.18 Michelangelo's Pietà, St. Peter's Basilica, Rome

Fig. 5.19 The Rondanini Pietà by Michelangelo, Museum of Antique Art, Milan

If you ever visit Florence, you simply must climb the steps to the top of the dome. Therein you will find that not only did Brunelleschi build a dome, he built a dome within the dome, thereby providing both structural reinforcement and a

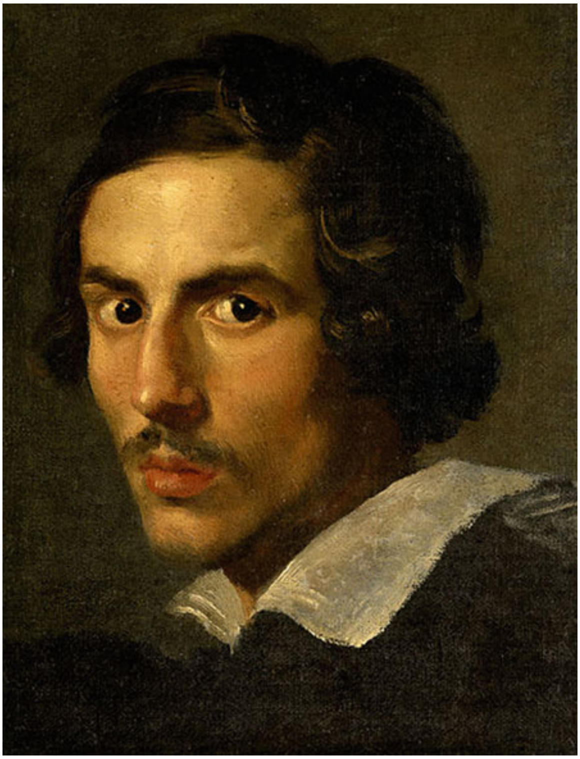


Fig. 5.20 Portrait of Bernini in the Galleria Borghese

means of ingress and egress from the lantern at the top. You will mount the stairs between the two domes, and once you arrive at the top and climb out onto the apron of the lantern, you will be treated to the most fabulous view in all of Florence.

I consider the construction of that dome to be the single most important mechanical development of the Renaissance. Not only did Brunelleschi accomplish something monumental and new in modern times, his dome was created with the help of numerous new mechanical devices designed to lift and place the bricks and stones within the dome into place at enormous heights above the city of Florence [38]. This was perhaps the greatest step forward for the science of mechanics during the Renaissance.

After the completion of the dome, a veritable construction boom began in Italy and spread outwards to the remainder of Europe. For example, the Holy See in Rome was apparently so irritated by the fabulous Brunelleschi Dome that they subsequently razed the now outdated Constantine's Cathedral in Rome and built St. Peter's Basilica. And before long, scientists were beginning to focus on producing theories capable of aiding in the design and construction of structures. Because of this, Brunelleschi is in my view the most important person of the Renaissance.

Fig. 5.21 Photo of Bernini's Colonnade in front of St. Peter's Basilica, Rome

Fig. 5.22 The Trevi Fountain in Rome, designed in part by Bernini

Da Vinci

Leonardo Da Vinci (1452–1519) was by all accounts a remarkable man, revered for his knowledge, his artistic abilities, and even his physical appearance and gentile nature in his own lifetime. His accomplishments were so broad and far-reaching that he is today considered to be the archetypal Renaissance Man. He was perhaps best known in his own time as the consummate painter, but his extant body of scientific and engineering work has demonstrated that there was practically nothing that failed to interest him. Mechanics, though it was only one of his interests, was surely one of his most passionate ones.

I've visited the reputed place of Da Vinci's birth on the hill overlooking Vinci (although in actuality no one really knows here he was born). I've also been to Da Vinci's villa in Amboise, the Close Luce, quite a few times, and I've visited his tomb at the Château d'Amboise down the hill by the Loire River. It is a fabulous place. François I, the King of France, treated him well in the last 3 years of his life. Leonardo seems to have been debilitated by a stroke during this period, so it must not have been as pleasant as could be expected for the period of time that he lived in France.

Da Vinci was an amazing polymath—a master of many different things—and he was known for it in his own lifetime. Very few scientific types have achieved such status in their own lifetime. However, he seems to have failed to transmit the predominant body of his knowledge to the public. To put it more concisely, he did not use his abilities to educate. On the contrary, as we know from his manuscripts, he was quite secretive. He went to some lengths to hide his work, writing backwards or even in shorthand quite often. As a result, much of his work lay dormant, hidden away for more than a century. In reality, most of his writings have come to the light of day only in the last 150 years or so. By that time many of his ideas were precluded by later icons. Thus, although this oversight can be forgiven as a custom during his time, Da Vinci may have missed an opportunity at a far greater immortality.

I will give you an example. Leonardo wrote the following in one of his notebooks:

> A heavy body which falls freely acquires one unit of velocity. In the second unit of time it will acquire two units of motion and two units of velocity, and so on in the way described above.

This quotation was discovered and published in 1890. A century after Leonardo's passing, Galileo wrote in his book *Dialogues Concerning Two New Sciences* [40], published in 1638:

> The spaces described by a body falling from rest with a uniformly accelerated motion are to each other as the squares of the time-intervals employed in traversing these distances.

It sounds like Galileo read Da Vinci's text a century after Da Vinci's passing and expanded on it, but Galileo was totally unaware of Da Vinci's description because it was still hidden away. If Galileo had been aware of Da Vinci's thoughts, is it possible that Galileo would have arrived at his views sooner, and perhaps even taken that additional step to the first universal law arrived at by Newton a mere 50 years later? We will never know, because the importance of Da Vinci's manuscripts was not perceived until long after his death.

In his excellent book entitled *A History of Mechanics*, René Dugas says that "Leonardo Da Vinci cuts the figure of a gifted amateur" [41]. Indeed, in his own words, Leonardo termed himself "an unlettered man" [42].

In the year 1516, now failing in health, Leonardo found himself in difficult financial circumstances. François I, the King of France, who was visiting Lombardy at the time, offered Leonardo a secure place near his palace in Amboise, France. Leonardo accepted this generous offer, thus spending the remaining 3 years of his life in the Clos Lucé, connected to the King's palace by a secret tunnel. History tells us that François and Leonardo shared many interesting conversations on a vast array of subjects before Leonardo's untimely death in 1519 [42].

Interestingly, at the time that François I ruled, France was considered to be a bit of a backwater compared to the rapidly flowering Renaissance cities across Italy. In the same year that Leonardo passed away, François began construction of a new edifice on the grounds of an old hunting lodge near Amboise called Chambord. Over the succeeding 22 years, up to François' death from a heart attack in 1547, the lodge was built into what is today the largest chateau on Earth. This was truly a massive project for that period of time in France. Anyone who has visited this magnificent chateau will immediately wonder what mechanics must have been employed to create such a formidable masterpiece.

Although we cannot be certain of this, some historians believe that Leonardo Da Vinci may in fact have been the original designer of Chambord. Whether this is true or not, we will perhaps never know. However, given Leonardo's undeniable talents, it would be nice to believe it is so, for in that case, Leonardo would perhaps be responsible at least in part for the Renaissance in France. In homage to Leonardo's possible involvement in the design of Chambord, the double helical staircase at the center of the chateau is today sometimes called 'Leonardo's Staircase'. If this conjecture is true, it would be fitting that Leonardo would have blended art and mechanics in such an attractive way.

Toward the end of the fifteenth century Leonardo, ever the dabbler, recorded what may be the first systematic attempt in history to measure the strength of a material. Leonardo writes in one of his manuscripts:

> The object of this test is to find the load an iron wire can carry. Attach an iron wire 2 bracchia (about 1.3 m) long to something that will firmly support it, then attach a basket or any similar container to the wire and feed into the basket some fine sand through a small hole placed at the end of a hopper. A spring is fixed so that it will close the hole as soon as the wire breaks. The basket is not upset while falling, since it falls through a very short distance. The weight of sand and the location of the fracture of the wire are to be recorded. The test is repeated several times to check results. Then a wire of one-half the previous length is tested and the additional weight it carries is recorded, then a wire of one-fourth length is tested and so forth, noting each time the ultimate strength and the location of the fracture.

The experiment described above has become in modern times the single most common means of measuring the so-called "elastic constants" for a material (see Chap. 9). These are a necessary input to modern models that predict the motions of solids due to externally applied loads. As such, Leonardo's place in the science of mechanics is assured.

Michelangelo

Michelangelo Buonarroti (1475–1564) is by some accounts the greatest artist of all time. I am not an art critic, but you will certainly receive no argument from me. I have seen nearly every piece of his magnificent oeuvre. But the real question is—where does he fit into a treatise on mechanics? That is indeed a very good question that I will expand on in some detail in Chap. 9, which elaborates on the relationship between art and mechanics.

But let me at least review a few of my own observations with respect to Michelangelo, the last of the great Renaissance artists. As I have alluded to previously, there was a blurring of responsibilities of artists during the Renaissance, as evidenced most vividly by the works of one of Michelangelo's adversaries, Leonardo Da Vinci. While Michelangelo was clearly not the polymath that Da Vinci was [43], he did nonetheless play a role in the development of mechanics.

For example, Michelangelo, expanding on the Santa Maria del Fiore dome designed and constructed by Brunelleschi, redesigned Bramante's original design for the dome of St. Peter's Basilica, thus forming a triumvirate of the three greatest stone/masonry domes on earth: the Pantheon, the Santa Maria del Fiore, and St. Peter's Basilica. These three massive domes have profoundly affected all subsequent domes built on Earth.

The main reason that I have chosen for including Michelangelo in this book is due to the quote attributed to him at the beginning of this chapter. I suggest that you read the book *Michelangelo and the Pope's Ceiling* by Ross King [43]. This treatise more than anything that I have read on Michelangelo captures the essence of this singular artist. Michelangelo, like Leonardo before him, had an obsession with perfection. And while there is no doubting the import of his two painted masterpieces in the Sistine Chapel, his sculptures are in my view the pinnacles of artistic experimental mechanics. Imagine taking a hammer and chisel and hacking away at an enormous chunk of undistinguished marble. Any school child can engage in such a practice of experimental mechanics, toying with the angle of the chisel and the force of the hammer in such a way as to produce cracks and subsequent spallation of the hunk before him/her. But to cause to emerge from this massive tangle of extremely hard and inconspicuous material something soft, ethereal, and capable of rending great emotional response is to this writer at the very pinnacle of the practice of experimental mechanics.

The first pietà (in St. Peter's Basilica) and the David are perhaps the finest examples of the mechanical arts in the history of mankind. And then there is the enormous Rondanini Pietà, the one that Michelangelo was working on when he died at the age of 88. Even this distorted work of an aged and failing Michelangelo holds enormous attraction for the mechanist within my soul.

Bernini

Gian Lorenzo Bernini (1598–1680) is not really a Renaissance artist (he came later), but he did have a profound impact on mechanics. Thus, I have included him herein. In Chap. 9 I will explain how great epochs in art precede great epochs in science. And so it is with Bernini. Spanning the lifetimes of Galileo and Newton, his baroque style of art and architecture brought breathtaking changes to the city of Rome. From the colonnade of St. Peter's Square to the fountains of Rome, the scope of his works are such as to enhance the imagination of all who see them. It is little wonder that tourists flock to every corner of Rome today in search of the masterpieces of Bernini.

Unfortunately, the experimental efforts undertaken by Brunelleschi, Da Vinci, and many others during the Renaissance did not immediately lead to significant advances in mechanics models, as most sages of that time period clung to the old Aristotelian principles, as we will see in the next chapter. Still, the impact of the experimental mechanics deployed by these artist/technologists eventually came to profoundly affect the science of mechanics.

Finding Our Way

6

The church says the earth is flat, but I know that it is round, for I have seen the shadow on the moon, and I have more faith in a shadow than in the church

Ferdinand Magellan (c. 1480–1521)

The Calendar

Perhaps no application is more important to the early developments in mechanics than the production of an accurate calendar. There is a fabulous book that has been written on the subject of the calendar, named appropriately *The Calendar*, by David Ewing Duncan [44]. For the simple reason that his book is all-encompassing, I will not go into great detail herein on this most important subject. I will instead attempt to summarize the evolution of our calendar, especially in sofar as it has impacted the science of mechanics (Figs. 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, 6.10, 6.11, 6.12, 6.13, 6.14, 6.15, 6.16, 6.17 and 6.18).

Let us begin with what we believe to be the first recorded reference to a calendar, carved on a bone, and discovered in France. This carving has been dated to about 32,000 BCE, and appears to be a lunar based calendar (see Chap. 1).

I will skip over many of the details in between and jump directly to the Egyptian calendar. As early as about 4,000 BCE, the Egyptians appear to have been constructing a solar based calendar that correlated the date of the arrival of the annual flood of the Nile to the day of the year on which Sirius (the Dog Star) rises in the eastern sky, and this evolved into what appears to be the oldest calendar that uses a 365 day period for a revolution of the Earth about the Sun. Other attempts at that time that were based on the Sun's position in the sky were apparently not quite as accurate, and calendars based on lunar motions were even less accurate.

Still later, in 238 BCE Ptolemy III ordered that a leap day be added every 4 years, thus improving the Egyptian calendar to 365.25 days. Unfortunately, this edict did not take hold in Egypt, as the religious clerics persisted in adhering to the 365 day calendar, despite the fact that scientists such as Hipparchus (see Chap. 2) had determined that this was in error.

For the purpose of the current discussion, it is important to recognize that the period of revolution of the Earth about its own axis, the period of revolution of the Moon about the Earth, and the period of revolution of the Earth about the Sun

D. H. Allen, *How Mechanics Shaped the Modern World*,
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Fig. 6.1 Statue of Julius Caesar in the Tuileries, Paris

are all independent of one another. Indeed, each of these can and are affected by motions of other objects in the universe, especially large ones that are close to Earth, and these effects are in most cases caused by gravitational forces.

Fig. 6.2 Portrait of Pope Gregory XIII by Lavinia Fontana

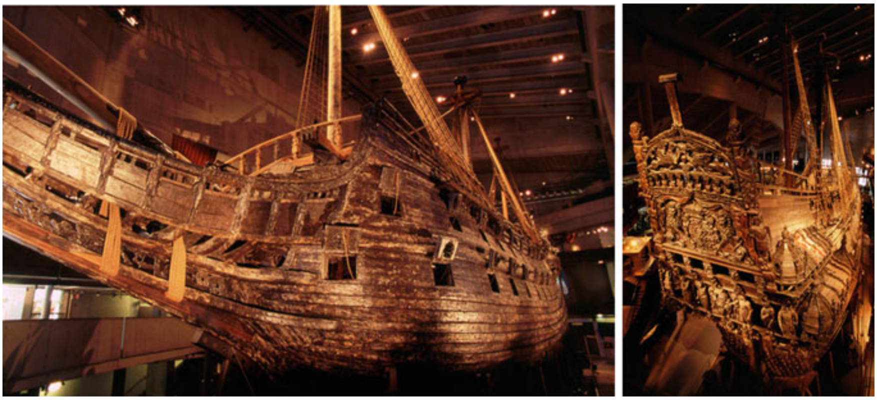


Fig. 6.3 Photos of the Wasa: Bow photo on *left*, stern photo on *right*

On rare occasions, when the Earth or the Moon is impacted by an object, the mechanics of these impacts can also affect the duration of a day or a year. The other spans of time that we humans use are wholly made up by us: a second, an hour, a week, a month, a decade, a millennium, etc. In fact, this is a distinguishing feature of our species compared to all others that we are aware of: *so far as we know, we are the only ones that measure time using a calendar*. This makes the duration of time measurable in an intimate way, which is a good thing. That way we know when we are supposed to report for work, a dinner engagement, or our own wedding, for example. Unfortunately, it may also make us the only species that is aware of our own mortality.

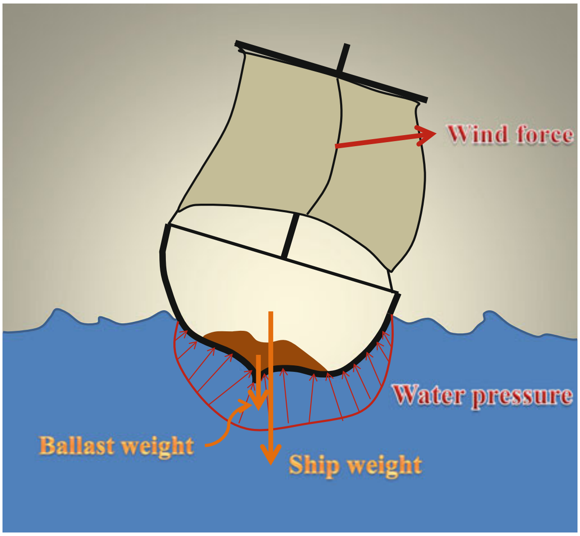


Fig. 6.4 Balancing water pressure and wind (*red*) with ship weight and ballast (*orange*)

Fig. 6.5 Recreation of L'Anse aux Meadows, Newfoundland

But I digress. Let us get back to the calendar. Let us now jump to the Romans, who possessed the military power to gain control over much of the world by the middle of the first century BCE. Julius Caesar (100-44 BCE) came to power in the

Fig. 6.6 Portrait of Marco Polo

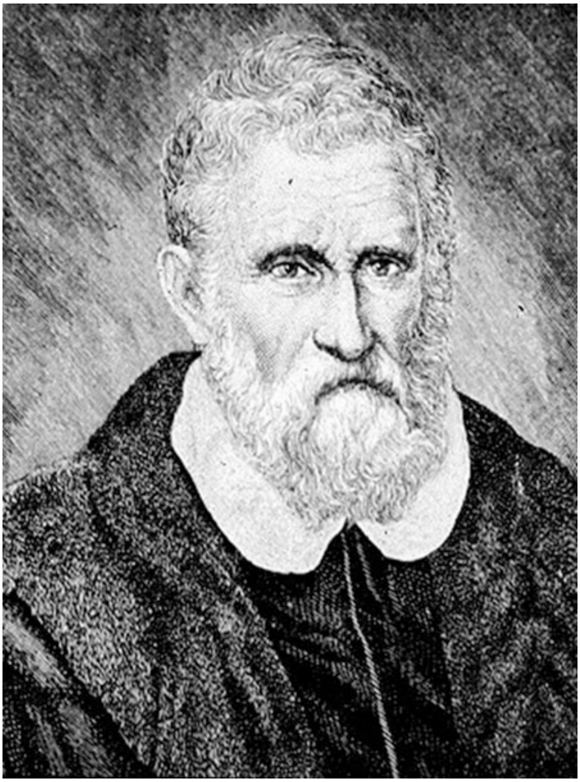


Fig. 6.7 Portrait of Christopher Columbus by Sebastiano del Piombo

Fig. 6.8 Portrait of Ferdinand Magellan

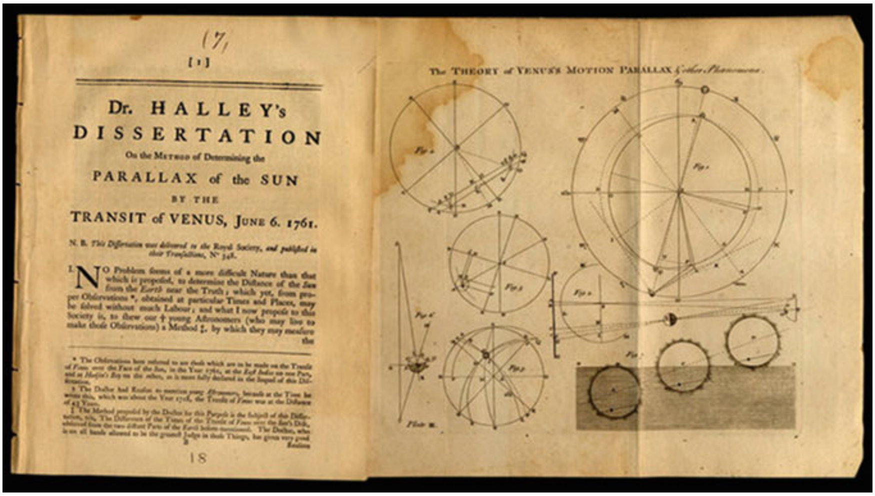
Fig. 6.9 The Victoria, the only ship in Magellan's Fleet to complete the first Circumnavigation of the earth

Fig. 6.10 Portrait of Francis Drake by Marcus Gheeraerts

Fig. 6.11 Portrait of Captain James Cook by Nathaniel Dance-Holland

middle of that century, and he eventually defeated Pompey Magnus (106-48 BCE), the First Man in Rome at the time, at the Battle of Pharsalus (Greece) in 48 BCE, and in so doing he dispatched the last of his enemies within the Roman Republic

Fig. 6.12 Portrait of Edmund Halley by Thomas Murray



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[1]

Dr. HALLEY's
DISSERTATION
On the METHOD of Determining the
PARALLAX of the SUN
BY THE
TRANSIT of VENUS, JUNE 6. 1761.

N. B. This Diſſertation was delivered to the Royal Society, and publiſhed in their Tranſactions, Nº 348.

I. NO Problem ſeems of a more difficult Nature than that which is propoſed, to determine the Diſtance of the Sun from the Earth near the Truth; which yet, from proper Obſervations *, obtained at particular Times and Places, may be ſolved without much Labour; and what I now propoſe to this Society is, to ſhew our † young Aſtronomers (who may live to make thoſe Obſervations) a Method ‡, by which they may meaſure the

18

Fig. 6.13 Diagram from Sir Edmund Halley's report to the Royal Society describing how to measure the distance to the Sun using the transit of venus

(at least for the time being). Perhaps fortuitously, Pompey was not killed in the battle, and he made his way to Egypt in hopes of finding refuge there.

Caesar pursued him with two of his (depleted) legions, and upon his arrival in Egypt he was informed that the youthful pharaoh Ptolemy XIII (c. 62–47 BCE) (as opposed to the scientist Ptolemy, who came later) had ordered that Pompey be beheaded upon his arrival in Egypt, and that this order had been duly carried out. Caesar was naturally furious at this revelation (perhaps because he wanted to have this privilege himself), and as a result he was not terribly endeared to the 14-year-old Ptolemy. Perhaps this had something to do with the fact that he fell in with Ptolemy's sister and opponent Cleopatra VII (69-30 BCE).

Fig. 6.14 The Endeavor leaving Whitby Harbor England in 1768

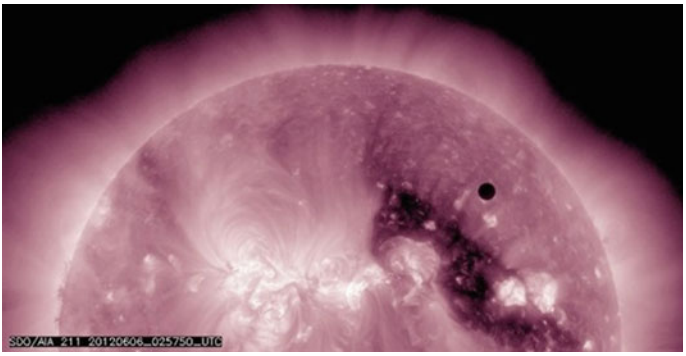


Fig. 6.15 Image of Venus transiting the Sun on June 5, 2012

In due course Caesar patched up the relationship between the two feuding siblings (only briefly), and Cleopatra threw a great party to celebrate this reunion. History tells us that during the party Caesar entered into a conversation with a scientist named Acoreus, who somewhat surreptitiously explained the Egyptian calendar to Caesar. This was apparently the first time that Caesar was informed of this, the most advanced calendar on Earth at the time. And lest it is not already obvious, the Egyptians devised this calendar using mechanics to measure and correlate the motions of the Earth and the Nile River.

Unfortunately, the sibling co-pharaohs could not be made to like each other. Thus, there ensued a civil war in Egypt, forcing Caesar to hang around for several months in Alexandria, long enough for him to sire a child by Cleopatra (named Caesarian). Eventually, Ptolemy was displaced by Caesar (the young pharaoh drowned in the Nile) and Cleopatra took the throne, thus making her the (last) pharaoh (She also later shared the throne briefly with her younger brother Ptolemy XIV (60-44 BCE)).

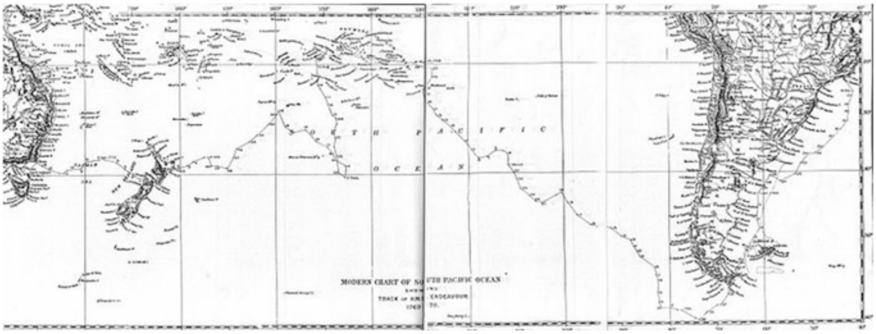


Fig. 6.16 Route of the Endeavor

Fig. 6.17 Captain cook memorial on Kealakekua Bay, Hawaii. *Note* that this is the site where he was killed

Fig. 6.18 Portrait of Joseph Banks by Sir Joshua Reynolds

The point of all of this background information is to explain that due to all of this squabbling Julius Caesar was forced to remain in Egypt for 9 months, and over the last 2 months of his tryst with Cleopatra the pair partook of a languid trip down the Nile. During this cruise he met Cleopatra's astronomer Sosigenes of Alexandria, who explained the Egyptian calendar in further detail. Their 365 day calendar that included a leap day every 4th year seemed to him to be a major improvement over the Roman calendar. Caesar was indeed quite interested in their calendar for reasons that would be obvious if you had lived in Rome at the time.

Somewhat inexplicably, despite their advanced society the Romans had never quite figured out how to handle the calendar. For them, the 1st day of the year was March 1st. The first 6 months of the year were named after the Gods, and the succeeding 4 months were named after numbers: 7 (September), 8 (October), 9 (November), and 10 (December). Their calendar, as originally set up by Romulus (or so the legend went), only contained 10 months. King Numa had added 2 months, Januarius and Ferbruarius, to the calendar in 700 BCE, but they were considered to be the 11th and 12th month of the year. This had brought the total number of days in the lunar based Roman calendar to $12 \times 29.5 = 354$ days (the Moon orbits the Earth about once every 29.5 days).

The remaining approximately 11 days were to be intercalated each year by decree of the Roman Senate. Unfortunately, the Senate had become so dysfunctional in Caesar's time that they had been unable to agree on what day to assign as March 1st, the 1st day of their year. Thus, by the middle of the first century BCE, the Roman calendar had become 2 months out of sync with the seasons, and this was quite obvious to everyone. It was against this backdrop that Caesar learned of the Egyptian calendar.

When he finally managed to clean up the mess in Egypt, Caesar returned to Rome, where he was forthwith made Dictator for 10 years by his own puppet Senate. Acting on his newfound power, he immediately summoned Sosigenes to Rome, along with several other sages on the subject of the calendar. Working together, the group constructed a completely new calendar and Caesar persuaded his puppet government to adopt this new calendar.

Caesar's calendar, called the Julian Calendar today, had 6 months of 31-day duration, interspersed with 6 months of 30 days duration, with the exception that Februarius had 29 days, extended to 30 days every 4th (leap) year. Caesar's final gesture was to change the 1st day of the year to January 1, presumably because it was closest to the winter solstice. The issue of weeks and days of the week was still up in the air, not to be sorted out for nearly 400 years (as described in Chap. 4).

Unfortunately, in order to bring the calendar back into synchrony with the Sun, it was necessary to intercalate a couple of months in the 1st year of the new calendar. Thus, the 1st year of the Julian Calendar had a total of 445 days! That 1st year of 46 BCE was a mess throughout the Roman Empire, especially for moneylenders, who charged interest based on the number of days the money was loaned (just as moneylenders do today!). As a result, they had no idea how much to charge. Still, Romans somehow managed to muddle through, and when January 1st rolled around in the year 45 BCE, the Romans suddenly had the most accurate calendar on Earth.

The following year Caesar was assassinated by members of the Senate on the Ides (15th) of March. Shortly thereafter, the Roman Senate proclaimed him a God (they apparently liked him much more so now that he was dead), subsequently renaming the month Quintilis to Julius in his honor. This wasn't so bad, but to make matters worse, the clerics began intercalating leap days every 3rd year instead of every 4th year, immediately undermining the brilliant work of Caesar's scientific advisors.

Caesar's nephew Augustus (nee Octavian) shortly gained power, and he corrected this error. He gained such power in time that the Roman Senate decided to award his name to the month of Sextilis, thus changing it to Augustus. Since the month named in honor of Julius Caesar had 31 days, the Senate deemed that Augustus should be treated equally, therefore awarding him 31 days as well. This of course made the year 1 day too long, so the Senate removed 1 day from the month of Februarius, changing it to 28 days, except for leap years, when it was to have 29 days. As a final gesture, they reversed the 30–31 day order for the last 4 months of the year, thus creating the chaotic order of the number of days in each month that we have today. *This is an example of excellent mechanics being corrupted by politics.* We shall see more examples of this in future chapters.

Interestingly, a number of other people have attempted to have months of the year named after themselves, including several Roman Emperors, but only the months named after Julius and Augustus Caesar survived. All of the other changes were eventually dropped by an unaccepting populace.

So the provinces of the now Roman Empire adopted the Julian Calendar, and things remained that way in the areas that comprised the provinces even after the fall of the Empire in 476 AD. And while the calendar became of little significance during the Middle Ages, when people simply lived from day to day attempting to eke out sufficient sustenance for survival, the Julian Calendar persisted in enough places that it eventually regained prominence across Western Europe as the Renaissance began to unfold in the fourteenth century.

Unfortunately, as we know today, a solar year on Earth does not take 365.25 days. It takes closer to about 365.24219 days. Thus, the Julian Calendar is incorrect by a small but nevertheless significant amount. In order to completely understand this difference, it is important to understand that there is more than one way to measure a year. The obvious version is called a sidereal year. This means of measuring a year determines the length of time that it takes for the Earth to complete one orbit of the Sun. Unfortunately, this means of determining the length of a year is not the most practical one.

There is another year called a solar (also called a tropical) year, and that year is more useful on Earth than is the sidereal year. The solar year is the span of time required for the Sun to return to the same position as seen from Earth (such as the equinox). This may sound like the same thing as the sidereal year, but it is not. The reason that it is not is because of the Earth's precession, as described in Chaps. 1 and 10.

Here is how this difference occurs. The Earth is not only orbiting the Sun and spinning as it does so, it is also wobbling, called precession. This precession was apparently first noticed by Hipparchus (see Chap. 2), although he did not know why it occurred. It was explained by Isaac Newton in *The Principia* (see Chap. 7). The reason for the Earth's precession is that the Sun and the Moon exert gravitational forces on the Earth that cause it to wobble, and this wobble has a period of about 25,772 years. This wobble is called 'precession' because the direction of the rotation of the wobble is in the same direction as the Earth's orbit about the Sun (as opposed to the direction of Earth's spin). Due to this precession the Sun returns to its position in the sky about 20 min before the Earth makes one full orbit of the sun each year.

Now, this 20 min difference can add up over time. In fact, it will add up to 1 year by the time the Earth has completed one complete revolution of its axial wobble, and due to this precession, the Earth will have actually traveled one additional revolution about the Sun. A similar (but slightly different) circumstance occurred in the movie *Around the World in 80 Days*, when the fictional character Phileas Fogg discovers on completing his circumnavigation of the Earth in 81 days that he has actually saved 1 day due to the rotation of the Earth on its axis.

More importantly, the question is—which measure of the length of a year is more practical? The seasons are determined by the Sun's position with respect to Earth, so for the purposes of farming, for example, it makes more sense to use the solar year than the sidereal year. This in itself is reason enough to use the solar year, but it isn't the main reason that the solar year was chosen.

The main reason that the solar year was chosen was because of the description for the date of Easter described in the Bible, which is very complicated, but a simplified version says that Easter falls on the first Sunday after the first full Moon after the vernal equinox. Thus, we use the solar year to measure time on Earth.

More importantly, the Julian Calendar is not quite right. No one is quite sure when folks started realizing that the Julian Calendar was incorrect. We do know that Dionysius Exiguus (c. 470–540), the monk that invented the Anno Domini (AD) dating system (badly, I might add), had some concerns about the date of Easter, but these do not appear to have been related to the error in the Julian Calendar.

As we know from Chap. 4, The Venerable Bede discovered that the Julian Calendar was in error in the early eighth century. However, it appears that the first person to actually complain about the error in the Julian Calendar was none other than Roger Bacon (c.1214–1294). As described in Chap. 4, Bacon was an Oxford educated lecturer who spent most of his career at the Universities of Paris and Oxford.

Bacon was apparently really smart, probably too smart for his own good. He ended up getting into quite a bit of trouble, and part of his trouble may have come about due to the fact that he had figured out that the Julian Calendar was in error, by about 9 days by his judgment, at the time he lived. So Bacon complained to the Pope that Easter was being celebrated on the wrong day because he knew how to calculate the date of the equinox. He subsequently got into trouble, and though the record is not very clear as to why, he appears to have been imprisoned for many years, perhaps at least in part because he complained about the calendar, which was nothing more than an issue in mechanics. Meanwhile, nobody paid too much attention to his complaints at the time (the late thirteenth century).

Eventually, however, the errors in the Julian Calendar became impossible to ignore (since the seasons did not agree with the calendar). Thus, in 1577 Pope Gregory XIII convened a scientific commission to develop an improved calendar. By that time more accurate instruments were available for measuring the position of the Earth with respect to the Sun, and the scientific commission used mechanics to determine that the Earth revolves about the Sun every 365.242 days, and they recommended that every year that is exactly divisible by four is a leap year, except for years that are exactly divisible by 100; with the exception that the centurial years that are exactly divisible by 400 are still leap years. For example, the year 1900 was not a leap year, but the year 2000 was a leap year.

This corrected the calendar to within one part in one million of the actual period of the Earth, thus improving things for a long time to come; that is, unless the Earth gets struck by a really big meteorite. Such an enormous impact would invariably change the Earth's orbital period (the duration of a year) about the Sun, as well as its rate of spin (the duration of a day). But then it won't matter, because there won't be any humans left on Earth anyway.

On February 24, 1582 Pope Gregory issued a papal bull altering the calendar to what is today termed the Gregorian Calendar. In order to correct the amount that the Julian Calendar had become in error by that point in time, he decreed that the commission's leap year formula be followed, and he also decreed that *on March 11 of that year the calendar be immediately advanced by 10 days to March 21*! Thus, if you were born between March 11 and 21, you missed a birthday that year!

This development didn't sit too well with a lot of people. In many villages it took years for the word to arrive. Others, such as the whole of England, were in the midst of the Protestant Reformation, and they didn't choose to follow any of the Pope's orders, so they ignored his papal bull. Thus, for many years lots of people had no idea what day it was!

In England Queen Elizabeth was generally in favor of the change, but the Archbishop of Canterbury protested (naturally!), with the result that they didn't accept the Gregorian Calendar until the year 1752, by which time it was necessary to remove 11 days from the calendar (instead of the ten ordered in the papal bull). Thus, for a period of nearly two centuries, if you wanted to have two birthdays in 1 year, all you had to do was celebrate it in France, and travel to England, making sure that you arrived there within 10 days.

This sort of nonsense was prevalent all over Western Europe, as well as other parts of the world until the Gregorian Calendar was finally accepted by the last holdout (China) in 1949. So while we can say that humankind is the only species that has invented our own units of time, it hasn't always been easy to agree on implementation. I would be remiss if I did not point out the obvious: all of this chaos resulted from nothing more than an exercise in mechanics.

The Explorers

In my view explorers deserve a special nod with respect to the science of mechanics, especially those who traveled by ship. There are a number of reasons for this assertion. First, ships are in and of themselves complicated structural entities that engender a variety of issues associated with mechanics. Second, the stability of a ship is by no means guaranteed during a voyage, as evidenced by the enormous number of ships resting on the bottom of the Earth's lakes, seas, and oceans today, and ship stability involves mechanics. Third, navigating a ship across vast bodies of water involves considerable understanding of mechanics.

The Wasa

My favorite example of a sunken ship is the Wasa (pronounced *Vasa*), a Swedish warship that sank in a light breeze on her maiden voyage in 1628, less than 2 km from her moorings in Stockholm harbor. The ship sank because there was insufficient ballast to resist the force of the wind and water pressure, and the ship listed to one side, thereby allowing water to rush in through the gun ports. This is a problem in mechanics.

There she lay for nearly 350 years, until Anders Franzén (1918–1993) discovered the wreck and convinced the Swedish government to float the ship in 1961. After many years of salvage and reconstruction, the ship went on public display at the Wasa Museum in Stockholm in 1987. The salvage process involved many projects based in mechanics. This museum should be visited by anyone who is interested not only in mechanics, but also in understanding the hardships that the great explorers of the past suffered in order to discover new lands.

Ship stability involves balancing the effects of wind, water pressure, ship weight, and ballast in such a way as to ensure that the water level remains below the deck of the ship. Otherwise, water may rush in and scuttle the ship. This is a rather complicated problem in mechanics. Today we can monitor ship stability by using Newton's Second Law (see Chap. 7), but until recent times ship stability was accomplished strictly by experimental means.

Pythéas

Perhaps the most famous of the ancient explorers is Pythéas (c. 350–285 BCE) [45]. He is the first person known to have sailed to Great Britain from Greece. He is also the first person to have recorded the midnight sun and the polar ice. And he is the first person known to have stated that the tides are caused by the Moon. This is a problem in mechanics, as the motions of the water on the surface of the Earth are profoundly affected by the gravitational pull of the Moon.

The Americas

Most people believe that Columbus discovered the Americas in 1492. However, there is some evidence to the contrary. In 1976 a shipwreck was discovered in the harbor of Guanabara near Rio de Janeiro, Brazil. Subsequent study of the site in 1982 by Robert Marx indicated that numerous amphora found at the site appeared to be of the same style as those used by the Romans in the third century BCE, thus making a circumstantial argument for the discovery of South America by Romans nearly 1,700 years before its previously supposed discovery.

Interestingly, when this discovery was reported in Brazil, many Italian transplants immediately claimed to be citizens of Brazil by force of discovery. Common belief holds that Brazil was discovered by Pedro Cabral (c. 1467–1520) in 1500. As a result, Portuguese citizens receive special treatment when applying for Brazilian citizenship, but Italians do not.

Is it possible that South America was discovered by Romans seventeen centuries earlier than previously held? If so, they were either blown a long way off course, or they must have had some pretty amazing means of measuring their location, a problem in mechanics.

We know today that Polynesians managed to inhabit essentially every inhabitable island in the Pacific Ocean beginning thousands of years ago. Jared Diamond's Pulitzer Prize winning book *Guns, Germs, Steel* explains much dealing with this expansion [46].

Apparently, the last string of islands settled by the Polynesians was the Hawaiian Island chain, which is the most remote land mass on Earth, sometime between 300 and 800 AD. They seem to have accomplished this amazing feat with little more than canoes and a gift for navigation via the stars at night. Here is a truly amazing feat in the study of celestial mechanics.

Although it has not been confirmed, it is also believed that the Polynesians actually discovered South America because sweet potatoes, which are indigenous to South America, can be found in several Polynesian Islands today.

According to Irish legend, St. Brendan of Clonfert (c. 484–577) sailed to North America in the sixth century. However, although there are some pretty tantalizing stone markings in the United States today, there is no extant proof of this voyage.

According to the Icelandic Sagas, Leif Ericson (c. 970–1020) established a colony on the island of Newfoundland in North America around 1000 AD. The settlement is today called L'Anse aux Meadows, thus providing corroboration of Ericson's discovery of the Americas. A careful examination of a map will show that it is possible to navigate around the North Atlantic without having to get too far from land (that is, once you get from Norway to Iceland!). Thus, Ericson's transatlantic navigation may not have required too much mechanics, but he nonetheless deserves mention here for surviving all of that ice, which surely required some appreciation of the mechanics of ice!

Marco Polo

Marco Polo (1254–1324) is by far the most famous of the explorers from the Middle Ages. He apparently traveled from Europe to China and back in 1271–1295. I mention him here because his descriptions of the East had a significant impact on later explorers who decided to sail west to get to the East, a challenging problem in mechanics.

Christopher Columbus

The fall of Constantinople (the last remnant of the Eastern Roman Empire) to the Ottomans in 1453 dealt a severe blow to Venetian trade with the East, from whence had heretofore come prized foodstuffs from the Spice Islands. Acting on the possibility of gaining wealth by sailing west and potentially arriving in the East, if indeed the Earth was a sphere, several explorers proposed voyages to the West in the latter part of the fifteenth century. Of course, as we all know, the first to do so and survive was Christopher Columbus (c. 1451–1506), an Italian sailing under the Spanish flag in 1492. He didn't actually make it to India, but he thought he had, from whence we have the terms "West Indies" and "American Indians."

What makes Columbus' voyage so impressive is that he managed to accomplish it without the aid of a modern day chronometer, a mechanical device that can be used to determine longitude (See Chap. 8). Of course, it was possible to determine latitude by using a sextant (a device for determining the angle of declination, such as of the North Star), but the lateral distance from your home port was strictly guesswork at that time, meaning that no one could determine longitude accurately. In other words, Columbus was lucky!

I am not going to go into detail regarding all of the other famous explorers of that time because you can find the history of exploration in any world history book, but I do want to mention three other explorers from that period due to their importance to the science of mechanics.

Ferdinand Magellan

First and foremost, we simply must mention Ferdinand Magellan (c. 1480–1521), who should be right at the top of anyone's list of explorers. He is the first person to circumnavigate the globe. He didn't actually do it himself, but he sailed west from Spain and made it to a longitude that others had made it to by going east, thereby proving that the Earth is a sphere.

Although Magellan was killed by natives in the Spice Islands, a (very) few of his crew continued sailing westward and actually made it all the way back to their home port in Sevilla. This has been noted by some historians as the beginning of the modern era, and his accomplishment as the greatest one in human history.

Why is this considered so great a feat? To understand that, you will need to read a book detailing his voyage. I personally recommend *Over the Edge of the World* by Laurence Bergreen [47]. Therein you will find out that Magellan overcame almost incomprehensible geographical and meteorological hurdles (most notably, navigating the Straits of Magellan), mutiny by his own sailors, and near starvation in the middle of the Pacific to accomplish this amazing feat that required considerable mechanics. But most important of all, Magellan's voyage finally established beyond a doubt that the Earth is a sphere.

Francis Drake

So incomprehensibly difficult was Magellan's voyage that it was not duplicated until almost 60 years later, and in between several voyages failed (with great loss of life). Indeed, the next person to circumnavigate the Earth was Sir Francis Drake (1540–1596). If you go to California, you will find him to be quite a hero. That is because he discovered the West Coast of North America, including California.

I am quite certain that there are a multitude of reasons why Captain Drake deserves recognition in a book on mechanics. I choose to employ this one. He explored the Eastern side of the "ring of fire," where many active volcanoes and earthquake-prone faults exist. And as we will see in Chap. 11, these are problems related to mechanics.

Captain James Cooke

The last oceanic explorer that I want to mention is Captain James Cook (1728–1779). He is my personal favorite for several reasons. First and foremost, his expeditions were expressly for the purpose of extending our knowledge of science. There are several other reasons.

As described in Richard Hough's book *Captain James Cook* [48], Captain Cook commanded three voyages to the South Pacific in the latter third of the eighteenth century. The first was perhaps the most important to the science of mechanics.

Here is a great story in the history of mechanics, indeed of all science. It seems that in 1663 the Scottish mathematician James Gregory had posited that using measurements at widely separated points on Earth, the distance to the Sun could be determined using parallax during the transit of Venus. Acting on this suggestion, the English scientist Edmund Halley (1656–1742) wrote a paper to the Royal Society in 1716 describing how parallax could be used to make this all-important calculation. Unfortunately, Halley did not live to see the next transit of Venus, since the transit of Venus only occurs twice (at an 8-year interval, due to retrograde planetary motion relative to Earth) in a little more than a century.

When the long awaited approaching transit of Venus came in 1761, it was expected by the scientific community that this long-sought distance would be measured. Unfortunately, the several expeditions that were sent out were either blocked by clouds or were not sufficiently far apart to measure the distance to either Venus or the Sun.

Thus, when the second transit in the 100-year cycle occurred in 1769, the English were prepared, sending one expedition to Hudson Bay in Northern Canada, and the other to Tahiti, under the command of Captain Cook on the ship Endeavor.

Captain Cook and the crew of his ship (including the soon-to-be world famous botanist Joseph Banks (1743–1820)) measured the transit of Venus from Point Venus on the island of Tahiti on June 3–4, 1769, thus providing the necessary measurements to determine that the Sun is approximately 149.60×10^6 km (93,000,000 mi, now called one astronomical unit) from Earth.

Still later in April 1770, Cook became the first European explorer to land in Australia, at Botany Bay. The Endeavor eventually circled the Earth, completing its mission, and in so doing becoming perhaps the most successful scientific expedition on this planet in history.

Captain Cook was to lead two more expeditions to the South Pacific. By the time he was killed by natives on the West Coast of The Big Island of Hawaii in 1779, he had charted and seen more of the Earth than anyone in the history of our planet up to that point in time.

Incidentally, Joseph Banks would later play a significant role in the history of mechanics, elected as president of the British Royal Society in 1778. As described in *The Age of Wonder* by Richard Holmes [49], Banks exercised a profound influence over British science for the remainder of his life. This included many achievements in the science of mechanics.

If you want to know just how significant these developments in world exploration are, you need to go on a deep sea fishing expedition in an open boat on a day with sea state IV. First of all, the mechanics of motion will very likely make you as sick as a dog (whatever that actually means!). The explorers endured this sickening weather often, sometimes for days on end. Second, while you are onboard ship try to guess the time of day without a watch. It is necessary to know the time of day in order to know your longitude. Without longitude, you have no idea how far east or west you have progressed.

Once you are out of sight of land, you will know the feeling of true terror. Being out of sight of land on the high seas can be completely disorienting. And yet, these amazingly courageous individuals succeeded in discovering most of the world before the invention of the chronometer (see Chap. 8). And had they not mapped the world using mechanics, it is hard to imagine where we would be today.

Mechanics Reborn

7

Mechanics is the paradise of mathematical sciences because here we come to the fruits of mathematics.
Leonardo Da Vinci (1452–1519)

As we have seen in the previous two chapters, beginning in the early thirteenth century, humankind began to emerge from the long and dark period of the Middle Ages. By the end of the fifteenth century, explorers were discovering new lands. Armed with these new-found developments and their attendant improvements in the quality of life, the world was poised for monumental changes to come beginning in the sixteenth century.

The Astronomers

As we now know, astronomy is one of the oldest of sciences. We know that the Sumerians and the Babylonians studied the heavens, as did the Minoans and the Egyptians. Apparently all of these ancients profoundly affected later developments by the Greeks. Unfortunately, after the fall of the Roman Empire, the West became cut off from the East for nearly a 1000 years. Thus, substantial advances that were made in the East, principally by the Arabians and the Indians, were not well known in the West. Furthermore, recently discovered advances in astronomy in the Americas were also unknown in Western Europe for obvious reasons. Because these latter developments were unknown to Westerners, they appear to have had little impact on the modern world of today. Thus, the most significant text on astronomy for Westerners remained Ptolemy's *Almagest* [50] for more than a 1000 years.

Copernicus

Nicolas Copernicus (1473–1543) was the first person in the West during the modern era to come forward and espouse a scientific theory of great significance. It is now believed that he was influenced by the great astronomers from India and Arabia. His *De Revolutionibus Orbium Coelestium* [51] is considered by many to

D. H. Allen, *How Mechanics Shaped the Modern World*,
DOI: 10.1007/978-3-319-01701-3_7,

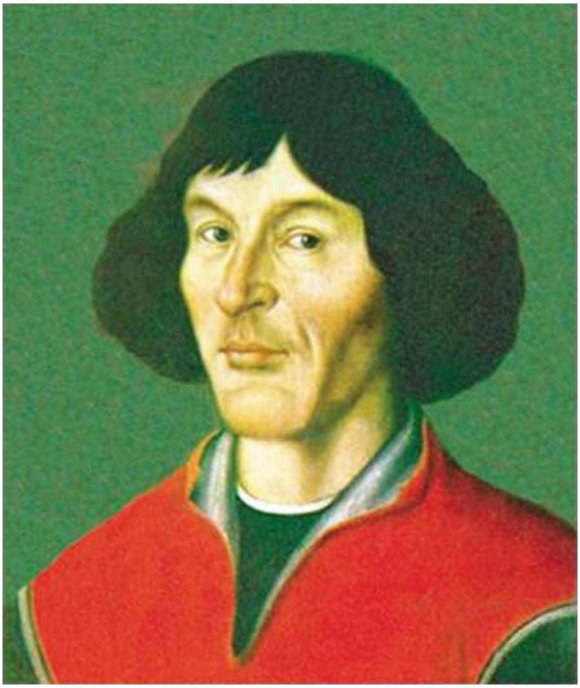


Fig. 7.1 Portrait of Nicolas Copernicus

be the most important scientific book ever written. In it, he refuted the Aristotelian and Ptolemaic theory of the Earth as the center of the universe and instead placed the Sun at the center of our solar system (Fig. 7.1).

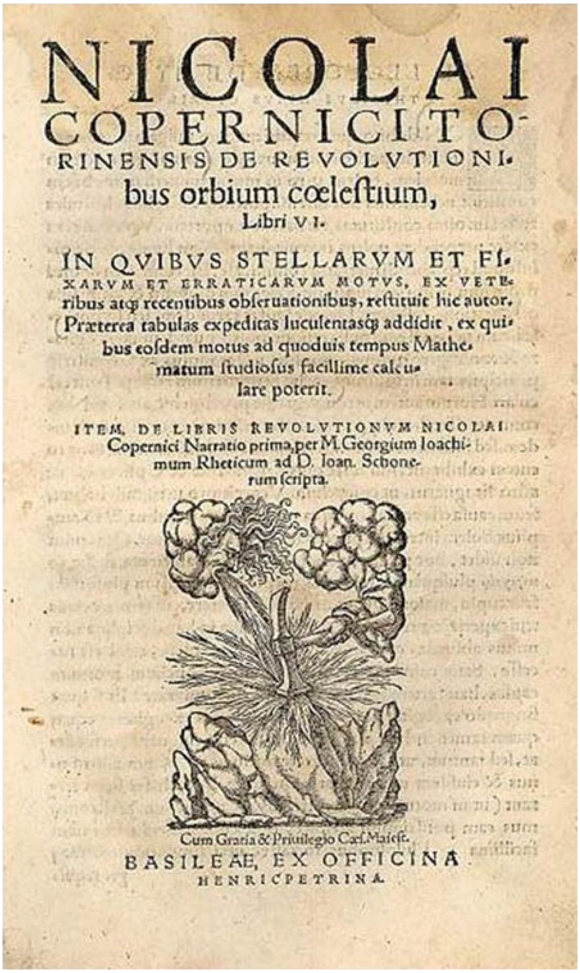
Copernicus was trained in law and medicine at the University of Padova (as well as Ferrara), thereafter teaching at several universities. In 1506, he returned to Frauenburg on the Baltic in northwest Poland. There he became enamored with the conflict over the possible errors in the Julian Calendar. Thus far several attempts had been made to correct the calendar, the most recent one by Pope Leo X.

Copernicus had an ideal location for astronomical observations on the landing of his apartment neighboring the harbor adjoining the Baltic Sea. He took up the challenge of determining the vernal equinox, beginning to make observations using an astrolabe, an armillary sphere, and something like a sextant. He soon realized that there was a problem with the measurement of the length of a year, for he was not aware of the precession of the equinoxes (see Chaps. 2, 6 and 10). But he was onto something much more exciting, thus he endured. Over the course of 30 years his measurements led him to the inescapable conclusion that Ptolemy's view of our solar system was not consistent with his own observations.

Fearing his views would lead to trouble with the Holy See, Copernicus procrastinated, but eventually his friends convinced him to publish his findings. Shortly after completing this monumental undertaking he contracted a mortal illness, and it is recorded that he was on his deathbed when the first copy of his book arrived, thus allowing him to see his completed work on the day he died [52].

The first printing of Copernicus' book was only a few hundred copies. Recently, Owen Gingrich decided to see how many of these copies he could locate. In his book *The Book That Nobody Read* [53] Gingrich gives a vivid account of his quest, and here is the best part—he has been able to verify via ownership and notes in the columns of extant copies that Copernicus' book was actually read by many great scientists who came thereafter. We all owe Copernicus a great debt of gratitude. His mechanics book unlocked the door to modern science (Fig. 7.2).

More than half a century would pass before additional significant advances occurred in astronomy, and the initial ones came principally from three great scientists: Tycho Brahe (1546–1601); Johannes Kepler (1571–1630); and Galileo Galilei (1564–1642).



NICOLAI
COPERNICI TO-
RINENSIS DE REVOLVTIONI-
bus orbium cœleſtium,
Libri VI.
IN QVIBVS STELLARVM ET FI-
XARVM ET ERRATICARVM MOTVS, EX VETE-
ribus atq; recentibus obſeruationibus, reſtituit hic autor.
Præterea tabulas expeditas luculentasq; addidit, ex qui-
bus eoſdem motus ad quoduis tempus Mathe-
matum ſtudioſus facillime calcu-
lare poterit.
ITEM, DE LIBRIS REVOLVTIONVM NICOLAI
Copernici Narratio prima, per M. Georgium Ioachi-
mum Rheticum ad D. Ioan. Schone-
rum ſcripta.
Cum Gratia & Priuilegio Cæſ. Maieſt.
BASILEAE, EX OFFICINA
HENRICPETRINA.

Fig. 7.2 Title page of *De Revolutionibus Orbium Coelestium* [51]

Brahe and Kepler

Tycho Brahe was perhaps the first great modern astronomer in the West (most Indian and Arabic astronomers' previous observations had not made it to the West), patiently recording the movements of the heavenly bodies over the span of a lifetime without the benefit of the telescope (although he did possess an enormous quadrant, as depicted in Fig. 8.13), which would come a short time later. Kepler, who became Brahe's assistant shortly before Brahe's passing, correctly interpreted Brahe's measurements, and created a model for predicting the motions of the planets that is still accurate today [54] (Figs. 7.3 and 7.4).

Galileo

Names were important in ancient times. Take for example the name Gaius Julius Caesar. We all know this name today, but in ancient times it was important to have the "right" name, because there was no television, no newspaper, indeed no

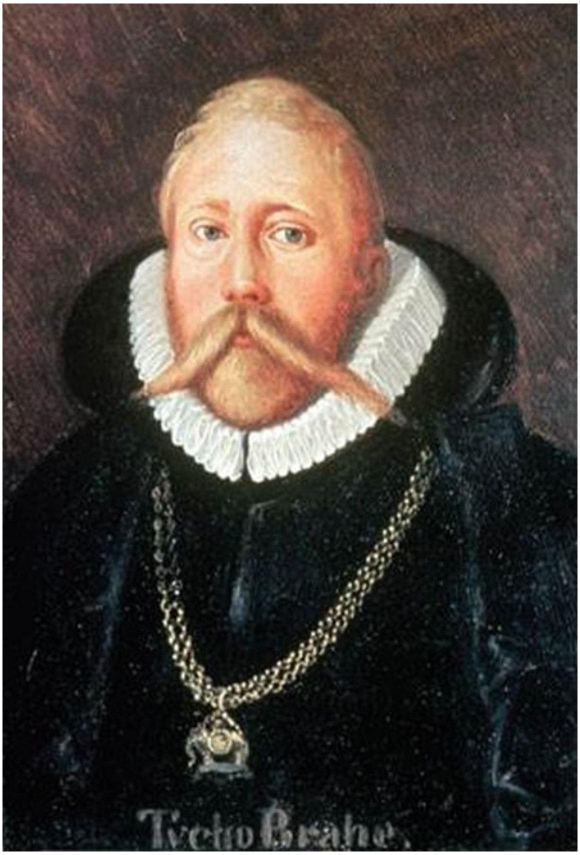


Fig. 7.3 Portrait of Tycho Brahe

Fig. 7.4 Portrait of Johannes Kepler

written means of communication for the masses to utilize for information purposes. Thus, the name needed to imply something about the person. In the case of Julius Caesar, the important name was Julius, meaning that he came from a patrician family called the Julii. The word patrician means that they were there at the start, when Rome was born, so that their place was a paternal one in society. No one really knows if the Julii were there in 753 BCE, when the Roman story was purported to have begun with the landing of Aeneus (from whom the Julii purportedly descended) and the subsequent births of Romulus and Remus. Indeed, nobody even knows if Romulus actually existed, but here is the important part—the name stuck, as the city we call Rome today was named after Romulus (Fig. 7.5).

Sometime around the end of the Roman Empire, which is today considered to have occurred in 476 (a story for another day), a person or persons migrated from the Sea of Galilee and settled in Italy. Because of where they came from, the name that they took up was Galilei, where the letter i on the end in Latin means plural, or the whole family. This was not a name that held any sort of status, as Julii did. It was more a moniker for foreigner, or outsider. Anyone who goes to Italy today, take Siena for instance, will find that the locals are to this day mistrustful of anyone that they consider to be an outsider (such as for example from another

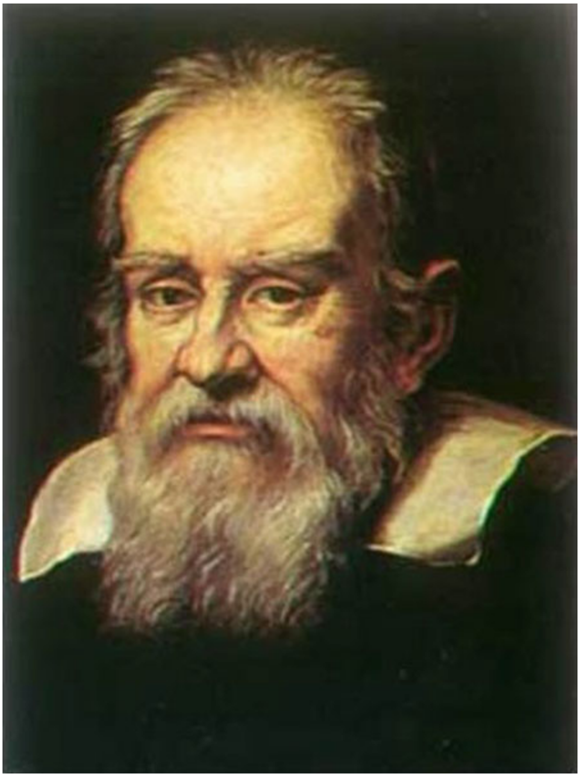


Fig. 7.5 Portrait of Galileo Galilei by Justus Sustermans

contrada right down the street!). So you had to be a part of the culture for a long time in order to become an insider—say—*a* 1000 years!

Thus, the members of the Galilei family were patient. They bided their time, and eventually, they graduated to become accepted Italians. Coincidentally, the Renaissance was born in Florence (*Firenze* to Italians), and the quality of life advanced dramatically. By the early sixteenth century, Florence was one of the most affluent cities on earth. Included under her protection was the placid city of Pisa, only 50 miles to her east.

On February 15, 1564, the baby that was destined to become the most famous of the Galilei was brought forth from his mother's womb in Pisa. He was the son of Vincenzo Galilei (c. 1520–1591), a well-known musician and musical theorist (see Chap. 8). The family moved to Florence when Galileo was 8-years old. Galileo grew up in the city famous for such persons as Cosimo the Elder, Dante Alighieri, Cellini, Brunelleschi, Leonardo da Vinci, Michelangelo Buonarroti, and the list goes on and on. In fact, no other city on Earth can boast to have sired so many world renowned persons.

Tourists who walk down the narrow passage in Florence in front of the Uffizi Gallery are confronted with statues of these famous persons; there are so many as to almost overwhelm the senses. One is staggered by the realization that Italy was not only the place that spawned the Roman Empire, but a 1000 years later, she rose up once again and spat out the Renaissance. No other place on Earth can make such a grand claim on the stage of history.

This is the world that Galileo Galilei was born into. Needless to say, the stakes were high: the Galilei family had lofty expectations for this new born babe. It would not take long for Galileo to prove his mettle, although in a very strange way. Ignoring his father's ambitions for him, Galileo chose to become a mathematician while studying medicine in Pisa. This caused him to more or less flunk out of the university, but he quickly redeemed himself while tutoring in Siena by publishing a paper in which *he calculated the volume of Hell!!!* Galileo utilized rudimentary mathematics and mechanics to accomplish this feat.

This may be an even trickier challenge today (since so many more people have since expired), but at the time everyone who was literate had at their fingertips the definitive volume containing a concise description of Hell—Dante's *Inferno.* So the math was, at least for Galileo, not too tough. The publication of his paper made him a small celebrity within the academic community, and he quickly gained the chair of mathematics back in Pisa.

I will not go into the details of Galileo's life, as the interested reader will find ample biographical background simply by searching his name on the Internet (I personally recommend the book *Galileo: A Life* by James Reston [55]). But suffice it to say that Galileo apparently lived a fabulously interesting existence despite never actually traveling outside the borders of Italy. He lived much of his life in Padova and Florence, and he travelled often to both Venice and Rome, maintaining an apartment in the former. Imagine living in the two most fabulous cities on Earth: Florence and Venice. That would be like splitting your time between New York City and Paris today. He was a lucky guy.

Galileo seems to have been beset by a personality flaw that is common to many academics today: he had a profound sense of intellectual superiority. As we will see, this was bad for him, but good for the rest of humankind. While he was indeed somewhat famous within his own academic community, he was relatively unknown to the vast majority of the people on Earth until the year 1610, when he was 46-years old.

During the summer of 1609, Galileo heard about an invention in Flanders. By placing two lenses in succession, it was possible to see objects as if they were larger than that visible to the naked eye. Galileo, always in need of extra cash to support his burgeoning family's needs, set to work attempting to reproduce this effect, and within a 3 week span of the late summer of that year, he successfully invented one of the first scientific telescopes. He accomplished this astounding feat by grinding his own lenses, carefully experimenting with the lens spacing, and building a long tube capable of both controlling the entering light and adjusting the lens spacing. Still, a short time later he confessed that he did not quite have the theory yet in place.

Shortly thereafter Galileo demonstrated his telescope to the *Signoria* of Venice (at the top of the Campanile in the Piazza San Marco), thereby securing a doubling

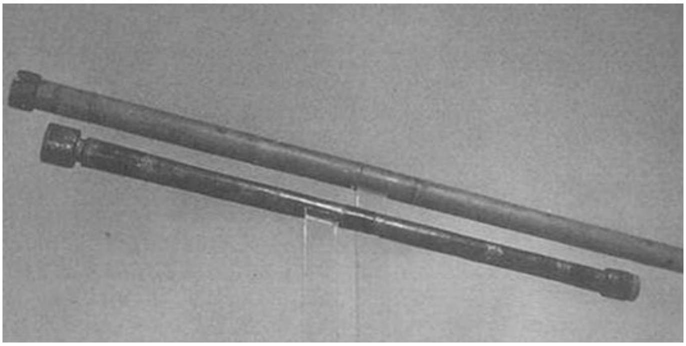


Fig. 7.6 Galileo's telescopes, Galileo Museum Florence

of his salary at The University of Padova. After all, the *Signoria* comprehended immediately that with the aide of Galileo's invention they would be the first to site out to sea and discern the arriving ships' produce flags, thereby allowing them to be the first to bid the price of the shortly-to-arrive products (Fig. 7.6).

But this is only the start of the story. Galileo seems to have been the only person at the time to completely understand the power of such an invention. He used his telescope to look at many things, but the most important thing was the night sky. In January 1610, he pointed his telescope toward Jupiter. Every school child should know this date. Just as 1492 is the date that "Columbus sailed the ocean blue", 1610 is the year that "Galileo made modern science begin". This event and his subsequent publication of his findings in a paper entitled *The Starry Messenger* that spring sparked the Scientific Renaissance. Using his telescopes, he discovered the moons of Jupiter, the mountains on the Moon, the phases of Venus, and the wobble of the Moon, to name but a few.

By the summer of 1610, Galileo Galilei was one of the most famous people on Earth. Eventually, he even became perhaps the *first* scientist in history (from this author's myopic perspective) to become world famous in his/her own lifetime. Unfortunately, it was not completely because of science. It was at least in part because of the conflict between science and religion.

Galileo claimed that objects orbited Jupiter, not the Earth, thus contradicting the Aristotelian view held by the Holy See. The Moon was not a perfect disk, but mountainous, even more so than the Earth, another contradiction of the position of the Holy See. And to be honest, both science and organized religion on this planet would never be same.

As for Galileo himself, he managed to keep out of trouble for almost the next quarter of a century, but eventually his own arrogance caught up with him. He was summoned to Rome for an inquisition into his religious transgressions in 1633, after his publication of *Dialogues Concerning the Two Chief World Systems* [56]. In a trumped-up process that garnered public attention across Europe, he was made the scapegoat for a changing world, convicted, and sentenced to death.

I seriously doubt that any of us can imagine today what Galileo was subjected to in those very dark hours of his life. The society that he lived in was dramatically different from the one we live in today. But to give the reader just a touch of the terror that Galileo felt, I suggest that you visit the Campo dei Fiori in downtown Rome.

Built on the site of an old Roman structure (isn't everything in Rome!), the Campo is today a spot used for every sort of mayhem—a market in the mornings, a drinkers' paradise in the evening, a dining spot at night, and a place of political protest into the wee hours of the morning. But in the year 1600, an infamous event occurred there, and it was perpetrated by the Holy See.

When you visit the Campo, check out the statue in the middle of the square. There disguised under a hood (as well as a fresh layer of pigeon droppings), you will find our modern day homage to Giordano Bruno—a quiet unassuming statue that most people do not even notice. Bruno was tied, tortured, convicted, held for 10 years in Castel Sant'Angelo (Hadrian's tomb), and finally burned at the stake in 1600 for espousing views that were not unlike those held by Galileo a scant 30 years later.

Interestingly, Galileo had actually previously met Bruno prior to the latter's incarceration. Thus, when confronted with the possibility of a similar ignominious fate, Galileo recanted. Whew…better late than never! Had he not, there would quite likely be a statue *of Galileo* in the Campo today. Upon receipt of Galileo's confession the Church graciously relented, and Galileo was allowed to spend the last nearly 9 years of his life under house arrest, most of it in his villa at Arcetri, on the hillside overlooking Florence.

So far so good, but the last chapter of his life was not exactly a cake walk (a festive game for school children). He went blind, became incontinent, and several of his family members died of plague. Throughout this ghastly incarceration he was only rarely allowed to leave his villa.

Galileo died in 1642, still in disgrace, having failed to see the acceptance of his scientific discoveries by the Holy See. The Holy See was understandably (at least in their minds) still outraged at the time of his death, so that his body was placed in a small unassuming chapel in the Basilica of Santa Croce in downtown Florence. There his mortal remains rested for 94 years…*for* 94 years!

A half century after Galileo's passing Isaac Newton verified (as well as amplified considerably) Galileo's science with the publication of *The Principia* in 1687 [57], and the world came to accept Galileo's place in history. Newton subsequently passed away in 1727, and was given his magnificent resting place in Westminster Abbey. And finally, in 1736, Galileo's remains were removed from the chapel, and he was accorded the splendid tomb that one can see today in the Santa Croce.

Many scientists seem to agree today that Galileo Galilei is the father of all modern science. Read Albert Einstein, Stephen Hawking, and Richard Feynman, and you will find their testimony to this belief. Galileo invented the scientific telescope, discovered the moons of Jupiter, discovered the mountains of the Moon, as well as its wobble, and I could go on and on (see the section on deformable body

Fig. 7.7 Galileo's tomb in the Santa Croce Basilica, Florence

mechanics later in this chapter), but his most important contribution to the world is that he developed the scientific method.

Today we would define science as any research with testable deniability. And although there were those before him who espoused such an approach (such as both Roger Bacon and Francis Bacon (1561–1626)), Galileo was the first to practice it faithfully. This is what we owe to Galileo (Figs. 7.7 and 7.8).

Mathematics After the Renaissance

Mathematics is another of those subjects that is far too broad to be covered in its entirety herein. Instead, I will make an attempt to synopsize developments in mathematics as they relate to mechanics, especially after the Renaissance.

Apparently, the Babylonians were the first to employ complex mathematics for the purpose of measuring the motions of heavenly bodies. As described in Dick Teresi's book *Lost Discoveries* [58], they began recording celestial movements shortly after the development of the Sumerian language about 3,000 BCE. There are now about 50,000 extant cuneiform tablets, a few depicting these records. But the Babylonians also seem to have carried their mathematics further, using these records to predict (with the help of additional mathematics tools) celestial events such as solar and lunar eclipses. Their models are surprisingly accurate even today.

