Chapter 3
History of Mechanics

Abstract Mechanics is the integral part of mechanical engineering. As a field of education, it started from the time of Aristotle. Many of the concepts provided by Aristotle are proven wrong, for example, his concept that the motion continues only as long as a force is applied on it. However, he started a tradition of logic in understanding the dynamics of bodies. During the third century BC, Archimedes contributed a lot to mechanics and invented many machines. His principle of buoyancy is taught in schools nowadays. The breakthrough in mechanics came since the time of Galileo. The principles of Galileo and Newton are used by mechanical engineers profoundly. Later on, a lot of developments took place in mechanics, notably the development of methods based on energy formulation, strength of materials and plasticity. Einstein developed a theory of relativity and established that Newton's laws are not valid in all circumstances. Nevertheless, for the most of the day to day applications, Newton's laws are good enough.

Keywords Mechanics · Aristotle · Archimedes · Galileo · Newton · Hero of Alexandria · Energy methods · Einstein · Theory of relativity · Calculus of variations · Strength of materials · Plasticity

3.1 Introduction

Engineering is as old as the human civilization, although the word "engineer" came into existence around 1325 AD. Our life is very much dependent on engineers and everyone has a feel of engineering, but for many persons there is often a lack of clarity about engineering. In the beginning, engineering was considered as an art. Engineers used to invent machines and structures. Mechanics originated as the branch of physics that deals with the theory of machines. One of the oldest machines is lever. With the help of a lever, a heavy weight can be lifted by the application of small force as shown in Fig. 3.1. There is evidence of use of lever even before 2500 BC. Weighing balance also works on lever principle. Lever is one such machine that is not obsolete even today. Figure 3.2 shows a scissor that also is

U.S. Dixit et al., *A Brief History of Mechanical Engineering*,
Materials Forming, Machining and Tribology,
DOI 10.1007/978-3-319-42916-8_3

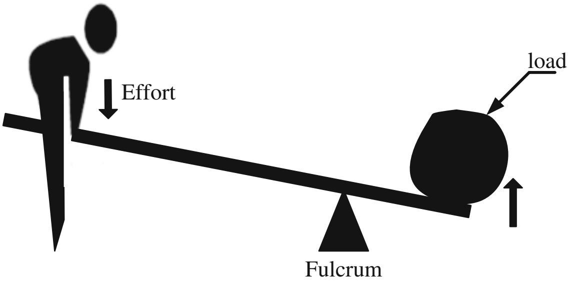

Fig. 3.1 A lever for lifting a heavy load

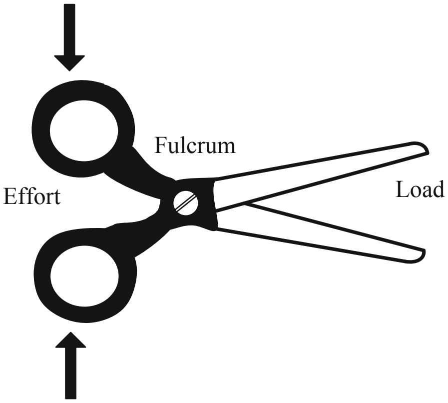

Fig. 3.2 A scissor

essentially a lever. It comprises two lever rods of type shown in Fig. 3.1. During the time of Aristotle, a law of lever was developed. This law is valid till today. Mechanics can be considered to have started during the time of Aristotle (384 BC–322 BC) mainly with the study of lever. Aristotle and some other philosophers of his time developed theories for many physical phenomena based on their intuition. Most of the theories have been proven wrong. However, those theories stimulated the logical thinking. A theory can be right or wrong; but in any case, it shows the ingenuity of human mind.

The history of science starts with the ancient Greek civilization, from the time of Socrates (469 BC–399 BC), who is credited with laying the foundation of western society. It is not that the Greek civilization was the only civilization during that time, but the modern science has its seeds mainly in the Greek civilization. From the ancient Greek civilization till today the science has been evolving like a continuous flow of water. Many other civilizations were either destroyed or could not continue the pace of development of science. India, for example, was also a very strong civilization and science was well developed as evident from the excavation carried out at Mohenjo-Daro and Harappa. It is believed that these well-developed cities were founded circa 2600 BC. The civilization called Indus Valley civilization dates back to about 6000 BC (Satyawadi 1994). In the first millennium after Christ, India was very strong in mathematics, astronomy and metallurgy. However, the continuity of scientific tradition got broken due to invasion of other civilizations and internal turmoil.

In this chapter, the history of mechanics is discussed briefly. It will be highlighted how the theoretical mechanics and experimental mechanics have influenced each other. A very brief biography of stalwarts of mechanics will also be presented. Many historical facts are debatable and any controversy is avoided here. The main focus of the present chapter is to discuss the evolution of mechanics.

3.2 Period of Aristotle

A formal study of mechanics can be traced to the period of Aristotle. Aristotle was born circa 384 BC in Stagira, Greece (Barnes 2003). At the age of 17, Aristotle joined Plato's Academy in 367 BC (Armytage' 1961). Aristotle founded his own school in Athens named Lyceum. Both Plato's Academy and Aristotle's Lyceum were important for promoting scientific thoughts. Plato was greatly influenced by the famous philosopher Socrates (Kahn 1996). It is well-known that Socrates was poisoned to death for propagating logical thinking in the Greece. Aristotle's father was Nicomachus, a court physician of the Macedonian king, Amynatas II. Nicomachus died when Aristotle was very young. Although Aristotle was a disciple of Plato, he disagreed with many philosophical treatise of Plato. His views of nature are set forth in his books Physics and Metaphysics, which mark the most serious differences between Arisotelianism and Platonism. Aristotle founded his own school in Athens in around 335 BC. He had a habit of teaching along with walking, due to which his students were nick named "peripatetic" meaning "one who travels about". Later on, an Aristotelian philosopher was called peripatetic. A famous student of Aristotle was Alexander the Great (356 BC–323 BC). Alexander became the king of Macedonia, adjacent to modern Greece, in 336 BC. Alexander expanded his kingdom. A very good relation existed between Aristotle and Alexander. After the death of Alexander, Aristotle had to leave democratic Athens due to political problems. Aristotle died of stomach problem in 322 BC in island of Euboea.

Aristotle believed that knowledge could be obtained through interacting with physical objects (Tuominen 2009). Of Aristotle's estimated 200 works, only 31 are still in circulation. He wrote on a variety of subjects like philosophy, political science, zoology, meteorology etc. He believed that there are 5 elements in nature: earth, water, air, fire and ether (space). Indian philosophers also used to believe that the world is composed of these five elements. In those days, there was a good amount of contacts between Greek and Indian Civilizations. Alexander invaded India in 326 BC. He invaded some areas of northwestern Indian subcontinent (now in Pakistan). King Porus gave a strong fight to Alexander in the battle of Jhelum that resulted in Alexander's retreat, although Porus was defeated. The first Indo-Greek kingdom was established circa 190 BC. There was a lot of cultural exchange between India and Greek in those days, although evidences of it have faded with time.

During Aristotle's times, it was believed that physical things change, while heavenly thing like the Sun and stars do not change. Aristotle classified the change in the following four categories:

(1) Change of substance (transformations, in particular of the elements earth, water, air and fire into each other). This is mainly a chemical change in the modern terms.
(2) Change of quantity (growth and shrinkage).
(3) Change of quality or alteration. For example, a hot object becomes a cold object.
(4) Change of place (locomotion).

A change can be caused because of the natural tendencies of the object or it can be a violent change. Natural things have their inner principle. For example, earth wants to join the earth. All objects composed of earth element get attracted towards the center of earth, which is also the center of universe. An object made of wood tends to fall down towards ground, because wood is an earthly material and thus has tendency to join earth. On the other hand, smoke has a tendency to move upward, because it is made of air. Aristotle also postulated that apart from the inner principle of change, natural things also follow stability. An object kept on the ground has tendency to remain stationary. For moving it, a force is needed. The object keeps on moving till the force is applied. As soon as the force is removed, the object comes to the rest. We know now, in light of Newton's laws, that Aristotle's theory on motion is wrong. An object will keep on moving in the absence of any retarding force.

On the motion of celestial bodies like the Sun and Moon, he postulated that they are composed of ether (quintessence) and hence have tendency to move in a circle, because circles are perfect. Explanation of how an arrow keeps on moving when released from bow is explained in the following manner. When an arrow moves, it creates a vacuum. As the nature abhors vacuum, the air rushes to fill up the vacuum left behind and in the process applies force on the tail of the arrow. Aristotle believed that an arrow would not be able to move in vacuum. We know today that it is wrong; in fact arrow will move more easily in vacuum, because of the absence of the drag force of the air.

About rains, Aristotle explained in the following matter. Water on earth is warmed by the Sun, changes into the air and rises up, because the air has a natural tendency to move up. Then the air cools down, changes into the water and becomes heavier, and finally falls down as the rain again. This description is weak from the point of view of modern science, but is reasonable considering the state of science during the days of Aristotle.