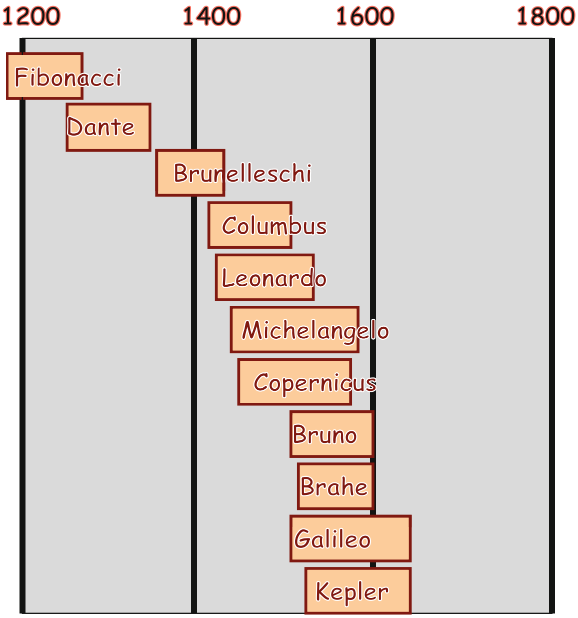


Fig. 7.8 Before Newton

Chasing Pi

A fascinating development in mathematics involved the search for the exact value of π, as described in Peter Beckmann's book *The History of Pi* [59]. The value of π is *really* important. That is because no one knows the area (or circumference, for that matter) of a circle as a function of its single rectilinear dimension, its radius. At least not precisely—unless you know the value of π. And despite the fact that it has now been calculated to ten trillion digits, no one knows the value of π, at least not exactly.

Most early efforts seem to have been focused on the process of approximating the area of a circle by replacing it with triangles, for which there is an exact formula for calculating the area. As mentioned in Chap. 2, Archimedes had a hand in this search. Although others had used the same approach, he seems to have been the first to bound π from above and below. By using the triangular area approach, he drew regular polyhedra both inside and outside of a circle, as shown below (simplified to six triangles), thus also bounding the value of π. Using the approach shown he increased the number of triangles to 96, thereby producing the bounds $3.1408 < \pi < 3.1429$. This estimate is made more profound when one realizes that in Archimedes' time there was no base ten numeral system (see Chap. 4) (Fig. 7.9).

As pointed out by Archimedes, by increasing the number of triangles, the accuracy of the estimate for the value of π can be successively improved. This method of estimating π, while technically correct, is quite cumbersome, especially when the calculations are performed by hand, as of course was necessary until the advent of high speed computers in the latter half of the twentieth century.

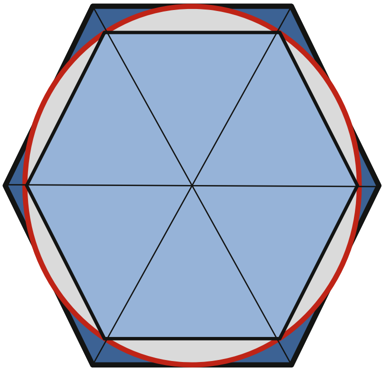


Fig. 7.9 Archimedes' method for bounding the area of a circle

Unknown to Westerners, an infinite series for determining the value of π was developed by Madhava (c. 1340–1425) in the fourteenth century. Madhava lived in the town of Sangamagrama (present day Irinjalakuda), India. Although his discoveries were largely unknown to Westerners, some historians theorize that his mathematics may have been transmitted to the west by missionaries. In any case, his use of infinite series can be said to be the first recorded use of such formulas, thus presaging modern mathematical analysis.

Madhava's derivation of his infinite series for the value of pi is perhaps too complicated for a text such as this, but I would be remiss if I did not at least describe the process whereby he developed his theorem. His primary interest appears to have been in evaluating astronomical coordinates, which must necessarily involve the calculation of trigonometric functions such as sine, cosine and tangent of angles. Although it is not known precisely how he came to such a conclusion, he apparently recognized that the first approximations of such functions could be obtained geometrically from triangles, and that these approximations could be successively improved by adding terms, each term improving the estimate of the trigonometric function by a slightly smaller amount than the previous one. By this method, he was able to discern that indeed an infinite number of terms would be necessary to calculate the value of the trigonometric function exactly. By this means he was able to produce infinite series for the sine, cosine, and tangent of a given angle. He then inverted the tangent function to produce the arc tangent function, which gave him an infinite sequence for the value of the angle. Using this series, and expanding it in powers, he was able to produce the first infinite series for the value of pi. Madhava's series is written as follows:

$$\pi = 4(1 - 1/3 + 1/5 - 1/7 + 1/9 - 1/11 + \cdots)$$

This series was later also developed independently by both Gottfried Wilhelm Leibniz (1646–1716) and James Gregory (1638–75) in the West. Thus, it is sometimes called the Madhava-Leibniz series, as well as the Gregory-Leibniz series.

As described in Beckmann's book, despite the development of infinite series for evaluating π (Leonhard Euler derived quite a few such sequences), the geometric method of estimating the value of π persisted well into the nineteenth century. This sort of irrational behavior has never been more apparent than in the search for the "exact" value of π, which so far as anyone knows is an irrational number.

Interestingly, Beckmann describes in detail an attempt to *legislate* the value of π in the year 1897 in the Indiana statehouse. In bill #246, now called *The Indiana Pi Bill*, it was proposed that the value be legislated to the value of 3.2. This could have led to a major disaster, because as everyone knows in the United States, once a law is enacted, it is nearly impossible to get rid of it (in Texas, for example, the state constitution makes it illegal to carry wire cutters in your pocket.). Worse still, other governments start to adopt it due to something called 'legal precedent'.

Fortunately for the rest of the world, there happened to be a mathematician named Clarence A. Waldo (1852–1926) from Purdue University in town that day, and due at least in part to his actions The Indiana Pi Bill was voted down in the State Senate. Talk about irrational behavior! We all owe a debt of gratitude to Dr. Waldo (Fig. 7.10).

While the calculation of π is in and of itself not an exercise in mechanics, possessing an accurate value of π is so pervasive in all of mechanics that it bears mentioning here. Furthermore, as pointed out by J.N. Reddy in his textbook *Introduction to the Finite Element Method* [60], the development of the finite element method in the latter half of the twentieth century (to be discussed in

Fig. 7.10 Photograph of Clarence A. Waldo

Chap. 13), an approximate method for solving continuum mechanics problems, is essentially an outgrowth of Archimedes' geometric method for approximating the value of π.

Descartes

A contemporary of Galileo, René Descartes (1596–1650) led the French school in the early sixteenth century, although he spent much of his life in other countries, including Holland (Fig. 7.11).

While it appears that Pierre de Fermat (1601–1665) was the first to employ a three-dimensional orthonormal rectilinear coordinate system, Descartes invented this same coordinate system independently and utilized the coordinate system that bears his name (Cartesian coordinates) to great effect in his exhaustive textbook *La Géométrie* [61].

Descartes' deployment of algebra in preference to geometry was revolutionary for his time. Prior to his treatise on this subject, geometry was studied graphically, without resort to mathematical equations (see for example Galileo's *Dialogues Concerning Two New Sciences* [62]). This new approach is today called analytic geometry, and Descartes is the father of this all-important field of mathematics. And as we all know today, it is not possible to predict motions without the use of analytic geometry. Thus, René Descartes paved the way for many of the mathematical developments to come in mechanics.

Fig. 7.11 Portrait of René Descartes by Frans Hals, Louvre Museum

Interestingly, Descartes is not remembered today so much for his enormous contributions to mathematics and mechanics because he is also one of the first great philosophers of modern times. Descartes is thus remembered today not only as the father of analytic geometry, but also as the father of modern philosophy.

Mechanical Calculators

No review of mathematics as it relates to mechanics would be complete without a discussion of mechanical devices used for mathematical calculations. These go back thousands of years, such as devices painted on cave walls for use as calendars, as described in Chap. 1. However, perhaps the oldest device used for systematic algebraic calculations is the Sumerian abacus (based on a hexadecimal numeric system), which first appeared around 2,500 BCE. By 600 BCE this type of device had been modified to the decimal system that we use today. It was successively employed by the Persians, Egyptians, Greeks, and Romans.

By the second century BCE, the Chinese had adapted the abacus into the device that is widely used to this day in many parts of the world. The abacus is perhaps the ultimate device for performing algebraic calculations mechanically (Fig. 7.12).

By the sixteenth century, mechanical devices for performing calculations had become quite commonplace in Western Europe. For example, Tycho Brahe possessed several mechanical devices at his observatory in Uraniborg for calculating the location of celestial objects within one arc minute accuracy (both the Indians and Arabs had apparently developed observatories centuries earlier for the same purpose) (Fig. 7.13).

Galileo Galilei is known to have developed a mechanical compass beginning in 1597 for the purpose of predicting the angle that a cannon should be pointed with respect to the horizon in order to launch a projectile a predetermined distance.

Blaise Pascal (1623–1662) appears to have been a polymath, exploring a wide range of scientific problems in his lifetime. Indeed, his first mathematical theorem was published at the age of 16.

In 1642, when Pascal was just 19-years old, he designed and built a mechanical calculator (called the Pascaline) that was so sophisticated that it is today

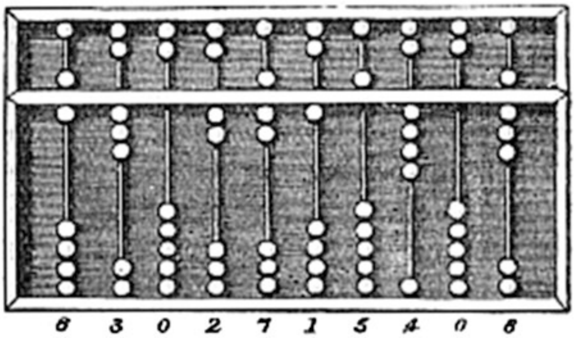


Fig. 7.12 Depiction of a Chinese Abacus

Fig. 7.13 Tycho Brahe charting the heavens

considered the forerunner of the modern computer. Unfortunately, his invention did not catch on because it was quite expensive. He designed and built 20 of these calculators, one of which is today on display at the Musée des Artes et Métiers in Paris (Fig. 7.14).

Although it was quite a long time before Pascal's invention took hold, the use of mechanical machines for the purpose of performing algebraic calculations eventually became widespread in the late nineteenth century. These calculators were based on the mechanical concept originally employed in the Pascaline. Between the 1890s and early 1970s, literally millions of these mechanical calculators were built worldwide. They were finally supplanted by electronic calculators in the late 1950s and 1960s that were developed by Casio, Canon, Mathatronics, Olivetti, SCM (Smith-Corona-Marchant), Sony, Toshiba, and Wang (Figs. 7.15 and 7.16).

John Oughtred (1575–1660) is credited with inventing the slide rule in 1622, using logarithms invented by John Napier (1550–1617). A slide rule is used most commonly for the purpose of multiplication and division, and proceeds from the well-known concept that in log space multiplication is transformed to addition.

Fig. 7.14 Portrait of Blaise Pascal by an unknown artist

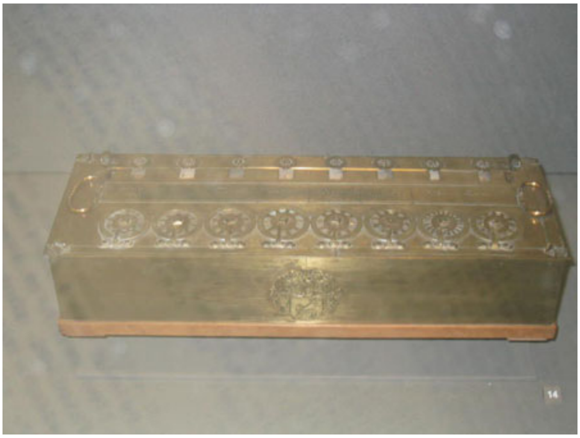


Fig. 7.15 Blaise Pascal's 'Pascaline' calculator, Musée des Artes et Métier, Paris

Thus, the slide rule is a mechanical adding machine that adds logarithms, but transforms them to multiplication via the use of a logarithmic scale (Fig. 7.17).

Few people born since 1970 would know how to operate a slide rule today, much less what one is. To them it is simply a device that has become obsolete, that is no longer needed because we have better tools. Indeed, throughout history such devices have been invented, only later to go extinct. We have the clepsydra

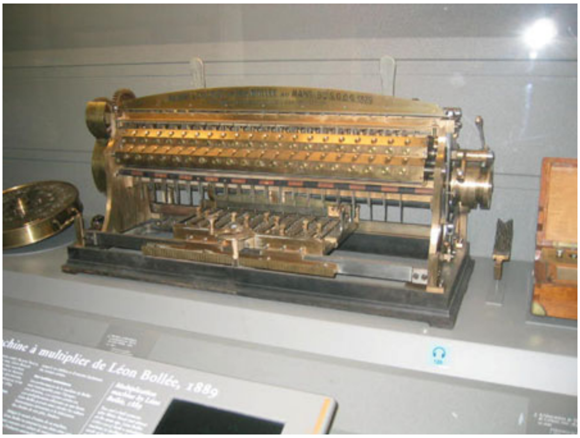


Fig. 7.16 Mechanical calculator created by Léon Bollée in 1889

(water clock), the sundial, the astrolabe, the water level, the gnomon….to name but a few. All have found ignominious graves. So the slide rule can be considered a metaphor for any of these. I have simply chosen the slide rule because it lived and died within my own span of time on this planet.

I was first introduced to the slide rule in 1964, when I was a freshman in high school. I was mathematically sharp, so I was allowed to participate in a program for advanced students called "number sense." My high school algebra teacher introduced us to the slide rule, which we quickly mastered. And when she asked me if I understood how it worked, what was the underlying principle, I quickly responded, "Yes, of course!" But I really didn't.

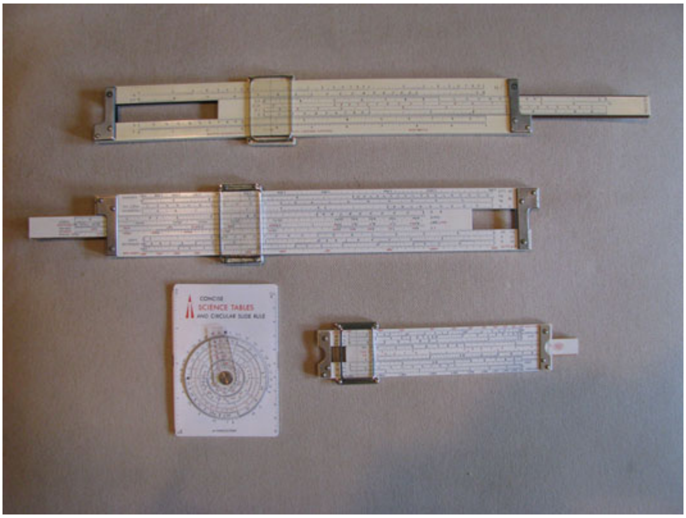


Fig. 7.17 Examples of slide rules

It wasn't until a couple of years later that I had my eureka moment with the slide rule. I still remember the event clearly. A friend and I were walking to take an exam when I noticed that he did not have his slide rule. In response to my query, he told me that he had lost his center slide. This was not uncommon, but to do so just before an exam could be catastrophic. "How can you take the exam?" I queried in horror.

He responded, almost casually, "Oh, it's no problem, I'll just slide these two pieces of log–log graph paper along one another and do the calculations that way." Up to that point, I don't believe that I ever really understood how a slide rule works. I knew it was using logs, but I did not properly realize that it was just an adding machine in another universe, the universe of log space. Once I understood that underlying principle, I suddenly realized that there might be all sorts of alternate universes wherein things could be simplified. Anyone who has ever wrestled with Laplace or Fourier transforms will recognize immediately where I am coming from on this one.

Parallel Mathematical Universes

Mankind has a long history of transforming into another mystical world in order to solve problems. As the saying goes, necessity is the mother of invention. So we transform into other worlds, worlds where things are easier (usually meaning math!). We cannot actually visit these worlds; we can only imagine them in our minds. And at the end of the day, after we have visited these worlds, we have to come back to our own imperfect world, where the math is decidedly more complex. Sometimes getting back to our own world can be cumbersome, so we have to make sure that it is worth the effort to get to these other worlds. Such is the case with Laplace transforms—the inversion process can be quite cumbersome.

Pierre-Simon Laplace (1749–1827) was a brilliant scientist in the late eighteenth and early nineteenth centuries. He was born in the small town of Beaumont-en-Auge in northwest France. His brilliance was unmatched in his time in France (of course, there was his contemporary Isaac Newton in England). He rose to become the most prominent scientist in Napoleon's enlightened society (Fig. 7.18).

In the late seventeenth century Isaac Newton invented calculus in order to develop his famous laws of motion. A result of his mathematics was the development of differential equations, thus introducing a whole new genre of complicated mathematics. Laplace extended a concept previously employed by Leonhard Euler to the application of differential equations, and in so doing invented the Laplace transform in 1785. This transform has the peculiar property (among others) that it converts the derivatives utilized in differential equations into algebraic quantities. In other words—differential equations become algebraic equations in Laplace space!!! This is the dream world of every student who has ever

Fig. 7.18 Portrait of Pierre-Simon Laplace

suffered through a first course in calculus. And as any practitioner of mechanics will know, differential equations are a necessary component of mechanics models.

Scientists today are developing a unifying theory of the universe called string theory. This theory admits the plausibility of alternate universes, introducing the possibility that our universe is nothing more than a portion of a larger "multiverse." Perhaps someday we will actually be able to travel to another universe within our multiverse. And perhaps in that universe something that is terribly difficult to the average person will become quite simple. For example, maybe we will all be able to travel at the speed of light, thereby making vacations to other planets less cumbersome. On the other hand, perhaps in that alternate universe some things will be more difficult. For example, perhaps addition in another universe will be harder than solving differential equations is in our own universe.

I doubt that I will ever travel to another universe, but perhaps my children's children will do so. If so, I hope that they will take a photograph of me along with them. That way, if I am waiting for them in that alternate universe, they will be able to verify that they are my grandchildren.

Counting

An interesting question that I used to wonder about is how well animals can count. After all, counting is clearly a mechanical endeavor. Can animals with fingers and toes count better than those with hooves and/or flippers? This question was apparently studied by mathematician Tobias Dantzig in his 1930 book *Number: The Language of Science* [63]. According to Dantzig, in an actual circumstance a squire determined to shoot a crow that had made its nest in his watchtower. He therefore brought along a rifle and intended to shoot the crow with it. The wily crow foresaw the squire's intentions and flew away, returning only after the squire had quitted his hunting perch.

The next day the squire brought along a friend and the pair hid within. The squire then entreated his companion to leave the tower. But the crow refused to return until both men had withdrawn. Thus, the squire brought along two friends the following day, entreating the pair to withdraw. Still the crow refused to return. This macabre game continued each succeeding day, with the squire increasing the number of participants by one until he had four friends accompanying him. When the four friends departed, the crow, thinking all the men had left, returned and the squire shot and killed it. From this the squire deduced that the crow could innately discern no more than four items.

When this tale became public it encouraged scientists to test how many items other species could count, and the number invariably came out to four. At some point the issue turned to humans, whereupon it was determined that, amazingly, humans can also innately discern only about four objects.

Dick Teresi [58] points out that the famous magician Harry Houdini understood this fact all too well. In one of his famous tricks, he would tell the audience that he could magically walk through a wall in the center of the stage. He would then have a group of ten bricklayers come out on stage and build the wall (five on each side of the wall), while he exited stage left. He would then simply don a bricklayer's uniform, join the bricklayers and gingerly cross to the other side of the stage in full view of the audience, all the while acting as if he were one of the workers. He would then exit stage right and remove the bricklayer's uniform, reappearing on the right side of the stage after the bricklayers had departed as if he had magically passed through the brick wall. The trick worked because no one realized that the number of bricklayers had increased by one.

I personally had an (inopportune) opportunity to test the squire's revelation about 5 years ago. I was traveling to Eastern Europe with a group of friends when, unknown to myself, I lost my passport in the airport in Berlin. A group of seven of us subsequently boarded a van for a night-time drive to Western Poland. When we arrived at the Polish border, I realized that I had lost my passport in Berlin. A border guard approached our van and asked for passports. Everyone passed their passports forward, and there were only six passports. The guard took the passports inside his headquarters and commenced to check them out.

While the border agent was perusing the passports the driver of our van said, “There were only six passports. Why are there only six, when there are seven of us?”

At this query, I realized that I needed to calm the other passengers, so I said, “A squire once had a crow.” And I began to tell the story related in Tobias Dantzig’s book. I confess that I embellished the story a bit, which turned out to be fortuitous, as the guard was engaged with the study of the six passports for several minutes. But he eventually returned to the van, handed over the passports, and announced that we were free to proceed into Poland, somehow having failed to discern that the number of passports was one short of the number of passengers. My friends were amazed, and I was relieved, at least until I realized that I was now in Poland illegally.

Two days later I traipsed down to the American Embassy in Warsaw. After standing in the obligatory line designated for U.S. citizens who had lost their passports, I eventually came before a consular officer, who asked politely, “Where did you lose your passport?”

I responded somewhat inanely, “In Berlin.”

At this admission the officer replied with obvious horror, “But then how did you get into Poland?”

To this query I answered with straight face, “A squire once had a crow.” By the time I had completed the account of my rather devious behavior the consular officer was so entranced with my account that he immediately issued me a replacement passport.

Sadly, my lost passport was never returned to me. Thus, there is now perhaps one more person walking around in the world with the same name as me, which is made disconcerting by the realization that our species is so inept at counting that I doubt my double will ever be apprehended, much less even counted.

So the next time a mathematician attempts to inform you with palpable condescension that counting is such a trivial matter, remind him or her of the account of the squire and the crow. And if you ever happen to meet me on the street, please make sure that I am not my larcenous double.

Mechanics is a field of science that is predictive in nature. Mathematics is the language of predictive science. Because of the multidimensional nature of our universe, the mathematics necessary to describe the motions of bodies is necessarily complicated. Thus, advanced mathematics is necessary in order to predict these motions. I have cited above just a few examples of developments in mathematics that have led to our modern ability to model the mechanics of bodies. The interested reader is encouraged to delve further into the history of mathematics, beginning with the references cited above.

Rigid Body Dynamics

We define a rigid body to be an object that does not deform during its motions. There is in actuality no such thing as a rigid body, since all objects in our universe are constantly undergoing deformations. However, for certain applications the assumption that the body is rigid may be sufficiently accurate for the purpose at hand. The study of the motions of rigid bodies is called rigid body dynamics, and as such it is a subset of mechanics.

Humans have been studying rigid body dynamics for as long as they have been looking at the night sky. Indeed, nearly all astronomers practice rigid body dynamics.

Galileo

The systematic study of the rigid body dynamic behavior of Earth-bound objects is fairly recent. Indeed, it appears that none other than Galileo Galilei was the first to report a rigorous scientific study of rigid body dynamics in his last book *Dialogues Concerning Two New Sciences* [62].

During his college studies in Pisa around 1586, the story goes that Galileo was sitting in the fabulous Pisa cathedral listening to a sermon one day when he had an epiphany. Perhaps his mind wandered that day, but I for one will forgive him, because in Galileo's time it was not uncommon for religious services to be held on more than 100 days each year (there were lots of saint's days by then), and everyone was required to go to service.

At any rate, Galileo was apparently watching the lantern (it has been replaced today) swaying back and forth overhead during the service, and on a whim he began measuring the time that it took for the pendulum to swing back and forth against his pulse rate, and in so doing he discovered the principle of the pendulum clock, which would be perfected by Christiaan Huygens shortly after Galileo's passing. As it turns out, the time that it takes for a pendulum to return to its original position is nearly independent of the amplitude of the motion, thus making a pendulum a reasonable means of keeping time. This is a wonderful problem in rigid body mechanics!

Galileo went on to study the motions of balls on inclined planes as well, and he reported the results in *Dialogues Concerning Two New Sciences*. Galileo reasoned that the same physics applied to balls rolling on inclined planes as those dropped vertically, but that he could slow down the motions sufficiently to actually measure the elapsed time accurately using a clepsydra. Presumably, he turned to inclined planes because he was unable to distinguish between the passage of time for balls of different sizes dropped from aloft (although there is no proof that he actually dropped balls from the Leaning Tower). His ingenious experiments set the stage for the monumental revelations of Isaac Newton a half century later (Figs. 7.19 and 7.20).

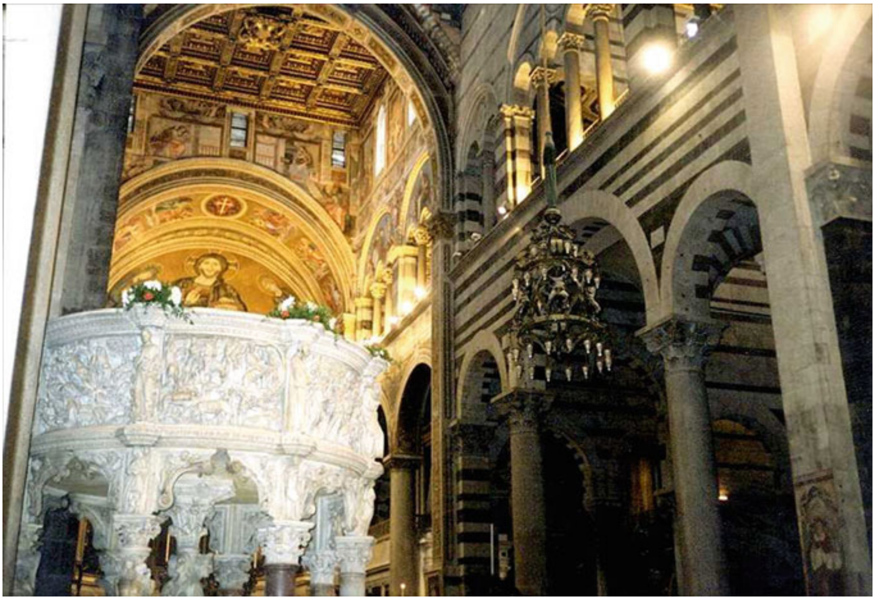


Fig. 7.19 Galileo's Lantern (not the original) adjacent to the Pulpit in the Pisa Cathedral

Fig. 7.20 Galileo's inclined plane (note the bells placed at intervals for the purpose of measuring the acceleration of balls), Galileo Museum, Florence

Newton

No book on mechanics could be complete without some discussion of Isaac Newton (1642 or 43–1727), but the real question is how far it should be taken. I prefer to be as brief as possible for the simple reason that I do expect the interested reader to delve deeper into the veritable cornucopia of literature about Newton and his discoveries. Thus, I will remark only briefly about his personal life. He was born at Woolsthorpe-by-Colstersworth in Loncolnshire, England, in either 1642 or 1643. The date of his birth depends on which calendar you choose to accept, for poor Isaac was born during that unfortunate period when the calendar was in dispute (see Chap. 6). He lived long, passing away in 1727. In between, he changed the world in ways that few others in history can match (Fig. 7.21).

Newton was a difficult man, possessed of an extremely obsessive, introverted nature throughout his life. Whether these were plusses or minuses is debatable, but he nonetheless matriculated to Cambridge University, and by the time he was in his 1920s, he was already making a scientific name for himself. Perhaps the most famous scientist of that time was Robert Hooke (see below), who would eventually become one of his greatest opponents. But it was not until the year 1687 that Newton's full potential became apparent, with the publication of *The Principia* [57] (Fig. 7.22).

Everyone who finds this book interesting should also read at least one biography of Isaac Newton. I personally like the one by James Gleick entitled *Isaac Newton* [64]. Furthermore, I consider a perusal of *The Principia* [57] essential to the understanding of anyone who is scientifically disposed. Newton's book is perhaps the greatest bargain on Earth. Try looking up the price on your favorite bookseller website. I will bet that you will agree with me.

Newton would later recall, "If I have seen farther than others it is because I was standing on the shoulders of giants." Indeed, there were many giants before Newton, but the two chief forerunners who affected his thinking on mechanics were Johannes Kepler and Galileo Galilei. The importance of their previous developments and how they led Newton to his discoveries will be elucidated herein, as described in Richard Feynman's book, *The Character of Physical Law* [65].

Newton tackled the most challenging scientific problem of his time—the nature of the mechanics of the solar system. Toward this end, he had at his fingertips the laws espoused by both Kepler and Galileo. Kepler had espoused his three laws of planetary motion:

1. Planets move in elliptical orbits about the Sun;
2. Planets sweep out equal areas in equal times during their orbits; and
3. The time it takes a planet to orbit the Sun is proportional to the square root of the radius of the orbit cubed.

These laws turn out to be approximately correct. In fact, they are accurate enough that they are still used today (Fig. 7.23).

Following Kepler's revelation on the mechanics of planetary motions, Galileo stated three laws governing the motions of bodies on Earth. These are:

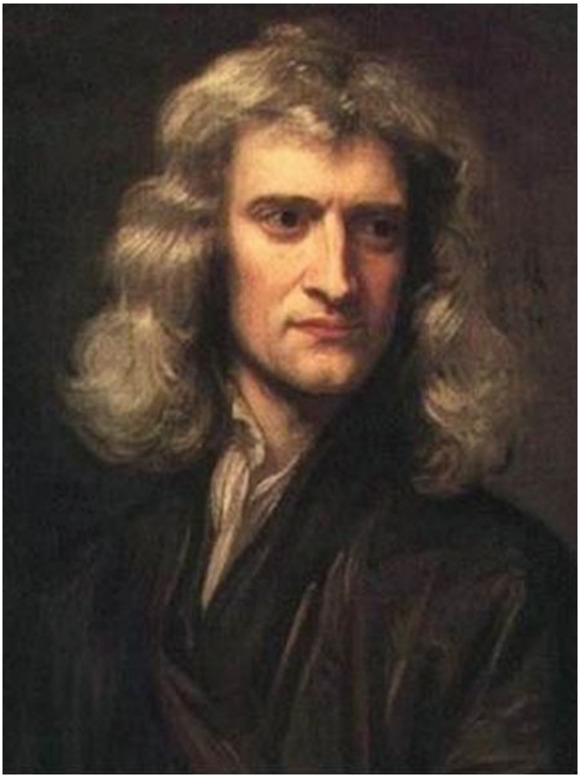
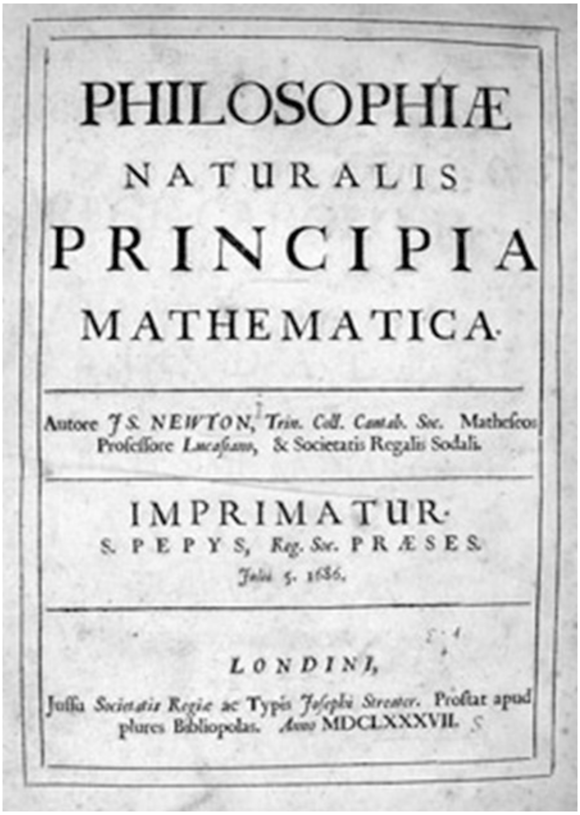


Fig. 7.21 Portrait of Isaac Newton by Sir Godfrey Kneller

1. A body moving at constant velocity in a straight line will continue at constant velocity forever unless acted on by some force;
2. A falling body will increase its velocity in proportion to the square of the time; and
3. The velocity of a falling object is independent of its mass.

Newton checked both Kepler's and Galileo's laws carefully, and he found that both sets appeared to be correct. But Newton was interested in constructing something much bigger. He believed that the same laws could be applied to both planetary motions and Earth-bound motions. Starting with Galileo's first law, he reasoned that the Moon could not travel in a curved line unless a lateral force was applied to it. He reasoned that this force must be applied by the Earth. Similarly, he reasoned that the Earth would travel in a straight line rather than to orbit about the Sun unless the Sun applied a lateral force to the Earth. He reasoned that this force was in direct proportion to the mass of the object exerting the force, and inversely proportional to the square of the distance between the two objects, thereby creating the following inverse square law:

$$F = G\frac{mM}{r^2}$$



PHILOSOPHIÆ

NATURALIS

PRINCIPIA

MATHEMATICA.

Autore *IS. NEWTON, Trin. Coll. Cantab. Soc.* Matheſeos
Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud
plures Bibliopolas. *Anno* MDCLXXXVII.

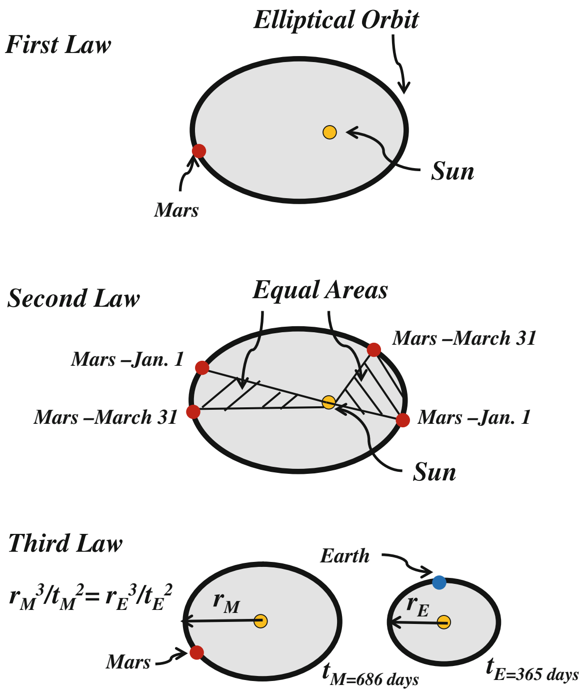
Fig. 7.22 Title page of *The Principia*

where F is the magnitude of the gravitational force applied to the orbiting body, G is the gravitational constant (of proportionality), m is the mass of the orbiting body, M is the mass of the central body, and r is the distance between the two bodies. The direction of this force is colinear with the straight line connecting the centers of mass of the two bodies, and this force is always attractive rather than repulsive.

The above law is today called Newton's Gravitational Law. It is rather intuitive if one considers that the surface area of a sphere is proportional to its radius squared. Thus, it can be seen that the force exerted by a body is inversely proportional to the area of the sphere enclosed by the distance, r, from the body. This implies that the force exerted by the body at a distance, r, multiplied by the area enclosed is a constant.

Newton then reasoned that Galileo's first and second laws implied that the force applied to a body was proportional to the rate of change of the momentum of the body (called Newton's Second Law of Motion):

Fig. 7.23 Kepler's laws of planetary motion



$$\vec{F} = \frac{d}{dt}(m\vec{v})$$

where $\vec{v}$ is the velocity of the body, and the product of the mass, m, and the velocity, $\vec{v}$, is defined to be the momentum of the body. In order to create this law Newton was obliged to invent a new form of mathematics that we now call calculus (he termed it "fluxions").

Newton knew that for the case of a body with constant mass traveling in a circle, the rate of change of the velocity in time is given by

$$\frac{dv}{dt} = \frac{v^2}{r}$$

Therefore, substituting this result into the above law of motion results in the following [66]:

$$F = mv^2/r$$

He then audaciously equated the above equation to his gravitational law, thus applying it to the motion of both the Earth and the Moon (which have constant mass), resulting in the following:

$$GmM/r^2 = mv^2/r$$

Amazingly, the mass cancelled out of the equations, which was in exact agreement with Galileo's third law. He then substituted the orbital velocity, given by

$$v = 2\pi r/t$$

where t is the orbital time period, into the equation, thus resulting in the following:

$$r^3/t^2 = GM/4\pi^2$$

thus *reproducing Kepler's third law!*

Newton now knew that he was onto something really big—a law that seemed to apply both to the motion of bodies on Earth and to the motion of planets. Today we know that Newton's laws are *universal laws*, meaning that they apply everywhere throughout the universe (except when a body is moving close to the speed of light). Newton subsequently showed that the Gravitational Law and his Second Law of Motion were in agreement with all six of Kepler's and Galileo's laws.

Not content with these astounding results, Newton went on to show that his laws were able to explain such phenomena as the Earth's tidal motions, the bulge of the Earth's equator, and the Earth's precession. It was left for others to apply his laws to all sorts of physical phenomena, each time proving to be in accord with Newton's laws (at least until Albert Einstein came along).

There is a downside to Newton's story. Shortly after the publication of *The Principia* he became embroiled in a controversy with Robert Hooke, who claimed primacy of the Gravitational Law. Although records suggest that Hooke had in fact proposed an inverse square law, Newton eventually won this battle because he not only espoused the inverse square law, he also demonstrated its veracity through numerous experimental verifications in his book, thus proving his law by adhering to the scientific method.

Newton subsequently became embroiled in a second controversy with Gottfried Leibniz (1746–1716), who claimed to have invented calculus prior to Newton. This particular disagreement was quite ugly, lasting many years. Today, historians agree that both Newton and Leibniz deserve some of the credit for inventing calculus.

Newton's book *The Principia* is considered by many historians to be the most important scientific book ever written. This text more than any, other ushered in the modern age of science and the primary topic of the book was mechanics. Indeed, it would not be a stretch to say that Isaac Newton invented classical mechanics (Fig. 7.24).

Over the course of the succeeding two centuries Newton's laws came to be applied to virtually every problem known to humankind that involves mechanics. Furthermore, additional universal laws that are totally unrelated to mechanics nonetheless owe much to Newton's Laws. Indeed, it is not possible to even

Fig. 7.24 Portrait of Gottfried Leibniz by Christoph Bernhard Francke

envision our modern world today without Newton's laws. As we will see in the next few chapters, virtually every advance in modern science since the publication of *The Principia* owes much to Isaac Newton.

Lagrange

It remained for Joseph-Louis Lagrange (1736–1813) to place the mechanics of rigid bodies on an essentially complete foundation that was both correct and clear over the course of the succeeding century. Using what is now termed variational calculus (a mathematical tool that can be utilized to deploy Newton's Laws), Lagrange opened the door at the end of the eighteenth century to the next great surge in the science of mechanics: the development of general three-dimensional theories of deformable bodies (Fig. 7.25).

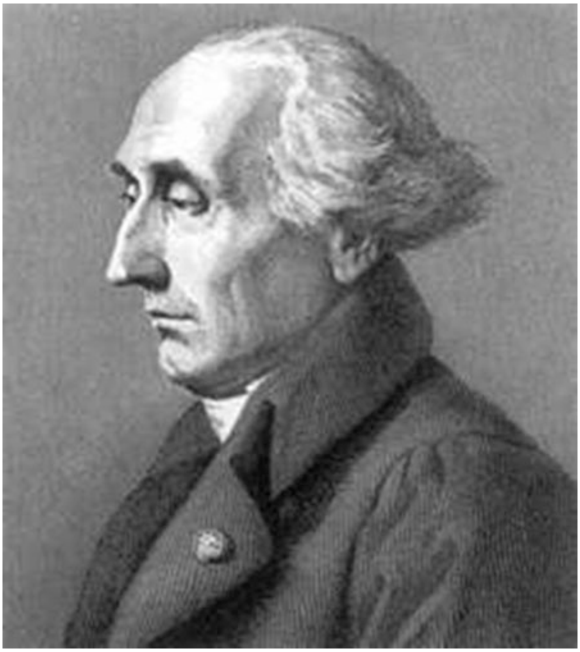


Fig. 7.25 Portrait of Joseph-Louis Lagrange

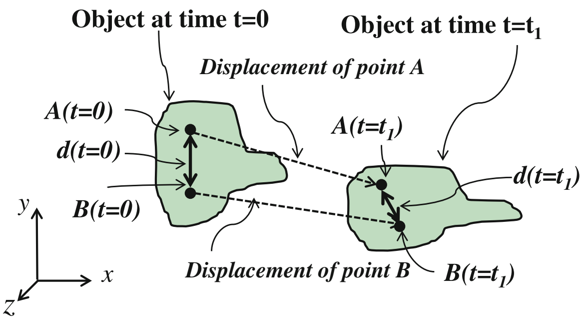
Deformable Body Mechanics

The theories enunciated by Newton were to be examined and verified in the early eighteenth century, especially by Pierre-Simon Laplace and Christiaan Huygens. But whereas initial efforts were preoccupied with the study of so-called rigid bodies (such as the planets), toward the middle half of the century scientists began to turn their attentions towards the development of accurate models for predicting the mechanics of so-called deformable bodies.

Galileo

Galileo's final masterpiece, *Dialogues Concerning Two New Sciences* [62] was published in 1638, while he was under house arrest at his villa in Arcetri, and in one way Galileo not only superseded Newton, he actually outdid him. This was in the area of deformable body mechanics. Today we define a deformable body as one in which at least two points within the body change their relative distance during the motion of the body, as shown below, where it can be seen that the distance, d, between the two arbitrary points A and B changes with time, t (Fig. 7.26).

Fig. 7.26 Depiction of a deformable body



In *Dialogues Concerning Two New Sciences,* Galileo's academic named Salviati (representing Galileo himself) expounds the following law on the First Day:

> …geometry teaches us that, in the case of similar solids, the ratio of two volumes is greater than the ratio of their surfaces…

This law has become known as *The Square-Cube Law*, and although the ancients appear to have understood this fact, Galileo is considered to be the first to state it concisely. He goes on to demonstrate this fact with an example as follows:

> Take, for example, a cube two inches on a side so that each face has an area of four square inches and the total area, i.e., the sum of the six faces, amounts to twenty-four square inches; now imagine this cube to be sawed through three times so as to divide it into eight smaller cubes, each one inch on the side, each face one inch square, and the total surface of each cube six square inches instead of twenty-four as in the case of the larger cube. It is evident therefore that the surface of the little cube is only one-fourth that of the larger, namely, the ratio of six to twenty-four; but the volume of the solid cube itself is only one-eighth; the volume and also the weight, diminishes therefore much more rapidly than the surface.

The Square-Cube Law can be said to be the beginning of modern deformable body mechanics, and Galileo points out that the load intensity, σ_1, on the larger cube is larger than the load intensity, σ_2, on the smaller cube due to its own weight and resulting from The Square-Cube Law, as shown below. Note that we have defined the load intensity to be the force per unit area (Fig. 7.27).

Galileo went on to show that this load intensity was important in determining the load carrying capability of uniaxial bars, beams, and even human bones. In so doing he invented the field of deformable body mechanics. Blaise Pascal (1623–62) would perform experiments on air in 1647 in which he would define the load intensity as air pressure, which today we know to be normal stress, a component of stress normal to a surface that is compressive rather than tensile. These early terms would later open the door to modern failure mechanics.

Galileo went on in the Second Day of his *Dialogues Concerning Two New Sciences* to discuss the loads and deformations in a cantilever beam, defined to be a long slender member that is fixed at one end and carries load normal to its long

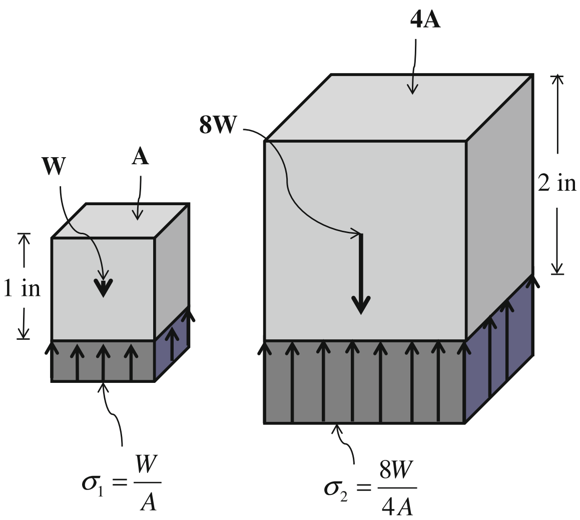


Fig. 7.27 Galileo's example depicting the Square-Cube Law

Fig. 7.28 Galileo's cantilever beam

axis, as shown below. Galileo hypothesized a model for the beam's response that was incorrect. Nonetheless, he had posed a very challenging problem for his successors to take up (Fig. 7.28).

Beam Theory

History records that the first attempts to use calculus to model the mechanics of deformable bodies were due to two of the Bernoulli's, brothers Jacob (1654–1705) and Johann (1667–1748). Jacob proposed that the curvature of a beam is proportional to the bending moment. John introduced the principle of virtual displacements. Although their attempts were incomplete they paved the way for the first useful theory of beams (Figs. 7.29 and 7.30).

Johann Bernoulli's son Daniel Bernoulli (1700–1782) became the chair of mathematics at The Russian Academy of Sciences in St. Petersburg in 1725. Shortly thereafter his former pupil from Basel, Switzerland, Leonard Euler (1707–1783), joined him in St. Petersburg [67]. Daniel Bernoulli would leave St. Petersburg in 1733, but he continued to correspond with Euler. Sometime during the succeeding years Daniel proposed a method of solution for beams that Euler took up in earnest, and this model appeared in Euler's book *Methodus Inveniendi Lineas Curvas* in 1744 [68] (Figs. 7.31 and 7.32).

Daniel Bernoulli proposed to Euler that the deformable body mechanics describing a beam, which is clearly a three-dimensional object, could be simplified mathematically to one dimension by assuming that cross-sections of the beam that are normal to the long axis could be assumed to remain planar and normal to the curved line of the long axis during deformation, as shown below. This deceptively simple assumption turns out not only to be in accordance with experimental observation, it dramatically simplifies the mathematics required to predict both the

Fig. 7.29 Portrait of Jacob Bernoulli

Fig. 7.30 Portrait of Johann Bernoulli

deformations and the failure due to excessive loading in beams [69]. The "Euler–Bernoulli Beam Theory," as it is now called, is one of the seminal events in the development of theories for modeling the deformations of solids, and this approach is still in use today for designing structural components.

As we will see in the succeeding chapters, the mechanics of deformable bodies became an issue of prime importance in the industrial age. As more and more inventions were developed, it became necessary to design and construct mechanical parts that could carry the mechanical loads required to operate these new inventions. The Euler–Bernoulli Beam Theory was the first cogent and accurate model for predicting the mechanical response of deformable bodies. As such, essentially all other models in deformable body mechanics owe their origin to this ingenious theory (Fig. 7.33).

Euler was perhaps the most influential scientist of the eighteenth century, establishing the first complete three dimensional mathematical models of the mechanics of rigid bodies (Newton had confined his models to geometric proofs), as well as a rigorous explanation of conservation of mass, and the introduction of strain (Fig. 7.34).

Finally, on the subject of deformable bodies, Galileo discussed the failure due to fracture of simply supported beams, as shown below. Thus, Galileo may be considered to be the father of both deformable body mechanics and failure mechanics (with a footnote to Da Vinci, see Chap. 5).

Fig. 7.31 Portrait of Daniel Bernoulli

Constitutive Models

The final piece of the puzzle necessary to model deformable bodies deals with the material behavior of the object in question. The material model is today called a constitutive model.

Toward the middle of the seventeenth century Robert Hooke (1635–1703) began performing experiments on all manner of metallic springs. He formulated his findings in the form of an anagram—ceiiinosssttuv—in 1675. His results, "ut tensio sic vis" (meaning "as the load, so the deformation"), published in 1678, became known as Hooke's Law, the forerunner of linear elastic constitutive models that are necessary to predict the mechanical response of elastic bodies [70] (Fig. 7.35).

Fig. 7.32 Portrait of Leonhard Euler

Fig. 7.33 Graphical depiction of the Euler–Bernoulli assumption for beams

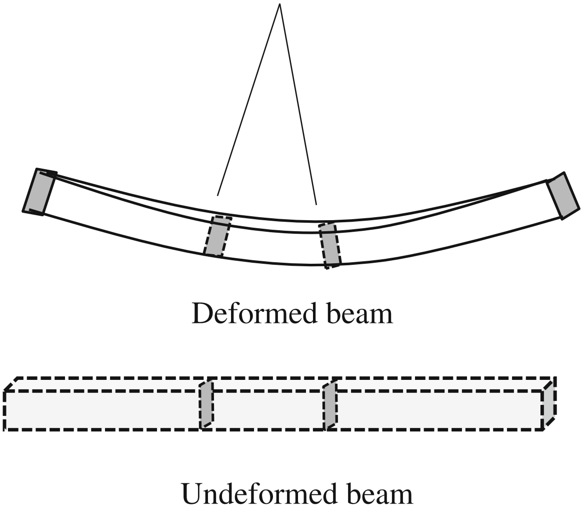


Fig. 7.34 Galileo's depictions of fractured beams

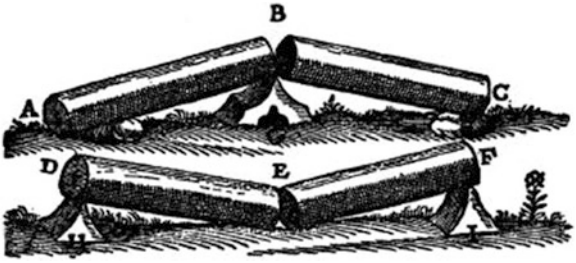


Fig. 7.35 Hooke's spring experiment

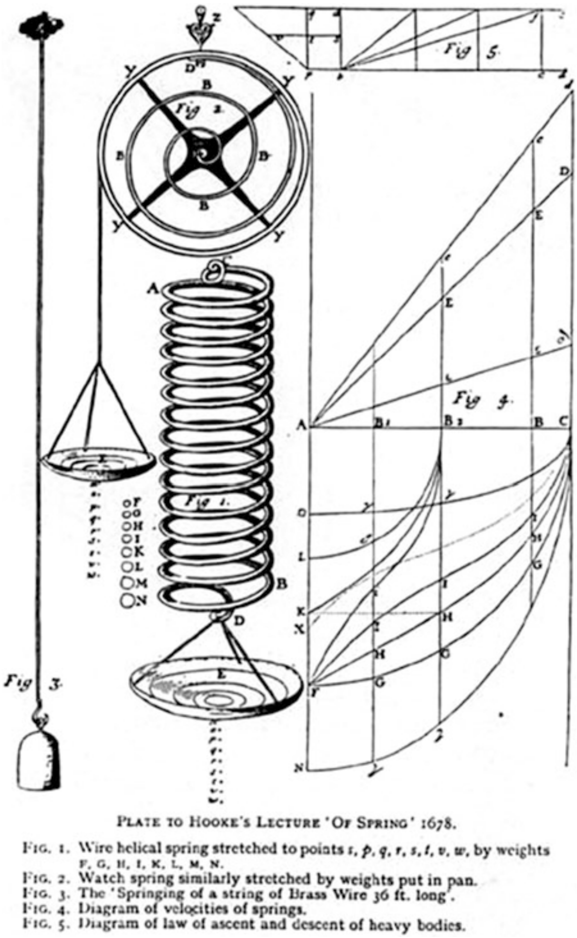


PLATE TO HOOKE'S LECTURE 'OF SPRING' 1678.

FIG. 1. Wire helical spring stretched to points *o, p, q, r, s, t, v, w*, by weights F, G, H, I, K, L, M, N.
FIG. 2. Watch spring similarly stretched by weights put in pan.
FIG. 3. The 'Springing of a string of Brass Wire 36 ft. long'.
FIG. 4. Diagram of velocities of springs.
FIG. 5. Diagram of law of ascent and descent of heavy bodies.

Hooke's Law would later be applied for both solids and liquids. In 1834 Émile Clapeyron would provide the so-called ideal gas law for gases

$$pV = nRT$$

In which p is the pressure of the gas, V is the volume of the gas, n is the number of moles of gas, R is the universal gas constant, and T is the temperature of the gas. The above may be restated as follows:

$$p = K\left(\frac{1}{V}\right)$$

where

$$K \equiv nRT$$

is a constant (at constant temperature), thus creating a linear relation between the kinetic pressure, p, and the kinematic deformation, $1/V$. This then is a demonstration of Hooke's Law for dilatation of a gas.

Gabriel Lamé (1795–1870) formulated the three-dimensional equations of elasticity for isotropic solids in 1852:

$$\sigma_{ij} = \lambda\varepsilon_{kk}\delta_{ij} + 2\mu\varepsilon_{ij}$$

where σ_{ij} are the components of Cauchy's second order stress tensor (see Chap. 9), ε_{ij} are the components of the strain tensor, δ_{ij} is the Kroneker delta, and λ and μ are material constants for linear elastic isotropic materials, thus creating a three-dimensional extension of Hooke's Law. Note that for simplicity the subscripts follow the indicial notation introduced in the twentieth century by Albert Einstein.

Elastic constitutive models are normally only accurate for solids. As mentioned above, they also apply to liquids and gases in bulk. However, if a fluid (liquid or gas) is deformed in shear, it is observed that the stress is related to the rate of the strain rather than the strain due to the fact that the molecules are not molecularly bound to one another. When this relation is linear, the material is called Newtonian after Isaac Newton, who was the first to notice this material behavior in fluids (Fig. 7.36).

Today we know that material models can be very complicated for various classes of materials. Thus, the field of constitutive theory has become an important subset of the field of deformable body mechanics.

In the time of Galileo, when he posed the problem of a cantilever beam in his book *Dialogues Concerning Two New Sciences,* the problem of a beam was of paramount importance to society because there was no extant rigorous design methodology for beams. When Leonhard Euler and Daniel Bernoulli solved the problem in the following century, they employed a kinematic approximation in order to produce a model that was not perfect, but it was accurate enough for most practical purposes. This approach set the stage for much of mechanics, and indeed of all science over the next two centuries. The approach was to develop an *approximate model* for which an *exact mathematical solution* could be obtained. In doing so, it acquired the name "strength of materials" [71].

Fig. 7.36 Portrait of Gabriel Lamé

By the early eighteenth century, scientists such as Fourier, Navier, Poisson, and Cauchy were producing *exact* models, but for most practical circumstances these models could not be solved due to the complexity introduced by the input loads, geometry, and material properties. Thus, the approximate models persisted well into the twentieth century before *approximate mathematical methods* began to be developed for solving the *exact model* sufficiently accurately to displace the approximate models (see Chap. 13).

Music and Measuring

8

It is so characteristic, that just when the mechanics of [musical] reproduction are so vastly improved, there are fewer and fewer people who know how the music should be played.
Ludwig Littgenstein (1889–1951)

Music

Believe it or not, music is profoundly related to mechanics. The propagation of sound through air is accomplished via mechanical waves. In addition, musical instruments can be rather complicated contraptions for producing sound that is pleasing to the human ear. Furthermore, we will see that the development of these complex artistically motivated instruments profoundly affected developments in many far-reaching technologies. Thus, the developments in music as they relate to mechanics are entirely appropriate within this book.

Modern music may be said to have begun in 1025, when the Benedictine monk Guido d'Arezzo (c. 991–1050) published his book *Micrologus* [72]. In this book he introduced the staff notation that we use today. Up to that time a neumatic notation had been utilized. Guido's notation made it much easier to record, remember, and translate music. It is noteworthy that this new "language" of music appeared in a time when the public was largely illiterate. In fact, the written version of our spoken language did not reemerge to the general public until 300 years later, when Dante's *The Divine Comedy* was published (see Chap. 4).

Medieval music was performed using a variety of relatively simple musical instruments such as the flute (replacing the older pan flute), which had holes along the sides. This instrument was altered several times during the Middles Ages, beginning as a wooden instrument, and evolving through several different forms to the metallic one that we have today with keyed hole covers. Other musical devices of the medieval period included stringed instruments such as the harp, lute, mandore, and psaltery. There were also instruments with sound boxes such as the jaw harp and fiddle, and as we will see below, these sound boxes served the function of mechanically amplifying the sounds produced by the instrument, long before the word "amplifier" became a stalwart term in our electromagnetic world of today. In addition, there were a number of tympanic instruments, as well as wind instruments such as an early version of the trombone. All of these instruments worked on principles of mechanics of both solids and fluids.

D. H. Allen, *How Mechanics Shaped the Modern World*,

DOI: 10.1007/978-3-319-01701-3_8,

Unfortunately, none of these instruments produced a particularly loud volume, nor did they possess great range. It was thus opportune for new instruments to be invented during and shortly after the Renaissance. As we will see in this chapter, among these were improvements of the percussive organ and the stringed hurdy-gurdy.

The Pipe Organ

Pipe organs seem to have been invented in the twelfth century, from whence they underwent a long and gradual evolution. By the seventeenth century, pipe organs were perhaps the most complicated mechanical devices on Earth. Because they were so intricate, large, and expensive, they were usually only constructed in large basilicas. However, once they were in place, they could fill a cathedral with sound-like nothing else available on our planet until the twentieth century.

The pipe organ is a purely mechanical device that uses compressed air blown through pipes of varying lengths via a complicated system of levers and pulleys to produce the full range of sounds. Sound, in case you didn't know it, is also purely mechanical, being produced by waves of compressed and/or sheared air. When air

Fig. 8.1 South dome organ from the Milan Cathedral, first constructed in 1395

at a higher than ambient pressure comes in contact with air at ambient pressure, the mechanics of gases are such that the air at higher pressure will push the air of lower density ahead of it, causing what we call convection. This means that the air molecules are actually being transported along, much like when you feel the air push against your body on a windy day. Compressed air pushed into a pipe will thus displace the air within, and this convection of the air will also induce mechanical waves (which do not transport the air) to be formed within the pipe. The frequency of these waves will depend on the length of the pipe, so that the length and diameter of the pipe can be used to control the pitch of the sound emanating from the pipe. The loudness of the sound is controlled by the pressure difference between the air entering the pipe and the ambient air pressure within the pipe. Thus, with a sufficient source of pressurized air, a pipe organ can be made to produce an impressive display of beautiful sounds of both differing pitch and volume within a cathedral.

This was the first complicated instrument on Earth that relied nearly completely on energy that was produced by means other than humans (at least indirectly, since humans typically pressurized the air supply with hand pumps). As such, the pipe organ can be said to be a significant forerunner of the industrial age (see Chap. 12) (Fig. 8.1).

The Harpsichord

The harpsichord appears to have been invented sometime around the beginning of the Renaissance. This was the first broad polyphonic instrument that was compact enough to be housed within a parlor room. Accordingly, the available pool of impressive music expanded exponentially after its invention. Composers such as François Couperin (1668–1733), Domenico Scarlatti (1685–1757), and Johann Sebastian Bach (1685–1750) utilized the harpsichord to take music to new heights.

Like the organ, this instrument is played with a keyboard. The principle of sound production is by plucking of strings, using a mechanical device that has a bird's quill attached to it (at least the early versions did). When the string is plucked, it vibrates, and the frequency of this vibration is dependent on the length of the string (as discovered by Pythagoras and quantified by Vincenzo Galilei, the father of Galileo Galilei). In addition, the harpsichord amplifies sound in an entirely different way from the pipe organ. Using the concept of a sound box (see the jaw harp and fiddle above, as well as the violin below) developed in other musical instruments, the inventors appended a thin wooden sheet to the bottom of the instrument. This wooden sheet, called a sound board, serves to amplify the sound produced by the vibrating strings of the harpsichord. When the waves sent out by the harpsichord strings strike the sound board, it vibrates in turn (hopefully at the same frequency) and sends out its own sound waves, and since the sound board is highly flexible it amplifies the sound produced by the instrument without requiring additional input energy (whereas the pipe organ amplifies the loudness by applying greater pressure).

This instrument was very popular in the sixteenth and seventeenth centuries. Eventually, it was supplanted by the fortepiano in the eighteenth century for two reasons. First of all, the tension of the strings applied to the wooden frame in a harpsichord caused the frame to distort rapidly, so that the instrument needed to be tuned quite often (in many cases, at least daily!), a problem in deformable body mechanics (see Chap. 7). Second, the plucking action was incapable of producing a range of loudness that the fortepiano later proved capable of providing, another problem in deformable body mechanics (Figs. 8.2 and 8.3).

The harpsichord was the first musical instrument that was capable of bringing complex solo music to homes and parlors. This fact, together with the enhanced level of mechanical complexity, served to prepare the populace for the coming industrial revolution, when complicated mechanical devices gradually became commonplace in the average household.

Fig. 8.2 Photograph of a harpsichord

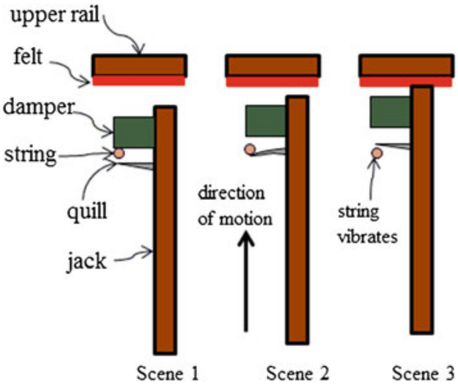


Fig. 8.3 Harpsichord plucking mechanism: scene 1—damper holds string; scene 2—jack drives upwards and quill plucks string; scene 3—quill passes string and string vibrates

The Piano

In order to mitigate the shortcomings of the harpsichord the fortepiano was invented by Bartolomeo Cristofori (1655–1731) around 1700 (his article on his invention did not appear until 1711). Working under the patronage of Ferdinando de Medici in Florence, Cristofori created several new musical instruments. There was one, however, that stood out. He named it *un cimbalo du cipresso di piano e forte,* "a keyboard of cypress with soft (*piano*) and loud (*forte*)". The most significant development in this instrument was that it was percussive, that is, instead of plucking the strings, hammers struck the keys, and while other percussive instruments had been previously invented, this one was such a marked departure from anything seen before that Cristofori today gets the credit for inventing the pianoforte (also called the fortepiano, as well as the modern term "piano") [73] (Fig. 8.4).

The oldest known remaining Cristofori fortepiano is shown below (Fig. 8.5).

It was in no small measure due to these complex mechanical instruments that classical music produced the likes of Johann Sebastian Bach (1685–1750), among a host of other extremely talented individuals [74]. It is said that when Bach first

Fig. 8.4 Portrait of Bartolomeo Cristofori

Fig. 8.5 Oldest surviving Cristofori fortepiano 1720, Metropolitan Museum New York

began playing the organ with his thumbs, musical pundits of the time claimed that he was "cheating". The next time you listen to his "Fugue in D Minor" see if you can detect his cheating (Fig. 8.6).

The height of the keyboard era arrived shortly thereafter with the births of Wolfgang Mozart (1756–1791), Ludwig Beethoven (1770–1827), and Frédéric Chopin (1810–1849), to name but a few. One wonders what the child prodigy

Fig. 8.6 Portrait of Johann Bach by Elias Haussmann, Old town hall, Leipzig

Mozart would have dabbled at had there not been keyboard instruments in his time. Furthermore, one cannot but question what might have transpired had not Beethoven gone deaf, or Mozart and Chopin died so young. Geniuses such as these used the mechanical arts to bring new dimensions to our lives (Figs. 8.7, 8.8 and 8.9).

The key difference between the fortepiano and the harpsichord is that the piano keyboard uses a mechanical system (called "the action") that causes a hammer to strike the key rather than pluck it. By employing a complicated mechanical system the force, velocity, and acceleration with which the hammer strikes the string can be made to be directly proportional to the force, velocity, and acceleration that the musician applies to the associated key on the piano. The magnitude of this force is subsequently also directly proportional to the amplitude of the sound wave that is produced by the string. Using this intricate mechanical assembly, the truly accomplished pianist can strike a key with just the right touch as to produce sounds that are capable of according him/her the title of virtuoso.

There were other ingenious changes made by Cristofori, including bigger and stronger strings, a more massive and durable harp, a more resonant and flexible sound board, and a sustain pedal. The improved strings were both more durable, so that they had to be replaced less often (or were broken by the musician, as Beethoven was often seen to do), and they also produced a more pure sound, meaning that the frequency content of the wave produced by the string was very nearly the desired one. The durable harp meant that the frame did not shrink as much with time due to the compressive loads applied to it by the tensioned strings, so that the piano maintained its pitch for much longer periods of time than had been the case with harpsichords.

Fig. 8.7 Detail from portrait of Wolfgang Mozart by Johann della Croce, Mozart House, Salzburg

Fig. 8.8 Portrait of Ludwig Beethoven by Joseph Stieler, Beethoven House, Bonn

Through careful experimentation by quite a few inventors (too numerous to name!) the sound board was iteratively modified over the succeeding two centuries by changing the type of wood employed (it is normally made of spruce today), as well as the thickness of the sheet of wood. The improved sound board amplified the sound waves striking it from the strings with more purity and greater amplitude, and the lacquer coating provided just the right amount of damping of acoustic waves produced by the keyboard. Although the nature of the vibration of the sound board was not completely understood at first, the experiments by Chladni in the early eighteenth century finally explained the mechanics of the soundboard (see Chap. 9). Thus, the fortepiano was converted into an instrument that rivaled the pipe organ in the enormous sound that could be produced. And this amazing instrument required no set of massive pipes or container of compressed air to support it.

By the beginning of the nineteenth century, the fortepiano had changed significantly, and during that century it essentially evolved into the instrument that it is today. Because grand pianos were too expensive for the middle class, a host of simplified pianos were invented, including so-called spinets, box pianos, and upright pianos. By the middle of the nineteenth century, pianos were even spreading across the American prairie. In addition, the piano action underwent a long and complex series of modifications that can be described as the height of the deployment of experimental mechanics. Thus, the mechanics of string vibrations became much more reliable [73].

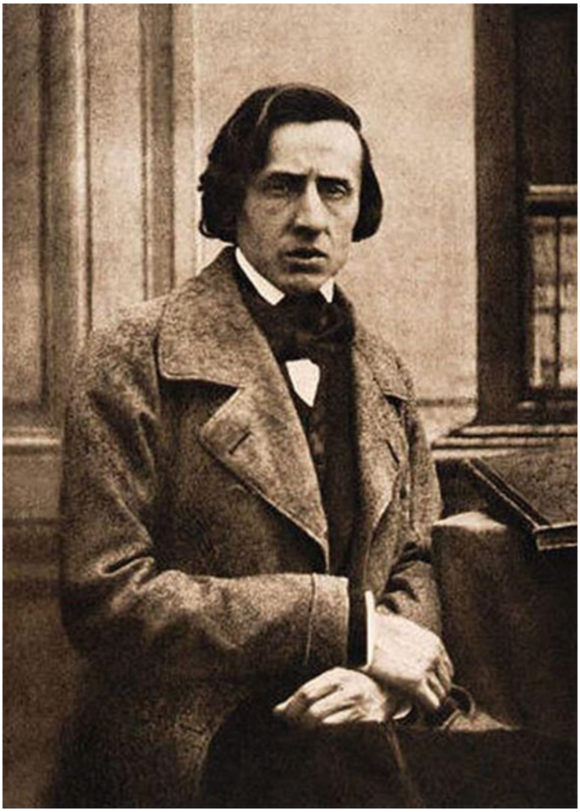


Fig. 8.9 Photograph of Frédéric Chopin

In the nineteenth century further improvements were made in the iron harp that carries the tension loads applied by the strings, so that the piano produced an even purer sound and also remained tuned for longer periods of time (the harp in a modern piano carries forty thousand pounds of force, but nevertheless holds its tune oftentimes up to a year). In addition, the peddles were tinkered with continuously right up to the twentieth century, eventually settling on the three peddle arrangement commonly employed today (at one time the peddles were actuated with the player's knees!).

By the late nineteenth century the piano had evolved into the first mass-produced large manufacturing product on Earth. A modern grand piano is indeed a masterpiece of the science of mechanics, both in its construction and in the way that sound is delivered by it to the human ear (Figs. 8.10 and 8.11).

Today a modern piano contains an action that is so exacting as to constitute half the price of the instrument (Fig. 8.12).

The evolution of the musical scale and the associated keyboard for the piano is a complicated issue involving mechanics. As described in Chap. 2, Pythagoras is the first person known to have noticed the relation between the length of strings

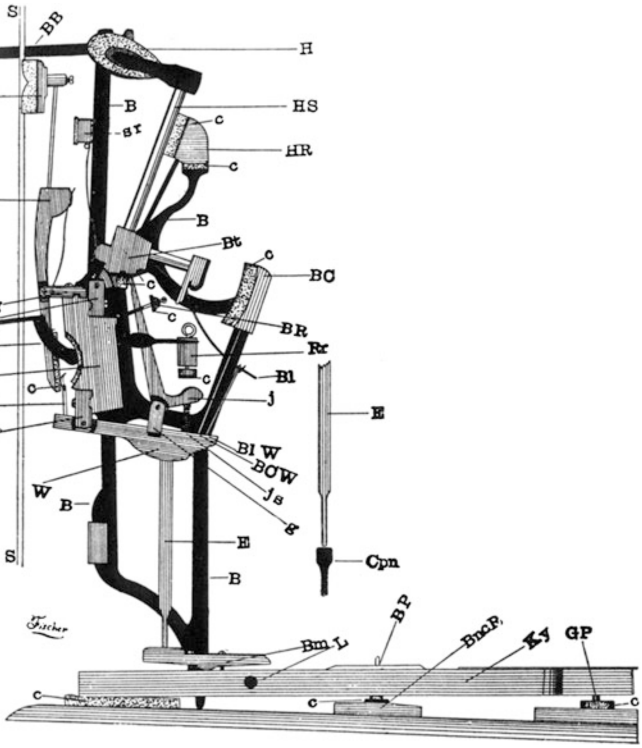


Fig. 8.10 Action from a 1907 upright piano

and harmonious sounds produced by them. Today we know that when a string of a given material, tension, and length is struck or strummed, it will vibrate at a constant frequency, which we measure in Hertz (Hz, the number of cycles per second). The vibrating string will cause acoustic waves to propagate in the surrounding air at this same frequency, and this is what our ears capture and our brains interpret as the pitch of the sound.

This problem was studied in significant scientific detail beginning in the sixteenth century, with a number of people contributing substantially to the now more-or-less universally accepted assigned frequencies for each of the strings in a piano and the accompanying musical instruments. Among those who made contributions are none other than Vincenzo Galilei (see Chap. 7), as well as Johann Sebastian Bach (see above), Zhu Zaiyu (1536–1611), and Simon Steven (1548–1620).

We term the range of frequency over which the frequency doubles an octave, because when one string vibrates at exactly twice the frequency of another, our brains interpret the two sounds as equivalent except for the doubling of the pitch. The range of frequencies in between these two notes is infinite. However, several of the frequencies in between are interpreted as harmonious by our brains, as noted by Pythagoras.

Fig. 8.11 Modern Young Chang 6’ 8” grand piano

Fig. 8.12 Pramberger grand piano action

By the middle ages it was common to split this range of frequencies within an octave into twelve steps called notes. Vincenzo Galilei seems to have been the first person to discuss the proper tempering of the twelve note scale in his book *Fronimo Dialogo* [75], published in 1584. The problem centers around the fact that it is mathematically impossible to produce a perfect progression of frequencies within an octave when the decision is made to divide the octave by twelve. Galilei proposed a means of spacing these twelve notes in such a way that it was pleasing to the ear. Today we call a twelve note scale that is properly tuned "well-tempered" due to an exhaustive study on the subject by Johann Sebastian Bach.

Today, there is a complicated formula that is agreed upon for determining the frequencies of the twelve notes in an octave, and the base note is the note A, set at 440 Hz, as shown below. This curve is called the Railsback curve, after Railsback [76], who created the modern well-tempered scale, for which the frequencies of successive notes are related by a constant ratio, thus producing the following formula for the frequency of the nth key

$$f(n) = \left(\sqrt[12]{2}\right)^{n-49} \times 440\ \text{Hz}$$

This formula produces the frequencies shown in Fig. 8.13.

The white notes on the scale are named after letters of the alphabet. This apparently evolved as a simplification of older mnemonic names given to the various notes (such as doh, reh, mee, etc.). The black notes also have names, but here it is a bit more complicated. The black note to the right of C is called either C sharp (denoted C#) or D flat (denoted Db) depending on the context that the artist is playing the note (in other words, it is complicated). The other black notes are named similarly.

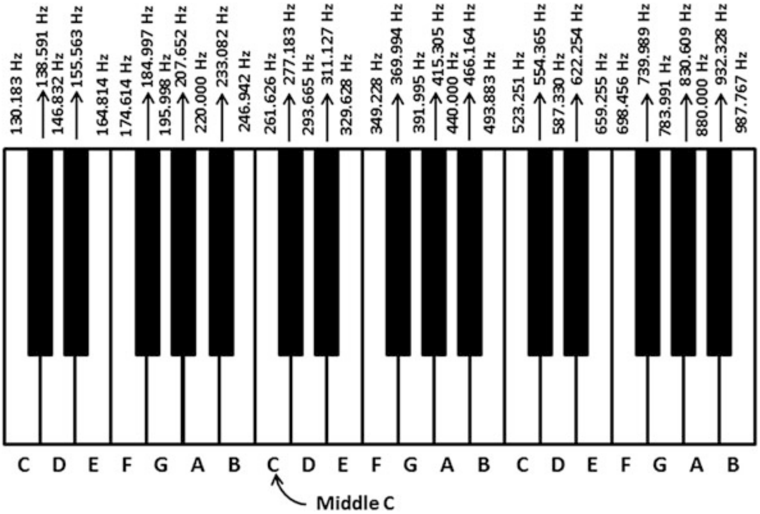


Fig. 8.13 Selected frequencies used for a well-tempered keyboard

If one starts with the note C and plays only white keys, it produces a scale of notes that is termed the key of C major. Note that when only the white keys are played, the second, fourth, seventh, ninth, and eleventh keys (the black ones) are skipped. This produces a harmonious scale called a major key, and this is the reason that the black notes are painted black. It is a simple reminder to avoid playing these keys when playing in the key of C major.

It should also be obvious that the black keys are shorter than the white keys. This is so that the average person can span an octave with either hand. Of course, these days humans are somewhat larger than when the piano was invented, so that many people can actually span more than an octave with one hand. Note that this choice is a mechanical one.

It should be apparent that one may just as well begin a major key with any note other than C on the keyboard, and assuming that the proper seven notes are played (by once again skipping the second, fourth, seventh, ninth and eleventh notes) (which includes at least one black key in all other keys), the eight notes in the scale will produce an essentially equivalent progression of notes to that produced in the key of C (unless it is what is termed a "minor" key, a story for another day). Note also that when this progression begins with any note other than C, at least one black key must be played. Thus, it can be seen that there are eleven major keys.

Now suppose that one first plays the eight notes contained in an octave by beginning with C. Next, one picks the fifth note in the scale of C major (which is G), and progresses through the corresponding eight notes beginning with this fifth note, thus, producing the scale of G. Once this is accomplished, the same procedure is repeated, beginning with the fifth note in the scale of G, which is D. This procedure can be repeated recursively through all eleven major keys, and in the process, the progression will return to the scale of C major. This process is called "the circle of fifths," as shown below, because one essentially circles through all possibilities by progressing to the succeeding scale by starting with the fifth note of the current scale. Thus, it can be seen that the mechanics of musical tones contains interesting mathematical progressions, and this is all due to nothing more than the mechanics of vibrating strings.

The interested reader may ask which major key is the preferable one, since all eleven are essentially algebraically equivalent. This is indeed a good question that does not have a simple answer. When the piano, harpsichord, or organ is played as a solo instrument, there is very little difference in the quality of sound produced by transposing from one key to another. Most people will detect no difference whatsoever. A very few people, possessed with something called "perfect pitch," will actually prefer one scale over another because there are subtle differences in the tones produced by a well-tempered instrument. Still this difference is minor.

However, when the piano is played in an ensemble with other musical instruments, the choice of key becomes all-important. This is due to the fact that many musical instruments can only play a few keys. One such instrument is the harp, which can only play in a few keys because the additional strings necessary to do so have been left out. Another obvious instrument that is key limited is the human voice. Most people are limited in the range of pitch that their voices can produce, so that they can sing a particular song in one key, but not in another (take *The Star Spangled Banner*, for instance). Thus, the fact that the choice of a particular key is mathematically equivalent can be very fortuitous to say the least (Fig. 8.14).

The invention and evolution of the piano may be said to have been a masterpiece of pure mechanics, producing what may be regarded as the most versatile of all mechanical musical instruments available today. A modern grand piano is perhaps the most complex entirely mechanical device that you will find within the home of the average consumer.

My piano has the ability to perform "mood altering" magic. This can be demonstrated by simply listening to (or better yet—playing!) *The Turkish March* by Mozart. This piece is guaranteed to turn any mood into happiness and gaiety. Conversely, try playing any one of Chopin's nocturnes, or one of his waltzes in a minor key and you will be near to tears by the ending of the piece. Thus, we see that mechanics has the ability to affect human emotions, leading one to ask the question—would these great composers have created such masterpieces that pervade our very existence had the piano never been invented? What would humankind be like if we did not have the pleasure of the music created in our world by the mechanical pipe organ, harpsichord, and piano over the past three centuries?

The Violin

Perhaps the most interesting of all virtuoso musical instruments is the violin. Although this stringed instrument dates to ancient times, the modern version used today dates to sixteenth century Italy (Fig. 8.15).

Many violins made in the seventeenth and eighteenth centuries, such as the famed Stradivari, have been studied significantly in the twentieth century. These instruments in some cases produce sounds that are so impressive that in the view of

Fig. 8.14 The circle of fifths

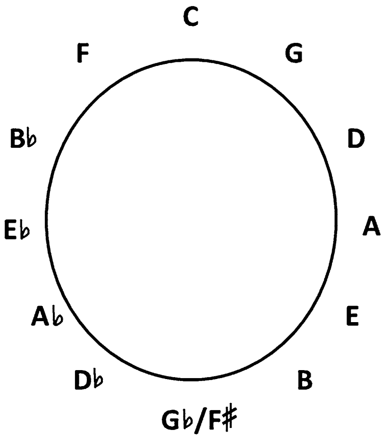


Fig. 8.15 Modern violin

many they cannot be reproduced today. No one is quite certain what means were used to produce these wonderful instruments, but we know that a great deal of the issue is related to mechanics (not to mention chemistry).

When a string is strummed with a bow (or even plucked with the finger), the string vibrates, normally in what is called its first fundamental mode, which is a technical term that means that the string vibrates in an arc with maximum amplitude at the center point of the string. As the string vibrates, its motion causes the air molecules adjacent to the string to vibrate as well, and these air molecules bump into their neighboring air molecules, thus propagating waves through the air. These waves propagate in every direction simultaneously (at the speed of sound in air), and some of these waves go through the opening to the violin’s interior, called the sound box, and they bounce into the back side of the violin.

The back side of the sound box is made of a very thin and flexible piece of wood, so that even waves with the smallest of amplitudes will cause the wood to also vibrate. The wood is mechanically excited by the incident wave to vibrate at the same frequency as the wave, which was itself induced by the violin string.

The vibrating box now sends out its own waves in every direction, but these waves have a much greater amplitude than did the waves generated by the string. That means that the molecules that produce the waves are bouncing really hard against their neighbors, so that the wave propagates much farther, and when it comes to the listener's ear, it still contains quite a lot of energy, so that the listener can enjoy the beautiful sound produced by the string from a much larger distance than had the box not been included.

The box also has the ability to make the sound more robust and pleasing to the ear, and this part is dependent on the material makeup, shape and resilience of the sound box. Through careful experimentation, the designers gradually developed a slightly rounded shape of the box that produced the purest of sounds. Further experimentation produced lacquer coatings that provided just the right amount of damping, so as to provide the most delicate of sounds. Much of the mechanical nature of the sound box was to be explained by the experiments of Chladni in the early eighteenth century (see Chap. 9). This is why each and every violin is unique (Fig. 8.16).

The violin is included herein as a representative of the virtuoso musical instruments (and arguably the most impressive one at that). The fact is, the harpsichord and the piano were and still are costly instruments that are for this reason inaccessible to the majority of those embarking on the quest to master a musical instrument. Thus, virtuoso instruments allowed for music to enter the average household at a fraction of the cost of the polyphonic harpsichords and pianos (except for Stradivari!). With the inventions of these fabulous mechanical instruments, music thus became ubiquitous in the home.

In addition, for those who mastered the virtuoso instruments, there was a relentless desire to "bond" with others possessing such talents, thereby creating the drive toward the development of duets, trios, quartets, and so on, culminating in the orchestra and symphony. Thus, the virtuoso instruments play an equally important role to the harpsichord and piano in the evolution of modern music.

We have seen in this section how mechanics played a pivotal role in the evolution of music. As the quality of musical instruments improved, the impetus flourished to utilize this newfound ability to produce ever more ethereal and exciting music. In Chap. 9 we will see how the reverse occurred—how art drove mechanics.

There is also another purely mechanical reason that musical instruments are important. The evolution of musical instruments can be said to have influenced the industrial age in the nineteenth century, as concepts deployed in musical

Fig. 8.16 Five stradivari violins

Fig. 8.17 Photograph of a Jacquard loom

instruments made their way into all sorts of technologies. For example, textile weaving machines such as the Jacquard loom, invented in 1801 by Joseph Jacquard, borrowed heavily from the piano in their design (Fig. 8.17).

Measuring Things

The British and the French have been fighting off and on for a long time. Nobody knows exactly when it all started, because they were fighting even before there was a sense of national pride. What everyone does know is that they got in a terrible row over the English crown when Edward the Confessor (c. 1003–1066) passed away in early 1066. The English Witenagemot selected Harold to succeed Edward despite the fact that William of Normandy seemed to hold the birthright of succession.

This enraged William, who subsequently put together an armada and sailed across the English Channel, making landfall at Hastings. In the ensuing battle William and his force dispatched Harold and his army after a day-long pitched

Fig. 8.18 Hunting scene from the eleventh century Bayeux tapestry

battle, and William thereby became the King of England [77]. This unfortunate event is of course portrayed (quite controversially) in the Bayeux tapestry, which was made using mechanics, but the tapestry itself is quite a story for another day [78] (Fig. 8.18).

The point is this: The Battle of Hastings caused unfortunate repercussions that some say have lasted right down to this very day, for the simple reason that it muddled the right of succession in both France and England whenever a king or queen died. These two neighbors, separated by a small body of water, have behaved at times like severe enemies, such as during the Hundred Years War (1337–1453) and the Napoleonic Wars (1803–1815). On other occasions they have behaved more like kissing cousins, such as during World War I (1914–1918) and World War II (1939–1945). Let's hope that they stick to their more recent pattern of relations.

So the English and the French have had plenty to bicker about for quite a long time. This intense rivalry seems to have spilled over into the scientific community at times, although the conflict seems to have stemmed more from public perception than from the scientists themselves. Nonetheless, there are numerous instances of "competitions" that seem to have sprung up from time to time between these two antagonists.

Among the enduring differences between the two nations was the race to be the founders of fundamental measures of time and distance. Inevitably, one nation won time (The English), and the other won distance (The French), but the tales of how they did so are quite interesting and convoluted.

Time

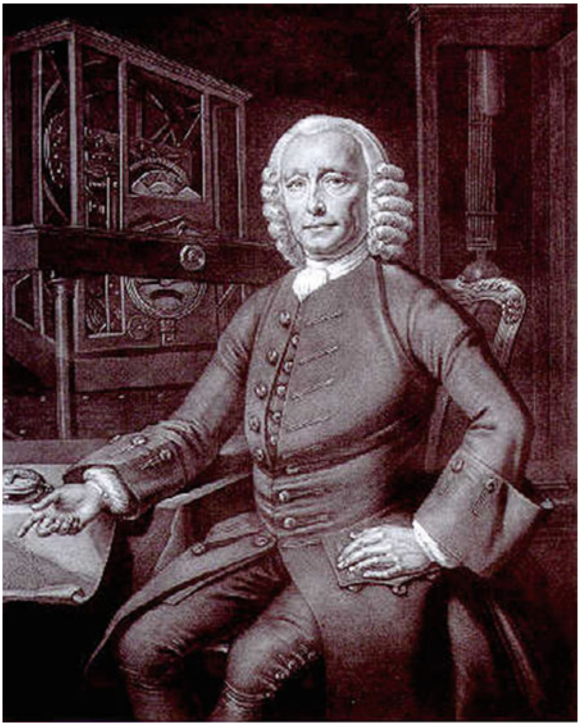
The contest over time came to a head in the early eighteenth century. In 1707 a British fleet was destroyed, along with 1,400 sailors, off the Isles of Scilly because it was not possible to measure longitude accurately at the time. Thus, a prize was set by the English monarchy to be awarded to the first person who could measure longitude accurately. There were many entrants, and a wide range of solution methods were proposed, all involving mechanics.

The prize was eventually claimed by John Harrison (in 1767), who invented the ship's chronometer, a clock that is capable of measuring time accurately on a ship at sea. Most competitors for the prize were attempting at the time to follow the general idea that Galileo had suggested a 100 years earlier—to use celestial measurements from different places on Earth and rely on parallax to determine longitude. While this approach was technically plausible, the measuring devices of that time were too inaccurate to make this approach feasible [79] (Fig. 8.19).

Harrison took a different approach. He figured to use a clock that kept London time no matter where you were on Earth. Thus, if you were in the South Pacific, and you measured high noon where you were by observing the highest point of the Sun in the sky, you knew what time it was where you were. Then all you had to do was look at your London clock, and from the difference in local and London time you could tell how far around the Earth you were from London (or actually Greenwich to be exact, site of the Royal Observatory in a suburb of London) because there are 360° in a circle and 24 hours in a day, or 15° of latitude per hour from Greenwich.

There was only one problem with this approach: all clocks at that time used Galileo's principle of the pendulum (perfected shortly thereafter by Christian Huygens). And as we all know, pendulums are not accurate on a ship that is pitching to and fro in the waves. This then is a problem in mechanics, specifically, rigid body dynamics (see Chap. 7) (Fig. 8.20).

Fig. 8.19 Portrait of John Harrison



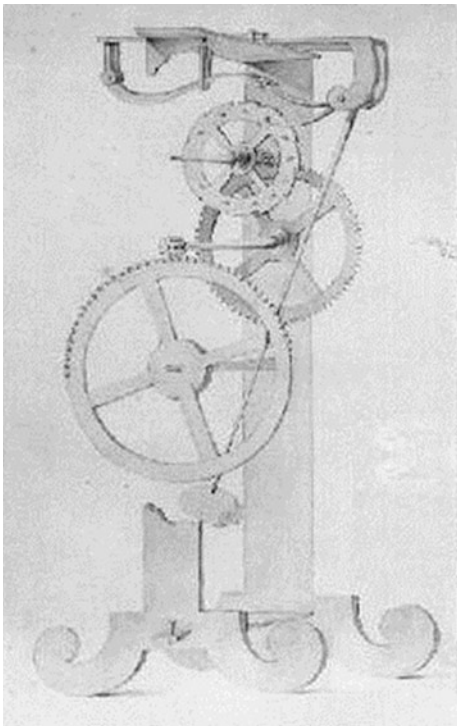


Fig. 8.20 Pendulum clock drawn by Galileo

John Harrison spent a lifetime studying this problem, and eventually he discovered how to make a clock that would keep time accurately on a ship. Harrison's four clocks, developed over a 31 year span, are still displayed today at the Royal Observatory in Greenwich, and it is for this reason that the English are credited with establishing time, and the Prime (zero degree) Meridian is universally accepted to be at the Greenwich Observatory (there is even a painted stripe on the pavement denoting the prime meridian!). A duplicate of Harrison's last version was carried on the Endeavor during Captain Cook's first journey around the world, the voyage to measure the distance to the Sun, as described in Chap. 6 (Fig. 8.21).

John Harrison understood that the rate of change of momentum (see Newton's Second Law in Chap. 7) is the culprit in a rocking ship. Wherever a pendulum is deployed in a mechanism, when the ship is in motion at non-constant velocity, as it almost always is, the motion of the ship will cause the pendulum to pitch wildly back and forth at varying amplitudes. Harrison devised a simple means of cancelling out the effect of such motions by constructing two pendulums of equal mass moving in opposite directions, thus cancelling out the momentum produced by the two. These counter-rotating pendulums are clearly recognizable in Harrison's first three clocks. To complete his ingenious design, he deployed frictionless bearings [79].

Fig. 8.21 Photos of John Harrison’s chronometers, numbers one through four clockwise from *top left*

The effects of Harrison’s invention are staggering to say the least. For the first time in history, both time and longitude could be measured accurately no matter what the circumstances. And although we have today replaced the chronometer as the standard measuring device with the motions of the cesium atom, the concept remains the same—measuring motion.

Perhaps fittingly, as a result of John Harrison’s invention, the British gained the honor of placing the Prime Meridian (zero degrees longitude) at the Royal Observatory at Greenwich, a location that is universally accepted by humankind today.

Fig. 8.22 Photo of platinum bar representing the meter in the Musée des Artes et Metiers, Paris

Distance

The French were not particularly enamored with this achievement by the English. They therefore set out to gain the upper hand in the race to quantify distance. Up to that point in time no one could agree on what a standard measure of length should be. In the Middle Ages, it was at one time set as the distance from the King's nose to his fingertip. Imagine what happened when the King died in the middle of a construction project.

Thus, the world was desperately in need of a universally accepted measure of distance. This was accomplished a quarter of a century after Harrison's invention of the chronometer by two French surveyors, Monsieurs Jean Baptiste Joseph Delambre (1749–1822) and Pierre Méchain (1744–1804).

During the French Revolution Delambre and Méchain were commissioned by the French Academy of Sciences to survey from Barcelona to the Pas de Calais so that the distance from the North Pole to the equator could be accurately determined [80]. The meter was subsequently defined to be one ten-millionth of that distance, and a platinum bar was constructed as a reference, as shown in the Fig. 8.22.

Today, the meter is accepted almost everywhere on Earth as the standard unit of distance. Accordingly, a unit of mass, called a gram, as it was originally conceived was defined to be the mass of one cubic centimeter of water at 0 °C This has now been altered (without destroying the original spirit of the definition) to the mass of a physical prototype preserved by the International Bureau of Weights and Measures.

And now that (most of) the world agrees on units of measure, studies involving mechanics are much easier to agree upon. But the world still manages to makes mistakes. On September 30, 1999 NASA lost a $125 M orbiter because Lockheed-Martin engineers used the English system of measurement, whereas the NASA team used the metric system of measurement.

9

Continuum Mechanics, Art and Structures

Men pass away, but their deeds abide.
Augustin Cauchy (1789–1858)

Continuum Mechanics

As described in Chap. 8, the French and the English were at odds over anything and everything for a very long time. At various periods over this same span of time, the two combative nations allowed their discord to even spill over into the realm of science. Indeed, from about 1650 to 1850, numerous contests between these two antagonists resulted in many of the premier developments in science and technology on Earth.

For example, for quite a long time the French believed the theories of Jacques Cassini (1677–1756) to be superior to those of Isaac Newton. The feud over each nation's scientific champion came to a head in 1735, when the French sent out an expedition to Ecuador to survey a sufficient arc of the equator for the purpose of proving that Cassini had been correct when he had asserted that the Earth has a larger polar circumference (a prolate spheroid) than equatorially. Alternatively, Newton had argued that the Earth is larger at the equator (an oblate spheroid). Isaac Newton turned out to be correct. The Earth bulges at the equator due both to angular momentum caused by its spin and gravitational forces from the Sun and the Moon. This also causes the Earth's precession, and this is all due to the mechanics of deformable bodies.

There is an interesting story related to the expedition to Ecuador, on the northwest coast of South America. While there, one of the French crewmen named Jean Godin married a local woman named Isabela de Grandmaison y Bruno who was of Portuguese descent. The two were separated at the end of the expedition and Jean promised to meet up with his wife later in French Guiana, on the northeast coast of South America. After several years, Isabela eventually tired of waiting and decided to join him in French Guiana. She and her brothers, along with several others set out to cross the continent of South America by traveling over the Western Mountain range and then by boat down the Amazon River. This turned out to be a very bad idea. Everyone in the expedition disappeared, never to be heard from again. That is, except for Isabela, who stumbled out of the jungle six weeks later, barely alive. This true event was to be the backdrop for many tales of

D. H. Allen, *How Mechanics Shaped the Modern World*,
DOI: 10.1007/978-3-319-01701-3_9,

monsters in the Amazon for the better part of the next two centuries. At any rate, Isabela survived and was reunited with her husband, whereupon the two retired to central France and spent the remainder of their lives together [81].

The British claim today to have won the scientific battle with the French, and indeed, this claim has merit. However, from one who is neither British nor French but admires both equally, I can say that my personal opinion is that this squabble is neither here nor there. The fact is, there are plenty of bragging rights to go around. Indeed, the historical record will show that the Italians, the Germans, the French, the British, the Poles, the Russians, and even the Scandinavians all made great contributions to the field of modern science prior to the twentieth century (although sadly, not the Americans, at least not prior to the twentieth century).

Still, the British could be said to have eked out a victory if one is keeping score. After all, they produced the following universal laws: gravity (Newton); momentum (again Newton); natural selection (Darwin); and electromagnetism (Maxwell). The other universal laws are: mass (either Euler-Russia/Switzerland or Lavoisier-France); energy (Rumford, Leibniz, Carnot, Lord Kelvin, or perhaps Clausius, depending on the version you choose, not possible to choose clearly); and energy–mass equivalence (Einstein-Germany/America). So the British get the blue ribbon in that contest (score: Great Britain 4, Germany 1, France (or Russia) 1), but if you split off Scotland from England, then it becomes much closer, as Maxwell was a Scot, and my experience with Scots is that they usually prefer to be split off from the English. On the other hand, Englishman Oliver Heaviside (1850–9125) reformulated Maxwell's model into the four equations that we utilize today, thus changing the score once again. Remove Darwin's Law, because we really have no way of knowing whether it actually applies everywhere throughout the universe, and it becomes very close to a dead heat. But the truth is, I prefer not to keep score when dealing with issues involving science.

As for units of measure (as discussed in Chap. 8), the British won time, and the French won distance, so that's also a dead heat unless you start including everything else, and that could go on and on. For example, the French clearly won food and drink…of course in this case I'm only comparing to the British, who are capable of losing this battle to any number of competitors.

But there is one scientific area where I think that the French clearly exceeded the Brits. That is in the area of continuum mechanics. From my viewpoint, it appears that the British were more adept at physics, especially experimental physics, and the French were more adept at mathematics. I say this with all due respect to Isaac Newton, the coinventor of calculus (with Leibniz, along with a footnote to Archimedes, as detailed in Chap. 2), but the fact is that the mathematics contained in Newton's *Principia* is not very mathematically rigorous or satisfying. Much of what he introduced in mathematics has had to be expanded and proven more rigorously by others, and quite a few of those were French, especially Augustin Cauchy (see below) [82]. The development of continuum mechanics is one of those areas where the French shone brightly.

By the end of the eighteenth century the world was in an enormous state of transition. In England, the industrial revolution was well underway. And in France, the Cultural Revolution was at an end. France had created the first successful democracy in modern Europe, and the consequences were profound, as the door was opened for science to succeed on a scale never seen before. Although the following discourse may seem tangential to this book, please bear with me and you will eventually see the connection.

It was at this point in time that Napoleon Bonaparte (1769–1821) took center stage in the study of mechanics. He had already convinced the French government to support his ambitious attempt to conquer Egypt in 1798 (see Chap. 1), and while this resulted in his first military failure, there were important positive scientific outcomes from his Egyptian campaign. He had fortuitously taken 167 *savants* (scientists) with him, along with 50,000 soldiers. Nearly all, including the scientists, had remained behind in Egypt until 1801, long after he had realized the folly of his excess and returned to France in the fall of 1799 [83] (Fig. 9.1).

Thus, imminent scientists such as Claude-Louis Berthollet (1748–1822) and Jean-Joseph Fourier (1768–1830) remained in Egypt for nearly 3 years. But it was Dominique Vivant, Baron de Denon (1747–1825) in particular who opened the eyes of the western world to the wonders of Egypt, a country that had heretofore been largely inaccessible to westerners.

Interestingly, during the campaign a French soldier named Pierre-François-Xavier Bouchard discovered a large granite stone in the coastal town of Rosetta in July 1799. This stone had a message carved into it in three different languages: Greek, Coptic, and Egyptian hieroglyphics. The stone, now called the Rosetta Stone, has become the subject of much historical discussion.

It eventually fell into the hands of the British (after intricate negotiations with the French) when the French vacated Egypt in 1801 (because the British forced them to), thus the Rosetta Stone is today in the British Museum in London. But the French got even with the British for the loss of the stone when Jean-François Champollion (1790–1832) (with a footnote to Thomas Young (1773–1829) [84]) deciphered the Rosetta Stone in 1822 and unlocked the mysterious Egyptian hieroglyphic language. This achievement, perhaps more than any other single feat, made ancient Egypt (and surreptitiously, Egyptian mechanics) accessible to the modern world today (Figs. 9.2, 9.3 and 9.4).

One of Napoleon's *savants*, the imminent scientist Jean-Joseph Fourier somehow came to understand the physics of heat while suffering through the hottest 3 years of his life during Napoleon's Egyptian campaign. You may ask—what does heat have to do with mechanics? My simplistic answer goes like this. At the molecular scale there is no such thing as heat. There is only motion, or equivalently, kinetic energy. But when we stand back far enough from a collection of molecules, we do not see their motions because they are indeed quite small relative to the scale of humans. Instead, we only feel the collective effect of their motions pounding on the surface of our bodies, and our senses interpret this pounding as heat because our own molecules get excited by this pounding, and our nerves interpret that excitation as heat.

Fig. 9.1 Portrait of Napoleon Bonaparte by Jacques-Louis David

Molecules may be supplied with additional energy by any one of a number of means, such as by moving them further from the center of mass of the Earth (called potential energy), radiating them (with solar energy, for example), or by chemical reactions. One simple way is to put them in contact with other molecules that are vibrating a lot more than they are. These vibrating molecules will cause their neighbors to vibrate more, thus increasing their kinetic energy. Thinking of a high school dance where some of the students start dancing really fast, thereby exciting the other students to do the same. That's heat!

Anyway, all of this excitation causes the molecules to vibrate like crazy, and when they come in contact with a human (such as your skin!), the molecules in the part of the human that is in contact with them also get excited and vibrate like crazy as well. Your sensory perception system will interpret that as a rise in temperature of that portion of your body. And if the vibrations possess enough

Fig. 9.2 The Rosetta Stone, British Museum, London

Fig. 9.3 Portrait of Jean-François Champollion by Léon Cogniet

Fig. 9.4 Portrait of Thomas Young

kinetic energy, it will actually (chemically) damage your body, which we call being burned. But in reality, all that is going on at the molecular scale is that a bunch of molecules are jostling around excitedly, which is nothing more than mechanics. Joseph Fourier somehow figured all of this out, and his theory of heat played a bit part in the developing theory of continuum mechanics in the early part of the nineteenth century (Fig. 9.5).

Now it so happens that two very interesting things were going on concomitantly in France just after the turn of the century. First, there were the nearly constant military campaigns of Napoleon, and these went on until 1815. Second, the recently formed French society of *liberté, egalité, fraternité,* was imbuing within the French people a new-found attitude of constructive and collective nationalism. And as we all now know, the French and the English were constantly competing with one another.

Here is a simplified version of events of that time as they relate to mechanics. Napoleon was quite interested in science and technology, and for obvious reasons. He saw technology as profoundly important to the success of his military campaigns. After all, he had read Julius Caesar's *The Gallic Wars* [85], and he knew that Caesar had conquered the Celts in France nearly two millennia earlier by using superior technology, as described in Chap. 12.

Fig. 9.5 Portrait of Joseph Fourier

So Napoleon used his authority as Emperor to push the French scientific community to solve his military problems for him. He even went so far as to be elected President of the French Academy of Science in 1801, France's answer to the British Royal Society.

Now, the most famous scientist in France at the turn of the century was Pierre-Simon Laplace (1751–1827), who was mentioned in Chap. 8. He is responsible for all sorts of scientific accomplishments, but perhaps his greatest legacy is his extraordinary ability to provide mathematically rigorous bases for many physically observed phenomena, especially those related to astrophysics [86].

In 1808 Laplace invited the German physicist and musician Ernst Chladni (1756–1827) to demonstrate a series of experiments on plates before the Paris Academy of Sciences. With great precision, Chladni strummed with a violin bow on glass plates covered with sand particles. In so doing, he demonstrated scientifically that the lines that formed on the surfaces of the plates due to the sand particles (now termed node lines) were repeatable but distinct for differing boundary conditions applied to the edges of the plates [87] (Figs. 9.6 and 9.7).

The Emperor Napoleon attended these demonstrations, and he was quite impressed with Chladni's experiments. The rumor was that Napoleon needed to know why his cannons kept blowing up and killing his own soldiers in battle, and apparently Laplace assured him that the solution to Chladni's plate problem would

Fig. 9.6 Portrait of Ernst Chladni

Fig. 9.7 Photograph of the Chladni plate experiment

pave the way for the solution to the cannon problem. Incidentally, this prediction turned out to be correct.

Napoleon was so impressed with Chladni's vibrating plate experiments that in 1809 he announced a prize of 20,000 French francs to the first person who could develop a model capable of predicting the experimental results obtained by

Chladni. The competition was to last 3 years. Unfortunately, at the entry deadline only a single entry had been submitted. That entry was written by a woman—Sophie Germain (1776–1831). The revelation that no man had submitted an entry was made even more profound by the fact that women were not allowed to study in higher education in France at that time.

Unfortunately, Ms. Germain's solution was erroneous, but the awards committee recommended that she continues her work on the subject. Under the tutelage of committee member Joseph-Louis Lagrange (1736–1813) (see Chap. 7), who died before the problem was completely solved, Ms. Germain was eventually awarded the prize in 1816, thus becoming the first woman to win a prize from the Paris Academy of Sciences [87] (Fig. 9.8).

Although her assumptions were flawed, her solution for the plate problem was the first (essentially correct) multidimensional continuum mechanics model ever reported for deformable bodies, and it paved the way for a flurry of profound developments over the succeeding decade. First, working independently, Siméon-Denis Poisson (1781–1840) and Claude-Louis Navier (1785–1836) developed the modern three-dimensional theory of fluids in 1821. Shortly thereafter (in the same year), Joseph Fourier (1768–1830) developed the modern theory of heat, as detailed above. Finally, Navier and Augustin Cauchy (1789–1857), independently developed the theory of elastic solids in 1821–1822, later elucidated further by Gabriel Lamé (1795–1870) (Figs. 9.9 and 9.10).

Fig. 9.8 Photo of the statue of Sophie Germain on the Rue Sophie Germain, Paris

Fig. 9.9 Portrait of Siméon-Denis Poisson

Fig. 9.10 Photo of a statue of Claude-Louis Navier

While several of these developments were initiated from a molecular base, they all eventually adopted a simpler framework utilized by Sophie Germain (as suggested by Joseph-Louis Lagrange) and perfected by Augustin Cauchy. This assumption maintains that the body of interest may be approximated to be everywhere continuous, a simplification that is today called “continuum mechanics”.

As we all know, Newton and Leibniz had previously cofounded calculus in the late seventeenth century, introducing the concept of a derivative. Furthermore, they had utilized this mathematical invention within equations containing these derivatives (such as Newton’s Second Law; see Chap. 7), and these equations came to be termed differential equations. But Newton and Leibniz concerned themselves primarily with derivatives in time, that is, the rate of change of a quantity with respect to time. An example is velocity, which is the rate of change of the location of an object with time.

But in the early part of the eighteenth century, scientists such as the Bernoulli family and Leonhard Euler had begun to utilize the calculus to construct derivatives with respect to spatial coordinates rather than time, such as that deployed in the Euler-Bernoulli theory of beams (see Chap. 7). Thus, the stage had already been set for the birth of continuum mechanics.

When the body is assumed to be continuous it is possible to employ the differential calculus cofounded by Newton and Leibniz to show using Newton’s Second Law that a set of partial differential equations (meaning in both space and time) must be satisfied at every point in a body in order for momentum to be conserved. One can also use an alternate but equivalent approach called variational methods to reach essentially the same conclusion, such as that employed by Lagrange and Germain. This approach, as well as the careful development of the modern interpretation of calculus (including the fundamental theorem of calculus) by Cauchy [88], laid the groundwork for the modern continuum mechanics theories of deformable bodies.

By 1822 the mechanics of solids and fluids (as well as the transfer of heat), had been reduced to mathematical problems in which a set of differential equations (including Newton’s laws) could be utilized to predict the motions, the state of loading, and the temperature as functions of time and spatial coordinates in an object of arbitrary shape. This was a truly monumental step forward for not only mechanics, but indeed for all of science (Fig. 9.11).

In the midst of these developments, Baron Cauchy introduced a definition for mechanical stress that has stood the test of time [89], becoming the single most important concept required for the purpose of predicting failure of solids due to yielding and/or fracture. Expanding on the previous work of Galileo and Pascal (see Chap. 7), he provided mathematical to the concept of load intensity (termed stress) within an object. His theorems (called Cauchy’s Formula and Cauchy’s Lemma) proved that there are nine unique components of the stress at any point in a continuous body, and that these nine components are both necessary and sufficient to determine the state of loading at any point in any continuous body. Today we call this the stress *tensor* because the mathematical properties of stress are such that a second order set of trigonometric functions is required to transform the

Fig. 9.11 Photograph of Augustin Cauchy

components of stress from one coordinate system to another that is rotated with respect to the former.

Thus, it can be seen that while no single person can claim credit for the modern theory of the mechanics of deformable bodies per se, there is credit enough to go around for Lagrange, Germain, Poisson, Fourier, Navier, Cauchy, and Lamé. Further credit must be accorded to those who are remembered for their contributions to the development of material properties: Hooke, Young, and Poisson, as well as the pioneers: Galileo, Newton, Pascal, the Bernoulli family, and Euler.

By 1822 the problem of predicting the mechanical response of a deformable body, whether fluid or solid, had been reduced to an exercise in applied mathematics. Unfortunately, accurate mathematical solutions for problems of this type were a hurdle that was not surmounted for more than a century. Early attempts at solutions focused on objects of specific and simplified shape, as pioneered by Jean Claude Barré de St. Venant (1797–1886). There grew a field of applied mechanics called “elasticity theory”, and this field flowered until well into the latter half of the twentieth century.

The components of Cauchy’s stress tensor transform from one rectilinear coordinate system to another (rotated one) in a complicated way, called a second-order tensor transformation. Carl Culmann (1821–1881) published a book in 1865

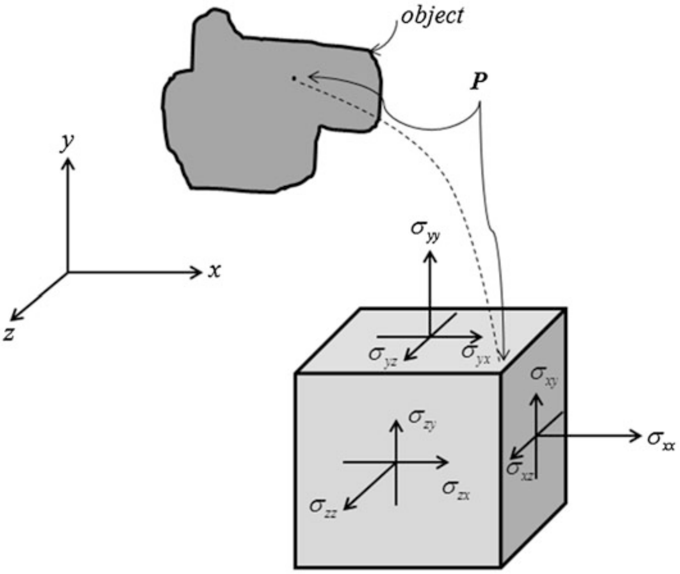


Fig. 9.12 Depiction of Cauchy's definition of stress at a point

entitled *Die Graphische Statik* [90] in which he introduced a graphical technique for transforming the stress state at a given point in an object from one coordinate system to another (under the special circumstance of generalized plane stress, the case wherein $\sigma_{xz} = \sigma_{zx} = \sigma_{yz} = \sigma_{zy} = 0$, as described in Fig. 9.12). Today this method is termed "Mohr's circle" because Otto Mohr (1835–1918) used it to great extent and showed how practical this technique was for predicting structural failure (Figs. 9.13 and 9.14).

An early example (in 1867) of the physical power of this method is demonstrated below [90–93]. The figure shows the *predicted* lines of principal stresses (the stress components on planes where there is no shearing stress) [94] in a crane analyzed by Culmann on the left. On the right is a depiction by Wolff of the *experimentally* observed trabecular alignment in the proximal femur of a human. This impressive demonstration of the importance of principal stresses (one of which is always the maximum normal stress component) is said to have occurred by coincidence when Professor Culmann visited the dissecting room of his colleague Hermann Meyer in Zurich. Upon seeing a section of bone, Culmann is said to have cried out, "That's my crane!" [93]. Thus, there was for the first time experimental verification that stress is the fundamental mechanism whereby mechanical loading is carried within an object (Fig. 9.15).

Although continuum mechanics did not reach fruition until the twentieth century, it gathered momentum over the latter part of the nineteenth century, so that by the beginning of the twentieth century, the time was right for the wholesale

Fig. 9.13 Photograph of Carl Culmann

development of a new wave of *mechanical* devices that were profoundly superior to anything that had heretofore been seen or envisioned on this planet.

The ability to predict the mechanics of structural failure reached maturity in the twentieth century, and while we still do not always understand it completely, we are doing an amazingly good job of avoiding structural failure across our planet, as we will see later in this chapter, as well as in Chaps. 12 and 13.

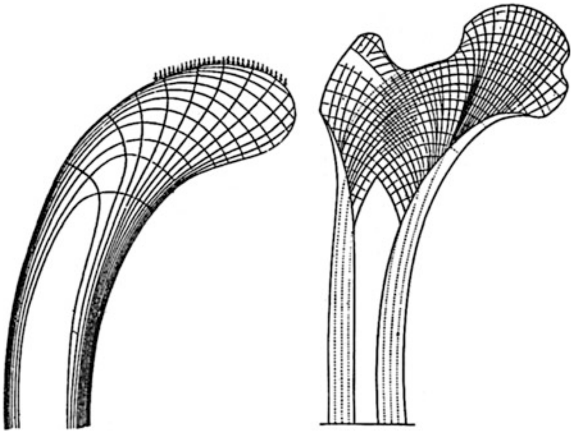
Over the course of the succeeding two centuries, it became clear that although nothing in the universe is actually continuous (being composed of discrete molecules, atoms, and even smaller particles), the assumption that a body can be treated as a continuum turns out to be sufficiently accurate for plenty of practical purposes.

Although the continuum mechanics models developed by the above pioneers were at first exceedingly complicated to solve for all but the simplest of cases, persistence by a great many scientists and engineers eventually proved this approach to be capable of predicting such phenomena as:

- Loads applied by fluids to a solid object such as an airfoil by gases or liquids passing over it
- Failure due to fracture of many solids due to mechanical loading
- The temperature at any point in an object due to heating, and mechanical failure of the object due to this heating
- The time that it takes for a tsunami to progress from the site of an earthquake to a coastline thousands of miles away

Fig. 9.14 Portrait of Christian Otto Mohr

Fig. 9.15 Lines of principal planes (*left*) in a curved crane compared to the trabecular alignment in a human proximal femur (*right*) [90–93]



- Plate tectonics on Earth
- Weather, including that on other planets
- The forming of mechanical parts due to solidification
- The construction of essentially all major structures on Earth
- The basis for all biomechanics in humans.

Lest the above predictive ability be underestimated by the reader, it should be pointed out that we would have virtually none of our modern technology today without the development of continuum mechanics.

I for one believe that for these profound revelations Baron Cauchy and his colleagues belong in the crypt of the French National Panthéon along with Lagrange, Marie Curie (1867–1934), and Pierre Curie (1859–1906) (who were both recently moved to the Panthéon from the selfsame Cemetière de Sceaux that Augustin Cauchy still rests within). In fact, I call upon the government of France to accord Baron Cauchy his proper historical resting place (Fig. 9.16).

Impressionist Art

Once again art enters into a book on mechanics. You may ask why such a preposterous thing has occurred, and also why so often herein. I offer the following—supposedly Albert Einstein was once asked if the Impressionist period of art had affected him. It is rumored that his answer was an emphatic denial. But to tell you the truth, if this story is true, I am not certain that Einstein was correct in his assessment. Is it possible that the Impressionist period opened the eyes of the populace in the late nineteenth century, encouraging the masses to "think outside the box"…perhaps even leading a young boy in Germany to wonder what it would be like to ride on a beam of light?

I read an interesting book a few years back entitled *Parallel Visions in Art and Science*, by Leonard Shlain [95]. Dr. Shlain (a medical doctor) explained in his book that his son once queried him as to why Édouard Manet's (1832–1883) painting *Le Dejeuner sur L'herbe* was regarded as so important to the Impressionist movement. He says that he had no answer for his son, and this sent him on a lengthy quest to uncover the answer to this question. By the time he was finished, he had the makings of his fabulous book mentioned above (Fig. 9.17).

Of course, the reasons why Manet's paintings, including *Le Dejeuner sur L'herbe*, are so important are complex. However, the public was completely taken with this new attitude to painting. There was a loss of perspective, as well as a defusing of realism, that seemed to both contradict and expand upon the recently invented field of photography, as depicted in Manet's *Olympia* (Figs. 9.18 and 9.19).

Within a short period of time other artists such as Claude Monet (1840–1926), Edgar Degas (1834–1917), and Pierre-Auguste Renoir (1841–1919) would create a revolution that would transcend art in the latter part of the nineteenth century (Figs. 9.20, 9.21, 9.22, 9.23 and 9.24).

Name	Life Span	Contribution to Mechanics
Henry Cavendish	1731-1810	weighed the Earth
Charles-Augustin de Coulomb	1736-1806	Coulomb friction
Gaspard Monge	1746-1818	father of differential geometry
Adrien-Marie Legendre	1752-1833	applied mathematics
Carl Friedrich Gauss	1777-1855	astronomy, geophysics, mathematics
Jean-Victor Poncelet	1788-1867	applied mechanics
Charles Babbage	1791-1871	father of the programmable computer
Nicolas L. Sadi Carnot	1796-1832	second law of thermodynamics
Jean_M. C. Duhamel	1797-1872	Duhamel’s principle, applied mechanics
Franz Ernst Neumann	1798-1895	crystallography, mineralogy
Benoit P. Émile Clapeyron	1799-1864	reversible processes, 2nd law of thermodynamics
Mikhail V. Ostrogradsky	1801-62	calculus of variations
George Biddell Airy	1801-92	astronomy, elasticity
William Rowan Hamilton	1805-65	Hamiltonian mechanics
Hermann von Helmholtz	1821-1894	physiology, thermodynamics
Gustav Robert Kirchhoff	1824-87	mechanics of plates, electromagnetics
William Thomson, Lord Kelvin	1824-1907	thermodynamics, Kelvin temperature scale
Elwin Bruno Christoffel	1829-1900	invariant theory, shock waves
Johann Bauschinger	1834-93	Bauschinger effect in materials science
Ernst Waldfried Mach	1838-1916	fluid mechanics
Josiah Willard Gibbs	1839-1903	statistical mechanics
John William Strutt, Lord Rayleigh	1842-1919	discovered argon, discovered Rayleigh scattering
Joseph V. Boussinesq	1842-1929	theoretical applied mechanics
Ludwig Eduard Boltzmann	1844-1906	statistical mechanics, kinetic theory of gases
Carlo Alberto Castigliano	1847-84	Castigliano’s method
Woldemar Voigt	1850-1919	Voigt model, Voigt notation
Jules Henri Poincaré	1854-1912	chaos theory, celestial mechanics
August Otto Föppl	1854-1924	large deflection plate theory
Pierre M. Marie Duhem	1861-1916	hydrodynamics, elasticity, thermodynamics
Augustus Edward H. Love	1863-1940	theory of elasticity

Fig. 9.16 Contributors to mechanics in the nineteenth century

I will not go into further details regarding the Impressionist period, partly because it really was about art rather than mechanics, but also because Ross King has written another fabulous book on this period appropriately entitled *The Judgment of Paris* [96]. And if you ever find yourself in Paris with a free afternoon, there is no place better to spend it than at the Musée D’Orsay, site of the greatest collection of Impressionist art on Earth.

By the 1890s the paintings of the recently deceased Vincent Van Gogh (1853–1890) would turn the world of art completely upside down, preparing all of humanity for the century to come. And there is a footnote to the sad fate of Van Gogh. As you doubtless know, he cut off his own ear. Based on symptoms described in letters to his brother, Medical experts today believe that he did so because he had an illness within his inner ear associated with balance, a problem in mechanics (Figs. 9.25 and 9.26).

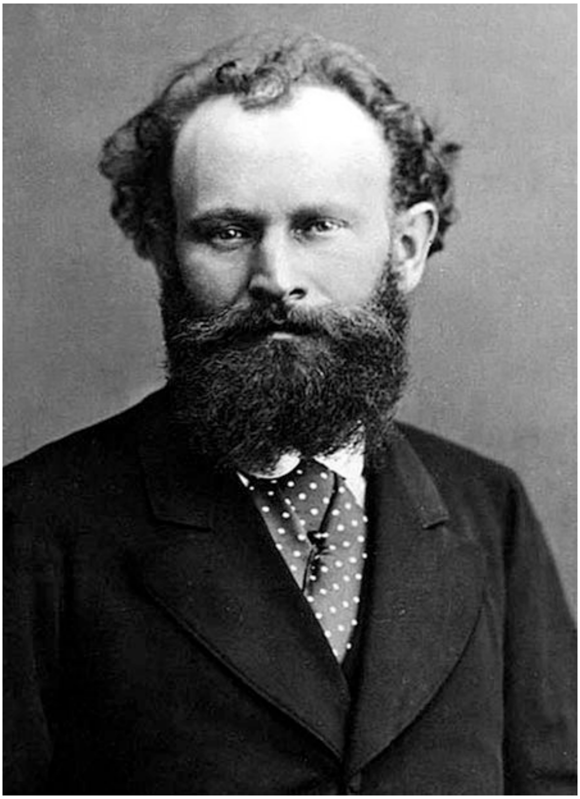


Fig. 9.17 Photograph of Édouard Manet

Fig. 9.18 Manet's *Le Dejeuner sur l'Herbe*, 1863, Musée D'Orsay. *Note* the discomforting distortion of perspective

Fig. 9.19 Manet's *Olympia*, 1863, Musée D'Orsay. *Note* the cat on the *right*

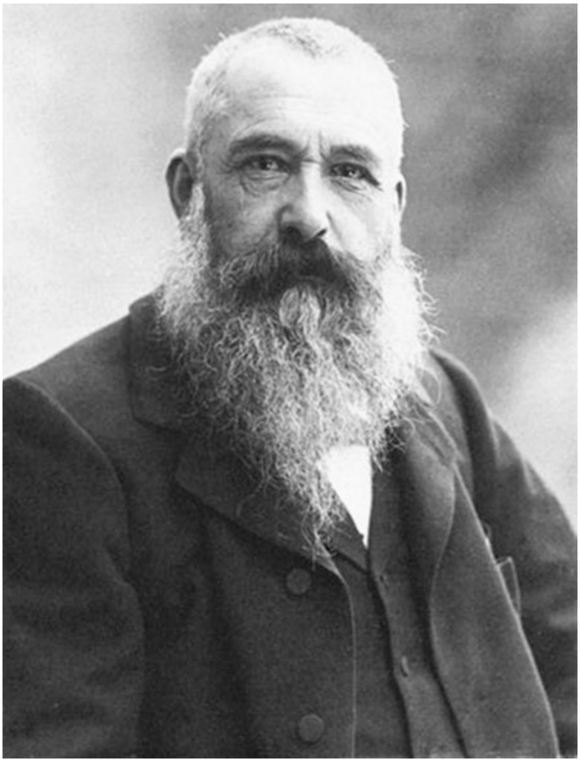


Fig. 9.20 Photograph of Claude Monet

Early twentieth century artists such as Pablo Picasso (1881–1973) would stretch art even beyond Van Gogh, providing impetus to enhance the imagination of all humankind (Figs. 9.27 and 9.28).

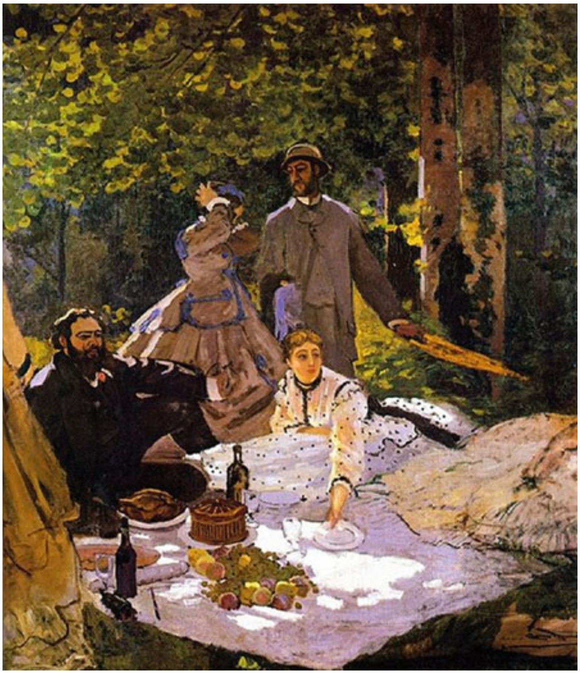


Fig. 9.21 The *right* section of Monet's *Le Dejeuner sur L'herbe*, Musée D'Orsay. *Note* the feeling of sunlight

Fig. 9.22 Self-portrait of Edgar Degas, Musée D'Orsay

Fig. 9.23 Photograph of Pierre-Auguste Renoir

Fig. 9.24 Pierre-Auguste Renoir's Bal du Moulin de la Galette, 1876, Musée D'Orsay. *Note* the feeling of shade interspersed with rays of sunlight

In his book *Parallel Visions in Art and Science* Leonard Shlain [95], presents the thesis that great epochs in art precede and perhaps even contribute to great epochs in science. Here, in chronological order, are just a few epochs that fit this

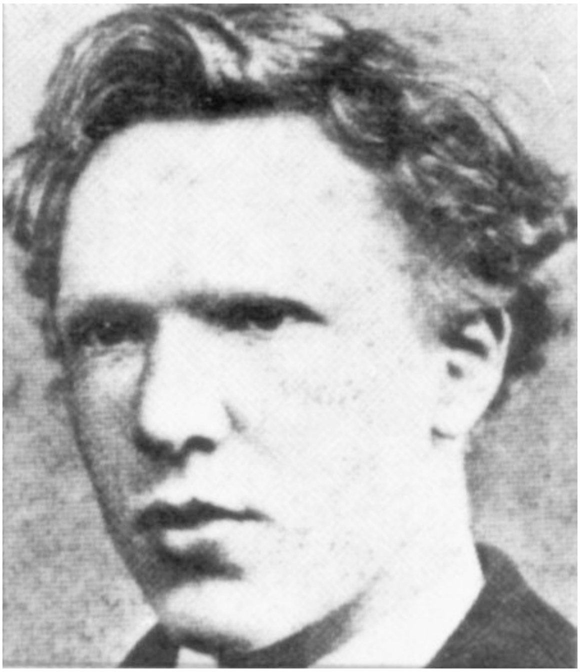


Fig. 9.25 Photograph of Vincent Van Gogh, c. 1871

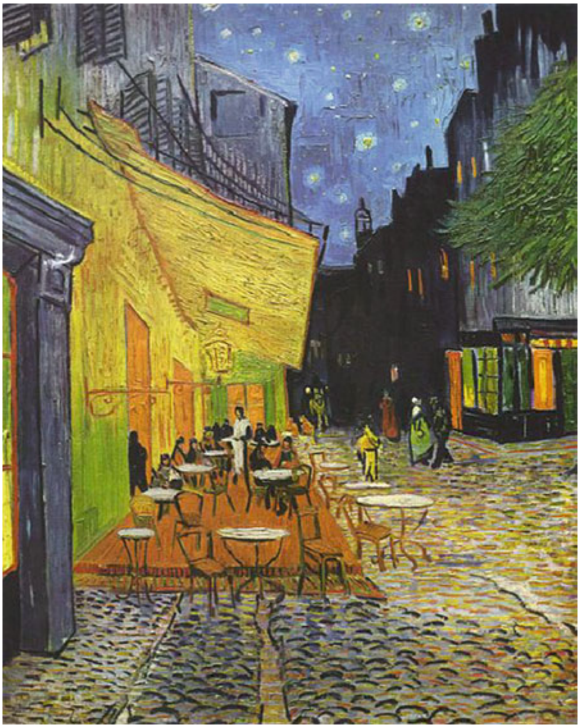


Fig. 9.26 Vincent Van Gogh's *Le Café le Nuit*, Kröller-Müller Museum

Fig. 9.27 Photograph of Pablo Picasso

Fig. 9.28 Pablo Picasso's *Les Demoiselles D'Avignon*, 1907, Museum of modern art, New York

hypothesis: the Greek Hellenistic period; the Italian Renaissance; and the French Impressionist period. Could his thesis possibly be true?

There seems to be some substance to Dr. Shlain's supposition. I for one believe it. Think about it. Pericles and his fellow patriots climbed up to the Acropolis, and shortly thereafter the resulting democracy spawned the first great scientific epoch up to that time on Earth.

During the Artistic Renaissance in Italy, the best artists, such as Brunelleschi, Da Vinci, Donatello, and Michelangelo were all sort of artist-technology hybrids. And in the same year that Michelangelo passed away, Galileo was born, thus growing up in a world of artistic wonders—a world that must surely have caused the imagination to flower. And then there is the Impressionist period, possibly influencing the creativity of not only Einstein, but perhaps the entire scientific community in the twentieth century.

Is it indeed possible that the resulting shifts that occur in societal perceptions both during and after revolutionary periods in art also affect the creativity with which science and technology are pursued? The evidence seems to support this hypothesis. The interested reader might do well to peruse the books by Leonard Shlain and Ross King and see if they do not come away with a similar feeling that epochs in art both predate and germinate epochs in science, including mechanics.

Structural Mechanics

Fueled by the developments in continuum mechanics described previously in this chapter, by the middle the nineteenth century engineers commenced building structures that were different from anything heretofore seen on Earth. First, they were almost all made of metal. Second, they were larger than almost anything ever built (the great pyramids excepted).

Fig. 9.29 Portrait of Thomas Telford by S. Lane

As described in the chapter by Henry Petroski entitled “Images of Progress: Conferences of Engineers” from the Book *Seeing Further* [97], perhaps the first of these major structures was the Menai Suspension Bridge, designed by Thomas Telford (1757–1834) and completed in 1826. This graceful suspension bridge connects the island of Anglesey to the mainland of Wales (Figs. 9.29 and 9.30).

Toward the middle of the nineteenth century the Britannia Bridge was constructed, again bridging the island of Anglesey to the mainland of Wales, but this time for rail service. This was perhaps the last massive bridge built in the old style (prior to the Impressionist Period), with the railroad tracks imbedded inside the massive iron structure (Fig. 9.31).

A quarter of a century later, the effects of the Impressionist period are clearly evident in structural design. For example, consider the Eiffel Tower, completed in 1889 for the Paris World’s Fair.

The Eiffel Tower was proposed as the main attraction for the 1889 Exposition Universelle, to be held in Paris. The initial idea for the tower was proposed to Gustave Eiffel (1832–1923) by Maurice Koechlin and Émile Nouguier, two engineers employed by Eiffel within Compagnie des Etablissements Eiffel, a French civil engineering company that had previously built iron railroad bridges in France [98]. Koechlin sketched out the initial concept for the tower with the thought that it would be constructed adjacent to the Seine River on the Champ de Mars (Fig. 9.32).

Gustave Eiffel was initially skeptical about the project, but he was persuaded to pursue the concept with the organizers of the exposition. The contract was eventually awarded to Eiffel’s company, and construction commenced in January, 1887. Three hundred workers began by constructing four concrete pylons at opposing corners of the tower. Meanwhile detailed drawings were completed for the 18,038 iron parts needed to construct the tower, and these were constructed at an ironworks in a Paris suburb. The parts were subsequently carted to the site and either bolted or riveted together as the project moved forward. Creeper cranes were

Fig. 9.30 Photograph of the Menai Suspension Bridge

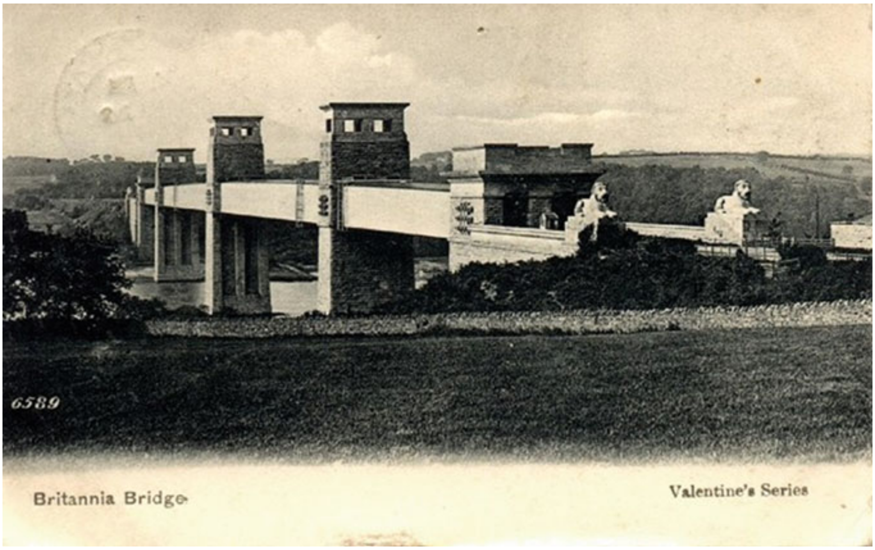


Fig. 9.31 Photograph of the Britannia Bridge

attached to the four legs of the structure once they had reached a certain height and subsequent construction used these cranes to inch upwards. Construction was completed in March, 1889. Miraculously, only one worker was killed during the construction of the tower.

When completed the Eiffel Tower was at 320 m (1,050 ft) the tallest structure on Earth. It consists of three levels reachable either by stairs or a system of impressive mechanical elevators. The entire structure is estimated to weigh approximately 9,000,000 kg. As a testament to the efficiency of the design, the primary lateral loading, wind, produces a maximum displacement of the summit of only about 7 cm. The tower is painted every 7 years with approximately 50,000 kg of paint. The color of the tower is sometimes changed during this process (Fig. 9.33).

Eiffel paid homage to the great French engineers, scientists, and mathematicians of the nineteenth century, inscribing the names of his favorite 72 icons above each of the fours arches of the lowest deck. These iconic names can still be seen today from street level beneath the tower (see the section above on Continuum Mechanics for the names of several of them).

Interestingly, the French people did not immediately embrace Eiffel's ambitious structure. Many thought that the tower was not in harmony with the traditional structures of Paris. Eiffel countered that the tower was the first of a new wave of artistically inspired structures that would reshape the modern world. Of course, he turned out to correct.

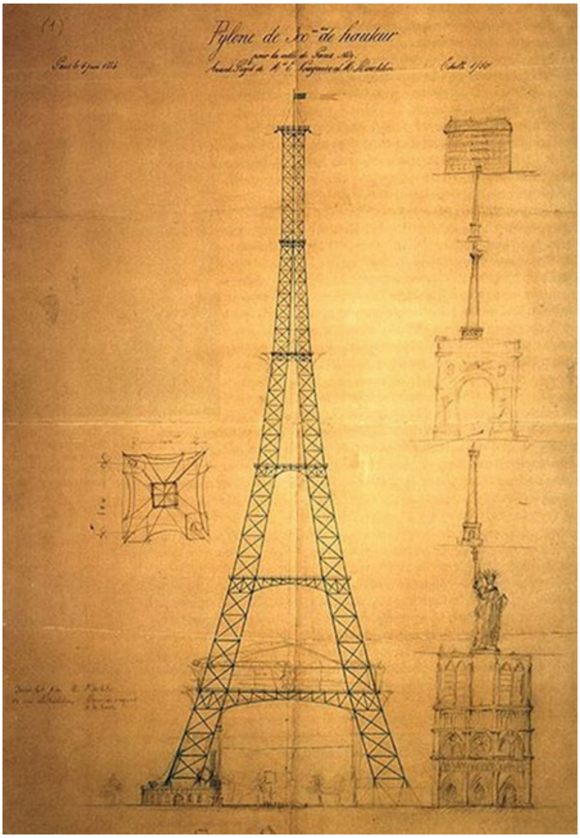


Fig. 9.32 Initial conceptual drawing of the Eiffel Tower sketched by Maurice Koechlin. *Note* the relative sizes of other iconic structures on the *right*

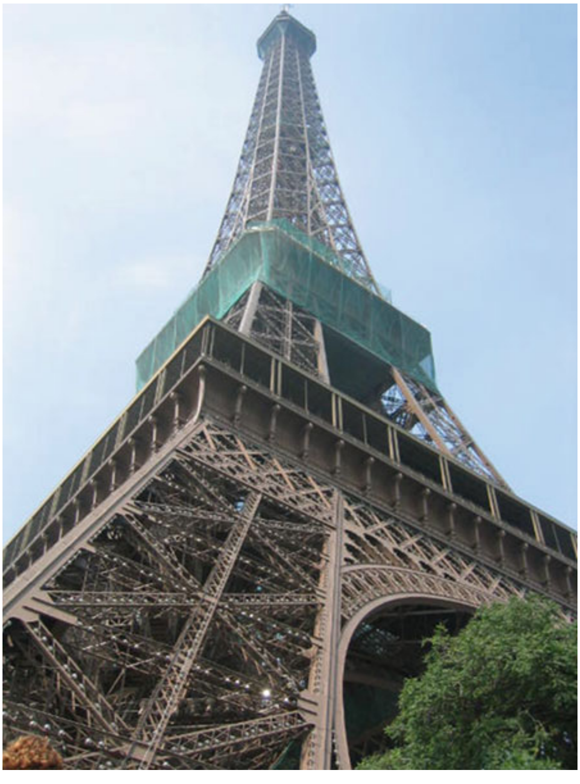
Since Eiffel had secured only a 20-year lease for the structure from the City of Paris, it was scheduled for demolition in 1909. However, before demolition commenced the advent of radio gave the tower new life. An antenna was attached to the top of the tower and it was utilized to transmit radio waves, a sign of things to come in the twentieth century. Shortly thereafter, World War I commenced. When the tower was used to successfully block radio transmission by the German Army, it gained the eternal admiration of the French people, thus avoiding demolition.

Today the Eiffel Tower is the most visited monument on Earth, with more than 7 million visitors each year. In addition, more than 250 million people have visited the Eiffel Tower since its opening in 1889. It is arguably the most famous structure on Earth, thus confirming the far-reaching vision of Gustave Eiffel (Fig. 9.34).

Have you ever wondered why The Eiffel Tower is shaped the way it is? As shown in the second figure below, there is clearly a relationship between the shape of the moment diagram for an evenly distributed loading (in this case—caused by wind loading) applied to a cantilever beam and the shape of the tower. The observant student will recognize that the moment diagram is nothing more than a

Fig. 9.33 Photographs of the Eiffel Tower during construction

Fig. 9.34 Gustav Eiffel's masterpiece today



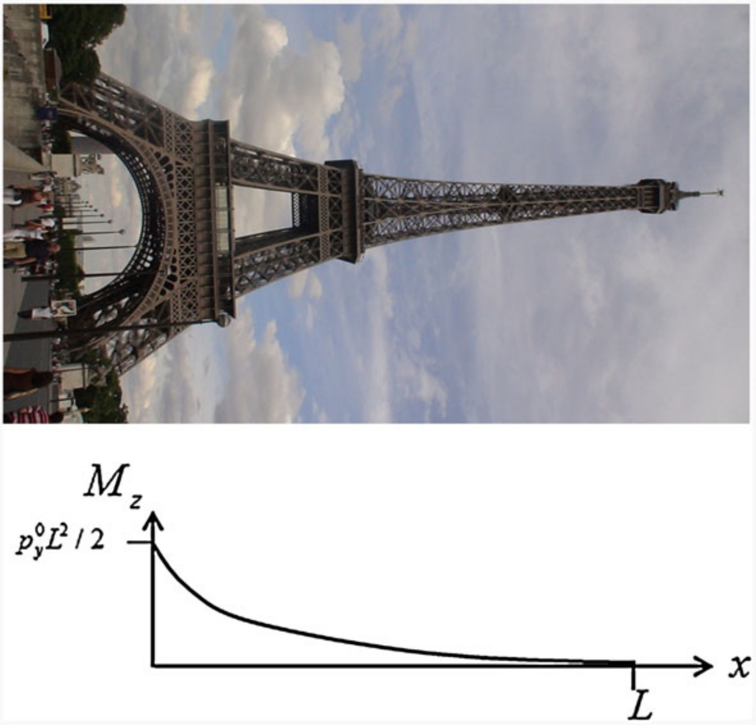


Fig. 9.35 Photo of the Eiffel Tower rotated 90° and depicted above the moment diagram for a cantilever beam with evenly distributed loading

careful mathematical deployment of Newton's First Law for a beam at rest, a problem in mechanics [94]. Although this relationship is clear, there is no extant evidence that Eiffel used anything more than a subjective understanding of beam theory to complete the structural design of the tower [98] (Fig. 9.35).

Another early example is the Firth of Forth Bridge, built across the Forth River north of Edinburgh, and completed in 1890. The bridge took 7 years to complete, and 63 persons died during construction. When completed, the bridge spanned 2,529 m, making it the longest bridge on Earth at that time.

Design of the bridge was begun by Sir Thomas Bouch (1822–1880), but the collapse of his previously designed Tay Bridge in 1879 caused a public calamity that led to his removal from the project. The contract was subsequently awarded to Sir John Fowler (1817–1898) and Sir Benjamin Baker (1840–1907). The project, which used 4,600 workers, was the first massive steel structure built on Earth, requiring the development of a fifty acre steel yard nearby. The bridge is still in use today.

Shown below the photo of the bridge is the moment diagram for an evenly distributed loading applied to a double cantilever beam, once again demonstrating the influence of mechanics on structural design (Fig. 9.36).

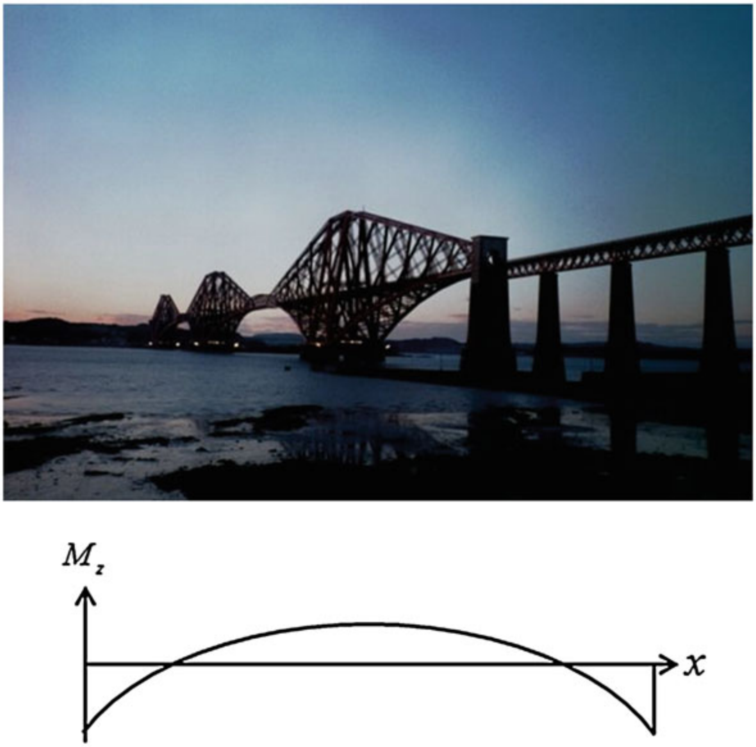


Fig. 9.36 Photo of the firth of forth bridge depicted above the moment diagram for a double cantilever beam with evenly distributed loading

But for perhaps the most impressive example of a modern structure transforming the world, consider the Brooklyn Bridge, completed in 1883, 6 years prior to the completion of the Eiffel Tower [99]. The initial design for the bridge was supplied by John A. Roebling (1806–1869), who had previously designed several other shorter suspension bridges. Unfortunately, Roebling died from an injury and his son Washington Roebling (1837–1926) took over the project. Shortly thereafter, the younger Roebling was debilitated during construction of the caissons for the bridge (by decompression sickness, which was at that time unknown, incurred while constructing the caissons beneath the surface of the water). His wife Emily W. Roebling (1843–1903) took over responsibility for the bridge. Under Washington's tutelage, Emily guided the project to completion in 1883. In so doing, she learned the proper mathematics and engineering and principles necessary to build the bridge (Fig. 9.37).

The construction of the caissons and their connection to the underlying bedrock turned out to be one of the main challenges. In addition, the theory for the unique and complex catenary system was developed by Mrs. Roebling. This was accomplished

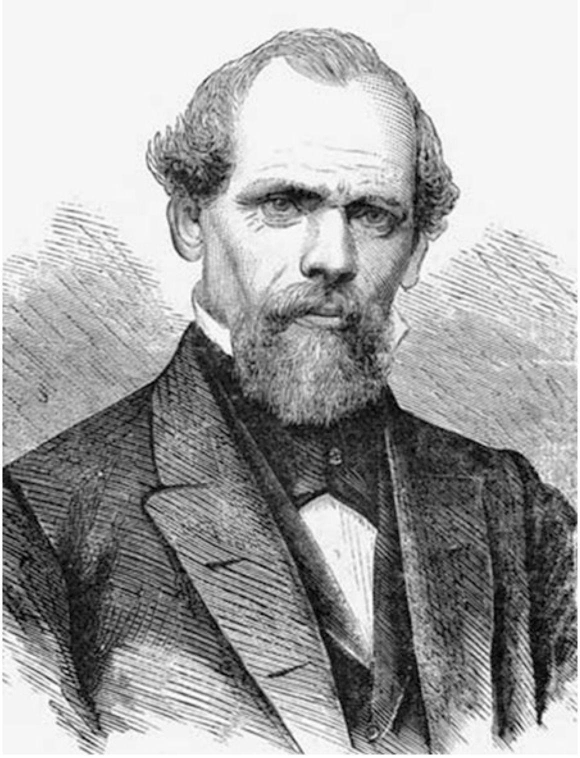


Fig. 9.37 Sketch of John A. Roebling

using the mechanics theories developed in the early part of the nineteenth century, as described earlier in this chapter. The bridge took 11 years to complete, and 27 people died during construction. When completed the bridge was at 486 m the longest suspension bridge in the world by a wide margin (Fig. 9.38).

The bridge was opened on May 24, 1883. President Chester Arthur was present at the opening ceremony, and Emily Roebling was the first person to cross the bridge. The Brooklyn Bridge was perhaps the first truly modern massive structure built on Earth. And for the first time, we have an example of modern mechanics leading the way in the United States. This suspension bridge was and still is a marvel of engineering, and it paved the way for numerous other suspension bridges such as the Golden Gate Bridge (completed in 1937) throughout the world over the succeeding century (Fig. 9.39).

Construction on the Golden Gate Bridge, connecting the northern tip of San Francisco to Marin County, began on January 5, 1933. The bridge opened on May 27, 1937. When completed, it was the longest suspension bridge in the world at 2,737 m (8,981 ft). The bridge contains 129,000 km of wire in the main cables, and there are approximately 1,200,000 rivets within the structure. The Golden Gate Bridge is the most photographed bridge in the history of humankind (Fig. 9.40).

Fig. 9.38 Portrait of Emily W. Roebling by Carolus Duran

As described in the section on continuum mechanics, pioneers in this field developed models that were capable of predicting the motions of solids subjected to mechanical loadings. Unfortunately, these models were much too difficult to solve exactly using the mathematical tools available in the nineteenth century. Thus, an approximate method for applying these continuum mechanics models developed that was called somewhat inappropriately "strength of materials". In this methodology, certain experimentally based kinematic assumptions were employed as a means of simplifying the continuum mechanics models for classes of structural components of specified geometry. For example, theories were

Fig. 9.39 Photograph of the Brooklyn Bridge

Fig. 9.40 Photo of the Golden Gate Bridge

developed for so-called uniaxial bars, torsion bars, beams, and plates, all of which are nothing more than components that are widely utilized in structural applications. For these simplified geometries it was possible to reduce the continuum mechanics problem for solids (developed by Germain, Navier and Cauchy) to sets of equations that could be solved using the mathematics available in the nineteenth century.

For example, beam theory, originally developed by Leonhard Euler and Daniel Bernoulli in the mid-eighteenth century (see Chap. 7), was perfected, thus leading to the development of all sorts of structures composed of beam components, such as the bridges and the Eiffel Tower described above. By the early twentieth century, these concepts were also being applied to automobiles and airplanes, and they would later be applied to spacecraft as well. This field of mechanics came to be called "structural mechanics".

There are mechanics models that are directly responsible for the striking similarities between the moment diagrams obtained using the theoretical models developed in the early part of the nineteenth century and the shapes of the resulting structures, and while these models were initially developed by the scientific community after the ground-breaking developments in continuum mechanics described earlier in this chapter, it was engineers like Gustav Eiffel who began applying these models in the late nineteenth century to the design of structures against failure. In the process, they also realized that structures could be designed not only to avoid failure, but also to simultaneously create landmarks that are both visually appealing and cost effective. Structures such as the Brooklyn Bridge, the Eiffel Tower, and the Firth of Forth Bridge are among the first significant structures built on earth that utilized modern structural mechanics to produce visually stunning structures that are nonetheless structurally sound. Perhaps these visionary engineers were even influenced by Impressionist Art. After these masterpieces were completed, it was not long before other similar structures began appearing all over the world, as shown below. These massive structures were just the beginning of many amazing developments due to structural mechanics in the twentieth century.

The Sydney Harbor Bridge is a steel arch bridge that was completed in 1932, spanning Sydney Harbor with a total length of 1,149 m (3,370 ft). Tourists visiting Sydney can take a guided tour to the top of the bridge at a height of 134 m (440 ft) (Fig. 9.41).

The Pont de Normandie is a cable-stayed bridge spanning the Seine River near Le Havre and Honfleur. The bridge took 7 years to construct, opening in January 1995 (Fig. 9.42).

The Jucelino Kubitschek (JK) Bridge is a steel and concrete bridge that spans Lake Paranoá in the capital city of Brasilia, Brazil. The bridge is 1,200 m (3,900 ft) long, and was opened in December 2002. It has won several international bridge awards due to its stunning arches that crisscross the roadway (Fig. 9.43).

The Millau Viaduct is a cable-stay bridge spanning the Tarn River Valley in Southern France. It is the tallest bridge in the world at 343 m (1,125 ft). The bridge received the 2006 International Association for Bridge and Structural Engineering Outstanding Structure Award (Fig. 9.44).

Fig. 9.41 Photograph of the Sydney Harbor Bridge

Fig. 9.42 Photograph of the Pont de Normandie

Fig. 9.43 Photograph of the Jucelino Kubitschek Bridge

Fig. 9.44 Photograph of the Millau Viaduct in Southern France

As we have seen in this chapter, mechanics played a new and profoundly important role in the nineteenth century, but this was only the beginning. Indeed, mechanics found its heyday in the twentieth century.

Weather

10

Water is the driving force of all nature.
Leonardo Da Vinci (1452–1519)

Weather is not very intuitive to most people, but I can assure you that the weather does indeed behave according to the same physical laws that we apply to other phenomena within our Universe. Our weather is primarily caused by chemistry, thermodynamics, and perhaps most of all—by mechanics. These three branches of science are inextricably connected, perhaps never more obviously so than in the weather on our planet.

The Galveston hurricane of 1900 was the worst natural disaster in the recorded history of the United States. About 10,000 lives were lost when the hurricane struck Galveston in early September. Because weather forecasting was in infancy at that time, the U.S. Weather Service did not realize that the storm that struck the Caribbean and Cuba was the same system that struck the coast of Texas a week later. Thus, warnings that could have saved many lives were not issued [100] (Fig. 10.1).

Because it occurred in the United States, the devastation caused by this hurricane was probably the single most important natural disaster that contributed to the rise of modern weather forecasting worldwide. Until that hurricane struck, our ability to predict the weather on this planet was largely forensic in nature, meaning that we simply looked at past events and made statistically supported forecasts based on them. The same approach has until recently been the primary way of practicing medicine on Earth. The field of medicine has seen much greater success via this forensically-based approach because the data set (such as the number of human deaths) is significantly larger than that for hurricanes. Thankfully, both fields of science are now progressing rapidly towards models based on predictive sciences rather than mortality statistics.

Almost all weather on our planet occurs in the Earth's atmosphere. Our planet has had an atmosphere for most of its existence. However, the composition of our atmosphere has changed dramatically over the life of our planet. The atmosphere as we know it today is perhaps only 600 million years old. It is mostly nitrogen (78 %), but there are also oxygen (20 %) and argon (1 %), as well as a number of trace gases. There is also about 0.4 % water vapor in our atmosphere, and as we

D. H. Allen, *How Mechanics Shaped the Modern World*,
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Fig. 10.1 Aftermath of the Galveston hurricane of 1900

will see shortly, this is the single most important molecule in our atmosphere with respect to our weather [101, 102].

In my mind, the primary causes of weather on Earth are related to two important inescapable realities. First, the Earth is approximately spherical; and second, water exists in three natural chemical states on our planet.

Let's consider these one at a time. First, the Earth is approximately spherical. This is due to Newton's Gravitational Law (see Chap. 7). As we know from this law, the force exerted by bodies is directly proportional to their mass. All massive solid bodies in the Universe are essentially spherical because their mass is sufficiently large to induce gravitational forces that cause stresses to overcome the fracture toughness of materials near the surface, thus pulling every object on their surface as close as possible to their center of mass.

Where the Earth is not spherical it is because chemical processes inside our planet produce forces that are sufficiently large to overcome the Earth's gravitational force, thus creating for example volcanoes and mountains. But from a distance of one diameter of the Earth, these variations appear small, so that from afar the Earth appears to be approximately spherical.

This is really an exercise in relativity. For example, suppose you could stretch a rope around the circumference of the Earth and pull it tight so that it rests directly on the surface. Now suppose you add 6 m of length to the rope. How high above the Earth's surface would the rope be if it were stretched out equidistant from the surface? The answer is about 1 m! This fact can be verified with some simple trigonometry (see Archimedes in Chap. 2). It seems remarkable, but that is because you the viewer are standing right next to the rope, and you are only around 2 m in height. But if you were standing one Earth radius away from the Earth's surface, you would not even be able to see this 1 m separation between the rope and the surface of the Earth. The viewer's opinion of the significance of the height of the rope above the Earth's surface is relative to the viewer's location with respect to the rope and the Earth's surface.

On the other hand, smaller objects within the Universe are often nowhere close to spherical, and this is due to the fact that the gravitational force of these small bodies, such as asteroids, is not sufficiently large to overcome the fracture toughness of the rocks or ice that they are made of, thereby causing them to remain irregular in shape. Gas giants such as Saturn and Jupiter are quite (oblate) spherical because the surface that we see is not a solid, but is in fact a gas, meaning that there are no molecular (solid) bonds to overcome (via fracture) by the gravitational forces. The surfaces of stars are combinations of liquids and gases, thus meaning that they are also quite spherical for the same reasons that gas giants are spherical. Thus, the Earth is at least approximately spherical, and this is the dominant reason for our global weather.

You may have heard of the First and Second Laws of Thermodynamics. Mechanics is inextricably connected to these two essential scientific principles. These two laws imply that every object will seek thermodynamic equilibrium. Since these are universal laws, the Earth itself behaves according to them. This would imply that every point on the Earth's surface would seek to be at the same temperature. But of course, since the Earth is spherical this is not possible so long as the Sun is out there heating our planet. When in the distant future our Sun burns out, every point on Earth will quickly reach thermodynamic equilibrium (very near to absolute zero!), but until then, we are doomed to have weather on this planet.

From Fig. 10.2 we can see that because the Sun is pretty far from Earth compared to the Earth's radius (about 24,000 Earth radii!), the radiation energy that comes to the Earth from the Sun appears to be planar from the perspective of Earth.

Thus, as we can see, because the equatorial regions of the Earth are nearly perpendicular to the Sun's rays, these regions must always receive more solar radiation than do the polar regions simply because the polar regions are quite oblique to the Sun's rays. Furthermore, because only one side of the Earth is visible to the Sun at any point in time, one side of the Earth is always receiving energy, while the other side is not, and the period of this difference is one day,

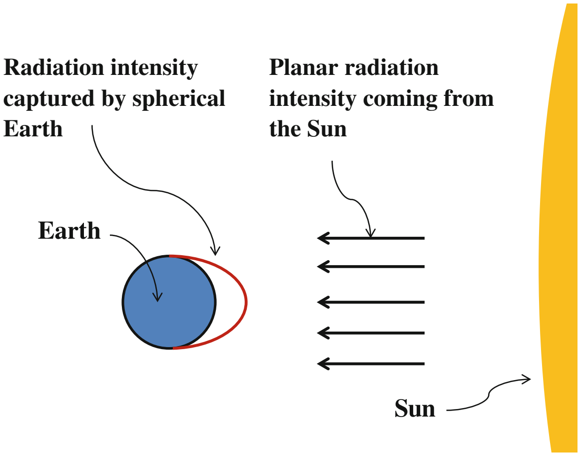


Fig. 10.2 Solar radiation intensity on Earth

Fig. 10.3 Artist's depiction of the impact of an Asteroid with the Earth that caused the Moon

which is determined by the rate of spin of the Earth. Both the shape and the spin of the Earth are due to mechanics.

Scientists think that the Earth's spin rate was determined primarily by the impact with another body about 2.5 billion years ago, and that impact produced our Moon. The date for this impact has been estimated by using mechanics. When the first astronauts landed on the Moon in 1969, they placed a mirror on its surface, and ever since then we have been measuring the time of flight of a reflected beam of light between the Earth and the Moon. From that measurement we have been able to calculate the rate at which the Moon is moving away from the Earth—about 3.8 cm per year. Thus, we can extrapolate backwards in time using Newton's second law of motion and estimate when the impact occurred (Fig. 10.3).

There is another effect of the impact that produced our Moon. When the two bodies collided, the Earth's axis of spin was tilted, so that this axis is now about 23.5° away from the perpendicular to the plane of the ecliptic, which is the plane that our solar system lies within. This tilt of the Earth's axis of spin is the primary cause for our seasons on Earth, and it is all due to mechanics.

Let's suppose that you live in St. Paul, Minnesota, which lies at a latitude of about 45°. On the day of the summer solstice (June 22), the Sun is at its maximum angle of $45° + 23.5° = 68.5°$ at high noon, whereas on the day of the winter solstice, the Sun is at its maximum angle at high noon of $45° - 23.5° = 21.5°$. Thus, St. Paul receives a maximum radiation rate from the Sun in winter of only about $\sin 21.5°/\sin 68.5° = 39.4\ \%$ of its maximum heating rate in summer. Connect that with the fact that the length of the day on December 22 in St. Paul is only 8 h long, whereas it is 16 h long on June 22, and the difference is staggering. St. Paul only receives about 20 % as much of the Sun's energy on December 22 as it does on June 22 (Fig. 10.4)!

Of course, the amount of solar radiation that the Earth receives at any particular location is a function of four physical variables, as shown in Fig. 10.5: the Sun's

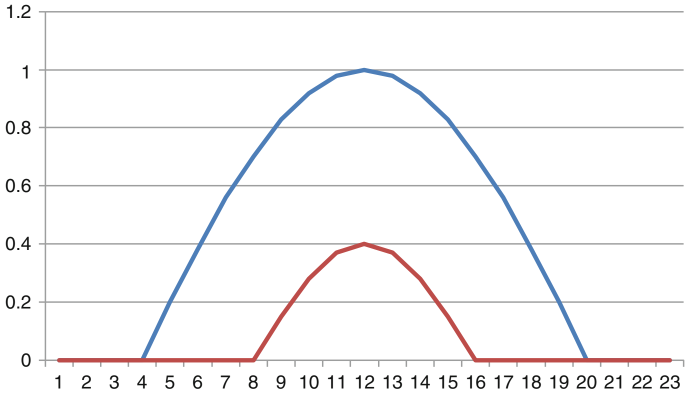


Fig. 10.4 Solar heating as a percent of maximum (*vertical axis*) versus time of day (*horizontal axis*) on June 22 (*blue line*) and December 22 (*red line*) in St. Paul, Minnesota

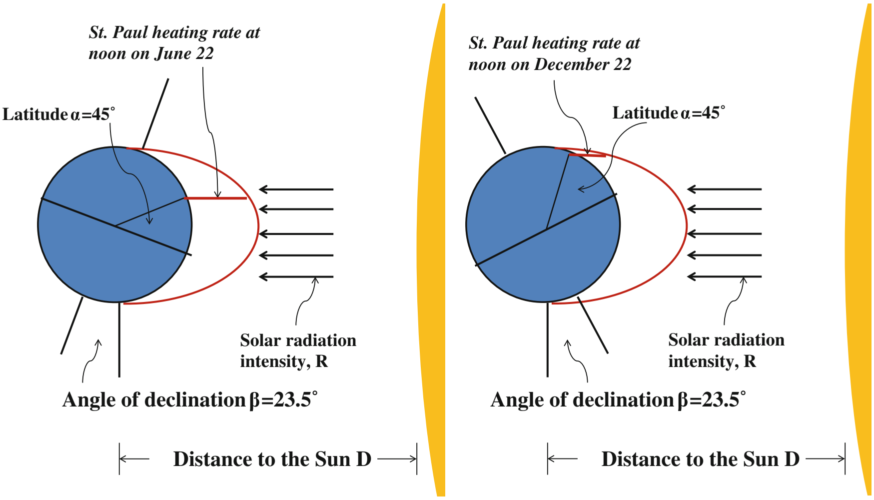


Fig. 10.5 Solar radiation in summer and winter in St. Paul, Minnesota

rate of energy radiation to Earth, *R*; the distance the Earth is from the Sun, *D*; the angle of declination of the Earth's spin, β; and, the latitude that you are located at, α. The last three of these variables are purely mechanical, and only the last two vary dramatically with when and where you are located on Earth. Furthermore, only the first—the Sun's radiation rate, is not mechanical. It is both chemical and thermodynamic, and it is usually constant when you are on the side of the Earth facing toward the Sun.

Because of the nonlinear character of trigonometric functions, this effect is even more pronounced at latitudes higher than St. Paul. Thus, if you live in Canada or

Sweden, you will have short and mild summers and harsh winters. At latitudes that are lower than St. Paul, this effect is less pronounced. Thus, if you live in Texas or Southern Italy, your winters will be milder, but your summers will be harsher. There are quite a few things that affect the climate where you live, but latitude is the most significant of these.

The axis of spin of the Earth is wobbling, called "precession", and the rate of precession of this wobble is about one cycle every 25,772 years, or 1° about every 72 years. This precession is pretty long compared to the human life span, so that it is not very apparent to us today. However, the "North Star" that is used today, as well as in the time of mariners such as Columbus and Magellan, was not all that close to North in ancient times due to the precession or wobble of the Earth's axis. According to the historical record, Hipparchus (c. 190–120 BCE) was the first person to notice this wobble (see Chap. 2) (Fig. 10.6).

You may have heard that we are now in the Age of Aquarius. This is due to the fact that the Earth's precession has caused the constellation Aquarius to be the one that is in the Sky when the Sun crosses the celestial equator at the moment of the vernal equinox. Because of the precession of the Earth, each of the constellations in the plane of the ecliptic gets its chance to be at this location at the vernal equinox, and depending on the size of that particular constellation, it gets the title "Age of…" for quite a while. Based on the 12 constellations in the plane of the ecliptic, this span of time works out to an average of 2,150 years for each constellation, but there is considerable disagreement due to the fact that some

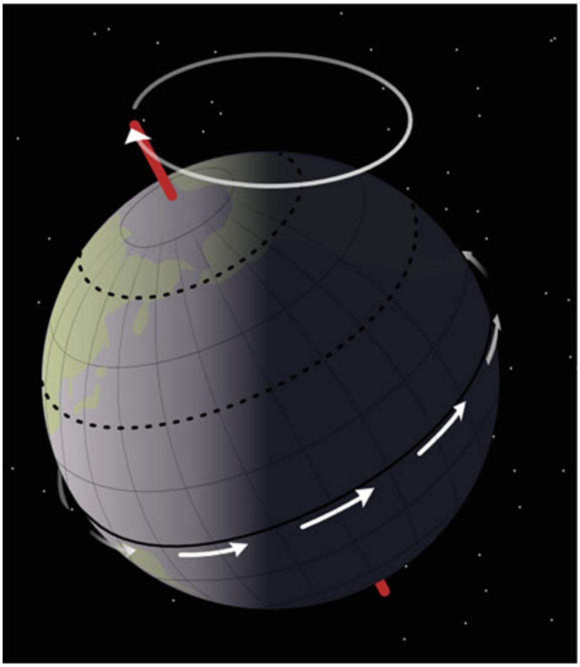


Fig. 10.6 Earth's precession

constellations are larger than others. After all, they were chosen more or less subjectively by humans. And while it is not an exact science, some astronomers agree that the Age of Aquarius has begun, so that we and our progeny will be living in the Age of Aquarius for quite a while to come.

No one knows for certain who invented the constellations. However, it is believed that they were invented primarily for the purpose of nighttime navigation at sea. Professor Archie Roy (1924–2012) of Glasgow University has proposed the (controversial) theory that the constellations were invented by the Minoans, and this theory is related to the Earth's precession [103]. According to the Author, the Minoans were at precisely the right latitude and precession at the time that the constellations were first named, making the Minoans the only seafaring nation capable of seeing all of the constellations in the night Sky from their particular location on Earth's surface at that point in time. This theory is based strictly on mechanics.

But I digress. Let's get back to the weather. What all of this spatially and time-wise uneven solar heating does to the Earth means that the Earth is never in thermodynamic equilibrium, which would only occur if the temperature at sea level on Earth was the same at every location. Since this is not the case, the Earth is in a constant state of thermal flux as it attempts to reach this thermodynamic nirvana.

A study of the First and Second Laws of Thermodynamics will show that wherever there is a temperature difference, heat will flow from hot to cold, and this is the main cause of our weather on Earth. Heat may be carried by a variety of means from hot to cold. One possibility is through the flux of heat in solids, wherein the molecules are molecularly bound. This occurs through the jostling of molecules against one another, thereby transferring kinetic energy from one molecule to the next without the molecules actually trading places (See the discussion on Joseph Fourier in Chap. 9).

What we find is that the time constant for this kind of heat flow is quite large compared to another means of transporting heat, and that is called convection. Convection can only occur in fluids (both liquids and gases), and it is accomplished through the physical transport of atoms and/or molecules, because in fluids they are not molecularly bound to a fixed physical location with respect to their neighboring molecules. The time constant for this type of heat transport is much smaller than that for heat transport in solids. What that means is that a whole lot of the transport of heat on our planet occurs in our atmosphere (a gas) and our oceans (a liquid), and not so much occurs through the Earth's crust (a solid).

There are global sized convective flow patterns set up within the oceans on Earth, and these flow patterns, such as the Gulf Stream and El Nino, are essentially constantly transporting heat from the equatorial regions to the polar regions in an attempt to make up for the spatial difference in heating from the Sun caused by Earth's spherical shape. The viscosity of water causes these currents to move rather slowly, but the latent heat capacity in the oceans causes enormous amounts of energy to be transported by this process (Fig. 10.7).

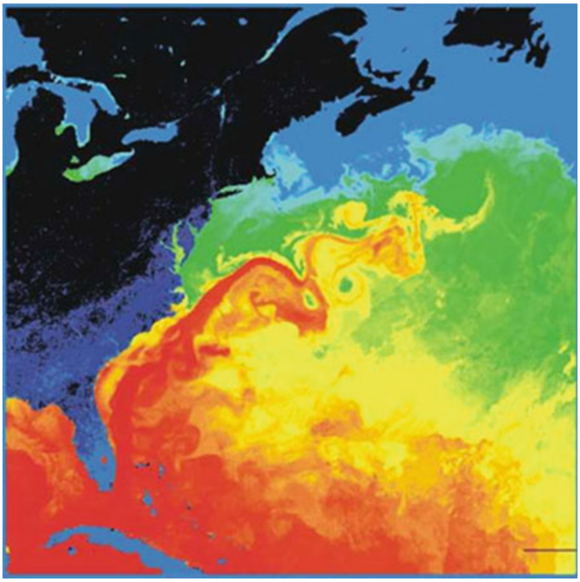


Fig. 10.7 Color enhanced satellite photo of water temperatures in the Gulf stream. *Note* the coast of North America on the *left*

The same phenomenon occurs in the Earth's atmosphere, but due to the much lower density and viscosity of air compared to water, a lot more interesting things happen in the Earth's atmosphere. We call this activity "weather".

When the wind blows where you live, this is essentially nothing more than molecules and atoms of gases in the air racing by you transporting heat by the process we call convection (meteorologists call the horizontal component "advection") from hotter regions to colder regions on Earth. What we refer to as heat is really nothing more than kinetic energy (of motions) stored within molecules and atoms, and these molecules and atoms are being transported to other locations on Earth in an attempt to restore thermodynamic equilibrium. So the next time the wind blows, remember—if the Earth were flat, we wouldn't need wind to reach thermodynamic equilibrium because the Sun would heat every point on Earth more or less equally.

In addition to the fact that the Earth is spherical, there is another interesting and unique feature of weather on Earth, and that is associated with water. So far, ours is the only planet in our immediate neighborhood (of a few light years) that we are aware of that has an abundance of water, and on which water occurs naturally in all three states: liquid, solid, and gas, and this is perhaps the single most important chemical attribute of weather on our planet (It should be pointed out that there appears to be a polar ice cap on Mercury. In addition, both Enseladus, the sixth largest moon of Saturn and Europa, one of the largest moons of Jupiter, are both covered with ice that appears to rest on top of giant oceans).

We're not exactly sure how all this water arrived on Earth. Some scientists think that our planet got hit by lots and lots of ice-laden asteroids early in its life. As a result, more than 70 % of the Earth's surface is covered by water, making it the most abundant material to humankind. Water is essential to all life on Earth. And yet, there is often a problem with water. There is either too much of it, or not enough.

There are about 10^{46} water molecules on this planet. That's a *lot* of water. Where did it all come from? In 2011 scientists photographed a quasar that is 11 billion light years from Earth. Since the Universe is about 13 billion years old, the light coming from that quasar left it only about 2 billion years after the Big Bang, making the light arriving to us from it a window into the distant past, a time that was not so long after the Universe was formed. Scientists were amazed to find a cloud of gas emanating from the quasar that contained about 1 trillion times as much water as there is on Earth. It is theorized that the water in that cloud was formed by the pressure wave that was caused by the creation of that star. That pressure wave created conditions sufficient to bond hydrogen and oxygen atoms into H_2O, which we call water. Thus, we know that water is formed when stars are created, and that it has been around in the Universe for a very long time.

It is theorized that most of the water on Earth was formed by just such a pressure wave shortly after our solar system was created around 4.5 billion years ago. Water is a very stable molecule—most water molecules on this planet mated for life, and their life (and marriage) has endured for an extremely long time!

Each human on this planet has in him or her about 10^{22} water molecules. That may seem like a lot, but as mentioned above, there are about 10^{46} water molecules on our planet. That may also seem like a lot, and to be honest—it is! To put it in perspective, there are about 10^{33} grains of sand on Earth. Scientists estimate there are also about 10^{33} stars in the Universe. So there are about 10 trillion more water molecules on Earth than there are stars in the Universe.

Sounds like a whole lot, doesn't it! But wait a minute, not all of it is the "good" kind of water. Only about 3 % of the water on Earth is potable. Most of it is salt water found in the oceans. Salt water is toxic to humans. Of the 3 % that is potable, about 68 % is bound up in ice, making it inconvenient for human consumption. The cheapest method by far of removing salt from water is to evaporate it naturally by allowing it to escape into the atmosphere (salt does not evaporate) and return to Earth as rain or snow. This could also be accomplished artificially using the process called distillation, but it's actually quite expensive because it requires the use of lots of heat, which is not cheap.

So there may not be enough water on Earth, especially if our population keeps growing at the current rate. There are now about 7 billion humans on Earth, more than have lived in our entire past history. To put it another way, the number of funerals (including my own) in the next century will eclipse all of those in the entire past history of humankind. And within about 50 years from now the world population is expected to double. Unfortunately, nature will not see fit to supply us with a doubling in the supply of water. We will have to solve that problem ourselves. *So there may not be enough water!*

Speaking of ice, water is a really interesting substance. It is the *only* one on our planet that occurs naturally as a liquid, a gas, and a solid, sometimes even at the same physical location. Water melts at 0 °C (under little or no pressure). That is not a coincidence. We humans chose our arbitrary system of measuring temperature to coincide with the melting and boiling points of water because water is so essential to our existence. Thus, just as water melts at 0 °C, it also boils (becoming a gas) at 100 °C.

For those of you who are interested, there is another temperature scale that is commonly used in the U.S. called the Fahrenheit scale. Unfortunately, the two points on this linear scale were chosen badly (apparently based on the climate in Germany), so that the scale results in water freezing at 32°, and becoming a gas at 212°, neither of which is very convenient or descriptive, so that this scale is not used for scientific purposes, or indeed for any purpose at all anywhere but in the United States these days.

And while we're at it, I may as well inform you that temperature is really a perception we humans have of molecular motions. Thus, what we perceive as temperature is really a sensing of mechanics (see Chap. 9). Furthermore, we also measure temperature using mechanics!

This is another transgression, but it's a good one. In the nineteenth century folks were dreaming up the First and Second Laws of Thermodynamics, and they did a darned good job of it, but for one thing—when they finished the Second Law, they realized that they had forgotten to define temperature (Newton forgot to define mass before he introduced the laws of motion, too!). So they came up with the Zeroth Law of Thermodynamics. I know—this sounds silly, but it is nonetheless true.

So the Zeroth Law, attributed to none other than James Clerk Maxwell, says the following: two bodies that are in thermal equilibrium with a third body are also in thermal equilibrium with one another. This sounds terribly simple, and actually, it is! But strange as it may seem, we can use this concept to define temperature, and without it, we have failed to define the most important variable in the Laws of Thermodynamics.

Here is how you can use the Zeroth Law to define temperature. Take a long thin vile holding a highly expandable liquid such as mercury, and put that vile in contact with a cube of ice that is melting. Make a mark on the vile where the meniscus of the mercury is. Next put the vile in contact with boiling water, and make a mark on the vile where the meniscus of the mercury is. Call the first marks 0 °C , and the second mark 100 °C , and then make 100 equidistant marks in between these two marks (because mercury behaves according to the ideal gas law, see Chap. 7). Call this your temperature scale. You may then put this vile in contact with any other object you wish (such as your tongue, which you would never dream of putting in contact with boiling water, but you wouldn't hesitate to put in contact with a thermometer), and when the meniscus stops moving, the object is deemed to be in thermodynamic equilibrium with the thermometer, thus the temperature shown on the thermometer is therefore also the temperature of the object. The thermometer is the so-called "third body" in the Zeroth Law of Thermodynamics.

Interestingly, as I mentioned above, in a similar oversight Isaac Newton forgot to define mass in his book "Principia", but mass had already been more-or-less agreed upon by scientists, via the use of a mechanical balance (described concisely by Archimedes in his principles of the lever, see Chap. 2), which is exactly the same principle as the Zeroth Law of Thermodynamics. Ergo, two objects placed on a balance that cause it to be level, will have the same mass as any other object placed on either end of the balance that causes it to remain level. This is entirely analogous to the measurement of temperature described above! From this we can see quite vividly that there is no way to measure either absolute mass or temperature. They can only be determined relative to something else.

The same principle applies to length, which is why we have chosen the meter arbitrarily to be one ten-millionth of the distance from the equator to the North Pole on Earth (see Chap. 8). Similarly, there is no absolute measure of time. We have simply chosen it at various times in history to be the span of a day on Earth, the span of a year on Earth, and the resonant period of some element such as cesium. It should be apparent by now that literally *everything* is relative!

Let's get back to water. Interestingly, water is denser in the liquid state than it is in the solid state. This is of course why ice floats in your glass of water. That physical property is diametrically opposite to the behavior of most substances known to man. It is so counterintuitive that a great dispute broke out in the early seventeenth century. This unusual behavior of water was actually confirmed by none other than Galileo Galilei.

Scientists today know that the reason for this rather bizarre circumstance is that oxygen forms covalent bonds with hydrogen in such a way that the molecules can pack together very tightly in the liquid state, even more tightly than they can in their crystallized solid state. Thus, ice floats in liquid water.

The complex packing of water in the liquid state also leads to very high surface tension in water, which allows water to exhibit capillary action. What this means is that water likes to climb upwards against Earth's gravitational force in thin tubes. This is the means whereby water goes upwards in plants. Without it there would be little or no plant life on Earth, at least not as we know it today. Need I say, this is yet another problem in mechanics.

Surface tension is also a contributor to evaporation. Although there is a lot of water on Earth, there is only about 0.001 % of it in the Earth's atmosphere. Nevertheless, this is where a lot of the interesting stuff goes on involving water. Most of the water in the atmosphere is popped off the surface of large bodies of water such as oceans, lakes, and rivers on our planet by this surface tension. These molecules get captured by the air at the interface to the water in a process we call evaporation. The surface of the liquefied water is typically heated by solar radiation during the daytime, and the water near the gas–liquid interface reradiates some of this energy at a different frequency back to the air above it, where it is captured by some of the molecules, thus heating the air that contains the evaporated water molecules.

All of this suspension gets excited (resulting in enhanced kinetic motions and therefore energy) and tries to rise above its neighbors. Anyone who has ever seen a hot air balloon in flight will understand that hot air rises. Those parcels of air that succeed in doing so rise further from the Earth's center, but they do so adiabatically,

Fig. 10.8 Firefly 7 hot air balloon in flight

meaning that their total energy remains constant. Since their potential energy is increasing as they rise, some other form of energy must be decreased due to the First Law of Thermodynamics. Typically, the first thing to decrease is the kinetic energy, meaning heat, as reflected in a decrease in temperature of the rising parcels. Eventually, the parcels rise far enough that their temperature is decreased sufficiently for the air to reach saturation, which is a fancy term meaning that the water molecules condense back into the liquid state (or sometimes even the solid state if the air temperature is below freezing), thus forming the bases of clouds (Fig. 10.8).

This is the reason that cloud bases formed by this process tend to be at more or less the same elevation from the Earth's surface. When this rising air is caused by vertical convection, the clouds that form are called cumulus clouds, those puffy clouds that we see so often in summer that appear to be similar to balls of cotton. Alternatively, when the rising air is captured by the wind driving the air nearly horizontally but with a slight uphill component, such as near mountain slopes, the clouds are typically called stratus clouds, those grey and plate-like clouds that we see so often in winter (Fig. 10.9).

As it turns out, this condensation of water into liquid in the atmosphere is another absolutely essential feature for virtually all life on our planet. That is because when water condenses, it undergoes a chemical phase change that releases energy into the atmosphere *(about 600 calories per gm of water vapor!)*, most of

Fig. 10.9 Cumulus clouds

which turns into heat [104]. As described previously, heat is nothing more than increased vibration of the molecules. So the molecules get excited, and they bump up against their neighbors, and that excites their neighboring molecules. A party breaks out, and sometimes the party gets out of hand. The partiers get more and more excited, and they become unstable. Armed with this new-found increase in kinetic energy, the parcels of air rise even more, and as they do so, more and more condensation occurs, creating more clouds, and releasing more energy into the atmosphere, causing the party to grow without any outside intervention. Now we are headed for a thunderstorm!

A thunderstorm occurs when the difference in the potential energy aloft and at the ground becomes so large that the most efficient way for the difference in energy (as required by the First Law) to be mitigated is through the transfer of energy electromagnetically. It takes a staggeringly large difference in potential energy between clouds and the Earth's surface for this to happen. When you see a lightning bolt, it is physically the same phenomenon that produces a shock to you when you walk across a rug at home, but since the distance between the cloud and the ground is so much larger, it takes a much larger energy difference for this to occur.

The thunderclap that results from lightening is nothing more than the acoustic wave produced by the air rushing back into the vacuum created within the shaft produced by the electromagnetic energy rushing from altitude to the ground. All of this happens because water releases energy to the atmosphere when it condenses, and this energy, just like all energy, is trying to reach thermodynamic equilibrium (once again due to the First Law of Thermodynamics) by the path of least resistance (Fig. 10.10).

A cold front is a mass of cold air that is pushing southward in an attempt to find thermodynamic equilibrium. It in turn pushes warm air Northwards ahead of the front (due to conservation of mass). A cold front is capable of producing dangerous thunderstorms. The warm air ahead of the front has moisture in it if it has travelled

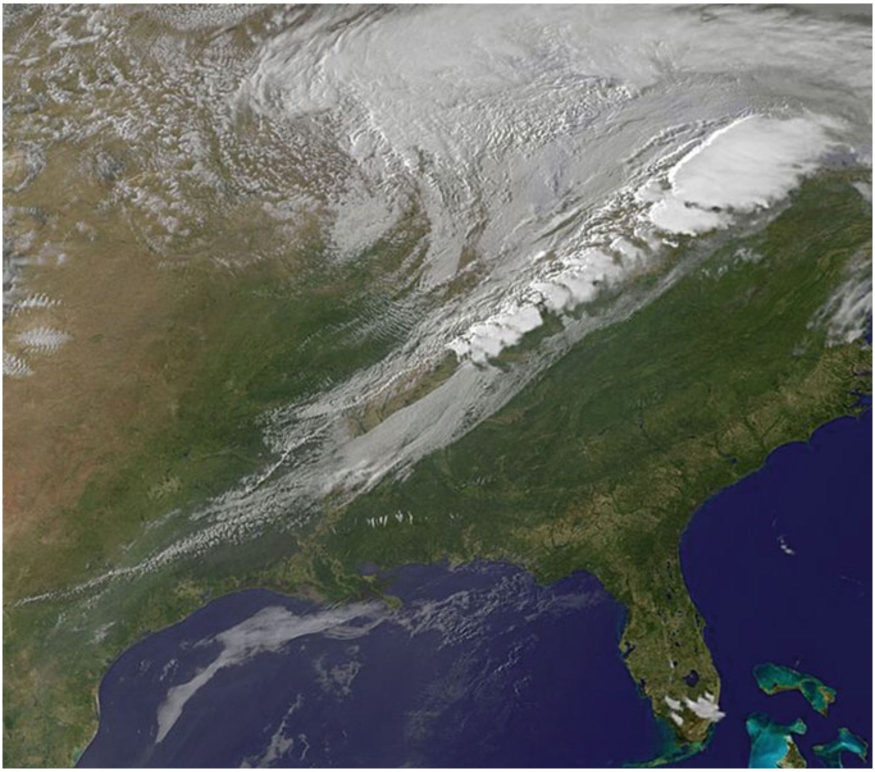


Fig. 10.10 Satellite photo of a line of thunderstorms over the Eastern U.S. on May 3, 2012, photo taken by the Goes-13 satellite

over a large body of water. In the United States, the large body of water that injects most of the moisture into the atmosphere ahead of cold fronts is the Gulf of Mexico. This is due to the fact that the air is flowing in a generally Northerly or Northeasterly direction ahead of the front. Because the Gulf of Mexico is south of only the eastern half of the country, cold fronts produce far fewer thunderstorms over the western half of the country (Fig. 10.11).

The mass of cold air pushing southwards forms a bubble that slides under the warm air. This is due to the fact that the warm air has more kinetic energy, so it rides over the cold air. The warm air has lots of moisture in it from the Gulf, and as it is pushed upwards by the cold bubble of air beneath it, the warm air is cooled adiabatically, thereby causing clouds to form (thus releasing energy to the atmosphere), and eventually enough condensation causes rain, and usually thunderstorms as well. This type of phenomenon would not be nearly so pronounced if we didn't have the Gulf of Mexico feeding moisture into the atmosphere. So the United States has some rather unique geography that encourages the formation of severe weather when cold fronts push south. All of this is driven at least in part by mechanics (Fig. 10.12).

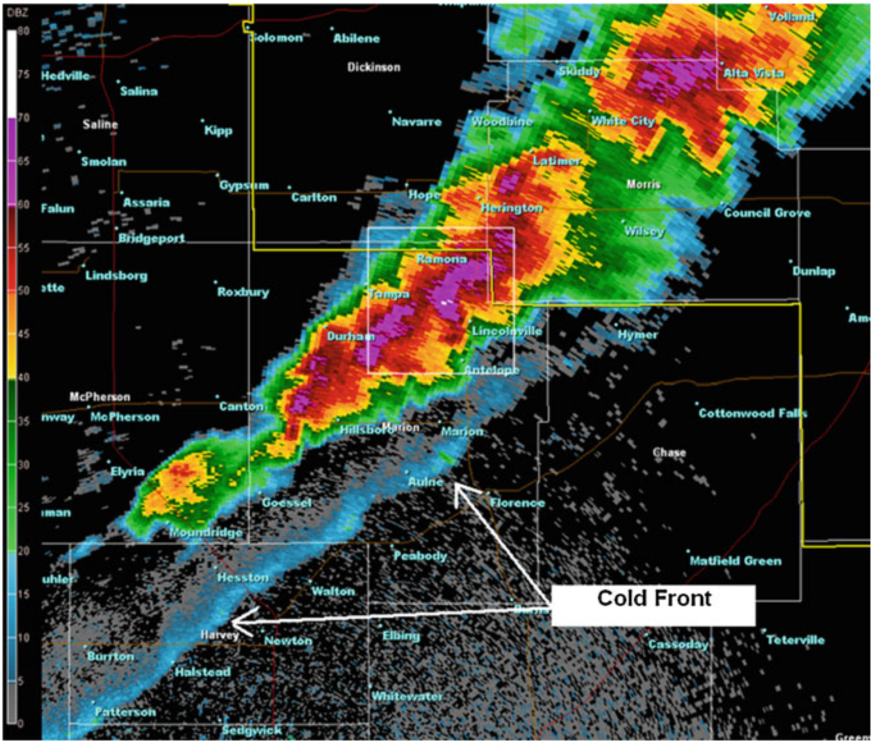
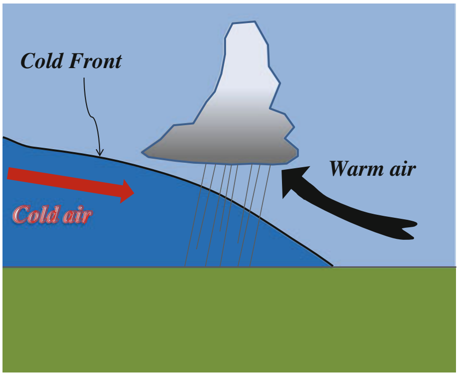


Fig. 10.11 Radar image taken by national weather service Wichita, Kansas WSR-88D on April 3, 2011

Fig. 10.12 Cross-section of a typical cold front



If water didn't undergo an exothermic reaction when it condenses in the atmosphere, the amount of rainfall on Earth would be negligibly small compared to what we experience. If that were the case, nearly all plant life would not exist on this planet. In that case we would not have an atmosphere, in which case there would be little animal life. So once again we come back to the realization that the peculiar chemical properties of water underlie the nature of our planet.

Now consider the "butterfly effect". This term seems to have been coined by MIT Professor Edward Lorenz in the 1960s. Dr. Lorenz noticed during simulations he was performing to model atmospheric physics that due to inherent nonlinearities in the model small changes in initial and boundary conditions could lead to amazingly large changes in the predicted response. This problem seems to have been first recognized by French Physicist Henri Poincaré in the 1890s, and is nowadays termed "chaos theory".

From a layman's perspective, an example serves to illustrate the issue. Suppose that a butterfly flaps its wings near a tree in West Africa. The tiny disturbance caused by the flap of its wings propagates into the nearby tree (or perhaps even a blade of grass), and this causes a small vortex of air to begin spinning counterclockwise. It has to be spinning counterclockwise, otherwise the Coriolis Force (to be described below) will cause the vortex to dissipate.

The conservation of the angular momentum (Newton's Second Law) in this vortex causes the vortex to tend to continue to spin. Additional energy is added to the vortex by the surrounding environment, and the vortex persists, expanding as it does so. The vortex is transported along by the prevailing breeze, whereupon it is transported over a body of water, whence it picks up water molecules by the evaporation process described above. Upward flow of water molecules within the vortex causes condensation, thereby injecting further energy into the vortex. This process becomes unstable, feeding on surrounding supplies of energy, primarily in the form of energy acquired from solar radiation and stored as heat in bodies of water. If the prevailing wind direction is just right, the vortex floats out over the ocean, and under just the right set of climatic conditions a hurricane is born.

As we have previously seen, the Earth is spherical (due to gravitational forces), and the radiation from the Sun comes to us in an essentially planar wave structure. Due to the incompatibility of these two shapes, more energy is supplied to equatorial regions of the Earth than at the poles, thus the Earth is constantly trying to reach thermodynamic equilibrium (due to the First and Second Laws of Thermodynamics).

Our newborn hurricane now goes on a quest to mitigate the spatial difference in energy state caused by the spherical shape of the Earth. So where does the hurricane go? The answer is—wherever it can equilibrate the spatial variation in the state of energy the most expediently. Typically, in the case of West Africa, the best place for this to occur is the Southeastern United States during the late summer months, where a great deal of heat has been stored up over the preceding summer months. So off goes this hurricane in search of plunder.

A typical category four hurricane has about 1 PW of power during the daytime. In layman's terms, this means that the hurricane is expending energy at the rate of about one ten megaton nuclear explosion every 20 min. Needless to say, it's a good idea to stay away from this monster if at all possible, but that is not always expedient. Thus far no one has figured out on this planet how to tame one of these wild freaks of nature. Until they do, the weather will be one of the most powerful

Fig. 10.13 Satellite photo of hurricane Katrina on August 28, 2005

destructive forces on our planet. Thus, as water giveth, it also taketh away (Fig. 10.13).

So we have these two major causes of global weather: the shape of the Earth; and, the peculiar properties of water. Without both of these, weather on this planet would be at the very least quite different.

Another interesting feature of our weather that is directly caused by mechanics is due to the Earth's spin on its axis. As we all know, the Earth makes one complete revolution on its axis every day, and that is in fact how we define the duration of a day. This rotation is caused by left over angular momentum from the impact of the Earth with an object about 2.5 billion years ago, as discussed above.

When the Earth was struck by this object the impact occurred at an angle that was oblique to the surface of the Earth, causing the Earth to start spinning. In the absence of any external forces, this momentum will persist forever. However, this left over angular momentum is slowly depreciating with time, so that a day is growing ever so slightly longer with time (about 1 s every 18 months). This slowing of the Earth's rotation is caused by tidal friction, thus causing the Earth to slowly transfer momentum to the Moon, which is causing the Moon to slowly move away from the Earth. In fact, if the Earth and the Moon continue on this pace, a day and a month will eventually converge, meaning that the Moon will be orbiting about the Earth at the same rate that the Earth is spinning, but you needn't worry about that happening any time soon.

Anyway, the Earth's spin about its own axis causes every point both within and on the Earth's surface to possess a small amount of angular momentum with respect to any coordinate system constructed relative to a given location on the Earth's surface. The force generated by this angular momentum is called the Coriolis Force, after Gaspard-Gustav Coriolis, who was the first to describe it in a scientific paper in 1835. The force is caused by the moment resulting from the angular momentum multiplied with the moment arm about the center of rotation of the object.

This force is the physical principle behind Foucault's pendulum, first demonstrated in 1851 by Léon Foucault (1819–1868) in the Paris Observatory. A few weeks later it was put on public display at the Panthéon in Paris (No, it's not the Roman Pantheon. That one is in Rome.). If you travel to Paris, make sure that you visit the Panthéon, because there is a reproduction of Foucault's pendulum therein, and it is 67 m tall!

Interestingly, if you are standing on the Earth's equator, the vector representing this angular momentum is parallel to the Earth's surface, as shown in Fig. 10.14. That means that the Earth's angular momentum tends to make you fall down. Of course, you do not fall down, and that is because this component is very small and your body is compensating for this.

Now note from Fig. 10.14 that if you are standing at the North Pole this vector causes you to want to spin around, but once again your body compensates for it

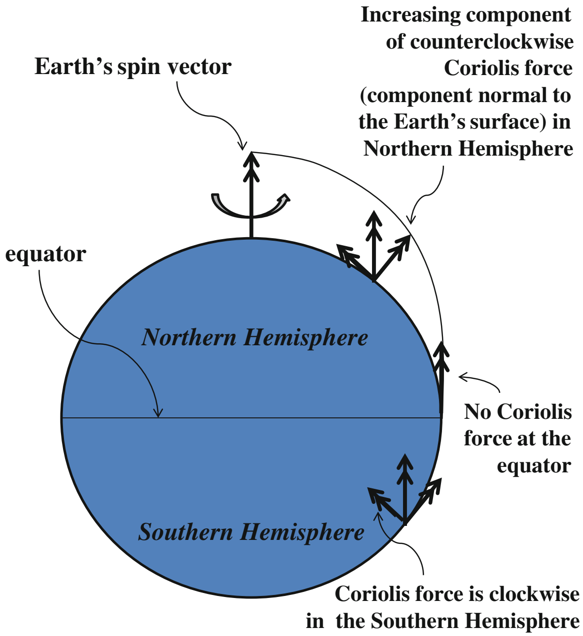


Fig. 10.14 The Coriolis force

(I'm assuming that you have actually been to the North Pole!). Still, the liquid and gaseous molecules within your body will tend to spin (at the rate of exactly one revolution per day) in a counterclockwise direction (and in a clockwise direction if you are at the South Pole, where, since you will naturally invert your coordinate system so that you are not standing on your head, thus resulting in a change in sign of the direction of spin relative to you). In between the poles, the component of spin normal to the Earth's surface decreases as you approach the equators, due to the decomposition of the angular momentum vector into components perpendicular and parallel to the Earth's surface, as shown in Fig. 10.14.

The Coriolis Force therefore tends to make liquids and gases appear to spin counterclockwise in the Northern hemisphere, and clockwise in the Southern hemisphere. I say "appear to" because it is really a matter of what coordinate system you are referring the movement with respect to, another example of relativity. If you use a coordinate system that is rotating with the surface of the Earth, it will appear that the object is rotating, but if the coordinate system itself is fixed so that the Earth spins with respect to it, the object will not appear to be spinning.

What all this means is that air in our atmosphere tends to spin counterclockwise with respect to a local coordinate system aligned with one axis pointed away from the center of the Earth in the Northern Hemisphere (and conversely, clockwise in the Southern Hemisphere), and this effect is ever more pronounced as the air approaches the North Pole because the component of the Coriolis Force perpendicular to the Earth's surface increases with latitude, as shown in Fig. 10.14.

Interestingly, right at the equator, the component of the Coriolis Force perpendicular to the Earth's surface is zero, so that air particles do not tend to spin horizontally at the Earth's equator. Unfortunately, there is sufficient force outside this equatorial band to nevertheless cause enough rotation to overcome the small amount of friction in the air, so that once a volume of air begins to rotate, the Coriolis Force is large enough to provide sufficient angular momentum to the spinning volume of air to keep it rotating. This is bad news, because air that is rotating counterclockwise in the Northern Hemisphere (and vice versa in the Southern Hemisphere) will have a small amount of what we call "convergence", which is a fancy term for molecules wanting to come to together, and this effect will inject more and more kinetic energy per unit volume into the atmosphere, thereby providing fuel for water vapor to condense. And as we now know, when water condenses, it injects more energy into the atmosphere. So this counterclockwise spinning seems to just keep going and going, almost as if it is self-fueling. But it really gets its start from the Coriolis Force. Later on, it gets its fuel from wherever it wants to, but a lot of it comes from condensation of water vapor in the atmosphere. And this is how major weather patterns are formed on our planet. So once again we see that mechanics plays a big part, but without water, weather wouldn't be very interesting.

Now we have a bit of an understanding of how big weather patterns get going. They can be hurricanes, but they can also be cold fronts. In either case, it's all about the Earth trying to reach thermodynamic equilibrium, thus pushing warm air

Fig. 10.15 Tornado in central Oklahoma, May, 1999, photo shot by en:VORTEX-99 team

towards the poles, and cold air towards the equator. These big weather systems can be on the scale of hundreds or even thousands of miles. But typically, the highly active portions of these systems are usually on a scale about one tenth of the Earth's radius, which is about 6,366 km (3820 mi). So a typical hurricane or cold front has an active portion on the order of 640 km (380 mi). Interestingly, there are nasty things that can happen on one length scale down from this, such as the width of a line or band of thunderstorms, which might be about 60 km (35 mi) in scale. And we can go down another length scale to about 6 km (3.5 mi), which is about the scale of a single cell in a line of thunderstorms. One more length scale down, and we come to the scale of a tornado, about 0.6 km (0.35 mi). And yes, we can go even further down, to about 0.06 km, (0.035 mi), which is the scale of a typical gust of wind (Fig. 10.15).

My, what a mess! We have nasty things occurring within our atmosphere on Earth at virtually every length scale up to the size of the Earth itself. Why is all of this occurring? The answer is—because it can! Whether it was a sadistic plan by a supernatural being, or whether it was just plain luck that produced the physics that govern our Universe is neither here nor there. The fact is, the physics that governs weather on our planet is nonlinear, and this nonlinearity causes really nasty things to occur on a wide range of length scales.

So let's talk a little bit about how that works. There are about 10^{44} molecules of air on Earth. That's a lot! Because there are so many, shortly after the turn of the nineteenth century, several scientists decided to assume that's pretty close to infinite. Thus, the field that we call today "continuum mechanics" was born (see Chap. 9). Among the early practitioners of continuum mechanics was the French scientist Claude-Louis Navier (1785–1836). He proposed a model for predicting the motions of liquids and gases in 1821 that was later more fully elucidated by George Gabriel Stokes (1819–1903), so that today we call the equations resulting from this model the Navier–Stokes equations. These equations have been shown to do a pretty good job of predicting the motions of most fluids, including liquid water and gaseous air. Unfortunately, these equations are nonlinear, and that nonlinearity introduces instabilities that cause all sorts of bad things to happen, not the least of which are spinning vortices on multiple length scales such as found in our global weather. So much of our problems with weather stem from mechanical nonlinearities in the way that fluids behave. In other words, mechanics plays a big part in Earth's weather.

But this doesn't explain the entire problem. The Navier–Stokes equations don't account for the chemistry resulting from water changing phases (from gas to liquid to solid), nor do they account for electromagnetic effects in our atmosphere (such as lightning). In order to account for these effects, the Navier–Stokes equations have to be modified and made quite a bit more complicated, and this has in fact been done by atmospheric physicists. What all of this means is this—we understand the chemistry, thermodynamics and mechanics of what goes on in our Earth's atmosphere, but *we nevertheless still cannot predict the weather accurately!*

This situation is rather baffling to most people who have never encountered such a complicated situation. However, there is in fact a similar situation that occurs in an application that many more people on our planet are studying than the weather, and that is the human body. So those of you who are in the medical field should understand what I am referring to when I say that we understand the problem, but we still can't solve it, because we have encountered the same situation with many diseases. We will discuss this problem more later, but for now, let's get back to the weather.

For the sake of convenience, let's just assume that if we had a model that could predict where every molecule in the Earth's atmosphere would go in the future as a function of time and space, then we could predict our global weather on Earth (because we do in fact already have this model!). Now, let's talk about taking that model and putting it into practice. As I said before, there are about 10^{44} molecules of air on Earth. In order to model each and every one of those molecules, we will have to deploy each of the equations in our model for every one of those molecules. That will raise the number of unknowns by about an order of magnitude, to 10^{45}, and we will have to know all of this information at each instant of time as far out in the future as we need to predict. So let's suppose that we can write up our model into a computer code for this purpose (because this has in fact been done!). Let's now go find a computer that will handle all of this computing for us. It shouldn't surprise you to know that we will need a computer that can handle 10^{45} pieces of information at each instant of time. Let's go find that computer.

Okay, first we'll look in our general neighborhood. The very best laptops that we can find today can handle about 10^{15} bits of information. That's not going to cut it. Well, let's get all of our neighbors together and link up our computers into a "cloud computer" (pun intended!). For convenience, suppose our neighborhood is really big, like it includes every person on Earth, and they all have this same powerful laptop. That will get us to 7 billion $\times$ 10^{15}, or about 10^{25}. Unfortunately, that's only a very tiny bit of the way there, so this approach is not going to work.

So let's go another way. Let's go find the best supercomputer that we can. The fastest supercomputers on Earth today can only run at speeds of tens of petaflops (10^{15} calculations per second). It is estimated that the ability to run at exaflop

Fig. 10.16 Photo of Earth taken from Apollo 17 showing the global scale of weather

(10^{18}) speeds are still about 20 years away. Therefore, we're not going to get there that way any time soon either (Fig. 10.16).

But wait a minute. Suppose we don't feel the need to model every molecule on Earth. What we'll do is only model one hemisphere (Say, the Northern). That will cut our time in half. But that is still not good enough. Let's just model North America. That will cut it down by an order of magnitude. So we're now down to perhaps 10^{44} calculations per second that are needed, but we still have no computer that is even close to what we need in order to model weather phenomena on multiple length scales.

How long will it be before we can solve this problem of predicting the weather accurately? Fortunately, we have an accurate model for that. It's called Moore's Law, named after Gordon E. Moore (1929), who reported his law in a journal article in 1965 [105]. What it says is that computers will double their performance every eighteen months, and Moore's Law has been accurate for more than a century now. So if Moore's Law continues to hold, how long will it be before we have a supercomputer large enough to predict global weather? The approximate answer to this question can be obtained by solving the following equation for n:

$$10^{46} = 2^n \times 10^{18}$$

Solving the above will tell us that there will have to be $n = 93$ doublings of computer capacity, or 140 years will pass before we have a computer powerful enough to make accurate predictions of global weather patterns. This is absolutely amazing! We seem to have a model, but we do not have the computing power to solve it. Our generation is not quite the first in human history to encounter this problem (see Chap. 9), but we are now encountering it in a number of disciplines. For the first time in human history, we understand a myriad of problems well enough to construct robust models, but we can't solve them using our current state of technology.

So if you were planning to become a meteorologist, this discussion should give you some comfort. The weather is not going to become concisely predictable any time soon, meaning that your chosen profession is likely to be needed for several generations to come, at least on planet Earth. Until then, we will likely continue to make weather forecasts that rely heavily on satellite imagery, another problem related to mechanics.

We have now seen that mechanics plays a pivotal role in the Earth's weather. So once again we come back to the subject of this book, and in this case we are talking about weather. Just exactly how does weather shape our world? Here is a partial list for starters:

- Erosion from rain and wind forms hills, valleys, and rivers
- Rain provides sustenance for plant and animal life
- Humans plan their travel based on weather where they are going, thus affecting global transportation networks
- Major storms bring many (or sometimes all) means of transportation to a halt
- Weather can upset world financial markets, such as when orange groves freeze in Florida
- Weather can make your day or ruin it
- Extreme weather is known to wipe out entire species (possibly someday including our own).

Thus, it should be clear that the mechanics of weather plays a major role in shaping our modern world.

Life Cycles

11

There is, in nature, perhaps nothing older than motion….
Galileo Galilei (1564–1642)

Recorded history, the period during which we have extant written records, spans less than 10,000 years on Earth. With very few exceptions, the Earth itself has been relatively unchanged during that span of time. However, if we could somehow speed up the clock and view a movie of the Earth over a much longer period of time, the Earth might indeed appear to be a living and breathing entity, as we will see in this chapter on life cycles.

The Big Bang

Scientists estimate that the Big Bang, originally proposed by Georges Lemaitre (1894–1966), occurred about 13.7 billion years ago. They estimate this by using mechanics—Albert Einstein's (1879–1955) general theory of relativity to be exact. Vesto Slipher (1875–1969) proposed that based on the red shift observed in the wavelengths received on Earth from stars throughout the galaxy it is possible to estimate the velocity that objects are moving away from one another. From these estimates one can extrapolate backwards in time and estimate the point in time at which all of these objects were at approximately the same location, ergo the Big Bang. Thus, we can infer that mechanics undoubtedly existed before the historical record began. In fact, mechanics was born the very moment that the Big Bang occurred.

By observing very remote objects in the universe it is possible to gather important information regarding the distant past. Using the Hubble telescope, astronomers have recently observed a quasar that is 13 billion light years from Earth. That means that the light from this star began its journey to Earth 13 billion years ago, when the universe was less than a billion years old, and interestingly, *almost nine billion years before the earth itself was formed!* The information that scientists have received from such distant objects thus far has confirmed that the mechanics principles that we are familiar with here on Earth not only seem to hold everywhere in the universe, but they also seem to have continued to apply throughout the history of the universe. For that reason, we call them "universal" laws (Fig. 11.1).

D. H. Allen, *How Mechanics Shaped the Modern World*,
DOI: 10.1007/978-3-319-01701-3_11,

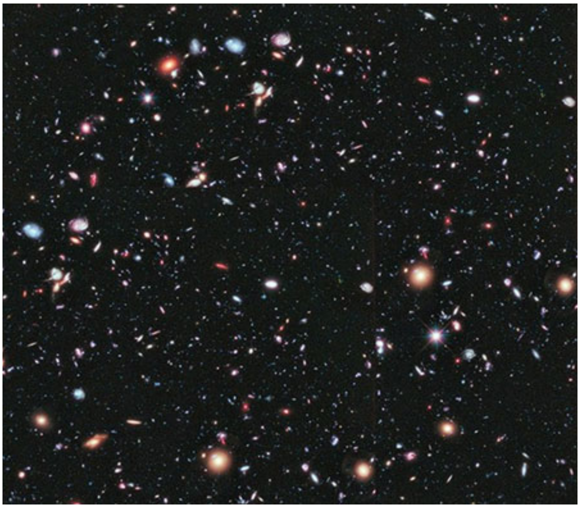


Fig. 11.1 Hubble telescope reveals the deepest view into the universe in a photograph that took 10 years to complete. Extreme deep field image captures thousands of galaxies billions of light years away

Scientists also tell us that there are four different kinds of forces (they actually call them “interactions”) in nature: gravitational forces, electromagnetic forces, strong atomic forces, and weak atomic forces. The weakest of all of these is the gravitational force, but despite this fact, by a quirk of nature, it is gravitational forces that govern our universe. Gravitational forces are inversely proportional to the square of the distance between the objects exerting the forces on one another (see Chap. 7), and because of this, gravitational forces act over very long distances, thus overtaking the other three forces in importance. Indeed, galaxies, solar systems, planets, moons, asteroids, comets,—all are formed by agglomeration resulting from gravitational forces. This is an example of mechanics on a truly enormous scale.

When the Big Bang occurred 13.7 billion years ago, the matter within the cosmos soon began interacting due to gravitational forces. And when our solar system was later formed, the planets evolved from countless impacts of bodies exerting gravitational forces on one another.

How do we know all of this today? The answer is that scientists study the motions of bodies in other solar systems across the universe. In other words, scientists use mechanics to measure the motions of objects that they observe through very sophisticated telescopes that are capable of distinguishing motions of stars and the objects orbiting them. For example, in most cases scientists don’t actually “see” a distant planet. Instead, they typically detect periodic motions of the star (or sometimes even two stars, called a binary system) that the planet of interest is orbiting, and from the frequency and amplitude of the motion of the parent star, scientists can utilize mechanics to estimate the mass and distance that the inferred planet is from the observed star. Armed with these two pieces of information, scientists can deduce additional information about the planet.

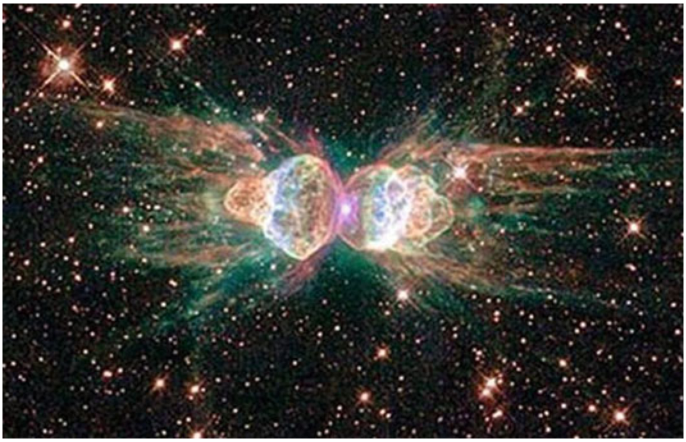


Fig. 11.2 The ant Nebula, a cloud of dust and gas whose technical name is Mz3, resembles an ant when observed using ground-based telescopes. The nebula lies within our galaxy between 3,000 and 6,000 light years from earth

Most of these stars are near to our planet on a cosmological time scale, meaning that they are a small number of light years away, so that the events that are being detected from these nearby solar systems have occurred in the very recent past (Fig. 11.2). But a few of them are also very far away (meaning that we are also looking into the distant past). By looking through this window into the past, it is possible to construe certain information regarding the historical nature of our universe. What we now know is that there are new solar systems being formed all the time. There are also old solar systems, some of which are in the process of dying (Fig. 11.3)

Fig. 11.3 Nebula NGC 2392, called Eskimo because it looks like a face surrounded by a furry hood. The hood is, in fact, a ring of *comet-shaped* objects flying away from a dying star. Eskimo is 5,000 light years from earth

Fig. 11.4 The trifid Nebula, 9,000 light years from earth, where new stars are being born

In fact, there is a broad distribution of ages of solar systems throughout the universe going right back to within a billion years after the Big Bang. It seems that galaxies, solar systems, and even planets are being formed all the time (Fig. 11.4). Just like humans, each one has a life span before they die, but their life span is usually much longer than that of any biological entities that we are aware of.

Our solar system appears to be almost middle aged, having been formed about 4.5 billion years ago, and with a total life expectancy of about 10 billion years. This last approximation is based on the amount of fuel scientists estimate is remaining for the sun to burn before it is extinguished.

Our solar system could perish at any time by a number of means that have low statistical probabilities, but that are nevertheless observed to occur elsewhere in the universe. Among these are strikes by asteroids large enough to upset the orbit of a planet sufficiently for that planet to impact another planet or even the Sun, thus causing the solar system to essentially become unstable and either explode or be cast off into space. Another possibility is that the large gas giants Saturn and Jupiter could exert gravitational forces on one or more other planets that are sufficiently large to upset the planetary orbits, thus causing them to change their orbits into an unstable configuration, thereby leading to the destruction of our solar system. Some scientists think that this jostling about of our planets may have already occurred at some point in the past, as it has been postulated that Uranus and Neptune may have interchanged their orbits.

Any of these theorized scenarios for the possible destruction of our solar system involve mechanics—motions involving kinetic energy so large as to be capable of destroying our entire solar system. Scientists have observed just such events elsewhere in our own galaxy (Fig. 11.5). We have only recently been able to determine that such impact events are still occurring, albeit with decreasing regularity, in our now middle-aged solar system. Fortunately for us, events on this scale seem to occur rarely, as we will see in the next section.

Fig. 11.5 The glowering eyes from 114 million light years away are the swirling cores of two merging galaxies called NGC 2207 and IC 2163 in the distant canis major constellation

Meteors

Much of what we know about meteor strikes emanated from the diligent work of the geologist Eugene Shoemaker (1928–1997) (Fig. 11.6). For his Ph.D. thesis at Princeton University, Dr. Shoemaker studied the Barringer Meteor Crater near Winslow, Arizona. This crater, considered by many to be the most perfectly intact meteor crater on Earth, was created about 50,000 years ago by a meteorite about 50 m in diameter (Fig. 11.7).

In the 1960s Dr. Shoemaker hypothesized that those round shapes on the Moon were not heretofore suspected extinct volcanoes, but that they were instead the remnants of meteor strikes. Of course, if true his theory would have enormous

Fig. 11.6 Photograph of Dr. Eugene Shoemaker

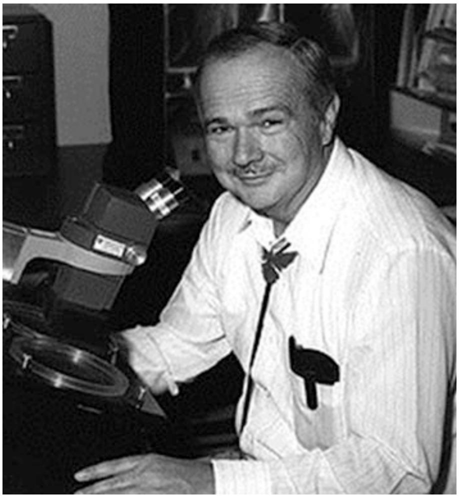


Fig. 11.7 Photograph of Barringer Crater, Arizona

implications for the Earth as well. This is due to the fact that our planet exerts much larger gravitational forces than does the Moon, thus implying an even greater likelihood of meteor impacts on Earth.

Dr. Shoemaker's assertions were initially discounted by many people, but he was undaunted by their doubts. Instead, he went searching for meteor craters on Earth. Other than the obvious Barringer Crater, there wasn't much to go on. But he kept at it, and eventually he began to hit pay dirt (literally).

Dr. Shoemaker was the first person to notice that meteor craters display a unique ring of shocked quartz called coesite from the pressure wave caused by the impact of the meteorite. Such pressures created by meteor impacts are so incredibly large as to cause chemical changes in the adjacent geologic structure, an example of coupling between mechanics and chemistry.

The most interesting meteor crater to me that Dr. Shoemaker discovered is in Nördlingen, in south central Germany. At the time that he was seeking corroboration of his theories there was very little satellite photography to rely on, but he had some images of the countryside surrounding Nördlingen that looked suspiciously circular in shape. He thus travelled to Nördlingen with a colleague and they climbed the small cathedral in the center of town to get a better look at the skyline surrounding the town. Things looked about right, but he still didn't have proof.

Dr. Shoemaker's eureka moment came when he climbed back down to Earth from the bell tower in Nördlingen and examined the stones used to make the cathedral walls (Fig. 11.8). He chipped some pieces off, and sure enough, a scan showed high levels of coesite, thus proving that it was a crater created by a meteor strike, now called the Nördlinger Ries crater, which has a diameter of 24 km. It was formed about 14.5 million years ago, during the Miocene.

Fig. 11.8 St. Georges Church, Nördlingen

There is another crater located 42 km to the west-southwest of the Nördlinger Ries crater called the Steinheim crater, which has a diameter of 3.8 km. The two craters are believed by scientists to have formed together in what is termed a binary event. Apparently one meteor split into two objects on encountering the Earth's atmosphere. Stones from the area also contain large amounts of microscopic diamonds, which were formed when the impact pressure caused naturally occurring graphite to form into diamonds, another example of a chemical process induced by mechanics.

Chemists explain this phenomenon using something called a phase diagram, which is nothing more than a graph of temperature versus pressure for a given atom or molecule that distinguishes the various bonding structures that are possible as functions of temperature and pressure. What is not stated explicitly on a phase diagram is the fact that pressure (as well as temperature) changes can be induced by mechanics, as in the case of meteor strikes on Earth. Thus, chemistry and mechanics are innately connected.

Dr. Shoemaker slowly assembled a growing body of evidence to support his contentions, but he wasn't finished yet. In 1993, Dr. Shoemaker, his wife Carolyn, and David Levy discovered a comet that was heading for Jupiter. It was subsequently named Shoemaker-Levy, and in July of 1994, it broke up into several meteors just before striking Jupiter in a string of spectacular explosions (make sure that you watch the film clip on YouTube!) (Fig. 11.9).

There was much excitement in the astronomy community, for this was the smoking gun as it were—the proof that Dr. Shoemaker's assertions regarding meteors, comets, and asteroids were correct. As we now know, those rings on the surface of the Moon are craters from meteor strikes instead of extinct volcanoes. And sure enough, within a few years of these revelations we had plenty of popular disaster movies predicting a catastrophic meteor strike on Earth. I'll bet you've seen several of them.

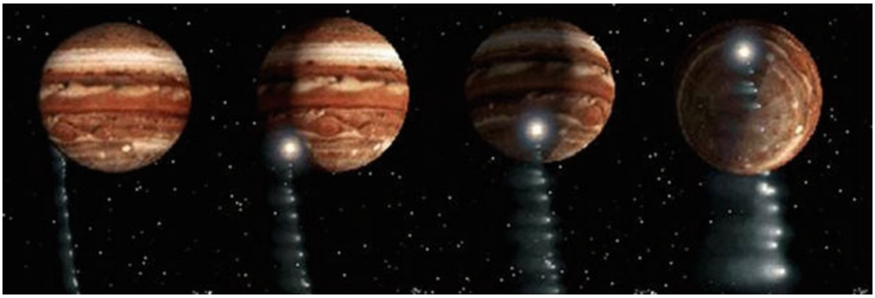
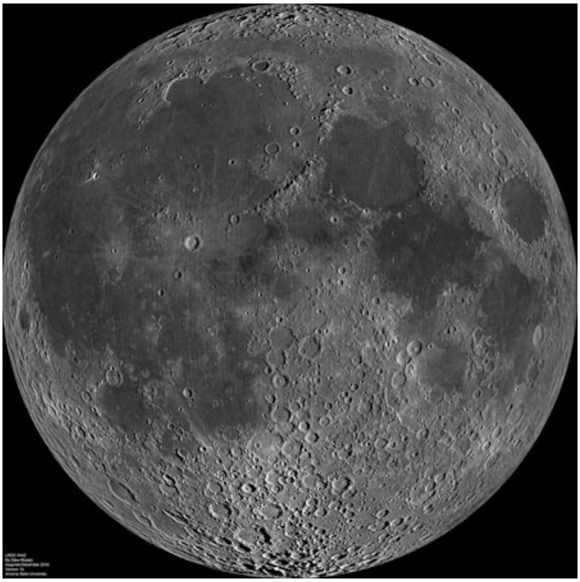


Fig. 11.9 Shoemaker-levy strikes Jupiter

Dr. Shoemaker was at one time in line to be one of the original astronauts in the 1960s, but he was excluded because he was diagnosed with Addison's disease. While that was surely not good for him, it may have been a good thing for the rest of the world. Otherwise, we might not have had all of these important discoveries regarding meteor strikes on Earth. And quite a few Hollywood movie employees would be out of work as well.

Dr. Shoemaker was unfortunately killed in an automobile accident in Australia while searching for a meteor crater. For his lifetime of scientific achievements, a portion of his ashes were transported to the Moon by the Lunar Prospector space probe, making him (at the time of this writing) the only human buried on the Moon (Fig. 11.10).

Fig. 11.10 Photo of the near side of the moon showing meteor craters



Geologists like to talk about a "geologic time scale". This is very interesting stuff. I don't want to go into too much detail here, because you can find a summary of geology in Bill Bryson's excellent book entitled *A Short History of Nearly Everything* [106]. Fortunately for me, he didn't cover a whole lot of mechanics, which I suppose is why the word *nearly* is in the title of his book.

A big part of the reason that the geologic time scale became important in this century is a by-product of carbon dating. If you find a chunk of geologic material, and you find a piece of biological material within it, you can guess how old the geologic material is by utilizing carbon (or other elemental) dating. This technique was initially developed by Willard Libby and his colleagues at the University of Chicago in 1949, for which Dr. Libby received the Nobel Prize in 1960.

The reader can look elsewhere for the details regarding this technique, but suffice it to say that the technique involves the experimental capture of the *motions* of decaying radioactive isotopes of carbon-14. Since all atoms are not carbon-14 in a given sample of carbon, it is therefore possible to estimate the age of a sample of carbon by determining the portion that is carbon-14. Thus, the measurement of the age of biologic material is determined by using our new-found friend mechanics. This is possible only in samples containing carbon, and this element is usually found prodigiously in biologic media. Thus, scientists look for dead creatures in samples of specimens whose age they are attempting to determine.

Carbon dating isn't always correct, because either older or newer carbon-laced materials can get into the geologic media and corrupt the estimate. Nevertheless, geologists have managed to utilize this technique to date most of the earth's geologic formations accurately. I will discuss this in more detail later in this chapter, but for now suffice it to say this: our planet's surface is constantly on the move, and this is inherently a problem in mechanics.

One thing you can do with carbon dating is to determine when all sorts of natural disasters occurred in the past. For example, we have the famous Chicxulub meteor strike in the Yucatan that may be responsible for wiping out the dinosaurs around 65 million years ago (Fig. 11.11). This strike was discovered by geologist Glen Penfield in the late 1970s. He found large amounts of coesite (as well as iridium, an element found in meteorites) in the region, thus confirming the strike. The crater is approximately 180 km in diameter, and is estimated to have been caused by a meteorite approximately 10 km in diameter, thus making it one of the largest known impact sites on Earth. The date of the impact is estimated by using carbon dating to determine the age of biologic materials found within the stones at the site.

On a geologic time scale, meteor strikes are pretty few and far between on Earth. The most recent event was in Siberia in 1908 (a meteorite also struck Russia during this writing in February of 2013). This impact, called the Tunguska event, is the largest in recorded history, resulting from a meteor estimated at approximately 100 m in diameter.

There have been approximately 50 other meteor craters discovered and confirmed on Earth to date. Unlike those on the Moon, they are difficult to spot because we have a tectonically active shifting crust, as well as an atmosphere that produces rain, wind and subsequent erosion (See Chap. 10).

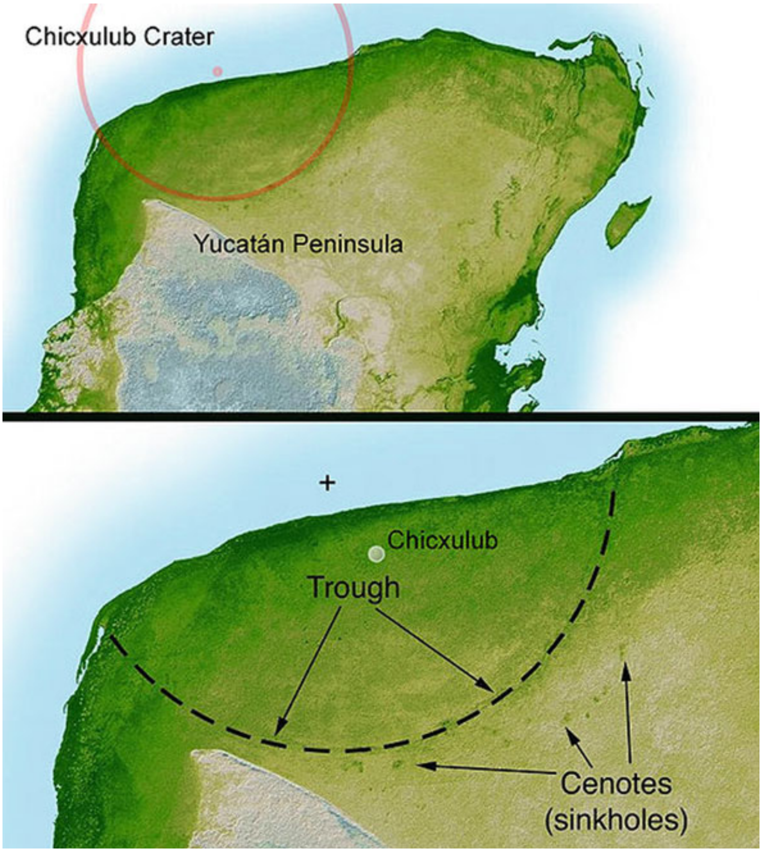


Fig. 11.11 Chicxulub crater

Of course, there have surely been a lot more than 50 meteor strikes on Earth in the past 4.5 billion years. After all, the Earth was formed early in our solar system's life due to the agglomeration of uncountable numbers of objects striking one another. But our geologically active planet has slowly wiped out the observable record of all save those that occurred since the Earth's geologic activity began to settle down, otherwise the surface of the Earth would look like the surface of the Moon. Thus, there are only a couple of known craters that are older than 2 billion years, and most are less than 500 million years in age.

Suffice it to say that the geologic record indicates that the probability of a large meteor strike on this planet on any given day is extremely remote. Furthermore, scientists nowadays have sophisticated mechanics-based tracking equipment that will give us plenty of advance warning if a large object heads our way. So don't pack up the car and start heading for the hills just yet. Still, should a kilometer (or greater)-sized object strike our planet, the kinetic energy contained within it will be sufficient to cause a global calamity that could wipe out most of the species on Earth, including our own (see Chap. 14).

Tectonic Plates

The current views of geologists were influenced by the meteorologist Alfred Wegner, who proposed the concept of continental drift in 1912. He noticed that the shape of the Eastern coast of South America bore a strong resemblance to the Western coast of Africa. Subsequent geologic examinations provided evidence that these two coastlines were at one time joined together.

While Wegner's views were initially discounted by the scientific community, he was eventually proven correct when it was discovered that the continents are drifting apart due to seafloor spreading. This is a fancy term that simply means that there are cracks on the sea floor out in the middle of the ocean that are slowly creating and spreading new surface material, and this is of course another example of global scale mechanics, this time involving long term flow of the Earth's crust.

The exterior of the Earth is composed of a series of tectonic plates that lie on the surface, called the lithosphere, which is about 200 km in thickness. These plates are relatively stiff and strong compared to the underlying layer, called the asthenosphere, which is viscoelastic (a combination of fluid- and solid-like), thus allowing the lithosphere to slowly slide over the asthenosphere. The plates slide due to a combination of gravitational forces, momentum induced by the Earth's spin, and most significantly by forces produced by convection of the underlying mantle. This produces a global scale problem in mechanics. These enormous forces slowly deform and translate the surface of the Earth over hundreds of millions of years.

About 200 million years ago the continents were all joined together (the last time) in a single super continent called Pangaea (from the Greek 'pan', meaning entire, and 'Gaia' meaning earth) by geologists. This term was apparently coined during a discussion on Wegner's theory in 1927. I will refrain from showing an image of Pangaea for the simple reason that through the miracle of the internet you can (and should) view a movie of the evolution of Pangaea on YouTube.

There are currently eight major plates covering the Earth's surface, as well as a number of smaller ones (Fig. 11.12). Because the continents are spreading apart in some places, it stands to reason that there must also be some places where the continents are coming together, since the surface area of the Earth is not changing. This is accomplished via plate subduction, which is another fancy term that simply means that one plate rides up over another. In other places the plates simply slide laterally with respect to one another (Fig. 11.13).

Relative motions between tectonic plates results in what we call earthquakes. The plates normally get stuck relative to one another for a period of time, but as the forces build up between the two plates attempting to slide relative to each other, eventually the forces will overcome the shearing load carrying capability of the two plates, and they will slip more or less instantaneously with respect to one another, thus producing an earthquake, which is nothing more than a mechanical wave passing through the Earth's crust.

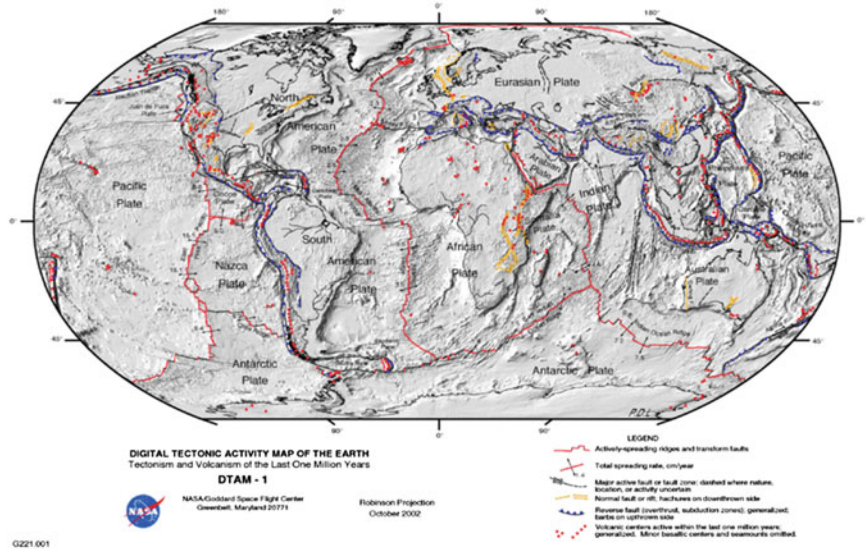


Fig. 11.12 The Earth's tectonic plates

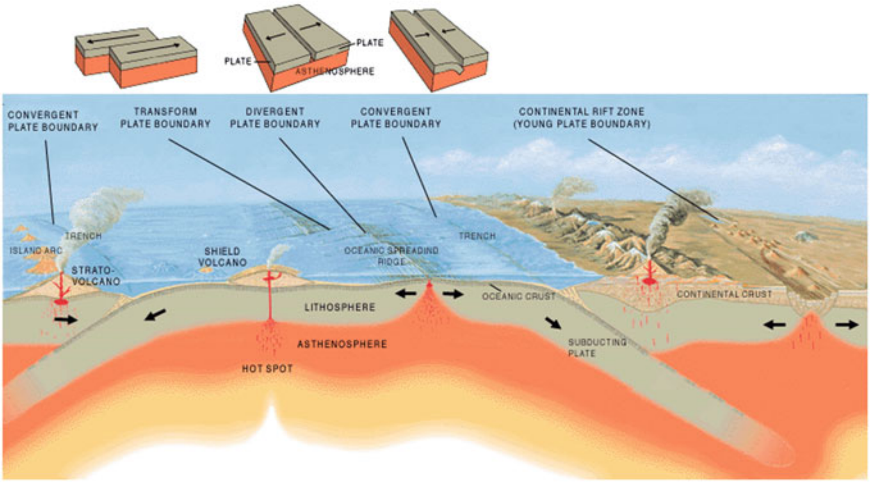


Fig. 11.13 Three types of tectonic plate boundaries

As described above, earthquakes can be caused by lateral sliding between two plates, or they can also be caused by one plate sliding on top of the other (subduction). This latter type can be particularly damaging when the two plates are in the ocean, because this type of earthquake produces a mechanical wave which may lead to a tsunami.

Water is a liquid. Liquids are viscous in shear, and elastic in compression. What this means is that they store energy extremely well in compression, but they dissipate it rather quickly in shear. So when a subduction zone produces an earthquake, the ocean wave that is produced is a compression wave, and this type of wave stores energy so well that it can cross an entire ocean without dissipating very much energy. This type of earthquake is capable of producing tsunamis thousands of miles from the quake site.

The wave is normally not very tall in the deep waters of the ocean, but as the wave moves through shallower and shallower water as it approaches the shoreline the wave is forced skywards as it seeks a means of propagating ahead. Normally the wave propagates *through* the ocean, without actually displacing the molecules. However, when the wave approaches the shoreline the water molecules are actually transported forward. The top part of the wave, near the surface of the water propagates forward faster than the water below, forcing the wave higher and higher above sea level as it races to shore. Eventually, the wave becomes unstable as the tip of the wave outraces the lower part, crashing on the shore with enormous energy. For example, a subduction earthquake occurred on December 26, 2004 off the coast of Sumatra, Indonesia. The resulting tsunamis struck the coast of virtually every land mass surrounding the Indian Ocean, sending thirty foot waves ashore, killing 230,000 people. This is a big problem in mechanics.

Scientists still cannot accurately predict when and where an earthquake will occur. However, fortunately for us, scientists now understand the mechanics of earthquakes sufficiently well that they can predict with some accuracy when and where a tsunami will strike the shore once an earthquake has occurred. For example, when the earthquake struck off the coast of Tōhoku, Japan on March 11, 2011, scientists issued tsunami warnings that saved countless lives.

Perhaps someday in the not-too-distant future scientists will be able to predict when and where earthquakes will occur. The logical succession of events would therefore be to utilize this information not just to forewarn the populace in the area affected, but perhaps even someday to undertake preventive measures to prevent both the earthquake and resulting tsunamis altogether. This solution, if it is ever to be realized, will doubtless involve the use of mechanics.

Volcanoes

Tectonic plate boundaries can also have imperfect contact with their neighboring plate, thereby producing gaps in the Earth's crust that allow magma to escape to the Earth's surface. Where this occurs violently, we call it a volcano. Most volcanoes occur along tectonic plate boundaries.

When one plate is riding over another, the lower plate is slowly pushed lower and lower beneath the plate on top. The plate on top is pushed upwards, thus producing the shoreline of land masses.

The lower plate has typically come from the ocean floor, so that it is saturated with water. As this water is pushed downward beneath the shoreline within the subducted plate, it can sometimes reduce the melting temperature of the overlying mantle, thus creating magma. Sometimes this magma cools before it reaches the surface, but occasionally the magma will boil upwards to the surface, thereby creating a volcano.

On other occasions the subducted plate induces cracks in the layer above, thereby allowing the magma to reach the surface, again causing a volcano to form. In either case the zone where the volcano is created is typically a few to a few hundred kilometers inland from a coastal area where the subduction is occurring, and this is why for example the volcanoes along the Pacific plate form the "Ring of Fire" somewhat inland from the plate subduction zone, which is in the seabed just off the coast.

A nice example of the power of carbon dating is illustrated by the photograph of Capo la Gala, shown below. Capo la Gala is located on the Sorrentino side of the Amalfi Peninsula, adjacent to the Bay of Naples in Southern Italy. More importantly, it is located about ten miles from Mt. Vesuvius (Fig. 11.14).

We all know about Mt. Vesuvius—that's the volcano that erupted in 79 AD, thereby inundating Pompeii (with volcanic ash) and Herculaneum (with lava) [107]. If you haven't been to either of these places, I strongly advise you to start making travel plans. I've been there quite a few times, and I've not even begun to tire of the treasure trove of information that was buried by this most famous of all volcanic eruptions in recorded history.

The reason that the 79 AD eruption is still so famous is multifold, but let's start with the photo shown in Fig. 11.14. One can readily see that the large stones thrusting downwards into the Bay of Naples are layered. Those are in fact layers of lava flows from eruptions of Mt. Vesuvius! By carbon dating biologic material contained in these layers, scientists have been able to determine that Mt. Vesuvius undergoes an enormous eruption about once every 2,000 years. The clock is

Fig. 11.14 Photograph of Capo la Gala on the Bay of Naples

Fig. 11.15 Street scene in Pompeii

ticking, folks. We are due for another major eruption of Mt. Vesuvius in the not-too-distant future. And we know this because we can carbon date geologic media using mechanics.

Scientists are preparing for the next eruption in a variety of ways. Archeologists studying Pompeii today have determined that the city suffered a major earthquake a few years before the last major eruption of Vesuvius in 79 AD [2] (Fig. 11.15). After the earthquake (and before the fatal eruption), locals began rebuilding the city, using bricks in many places to support the partially destroyed stone columns, similar to that shown below. It is also interesting to note that the Romans cut the lateral beams on an angle in order to provide added friction against failure, a problem in mechanics, as shown in the photo (Fig. 11.16).

Fig. 11.16 Reconstruction of columns in the forum at Pompeii. *Note* the angular cuts in the beams mounted above the columns

The area around the Bay of Naples is today equipped with seismometers, mechanics devices that measure large and rapid motions of the Earth's surface. Thus, assuming that earthquakes will precede the next eruption, we appear to be well equipped to receive plenty of advance warning before the next major eruption of Mt. Vesuvius. The real challenge will be to convince the approximately three million people who are in the predicted path of destruction of the volcano to evacuate before it erupts, because we may not be able to predict with precise accuracy exactly when the next eruption will occur.

There is an interesting footnote to this story. The Mt. Vesuvius eruption in 79 AD was described by Pliny the Younger (his uncle, Pliny the Elder, was killed when he attempted to rescue persons fleeing the eruption), and his description is still extant today. It reads as follows:

> The carts that we had ordered brought were moving in opposite directions, though the ground was perfectly flat, and they wouldn't stay in place even with their wheels blocked by stones. In addition, it seemed as though the sea was being sucked backwards, as if it were being pushed back by the shaking of the land. Certainly the shoreline moved outwards, and many sea creatures were left on dry sand. Behind us were frightening dark clouds, rent by lightning twisted and hurled, opening to reveal huge figures of flame. These were like lightning, but bigger. At that point the Spanish friend urged us strongly: "If your brother and uncle is alive, he wants you to be safe. If he has perished, he wanted you to survive him. So why are you reluctant to escape?" We responded that we would not look to our own safety as long as we were uncertain about his. Waiting no longer, he took himself off from the danger at a mad pace. It wasn't long thereafter that the cloud stretched down to the ground and covered the sea. It girdled Capri and made it vanish, it hid Misenum's promontory. Then my mother began to beg and urge and order me to flee however I might, saying that a young man could make it, that she, weighed down in years and body, would die happy if she escaped being the cause of my death. I replied that I wouldn't save myself without her, and then I took her hand and made her walk a little faster. She obeyed with difficulty, and blamed herself for delaying me.
>
> Now came the dust, though still thinly. I look back: a dense cloud looms behind us, following us like a flood poured across the land. "Let us turn aside while we can still see, lest we be knocked over in the street and crushed by the crowd of our companions". We had scarcely sat down when a darkness came that was not like a moonless or cloudy night, but more like the black of closed and unlighted rooms. You could hear women lamenting, children crying, men shouting. Some were calling for parents, others for children or spouses; they could only recognize them by their voices. Some bemoaned their own lot, other that of their near and dear. There were some so afraid of death that they prayed for death. Many raised their hands to the gods, and even more believed that there were no gods any longer and that this was one last unending night for the world. Nor were we without people who magnified real dangers with fictitious horrors. Some announced that one or another part of Misenum had collapsed or burned; lies, but they found believers. It grew lighter, though that seemed not a return of day, but a sign that the fire was approaching. The fire itself actually stopped some distance away, but darkness and ashes came again, a great weight of them. We stood up and shook the ash off again and again, otherwise we would have been covered with it and crushed by the weight. I might boast that no groan escaped me in such perils, no cowardly word, but that I believed that I was perishing with the world, and the world with me, which was a great consolation for death.
>
> At last the cloud thinned out and dwindled to no more than smoke or fog. Soon there was real daylight. The sun was even shining, though with the lurid glow it has after an eclipse. The sight that met our still terrified eyes was a changed world, buried in ash like

> snow. We returned to Misenum and took care of our bodily needs, but spent the night dangling between hope and fear. Fear was the stronger, for the earth was still quaking and a number of people who had gone mad were mocking the evils that had happened to them and others with terrifying prognostications. We still refused to go until we heard news of my uncle, although we had felt danger and expected more.
>
> You will read what I have written, but will not take up your pen, as the material is not the stuff of history. You have only yourself to blame if it seems not even proper stuff for a letter. Farewell [108].

For those who do not know, Misenum is the ancient name for modern day Miseno, a port on the opposite side of the Bay of Naples from Mt. Vesuvius, about 30 km from the crater. That's quite a large distance for the amount of destruction described above by Pliny.

Pliny's description of the eruption is so inconceivable that it was actually discounted by most credible sources until recently, when Mt. St. Helens erupted in 1980 and demonstrated to the modern world the power of volcanoes. The next eruption of Mt. Vesuvius thus looms large (Fig. 11.17).

Fig. 11.17 Mt. St. Helens eruption on May 18, 1980

As mentioned above, volcanoes are caused by mechanically induced tears or imperfections in the Earth's crust, thereby allowing magma, ash, and noxious gases to escape to the Earth's surface. Most volcanoes can be found along the boundaries of tectonic plates that are either converging or diverging. Thus, volcanic eruptions are a result of deformable body mechanics. These eruptions can spew out incredible amounts of magma, which subsequently hardens and causes major changes in the landscape. In addition, the enormous ash plume spewed out from some volcanoes is sufficient to blot out the Sun and cause global climate change for years to come.

There have been some spectacular volcanic eruptions down through the history of our planet. Of course, really old ones are difficult to study due to erosion of the Earth's surface with time, another mechanics issue. Within the span of recorded history, the most famous eruptions are in chronological order: Santorini (c. 1600 BCE), Vesuvius (79 AD), mentioned above, and Krakatoa (1883). But there are less famous volcanoes erupting quite often all over the Earth.

The Santorini eruption, sometimes called by its ancient name of Thera, occurred about 3,600 years ago on the Greek island of Santorini, blowing the entire center of the island away, and with it virtually the entire Minoan civilization (Fig. 11.18). The resulting tsunami apparently also destroyed the main portion of the Minoan civilization on the island of Crete, a 100 km to the south. Some believe that this eruption, perhaps the largest in recorded history, is the source of the legend of Atlantis, the lost continent [109]. There is a fabulous archeological dig at Akrotiri on the south side of Santorini, demonstrating the city as it appeared before the eruption.

Fig. 11.18 Satellite view of Santorini, showing the part of the Island destroyed in the eruption. *Note* the re-emerging cone in the center of the bay

Fig. 11.19 Photograph of the Volcanic Island recently formed by the Santorini Caldera. *Note* the cliffs of the island inundated by the eruption in the background

The lava dome at Santorini has grown back to the surface of the sea, so that you can take a tour out to the recently formed island, where you will find plenty of solidified lava, along with vents of noxious gases. This is a must see for anyone who travels to Santorini on vacation (Fig. 11.19).

Krakatoa is situated between the islands of Java and Sumatra in the Dutch East Indies. The Krakatoa eruption of 1883 is the largest recorded volcanic event on Earth since the eruption at Santorini. It is estimated that the eruption had a total energy equivalent to about 13,000 times the energy of the atomic bomb that was dropped on Hiroshima in 1945. The eruption was so loud that it was heard at a distance of 5,000 km. Krakatoa is a very active volcano, having erupted several times recently. In addition, the terrain around the volcano is punching through the surface of the ocean quite rapidly, suggesting that other eruptions may be due soon (Fig. 11.20).

Perhaps the most dangerous of all the volcanoes on Earth is the supervolcano at Yellowstone. It is called a supervolcano because of the enormous size of the magma bubble beneath the surface of the Earth in Yellowstone. There have been 142 caldera forming events caused by the Yellowstone hotspot in the past 17 million years. The last super-eruption occurred about 640,000 years ago, ejecting about 1,000 km^3 of rock and ash into the atmosphere. The next time this volcano erupts, and it most certainly will someday, it will wipe out perhaps as

Fig. 11.20 Satellite photo of Anakrakatoa taken in 2007

much as half of North America. Since the last major eruption prior to the latest one was about 1.3 million years ago, we could be due for another one at any time (Fig. 11.21).

My favorite volcano is actually a field of volcanoes that created the Hawaiian Islands. These are the gentlest type of volcanoes that we know of. The Hawaiian Islands were formed entirely by magma seeping through a tear called a hotspot in the Hawaii-Seamount Chain in the mid-Pacific Ocean. These islands are actually part of an extended chain of volcanoes that are continuously being formed by the slow southeastward sliding of this hotspot (5–10 cm per year) on the ocean seafloor (Fig. 11.22).

The Midway Island Atoll, nearly a thousand miles to the northwest of the state of Hawaii is at 28 million years the oldest portion of the Hawaii-Seamount chain. At 800,000 years of age Hawaii is the newest and farthest southeast, and is also the largest island in the chain. The other islands in the chain grow progressively older as one scans northwest along the chain (Fig. 11.23).

Since the volcanoes Mauna Loa and Kilauea are still active on the Big Island of Hawaii, this island is still growing and thus exhibits cone-like orography. In fact, one can see the effects of recent lava flows on the geography of the island by traveling along the southern part of the island. The most recent flow fields display little erosion and have very little vegetation, whereas progressively older flow fields show increasing erosion and vegetation. It only takes a few years for marked changes to be readily apparent. Thus, this island is a living laboratory of the effects of nature on very young lava fields (Fig. 11.24).

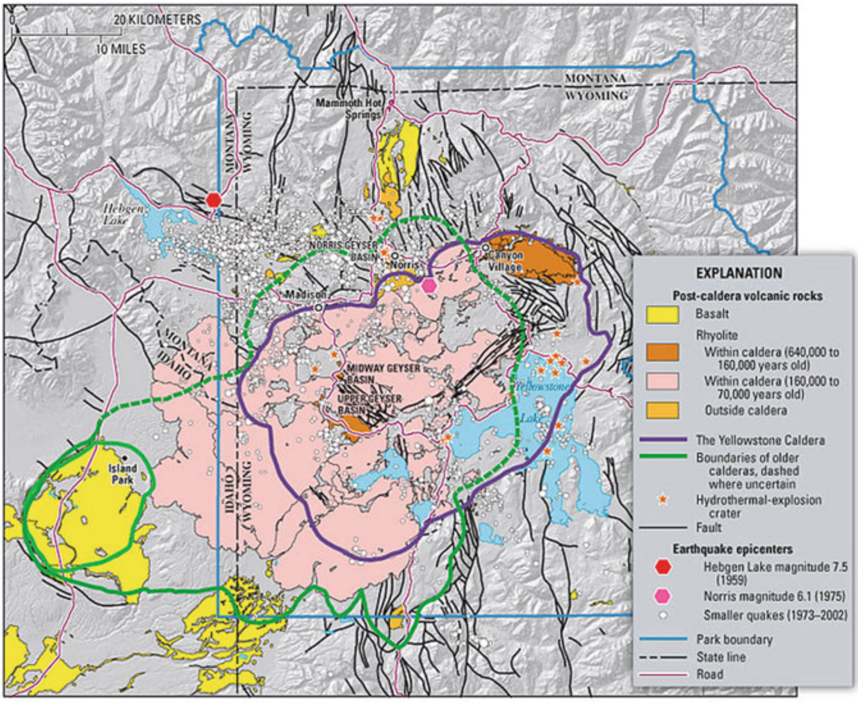


Fig. 11.21 The yellowstone calderas

Mauna Loa rises nearly 14,000 ft (4,169 m) above sea level on the Big Island of Hawaii. Since the floor of the ocean is 20,000 feet below sea level in this part of the Pacific, this would be the tallest (and most massive) mountain on Earth if it were measured from its base. When it snows on top of this massive mountain as well as its sister Mauna Kea, locals are known to take up skiing until the snow melts (Fig. 11.25).

As one moves to the northwest from Hawaii to Maui (Fig. 11.26), it is apparent that this island is in reality two separate islands that joined together due to erosion of the mountains created by two separate volcanoes (Fig. 11.27). On this island one sees more of the effects of erosion with time, especially on the older northwestern portion of the island, near the ‘Iao Needle (Fig. 11.28).

This erosion is caused by the uplifting of air currents as they move over the mountainous volcanoes, thus causing adiabatic (constant energy) cooling, and resulting rain that leads to erosion (see Chap. 10), thereby creating the gorgeous valleys that dot the older of the Hawaiian Islands.

The southern portion of Maui contains the volcano Haleakala, which is classified as dormant. Although it last erupted in 1790, don’t count it as extinct just yet. There may be more to come from this massive volcano (Fig. 11.29).

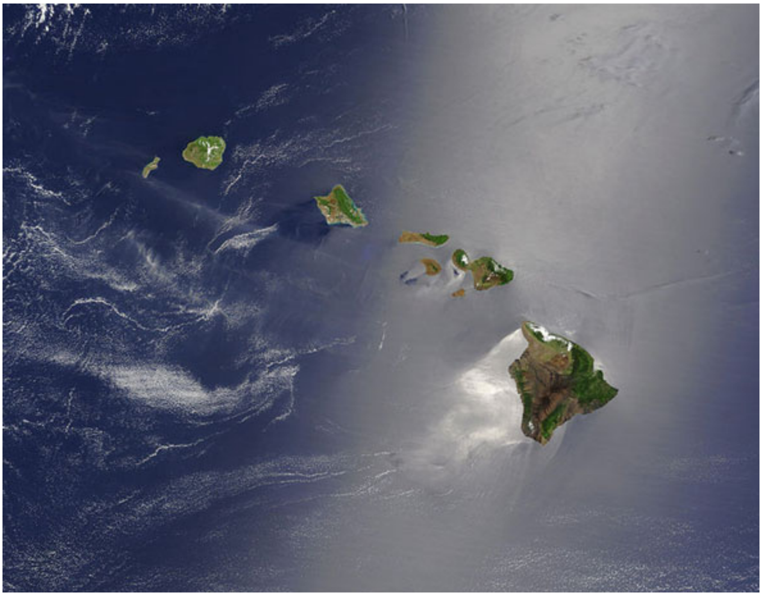


Fig. 11.22 Satellite photo of the Hawaiian Islands, showing from *top left* Niihau, Kauai, Oahu, Molokai, Lanai, Maui, Kahoolawe and Hawaii

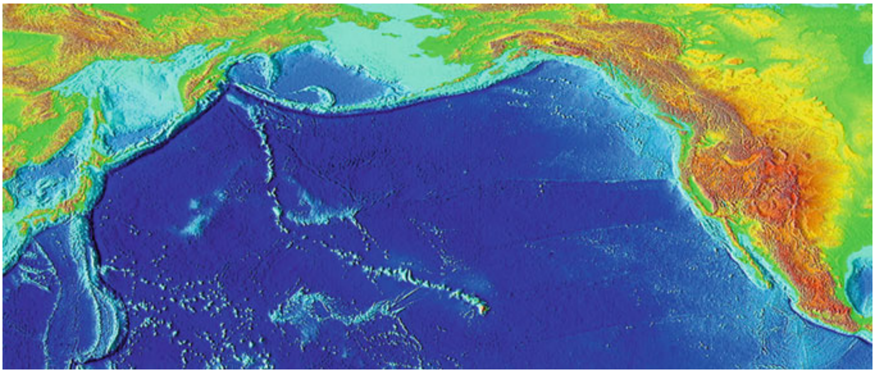


Fig. 11.23 The Hawaii-seamount chain

Near the northwest end of the Hawaiian chain one finds Kauai. At 6 million years in age, it is the oldest of the large Hawaiian Islands. Volcanoes on this island stopped erupting several million years ago. Today it is a contender for the wettest place on Earth, producing 12 m (40 ft!) of rainfall annually on Mount Wai-‘ale-‘ale, in the Alaka’i swamp, the highest swamp on Earth.

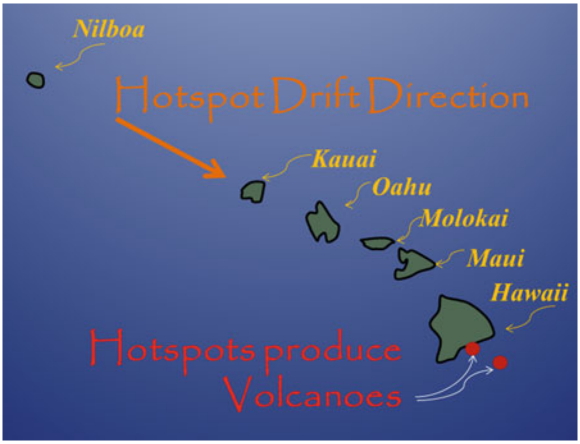


Fig. 11.24 Hotspot drift slowly shifts the active volcanoes southeast

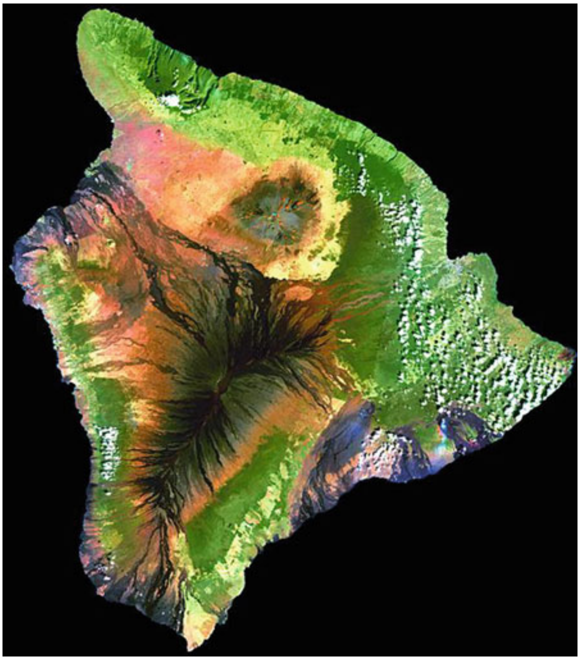


Fig. 11.25 Satellite photo of the big island

For sheer beauty caused by erosion, Kauai is the best of the Hawaiian Islands to visit. Waimea Canyon (Fig. 11.30) and the Na Pali Coast (Fig. 11.31) are quite spectacular, having been carved out by all that rain rushing down from the Alaka'i Swamp for millions of years.

Someday all of this erosion will cause Kauai to look like the now-nearly flat Wake Island. And someday Wake Island, on the northwest end of the Hawaiian Island Chain, will disappear beneath the waves of the Pacific Ocean. On the other end of the chain, 35 km to the southeast of Hawaii, the newest island is forming,

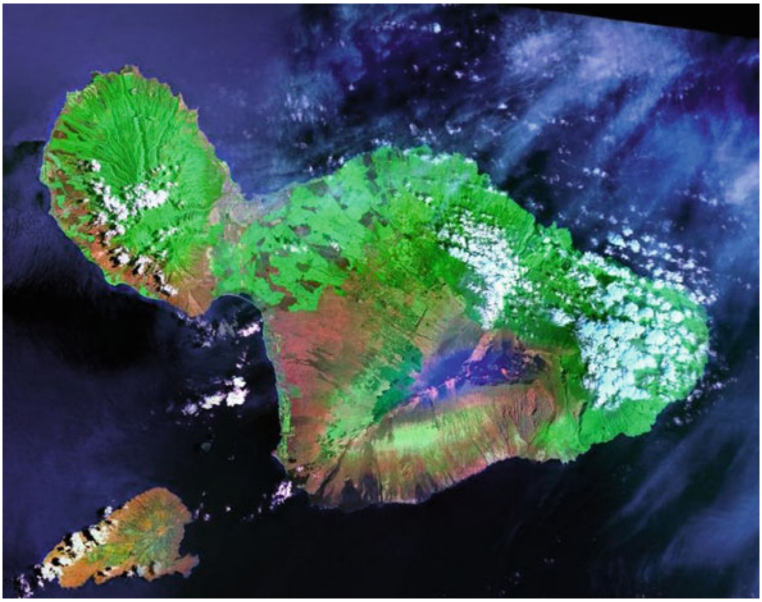
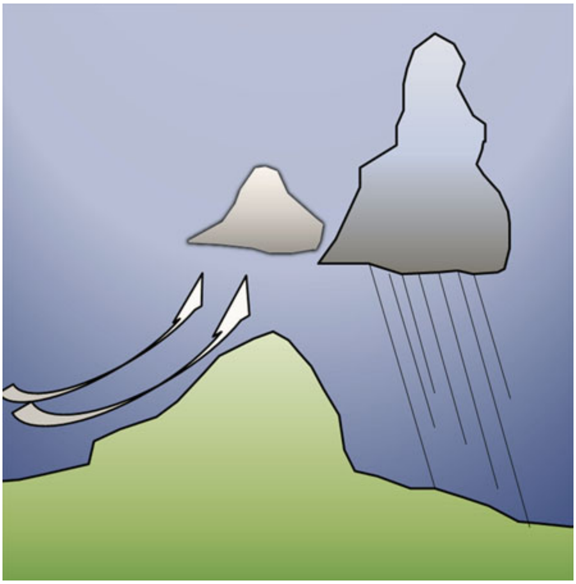


Fig. 11.26 Satellite photo of Maui

Fig. 11.27 How adiabatic uplifting of air over mountains produces clouds and subsequent rainfall



and though it is still about 975 m beneath the surface of the ocean, Hawaiians have already named it Lo'ihi. It is expected to make its first appearance above sea level in 1–100,000 years.

Fig. 11.28 Photograph of the ‘Iao Needle

Fig. 11.29 Haleakala crater

Thus, volcanoes are born, and they live long and constantly varying lives, and then one day they die, and in the case of the Hawaiian Islands, they are buried at sea. The Hawaiian Islands are in my view the best place on Earth to see the effects of the mechanics of volcanoes.

Fig. 11.30 Photo of Waimea Canyon

Fig. 11.31 The Na Pali Coast of Kauai

Glaciers

At various times in history, glaciers have played a profound role in the geography of our planet. When the climate on Earth cools, glaciers advance from polar and elevated regions, and the results can be quite impressive.

Glaciers are formed by precipitation occurring at elevations sufficiently high that the precipitation is frozen (usually in the form of snow). This solid form of water normally falls on mountains, and gravitational forces cause it to congregate in the valleys beneath the mountain peaks. If the accumulating snow is not heated sufficiently for it to melt, then the accumulation of more and more snow causes the layers near the bottom of the heap to be compacted by the snow above, thus gradually converting the snow to much denser ice. The ice grows into a field that we call a glacier, and this is all caused by mechanics (Fig. 11.32).

Fig. 11.32 The black rapids glacier, Alaska

I've visited several glaciers in my lifetime. Most of them are enormous and overwhelming in their size and power. My favorite is the Mer de Glace (meaning sea of ice) in Chamonix, France. It's not the biggest, but it's one of the most accessible in the world, and that alone makes it a hit with me (Fig. 11.33).

But there is much more to see when you visit this glacier. First of all, there is the famous Montenvers train, completed in 1909 (Fig. 11.34). The train is in and of itself a marvel of the power of modern mechanics. It was one of the first trains ever built that could traverse steep inclines, and this was accomplished by constructing a geared drive system beneath the train, a challenging problem in mechanics.

But wait, there is still more! When the visitor arrives aboard the train at the Montenvers station from Chamonix, he/she is treated to a fabulous view of the glacier from above. The glacier itself looks very much like the surface of a sea that is covered with debris. The first impression is not of ice, but more like lots of dirt with ripples on the surface.

The visitor can go *inside* the Mer de Glace. This is a fracture mechanist's dream world (see Chap. 13). The ice inside this magnificent glacier, unlike that on the surface above, is clear and pristine. Thus, one can actually see crystalline grain boundaries, and even more impressive, the interfaces of enormous cracks inside the glacier (Fig. 11.35).

In the eighteenth and nineteenth centuries the Mer de Glace extended right down into the edge of Chamonix, at the base of the valley beneath Mont Blanc, the tallest mountain in Europe. Due to climate change, the foot of the glacier began to recede in the mid-nineteenth century, and it is now no longer visible from the city below.

Fig. 11.33 The Mer de Glace

The surface of the glacier has also dropped several hundred feet just in the past 40 years (my first visit there was in 1971, and my most recent was in 2012). Despite this, the man-made grotto that one can enter to see the inside of the glacier continues to slide down the valley at a rate of about 90 m per year. Thus, the grotto has to be constantly reconstructed for the burgeoning flow of tourists who visit the glacier every year. If you've never seen a glacier, the Mer de Glace should be your first one to visit.

Like other natural physical phenomena on our planet, glaciers have life spans. They grow in colder times, and they recede in warmer ones. The last Ice Age on Earth ended about 13,000 years ago, but before it ended, there were lots of interesting differences from today.

Because there was so much ice on Earth, the sea level was much lower then. For example, there was a land bridge that connected Asia to Alaska, and scientists think that is how people first populated the Americas. The British Isles were also connected to Europe, thus allowing easy access for indigenous peoples to Britain,

Fig. 11.34 Chamonix-Montenvers train

Fig. 11.35 Entrance to the grotto inside the Mer de Glace

but later on they found it difficult to depart when the ice receded and the sea level rose, cutting them off from mainland Europe.

If the valley that the glacier rests in is in a polar region, then it may undergo little change over a long period of time. On the other hand, if the glacier is in a region that experiences some melting, then the coefficient of friction between the glacier and the valley floor may be reduced sufficiently for the glacier to actually travel down the valley, and depending on the slope and the roughness of the valley, at varying speeds. This sliding of the glacier over the surface of the Earth can cause all sorts of interesting things to happen, all of them resulting from mechanics.

Fig. 11.36 Moraine in the foreground at Lake Louise, Canada

There are lots of remnants of the mechanical effects of massive glaciers from the previous ice age. For example, there was a field of glaciers in Canada that were so massive that they pushed the Earth's crust downwards, perhaps partially creating the Hudson Bay, which is shallow in depth, but enormous in breadth. The Great Lakes developed when receding glaciers carved out valleys that subsequently filled with fresh water.

Fig. 11.37 Cape Cod viewed from space

Fig. 11.38 Photograph of Half Dome at Yosemite National Park

As the ice age took hold in the recent past, the glaciers pushed further and further southwards, reaching well into what is now the United States. Most of Canada was under ice. As the glaciers slowly extended southwards, they pushed enormous mounds of dirt ahead of them, but when the climate began to warm again, they receded, and the mounds of dirt were left stranded. We call these mounds of dirt and debris moraines, and today we can tell how far south the glaciers advanced from the remnants of these moraines (Fig. 11.36). There are moraines all across the U.S. Midwest, thus demonstrating the southernmost extent of the last ice age. For example, Cape Cod is the remnant of a moraine (Fig. 11.37).

Due to their enormous mass and size, glaciers can have great destructive power. Imagine if you will making a time lapse movie of a glacier over a span of perhaps a 100,000 years, and then running that movie fast forward in just a few minutes. You would see the glacier carving out valleys, and defacing mountains as it plowed its way down the valley, and then leaving the remnants of its destruction behind as it receded.

A great place to go and see the remains of such destructive power of glaciers is Yosemite National Park. There is so much to see there that it is almost beyond comprehension. The glaciers have receded now, but when they plowed down through the main valley, they gouged out now jaw-dropping scenery everywhere one looks. My favorite is Half Dome, an enormous granite monolith formed by a volcanic magma bubble ten million years ago (Fig. 11.38). When the glaciers came to the valley later, the front face of the previously formed dome was sheared off, thereby creating one of the tallest vertical faces on Earth. All of this was created by

Entity	Life Span	Ratio to the Universe Life Span
Universe	10^{12} years	
Galaxies	10^{11} years	1/10
Our solar System	10^{10} years	1/100
Pangaea	10^{8} years	1/10,000
Volcano	10^{7} years	1/100,000
Glacier	10^{5} years	1/10,000,000
Humans control Earth	10^{4} years	1/100,000,000
Roman Empire	10^{3} years	1/1,000,000,000
Human	10^{2} years	1/10,000,000,000
Hurricane	0.1 year	1/10,000,000,000,000
Tornado	0.01 year	1/100,000,000,000,000

Fig. 11.39 Average lifespans of various entities within the cosmos

mechanics. You simply cannot understand how enormous Half Dome is without visiting Yosemite. And if you go there, starting preparing now to climb to the top of Half Dome. It can be reached without climbing gear from the smaller mound on the east side called Quarter Dome.

So we have now seen that the universe, galaxies, solar systems, volcanoes, glaciers, and people all have their own life cycles. There are lots of theories about how long the universe will last. Above is one guess compared to other life spans (Fig. 11.39).

The Quality of Our Lives

12

> *I know not with what weapons World War III will be fought, but World War IV will be fought with sticks and stones.*
>
> Albert Einstein (1879–1955)

There is no doubt that mechanics has had an enormous impact on the quality of life for humans, as well as many other species on this planet. Most of the time it has been for the better, but not always, as we will see in this chapter (see also Chap. 7).

Transportation

Mechanics has played a major role in the evolution of transportation on Earth. As we have already discussed, the wheeled chariot was in existence around 2,000 BCE. Merchants later realized that these vehicles required roadways in order to ensure that commerce was not at the mercy of weather. As we have also seen, the Romans built an enormous network of roadways in ancient times. Despite this fact, the primary means of transportation over land was by foot or horseback until little more than two centuries ago.

In ancient times ships were the primary means of transporting large amounts of goods. While it may not be obvious, this remained the primary means of commerce until about a century ago. As evidence of this, note that nearly every large city on Earth has a seaport. Those that do not were invariably quite small until the advent of the railroad in the nineteenth century.

The steam engine was first developed by Hero of Alexandria (c. 10–70 AD) in ancient times. Several others developed steam engines over time, but the first steam engine developed for commercial purposes was a water pump developed by Thomas Savory in 1698. This early device was utilized to pump water out of mines. Thereafter, a more successful steam engine was developed by Thomas Newcomen in 1712.

It was not until 1774 that the modern steam engine of James Watt (1736–1819) (Fig. 12.1) was invented. This fabulous partly mechanical invention not only drove the industrial revolution, it also revolutionized transportation via the development of the locomotive in the early nineteenth century [110]. As described in *The Most Powerful Idea in the World* by William Rosen [111], the relentless drive to convert

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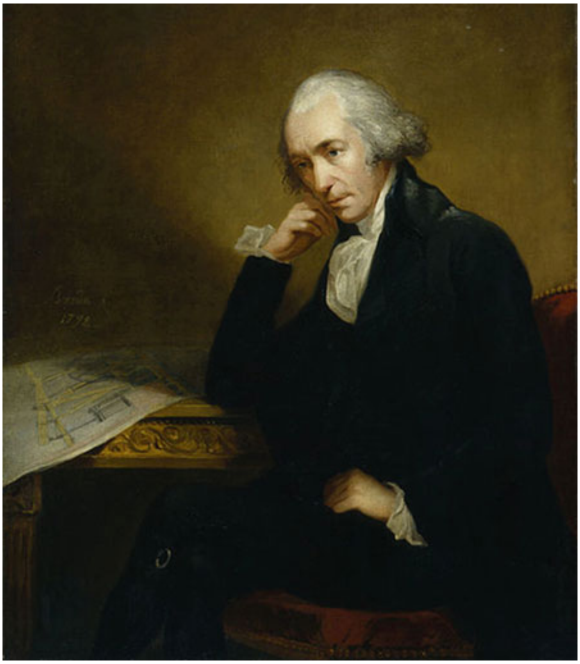


Fig. 12.1 Portrait of James Watt by Carl Frederik von Breda, national portrait gallery, London

industry from man-powered to steam powered required numerous innovations, many encompassed by mechanics. Steam engines were subsequently invented for providing rotary motion, thereby allowing the production of all sorts of modern machinery, including locomotives. Prior to this point in the history of our species almost all industry was powered by humans and animals.

The first operational steam powered railroad went into service in 1804. Early locomotives were designed by Richard Trevithick (1771–1833), Matthew Murray (1765–1826), Christopher Blackett, William Hedley (1779–1843), and George Stephenson. The Puffing Billy, designed by engineer William Hedley, Christopher Blackett, engine wright Jonathan Forster, and blacksmith Timothy Hackworth (1786–1850) went into operation in 1813. It is the oldest steam locomotive still in existence today (Fig. 12.2).

By the middle of the nineteenth century, the modern steam locomotive had become the primary means of land transport over much of the Earth. By the early twentieth century other types of locomotives were being built, including diesel and even electric. Rail transport remains one of the most efficient means of ground transport on Earth to this date. This is a magnificent example of the use of mechanics in our modern world (Fig. 12.3).

While engineers had experimented with steam powered vehicles without rails as early as 1769, this was not a practical solution for single passenger powered transport. However, with the invention of the internal combustion engine, another device that uses mechanics, the automobile came into existence in the 1880s.

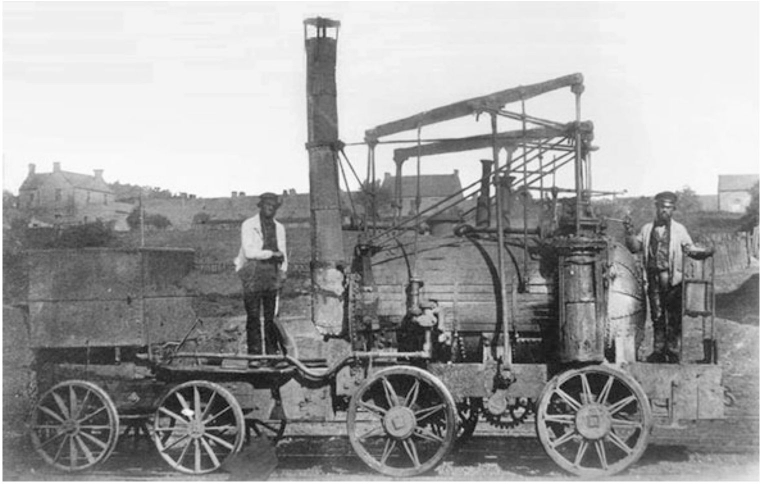


Fig. 12.2 Photo of the puffing billy—an early steam locomotive

Fig. 12.3 Photo of a modern steam locomotive

Henry Ford (1863–1947) was instrumental in developing mass production techniques that made the automobile affordable by the masses (Fig. 12.4).

Today surely everyone knows the history of the automobile. I will therefore not delve further into the history of this most versatile transportation vehicle. Suffice it to say that there are more than one billion automobiles on Earth today. It is arguably the single most important mechanical invention in the history of mankind. If you don't think so, just imagine a world without the automobile.

When I was in France a few years ago I discovered that the French believed that someone other than the Wright Brothers was the first to fly in a powered aircraft on Earth. I found this to be both shocking and upsetting. My own roots in aerospace

Fig. 12.4 Photograph of Mr. and Mrs. Henry Ford in his first automobile

engineering made me feel outrage at this transgression by the French. A year later I was in Brazil, and to my surprise, I found that the people of Brazil also had a national hero that they believed to have been the first to fly.

Fig. 12.5 Photograph of Alberto Santos-Dumont

Fig. 12.6 Santos-Dumont rounding the Eiffel Tower in 1901

"What is going here?" I asked myself. "Does every country in the world declare their own first person to fly?" As it turned out, both the French and the Brazilians were speaking of the same person—Alberto Santos-Dumont (1873–1932) (Fig. 12.5). Upon discovering this revelation, I decided to do some research on this character, whoever he was. I subsequently discovered a wonderful book about Santos-Dumont written by Paul Hoffman entitled *Wings of Madness* [112].

Alberto Santos-Dumont is one of the truly amazing characters in the history of aviation. Born in Brazil, he migrated to Paris, France, where he became a local celebrity by inventing small dirigibles that transported him all over the city. He would magically descend from the sky in front of Maxim's Restaurant in his personal dirigible to the delight of the locals, thereby amazing one and all with his hair-brained ploys. It is said that he had a very tall dining room table in his apartment with chairs that had to be mounted with a ladder, so that his guests could get a feel for the concept of floating in air.

Santos-Dumont was a bit of a showman, a marketer, and a dreamer. He does not appear to have been much of an engineer, but he was somehow able to assemble flying contraptions, make them work, and most importantly, he did so without killing himself. In fact, Santos-Dumont flew his powered dirigible around the Eiffel Tower in a competition in 1901, thus winning the Deutsch de la Meurthe Prize. Score one for the French and the Brazilians (Fig. 12.6).

On the other hand, Orville (1871–1948) (Fig. 12.7) and Wilbur (1867–1912) Wright (Fig. 12.8) flew a *heavier-than air* vehicle. Thus, controversy regarding primacy was born. While the world was told that the Wright Brothers flew at Kitty

Fig. 12.7 Photograph of Orville Wright

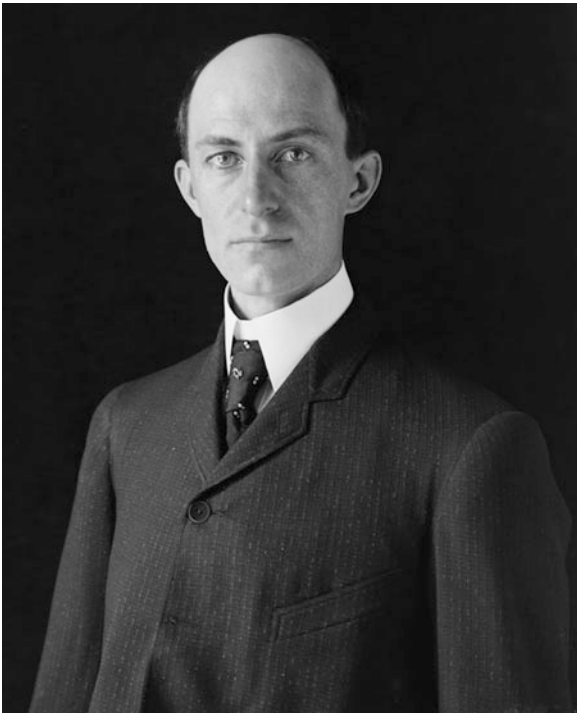


Fig. 12.8 Photograph of Wilbur Wright

Fig. 12.9 The first manned flight of a heavier-than-air vehicle on December 17, 1903

Hawk in 1903, and there was indeed a movie of it, there was no proof that it had actually occurred when they claimed it had. After all, film clips of the time had no date on them, and it was furthermore conceivable that the entire film was a fake for the simple reason that there were no witnesses to the famous flight (Fig. 12.9).

Enter Alberto Santos-Dumont once again. The French set a prize for the first person to fly a closed course in front of witnesses in a heavier-than-air vehicle. On October 23, 1906 Santos-Dumont flew his aircraft the 14-Bis for the first time before a large crowd in Paris, traversing a distance of 60 meters. On November 12 of that same year, he flew his aircraft 220 meters, setting the first world record for flight of a heavier-than-air vehicle recognized by the French Fédération Aéronautique Internationale (Fig. 12.10).

So who gets the prize for being the first to fly? The truth is—there is to this very day a disagreement over who was the first to fly. The reason is that Santos-Dumont had wheels on the undercarriage of his aircraft, whereas the Wright Brothers used skids, which required them to set the aircraft on a dolly running on tracks. The French (and Brazilians) claimed that this was cheating, since the aircraft was supposed to take off on its own.

There is an interesting *denouement* (French for footnote) to this captivating story. Santos-Dumont is credited by some for inventing the wristwatch. This is not really true. In actuality, the wristwatch had been previously invented by the Swiss company Patek Philippe sometime earlier. Thus, when in 1904 Santos-Dumont complained to his friend Louis Cartier that his pocket watch was inconvenient, Cartier "reinvented" the wristwatch, thereby proliferating the myth that Santos-Dumont invented the wristwatch. So the end of the story seems to be that the Wright Brothers actually flew first, but Santos-Dumont won the gold wristwatch.

M. SANTOS DUMONT'S FIRST SUCCESS WITH A FLYING MACHINE.

M. Santos Dumont, after several preliminary trials in Paris on November 12th, when his flying machine had flown 75, 128, and 142 yards, decided to return to his starting point by going against the wind. For thirty yards the motor ran along the ground, then suddenly it rose to a height of about five yards, and appearing like a great white bird, it soared half-way down the course. M. Santos Dumont, startled by some spectators in his way, twisted his rudder quickly, and the machine came heavily to the ground, damaging one of its wings. The experiment, however was a triumph, for actual flight was achieved; and it seems as though it were only a matter of time for the conquest of the air to be accomplished. The 235 yards were traversed in twenty-one seconds.

Fig. 12.10 Illustration of Santos-Dumont's flight of November 12, 1906

Regardless of who was the first to fly, there are certain truths that can be said. The Wright Brothers were consummate engineers, working tirelessly over a period of years, using the scientific method to study the mechanics of both flight and flight vehicles. Thus, the evidence lends credence to their claim to be the fathers of manned flight.

There is a sad downside to this whole story. Because the Wright Brothers were attempting to sell their aircraft, they insisted on flying in secret. As a result, the world doubted their claims for several years. Indeed, the Paris Edition of the *New York Herald* reported in 1906:

> The Wrights have flown or they have not flown. They possess a machine or they do not possess one. They are in fact either fliers or liars. It is difficult to fly. It's easy to say, 'We have flown.' [113].

But the Wright Brothers persisted, finally convincing the US Army to purchase prototypes of their aircraft in December 1907. In the following year the Wright Brothers demonstrated their aircraft in Le Mans, France for the first time, and in the year after that they once again demonstrated their flying machine in France. On their return to the US in 1909 they were welcomed at the Whitehouse by President Taft. They had finally gained credibility. In October of that year Wilbur flew the Wright aircraft around the Statue of Liberty on a flight that lasted 33 min and was seen by more than a million onlookers.

But their joy was short-lived. Several patent violation suits were filed, adding stress to their already pressured lives. In 1912 Wilbur died of typhoid fever. There followed several fatal crashes of the Wright aircraft. To make matters still worse,

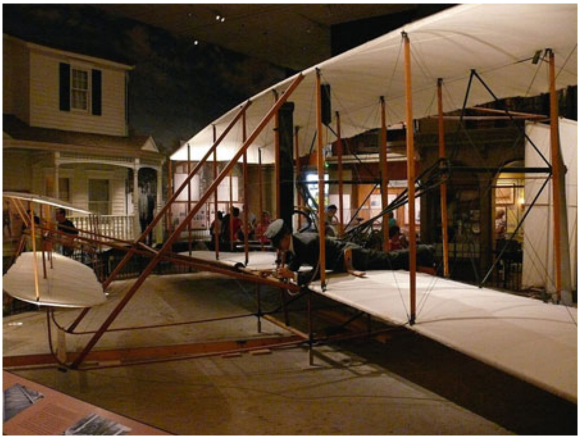


Fig. 12.11 Wright aircraft, national air, and space museum

beginning in 1914 a feud broke out with the Smithsonian Institute, which had held to the notion that Samuel Langley (1834–1906) had been the first to develop a heavier-than-air vehicle capable of flying. Orville countered by loaning the original Wright aircraft to the London Science Museum in 1928.

Finally, 6 years after the death of Orville Wright, the Smithsonian Museum agreed to accord the Wright Brothers their proper places as the first to fly, and the 1903 Wright aircraft was transferred to the Smithsonian Air and Space Museum, where it remains to this day (Fig. 12.11).

Perhaps the saddest part of all is the fate of Alberto Santos-Dumont. His last flight came in 1910, ending in a serious accident. Shortly thereafter he was diagnosed with multiple sclerosis. He moved to the French seaside, but was accused of spying for the Germans, perhaps because his telescope was German, and his accent was foreign. During World War I he slipped into depression, as the aircraft was utilized more and more as a means of destruction of human life.

In 1931 he returned to his homeland of Brazil, only to be serenaded by a group of Brazilian scientists flying in an aircraft as a salute to his accomplishments. The aircraft crashed, killing all on board. On July 23, 1932, he committed suicide by hanging himself.

These sad tales of the fathers of manned flight give us pause. We owe much to those who dared to fly. Today, we simply take it for granted, but not so long ago only birds flew, and many of those humans who attempted to imitate birds perished from their attempts.

Now, a little more than a century on, the age of flight seems to have reached an amazing state of maturity. In Chap. 1 we learned that the Egyptians built the great pyramid around 2,500 BCE, and it remained the tallest structure on Earth for close to four millennia. It is now just over a century since the birth of the age of manned flight. In that miniscule span of time we have seen the following developments in aviation:

First Transatlantic flight (Charles Lindbergh (1902–1974)) 1927 (Figs. 12.12 and 12.13)

First Flight around the world (Charles Kingsford Smith (1897–1935)) 1929
First Supersonic Flight (Charles "Chuck" Yeager (1923–)) 1947
First Flight over 100,000 feet (X-15) 1959
First commercial supersonic flight (Concorde) 1976 (Fig. 12.14)
Fastest flight (Lockheed SR-71–3529.6 km/hr) 1976.

But we haven't stopped there. Within 60 years of the Wright Brothers' first flight, we leaped into space! And now we have the following accomplishments in spaceflight:

First launch into space (sputnik) 1957
First human in space (Yuri Gagarin (1934–1968)) 1961
First American in orbit (John Glenn (1921–)) 1962
First human on the Moon (Neil Armstrong (1930–2012)) 1969 (Figs. 12.15, 12.16, and 12.17)
First unmanned vehicle on Mars (Viking Lander) 1976
First unmanned vehicle to leave our solar system (Pioneer 10) 1983.

Today, the number of satellites orbiting our planet is nearly 10,000! And we take all of this for granted. This is truly amazing stuff, representing some of the finest developments in mechanics in the history of our planet.

Fig. 12.12 Photograph of Charles Lindbergh, library of congress

Fig. 12.13 Lindbergh Arrives in Paris

Fig. 12.14 Photograph of the concorde

Sadly, we seem to have lost interest in space in recent years despite the fact that studies have shown that the spinoffs in technology to humankind have far exceeded the cost of the space program. I am reminded of the statement by Carl Sagan, who said something like this, "I was naive enough to think that the space race was about science. It wasn't. It was an arms race with the Russians" [114].

This is a very sad indictment of our society today. There doesn't seem to be a nation on Earth that knows how to optimize the expenditure of its own resources, which reminds me of another quote attributed to Winston Churchill, "The best argument against capitalism is a five minute conversation with the average voter" [115].

Mechanics provided a major portion of what was needed to solve the problem of transportation in the modern era, but in truth this is a multi-disciplinary problem. It involves not only mechanics, but also thermodynamics, chemistry, and today more than ever before electro-magnetism. Still, in the early days of the

Fig. 12.15 Photograph of Neil Armstrong

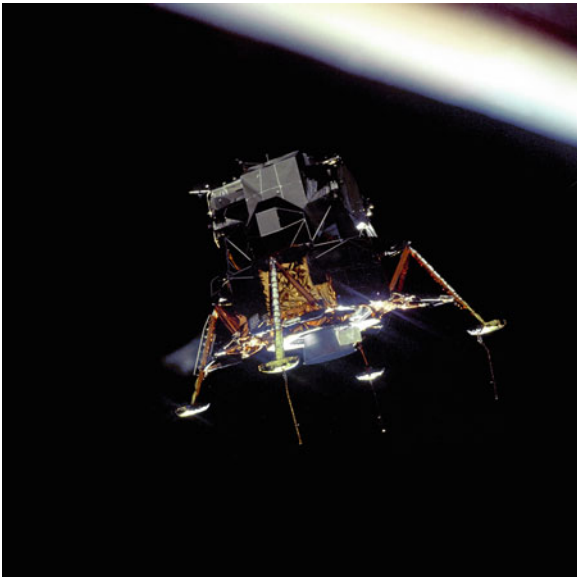


Fig. 12.16 The eagle lunar lander after separation

Fig. 12.17 Neil Armstrong steps onto the moon

industrial age, the developments that were simultaneously occurring in mechanics (see Chap. 9) were pivotal to the success of transportation.

The steam engine, for example, required many moving parts to transfer the force generated by the engine to the apparatus that it was intended to drive (such as a locomotive). These mechanical parts were designed using mathematical and experimental models harvested by engineers from the newly developed field of continuum mechanics. As time went on, these models continued to improve, with the result that the mechanical parts became both lighter and stronger, thus improving the efficiency of transportation vehicles.

By the time of the Wright Brothers, the technique of using both experimental and theoretical mechanics was well known in the machine industry. The Wright Brothers began applying this approach to bicycle technology, but they very quickly moved on to flight vehicles. They designed and built airfoils of various shapes and tested them in crude wind tunnels, experimental apparatuses used to measure lift and drag caused by air passing over airfoils. Similar techniques were subsequently employed throughout the automobile and aeronautical industries that exploded across the world a short time later. Mass production had arrived on this planet, and mechanics was ubiquitous throughout these industries.

In the late 1950s the United States undertook to build an interstate highway network. I distinctly remember that era. New ultra-fast (and sparsely utilized) highways were opening all across the country. At the time, President Eisenhower touted this revolutionary system as a necessity for the nation's military defense. It was in truth far more than that. Our nation's interstate highway system was the catalyst that transformed our nation from the post-war era to the most advanced country on Earth.

Just as the Roman's road network at the height of their empire catapulted them to domination, our roadways allowed us to move goods faster and cheaper than any other country in the history of the Earth. And shortly thereafter, we stair-cased directly into the world's most advanced air transportation system, thereby further reinforcing our ability to move goods on an unprecedented scale virtually anywhere in the world. Much of these developments were accomplished via the mechanics models developed in the nineteenth century and fine-tuned in the twentieth. I may be reaching when I say this, but in my view, next to education, transportation is the single greatest achievement of humankind.

Sports

Mechanics is omnipresent in the world of sports today. Indeed, it is virtually impossible to imagine our modern world without sports, and conversely, our modern sports could not exist without mechanics. To better comprehend the role that mechanics plays in various sports, let's consider a few examples.

Perhaps the sport that has seen the most amazing developments due to mechanics is golf. The modern game of golf was apparently invented sometime in the fifteenth century in Scotland, although both the Dutch and the Chinese claim to have invented precursors long before the game appeared in Scotland. By the time James VI of Scotland succeeded to the throne in England in 1603 (becoming James I of England), the game was well known in the British Isles. It is said that the game became so popular that it had to be banned on the Sabbath during the Reformation. Rumors are that golf addicts played on Sundays with burlap bags over their heads in order to avoid excommunication from the church. I certainly hope that the offending players also disguised their swings on the Sabbath.

Apparently, golf has been a consuming sport for humans for a long time. However, technological developments over the past century have clearly elevated the sport to new heights. Note that I use the term "sport" loosely; as the worship of the sport by many seems to indicate that it has taken on cult status.

Mechanics has played an enormous role in the evolution of golf. When I was a child growing up in the 1950s, my father gave me my first set of golf clubs, made (I think) in the 1930s. Thus, I have in my lifetime been witness to a veritable cornucopia of inventions in the game of golf. Almost all of these inventions have been purely mechanical in nature (with the notable exception of electronic devices such as GPS-based range finders for determining the distance to the hole, although even these have a mechanical basis and objective).

Let's now look at how mechanics has affected the sport of golf. First, the golf ball has been dramatically altered over the past century. As recently as a 100 years ago, golfers were still using a gutta percha golf ball. This type of ball has a leather cover that is filled with feathers. As a result, it doesn't fly very far (or reliably straight, for that matter). From the standpoint of economics, this would seem to be the ideal type of ball, because golf courses could be made shorter and therefore less expensive without affecting the main objective of the game, which is to hit the ball in a distant hole in the fewest number of strokes. But as confounding as it may seem, the golf ball manufacturers keep attempting to make the ball fly farther and farther.

This is accomplished by one of two means. First, and most obviously, experimentation with the mechanics of the materials used to make the golf ball has resulted in a plethora of design changes that have dramatically increased the distance that a golf ball will fly just in the last century.

Next, consider developments in the materials used in golf balls. The biggest change in golf ball materials came when the golf ball was changed to rubber. The story of rubber is in itself an interesting tale involving mechanics. Rubber is indigenous to South America, principally the Amazon. Charles Marie de la Condamine is credited with first introducing rubber to Europe in 1736. The amazing properties of rubber began to be exploited in the latter part of the nineteenth century. Because of rubber the city of Manaus, the principal site from which rubber was transported to the rest of the world from the Amazon, was at one time one of the richest cities on Earth. Unfortunately, rubber trees were smuggled out of Brazil to other parts of the world, principally to Southeast Asia, destroying the monopoly held by land barons in South America, and thereby making rubber more cost effective.

But I digress. The golf ball was changed to rubber, and later on, with the rise of artificial materials such as plastics, golf ball manufacturers kept experimenting (especially with multilayered configurations), with the result that I can today hit a golf ball further than I could nearly 50 years ago, when I was both young and strong. All of this is related to the mechanics of deformable solids [116], and it has put pressure on golf course designers to make golf courses both longer and more difficult, thereby increasing the cost of golf course construction exponentially.

In addition to advances in materials used for golf balls, the surface geometry of the golf ball has been altered via careful study of the aerodynamics of the flow of air about the ball. The dimples create a thin layer of turbulence (called a boundary layer) close to the surface of the ball, and depending on the geometry of these dimples, the overall drag on the ball can be decreased in such a way as to increase the distance the ball will fly. In addition, the dimple geometry can be utilized to control the spin rate of the golf ball, thus also affecting the performance of the ball. All of this is related to the mechanics of fluids.

In addition to the evolution of golf balls, golf clubs have changed dramatically over the last century. First, the shafts were changed from metals to high stiffness fibrous composites, providing just the right ratio of stiffness to weight, thereby increasing the velocity of the club head at impact. Next, wooden headed clubs (called "woods"!) were changed to lightweight metals (but still somewhat inanely called "woods" by many purists despite the fact that they are made of metal), thus also improving the stiffness of the club head, which increased the velocity at which the ball flies off the club head at impact. The clubs for shorter shots, called "irons" (despite the fact that the club heads are typically made of steel), were also dramatically improved by redistributing the weight within the club head. Once again, we see that this is all related to mechanics.

Then we have all of this business related to grooves on the club head. The depth, spacing, and shape of the grooves can be designed so as to further control the spin rate of the golf ball, and this has a profound impact on how the ball flies,

Fig. 12.18 Photograph of a SAFER barrier

whether it will curve (called a ‘hook’ or a ‘slice’, or if only slightly, then a ‘draw’ or a ‘fade’), how far it will fly, how the wind will affect it, and how quickly it will stop when it hits the ‘green’ (the closely cropped area surrounding the hole).

I’m really not sure what to think of all of this technology. Suppose that each team in a basketball game got to choose how springy their shoes are, and each team could choose a different basketball. Suppose that baseball had a new ball that would travel six hundred feet, so that we would have to enlarge all of the baseball stadiums. Suppose that billiards players were allowed to carry a computer device that would accurately determine the precise angle necessary to make a bank or a combination shot. Suppose that tennis players could bring their own balls to the match, choosing a different ball for each serve.

Similar although less profound technological improvements have occurred in other sports, all of which are due to improved mechanics. For example, we have high strength carbon composite tennis rackets and metal baseball bats (not allowed at the pro level).

In the area of sports safety, we have numerous technological improvements due to mechanics. In football, we have countless energy dispersing devices that obviate or mitigate injuries, including shoulder pads, knee pads, and helmets. These products are designed using mechanics to decrease the stresses applied to participants so that injuries occur less often.

Next to golf, downhill skiing has perhaps seen the most innovative mechanically inspired technological developments over the most recent half century. In addition to other safety devices, engineers have invented ingenious bindings that cause the ski boot to twist out of the ski during a fall rather than the ski breaking the skier's leg or ankle. These developments have dramatically decreased skiing injuries, which were much more common in the first half of the twentieth century.

In auto racing, we have the steel and foam energy reduction (SAFER) barrier, invented by Dean Sicking and co-workers at The University of Nebraska-Lincoln, used to decrease impact forces when a race car hits the wall during a race (Fig. 12.18). Sophisticated modern computational algorithms have been utilized to design roadway safety devices such as this so that when the driver of a vehicle strikes the barrier the forces applied to the driver by the impact do not cause life-threatening injuries. Barriers such as these are now deployed ubiquitously along our nation's high speed thoroughfares, thereby saving countless lives every year.

I could go on and on about mechanics in sports, but I think that you get my point—mechanics has had a profound impact on the evolution of not just golf, but all sports. Sports are really marvelous examples of the utilization of mechanics for entertainment value, and they are undeniably good for the physical welfare of humans. Furthermore, as we have seen, inventions in sports sometimes transcend the field of sports, thereby affecting humans in a much more profound way.

As recently as a 100 years ago, the pursuit of sports was essentially an amateur pastime (with the possible exception of the Gladiator era in Rome). Within a short span of time, professional sports have emerged and spread across the globe. And while the particular sport(s) of interest varies from country to country, the fact is that the general populace of nearly every developed country on Earth has become obsessed with sports.

Is this obsessive behavior a good thing? I for one believe that sports have a third important goal: to provide a means of avoiding war. Who knows—had we had organized sports in the United States in the nineteenth century, perhaps we could have avoided the Civil War, our nation's most inexplicable, lamentable, and destructive conflagration.

But here is the tricky part—exactly what role has mechanics played in the rise of this potentially sedating influence on the populace of the world? I confess, this part of the question does not have an easy answer. Here is my perhaps weak explanation. It seems to me that the most important aspect of organized sports is the entertainment value. Throughout the course of history, whenever societies have become affluent, entertainment for the masses has flowered, and organized sports has been one of the main forms of entertainment.

But the masses quickly grow bored with the same old sports over and over again. History tells us that the Romans were driven to constantly amplify their somewhat gruesome gladiatorial performances over time (see Chap. 3), thereby maintaining the attention of the mob. Today, we see similarities in organized sports. Professional football constantly alters the rules so as to favor offensive play, thereby running up the score to the delight of the fans. Baseball has seen unprecedented increases in the rate of production of home runs, thus increasing heretofore sagging ticket sales.

But the undisputed king of producing ever more exciting physical outcomes has to be golf. While it is true that humans have grown stronger and more fit over the last century, little of the advances in golf prowess can be attributed to this. Golf, like no other sport, has benefitted from profound performance increases introduced by employing advanced mechanics. Thus, it is no wonder that golf has attracted the largest increases in fan base over the last half century across the world. So in a nutshell: mechanics drives sports; sports provides entertainment; and entertainment sedates the masses. And if the masses are not sufficiently sedated and distracted, sometimes war follows.

Warfare

I am a baby boomer. For those of you who do not recognize that term, it means that I was born a few short years after World War II. Apparently, when the soldiers came home from the war, there was a boom of births, now called baby boomers, despite the fact that we are all by now middle-aged.

So I grew up in the shadow of World War II. Now, 60 years on, I have been so saturated with movies, documentaries, and books on the war, that I almost feel as if I lived through it myself. I believe that I can speak for my generation when I say that the memory of that war remains fresh in our minds.

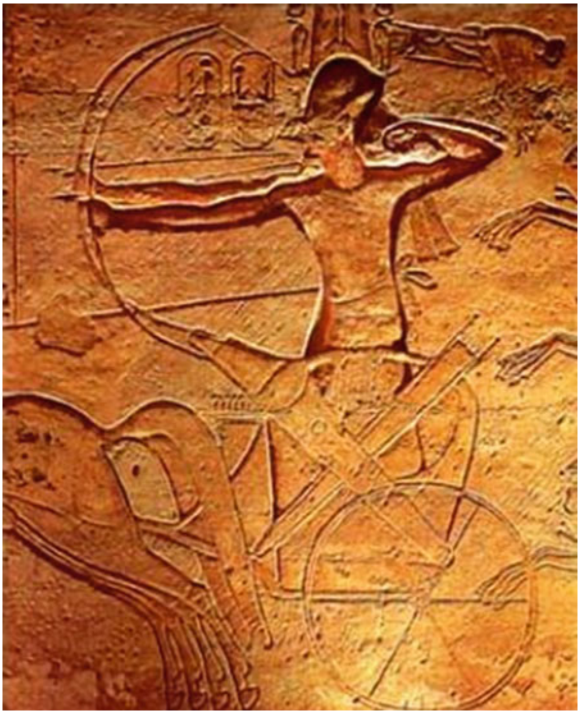
After I grew up, I served in the US Air Force towards the end of the Vietnam War (although I did not go to Vietnam). And over the most recent decade and more, our country has been embroiled in its lengthiest (and perhaps costliest) war in our history. Thus, war is very much a part of our existence in the US.

Mechanics has played a profound role in the history of warfare. We know that humans have been fighting one another since the dawn of recorded history. Archeologists have found implements of war made by humans even much farther back in time. War is not new, nor is it likely to go away any time soon.

The first mechanical implements of war used by humans were apparently stone clubs, as described in Chap. 1. Arrowheads made from stone date to about 60,000 years ago. Larger implements of war appear to have been invented only since the last ice age. By the beginning of the Bronze Age around 3,500 BCE, we know that weapons were being forged in the Middle East. These included axes and swords. By the beginning of the Iron Age in about 1,200 BCE, these weapons were growing larger and still more lethal. In addition, we know that the Sumerians, Hittites, Mesopotamians, Babylonians and Egyptians possessed the wheel, and they used it to make chariots as early as 2,000 BCE. These killing machines were perhaps the first truly terrifying military weapons in history (Fig. 12.19).

Warships were also apparently invented around 3,000 BCE, as evidenced by the Cheops Ship found at the site of the Great Pyramids (Fig. 12.20). Still, later, Greek triremes became formidable weapons on the high seas of the Mediterranean.

Fig. 12.19 Depiction of Ramses II riding a chariot at the battle of kadesh in 1274 BCE



Thucydides (c. 460–c. 398 BCE) describes amazing weaponry in his history of the Peloponnesian War (431–404 BCE) [117]. By the time of Alexander the Great (356–23 BCE) (Fig. 12.21), archery, spears, Elephant corps, javelin throwers, cavalry, and other weapons of mobility were commonplace. Massive siege weapons were just around the corner.

Fig. 12.20 Cheops ship at the great pyramids (c. 2550 BCE)

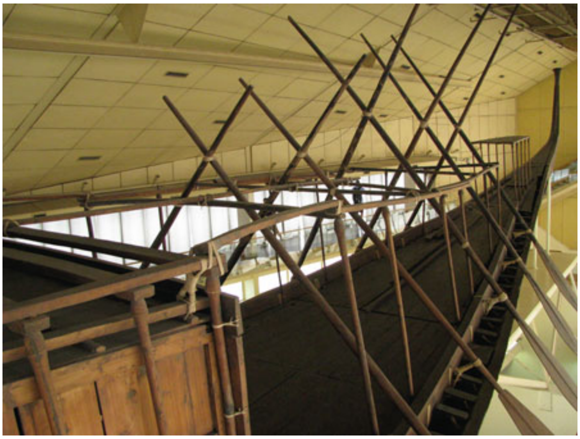


Fig. 12.21 Statue of Alexander the Great, Istanbul museum

Of course, we are well aware of the superiority of the weapons utilized by the Romans in ancient times because we have historical records such as *The Gallic Wars* by Julius Caesar [118]. In this fascinating account, Caesar explained how he and his army of about fifty thousand legionnaires wandered into Gaul (modern-day France) *on purpose* and managed to defeat a Celtic populace of more than three million. In the decisive battle at Alesia in 52 BCE, the diminutive Romans were encircled by perhaps three hundred thousand rather hefty Celtic warriors, and in a pitched battle that lasted four days, they thoroughly annihilated the Celts, thus making Gaul a province in the Roman Republic (Fig. 12.22).

The story of how Caesar and his legionnaires accomplished this is quite spectacular, and it involves the widespread use of mechanics by his troops. The Roman legions built massive defensive structures that included water-filled and stake-implanted deep ditches, siege towers, and fortified walls [119].

One can visit the battlefield today in central France, about 70 km west of Dijon. Recently, the French government has reconstructed a sample of the defensive barriers constructed by Caesar's engineers for the battle in the valley below Alesia (Fig. 12.23). The ability of engineers in that period of time to construct breastworks capable of defeating their enemies is truly astounding (Fig. 12.24). If you want to see a great example, watch the opening scene of the movie *The Gladiator*, which I can assure you is well-researched and accurate.

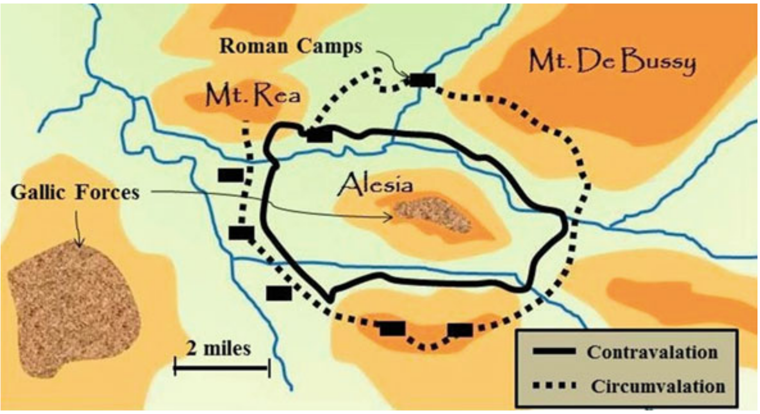


Fig. 12.22 Siege of Alesia

Fig. 12.23 Photograph of reconstruction of the Roman fortifications at Alesia

Fig. 12.24 Trebuchet at Les Baux

Fig. 12.25 Statue of Vercingetorix at Alise-Sainte-Reine

During the latter third of the nineteenth century the French became enamored with Julius Caesar's book *The Gallic Wars* [120]. The emperor Napoleon II decided to attempt to locate the battlefield of Alesia. Archeologists were able to confirm the location at modern-day Alise-Sainte-Reine. A massive statue of Vercingetorix was subsequently erected on top of the hill, and today Vercingetorix is remembered as the first French national hero, despite the fact that there was no France in 52 BCE (and let us not forget that he was also the loser) (Fig. 12.25).

History indicates that mechanics was used to construct both offensive weapons and defensive weapons as far back as there is a written record. Those with chariots defeated those without. Those with bronze weapons defeated those without. Those with superior roadways defeated those without. Those with superior cannons defeated those without. Those with superior ships defeated those without. Those with superior tanks defeated those without. Those with superior aircraft defeated those without. Those with nuclear weapons defeated those without. All of these weapons were invented and produced using mechanics.

And so it has gone throughout history. In more or less every war in history, mechanics has played a profound role. And only on rare occasions have the victors possessed inferior mechanical weapons. In other words, wars are not usually won on the battlefields. They are won in the manufacturing centers, and by the engineering corps. Alexander understood this. Hannibal understood this.

Caesar understood this. Henry V understood this. Napoleon understood this. Patton understood this.

Though mechanics has played a profound role in warfare throughout history, it has had no moral responsibility whatsoever. Indeed, mechanics possesses no soul at all. It is simply a pawn of the powerful. Heaven help us if superior mechanics ever falls into the hands of an immoral aggressor.

Mechanics Today

13

Time and space—time to be alone, space to move about—these may well become the greatest scarcities of tomorrow.
Edwin Way Teale (1899–1980)

In the foreword to this book I mentioned that I "rode the crest of the wave" that was mechanics. This is a fitting analogy, for mechanics transmits information via the propagation of waves. As we know from the application of Newton's second law to deformable bodies, the mechanical behavior of bodies can be modeled using continuum mechanics (see Chap. 9), and this approach results in hyperbolic partial differential equations in spatial coordinates. In other words, they are wave equations, meaning that when mechanical loads are applied to bodies, the effects of these loads are transmitted via traveling waves, and these mechanical waves are propagated in both fluids and solids.

The square of the speed of these mechanical waves is proportional to the material stiffness of the object in question, and it is inversely proportional to the density. The resulting wave speed is what we term "the speed of sound" because these waves can be heard if they are within the frequency range that is audible to humans. This speed varies somewhat from one material to another, but it is around 343 m per second in air at sea level, and 1484 m per second in water. In addition, it takes a not insignificant amount of energy to transport information via mechanical waves.

As an example, when an earthquake occurs in the ocean off the coast of South America, it takes several hours for the resulting waves to reach the Hawaiian Islands, so that warnings can be sent out far enough in advance to permit the locals to evacuate to high ground before the tsunami arrives. Thus, while mechanical waves may appear to move rapidly, they move at a velocity that is slow enough to be perceptible to humans.

Time-Space

In 1861 James Clerk Maxwell (1831–1879) published the first of three papers formulating a model for electromagnetic phenomena [120] (Fig. 13.1). In that theory, he hypothesized that electromagnetic energy is transmitted via waves. As it

D. H. Allen, *How Mechanics Shaped the Modern World*,
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Fig. 13.1 Photograph of James Clerk Maxwell

turns out, visible light is one form of electromagnetic energy. Light travels at the speed of light, which is about 300,000,000 m/s. Also, the speed of light is much less sensitive to the material that the light is flowing through than are mechanical waves. Furthermore, all electromagnetic energy travels via waves at the speed of light, and it takes very little energy to propagate these waves when compared to the energy necessary to propagate mechanical waves.

So think about the earthquake off the coast of South America. If the resulting mechanical waves propagated at the speed of light, there would be insufficient time for a tsunami warning to be useful, because the waves would strike the shore in Hawaii in a little more than one one-hundredth of a second after the earthquake occurred several thousand miles away. Whew! We are lucky that mechanical waves travel slowly on Earth.

But there is a downside to this analogy. Because mechanical waves travel at a perceptible speed to humans (sound is also a mechanical wave), we tend to not relate very well to electromagnetic waves. I would venture to say that to most humans, their perception is that from a practical perspective light travels at infinite speed.

Light travels almost a million times faster than sound. So let's suppose you have two significant others. One lives on the surface of the Moon, and the other lives about 400 m (1,350 ft) from you. You communicate with the one on the Moon by direct cell phone, and you communicate with the local one by speaking directly to him/her via two tin cans connected by a string. Since the Moon is on average about 375,000 km (235,000 mi) from the Earth, that means that it will take the same amount of time for your verbal correspondence to reach each recipient. So you will have to make the choice as to whether you want your significant other to be close by or whether you want a long distance relationship, because they will both receive your communications simultaneously.

Professor Maxwell knew exactly what he had stumbled upon. He understood full well that electromagnetic information could be transmitted about a million times faster than mechanical energy, and he also understood that it took a lot less energy to do so. Suppose you are a businessman. Suppose someone tells you that they can make a product that functions both cheaper *and* faster. And now here is the difference—they can make it a *million times* faster. Are you going to invest in that? This is a no-brainer. Of course you are going to invest in that!

And that, reader, is exactly what happened to humankind in the twentieth century. In the span of 100 years, our species transformed from a primarily mechanical world to an ever increasing electromagnetic one. It was *a no-brainer!* Cheaper and faster will (almost) always trump any other opponent. The lone exception occurs when it turns out later that it is toxic. We have thus far found no evidence that electromagnetism is harmful to human health, but heaven help us if we ever do, because we will be in a world of trouble!

Let's look at time-space from a pragmatic viewpoint. A light year, despite its deceptive name, is *not* a unit of time. It is a unit of length defined to be the distance traveled by light in a year. Since light travels about 299.79×10^6 m/s, when this is multiplied by the length of a year (about 365.24 days), we get a distance of about 9.46×10^{15} m.

So just how far is that? The Earth is 40,000,000 m in circumference (see Chap. 8). Thus, dividing the former by the later, we determine that a beam of light could circle the Earth 236,500,000 times in a single year. Wow! So light travels an extremely long way in a single year. In fact, it travels so far that scientists don't even think in terms of meters when they are determining distances in the universe. For this they use a light year—the distance light travels in a year.

Below is a table of approximate sizes of various things found in our universe, and for your edification, I have written everything in meters, which is about 1.1 yards, or 3.3 ft, rather than in light years (Fig. 13.2). I have a reason for this. I think that using light years, somewhat like using logarithms, obfuscates reality for the average person. To see how this confusion occurs, let's take the U.S. national debt as an example. Our debt at the time of this writing is approximately 17 trillion U.S. dollars. That sounds like a lot of money, but if we view it in powers of ten, it doesn't look so bad—$\$17 \times 10^{12}$. As a means of comparison, a million dollars is written in powers of ten as $\$1 \times 10^6$. Comparing the powers of the above two numbers, it is easy to get confused (sometimes I think our Congress does this) and think that a million is about half of 17 trillion, but the reality is that a million is only about $1/(17 \times 10^6)$ of our national debt. To put it another way, in order to pay off the U.S. national debt, we would need 17,000,000 people to put up $1,000,000 *apiece*! This same analogy applies to light years. So I don't like to think in light years—it's really misleading to the average person.

Entity	**Length Span**	**Ratio to the Universe Length Span**
Universe	**10^{26} m**	
Milky Way Galaxy	**10^{21} m**	**$1/10^{5}$**
Our Solar System	**10^{14} m**	**$1/10^{12}$**
Earth	**10^{7} m**	**$1/10^{19}$**
Hurricane	**10^{5} m**	**$1/10^{21}$**
Tornado	**10^{3} m**	**$1/10^{23}$**
Human	**2 m**	**$2/10^{25}$**
Human Cell	**10^{-5} m**	**$1/10^{31}$**
Water Molecule	**10^{-10} m**	**$1/10^{36}$**
Atom	**10^{-15} m**	**$1/10^{41}$**
Electron	**10^{-22} m**	**$1/10^{48}$**

Fig. 13.2 Average length spans of various entities within the Cosmos

There are some very interesting revelations embedded within this table. For example, the universe is about 10^{25} times as large as a human. A human is about 10^{23} times as large as an electron. What that means is—if you were an electron, a human would look (within a couple of orders of magnitude) about the same size to you as the universe does to a human. Thus, if you were an electron within the head of a human, the toe of that human would be on the far side of your universe.

The point of this discussion is to introduce the concept of length scales. There are perhaps an infinite number of length scales in existence in our multiverse. We really aren't sure, because we can't see anything larger than our universe, or smaller than an electron (heck, we can't even "see" an electron!). There may be objects larger than our universe, but we cannot see anything further than 13.7 billion light years from Earth for the simple reason that our universe has only existed that long, so that light from farther away could not exist (or so we think). On the other extreme, there is conclusive evidence that there are objects smaller than an electron. And perhaps most interestingly of all, both limits are growing (or shrinking) with every passing discovery.

This enormous variation in the size of things is so large as to be almost incomprehensible to humans. We can relate to things within about five or six orders of magnitude of our own size, but above that or below that, we have a hard time comprehending the immensity or miniscule nature of the object in question.

What all this means is that with our simple view of the way things are from the viewpoint of our experience on Earth, we humans tend to get a distorted impression of the universe. That is probably the biggest reason that nobody thought of relativity before Albert Einstein (1879–1955). His views were just counterintuitive to most people [121].

To see how confusing things can be, consider the Sombrero Galaxy, shown below (Fig. 13.3). This galaxy is 28 million light years from Earth. More importantly, it is 50,000 light years *in diameter*! What this means is, the light coming to us from the near side of the Sombrero Galaxy is 50,000 years newer than the light coming to us from the far side. Hold on a minute! This doesn't sound like a single image. It's as if you took photos of yourself over a 50-year span of time and assembled them by increasing age in strips one inch wide from top to bottom. The result would not look like you at all! So what we are seeing from Hubble may look nothing like the Sombrero Galaxy actually is at any instant in time. More importantly, for objects that span such large distances, there is no way to ever view them as they really are at any instant in time. Thus, we have the unfortunate reality that time and space are inseparable when we talk about large distances, ergo time-space, united as one.

To see how the speed of light distorts things visually, we really need to think of some thought experiments that the average person can relate to. Perhaps the best way is to imagine an everyday experience that most of us have encountered. Suppose that you have a very slow computer, one that is so slow that images tend

Fig. 13.3 The Sombrero galaxy-28 million light years from Earth. The dimensions of the galaxy, officially called M104, are as spectacular as its appearance. It has 800 billion Suns and is 50,000 light years across

to come up on the screen in slow motion. Almost everyone has encountered this sort of thing at one time or another. So parts of the image that show up first are like the beams of light that start out closest to Earth. The parts that show up later are like the beams of light that started out later. And here is a really bizarre twist on the whole image before you. Because of the time lapse, some parts of the image may actually look quite different if we could assemble them at the same instant in time, or they might in fact no longer exist at all, having been blown into the cosmos a long time ago. So time-space is not something that most humans will ever be able to grasp.

Electromagnetism has revolutionized the world we live in, from the telegraph, to the telephone, to the radio, to the television, to the computer, to wireless technologies. But there are some things that electromagnetism simply cannot do. For those things, we still need mechanics. So let's get back down to Earth! This chapter is about the developments in mechanics in the twentieth century.

The primary subject of this book is classical mechanics. As such, the subject of quantum mechanics falls outside the scope of this treatise. As Richard Feynman once said, "Nobody understands quantum theory". I therefore reserve the right to put off this subject for a future offering on nonclassical mechanics.

Computational Mechanics

Over the most recent half century the rise of computers worldwide has had a profound effect on the field of mechanics. Much of the formal mathematical structure of our modern models in the field of mechanics was in place by the middle of the twentieth century. Unfortunately, these models were so mathematically complicated that their structure precluded accurate solutions by analytic means for all but the simplest (as well as impractical) of circumstances. Perhaps this is best illustrated by an example.

In the field of elasticity, the equations describing the mechanical response of a linear elastic body at rest to externally applied loads was formulated in the early nineteenth century due to the collective efforts of Navier, Cauchy, and Lamé, among others [122], as described in Chap. 9. The model is composed of fifteen coupled equations in fifteen unknowns (nine are differential equations, and six are algebraic). These unknowns are the three components of the displacement vector, the six components of the (symmetrized) stress tensor, and the six components of the strain tensor. Using the model, it is possible to predict all fifteen of these output variables at every point in a linear elastic solid of arbitrary shape subjected to external loads, at least theoretically. The problem comes in when the object is not simple in shape. And all one has to do to understand the importance of the shape of the structural object is to look under the hood of any automobile, wherein virtually no part is simple in shape. The shapes of parts in air- and spacecraft (wherein minimization of mass is of heightened importance) can be even more complex.

Thus, for the better part of a century and a half, applied mathematicians such as Barré de St. Venant (1797–1886) went about the task of attempting to solve this complex problem for solid objects of varying shape, each difference in shape requiring a completely new solution. This was (and still is!) quite labor-intensive [123]. Much of the theory necessary to perform such modeling was transported to the United States by Stephen Timoshenko (1878–1972) after his immigration to the U.S. in 1922 [124] (Fig. 13.4).

So-called "closed form" solutions (meaning mathematically exact) to these problems were pursued in great detail right up to the 1970s, but a change was in the wind. In the 1930s and 1940s, engineers were attempting to develop methods for obtaining approximate solutions to these problems for purposes of designing aircraft. Coincidentally, mathematicians such as Richard Courant (1888–1972) were developing approximate mathematical approaches for solving generic sets of coupled differential equations. These two diverging approaches began to come together at precisely the same time that the high speed computer was coming into vogue in the U.S.—during the late 1950s.

Richard Feynman (1918–1988) was a Nobel prize-winning physicist who worked on the Manhattan Project during World War II. He is credited with inventing quantum computing. It seems that during the period when scientists at Los Alamos were attempting to determine exactly how much mass was needed to

Fig. 13.4 Photograph of Stephen Timoshenko

produce unstable nuclear reactions, thereby leading to an atomic explosion, Feynman was given this assignment. He responded by “drafting” a wave of brilliant math students from eastern seaboard universities who would otherwise have been shipped off to war [125].

The determination of how much mass is needed to create unstable nuclear reactions is a challenge in quantum mechanics (I know, I said I would not talk about this subject, but bear with me). Feynman set his army of mathematicians to calculating the statistical nature of this process *by hand*! He gave each math whiz a piece of paper telling him/her exactly what calculation to do, and then he handed the first one in the line a table with a number on it, requiring him/her to preform the calculation using that number, record the result on the table, and pass the table to his/her neighboring math whiz. This process went on for months and months, with each math whiz doing the same calculation over and over, day after day, month after month, and it eventually resulted in the determination of the amount of mass required in Little Boy and Fat Man, the two atomic bombs dropped on Japan in 1945.

Feynman later claimed that he had produced the first main frame computer in history. He argued that his army of math whizzes worked essentially just like any other computer, and he was indeed correct. The only difference between Feynman’s “computer” and later computers was the speed with which the information was passed from one operator to the next. As we now know from our discussion of Maxwell’s model, this processing of information can be done at the speed of light, and it is precisely this fact that allows us to perform incredibly complex mathematical operations so quickly today. All computers today transfer information at the speed of light, and we have managed to continue to increase the speed at which computers produce results by continuously decreasing the distance that the information is transported within computers (thus resulting in the field of nanotechnology, also attributed to Feynman), thereby constantly increasing the speed with which computers can compute results. This is a bit of a stretch, but this continuous improvement in computer speed is at least due in part to mechanics, as our ability to make computer chips smaller and smaller is a direct result of our creation of mechanical devices for fabricating tiny chips.

Fortunately for humankind, a computational method was developed in the twentieth century, and this method is today termed ‘the finite element method’. The term ‘finite element’ was coined by Ray Clough (1920–), a professor at UC-Berkeley in 1960. This terminology stuck, as did the methodology developed by the rapidly growing group of scientists and engineers researching within this exciting field of mechanics. The finite element method was first applied to the elasticity problem described above, but it rapidly expanded to other problems in applied mathematics and physics. Wherever there were sets of partial differential equations to be solved, the finite element method found a home. This included elasticity, elasto-plasticity, elastodynamics, structural vibrations, fluid dynamics, viscoelasticity, heat transfer, and electrodynamics, to name just a few, and almost all of which fall under the umbrella of mechanics.

The finite element method works by *assuming* the form of the solution in spatial coordinates over a small subdomain (volume) of the problem of interest called a *finite element*, as shown in Fig. 13.5. This element is then joined with other elements to approximate the shape of the object of interest, and although this analysis is fundamentally approximate in nature, it can be performed as accurately as desired by simply using smaller and smaller elements (called refining the finite element mesh).

When this technique was first introduced in the 1960s computers contained insufficient real addressable memory (RAM) to be capable of solving really complex problems. But with the advance of computer power (see the discussion on Moore's Law in Chap. 10), it quickly became possible to obtain solutions to more and more complicated problems computationally by using the finite element method. Thus arose a field of mechanics termed computational mechanics.

Today it is possible to model just about any problem governed by a set of differential equations in spatial coordinates, whether linear or nonlinear, by using the finite element method. The added complexity associated with accounting for time can be handled by utilizing well-understood time stepping algorithms. And furthermore, software has been developed that makes the solution process extremely user friendly. For example, it is now possible to use a hand-held global positioning system (GPS) device to survey the surface of virtually any three-dimensional object, and a software package will create an image of the shape of the object. Another

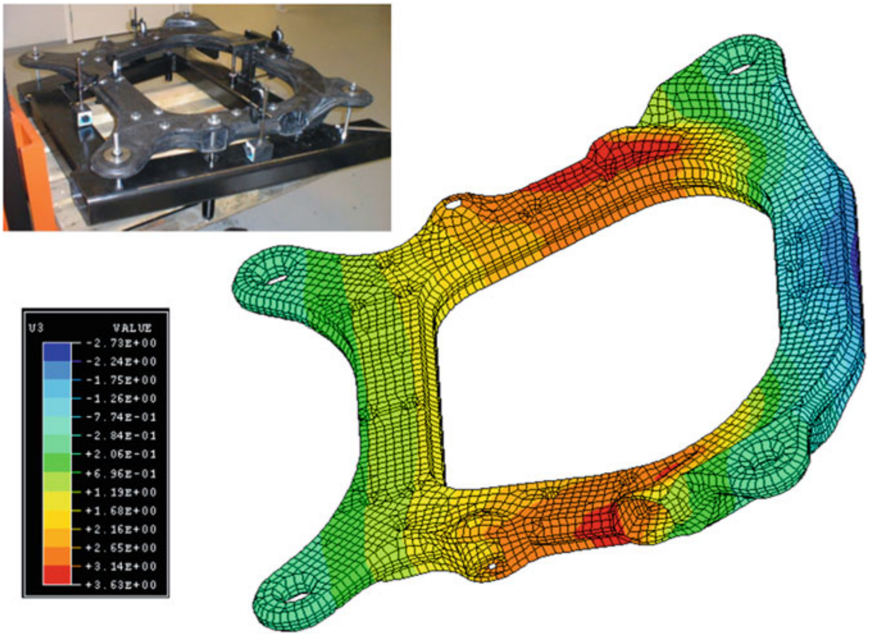


Fig. 13.5 Finite element analysis of a Volvo substructure assembly showing predicted vertical displacement component. *Note* experiment at upper left

software package will then be utilized to construct a finite element mesh, and all of this occurs in the span of no more than a few seconds. Predictions that would have taken an army of mathematicians several years to solve 50 years ago can now be solved by a single person using a laptop computer in a matter of minutes.

I like to site the example of my youth. When I was a child growing up in the 1950s our (even new!) cars used to break down all the time. The reason for this was that we did not have mathematical tools for designing the mechanical parts precisely. Thus, every mechanical part in a car was designed experimentally, by putting it out there and seeing how it performed. Lots of parts failed, and they had to constantly be replaced. Far worse, sometimes the failure of these parts led to the loss of human lives.

With the rise of the finite element method, most structural parts are now designed with finite element computer codes that ensure the parts will not break. Today, the average automobile will go one hundred thousand miles without a single major structural failure anywhere on the vehicle. This is just a single example of how computational mechanics has shaped the modern world, and this technology has reached maturity only in the past few years.

Mechanics of Materials

Over the past century there have been amazing developments in materials technologies. Perhaps the most far-reaching developments are due to the invention of plastics, but there are numerous other materials that have burst onto the scene, including advanced concrete, asphalt concrete, high strength metals, polymer composites, and metal-matrix composites. A number of adaptive materials, also termed ‘smart’ or ‘active’ have also been developed. The deformable body mechanics of these materials can be quite complex.

In my career I have been involved in research dealing with polymers, plastics, polymer composites, metals, metal-matrix composites, geologic salt, sea ice, mud, geologic soils, rubber, human tissue, wood, and rocks. Because I find it to be the most interesting material of all, I will discuss just one example herein—asphalt concrete (Fig. 13.6).

I have been working in the field of asphalt technology for many years. Asphalt (also called bitumen) is the gooey stuff that comes out of the wellhead when an oil well strikes crude oil. During the refining process much of the heavy stuff that settles out is asphalt. It’s a good thing we have roadways, because otherwise most asphalt would be useless since it can’t be utilized as a fuel. So asphalt is the cheapest binder that we have naturally available in large quantities on this planet. And in most cases, it is nothing more than dead creatures that have been compressed over a very long period of time.

We call the composite material made by mixing asphalt with geologic aggregate asphalt concrete, and this material is used to surface roadways throughout the world. In fact, asphalt concrete is one of the most commonly used structural materials on Earth. The reason for this is quite obvious: asphalt concrete is cheap!

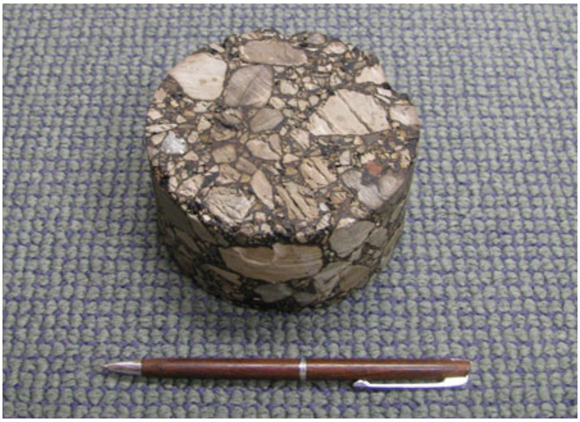


Fig. 13.6 Photograph of a core sample of asphalt concrete

Asphalt concrete is a typical example of what we term a “composite material”. This is a catch-all phrase for a material that is made by mechanically (as opposed to chemically) combining two or more separate constituents. The objective is to take one material that displays poor performance and embed it with another constituent that will improve the poor performance characteristic of the former material. When the two constituents undergo a chemical process as a result of their combination, the resulting material is called a compound rather than a composite. But when the two or more constituents undergo little or no chemical change, but instead combine only mechanically, the new material is called a composite.

Asphalt is technically a liquid, albeit one with a very high viscosity. It is also quite compliant, being unable to withstand significant loading. When I was a child, there used to be a chemical plant near our house. Asphalt was put in large oil drums and stored for transportation to dumping sites. We would take a penny and place it on top of the surface of the asphalt filled drum. Although the surface appeared to be solid, if you came back the next day, the penny could be seen to be sinking into the surface very slowly. After a week, the penny would have disappeared completely from view. Thus, driving a vehicle over something this compliant and viscous is a lost cause.

But asphalt is so cheap! Thus, engineers have utilized its most admirable property to mitigate its least meritorious ones. Asphalt is really sticky, thus it makes a great binder with whatever is embedded within it. And stone aggregate is (literally) dirt cheap, making it the perfect material to embed in asphalt, thereby creating asphalt concrete. Unfortunately, asphalt insists on behaving badly much of the time. This bad behavior can lead to premature failure of the roadway, and in some cases it can even put drivers in mortal danger.

I never cease to be amazed at the complexity of asphalt concrete. The performance of roadways made of asphalt and aggregates depends on just about anything and everything that can be imagined, making it not only one of the cheapest materials, but also one of the most complicated materials known to humankind (perhaps second only to living tissue, especially that of humans). Asphalt

Fig. 13.7 Photograph of asphalt pavement that is both rutted and cracked

roadways crack, rut, separate, buckle, degrade (called aging), discolor, and spall, due to such things as long-term cyclic tire loadings, rain, snow, ice, temperature variations, other environmental effects such as chemical spills, and even impacts from foreign objects such as IED's (improvised explosive devices). All of these are problems associated with mechanics (Fig. 13.7).

The design of a roadway is an open-ended design problem, meaning that there are numerous designs that may satisfy all of the design constraints, but of course, we are seeking the *cheapest and safest* solution that will work. And this is not easy to predict at all.

Part of the reason for the difficulty is that the loads applied to the roadway are not always well controlled. For example, tires that are either underinflated or overinflated will cause the evolution of roadway damage to increase dramatically, to the point that a single large truck with underinflated tires can cause substantial cracking and loss of roadway life. Furthermore, increasing the loads on the roadway just a small amount can increase the rate of roadway degradation exponentially, meaning that it only takes a few trucks that are overweight to completely destroy a roadway. For the same reason, smaller vehicles such as automobiles and motorcycles normally do almost no damage at all to roadways.

I remember I used to live on an asphalt roadway in the country. It worked fine for ten years, and then one day they struck oil. The big oil tankers that drove up and down that country road destroyed it in less than a year.

There is perhaps one hundred billion U.S. dollars worth of asphalt concrete poured on our planet each year. That is one with eleven zeros!!! That is a LOT of money. Suppose that we could decrease this cost by just 50 %. We could save fifty billion dollars a year. This could conceivably be done, but it has not because robust models for predicting pavement performance have not yet been developed. So let's suppose that the governments of the world got together and decided to invest in the development of a model that could improve pavement models to the point that the amount of asphalt concrete poured per year could in fact be decreased by 50 %. I estimate that this problem could be solved with an investment of no more than

500 million dollars (and most likely a LOT less even than that). That means that in the first year that this new model is in use, the world will save 49.5 billion dollars! Why don't we solve this problem? We have the scientific know-how. We have the resources. We have the technology, and the solution to the problem of asphalt concrete is primarily a problem in mechanics, but it also appears that the lack of a solution is related to politics.

The most important material to be developed in my lifetime is undoubtedly plastics. The affect of plastics on our world is nothing short of miraculous. The next time you think about it, go outside and bang about on your automobile. You will find an amazing number of parts made of plastic. Just 50 years ago, there was virtually no plastic at all in automobiles.

Materials development is one of the primary drivers of technology in humankind. From the Stone Age, to the Bronze Age, to the Iron Age, to the Modern Age, each new material has wrought fundamental changes in the way that humans live. Today more than ever before new materials affect our lives. Mechanics has played an enormous role in the development of these new materials.

Mechanics has been utilized both in the development and deployment of new materials across our planet. Utilizing mechanics models we are today able to design structural components so that they will not fail due to excessive deformations or fracture. Thus, mechanics of materials has contributed literally to the *shapes* in our modern world today.

Massive Construction Projects

The twentieth century produced massive construction projects not seen since the great pyramids were built nearly five millennia ago. We can even say that in some cases we have actually outdone the ancient Egyptians.

The Suez Canal

Although the Suez Canal was not actually built in the twentieth century, it seems like an appropriate project to begin with. At the time that it was proposed, nothing quite so audacious had been attempted since ancient times (there actually was a canal connecting the Mediterranean to the Red Sea in antiquity). The modern canal is approximately 162 km long, connecting the Mediterranean to the Red Sea. Completed in the year 1869 after 10 years of construction, the project linked Europe to the East by water, reducing water-born travel time by months (Figs. 13.8 and 13.9).

The canal was built under the guidance of Ferdinand de Lesseps (1805–1894) of the Suez Canal Company (Fig. 13.10). It is estimated that more than 1.5 million workers participated in the project, and that literally thousands died before the

Fig. 13.8 The Suez Canal viewed from space

project was completed, making it one of the most costly construction project in terms of human lives in history.

The canal is 193 km long and approximately 205 m wide. It is built entirely at sea level, meaning that no locks are necessary. Thus, water can flow freely from the Red Sea to the Mediterranean. This was actually an issue during construction, as some people believed that sea level might be different in the Mediterranean and the Red Sea, so that when the canal was completed, one or the other might empty into the other, like a bathtub emptying out. Of course, sea level is essentially spatially constant on Earth, so that no such problems developed.

The canal took 10 years to complete and used slave laborers, mostly from Egypt. Although steam engines were available for both digging and transporting dirt, much of the construction was done by hand by an average workforce of about 30,000 laborers. This was truly the first massive project using mechanics in modern times.

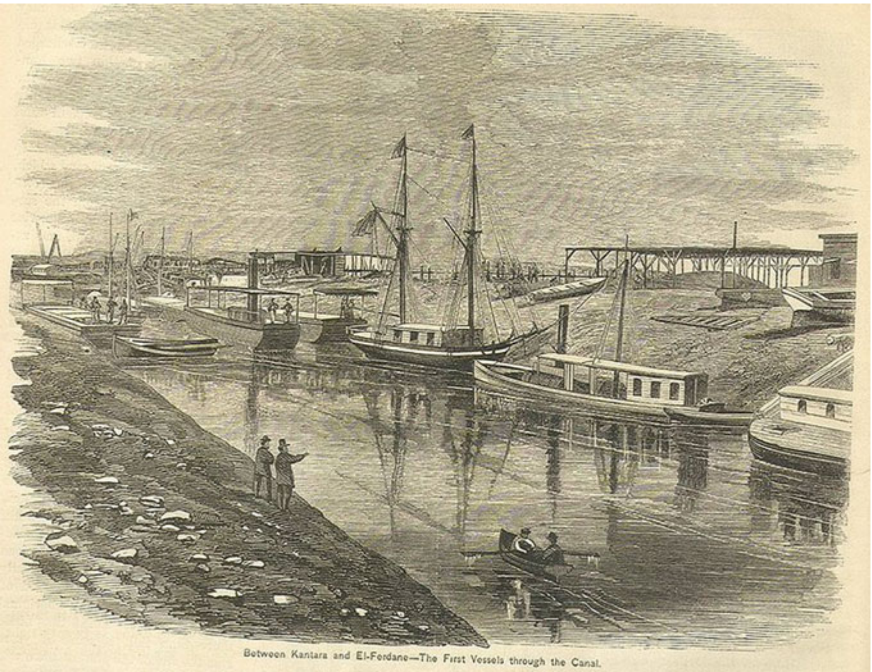


Fig. 13.9 Depiction of one of the first Suez Canal crossings

The Corinth Canal

The Corinth Canal, completed in 1893, connected the Gulf of Corinth with the Aegean Sea in Greece, a distance of some 6.4 km. Although several attempts were made to construct a Corinth Canal in antiquity, they all failed due to the massive amount of stone that had to be removed (the canal has a peak height of 90 m). The modern project, although not as massive as the Suez Canal project, was nevertheless enormous in scope because the canal was quarried (mostly by hand) from sedimentary stone. The canal walls, at an angle of eighty degrees to the horizontal, are an impressive site. Unfortunately, the base width (21.3 m) is too narrow for modern tankers, so that the canal is used mostly by tourist ships today (Fig. 13.11).

The Panama Canal

After completing the Suez Canal, Ferdinand de Lesseps attempted to dig a canal at Panama beginning in 1881. Unfortunately, this nearly 10-year effort failed with the loss of approximately 22,000 lives, mostly due to yellow fever and malaria. The tropical jungle, together with frequent torrential rains that destabilized the soil, doomed the project to failure.

Fig. 13.10 Portrait of Ferdinand de Lesseps

Fig. 13.11 Aerial photograph of the Corinth Canal

Fig. 13.12 The Panama Canal viewed from space

A second attempt was undertaken by the United States beginning in 1904, and this resulted in completion of the canal in 1914 (Fig. 13.12). By that time more advanced construction equipment was available than when the Suez Canal was built. This included the Panama Railway, a heavy duty railroad designed and constructed for the purpose of hauling the heavy equipment in, and the quarried material out. In addition, modern steam shovels and dredges were utilized for much of the canal construction. Finally, an enormous infrastructure had to be built in order to accommodate the needs of the thousands of workers who participated. The scale of this construction project was indeed larger than anything seen on Earth since the building of the Great Pyramids (Fig. 13.13).

The canal is 77.1 km in length, but more importantly, it traverses a hilly region, connecting near its center to Lake Gatun at 26 m above sea level. Thus, it is necessary to employ locks within the canal, a challenge that made the project considerably more difficult than the Suez Canal. Completion of the canal cut average travel time from the Atlantic nations to the Pacific ones in half (Fig. 13.14). To date nearly 900,000 ships have transited the canal, making it the most successful canal in history. Because of excessive demand, the canal is at the time of this writing undergoing a much-needed expansion.

Fig. 13.13 Photograph taken in 1913 showing the Panama railway, the steam shovels, and the locks in the Panama Canal project

Fig. 13.14 Photograph of the SS Kroonland transiting the Panama Canal in 1915

The Panama Canal is to this day perhaps the most ambitious construction project employing mechanics ever undertaken on Earth. Indeed, the American Society of Civil Engineers has named the Panama Canal one of the seven modern wonders of the world.

The Hoover Dam

The twentieth century saw the construction of many enormous hydroelectric dams. Perhaps the most famous of these is the Hoover Dam, built on the Colorado River in Southern Nevada. This dam was constructed in a 5-year span from 1931 to 1936, and at 221.5 m was the tallest dam in the world at the time, but this massive project opened the floodgates, as it were. Today there are more than forty dams over 200 m in height, and the Hoover Dam has slipped to number 23 in total height (Figs. 13.15 and 13.16).

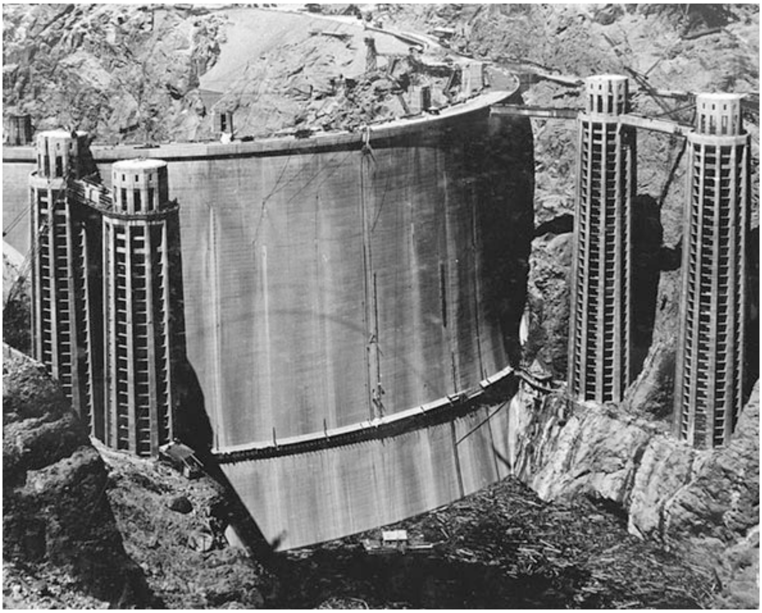


Fig. 13.15 Photograph of Lake Mead slowly filling on the upstream side of the Hoover dam in 1935

Even in ancient times the Romans understood that bridges spanning rivers should be curved toward the upstream direction, much like an arch lain on its side in order to maintain compression within the dam structure, as evidenced in the construction of the Pont du Gard (see Chap. 3). And so it was with the Hoover Dam. It was designed as a curved structure, with the apex on the upstream side. Furthermore, in order to support the massive weight of the dam while at the same time withstanding the water pressure (caused by Lake Mead, the result of the dam project) that would increase linearly with depth, it was necessary to make the dam thicker with depth. Thus, the completed design was to be 14 m thick at the top, gently widening to 200 m thick at the base (as well as 221.5 m in height, as mentioned above). The shear ingenuity of the conceptual design was reminiscent of the roof structure of the Pantheon, built by the Romans nearly two millennia earlier. And although the Pantheon dome was also made of concrete, no concrete structure of this size had heretofore been constructed on Earth.

Prior to construction it was necessary to lay a railroad from Las Vegas to the site. Upon completion of this project a workers' city was built on the site (now called Boulder City), and the massive infrastructure necessary to complete the project was transported to the site.

As for the actual dam project itself, it was first necessary to divert the water from the Colorado River so that the dam could be constructed. This was accomplished by digging four massive tunnels through the surrounding rock faces. Two

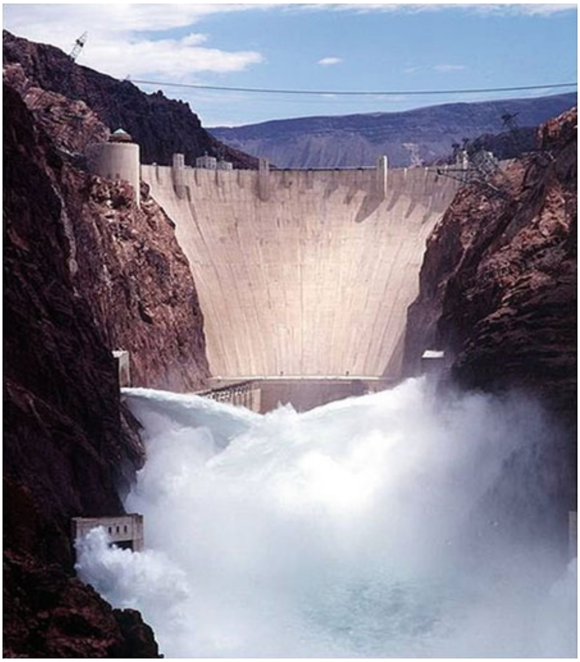


Fig. 13.16 Downstream view of the Hoover dam

were on the Eastern (Utah) side, and two were on the Western (Nevada) side of the river. Each of these tunnels was 17 m in diameter, and they spanned a total combined distance of 5 km. Once the tunnels were completed a temporary cofferdam was constructed that diverted the water from the river into the tunnels. In order to protect the project against possible flooding of the river, two additional cofferdams were constructed. The upper cofferdam, made from rock, was 29 m high and 230 m thick at its base (Fig. 13.17).

Next it was necessary to remove loose rocks from the canyon walls so that the massive dam would have a firm foundation. A group of workers called “high scalers” carried out this dangerous task using jackhammers and dynamite. The walls of the canyon were subsequently filled and reinforced, so that the project was now prepared for the actual construction of the dam.

The pouring of the concrete for the dam commenced in June of 1933. Careful modeling had indicated that pouring the dam in a single casting would mean that the concrete would require more than a century to cure properly. This is another problem in mechanics. When concrete is poured it is in a liquid state, having been mixed with water. The water must then slowly diffuse to the surface and evaporate, and this process can be modeled with an application of conservation of mass called Fick’s law. The diffusion of water outwards causes shrinkage to occur, and if the structure is not designed properly the shrinkage will induce stresses that are sufficiently large to cause the structure to undergo multiple fractures.

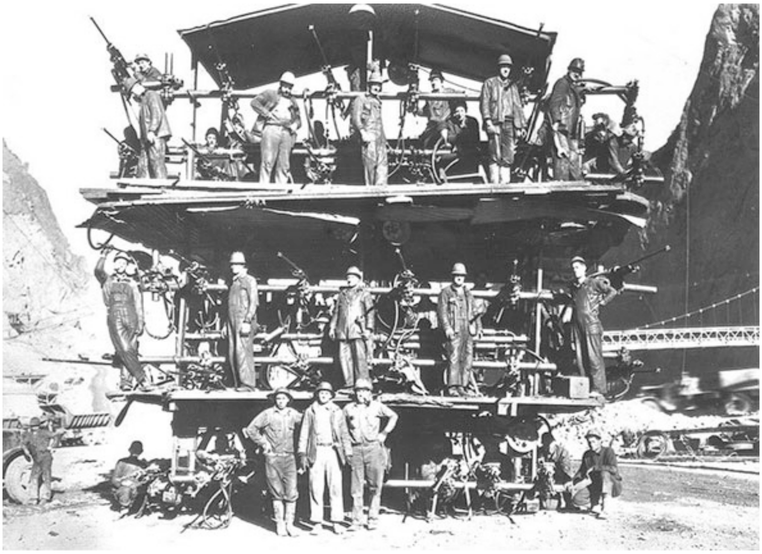


Fig. 13.17 Photograph of a jumbo rig used to dig tunnels during the construction of Hoover dam

An example of a naturally formed structure that has fractured during cooling and curing is the Devil's Tower, in northeastern Wyoming. This monolithic 386 m tall structure was formed about 40 million years ago, when the region was volcanically active. Although scientists are not quite sure how the tower was formed, there is one thing they do agree on—as the molten lava that formed the tower cooled it fractured into a horizontally hexagonal pattern that then extended vertically, thus creating the curious geometric pattern that we observe today. Similar naturally formed geologic patterns are found at the Devil's Postpile in California and the Giant's Causeway in Northern Ireland (or simply check out a nearby mudflat that has dried out). Had the Hoover Dam not been designed properly against diffusion induced fracture, it would have most likely looked something like the Devil's Tower, thus obviating its use as a dam (Fig. 13.18).

As one might expect, the further the distance the water must diffuse to the surface, the longer it will take for curing to reach completion. Thus, it was determined that in order to reduce the curing time and allow free shrinkage so that no cracking occurred, it would be necessary to pour the concrete in a series of blocks, as shown in Fig. 13.19. These blocks were typically about 5 m in height, and as much as 50 m^2 in cross-sectional area. Each block contained steel pipes that were used to run cool water through the blocks, so that curing progressed at a rate that resulted in proper curing and contraction without fracturing the concrete. Once the blocks were cured, the pipes were filled, as were the spaces between the blocks. This laborious process was carried out over a nearly 2 year period, with a total of 2.5 million cubic meters of concrete being poured from massive buckets

Fig. 13.18 Photograph of the Devil's tower in northeastern Wyoming

suspended from cranes. This is enough concrete to *build a two lane highway across the entire United States*!

The completed dam was dedicated by President Franklin D. Roosevelt on September 30, 1935 (former President Herbert Hoover, for whom the dam is named, was not in attendance). The project was completed in just over 5 years, with an average workforce of about 4,000 laborers, and a total of 112 deaths during construction.

There are also several other dams that, although not overly impressive in height, are distinguished by their enormous lengths. Perhaps the first of these was the Aswan Low Dam, built at the first cataract of the Nile in 1899–1902. At 1950 m in length, the dam was the longest in the world at the time. Unfortunately, this dam had to be raised on several occasions because the Nile overflowed it. The Aswan High Dam was subsequently built 6 km upstream in 1970, thus creating Lake Nasser south of Aswan, and doing away with the annual flooding of the Nile for the foreseeable future (Figs. 13.20 and 13.21).

The Relocation of Abu Simbel

One of my favorite construction projects involving mechanics in the twentieth century was the reconstruction of the ancient Egyptian Temples at Abu Simbel. These two temples were built in the thirteenth century BCE by Ramses II to show his power to the Nubians way up the Nile beyond Aswan. Unfortunately, the temples were built adjacent to the Nile River at a level near that of the river.

The construction of the Aswan high dam between 1960 and 1970 created Lake Nasser. Since the water level of the lake was to be much higher than the level of

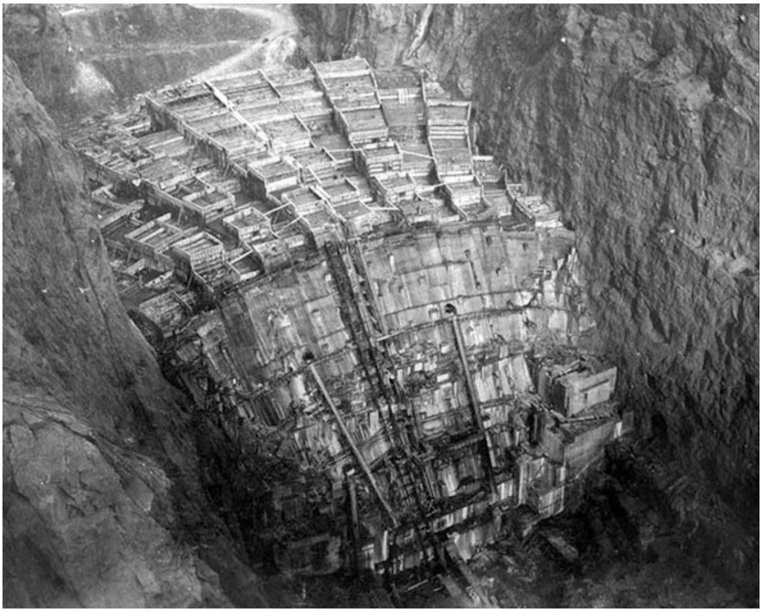


Fig. 13.19 Photograph showing the formworks for the massive concrete columns in Hoover dam

Fig. 13.20 Photograph of the Aswan high dam from space

the Nile, the lake would have inundated these invaluable temples. Therefore, after considering various options the Egyptian government decided to *move the temples to higher ground!*

Working under the aegis of UNESCO, a team of international engineers devised a plan to transport the temples to the cliff above the river gorge. Construction began

Fig. 13.21 Satellite photo of lake Nasser, the world's second largest artificial lake

in 1964. The new site was directly above the old site that was carved into the cliffs along the Nile. Since there were no cliffs at the higher location, two artificial hills were first built above the cliffs. Next, the temples were carefully cut with large power saws into blocks averaging 18,000 kg in weight. These were then lifted with cranes 65 m to the top of the cliff and fitted together in exactly the same configuration in which they had been originally constructed more than three thousand years ago.

It was important to retain precisely the same orientation during this process, as the temples had been designed to align with the Sun at certain times of the year. In addition, the interiors of the temples were rather ornate and large, so that the project involved much more than reassembling the surface features of the two temples. This truly amazing feat of modern civil engineering involving mechanics was completed in 1968, thus allowing thousands of tourists to visit the site every day. One of the greatest treasures from Egyptian antiquity was thus preserved for us to see today (Figs. 13.22 and 13.23).

The Venice MOSE Project

Another rather unique dam project that is underway today is the Venice MOdulo Sperimentale Elettromeccanico (MOSE) Project. When completed, this massive construction project in mechanics is expected to mitigate flooding in Venice by utilizing ingenious pop-up dams that will surface only during periods of high tides (Figs. 13.24 and 13.25).

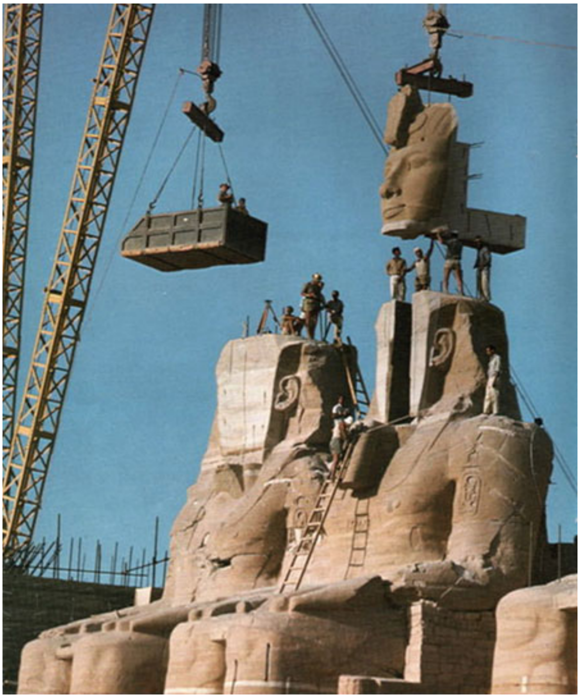


Fig. 13.22 Photograph of Ramses II's temple during reconstruction

The Chunnel

Another massive construction project was The Chunnel, the underground tunnel connecting England to France. Completed in 1994 at a cost of £4.65B (1985), this 50.5 km tunnel is a marvel of modern mechanics. While it may be slightly more expensive than the airfare from London to Paris, when the total cost and time of airport transfers is included, it is quite a bargain (Fig. 13.26).

The Egyptian pyramids astounded the world for nearly five millennia. But with the rise of modern mechanics, applications of this science have produced an ever increasing plethora of truly massive construction projects on Earth. It is no stretch to say that in our time we humans believe that virtually anything can be built on Earth. Such is the impact of mechanics on our planet.

Modern Failure Mechanics

Sometimes human-made structures fail to perform as intended. There are numerous possible modes of physical failure in solids. Broadly speaking, failure can be induced mechanically, chemically, thermally, or even electromagnetically. A simple example of a thermally induced failure would be melting of a solid. For example, the failure of the Space Shuttle Columbia in 2003 seems to have been induced at least in

Fig. 13.23 Photograph of the reconstructed Ramses II's temple at Abu Simbel

Fig. 13.24 Satellite photo of Venice showing main entrance to the Lagoon

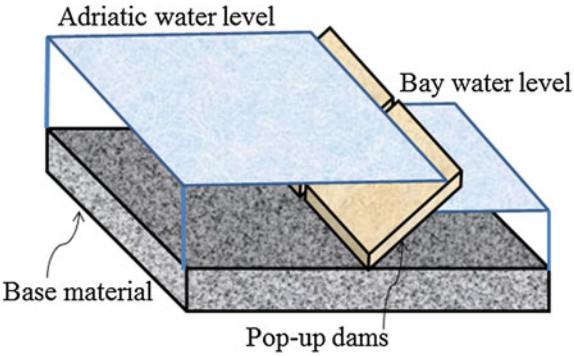


Fig. 13.25 Schematic drawing of dams utilized in Venice MOSE project

Fig. 13.26 Photo of full scale model of section of Chunnel at National Railway Museum in York, England

part by overheating and subsequent melting of the structure during reentry to the Earth's atmosphere. Of course, in this text we are concerned only with the first of these—mechanically induced failure.

Mechanical failure normally occurs in one of several different ways, including permanent deformation, fracture, excessive deformation, or structural instability. Consider for example failure due to excessive deformations. A case in point is that of the C-5 military transport aircraft, built in the 1960s. This aircraft was the largest ever built in the U.S. Unfortunately, when the aircraft was fully loaded to its design configuration; the wingtips were capable of touching down on landing. This is an example of failure by excessive deformations. Thankfully, this type of failure does not occur too often, because it is actually one of the easiest failure modes to predict. That is due to the fact that our modern continuum mechanics models predict deformations, usually quite accurately.

Tacoma Narrows Bridge Collapse

A very famous failure toward the middle of the twentieth century was the Tacoma Narrows Bridge collapse. This bridge failed dynamically due to structural resonance brought about by a steady wind through the narrows. This is a mechanically induced phenomenon within the discipline called aeroelasticity, in which the aerodynamic forces due to the wind interact with the structure in such a way that the forces applied by the wind change with time due to the deformations of the bridge. In the case of the Tacoma Narrows Bridge, this interaction caused the steady wind to induce cyclic loading in time that caused the bridge displacement amplitude to increase over time until the bridge collapsed. It was subsequently determined that the bridge decking was too flexible for the wind loads applied to the bridge (Fig. 13.27).

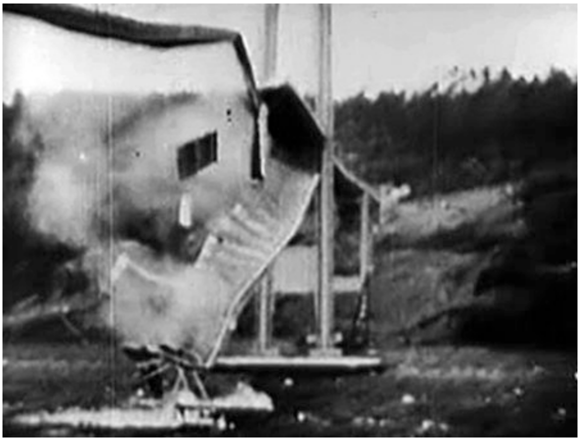
One mode of failure that was studied to great extent over most of the twentieth century is the subject of fracture mechanics. Solids are distinguished from fluids by the fact that they can undergo fracture, and this process can often (though not always) lead to failure of a structure to perform its intended task. Cracks can occur on very large length scales, such as Halfdome at Yosemite National Park (see Chap. 11).

The pivotal question with a crack in a solid is: when will it grow, and where will it go? I suppose that is really two questions. And as it turns out, neither of them has an easy answer. On the surface of it, one would have thought that the issue would have been resolved within the field of materials science, but that has not turned out to be the case. Instead, the problem has been at least partially solved using the science of mechanics.

Early twentieth century structural failures such as the sinking of the Titanic (see below) led researchers to study the underlying cause of crack propagation in solids. The first significant paper on this subject was published by Charles Inglis (1875–1952), a British civil engineer, in 1913. In his seminal paper, Inglis noticed that rivet holes in the hulls of ships tended to be elliptical in shape, leading him to study stress concentrations at the edges of elliptical defects.

Drawing on Inglis' ground-breaking work, Alan A. Griffith (1893–1963) proposed in 1921 that a crack of length, a, can be predicted to propagate when the available energy for crack growth, G, exceeds the required energy for crack

Fig. 13.27 Photograph of the Tacoma narrows bridge collapse



growth, G_c, a material property. This concept can be said to have been the birth of modern fracture mechanics. Stated mathematically, it reads as follows [126]:

$$G > G_c \Rightarrow \dot{a} > 0$$

where the dot over a means the time derivative and the symbol ⇒means ‘implies that”. This model has turned out to be quite accurate for many materials.

While the above concept is simple, its consequences are profound. Furthermore, its implementation and deployment is exceedingly complicated. First, you should have a solid object with a crack in it. Then, you have to know the material property G_c, the intrinsic ability of the material to resist crack extension. This property is hard to measure experimentally, but most of the time it can in principle be done, and in many materials it is in fact a material constant. Armed with this property and the ability to predict stresses in structural components using the finite element method (see above section on Computational Mechanics), it is in principle possible to predict when a crack will grow and where it will go. Further seminal works on the mechanics of fracture were reported by D. S. Dugdale, Grigory Barenblatt (1927–), George R. Irwin (1907–1998), and James R. Rice (1940–), to name a few. The above explanation is an oversimplification of this still developing field of mechanics, but it serves to elucidate the complexity associated with the subject of fracture mechanics.

The above fracture model is just one example of a failure model. The twentieth century produced a plethora of new design methodologies for structures that are based on the mechanics models introduced in this century. The important point to be noted herein is that the continuum mechanics models developed in the nineteenth century do not predict failure in and of themselves. They must be adjoined with additional physically inspired mathematical constraints such as the Griffith criterion for crack growth mentioned above.

The interested observer need only look as far as automobiles, bridges, buildings, aircraft, spacecraft, and modern windmills to see the worldwide impact of these failure models. The seminal concept is this: if one can predict failure of an object theoretically a priori, then one can utilize this information to design the object so that failure is completely obviated. This is a powerful outcome of the ability to predict the future. Using this concept, the design of essentially all modern load carrying structures emanates from the mechanics concepts developed in the nineteenth century. Unfortunately, our understanding is still imperfect, so that failures still occur, as we will see below.

Sinking of the Titanic

A successful structural design requires that the object satisfy all of the design constraints. If the design fails to satisfy even one of the design constraints it has failed. One of the most famous structural failures in modern times is the case of the ill-fated RMS Titanic. As the reader may well know, at the time the ship was built (1912) it was the largest passenger liner in the world. It went down in the North Atlantic on its maiden voyage when it struck an iceberg. There were 1,517 persons killed in the disaster (Fig. 13.28).

Investigations determined that the ship went down due to a complex series of related design flaws. Large ships are designed with bulkheads spaced along their length so that if the hull is pierced, several of the bulkhead-separated compartments can flood without causing the ship to sink. In the case of the Titanic, the ship was designed to remain afloat if four bulkheads were flooded. Unfortunately, when the ship struck the iceberg, it scraped along the starboard (right) side for nearly the entire length of the ship. The ship had exposed rivets along its length, and these rivets were made of somewhat brittle steel that may have been further embrittled by the cold waters in the North Atlantic. A more recent investigation of the debris field adjacent to the ship on the floor of the Atlantic has disclosed the presence of large stones that have been traced to the coast of Greenland. These stones may have been imbedded in the iceberg, thereby providing a sharp edge that further enhanced the cutting ability of the iceberg as it slid along the hull of the ship.

At any rate, the iceberg both sheared off the heads of these rivets as well as produced cracks in the hull, allowing water to begin flooding the first five compartments. Furthermore, as the ship canted from the flooding in these compartments, water poured over the tops of some of the bulkheads (another design flaw), causing the aft compartments to flood more rapidly. The Titanic disaster caused a worldwide calamity that led to significant changes in the design of modern ships.

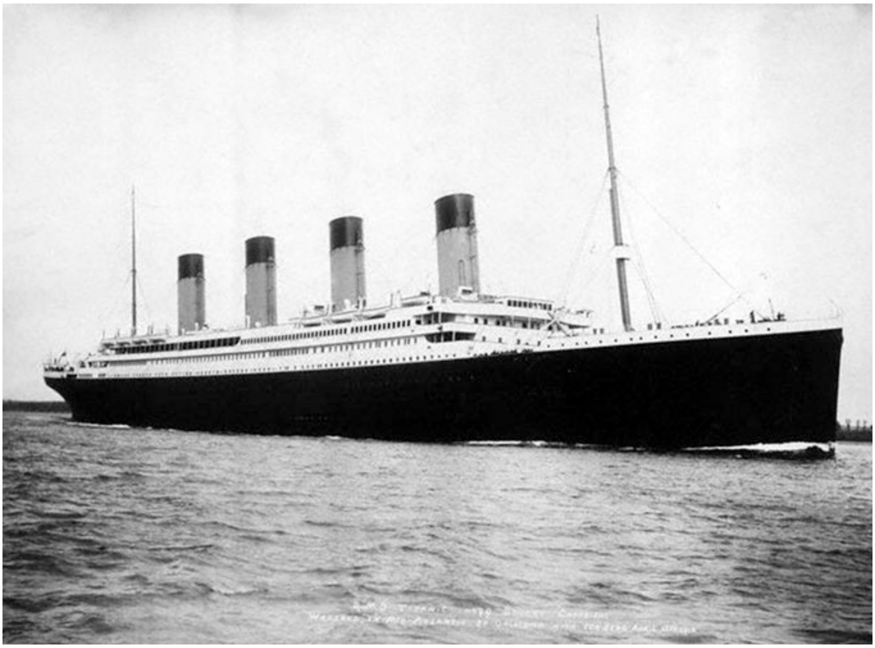


Fig. 13.28 Photo by F.G.O. Stuart of RMS Titanic departing Southampton on April 10, 1912

The Failure of the Space Shuttle Challenger

Although the design constraints are often known precisely, this is not always the case. An example of a case wherein the design constraints were not known a priori sufficiently to avert structural failure is the 1986 failure of the Space Shuttle Challenger. Challenger blew up during launch on January, 28, 1986 (Fig. 13.29).

The Rogers Commission was appointed by President Reagan after the disaster for the purpose of determining the cause of the failure. Over the succeeding nearly 3 years, this commission gathered information, finally determining that the major contributory factor to the failure of the Challenger was the temperature at launch, which was −8 °C (18 °F). As pointed out on television by Cal Tech Professor Richard Feynman (see the section above on computational mechanics), a member of the commission, the O-rings in the shuttle rocket motor booster casings were embrittled at this low temperature, causing them to fail during launch (you can check the film clip of Dr. Feynman out on YouTube). All seven members of the on-board launch crew were killed.

The Rogers Commission found another more serious cause for the disaster. They determined that engineers and scientists had warned upper management that launching at such low temperatures could cause failure of the shuttle. However, senior management had overruled the technical staff and allowed the launch to proceed. As a result of these findings, there was a major overhaul of the procedures

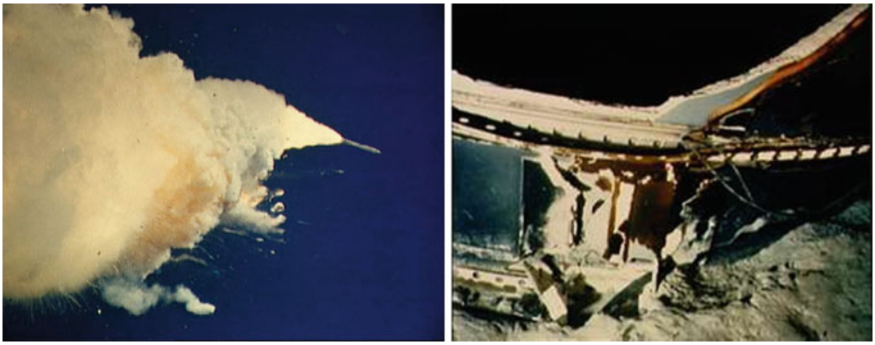


Fig. 13.29 Photos of the challenger disaster; explosion on the *left*; Challenger underwater on the *right*

used at both NASA and other scientific agencies in the United States. Management is no longer allowed to overrule technical staff in such matters. This is an example of a mechanical failure that was caused by poor oversight by managers.

Other modes of failure can be much more difficult to predict. Perhaps the most difficult mode of failure to predict is failure of structural components due to long-term cyclic loading. Somewhat incongruously, the prediction of failure by this mode is termed "life prediction". Perhaps "death prediction" would be more appropriate, but it may be a bit too ghoulish a term.

1988 Aloha Airlines Disaster

An example of failure due to cyclic loading is the case of the 1988 Aloha Airlines disaster, where corrosion due to the salty environment in the Hawaiian Islands contributed to the development of fatigue cracks in the aircraft fuselage. As shown below, a large portion of the fuselage was instantaneously popped off of the aircraft while in flight. A flight attendant was swept out to her death, but miraculously, the aircraft landed safely and no one else was seriously injured. As a result of this world-famous accident, safety inspections have been implemented that have thus far obviated further commercial aircraft disasters of this type (Fig. 13.30).

I-35 Minneapolis Bridge Collapse

Another recent major failure caused by chemically induced fracture and fatigue was the collapse of the I-35 W Mississippi River Bridge in Minneapolis on August 1, 2007. A post-mortem inspection of the bridge revealed that the beam connection plates had corroded over time, thus reducing the material properties of the plates. This corrosion, together with long term bridge overloading caused by adding two lanes of traffic to the initial design, contributed to unstable crack propagation and

Fig. 13.30 Photo of Aloha airlines disaster

collapse of several sections of the bridge. Thirteen people were killed and 145 people were injured. Although inspections have been stepped up subsequent to this tragedy, our nation's aging infrastructure is likely due for more structural failures unless further safety measures are implemented (Fig. 13.31).

The UA Flight 232 Crash

Small cracks subjected to cyclic loadings can also lead to long-term catastrophic failure, as in the case of the Sioux City UA flight 232 (DC-10) aircraft crash on July 19, 1989. It was found that cracks in the number 2 (tail mounted) engine stage 1 fan disk propagated in an unstable manner, thereby causing portions of the engine to break off and damage the aircraft tail and controls [127]. The aircraft subsequently broke up during an emergency landing at Sioux Gateway Airport. Although 185 passengers survived, 111 passengers were killed. The fan disk was found in a cornfield 3 months after the disaster, and it was reconstructed (Fig. 13.32).

Fig. 13.31 Photo on *left* of the Minneapolis bridge collapse; photo on *right* showing fracture in gusset plate

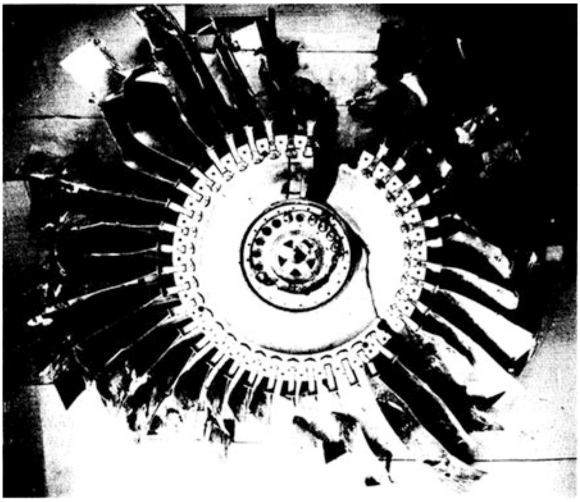


Fig. 13.32 Photo of reconstruction of the stage 1 fan disk in the Sioux city aircraft crash of flight UA 232 on July 19, 1989. *Note* the large crack in the disk

The ability to predict when a crack will grow and where it will go depends on the material utilized in the solid under consideration. Brittle solids generally are the class of materials for which fracture can be most easily predicted. However, in the case where the brittle solid of interest is not isotropic, such as a laminated continuous carbon fiber composite currently being deployed in the Boeing 787 Dreamliner, the Airbus 350 and the Airbus A380, the prediction of fracture is an advanced topic in mechanics (Fig. 13.33).

The Chernobyl Reactor Meltdown

One of the most significant failures of the twentieth century was the meltdown of the nuclear reactor at Chernobyl on April 26, 1986. This disaster was initiated by mechanics of nuclear fission at the molecular scale, and progressed to an environmental disaster that is still being assessed. Various agencies estimate that the death toll due to cancers caused by this accident will range between 25,000 and 200,000 (Fig. 13.34).

The Tōhoku Earthquake and Tsunami

The 2011 Tōhoku earthquake and subsequent tsunami in Japan reminds us all of the power of mechanics. The earthquake, a mechanical disruption of two tectonic plates, as described in Chap. 11, resulted in the propagation of a mechanical wave in the ocean. The two events combined to create a disaster of incomprehensible

Fig. 13.33 Boeing 787 dreamliner on *left* Airbus A380 on *right*

Fig. 13.34 Photograph taken in 2006 of the Chernobyl Sarcophogus

proportions. The World Bank estimated the total loss at $235 billion USD, making it the costliest disaster in recorded history. Perhaps one day we will possess the mechanical technology to avoid such disasters (see Chap. 11) (Fig. 13.35).

The Leaning Tower of Pisa

On a brilliant Sunday morning in the summer of 1971, I stepped down from the train in Pisa, stored my pack in a luggage locker, and headed for the center of town. I arrived in the Piazza del Miracoli (Square of the Miracles), and to my surprise, I was entirely alone in the square. I walked gingerly over to the Leaning Tower and began my pilgrimage to the top (Fig. 13.36).

Fig. 13.35 Photos of buildings collapsed by the Tōhoku earthquake

At that age I was cursed with a case of acrophobia. Thus, when I arrived alone and breathless at the precipice moments later, I found it nearly impossible to stand. Indeed, I groped for the iron railing on hands and knees, unable to summon the bravado to stand. Finally, calling upon my innermost strength, I rose, white-knuckled hands gripping the railing, and took in the magnificent view, all the while fearing that I would totter from the summit.

I visited the summit once again 9 years later, but my next trip to the top would not occur for nearly a quarter of a century, in 2004. In the interim period the tower was closed due to fear that it would topple. By the time the tower was reopened, the Piazza dei Miracoli had changed from the quiet spot remembered from my youth to something resembling a circus. The age of frenzied and ubiquitous air travel had arrived on our planet within that span of time, and Italy was the destination of choice for the multitudes.

The Leaning Tower of Pisa is perhaps the most famous example on Earth of a failure that somehow succeeded. Indeed, when the tower came dangerously close to collapsing in the 1990s, the International Commission wisely realized that their goal was not to right the tower to vertical. Instead, they sought to decrease the tilt only enough to ensure the safety of the tower, while retaining sufficient tilt for the tower to continue to attract tourists.

I was fortunate enough to be living in Italy for two summers in 1996 and 1997, and during that period one of the members of the International Commission gave a speech at our study center. The Leaning Tower is a fascinating challenge in mechanics. When the tower was first begun in 1173, the foundation was poorly

Fig. 13.36 Photograph of the Leaning Tower of Pisa

designed. Workers did not comprehend that the soil beneath the foundation was partially saturated from the nearby Arno River. Thus, by the time the first level had been completed the bell tower was already listing away from the river. Workers attempted to correct this by building the second level leaning slightly toward the river, but this caused the tower to begin listing instead toward the river. Construction was therefore halted, and the tower was left incomplete for nearly a century [128].

Construction recommenced in 1272. By then it was assumed that the underlying soil had stabilized. Thus, workers attempted to correct subsequent levels, thereby creating the slightly curved structure that is plainly visible to the observer today. The tower was finally completed in 1372, an enormous span of time for such a seemingly straightforward project.

Unfortunately, the tower continued to list, the angle growing ever so slowly over the centuries, as the foundation crept due to the overbearing load of the structure on the viscoelastic soil beneath. By the twentieth century the angle of tilt had increased to about 4 degrees from the vertical. I say “about” because the angle of tilt of the tower is continuously changing. A plumb bob was at one time dropped from the center of the interior of the tower, and this device plotted a continuously changing path on the floor of the tower due to the actions of Sun and wind on the structure. Thus, in order to determine if the tilt is actually increasing in time, a three month average of the plumb bob's path was taken in order to measure the change of tilt in time. This is a fabulous problem in mechanics!

In 1989 the Civic Tower of Pavia collapsed, killing one person. This disaster caused officials to close the Leaning Tower, and it remained closed while the International Commission deliberated on a corrective course of action. It was well known that previous attempts had come to nought. For example, Mussolini had injected concrete into the base in the 1930s with the result that the tower had lurched still further.

Still later, liquid nitrogen was injected into the ground in an attempt to slow the progression of the tilt, but this had caused the tower to lurch even further, perhaps in part due to Mussolini's previous error in judgment.

The International Commission finally settled on applying lead weights to the high side of the foundation. This did in fact slow the progression of the tilt, but the foundation was not wide enough to provide sufficient moment arm for the weights to reverse the tilt. Thus, a second approach was taken. A girdle was built about the third level of the tower, and cables were attached to the girdle. These were then pulled on by two wenches attached to the cables.

I visited the tower on several occasions during this period of weighting and tugging, and I don't mind telling you, each successive time I saw the Leaning Tower, I presumed that it would be my last because to my eye it appeared that this approach might in fact induce the tower to collapse.

Fortunately, a third attempt at a solution was formulated by the commission, and this final approach was successful. Engineers poked large hypodermic needles into the ground on the high side of the apron and sucked 38 m^3 of soil from the ground beneath the tower. The tower straightened by 45 cm, thereby returning to the angle of tilt of 1838 (Fig. 13.37).

The Leaning Tower of Pisa was reopened to the public on December 15, 2001. A second removal of 70 metric tons of soil in 2008 has further stabilized the structure. Unfortunately, all of this has only increased the volume of tourist traffic, to the point that it is necessary to wait in line, buy tickets and then wait still further before climbing the tower. Thus, my advice to those who wish to go to the top of the tower is—*plan ahead!* After all, the Leaning Tower is really worth visiting, and many of you may only get one chance to go to the top.

Every time we lose a commercial aircraft somewhere in the world, the general public is horrified, as well they should be. Indeed, I know people who refuse to fly in an aircraft because they are afraid that such a catastrophe will befall them. But let's look at the statistics of commercial aircraft crashes. We have about 35,000 commercial flights per day in the U.S. That translates to about 12.8 million flights per year. Lately, there has been about one commercial aircraft crash per year in the U.S. So your odds of being in a crash are about one in 12.8 million. That's pretty low odds! It is in fact not too dissimilar to the odds of winning the lottery. So if you think you are going to win the lottery, you should also avoid flying on airplanes. In fact, your odds of being killed in an automobile are significantly higher than this. Furthermore, your odds of being killed while crossing the street *on foot* are higher than your odds of being killed in a commercial aircraft.

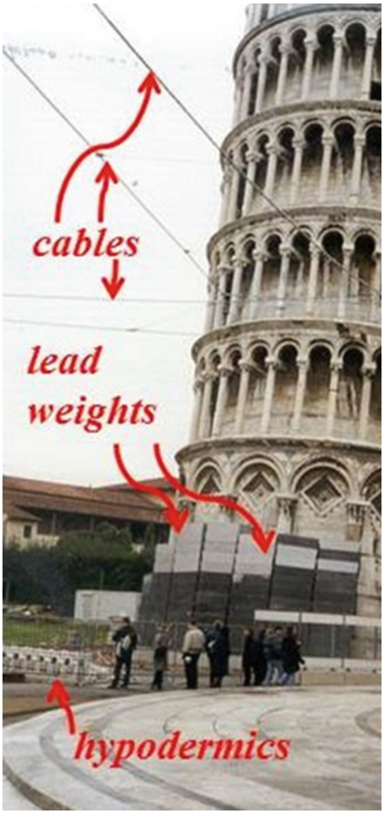


Fig. 13.37 Photograph of the lead weights placed on the foundation of the Leaning Tower. *Note* the row of hypodermics can also be seen at the *left* edge of the photo, as well as tension cables attached to the third level

Commercial aviation is in fact the safest form of transportation in the history of our planet, and it is virtually entirely an outgrowth of mechanics.

We can now say that while classical mechanics does not have all of the answers, it has nonetheless served us well. Despite the fact that we continue to experience highly visible catastrophes due to our imperfect understanding of mechanics, we are a far more advanced and successful species than has ever before inhabited this planet, or any other, for all we know.

The Future of Mechanics

14

Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning.

Albert Einstein

As I mentioned in the preface to this book, I am a big fan of Carl Sagan. I am also a tremendous fan of Michio Kaku. Dr. Kaku has published a recent book entitled *Physics of the Future: How Science Will Shape Human Destiny and Our Daily Lives by the Year 2100* [129]. This is a fabulous book. I recommend it highly to anyone who finds my book interesting.

In his book, Dr. Kaku has laid out a carefully researched vision of the effects of science and technology on our future. Therefore, you may say that the final chapter in this book is either redundant or unnecessary. My response to that is this: Dr. Kaku has painted a grand vision of the world a century from now, whereas my ambition is much less lofty. I simply intend to describe developments in the field of mechanics that are either already underway, or are expected to be realized shortly.

Biomechanics

I am not a young man any more. When I go to see the doctor, I am usually informed of something called 'risk factors', such as, "You have a greater risk of developing heart disease because you have high blood pressure, and the statistics show that more people with high blood pressure die of heart attacks," or, "You have a greater risk of dying of glaucoma because your parent had glaucoma." Neither of these diagnoses is actually the case for me.

This sort of talk concerns me greatly. When I hear the term "risk factor" the first thing that I think of is statistics. In and of itself, statistics is a quite reputable field of mathematics. Unfortunately, the term "risk factor", when it is used in the context of medicine, implies that no predictive methodology, ergo understanding of the underlying causes, has been employed with respect to the illness in question.

Here is more like what I would prefer to hear. "You have high blood pressure. Research has shown that high blood pressure causes cells to undergo chemical changes in the lining of the heart. A ten percent increase in blood pressure has been

D. H. Allen, *How Mechanics Shaped the Modern World*,
DOI: 10.1007/978-3-319-01701-3_14, © Springer International Publishing Switzerland 2014

shown to induce chemical changes in heart cells that causes them to die at the rate of etc., and we now have a model in place for both predicting the cause of this problem, as well as how to correct it". Now that's what I mean by employing mechanics in medicine to produce a predictive methodology.

Within the fields of science and engineering, predictive methodologies have been the focus of much endeavor since the time of Galileo. Indeed, it would not be presumptive to say that the entire world of science is predictive in nature, constantly seeking explanations for cause and effect, and testing those predictions with carefully controlled experiments.

But in the field of medicine, we are constantly bombarded with "risk factors", implying to me that there is no model yet available to explain the underlying causes of the illness in question. In fact, this sort of approach is entirely forensic in nature. Quite a lot of people have died on this planet (nearly as many as are alive today), and simply by keeping a record of the causes of their deaths, we can construct a forensically based methodology for defining the future. Unfortunately, this approach to predicting the future contains no scientific model for cause and effect. As I indicated in Chap. 10, this is tantamount to predicting where a hurricane will go based strictly on past hurricane tracks.

So what is going on here? Why has the medical profession not yet completely embraced the scientific method? The answer to this question is complicated. In fact, there is good news, but there is also bad news. Let's take the bad news first. The medical profession, like any other profession, is possessed of a certain amount of inertia. The learned doctors teach the newcomers, and this system encourages a certain amount of adherence to the old artistic ways. Artisty in medicine is in and of itself a good thing, but too much of it can be a bad thing. This then is the bad news.

But there is also good news. The medical profession is changing, albeit somewhat too slowly from my perspective. Here is a bit of reality. The human body is filled with all sorts of items that are essentially mechanical devices. Bones, muscles, tendons—all are designed to perform mechanical functions. And the failure of the aorta that killed Albert Einstein was essentially a mechanical failure, resulting from the fracture of the wall of the aorta. These kinds of illnesses that are driven by mechanics can be predicted using models already under development by the scientific and engineering communities, and in some cases this is already reaching medical practice.

The first case that I am aware of wherein a significant scientific discovery was made regarding the mechanics of the human body was by William Harvey in 1628. He discovered the nature of the blood circulatory system. After that, other major developments in medicine related to mechanics were few and far between.

In the 1960s a professor at Cal Tech named Yuan-Cheng "Bert" Fung (1919) began studying mice. He made mice do psychologically stressful things, and then he quickly cut them open and found that their veins doubled back over themselves when they were slit open. This did not occur when the mice were not psychologically stressed. This was the first scientific evidence (to my knowledge) that psychological stress results in physiological stress. In other words, mechanics is a big part of human health. If you stress yourself out a lot psychologically, you are literally killing yourself with mechanics. As a result of his groundbreaking research, Dr. Fung is today considered to be the father of modern biomechanics.

These days more and more medical problems are being addressed with the help of mechanics. This is a truly exciting area of research that promises to change the field of medicine from a forensically based profession to a predictively based profession. Imagine a world in which when you go to the doctor and there is a problem, he or she can tell you, “there is a predictive model for this illness, and using this model, there is every reason to expect that we will be able to not only prolong your life, but to also eradicate your illness using proven scientific methods”.

And now let me finally pay homage to the medical profession that I have just maligned. Of course, I was concealing the difficulty of the problems they face just to make a point. The reason that scientists and engineers have been able to develop numerous accurate predictive models outside the field of medicine is that in most cases they have been working with inanimate objects that undergo no (or in some cases rather limited and straightforward) chemical and/or biological change. When you take chemistry out of the problem, things are *vastly* simpler.

In the case of humans, when you take chemistry and biology out of the problem, the patient is already dead! The point of this is to say—there are almost no human illnesses that do not entail at least some chemistry and biology. Thus, while mechanics may be a significant part of the illness, it is rarely *all of the illness*. By itself, chemistry is well understood, as is mechanics, as we have seen herein. But when you mix chemistry and mechanics and add in biology you have what is to this eye the most complex scientific challenge on our planet, and that is exactly what we face with a living human.

So I was picking on the medical profession to make my point. I have nothing but the greatest respect for our medical specialists. But I do nevertheless have some advice for them: work with people outside your profession! By working together, we will move toward more and better scientifically based predictive models for illnesses, and some of these solutions will necessarily entail mechanics.

Unfortunately, despite the fact that mechanics plays an enormous role in the performance of the human body, professionals in the medical field are not usually trained in the science of mechanics. Alternatively, they receive substantial training in the fields of chemistry and biology. As an example, it has recently been suggested that aging is caused by the long-term statistical nature of chemical processes. The cells in all living beings are constantly being replenished, and as a result of the statistical nature of the chemical processes involved, a few of the chemical bonds are not formed correctly. It is hypothesized that the accumulation of these incorrect processes over time causes aging. Therefore, much medical research is currently focused on decreasing the probability of these incorrect recombinations and/or replacing them with correct ones. The leading supposition here is that if this can be accomplished, life can be made infinite.

Unfortunately, this is wishful thinking, because chemistry is not the only cause of aging. Aging is also caused by mechanics. This has never been more apparent than when astronauts began coming back to Earth after long stays in space. When they exit the reentry module, they are observed to have difficulty performing normal functions such as walking. This is due to the fact that they have been in a zero gravity environment for so long.

Because almost everyone who has ever lived on this planet has been subjected to Earth's gravitational field for their entire lives, it is difficult for us to conceive of what zero gravity would feel like. Albert Einstein is said to have once commented that humans cannot feel their own weight when experiencing freefall in an elevator. The next time you want to feel what zero gravity is like, try freefall in an elevator (or even better, on a roller coaster!). But don't do it for more than about a second, or you might be fatally injured when the elevator stops!

Another possible way to experience zero gravity (without going into space) is to fly on the so-called "Vomit Comet", NASA's aircraft that flies to a high altitude and then performs a slow arcing maneuver so that the force due to the Earth's gravitational field is balanced by the aircraft's rate of change of momentum (Fig. 14.1). This circumstance can be maintained for about a minute. That is actually the same physical means by which astronauts attain zero gravity in space, except that the rate of change of the momentum of the spacecraft in orbit has been purposefully designed to balance the Earth's gravitational force for much longer periods of time.

What all this is getting at is this—we Earthlings live in a gravitational field that exerts force on our bodies from the moment we are conceived right up to the instant we die (and even thereafter). This force invariably causes mechanical aging in all of us. All human tissue contains a significant amount of liquid within it, which causes the mechanical material behavior of our soft tissue to be what we call viscoelastic. All viscoelastic materials creep with time *under constant loading conditions.* What this means is that every bit of the soft tissue in your body is slowly deforming toward the center of the Earth throughout your lifetime. Other than standing on your head (which actually won't work anyway), the only way to reverse this process is to either replace the tissue, or tug it back the other way, typically using cosmetic surgery.

Fig. 14.1 Weightlessness in the "Vomit Comet"

Over the last 30 years, the field of medicine called biomechanics has developed. In this field of study, the mechanical material behavior of soft tissue is accounted for in the models used to predict failure of human organs. What we now know is that chemistry and mechanics are inately coupled within the human body. Mechanical stress causes some deteriorating chemical processes to speed up, and the resulting deterioration of the mechanical material properties further speeds up the associated chemical processes.

An example is the superficial muscular aponeurotic system (SMAS), the set of muscles within your face. Anyone knows what I am talking about when I mention aging of the face. Your facial tissue creeps with time, which is a fancy way of saying, your soft tissue is continuously sagging more and more toward the center of the Earth. The SMAS sags more rapidly in some people than it does in others, but no one is completely immune to this facial creep process over time.

Another example is glaucoma. Medical professionals have determined that there is a significant probability that people with high blood pressure will develop glaucoma, which is a progressive disease that can lead to blindness. Apparently many people with high blood pressure also exhibit high fluid pressure in the ocular cavity, called ocular hypertension. This high fluid pressure can cause deterioration of the optic nerve, which is chemical in nature. In other words, mechanical stress induces chemical change that leads to death of axons within the optic nerve, thereby eventually leading to partial or total blindness. Thus, we have another example of the coupling between mechanics and chemistry in the human body.

Still another example is the case of abdominal aortic aneurysms. Albert Einstein was told that he had an abdominal aortic aneurysm, and that, based on the available mortality statistics from previous patients suffering this sort of illness, he would die in a few years (he died seven years later). This is not good science. Good science would seek a cause of the aneurysm and attempt to intervene accordingly on the patient's behalf (Einstein did undergo repair surgery in 1948, but he chose to forego further surgery when his aorta ruptured in 1955) (Fig. 14.2).

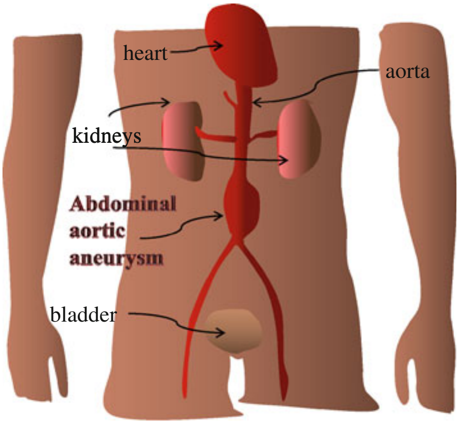


Fig. 14.2 A section of the aorta showing an abdominal aneurysm

A further example is the case of traumatic brain injury (TBI) induced by improvised explosive devices (IED's). This type of brain injury came to the forefront during the most recent war in Iraq. Insurgents made IED's that induced blast waves when detonated. In quite a few cases soldiers were impacted by these blast waves, subsequently exhibiting a variety of injuries and illnesses. The prevailing medical information suggests that the blast wave impacts the head of the soldier, thereby inducing a secondary mechanical wave to pass through the brain of the soldier, and this mechanical wave subsequently induces either mechanical damage to the brain such as the breaking down of cell walls, or mechanically induced chemical damage to the brain, such as cell death due to trauma. In some cases the effects of this damage are not observed until several months after the impact event. This type of mechanically induced brain damage is not yet well understood.

So what are the solutions to these multidisciplinary problems? The answers all point to multidisplinary research and development. The National Institute for Health is today funding more and more research that involves teams of doctors and other scientists and engineers who are not medical doctors. These highly accomplished scientific teams are working closely together to attack problems in a way that is revolutionary in nature.

As outlined by Dr. Kaku in his book mentioned above, we will see changes in the predictive nature of medicine that will dramatically alter the world in the next century, and many of them will involve mechanics. As an example, Dr. Kaku predicts that your toilet will perhaps become a device for diagnosing potential medical problems years in advance of the current diagnostic tools. This is a problem whose solution involves mechanics.

Another area of medicine wherein mechanics will play a significant role is in the insertion of devices inside the human body. We already have numerous procedures for inserting mechanically designed prosthetic devices inside the body, such as artificial hips, knee implants, heartbeat regulators, arterial stents, etc. In addition, quite a few surgical devices have been developed that either mitigate or completely do away with the necessity to make incisions in the patient.

In the future, many incisions will become unnecessary, and many others will be made by robotic devices that are inserted into natural orifices so that the patient is not subjected to life-threatening incisions. An example is the case of robotic devices injected down the esophogus of the patient and into the stomach. An incision is made in the lining of the stomach, where there are no nerve endings, and the robot crawls out onto the outer surface of the organs and performs laparoscopic surgery, such as the removal of the appendix. The patient then goes home without even having an incision on the extremity of his or her body. The technology already exists to perform these types of surgeries, which involves the use of mechanics (Fig. 14.3).

So long as there is the necessity to have a physical interface between the patient and the medical team, there will be applications involving mechanics. What we can say is that these devices will continue to grow both smaller and more intricate as the technology becomes available.

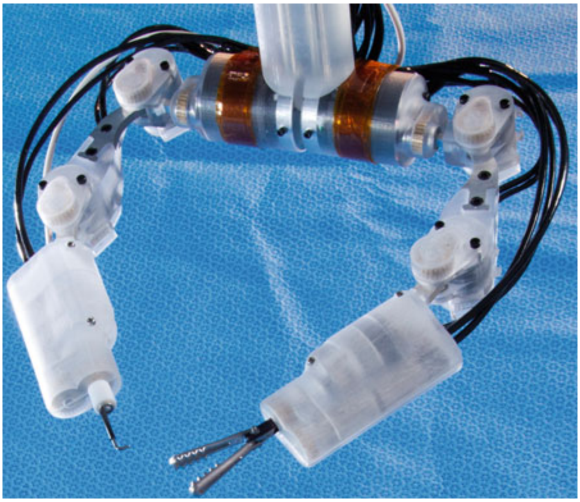


Fig. 14.3 Photograph of surgical robotic devices inserted through the stomach

The human body is perhaps the ultimate mechanical device ever devised on our planet. True, it has required millions of years of evolution for our species to reach our current state, but it is readily apparent to the average person that we are much more than the most intelligent species on our planet. In fact, anthropologists agree that a large part of the reason that our brains are so large compared to our total volume is that the superior mechanics of our bodies allowed for our brains to grow disproportionately to other species on Earth. An obvious example is our thumb, which can be utilized in a pincher movement to carry weapons to fend off the saber-toothed tiger.

I will not go into further detail on this subject, but suffice it to say this—as long as humans dominate this planet, mechanics will be a necessary part of our existence for the simple reason that our bodies deploy mechanics with each and every movement. And as long as humans exist, we will continue to find ways that employ the science of mechanics to improve human health.

Mechanics and Extraterrestrials

At some point, should our species survive long enough, we will surely encounter organisms from somewhere else in the universe. I am always a bit nonplussed by the shortsightedness displayed by Hollywood producers when I see another installment of their endless collection of movies that depict extraterrestrials arriving here on Earth. For some reason the hypothetical visitors in these movies always bear a distinct resemblance to us. For example, they almost invariably have two arms and two legs, and they have a head. They are normally no more than two feet taller than us, nor less than two feet shorter than us (ET excepted!).

I have the sneaky suspicion that most of this emanates from the unavoidable reality that if you want to allow a human to play the role of an extraterrestrial by suiting him or her up in a body suit, it will be unlikely that the body suit will be dramatically different in size from the range of available human talent.

However, there is hope! With the rise of electronically generated images in movies, we are beginning to see a few depictions of extraterrestrials that the science of mechanics suggests are more likely. Indeed, the mechanics of other planets may contribute to species that are *dramatically* different from us. After all, there are quite a few significantly different species from ours right here on Earth (take the giant squid, for instance).

So here are a few things for our Hollywood pundits to think about when planning future movies depicting extraterrestrials. First of all, there is no reason that life cannot be sustained and even flourish and evolve on planets (or moons!) of considerably different mass (and therefore gravity) from Earth. The planet that our visitors come from might be larger or smaller than Earth. If it is larger, then the larger gravitational field will most likely cause life from that planet to be much smaller than us. When I say much, I mean perhaps a whole lot! As we already know, there are some very small creatures on Earth. And there is no reason that they cannot have superior intelligence, because the molecular scale is considerably smaller even than the scale of single cells. For example, a single cell in the human body typically contains about 10^{16} atoms. Therefore we can conclude that the arriving extraterrestrials could be quite small without sacrificing superior intelligence.

Perhaps our visitors will not be tiny, but instead quite short and really wide! Perhaps they will be a thin film stretching over several acres, but only a few centimeters in thickness. That might not be unrealistic on the massive planet that they come from, where the force of gravity would kill you in the span of a few hours. And if they are shaped like that, I doubt that they will have two arms and two legs. They might have a head, but it will be rather compact vertically, and speaking of that, they will undoubtedly not be thin-skinned, as their enormous gravity will require them to have a very thick and durable skin in order to keep them from breaking apart.

By the way, when these short and wide extraterrestrials arrive on our planet, they will perform like super humans. They will quite likely win almost any sports event they enter on Earth because the gravity will be so slight to them that they will feel like they are floating in nothing. Think of Alan Shepard playing golf on the Moon during the Apollo 14 mission in 1971. This is of course where the idea for the comic book hero Superman came from, although for some reason he looked exactly like we Earthlings do.

Now let’s consider extraterrestrials that come from a planet with a significantly smaller gravity than on Earth. Consider for example a planet somewhat like the Moon in size, which has a gravitational constant about one-tenth of the Earth’s. These extraterrestrials will not be happy on Earth. They will likely be very slender and willowy. I seriously doubt that they will even be able to stand up on our planet. They will feel like humans would feel if we went to Jupiter—actually worse!

When you ride on a roller coaster, you feel like you are really heavy when you ride inside a loop due to the rate of change of momentum caused by the moving cars, and this is about how you would feel on Jupiter, because Jupiter's gravitational constant is about 2.65 times that of Earth's.

But that doesn't mean that there cannot be life on Jupiter. Jupiter's gravity is a mechanics issue, but that in and of itself does not preclude life. What precludes life is chemistry—a lack of the basic chemical elements for life, meaning carbon, oxygen, hydrogen, and nitrogen. If Jupiter had all of these (and perhaps a bit more sunlight), there is no reason that life could not flourish there. But those organisms would nevertheless most likely be short and wide due to the substantial gravitational field on their planet.

So we've discussed the effect of gravitational forces on the evolution of extraterrestrials, now let's talk about other effects caused by mechanics. On Earth all life is profoundly affected by several time constants that are specific to our planet. These include the time it takes the Earth to revolve on its own axis, the time it takes the Earth to revolve around the Sun, and the Earth's tilt with respect to the plane of the ecliptic (causing the seasons). Because of these, for example, we humans sleep once a day on average, and if we don't we eventually die. Many other species on Earth have similar sleep habits, although not necessarily identical to ours. Take bears for example. They sometimes sleep for months, called hibernation, but they are nevertheless constrained to their sleep patterns by our planet's mechanics of motion.

Now imagine that our visitors come from a galaxy where their home planet is the same size as ours, but it spins on its axis once every year (a day to them!), and it orbits their Sun once every 6 months (a year to them!), and somewhat bizarrely, their planet's axis of spin is oriented perpendicular to the plane of the ecliptic in their home solar system (implying that they would have no seasons). What I'm getting at is this—there is absolutely no reason to expect that they would be even close to what we humans are like despite the fact that their planet exerts the same gravitational force on them.

And here is an even more shocking revelation—because the natural time constants associated with their solar system will be radically different from ours, their sense of time will most likely be *totally* different from ours. They will not conceive of an hour, a day, a month, a year, or indeed anything at all that we use—with one possible exception. Perhaps they will use a second, the approximate duration of a human heartbeat. This span of time seems to be wholly dependent on Earth's gravitational constant, thus driving the volume of blood that can be pumped to the extremities of our bodies in Earth's gravitational field.

Therefore, if as I suggested their planet is the same size as ours, they might relate to our second, the approximate duration of a heartbeat. On the other hand, if their planet's mass is different from ours, even their conception of a second will most likely fail to coincide with ours, since their blood (if indeed they have blood at all!) will need to be pumped sufficiently to overcome their local gravitational field. Indeed, there may be no comparison at all between our two time scales. They might grow old in twenty seconds, or more ominous, they might not grow old in ten thousand years! In the latter case, let's hope that they move *very* slowly compared to us.

Okay, now let's take the other extreme. Let's suppose that our visitors come from a solar system that is *exactly* like ours, and that they live on the third planet from their Sun, and that it's mechanics of motion are *identical* to ours. This is highly unlikely (at least in a nearby galaxy), but nevertheless possible. What could we expect from these visitors? Even in this unlikely physically identical scenario it is extremely far-fetched to expect that they would be just like us. The reason for this is that the evolution of life is nonlinear and statistical in nature, and more importantly, it is chaotic (see Chap. 10). What that means is if you do the same experiment over and over again, very small perturbations in any of the conditions will lead to very large differences in the evolution of the species. Thus, I'm sorry to say that just due to the statistical nature of evolution, they will still most likely bear little resemblance to us. So the scene in the bar that we've all observed in *Star Wars*, despite the fact that we have all considered the beings in that scene to be amazingly different from us, depicts extraterrestrials most likely nowhere near as different from us as the actual beings will be when we finally meet them.

The most likely scenario for our visitors to be similar to us is the case whereby we evolved from the same biological ancestors. As we now know, the planets in our solar system have communicated with one another since the inception of the solar system via impacts from foreign objects that have knocked chunks of material into space and transported these chunks as meteors from one planet to another. This same physical phenomenon, caused by mechanics, could have transported biologic material from one solar system to another, or (more unlikely, but still statistically possible) even from one galaxy to another.

In this case the likelihood that we will be similar to our biologic cousins, though much higher than were we not biologically related, will nonetheless decrease with the time span since the material arrived on our two respective planets. Despite the possibility that the two pieces of arriving biologic materials may have been identical when they arrived on the two planets, differing physical conditions on the two planets, as well as the statistical nature of evolution, would invariably cause the two identical biologic entities to diverge with evolution, thus leading to significantly different cousins.

We of course know this to be the case because we have extant examples right here on Earth. For example, consider the fact that identical species on Earth diverged when Pangaea began to break up 200 million years ago. Thus, almost all of the marsupials on Earth today are in Australia, implying that they developed after Australia split off from Pangaea.

Now recall the fact that the Earth is 4.5 billion years old. And we just happen to have evolved into a superior species capable of manned space exploration in the past century. What if our visitors from an *identical* planet came from a solar system that was formed 10 billion years ago, or 5.5 billion years *before* ours was formed. What will they be like? There's no telling, but I can guarantee you this, if we humans are still around on this planet in another 5.5 billion years, at the point in time when our planet would be the same age as theirs is now, we will undoubtedly be quite different from what we are today, because 5.5 billion years represents about 280 million generations (and 7 billion gestation cycles) of our species, during which time we could well evolve from what we are today into a species that you could not even begin to imagine, all due to both mechanics and Darwin's law. If we are still around in 5.5 billion years, we might have wings, antlers, and legs like frogs. Hopefully, we will nonetheless still be attractive to the opposite sex. Otherwise, we will shortly thereafter become extinct.

So when we consider what our visitors from other planets will be like, we need to consider both length and time scales, as it is unlikely that they have evolved in any way similar to us. And need I say, virtually all of the possible differences I have mentioned above are due to nothing more than mechanics. Fortunately for our species, the distance between inhabitable planets in our universe over the span of time that we humans have become dominant is sufficiently large as to make the probability of actual direct interactions of intelligent beings from different planets to be unlikely.

The Mechanics of Our Destruction

Sooner or later our species will become extinct. This is due to the principle that if time is infinite, all events with finite probability will necessarily occur sooner or later. We have no way of knowing exactly how our extinction will occur, but we can be relatively certain that mechanics will be a factor, no matter what the cause will be. Here are a few of the most likely scenarios.

Destruction by the Sun

A solar flare event is likely to strike the Earth within the next few thousand years, and this would indeed cause widespread damage on Earth, including knocking out our power grid. However, scientists estimate that the loss of human life would be minimal, thus most likely obviating the possibility of extinction of our species from solar flares.

Scientists predict that our Sun will run out of fuel in about 5.5 billion years. However, before that the Sun will burn enough of its fuel that it will slowly expand, becoming a Red Giant. During this period, the Sun will expand to thirty times its current size and will glow so hot that it will burn away the outer crust of the Earth. If we humans are still around that far in the future, we will most certainly not survive this event. The Sun will eventually become a White Dwarf, but by then we will either all be dead, or we will have employed mechanical devices called spaceships to depart our dying planet for greener pastures.

Meteor Impact

As we all know, scientists theorize that the dinosaurs were wiped out by the meteor that struck the Earth at Chixculub 65 million years ago. That meteor was about 6 km in diameter. Around 35 million years ago a meteor 1 km in diameter struck the eastern coast of the U.S., creating Chesapeake Bay (Fig. 14.4). We know today that while this latter event caused an enormous conflagration, it did not rise to the level of species extinction that the Chixculub event caused. Thus, evidence suggests that it will take a meteor of the scale of several kilometers in size to destroy humankind.

There are two most likely sources for a meteor strike of this scale. We could be struck by either an asteroid or a comet. In either case, our best chance of survival is to prepare in advance and launch a vehicle into space with the intent to deflect the meteor away from our planet.

First, there is the possibility of an asteroid strike. Since there are many more large asteroids (that we are aware of) than comets, this scenario is the more likely of the two possibilities. That is the bad news. The good news is that because the

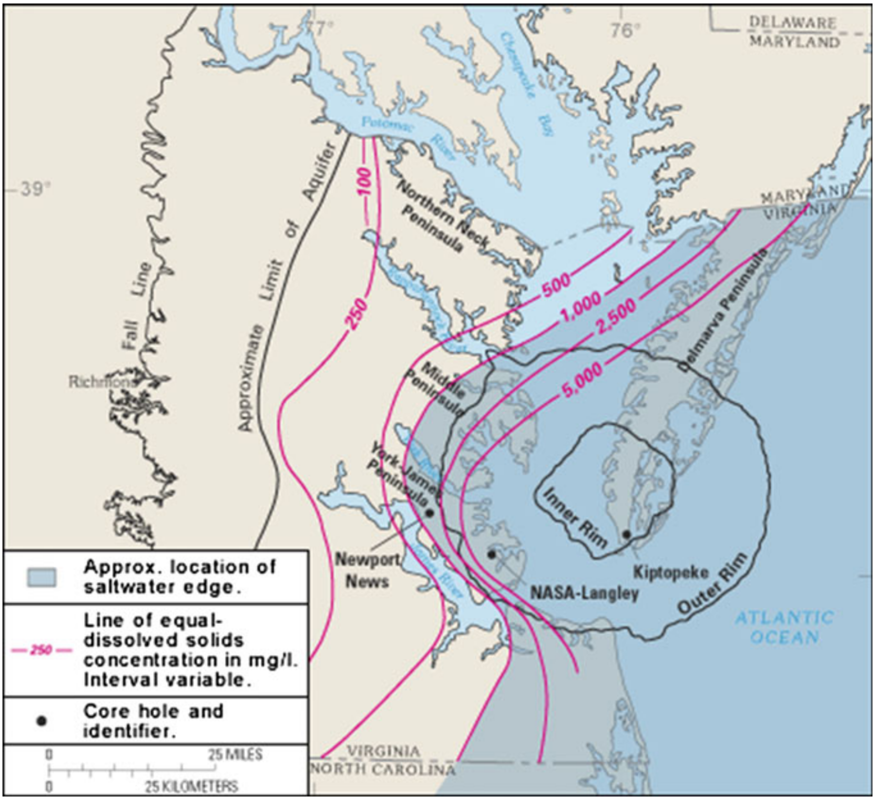


Fig. 14.4 Depiction of the Chesapeake Bay Meteor Crater

asteroid belt is fairly close to our planet we can (and actually do) track all of the kilometer sized asteroids, and we have the technology to predict several years in advance the probability that one will strike Earth. Thus, we will have plenty of time to send out a vehicle to divert this disaster.

And the earlier we do so, the smaller the force that will be necessary to divert the asteroid, a problem in rigid body dynamics. Scientists think that it will most likely not even be necessary to land on the asteroid. Simply flying a vehicle close by will cause sufficient gravitational interactions to divert the asteroid away from its destructive path toward Earth.

Second, there is the possibility of a comet strike. These come from deep space, and for this reason they are difficult to discover more than a few months in advance. Should a large comet come barreling down on Earth, we will only have a short period of time to attempt to deflect it from striking our planet. Thus, while this possibility is much more remote than the possibility of an asteroid strike, we will need to have our mechanics ducks in row, as it were, in order to avert the destruction of our species.

Scientists estimate the odds of a world devastating meteor strike occurring within the typical human lifetime is slightly greater than one in a million. And needless to say, this would be a mechanical event of global proportions.

Interstellar Radiation Event

There are stars blowing up in our universe all the time. Every so often one of them sends out a detectable amount of radiation via a supernova event or a gamma ray event. These types of events are unavoidable on Earth. Furthermore, there would be no forewarning of such an event because they travel at the speed of light. If sufficiently close to our planet, either one would wipe out all life on Earth. Scientists estimate the probability of one of these events destroying Earth at less than one in ten million. Although the rays emanating from these ill-fated stars are not mechanics per se, they both involve mechanics (explosions) and the results of their arrival on Earth will most certainly induce mechanics events on a global scale.

Pandemic

We now know that whole species can become extinct as a result of global scale disease. The transmission of disease is related to the mechanics of diffusion, fluid dynamics, flight (i.e. birds), wind and atmospheric phenomena, contamination of aquifers, typhoid, all directly related to mechanics.

Climate Change

Climate change is a hot topic these days (pun intended). There seems to be quite a lot of evidence that our climate is changing. However, it is difficult to determine the causes of this, as the process of climate change is extremely complex on our planet. Furthermore, it is presumptive to conclude that the current changes in our climate will be destructive to life, as the time scale of most observed climate changes in our planet's past have evolved over a scale of time that is much longer than the time span that we have been keeping scientific records. Thus, we continue to have major debates worldwide over climate change.

Another issue surrounding the subject of climate change is—if our climate is really changing, what if anything can we do about it? This is an interesting subject because it involves scientific challenges on a global scale. Just exactly what could we do to change our climate? Only a few attempts have been made in the past to control our climate (such as cloud seeding), and these have for the most part been unsuccessful.

Processes in our planet's atmosphere involve almost incomprehensible amounts of energy (see Chap. 10). Thus, in order to solve this problem, we will have to develop the ability to purposefully control enormous amounts of energy. I say purposefully because we seem to have already caused significant changes in the greenhouse effect on our planet via the burning of fossil fuels and emission of other gases that have depleted the ozone layer. Thus, some of our climate change could in fact be induced by our own ignorance and/or poor judgment. And where it is possible to affect our climate accidentally for the worse, the reverse should also be possible. This problem will necessarily involve mechanics, and it will most likely be addressed (and perhaps even solved) within the near future.

Human Initiated Extinction

Of all of the possibilities for destruction of our species, our own self-destruction is the most likely scenario. Among these are the following:

- Global nuclear warfare
- Human-induced climate change (mentioned above)
- Human-induced disease
- Economic collapse.

As unusual as some of the above possibilities may seem, it is nonetheless believed by many experts that human initiated extinction is by far the most likely scenario for the demise of humankind. I will cite just one example. In 1961, U.S. Air Force first Lt. Jack ReVelle received a midnight phone call from his commander. ReVelle remembers his commander saying, "Jack, I got a real one for you" [130].

Lt. ReVelle arrived at the site of the crash of a B-52 aircraft to find that two nuclear weapons had been onboard the aircraft when it went down. Fortunately for all of us, Lt. ReVelle and his team defused the bombs without incident. Had he not done so, we could have had a major nuclear disaster right here in the U.S., an event due in large measure to mechanics, in this case the failure of the aircraft, which broke up in flight. This type of human-induced event could quite possibly lead to extinction of our species.

Another possibility is that in our attempts to wipe out certain types of illness, we might actually insert chemicals into the environment that are capable of causing our own demise. An example that comes to mind is thalidomide, a drug that was introduced in the 1950s as a means of inducing sleep. It was subsequently found that when taken by pregnant women, the drug induced quite significant birth defects in their children.

We humans are not perfect, and where we have perfected weapons of mass destruction, we have created conduits for own destruction via our own imperfections. Scientists do not normally hazard a guess at the likelihood of our own self-destruction, but it would seem that of all the possibilities cited herein, this one is the most dangerous and likely, and in the most likely scenarios, mechanics plays a significant role.

Mechanics and Toilet Paper

We are finally coming to the end of our journey through the history of mechanics. Thus, now we can show the evolutionary family tree of mechanics (Fig. 14.5).

You may ask, where is this all leading to? I confess that I do not know. But as you now know from reading this book, it certainly will not stop me from hypothesizing. So here goes…to me, the future of mechanics is not unlike the future of toilet paper. Seriously!

It wasn't too long ago that toilet paper didn't even exist. Paper has been used for hygienic purposes as far back as the sixth century in China, and toilet paper is known to have been mass produced as far back as the fourteenth century. But the first rolled toilet paper was patented in 1883. Before toilet paper, people used all sorts of naturally available items such as leaves, grass, stones, and even sand (ugh!).

During the American Civil War, it is known that soldiers destroyed books wholesale by tearing out the pages in order to use them for purposes of personal hygiene. Think about living in a world where the only means of preserving personal hygiene is to destroy knowledge—not an easy choice by any means.

In the twentieth century, toilet paper seems to have reached the zenith of technological perfection. Two inventions substantially improved toilet paper, both of them rooted in mechanics. First, the softness of toilet paper was significantly improved by imbedding small amounts of nonevaporative liquids (typically nontoxic oils) in the paper. This made toilet paper much better at maintaining cleanliness without physically damaging the user (related to the mechanics of

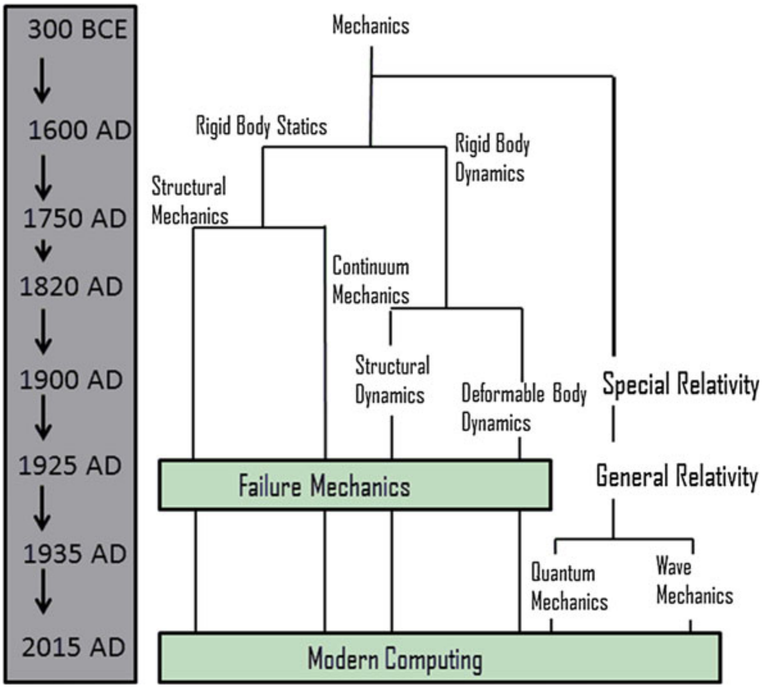


Fig. 14.5 The evolutionary family tree of mechanics

deformation of the user). Coincidentally, this also made it less likely that toilets would get stopped up, another problem in mechanics.

Second, toilet paper on rolls was perforated at spatial intervals in order to make it easier to tear from the roll (related to the mechanics of fracture of the paper). Both of these inventions seem to have been optimized within my own lifetime. And interestingly, they seem to have propagated across most of our planet, but at varying velocities.

This is an example of the interaction between mechanics and economics. You see, soft toilet paper that is easy to tear is not a necessity, it is a luxury! Soft and perforated toilet paper is also somewhat more expensive than rough and un-perforated toilet paper. For that reason, one tends to find more luxurious toilet paper in economically advanced countries (and luxurious hotels within those countries!), and less luxurious toilet paper in poor countries. Check it out the next time you visit another country.

Actually, you can test it out right here in the United States by visiting the bathrooms of various businesses and public facilities. If the quality of toilet paper therein is very low, you can bet that the company in question is in real trouble, because they can’t even afford toilet paper! Try this theory out at a public university. By examining the quality of toilet paper within the bathrooms in our public universities, you can get a good idea just how far our higher education complex has fallen from its lofty post-World War II pedestal. At my university, they are constantly changing toilet paper vendors in an attempt to save money.

How does this little discourse on toilet paper relate to mechanics? The answer is—not too much from the theoretical standpoint, because a single unit of toilet paper is so cheap that the product can be designed essentially experimentally, without recourse to much theory. On the other hand, it serves as a guide for those who are plotting out the rise and fall of a particular society or country. I submit to you that if you plot the quality of toilet paper versus time in the United States, you will observe a peak in the curve that coincides with the zenith of our country's *real* Gross Domestic Product (GDP), which appears to have occurred sometime shortly after the turn of the millennium.

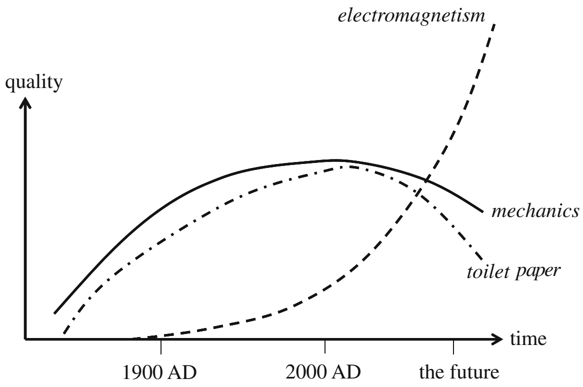
I am simply using toilet paper as a euphemism for the history of mechanics. Sadly, although there is not necessarily a connection between the two, the science and application of mechanics seems to have peaked around the same point in time that toilet paper reached its zenith.

Indeed, like the quality of toilet paper in the United States, mechanics appears to have reached its pinnacle. Unless and until there is a conflagration on this planet that somehow wipes out our ability to deploy the now superior field of electromagnetism, the wave that was mechanics has broken on the shore, and is destined to be a field of diminishing importance in the lives of humans (Fig. 14.6).

Where might this new-found scientific teenager called electromagnetism take us in the future? Perhaps we will no longer actually *go* on vacation. Perhaps we will simply *simulate* a vacation, thereby removing mechanics entirely from our pleasurable journey. You can already simulate a visit to Ancient Rome and walk through the Forum on Google Earth. Perhaps you will meet your next significant other while doing so. *Perhaps we humans will even evolve into less mechanical beings.*

After all, who needs to climb up the Eiffel Tower, or even the Leaning Tower for that matter, when we can *simulate it* electromagnetically for a lot less money! And forget golf, it will perish as well. It is simply too expensive! We will *simulate* a round of golf (this technology already exists), just as we will simulate most other

Fig. 14.6 The rise and fall of the quality of toilet paper



sporting activities (also already in existence). However, those who choose to *simulate* exercise will most likely shorten their lifespans.

Perhaps humans will not go to work in the future. We will *simulate* going to work electromagnetically. Gasoline (or any other source of energy) simply costs too much to drive anywhere. Not unlike the futuristic movie *Surrogates*, we will perhaps send a genetically perfect (and eternally youthful) image of ourselves to work on the wings of our electromagnetic devices.

Like many now extinct mechanical devices such as the astrolabe, the mechanical level, and the slide rule, the death of many additional mechanical devices is just around the corner. The mechanical wristwatch (see Chap. 12), the printed book, and the internal combustion engine (see Chap. 12) are all destined to become extinct before too long. Indeed, perhaps the entire mechanical world I was born into is rapidly approaching extinction.

I for one feel fortunate to have been alive during that brief period when mechanics was at the crest of the wave. I for one believe that the world of mechanics is the real world—a world wherein humankind has had the luxury to touch, to feel, and to experience the thrill of existence. And that, dear reader, for a mechanical species such as ours is simply as good as it gets!

Errata to: How Mechanics Shaped the Modern World

15

David H. Allen

Errata to:
D. H. Allen, *How Mechanics Shaped the Modern World*, DOI 10.1007/978-3-319-01701-3

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Chapter 1

Fig. 1.1 Painting of a Giant Deer from Lascaux showing dots representing lunar calendar, photo by HTO accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Lascaus,_Megaloceros.JPG (released to public domain by the author)
Fig. 1.3 Front and back views of Narmer's Palette, photo by Captmondo accessed in January, 2013 at http://en.wikipedia.org/wiki/File:NarmerPalette_ROM-gamma.jpg (released to public domain by the author)
Fig. 1.5 Snefru's Meidum pyramid, photo by Neithsabes accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Meidoum_pyramide_003.JPG (released to public domain by the author)
Fig. 1.7 Snefru's Red pyramid, photo by Ivrienen accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Snofrus_Red_Pyramid_in_Dahshur_(2).jpg {{CC-BY-3.0}}

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D. H. Allen (✉)
Civil Engineering Department, Texas A&M University, College Station, TX, USA
e-mail: dallen@pavesci.com

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Fig. 1.16 Sketch Map of East Valley of the Kings, drawing by James Baikie accessed in January, 2013 at http://en.wikipedia.org/wiki/File:East_Valley_of_the_Kings_Sketch_Map_(Topo).png (released to public domain by the author)
Fig. 1.17 Giovanni Battista Belzoni, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Belzoni1.jpg {{PD-1923}}
Fig. 1.18 Bust of Akhenaten from the Cairo Museum, photo by qwelk accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Akenaton.jpg (photo released to public domain by the author)
Fig. 1.19 Howard Carter examining King Tut's Sarcophogus, published by The *New York Times* in 1923 http://upload.wikimedia.org/wikipedia/commons/c/c9/Tuts_Tomb_Opened.JPG {{PD-US}}
Fig. 1.20 Mummy of King Tut, photo accessed in January, 2013 at http://it.bing.com/images/search?q=King+Tut+photos+Wikimedia&view=detail&id=DB7990ADF9DCAE52898ED0286A3CEA42F3FDFE68&first=91 {{PD-1923}}
Fig. 1.22 Ginger—a naturally mummified body, photo by Ernest Alfred Wallis Budge accessed at http://en.wikipedia.org/wiki/File:Ginger_(mummy)_1920.png {{PD-1923}}
Fig. 1.24 Granite head of statue of Amenhotep III (1370 BCE) discovered at the Temple of Mut in Karnak by Giovanni Belzoni and Henry Beechey in 1817, now in the British Museum, photo by Jon Bodsworth accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Granite_head_of_Amenhotep_III.jpg (released to public domain by the author)
Fig. 1.30 Sixteenth century engraving of the Hanging Gardens of Babylon by Maarten van Heemskerck, drawing accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Heemskerck-hanginggardens.jpg {{PD-1923}}
Fig. 1.31 Sixteenth century image of the Temple of Artemis by Maarten van Heemskerck, drawing accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Temple_of_Artemis.jpg {{PD-1923}}
Fig. 1.32 Sixteenth century rendition of the statue of Zeus at Olympia by Maarten van Heemskerck, photo accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Statue_of_Zeus.jpg {{PD-1923}}
Fig. 1.33 Mausoleum of Halicarnassus today, photo taken by Monsieurdl accessed in January, 2013 at http://en.wikipedia.org/wiki/File:MausoleumHALICARNASSUS.JPG (photo released to public domain by the author)
Fig. 1.34 1880 depiction of the Colossus of Rhodes, drawing accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Colosse_de_Rhodes_(Barclay).jpg {{PD-1923}}
Fig. 1.35 1909 drawing of the Lighthouse of Alexandria by H. Thiersch, drawing accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Lighthouse_-_Thiersch.gif {{PD-1923}}

Chapter 2

Fig. 2.2 Bust of Pericles, Vatican Museum, photo by Jastrow accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Pericles_Pio-Clementino_Inv269.jpg (photo released to public domain by the author)
Fig. 2.4 Depiction of Thales of Miletus, drawing accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Thales.jpg {{PD-1923}}
Fig. 2.6 Depiction of Democritus, drawing accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Democritus2.jpg {{PD-1923}}
Fig. 2.7 Bust of Aristotle, National Museum of Rome, photo by Jastrow accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Aristotle_Altemps_Inv8575.jpg (photo released to public domain by the author)
Fig. 2.8 Photograph of one of the oldest surviving fragments of Euclid's *elements*, photo accessed in May, 2013 at http://www.math.ubc.ca/~cass/Euclid/papyrus/tha.jpg {{PD-1923}}
Fig. 2.9 Tenth century AD Greek copy of Aristachus' second century BCE calculations of the relative sizes of the Sun, Moon and the Earth, Library of Congress Vatican Exhibit, photo accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Aristarchus_working.jpg {{PD-1923}}
Fig. 2.10 Modern Portrait of Archimedes by Domenico Fetti, Gëmaldegalerie Alte Meister, Dresden, photo accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Domenico-Fetti_Archimedes_1620.jpg {{PD-1923}}
Fig. 2.15 The Archimedes Palimpsest, showing the original text of Archimedes on the *right*, and the overwritten text on the *left*, typical pages from the Archimedes Palimpsest, *source* http://www.archimedespalimpsest.net, approved for reproduction by Walters Museum Curator Walter Noel under Creative Commons License {{CC-BY-SA-3.0}}
Fig. 2.16 Painting depicting Cicero discovering Archimedes' tomb by Benjamin West (1797), photo accessed in January, 2013 at http://www.wikipaintings.org/en/benjamin-west/cicero-and-the-magistrates-discovering-the-tomb-of-archimedes {{PD-1923}}
Fig. 2.17 Depiction of Eratosthenes, drawing accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Portrait_of_Eratosthenes.png {{PD-1923}}
Fig. 2.19 Image of Claudius Ptolemy, drawing accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Ptolemaeus.jpg {{PD-1923}}
Fig. 2.22 Depiction of the story of the Trojan horse in the art of ancient Gandhara, British Museum, accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:IndoGreeksTrojanHorse.jpg (photo released to public domain by the author)
Fig. 2.23 Photograph of Frank Calvert, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Frank_calvert_portrait.png {{PD-1923}}
Fig. 2.24 Photograph of Heinrich Schliemann, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/1/15/Heinrich_Schliemann.jpg {{PD-1923}}

Fig. 2.25 Plan of ancient Troy, drawing by Bibi Saint-Pol accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/c/c1/Plan_Troy-Hisarlik-en.svg (released to public domain by the author)
Fig. 2.26 Photograph of Kyriakos Pittakis, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Kyriakos_Pittakis.jpg {{PD-1923}}
Fig. 2.27 Photograph taken circa 1884 of the Lion's Gate at Mycenae, accessed in February, 2013 at http://commons.wikimedia.org/wiki/File:Mykene_Loewentor_mit_Doerpfeld_und_Schliemann.jpg {{PD-1923}}
Fig. 2.28 Photograph of the Mask of Agamemnon, Athens Museum, photo by User:Mountain accessed in January, 2013 at

http://upload.wikimedia.org/wikipedia/commons/1/1c/Golden_mask_of_Agamemnon.jpg (photo released to public domain by the author)

Chapter 3

Fig. 3.4 Depiction of the Roman roads in Italy by Agamemnus, drawing accessed in January, 2013 at http://en.wikipedia.org/w/index.php?title=File:The_Ancient_Roads_of_Italy_and_Sicily_nopng.svg&page=1 (drawing released to public domain by the author)
Fig. 3.5 A depiction of a Roman road, drawing accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Via_Munita.png {{PD-1923}}
Fig. 3.6 Via Appia, photo by Radislaw Botev accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Via_Appia_Antica_Rome_2006.jpg (approved by the author for any use under {{CC-BY-SA-2.5-PL}}
Fig. 3.7 Nineteenth century depiction of the temple of Jupiter Optimus Maximus in Roman times, drawing accessed in January, 2013 at http://en.wikipedia.org/wiki/File:City_of_Rome_during_time_of_republic.jpg {{PD-1923}}
Fig. 3.9 1873 depiction of the Roman Coliseum, drawing accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Coliseum_at_Rome_I.jpg {{PD-1923}}
Fig. 3.13 Photograph of Hadrian's wall, photo taken by Adam Cuerden accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Milecastle_39_on_Hadrian%27s_Wall.jpg (photo released to public domain by the author)
Fig. 3.16 Centaur raping a nymph by Laurent Marqueste (1848–1920) in the Tuileries, photo taken by Jastrow accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Centaur_nymph_Marqueste_Tuileries.jpg (photo released to public domain by the author)
Fig. 3.19 Segovia Aqueduct, photo by Jebulon accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Aqueduct_Segovia_dusk.jpg {{CC-BY-1.0}}
Fig. 3.20 Ruins of the Barbegal Watermill, photo by Maarjaara accessed in December, 2012 at http://en.wikipedia.org/wiki/File:Barbegal_mill_02.jpg {{CC-BY-2.0}}

Chapter 4

Fig. 4.1 Photograph of the Hagia Sophia, photo by Gokhan accessed in February, 2013 at http://commons.wikimedia.org/wiki/File:Hagia_Sophia_weekend.jpg (photo released to public domain by the author)
Fig. 4.3 Depiction of the relation between the Sun and Earth drawn by Tau'olunga, showing the solstices (at the extremities) and the equinoxes of the Earth, accessed in February, 2013 at http://en.wikipedia.org/wiki/File:North_season.jpg (photo released to public domain by the author)
Fig. 4.4 Portrait of Bede on the *left*, portrait accessed in January, 2013 at http://en.wikipedia.org/wiki/File:The_Venerable_Bede_translates_John_1902.jpg {{PD-ART-LIFE-70}}, His Tomb on the *right*, photo by Robin Widdison accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Bede.jpg (photo released to public domain by the author)
Fig. 4.5 Painting by Charles de Steuben depicting the Battle of Tours, Palace of Versailles, painting accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Steuben_-_Bataille_de_Poitiers.png {{PD-1923}}
Fig. 4.8 Sculpture of St. Denis at the left portico of Notre Dame Cathedral, Paris, photo by Urban accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Saintdenis.gif (photo released to public domain by the author)
Fig. 4.12 Early Flying Buttress (c. 1170) attached to the Choir of the Cathedral of St. Remi in Reims, photo by Ragatt2000 accessed in January, 2013 at http://en.wikipedia.org/wiki/File:St_Remi_choir_from_south_east.jpg (photo released to public domain by the author)
Fig. 4.13 Multi-tiered Flying Buttresses attached to Bourges Cathedral, photo by sybarite48 accessed in December, 2012 at http://en.wikipedia.org/wiki/File:Cath%C3%A9drale_de_Bourges_(Cher).jpg {{CC-BY-2.0}}
Fig. 4.15 Photo of Beauvais Cathedral, photo by Sokojan accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Beauv_kated_od_VJV_DSCN4393.JPG (photo released to public domain by the author)
Fig. 4.18 Image of Muhamed ibn MūsāAl-Kwārizmī on a Russian Stamp, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Abu_Abdullah_Muhammad_bin_Musa_al-Khwarizmi_edit.png (this work is not an object of copyright according to Part IV of Civil Code No. 230-FZ of the Russian Federation of December 18, 2006)
Fig. 4.19 A Page from *Aljebr,* accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Image-Al-Kit%C4%81b_al-mu%E1%B8%ABta%E1%B9%A3ar_f%C4%AB_%E1%B8%A5is%C4%81b_al-%C4%9Fabr_wa-l-muq%C4%81bala.jpg {{PD-1923}}
Fig. 4.20 Portrait of Leonardo do Pisa by an unknown artist, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/a/a2/Fibonacci.jpg {{PD-1923}}
Fig. 4.21 A page from Leonardo do Pisa's book *Liber Abaci* showing the Fibonacci numbers in the right-hand column, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Liber_abbaci_magliab_f124r.jpg {{PD-1923}}

Fig. 4.22 The Tomb of Robert Grosseteste in Lincoln Cathedral, photo by Agicus accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Grosseteste_Chapel.jpg (photo released to public domain by the author)
Fig. 4.23 Sketch of Roger Bacon, accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Roger_Bacon.jpeg?uselang=fr {{PD-1923}}
Fig. 4.24 Sketch of William of Ockham from a 1341 manuscript, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:William_of_Ockham_-_Logica_-_1341.jpg {{PD-1923}}
Fig. 4.25 Portrait of Dante by Giotto, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Dante-alighieri.jpg {{PD-1923}}
Fig. 4.29 Depiction of torture rack, drawing accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Streckbett.jpg {{PD-1923}}

Chapter 5

Fig. 5.1 A possible self-portrait of Giotto, Basilica of Santa Croce, Florence, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Giotto_face_restored.jpg {{PD-1923}}
Fig. 5.2 Cimabue's Maestà, Uffizi Gallery, Florence, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/9/9f/Cimabue_033.jpg {{PD-1923}}
Fig. 5.3 Giotto's Lamentation (The Mourning of Christ), Scrovegni Chapel, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/4/40/Giotto_-_Scrovegni_-_-36-_-_Lamentation_(The_Mourning_of_Christ).jpg {{PD-1923}}
Fig. 5.5 The tower of the winds in Athens, photo by Georg Zumstrull accessed in December, 2012 at http://en.wikipedia.org/wiki/File:Tower_of_the_Winds.jpg {{CC-BY-2.0-DE}}
Fig. 5.6 Portrait of Christiaan Huygens, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Christiaan_Huygens.jpg {{PD-1923}}
Fig. 5.11 Da Vinci self portrait, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Leonardo_da_Vinci_-_Self-Portrait_-_WGA12798.jpg {{PD-1923}}
Fig. 5.13 Painting by Jean Auguste Dominique Ingres depicting Leonardo Da Vinci on his death bed at the Clos Lucé, held in the arms of the French King François I, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/7/79/Francois_I_recoit_les_derniers_soupirs_de_Leonard_de_Vinci_by_Ingres.jpg {{PD-1923}}
Fig. 5.16 Portrait of Michelangelo by Jacopinto del Conte (c. 1535), accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/c/ca/Michelangelo-Buonarroti1.jpg {{PD-1923}}
Fig. 5.17 Michelangelo's Dome above St. Peter's Basilica, photo by mtsrs accessed in December, 2012 at http://commons.wikimedia.org/wiki/File:St_Peters_Basilica.jpg {{CC-BY-2.0}}

Fig. 5.18 Michelangelo's Pietà, St. Peter's Basilica, Rome, photo by Stanislav Traykov accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Michelangelo%27s_Pieta_5450_cropncleaned_edit.jpg {{CC-BY-2.5}}
Fig. 5.19 The Rondanini Pietà by Michelangelo, Museum of Antique Art, Milan, photo by Giovanni Dall'Orto accessed in December, 2012 at http://commons.wikimedia.org/wiki/File:Milano_-_Castello_sforzesco_-_Michelangelo,_Piet%C3%A0_Rondanini_by_Michelangelo_(1564)_-_Foto_Giovanni_Dall'Orto,_6-jan-2006_-_03.jpg (photo released to public domain by the author)
Fig. 5.20 Portrait of Bernini in the Galleria Borghese, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/d/d5/Gian_Lorenzo_Bernini,_self-portrait,_c1623.jpg {{PD-1923}}
Fig. 5.21 1909 photo of Bernini's Colonnade in front of St. Peter's Basilica, Rome, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Piazza_st._peters_rome_1909.jpg {{PD-1923}}
Fig. 5.22 The Trevi Fountain in Rome, designed in part by Bernini, photo by Diliff accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Trevi_Fountain,_Rome,_Italy_2_-_May_2007.jpg {{CC-BY-3.0}}

Chapter 6

Fig. 6.2 Portrait of Pope Gregory XIII by Lavinia Fontana, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/5/50/Gregory_XIII.jpg {{PD-1923}}
Fig. 6.3 Photos of the Wasa: bow photo on *left* by Nick Lott accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:The_Wasa_from_the_Bow.jpg {{CC-BY-2.0}}, stern photo on *right* by Nick Lott accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:The_Wasa_from_the_stern.jpg {{CC-BY-2.0}}
Fig. 6.5 Recreation of L'Anse aux Meadows, Newfoundland, photo by Fruggo accessed in December, 2012 at http://en.wikipedia.org/wiki/File:Authentic_Viking_recreation.jpg {{CC-BY-2.0}}
Fig. 6.6 Portrait of Marco Polo, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/5/54/Marco_Polo_portrait.jpg {{PD-1923}}
Fig. 6.7 Portrait of Christopher Columbus by Sebastiano del Piombo, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Christopher_Columbus.PNG {{PD-1923}}
Fig. 6.8 Portrait of Ferdinand Magellan, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Ferdinand_Magellan.jpg {{PD-1923}}
Fig. 6.9 The Victoria, the only ship in Magellan's Fleet to complete the Voyage, detail from a map by Ortelius, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Detail_from_a_map_of_Ortelius_-_Magellan%27s_ship_Victoria.png {{PD-1923}}
Fig. 6.10 Portrait of Francis Drake by Marcus Gheeraerts, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:1590_or_later_Marcus_Gheeraerts,_Sir_Francis_Drake_Buckland_Abbey,_Devon.jpg {{PD-1923}}

Fig. 6.11 Portrait of Captain James Cook by Nathaniel Dance-Holland, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Captainjamescookportrait.jpg {{PD-1923}}
Fig. 6.12 Portrait of Edmund Halley by Thomas Murray, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Edmund_Halley.gif {{PD-1923}}
Fig. 6.13 Diagram from Sir Edmund Halley's report to the Royal Society describing how to measure the distance to the Sun using the transit of venus, accessed in February, 2013 at http://en.wikipedia.org/wiki/File:Halley_1716_proposal_of_determining_the_parallax_of_the_sun.jpg {{PD-1923}}
Fig. 6.14 The Endeavor leaving Whitby Harbor England in 1768, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/2/2f/Endeavour,_Thomas_Luny_1768.jpg {{PD-1923}}
Fig. 6.15 Image of Venus transiting the Sun on June 5, 2012 {{PD-USGov-NASA}}
Fig. 6.16 Route of the Endeavor, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Endeavour_track_chart.jpg {{PD-1923}}
Fig. 6.17 Captain Cook Memorial on Kealakekua Bay, Hawaii, photo by surfsupusa accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Cook_Monument_Kealakekua.jpg (photo released to public domain by the author)
Fig. 6.18 Portrait of Joseph Banks by Sir Joshua Reynolds, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/6/6e/Joseph_Banks_1773_Reynolds.jpg {{PD-1923}}

Chapter 7

Fig. 7.1 Portrait of Nicolas Copernicus, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Nikolaus_Kopernikus.jpg {{PD-1923}}
Fig. 7.2 Title page of *De Revolutionibus Orbium Coelestium* [51], accessed in January, 2013 at http://en.wikipedia.org/wiki/File:De_revolutionibus_orbium_coelestium.jpg {{PD-1923}}
Fig. 7.3 Portrait of Tycho Brahe, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Tycho_Brahe.JPG {{PD-1923}}
Fig. 7.4 Portrait of Johannes Kepler, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Johannes_Kepler_1610.jpg {{PD-1923}}
Fig. 7.5 Portrait of Galileo Galilei by Justus Sustermans, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Justus_Sustermans_-_Portrait_of_Galileo_Galilei,_1636.jpg {{PD-1923}}
Fig. 7.10 Photograph of Clarence A. Waldo, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:ProfWaldo99.jpg {{PD-1923}}
Fig. 7.11 Portrait of René Descartes by Frans Hals, Louvre Museum, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Frans_Hals_-_Portret_van_Ren%C3%A9_Descartes.jpg {{PD-1923}}
Fig. 7.12 Depiction of a Chinese Abacus, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Abacus_6.png {{PD-1923}}

Fig. 7.13 Tycho Brahe charting the heavens, accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Tycho-Brahe-Mural-Quadrant.jpg {{PD-1923}}
Fig. 7.14 Portrait of Blaise Pascal by an unknown artist, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Blaise_Pascal_2.jpg {{PD-1923}}
Fig. 7.18 Portrait of Pierre-Simon Laplace, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/e/e3/Pierre-Simon_Laplace.jpg {{PD-1923}}
Fig. 7.21 Portrait of Isaac Newton by Sir Godfrey Kneller, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:GodfreyKneller-IsaacNewton-1689.jpg {{PD-1923}}
Fig. 7.22 Title page of *The Principia*, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Prinicipia-title.png {{PD-1923}}
Fig. 7.24 Portrait of Gottfried Leibniz by Christoph Bernhard Francke, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Gottfried_Wilhelm_von_Leibniz.jpg {{PD-1923}}
Fig. 7.25 Portrait of Joseph-Louis Lagrange, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Langrange_portrait.jpg {{PD-1923}}
Fig. 7.28 Galileo's Cantilever Beam, taken from Galileo Galilei's book *Discourses on Two New Sciences (1638)* {{PD-1923}}
Fig. 7.29 Portrait of Jacob Bernoulli, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Jakob_Bernoulli.jpg {{PD-1923}}
Fig. 7.30 Portrait of Johann Bernoulli, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Johann_Bernoulli2.jpg {{PD-1923}}
Fig. 7.31 Portrait of Daniel Bernoulli, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Daniel_Bernoulli_001.jpg {{PD-1923}}
Fig. 7.32 Portrait of Leonhard Euler, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Leonhard_Euler_2.jpg {{PD-1923}}
Fig. 7.34 Galileo's depictions of fractured beams, taken from Galileo Galilei's book *Discourses on Two New Sciences (1638)* {{PD-1923}}
Fig. 7.35 Hooke's spring experiment, plate to Robert Hooke's lecture "Of Spring," 1678, {{PD-1923}}
Fig. 7.36 Portrait of Gabriel Lamé, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/1/18/Gabriel-Lam%C3%A9.jpeg {{PD-1923}}

Chapter 8

Fig. 8.1 South dome organ from the Milan Cathedral, first constructed in 1395, photo by Lorenzo Fratti accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Organo_sud_duomo_milano.jpg (photo released to public domain by the author)
Fig. 8.2 Photograph of a Harpsichord, photo by Nick Michael accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Flemish_harpsichord.jpg (photo released to public domain by the author)
Fig. 8.4 Portrait of Bartolomeo Cristofori, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:BartolomeoCristofori.jpg {{PD-1923}}

Fig. 8.5 Oldest surviving Cristofori fortepiano 1720, Metropolitan Museum New York, photo by Shriram Rajagopalan accessed in December, 2012 at http://en.wikipedia.org/wiki/File:Pianoforte_Cristofori_1720.jpg {{CC-BY-2.0}}
Fig. 8.6 Portrait of Johann Bach by Elias Haussmann, Old Town Hall, Leipzig, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/6/6a/Johann_Sebastian_Bach.jpg {{PD-1923}}
Fig. 8.7 Detail from Portrait of Wolfgang Mozart by Johann della Croce, Mozart House, Salzburg, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/4/47/Croce-Mozart-Detail.jpg {{PD-1923}}
Fig. 8.8 Portrait of Ludwig Beethoven by Joseph Stieler, Beethoven House, Bonn, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/6/6f/Beethoven.jpg {{PD-1923}}
Fig. 8.9 Photograph of Frédéric Chopin, accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Frederic_Chopin_photo_sepia.jpeg {{PD-1923}}
Fig. 8.10 Action from a 1907 upright piano, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Piano_action_-_Project_Gutenberg_eText_17571.jpg {{PD-1923}}
Fig. 8.15 Modern Violin, photo by Just Plain Bill accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Violin_VL100.jpg (photo released to public domain by the author)
Fig. 8.16 Five stradivari violins {{PD-USGov-Congress}}
Fig. 8.17 Photograph of a Jacquard Loom, photo by Dmm2va7 accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:DMM_29263ab_Jacquardwebstuhl.jpg?uselang=de {{CC-BY-3.0}}
Fig. 8.18 Hunting scene from the eleventh century Bayeux Tapestry, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Bayeux_hawking.jpg {{PD-1923}}
Fig. 8.19 Portrait of John Harrison, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:John_Harrison_Uhrmacher.jpg {{PD-1923}}
Fig. 8.20 Pendulum clock drawn by Galileo, accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Galileo_Pendulum_Clock.jpg {{PD-1923}}

Chapter 9

Fig. 9.1 Portrait of Napoleon Bonaparte by Jacques-Louis David, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Napoleon_in_His_Study.jpg {{PD-1923}}
Fig. 9.3 Portrait of Jean-François Champollion by Léon Cogniet, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Leon_Cogniet_-_Jean-Francois_Champollion.jpg {{PD-1923}}
Fig. 9.4 Portrait of Thomas Young, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Thomas_Young_(scientist).jpg {{PD-1923}}
Fig. 9.5 Portrait of Joseph Fourier, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Fourier2.jpg {{PD-1923}}

Fig. 9.6 Portrait of Ernst Chladni, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/d/d1/Echladni.jpg {{PD-1923}}
Fig. 9.9 Portrait of Siméon-Denis Poisson, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Simeon_Poisson.jpg {{PD-1923}}
Fig. 9.10 Photo of a Statue of Claude-Louis Navier, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Claude-Louis_Navier.jpg {{PD-1923}}
Fig. 9.11 Photograph of Augustin Cauchy, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Augustin-Louis_Cauchy.jpg {{PD-1923}}
Fig. 9.13 Photograph of Carl Culmann, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/f/f2/Karl_Culmann.jpg {{PD-1923}}
Fig. 9.14 Portrait of Christian Otto Mohr, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Otto_Mohr.JPG {{PD-1923}}
Fig. 9.15 Lines of principal planes (*left*) in a curved crane compared to the trabecular alignment in a human proximal femur (*right*) [90–93], photo published in Thompson [93] from previous publications by Culmann [90], Meyer [91] and Wolff [92], photo in the public domain under {{PD-US}}
Fig. 9.17 Photograph of Édouard Manet, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/9/9b/%C3%89douard_Manet-crop.jpg {{PD-1923}}
Fig. 9.18 Manet's *Le Dejeuner sur l'Herbe*, 1863, Musée D'Orsay, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/f/f1/Manet,_Edouard_-_Le_D%C3%A9jeuner_sur_l'Herbe_(The_Picnic)_(1).jpg {{PD-1923}}
Fig. 9.19 Manet's *Olympia*, 1863, Musée D'Orsay, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:%C3%89DOUARD_MANET_-_Olympia_(Museo_de_Orsay,_Par%C3%ADs,_1863._%C3%93leo_sobre_lienzo,_130_x_190_cm).jpg {{PD-1923}}
Fig. 9.20 Photograph of Claude Monet, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/3/33/Claude_Monet_1899_Nadar.jpg {{PD-1923}}
Fig. 9.21 The right section of Monet's *Le Dejeuner sur L'herbe*, Musée D'Orsay, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Monet_dejeunersurlherbe.jpg {{PD-1923}}
Fig. 9.22 Self-portrait of Edgar Degas, Musée D'Orsay, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/a/a1/Edgar_Degas_self_portrait_1855.jpeg {{PD-1923}}
Fig. 9.23 Photograph of Pierre-Auguste Renoir, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/f/fd/PARenoir.jpg {{PD-1923}}
Fig. 9.24 Pierre-Auguste Renoir's Bal du Moulin de la Galette, 1876, Musée D'Orsay, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/2/21/Pierre-Auguste_Renoir,_Le_Moulin_de_la_Galette.jpg {{PD-1923}}
Fig. 9.25 Photograph of Vincent Van Gogh, c. 1871, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/7/74/VincentVanGoghFoto.jpg {{PD-1923}}

Fig. 9.26 Vincent Van Gogh's *Le Café le Nuit*, Kröller-Müller Museum, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/7/7e/Vincent_Willem_van_Gogh_015.jpg {{PD-1923}}
Fig. 9.27 Photograph of Pablo Picasso, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/9/98/Pablo_picasso_1.jpg {{PD-1923}}
Fig. 9.28 Pablo Picasso's *Les Demoiselles D'Avignon*, 1907, Museum of Modern Art, New York, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/en/4/4c/Les_Demoiselles_d'Avignon.jpg {{PD-1923}}
Fig. 9.29 Portrait of Thomas Telford by S. Lane, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/b/b8/ThomasTelford.jpg {{PD-1923}}
Fig. 9.30 Photograph of the Menai Suspension Bridge, photo by Velela accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Menai_Bridge_painting.jpg (photo released to public domain by the author)
Fig. 9.31 Photograph of the Britannia Bridge, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/f/ff/Britanniabruecke_Postkarte.jpg {{PD-1923}}
Fig. 9.32 Initial conceptual drawing of the Eiffel Tower sketched by Maurice Koechlin, accessed in February, 2013 at http://en.wikipedia.org/wiki/File:Maurice_koechlin_pylone.jpg {{PD-1923}}
Fig. 9.33 Photographs of the Eiffel Tower during construction, accessed in February, 2013 at http://en.wikipedia.org/wiki/File:Construction_of_the_Eiffel_Tower.JPG {{PD-1923}}
Fig. 9.36 Photo of the firth of forth bridge depicted above the moment diagram for a double cantilever beam with evenly distributed loading, photo by Renata accessed in January, 2013 at http://en.wikipedia.org/wiki/File:ForthBridge-Edinburgh.jpg (photo released to public domain by the author)
Fig. 9.37 Sketch of John A. Roebling, accessed in February, 2013 at http://en.wikipedia.org/wiki/File:Roebling.jpg {{PD-1923}}
Fig. 9.38 Portrait of Emily W. Roebling by Carolus Duran, accessed in February, 2013 at http://en.wikipedia.org/wiki/File:Brooklyn_Museum_-_Portrait_of_Emily_Warren_Roebling_-_Charles-%C3%89mile-Auguste_Carolus-Duran.jpg {{PD-1923}}
Fig. 9.39 Photograph of the Brooklyn Bridge, photo by Simone Roda accessed in December, 2012 at http://commons.wikimedia.org/wiki/File:Brooklyn_Bridge_-_New_York_City.jpg {{CC-BY-2.0}}
Fig. 9.40 Photo of the Golden Gate Bridge, photo by Rich Niewiroswki, Jr. accessed in December, 2012 at http://en.wikipedia.org/wiki/File:GoldenGateBridge-001.jpg {{CC-BY-2.5}}
Fig. 9.41 Photograph of the Sydney Harbor Bridge, photo taken by Adam J.W.C. accessed in December, 2012 at http://commons.wikimedia.org/wiki/File:Sydney_harbour_bridge_new_south_wales.jpg {{CC-BY-3.0}}
Fig. 9.42 Photograph of the Pont de Normandie, photo by Citron accessed in January, 2013 at http://fr.wikipedia.org/wiki/Fichier:Pont_de_Normandie_from_above-edit.jpg {{CC-BY-2.0}}

Fig. 9.44 Photograph of the Millau Viaduct in Southern France, photo by Vincent accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Viaduc_de_Millau_1.jpg (photo released to public domain by the author)

Chapter 10

Fig. 10.1 Aftermath of the Galveston Hurricane of 1900, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/4/47/Galveston_-_1900_wreckage.jpg {{PD-US}}
Fig. 10.3 Artist's depiction of the impact of an Asteroid with the Earth that caused the Moon {{PD-USGov-NASA}}
Fig. 10.6 Earth's precession {{PD-USGov-NASA}}
Fig. 10.7 Color enhanced satellite photo of water temperatures in the gulf stream {{PD-USGov-NASA}}
Fig. 10.8 Firefly 7 hot air balloon in flight, photo by DrWhatIKnow accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Joy_Ride_hot_air_balloon.jpg (photo released to public domain by the author)
Fig. 10.9 Cumulus clouds, photo by Janne Naukkarinen accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Cumulus_mediocris_3.JPG (photo released to public domain by the author)
Fig. 10.10 Satellite photo of a line of thunderstorms over the Eastern U.S. on May 3, 2012, photo taken by the Goes-13 Satellite {{PD-USGov-NOAA}}
Fig. 10.11 Radar image taken by National Weather Service Wichita, Kansas WSR-88D on April 3, 2011 {{PD-NWS}}
Fig. 10.13 Satellite photo of Hurricane Katrina on August 28, 2005 {{PD-USGov-NASA}}
Fig. 10.15 Tornado in Central Oklahoma, May, 1999, photo shot by en:VORTEX-99 Team {{PD-USGov-NOAA}}
Fig. 10.16 Photo of Earth taken from Apollo 17 showing the global scale of weather {{PD-USGov-NASA}}

Chapter 11

Fig. 11.1 Hubble telescope reveals the deepest view into the universe in a photograph that took 10 years to complete. Extreme deep field image captures thousands of galaxies billions of light years away {{PD-USGov-NASA}}
Fig. 11.2 The Ant Nebula, a cloud of dust and gas whose technical name is Mz3, resembles an ant when observed using ground-based telescopes. The nebula lies within our galaxy between 3,000 and 6,000 light years from Earth {{PD-USGov-NASA}}
Fig. 11.3 Above is Nebula NGC 2392, called Eskimo because it looks like a face surrounded by a furry hood. The hood is, in fact, a ring of comet-shaped objects flying away from a dying star. Eskimo is 5,000 light years from earth {{PD-USGov-NASA}}
Fig. 11.4 The Trifid Nebula, 9,000 light years from earth, where new stars are being born {{PD-USGov-NASA}}

Fig. 11.5 The glowering eyes from 114 million light years away are the swirling cores of two merging galaxies called NGC 2207 and IC 2163 in the distant Canis Major constellation {{PD-USGov-NASA}}
Fig. 11.6 Photograph of Dr. Eugene Shoemaker {{PD-USGov-USGS}}
Fig. 11.7 Photograph of Barringer Crater, Arizona {{PD-USGov-USGS}}
Fig. 11.9 Shoemaker-Levy strikes Jupiter {{PD-USGov-NASA}}
Fig. 11.10 Photo of the near side of the moon showing meteor craters {{PD-USGov-NASA}}
Fig. 11.11 Chicxulub crater {{PD-USGov-NASA}}
Fig. 11.12 The Earth's tectonic plates {{PD-USGov-NASA}}
Fig. 11.13 Three types of tectonic plate boundaries {{PD-USGov-USGS}}
Fig. 11.17 Mt. St. Helens eruption on May 18, 1980 {{PD-USGov-USGS}}
Fig. 11.18 Satellite view of Santorini, showing the part of the Island destroyed in the eruption {{PD-USGov-NASA}}
Fig. 11.20 Satellite photo of Anakrakatoa taken in 2007 {{PD-USGov-NASA}}
Fig. 11.21 The yellowstone calderas {{PD-USGov-USGS}}
Fig. 11.22 Satellite photo of the Hawaiian Islands, showing from *top left* Niihau, Kauai, Oahu, Molokai, Lanai, Maui, Kahoolawe and Hawaii {{PD-USGov-NASA}}
Fig. 11.23 The Hawaii-Seamount Chain {{PD-USGov-USGS}}
Fig. 11.25 Satellite photo of the Big Island {{PD-USGov-NOAA}}
Fig. 11.26 Satellite photo of Maui {{PD-USGov-NASA}}
Fig. 11.30 Photo of Waimea Canyon, photo taken by Redshirt accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Overlooking_Waimea_Canyon.jpg (photo released to public domain by the author)
Fig. 11.31 The Na Pali Coast of Hawaii, photo taken by Remember accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Real_Kaui_Panorama1.jpg (photo released to public domain by the author)
Fig. 11.32 The black rapids glacier, Alaska, accessed in January, 2013 at http://ak.water.usgs.gov/glaciology/black_rapids/index.htm {{PD-USGov-USGS}}
Fig. 11.33 The Mer de Glace, photo by Didier Baertschiger accessed in December, 2012 at http://commons.wikimedia.org/wiki/File:Mer_de_Glace,_31_October_2009.jpg?uselang=fr {{CC-BY-2.0}}
Fig. 11.34 Chamonix-Montenvers train, photo by trams aux fils accessed in December, 2012 at http://fr.wikipedia.org/wiki/Fichier:Train_du_Montenvers_-_rame_53_au_Montenvers.jpg {{CC-BY-2.0}}
Fig. 11.36 Moraine in the foreground at Lake Louise, Canada, photo taken by Wilson44691 accessed in January, 2013 at http://en.wikipedia.org/wiki/File:MorainesLakeLouise.JPG (photo released to public domain by the author)
Fig. 11.37 Cape Cod viewed from space {{PD-USGov-NASA}}

Chapter 12

Fig. 12.1 Portrait of James Watt by Carl Frederik von Breda, National Portrait Gallery, London, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/1/15/Watt_James_von_Breda.jpg {{PD-1923}}
Fig. 12.2 Photo of the Puffing Billy—an early steam locomotive, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Puffing_Billy_1862.jpg {{PD-1923}}
Fig. 12.3 Photo of a modern steam locomotive, photo by Oslo Pardo accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Steam_locomotive_555.0153.jpg (photo released to public domain by the author)
Fig. 12.4 Photograph of Mr. and Mrs. Henry Ford in his first automobile, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/d/d3/Mr_and_Mrs_Henry_Ford_in_his_first_car.jpg {{PD-1923}}
Fig. 12.5 Photograph of Alberto Santos-Dumont, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/en/4/44/Alberto_Santos-Dumont_1910_circa.jpg {{PD-1923}}
Fig. 12.6 Santos-Dumont rounding the Eiffel Tower in 1901, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/9/9c/Sd_num6_rounding_tower.jpg {{PD-1923}}
Fig. 12.7 Photograph of Orville Wright, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/c/cb/Orville_Wright.jpg {{PD-1923}}
Fig. 12.8 Photograph of Wilbur Wright, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Wilbur_Wright.jpg {{PD-1923}}
Fig. 12.9 The first manned flight of a heavier-than-air vehicle on December 17, 1903, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/8/86/First_flight2.jpg {{PD-1923}}
Fig. 12.10 Illustration of Santos-Dumont's flight of November 12, 1906, accessed in January, 2013 at http://upload.wikimedia.org/wikipedia/commons/3/3f/Santos_-_Nov12_1906.jpg {{PD-1923}}
Fig. 12.11 Wright aircraft, national air and space museum, photo by Ad Meskens accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Wright_flyer3.jpg (photo released by the author for any use under {{CC-BY-SA-1.0}})
Fig. 12.12 Photograph of Charles Lindbergh, Library of Congress, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Col_Charles_Lindbergh.jpg {{PD-1923}}
Fig. 12.13 Lindbergh arrives in Paris, accessed in January, 2013 at http://www.deathandtaxesmag.com/92144/charles-lindberghs-transatlantic-flight-the-day-the-earth-shrank/ {{PD-US-not renewed}}
Fig. 12.14 Photograph of the Concorde, photo by Arpingstone accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Concorde_on_Bristol.jpg (photo released to public domain by the author)
Fig. 12.15 Photograph of Neil Armstrong {{PD-USGov-NASA-AP}}
Fig. 12.16 The eagle lunar lander after separation {{PD-USGov-NASA}}
Fig. 12.17 Neil Armstrong steps onto the moon {{PD-USGov-NASA}}

Fig. 12.18 Photograph of a SAFER barrier, photo by Freekee accessed in February, 2013 at http://en.wikipedia.org/wiki/File:Milwaukee-Mile_Aug2009_wall.jpg (photo released to public domain by the author)
Fig. 12.19 Depiction of Ramses II riding a chariot at the Battle of Kadesh in 1274 BCE, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Ramses_II_at_Kadesh.jpg {{PD-1923}}
Fig. 12.21 Statue of Alexander the Great, Istanbul Museum, photo by tkbwikmed accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Alexander1256.jpg (photo released to public domain by the author)
Fig. 12.23 Photograph of reconstruction of the fortifications at Alesia, uploaded to Wikipedia by user Mariule (with permission) from http://www.angelfire.com/me/ik/alesia2.html and accessed in December, 2012 at http://en.wikipedia.org/wiki/File:AlesiaFortifications.JPG {{CC-BY-SA-3.0}}*(*in this instance we have been unable to trace or contact the copyright holder. If notified the publisher will be pleased to rectify any errors or omissions at the earliest opportunity*)*

Chapter 13

Fig. 13.1 Photograph of James Clerk Maxwell, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:James_Clerk_Maxwell.png {{PD-1923}}
Fig. 13.3 The Sombrero Galaxy—28 million light years from Earth. The dimensions of the galaxy, officially called M104, are as spectacular as its appearance. It has 800 billion Suns and is 50,000 light years across {{PD-USGov-NASA}}
Fig. 13.4 Photograph of Stephen Timoshenko, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Timoshenko.jpg (This work is in the public domain in Russia according to article 6 of Law No. 231-FZ of the Russian Federation of December 18, 2006)
Fig. 13.8 The Suez Canal viewed from space {{PD-USGov-NASA}}
Fig. 13.9 Depiction of one of the first Suez Canal crossings, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:SuezCanalKantara.jpg {{PD-1923}}
Fig. 13.10 Portrait of Ferdinand de Lesseps, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Ferdinand_de_Lesseps.jpg {{PD-1923}}
Fig. 13.11 Aerial photograph Corinth Canal, photo by Vancouverquadra accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Canal_of_korinth_greece.jpg (photo released to public domain by the author)
Fig. 13.12 The Panama Canal viewed from space {{PD-USGov-NASA}}
Fig. 13.13 Photograph taken in 1913 showing the Panama railway, the steam shovels, and the locks in the Panama Canal project, accessed in February, 2013 at http://en.wikipedia.org/wiki/File:PanamaCanal1913a.jpg {{PD-1923}}
Fig. 13.14 Photograph of the SS Kroonland transiting the Panama Canal in 1915, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Kroonland_in_Panama_Canal,_1915.jpg {{PD-1923}}
Fig. 13.15 Photograph of Lake Mead slowly filling on the upstream side of the Hoover Dam in 1935, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:Damupstream.jpg {{PD-USGov-Interior-USBR}}

Fig. 13.16 Downstream view of the Hoover Dam, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:HooverDamFrontWater.jpg {{PD-USGov-Interior-USBR}}
Fig. 13.17 Photograph of a jumbo rig used to dig tunnels during the construction of Hoover Dam, accessed in February, 2013 at http://en.wikipedia.org/wiki/File:HooverDamJumboRig.jpg {{PD-USGov-Interior-USBR}}
Fig. 13.18 Photograph of the Devil's Tower in northeastern Wyoming, photo by Colin.faulkingham accessed in February, 2013 at http://en.wikipedia.org/wiki/File:Devils_Tower_CROP.jpg (photo released to public domain by the author)
Fig. 13.19 Photograph showing the formworks for the massive concrete columns in Hoover Dam, accessed in February, 2013 at http://en.wikipedia.org/wiki/File:Damforms.jpg {{PD-USGov-Interior-USBR}}
Fig. 13.20 Photograph of the Aswan high dam from space, accessed in January, 2013 at http://en.wikipedia.org/wiki/File:BarragemAssu%C3%A3o.jpg {{PD-USGov-NASA}}
Fig. 13.21 Satellite photo of Lake Nasser, the world's second largest artificial lake, accessed in January, 2013 at http://earth.jsc.nasa.gov/sseop/EFS/printinfo.pl?PHOTO=STS052-102-103 {{PD-USGov-NASA}}
Fig. 13.22 Photograph of Ramses II's Temple during reconstruction, photo by Per-Olow Anderson accessed in February, 2013 at http://es.wikipedia.org/wiki/Archivo:Abusimbel.jpg {{PD-Sweden-photo}}
Fig. 13.24 Satellite photo of Venice showing main entrance to the Lagoon, accessed in January, 2013 at http://www.wunderground.com/blog/JeffMasters/comment.html?entrynum=1163 {{PD-USGov-NASA}}
Fig. 13.26 Photo of full scale model of section of Chunnel at National Railway Museum in York, England, photo by Xtrememachineuk accessed in December, 2012 at http://en.wikipedia.org/wiki/File:Channel_Tunnel_NRM.jpg {{CC-BY-2.5}}
Fig. 13.27 Photograph of the Tacoma Narrows Bridge collapse, uploaded by Qutezuce accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Tacoma_Narrows_Bridge_Falling.png (photo released to public domain by the author)
Fig. 13.28 Photo by F.G.O. Stuart of RMS Titanic departing Southampton on April 10, 1912 {{PD-1923}}
Fig. 13.29 Photos of the Challenger disaster; explosion on the *left*; challenger underwater on the *right* {{PD-USGov-NASA}}
Fig. 13.30 Photo of Aloha Airlines disaster {{PD-USGov-FAA}}
Fig. 13.31 Photo on *left* of the Minneapolis bridge collapse {{PD-USGov-DHS-CG}}; photo on *right* showing fracture in gusset plate {{PD-USGov-NTSB}}
Fig. 13.32 Photo of reconstruction of the stage 1 fan disk in the Sioux City aircraft crash of flight UA 232 on July 19, 1989 {{PD-USGov-NTSB}}
Fig. 13.33 Boeing 787 Dreamliner on *left*; photo by Dave Sizer accessed in December, 2012 at http://en.wikipedia.org/wiki/File:Boeing_787_first_flight.jpg {{CC-BY-2.0}}; Airbus A380 on *right*; photo by Dmitry A. Mottl accessed in January, 2013 at http://commons.wikimedia.org/wiki/File:Airbus_A380.jpg (photo released to public domain by the author)

Fig. 13.34 Photograph taken in 2006 of the Chernobyl Sarcophogus, photo by Carl Montgomery accessed in December, 2012 at http://commons.wikimedia.org/wiki/File:Chernobylreactor_1.jpg {{CC-BY-2.0}}
Fig. 13.35 Photos of buildings collapsed by the Tōhoku earthquake, accessed in December, 2012 at http://spacecoalition.com/blog/benefits-of-space-exploration/u-s-european-satellites-enable-scientists-to-explain-japanese-earthquake's-destructive-force (courtesy BBC)

Chapter 14

Fig. 14.1 Weightlessness in the "Vomit Comet" {{PD-USGov-NASA}}
Fig. 14.3 Photograph of a surgical robotic device inserted through the stomach (photo courtesy Drs. Shane Farritor and Dimitri Olenykov, University of Nebraska)
Fig. 14.4 Depiction of the Chesapeake Bay Meteor impact site, accessed in February, 2013 at http://en.wikipedia.org/wiki/File:Chesapeake_Crater_boundaries_map.png {{PD-USGov-USGS}}

About the Author

David H. Allenis currently the Chief Scientist for Pavement Scientific International. He is also an adjunct professor of Civil Engineering at Texas A&M University. Dr. Allen spent most of his career in academia, having taught for nearly 40 years at four major universities across the U.S. He has also taught abroad in more than 20 countries on four continents. He is the author of three textbooks and more than 100 journal articles and archival publications.

Dr. Allen welcomes comments regarding his publications. He may be contacted at drdavidhallen@hotmail.com. In addition, the interested reader will find further information about the events chronicled in this book at the author's website: http://drdavidhallen.com/.

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Author Index

A
Abbott Suger, 85
Acoreus, 133
Aeneus, 53, 149
Akhenaten, 20–22
Alan Shepard, 370
Albert Einstein, 153, 173, 183
Alberto Santos–Dumont, 303, 305, 307
Alexander Marshack, 2
Alexander the Great, 40, 317
Al–Kwārizmī, 94
Alan A. Griffiths, 350, 351
Ambrogio Lorenzetti, 115
Amenhotep I, 6, 18
Amenhotep II, 27
Amenhotep III, 27
Anaximander, 38
Anders Franzén, 139
Antinous, 76
Antoni Gaudi, 89
Antony, 26
Archie Roy, 249
Archimedes, 41, 42, 44–46
Aristarchus, 42
Aristotle, 40, 42, 94
Arnolfo de Cambio, 110
Augustin Cauchy, 208, 215, 217, 222
Augustus, 26, 69

B
Bartolomeo Cristofori, 189
Bede, 81, 82, 95
Benjamin Franklin, xviii
Bill Bryson, 275
Blaise Pascal, 159, 161, 176

C
Cardinal Ippolito, 76
Carl Culmann, 218
Carl Sagan, 309
Carnot, 208
Carolyn Shoemaker, 273
Charlemagne, 84
Charles “Chuck” Yeager, 308
Charles Inglis, 350
Charles Kingsford Smith, 307
Charles Lindbergh, 307
Charles Marie de la Condamine, 313
Charles Martel, 83
Chester Arthur, 237
Christiaan Huygens, 108
Christopher Blackett, 300
Christopher Columbus, 141
Cicero, 48
Cimabue, 99, 105
Clarence Waldo, 157
Clauda–Louis Berthollet, 209
Claude Monet, 222
Claude–Louis Navier, 215
Claudius Ptolemy, 51
Cleopatra, 7, 26
Clovis, 85
Clytemnestra, 58
Constantine, 73, 77, 79, 80, 85, 118
Copernicus, 51, 145–147

D
Daniel Bernoulli, 178, 183
Dante Alighieri, 99, 100
David Ewing Duncan, 125
David Levy, 273
Dean Sicking, 315
Democritus, 39
Dick Teresi, 5, 6
Dionysius Exiguus, 137
Djoser, 9
Domenico Scarlatti, 187
Dominique Vivant, Baron, de Denon, 209
Donatello, 108, 115
Dugdale, D.S., 351

D. H. Allen, *How Mechanics Shaped the Modern World*,
DOI: 10.1007/978-3-319-01701-3,

E
Edgar Degas, 222
Edmund Halley, 142
Édouard Manet, 222
Edward Lorenz, 258
Edward the Confessor, 201
Émile Clapeyron, 182
Émile Nouguier, 231
Emily W. Roebling, 236
Eratosthenes, 49, 50
Ernest Zebrowski, Jr., 5
Ernst Chladni, 213
Euclid, 41
Eudoxos, 46
Eugene Shoemaker, 271

F
Ferdinand de Lesseps, 335, 337
Ferdinand Magellan, 141
Ferdinando de Medici, 189
Filippo Brunelleschi, 108
Francis Drake, 142
François Couperin, 187
François I, 120, 121
Frank Calvert, 54
Franklin D. Roosevelt, 344
Frédéric Chopin, 190, 191, 193, 198

G
Gabriel Lamé, 183
Gaius Julius Ceasar, 65
Gaius Marius, 62, 65
Gaius Sulpicius Gallus, 59
Galileo Galilei, 40, 108, 120, 123, 147, 151–153, 159, 167, 169
Gaspard–Gustav Coriolis, 260
George Gabriel Stokes, 262
George Herbert, 22
George R. Irwin, 351
George Stephenson, 300
Georges Lemaitre, 267
Gian Lorenzo Bernini, 123
Giordano Bruno, 40
Giotto di Bondone, 99, 105
Giovanni Battista Belzoni, 20
Glen Penfield, 275
Gordon E. Moore, 264
Gottfried Leibniz, 173
Grigory Barenblatt, 351
Guido D'Arezzo, 185
Gustave Eiffel, 231, 233

H
Hadrian, 75, 76
Harold, 201
Harry Houdini, 165
Hathshepsut, 29
Heinrich Schliemann, 54
Henri Poincaré, 258
Henry Ford, 301
Henry Petroski, 231
Hermann Meyer, 219
Herodotus, 35
Hipparchus, 51
Homer, 35, 53, 54
Howard Carter, 22

I
Isaac Newton, 153, 163, 167, 169, 173, 174, 183
Isabela de Grandmaison y Bruno, 207

J
J.N. Reddy, 157
Jack ReVelle, 376
Jacob Bernoulli, 178
Jacques Cassini, 207
Jacques Heyman, 86
James Clerk Maxwell, xviii, 49, 252, 323
James Cooke, 142
James Gleick, 169
James Gregory, 142
James R. Rice, 351
James Reston, 151
James VI, 312
James Watt, 299
Jared Diamond, 140
Jean Baptiste Joseph Delambre, 206
Jean Claude Barré de St. Venant, 218
Jean Godin, 207
Jean–François Champollion, 209
Jean–Joseph Fourier, 209
Jean–Pierre Houdin, 14
Johan Sebastian Bach, 187, 189, 194
Johann Bernoulli, 178
Johannes Kepler, 40, 147, 169
John A. Roebling, 236
John Glenn, 308
John Harrison, 203–205
John Napier, 160
John Oughtred, 160
John Smeaton, 75
Jonathan Forster, 300
Joseph Banks, 143

Joseph Jacquard, 201
Joseph Monier, 75
Joseph–Louis Lagrange, 174

K
Khufu, 11–13, 16, 18
King Numa, 135
King Tut, 20, 22, 3
Kyriakos Pittakis, 54

L
Laurence Bergreen, 142
Lavoisier, 208
Leif Ericson, 140
Leonardo Da Vinci, 120–122
Leonardo do Pisa, 94
Leonard Schlain, 222
Léon Foucault, 260
Leonhard Euler, 157, 163, 183
Livy, 60
Lord Kelvin, 208
Lorenzo Ghiberti, 108
Louis Cartier, 305
Louis XVI, 85
Lucilius Junior, 59
Ludwig Beethoven, 190, 192
Lyn Wadley, 1

M
Madhava, 156
Marco Polo, 141
Marcus Agrippa, 70, 76
Marie Curie, 222
Matthew Murray, 300
Maurice Koechlin, 231
Maxentius, 79
Maximian, 80
Michael Faraday, xviii
Michael Rappenglueck, 2
Michelangelo Buonarroti, 122
Michio Kaku, 363
Moses, 24
Muhammad, 82

N
Napoleon, 7, 20
Napoleon Bonaparte, 209
Narmer, 8
Neil Armstrong, 308
Neri, 75
Nero, 74
Newton, 40, 42, 49
Nicolas Copernicus, 145

O
Octavian, 69
Oliver Heaviside, 208
Orville Wright, 307
Otto Mohr, 219
Owen Gingrich, 147

P
Pablo Picasso, 225
Paul Hoffman, 303
Pedro Cabral, 140
Pericles, 36
Peter Beckmann, 155
Phileas Fogg, 137
Pierre–Auguste Renoir, 222
Pierre Curie, 222
Pierre–François–Xavier Bouchard, 209
Pierre Méchain, 206
Pierre–Simon Laplace, 163, 175
Pliny the Elder, 282
Pliny the Younger, 282
Polybius, 35
Pompey Magnus, 131
Pope Gregory XIII, 138
Ptolemy III, 125
Ptolemy XIII, 132
Ptolemy XIV, 133
Pythagoras, 38, 39
Pythéas, 139

Q
Queen Elizabeth, 138

R
Railsback, O.L., 196
Ramses II, 24, 26
Ramses V, 22
Ramses VII, 20
Remus, 60
René Descartes, 158
René Dugas, 121
Richard Courant, 329
Richard Feynman, 153, 169
Richard Holmes, 143
Richard Hough, 142
Richard Trevithick, 300

Robert Grosseteste, 94, 95
Robert Hooke, 169, 173, 180
Robert Kaplan, 6
Roger Bacon, 95
Romulus, 60
Ross King, 122
Rumford, 208

S
Salviati, 176
Samuel Langley, 307
Senusret I, 26
Seti I, 20
Shannon McPherron, 1
Siméon–Denis Poisson, 215
Simon Steven, 194
Sir Benjamin Baker, 235
Sir John Fowler, 235
Sir Thomas Bouch, 235
Snefru, 10, 11
Sophie Germain, 215, 217
Sosigenes, 135
St. Brendon of Clonfert, 140
St. Denis, 85
Stephen Hawking, 153
Stephen Timoshenko, 329

T
Thales, 12, 38
Thomas Telford, 231
Thomas Young, 209
Thucydides, 35
Thutmose I, 18
Thutmose II, 27
Timothy Hackworth, 300
Titus, 70
Tobias Dantzig, 165, 166
Trajan, 75
Tycho Brahe, 147, 148, 159

V
Vercingetorix, 320
Vespasian, 70
Vesto Slipher, 267
Victor Hugo, 88
Vincent Van Gogh, 223
Vincenzo Galilei, 150

W
Washington Roebling, 236
Wilbur Wright, 304
Willard Libby, 275
William Hedley, 300
William of Normandy, 201
William of Ockham, 95
William Rosen, 299
Winston Churchill, 309
Wolfgang Mozart, 190
Wright Brothers, 301, 303, 305–308, 311

X
Xenophon, 35

Y
Yuan–Cheng “Bert” Fung, 364
Yuri Gagarin, 308

Z
Zhu Zaiyu, 194

Subject Index

A
Abdominal aortic aneurysm, 367
Abu Simbel, 344
Acropolis, 36
Adaptive materials, 332
Aeneid, 53
Aerodynamics, 313
Aeroelasticity, 350
Age of Aquarius, 248, 249
Agia Sophia, 80, 84
Airbus 350, 356
Airbus 380, 356
Akrotiri, 284
Alesia, 69, 70
Aljebr, 94
Almagest, 51
Aloha airlines disaster, 354
Amarna, 20, 22
Amazon River, 207
Anno Domini, 137
Antikythera clock, 46
Arc de Triomphe, 78
Arcetri, 153, 175
Arch, 59, 74–77
Arch of Constantine, 73
Aristotelian school, 35
Arrowheads, 1
Asphalt concrete, 332
Asthenosphere, 227
Aswan High Dam, 344
Athens, 36
Atmosphere, 243, 249, 250, 251, 253, 254, 255, 256, 257, 261, 262, 263
Atomistic school, 35
Avebury, 3, 5
Axis of spin, 246, 248

B
Babylonians, 5, 6
Barbegal, 77
Barcelona, 206
Barringer Crater, 272
Basilica of San Francesco, 99
Basilica of San Marco, 84
Battle of Actium, 69
Battle of Hastings, 202
Battle of Tours, 83
Bayeux tapestry, 202
Beam theory, 178, 179, 240
Beauvais Cathedral, 88, 91
Beltany, 3
Bent Pyramid, 10
Bernini's Colonnade, 178
Binary system, 268
Biomechanics, 363, 365, 367
Boeing 787 Dreamliner, 356
Botany Bay, 143
Bourges Cathedral, 88, 90
Britannia Bridge, 231
Brooklyn Bridge, 236, 237, 240
Butterfly effect, 258

C
Cairo museum, 22, 44
Calendar, 125
Campidoglio, 67
Campo dei Fiori, 153
Canopus, 76
Capo la Gala, 280
Carbon dating, 275, 280
Carthaginians, 46, 61
Catacombs of San Callisto, 60
Cathedral at St. Denis, 85
Cathedral of St. Remi, 90
Cauchy's formula, 217
Cauchy's lemma, 217
Cave of El Castillo, 2
Celsius, 251, 252
Celts, 67
Cemetière de Sceaux, 222
Challenger, 353
Chambord, 121

D. H. Allen, *How Mechanics Shaped the Modern World*,
DOI: 10.1007/978-3-319-01701-3,

Champ de Mars, 231
Chaos theory, 258
Château d'Amboise, 120
Chauvet, 2
Cheops ship, 316
Chernobyl reactor, 356
Chesapeake Bay meteor crater, 272
Chixculub meteor, 275
Chladni's experiments, 213
Christianity, 79, 85, 100
Chunnel, 347
Clepsydra, 83, 107, 161, 167
Climate change, 376
Clock towers, 107
Clos Lucé, 121
Clouds, 254–256
Coesite, 272, 275
Cold front, 255, 256, 261
Coliseum, 59, 70, 74, 75
Colossus of Rhodes, 31
Composite material, 332, 333
Computational mechanics, 331, 332, 351, 353
Concorde, 308
Condensation, 254–256, 258, 261
Constantine's Cathedral, 118
Constellations, 248, 249
Constitutive models, 180, 183
Continuum mechanics, 208, 212, 215, 217, 219, 220, 222, 230, 232, 238, 240
Convection, 249, 250, 254
Corbelled Arch, 12, 26
Corinth Canal, 337
Coriolis force, 258, 260, 261
Council Nicaea, 80
Counting, 165, 166
Cumulus, 254
Cuneiform tablets, 2, 154

D
Darwin's law, xxi, 100, 208
Dashur, 10
Deformable body mechanics, 20, 175, 176, 178, 179, 183, 188, 284
Devil's Postpile, 343
Devil's Tower, 343
Differential equations, 323, 328–331
Distance, 6, 39, 44, 49–51, 106, 142, 159, 170, 175, 200, 202, 206, 255, 268, 283, 285, 305, 325, 330, 337, 342
DNA, xx
Dome, 108, 110, 111, 115, 117, 118, 122

E
Eagle Lunar Lander, 2, 3, 53
Easter, 79, 80, 82
Eastern Empire, 80
Edict of Milan, 79, 85
Egyptian calendar, 125, 135
Egyptians, 6, 7, 9, 22, 24, 26, 28, 30
Eiffel Tower, 231–233, 236, 240
Elasticity theory, 218
Electromagnetic phenomena, 323
El Nino, 249
Endeavor, xvii, 3, 143, 165, 204, 364
English system, 206
EPCOT Center, 2
Equinox, 51, 80, 82, 136, 137, 146, 248
Euler–Bernoulli beam theory, 179
Eureka, 44
Experimental mechanics, 2
Explorers, 139, 141, 143, 145
Extraterrestrials, 369–372

F
Fahrenheit scale, 252
Failure mechanics, 176, 346
Fibonacci numbers, 94
Finite element, 330, 331, 351
Finite element method, 330–332
First law of thermodynamics, 254, 255
Firth of Forth Bridge, 235, 240
Florence Baptistry, 114
Fluxions, 172
Flying buttresses, 88
Fracture, 4, 26, 88, 179, 217, 220, 244, 245, 293, 335, 343, 349, 351, 364
Fracture mechanics, 350, 351
French Guiana, 207
Frequency, 187, 191, 194, 196, 199
Frictionless bearings, 204

G
Galileo's laws, 170, 173
Galveston hurricane, 243
Giant's Causeway, 343
Giza, 10, 12, 17
Glaciers, 292–294, 296–298
Glaucoma, 363, 367
Gnomon, 12
Golden Gate Bridge, 237
Golf, 312, 313, 315, 316
Golf ball, 312, 313

Gothic cathedrals, 84, 85, 88, 89
Great Pyramid, 10–14, 16, 18
Great Wall, 18
Greeks, 6, 7, 35, 36, 53, 54, 58
Greenwich, 203–205
Gregorian calendar, 138
Griffith criterion, 351
Gulf Stream, 249
Gust of wind, 262

H
Hadrian's Villa, 76
Hadrian's Wall, 75
Haleakala, 287
Half Dome, 297, 298
Hanging Gardens of Babylon, 31
Harp, 185, 187, 191, 197, 200
Harpsichord, 187–189, 191, 197, 200
Hawaii, 286, 287, 289
Hawaii—seamount chain, 286
Herculaneum, 280
Hindu numbers, 94
Hisarlik, 54
History Channel, 4, 5
Holocene, 5
Hooke's law, 180, 182, 183
Hoover Dam, 340, 341, 343
Hotspot, 285, 286
Hubble telescope, 267
Human initiated extinction, 376
Huns, 80
Hurricane, 243, 261
Hypogeum, 74

I
I–35 Minneapolis Bridge, 354
Icelandic Sagas, 140
Ideal gas law, 182, 252
IED, 368
Iliad, 35, 53, 54
Impressionist art, 223, 240
Inclined planes, 167
Indiana Pi Bill, 157
Interstellar radiation event, 375
Iron age, 5
Isles of Scilly, 202

J
Jacquard loom, 201
Jucelino Kubitschek Bridge, 240
Julian calendar, 79, 80, 95

K
Kauai, 288, 289
Kepler's laws, 172, 173
Keystone, 59
Kilauea, 286
Kitty Hawk, 303
Krakatoa, 284, 285
Kroneker delta, 183

L
Lake Nasser, 344
Language, 99–101
L'Anse aux Meadows, 140
Laplace transforms, 163
Lascaux, 2
Leaning Tower, 167
Leaning Tower of Pisa, 357, 358, 360
Length spans, 326
Life prediction, 354
Life spans, 294, 298
Lighthouse at Alexandria, 31
Light year, 325–327
Lincoln Cathedral, 12
Lion's Gate, 54
Lithosphere, 277
Lo'ihi, 290
Lockheed SR–71, 308
Locomotives, 300
Logarithms, 160, 161, 325
Lower Awash Valley, 1
Lunar calendar, 2, 3
Luxor, 13, 20, 27, 28

M
Magma, 279, 280, 284, 285, 286, 297
Manhattan Project, 329
Mask of Agamemnon, 58
Mastaba, 9, 10
Materials development, 335
Maui, 287
Mauna Kea, 287
Mauna Loa, 286, 287
Mausoleum at Halicarnassus, 31
Mechanical wave, 277
Mechanics, 1, 6, 12, 18, 25, 28, 34, 39, 42, 47, 49, 51, 58, 67, 75, 79, 82, 85, 89, 92, 95, 102, 106, 108, 121, 107, 136, 142, 147, 151, 159, 169, 174, 185, 199, 212, 217, 230, 238, 240, 246, 252, 265, 267, 272, 281, 292, 300, 328, 335, 342, 347, 351, 364, 365
Mechanics of materials, 332, 335

Meidum, 10
Menai Suspension Bridge, 231
Mer de Glace, 293, 294
Mesopotamians, 2
Meteor impact, 374
Meteors, 273
Meter, 244, 253
Metric system, 206
Michelangelo's Dome, 116
Middle ages, 80, 82, 84, 88, 93, 102
Military weapons, 316
Millau Viaduct, 240
Minoans, 249
Mohr's circle, 219
Moon, 3, 6
Moore's law, 264
Moraine, 297
Mt. St. Helens, 283
Mt. Vesuvius, 280, 281, 283
Multiverse, 164, 326
Mummy, 20, 26
Musée D'Orsay, 223
Museo dell'Opera del Duomo, 115
Mycenae, 54

N
Na Pali Coast, 289
Natron, 24
Navier–Stokes equations, 262, 263
New Kingdom, 18, 22, 26
Newton's gravitational law, 171, 244
Newton's laws, 88, 173, 174, 217
Nile, 8, 9, 18, 23, 26, 30
Nördlinger Ries crater, 272, 273
Notre Dame Cathedral, 88

O
Obelisk, 26, 28, 31
Octave, 194, 196, 197
Odyssey, 35, 53
Old Kingdom, 8–10
Oxygen, 243, 251, 253

P
Palimpsest, 47
Panama Canal, 340
Pandemic, 375
Pangaea, 277
Pantheon, 70, 75, 76
Panthéon, 222
Parc de Sceaux, 76
Parthenon, 36, 58
Pascaline, 159, 160
Pas de Calais, 206
Peddles, 193
Pendulum clock, 167
Phase diagram, 273
pi, 44
Piano, 189, 191–94, 197, 198, 200, 201
Pianoforte, 189
Pietà, 115, 123
Pioneer 10, 308
Pipe organ, 186, 187, 192, 198
Place de la Concorde, 27
Pleistocene Era, 2
Plucking action, 188
Pompeii, 280, 281
Pont de Normandie, 240
Pont du Gard, 76
Pont St. Bénezet, 93
Precession, 51, 248, 249
Prime meridian, 204, 205
Principle of the lever, 42, 44
Protestant reformation, 138
Puffing Billy, 300
Punic wars, 61
Pyramids, 9, 10, 12, 14, 16, 17, 20, 31
Pythagorean School, 35, 38
Pythagorean theorem, 6, 39

Q
Quantum mechanics, 328, 330
Quarry, 9, 20, 28

R
Red Pyramid, 11, 12
Rigid body dynamics, 167, 203
Risk factor, 363, 364
Roads Greeks, 60
Romans, 6, 26, 59–61, 67, 70, 74–78
Rosetta Stone, 209
Royal observatory, 203–205
Rubber, 313

S
Sagrada Familia, 89
Santa Maria del Fiori Cathedral, 116
Santorini, 284, 285
San Vitale, 80, 84
Saqqara, 10

Science, 6, 35, 36, 38, 39, 42, 58, 59, 78–81, 83, 84, 94, 95, 99, 105, 106, 108, 113, 115, 118, 120, 122, 123, 125, 139, 141–143, 145, 147, 152–154, 158, 165–167, 173–176, 178, 183, 193, 206–209, 212, 213, 215, 217, 222, 227, 230, 243, 249, 347, 350, 363–365
Scrovegni chapel, 105
Second law of motion, 171
Second law of thermodynamics, 245, 249, 252, 258
Segovia, 77
Sexigesimal system, 5
Shellal, 28
She–wolf, 60
Ship stability, 139
Shoemaker–Levy comet, 273
Sibudu Cave, 1
Siege weapons, 317
Sippar, 2
Sistene Chapel, 122
Slide rule, xviii, 161–163
SMAS, 367
Socratic school, 35
Solar calendar, 2
Solar flare, 373
Solar radiation, 245, 246, 253, 258
Sombrero Galaxy, 327
Speed of light, 324, 327, 330
Spice Islands, 141
Sports, 312, 314–316
Square–Cube Law, 176
Statue of Zeus, 31
Steam engine, 299, 300, 311
Steinheim crater, 273
Step pyramid, 9
Stoic school, 35
Stone calendar, 3
Stone weapons, 1, 6
Stonehenge, 3–5
Stradivari, 198, 200
Straits of Magellan, 142
Stratus, 254
Stress, 217–219
Stress transformations, 218
String theory, 164
Structural mechanics, 240
Subduction, 277–280
Suez Canal, 335, 337, 339
Sumerians, 5, 6
Surface tension, 253
Surgical devices, 368
Swenet, 9
Sydney Harbour Bridge, 240
Syracuse, 44, 46, 47

T

Tacoma Narrows Bridge, 350
Tay Bridge, 235
TBI, 368
Tectonic plates, 277, 284
Telescope, 148, 151–153, 267
Temple of Artemis, 31
Temple of Jupiter Optimus Maximus, 67
Temple of Karnak, 13, 27
Tensor, 217, 218
Thalidomide, 377
The Big Bang, 267, 268, 270
Theory of elastic solids, 215
Theory of fluids, 215
Theory of heat, 212, 215
Thera, 284
Thermometer, 252
Thunderstorm, 255, 256, 262
Time, 185, 198, 190, 191, 193, 201–206
Time−space, 325, 327, 328
Titanic, 350, 352
Tōhoku earthquake, 356
Toilet paper, 377–379
Tornado, 262
Torture, 101, 103
Tower of the Winds, 107
Transit of Venus, 132, 142, 143
Transportation, 299, 301, 309, 311
Trebuchet, 67
Trevi fountain, 119
Trojan wars, 54
Tsunami, 278, 279
Tuileries, 76
Tunguska event, 275

U

UA Flight 232, 355
Uffizi gallery, 107
Unfinished obelisk, 27, 28
Universities, 93
University of Bologna, 93
University of Padova, 146, 152
Ur, 6
Uruk, xx

V
Valley of the Kings, 19, 20, 22, 23, 28
Vandals, 80
Variational methods, 217
Venice, 8, 80, 84, 151, 346
Venice MOSE Project, 346
Vernal equinox, 80, 82
Via Appia, 60
Vibrating plate experiments, 214
Vibrating strings, 39
Vibration, 187, 192
Viking Lander, 308
Villa D'Este, 76
Vindolanda, 75
Violin, 187, 198–200
Visigoths, 80
Volcano, 271, 273, 279–288, 291, 298
Vomit Comet, 268, 273

W
Waimea Canyon, 289
Warfare, 316, 321
Wasa, 127, 139
Washington Monument, 31
Water, 243, 249–259, 261–263
Weather, 243–245, 249, 250, 256, 258, 259, 261–265
Well–tempered, 196, 197
Western Empire, 80

Y
Yellowstone, 285
Yosemite, 17, 297

Z
Zeroth law of thermodynamics, 252, 253