The pseudo-Aristotelian Mechanical Problems is considered to be the first surviving ancient Greek text on mechanics (Coxhead 2012). The prefix pseudo is used because it is not certain if the book was actually authored by Aristotle or embodies his concepts. Some say that Mechanical Problems was written by Archytas (428–347 BC) who was an ancient Greek philosopher, astronomer, statesman and strategist (Winter 2007). He belonged to the Pythagorean School. Pythagoras (circa 569 BC–circa 475 BC) is often called the first mathematician of the world. He provided the proof that in a right angle triangle, the square of the hypotenuse is equal to the sum of the squares of the other two sides. Archytas was a good friend of Plato. Whoever be the author of the book, it depicts that seeds of mechanics were sown during the ancient Greek period. In the introduction of the book, the author presents that the focus of the book is on questions of mechanical kinds, in particular questions connected with lever. There are 35 questions in the book. Some of them are as follows:

(1) Why does the exercise of little force raise great weights with the help of a lever, in spite of the added weight of the lever?
(2) Why do the men at the middle of the boat move the boat most? Is it because the oar is a lever?
(3) Why does a steering oar, small as it is, and at the end of the boat has such force that with one little handle and the force of one man, and that gentle, it moves the great bulk of ships? Is it because steering oar is a lever?
(4) Why are round things easier to move than things of other shape?
(5) Why, with larger circles, whether wheels, pulleys, or rollers, do we move more easily and quickly the things which are lifted or pulled? Is it because the farther from the center, the greater space is traveled in equal time?
(6) Why is it that the longer a board is, the weaker it gets?
(7) Why are big heavy bodies split by little wedges?
(8) Why are the so-called pebbles on the beaches round?
(9) Why do doctors pull out teeth more easily even adding weight—that of the tooth-puller—than with the bare hand? Is it because tooth-puller is two opposed levers?
(10) Why do they construct the bed so that one dimension is double the other?
(11) Why in eddying water does everything end up getting carried into the middle?

The answer to a question is in the form of a question starting with “is it because”. The questions in the Mechanical Problems have been taken from the diverse fields and the author tries to correlate many of them with the principle of lever.

Today most of the ideas of Aristotle are proven wrong. However, he cannot be blamed for it. It was just the beginning of science. In his time, quantitative physics was not well developed. Even speed was not defined quantitatively. It was described in terms of slow and fast. Similarly, temperature was also not defined in any scale like °C. People only had idea about hot and cold. Probably, they were able to appreciate that among two bodies which one is hotter, but they could not quantify it. The concept of friction was not known. Hence, it was natural for Aristotle to believe that when we remove a force from an object, it stops because it has natural tendency to stop.

3.3 Period of Archimedes

Almost all the laws of mechanics by Aristotle have been proven wrong. Thirty five years after the death of Aristotle, Archimedes was born in circa 287 BC in the city of Syracuse on the coast of Sicily (Ceccarelli 2014). This place is in Italy now. Archimedes' many laws and theorems are still valid. In that sense, Archimedes can be called as the father of mechanics. Archimedes' father, Phidias, was an astronomer, who estimated the ratio of the diameters of the Sun and the Moon. The word Archimedes in Greek means master of thought. As per his name, Archimedes has contributed a lot to mathematics and mechanical engineering. Figure 3.3 depicts a portrait of Archimedes.

Archimedes spent some time in the city of Alexandria in Egypt. In those days, the Alexandria was the center of Greek science. There were a lot of disciples of Euclid in Alexandria. Euclid was very active around 300 BC on whose name there is a branch of mathematics called Euclidean Geometry. The exact years of his birth and death are not known. Euclid had published a famous book on geometry called The Element. With the disciples of Euclid, Archimedes studied geometry. Archimedes was able to determine the area, volume and center of many important shapes (Assis 2010).

Archimedes is considered as the pioneer in statics and hydrostatics. Although he was a great mathematician, he is remembered more for applying the physics and mathematics to practical problems. The king of Sicily, Hiero II, was great admirer of Archimedes and based on his requirement, Archimedes invented many mechanical gadgets. He invented many weapons, for example catapult. Thus, he

Fig. 3.3 A portrait of Archimedes [With permission from Ceccarelli (2014), copyright Elsevier (2014)]

laid down the foundation of military engineering. There is a legend that he burnt Roman ships by concentrating the solar energy through mirrors.

One story about Archimedes is very popular. The king, Hiero II, wanted to know the purity of the gold used in making a crown. He suspected that the goldsmith might have mixed silver with it. Archimedes kept thinking about this problem. When he was taking the bath in a tub, he observed that the tub water got displaced in proportion to his submerged body. He got the idea that if the crown is submerged in a pot full of water, it will displace the water. The volume of water displaced can be easily measured, which will be the volume of the crown. The weight of the crown is known. A similar weight of any gold object should also displace the same amount of water. If the crown displaces more amount of water, then the gold in crown might have been polluted by the silver, because for the same weight, silver has more volume. He applied this method and found that indeed the goldsmith had polluted the gold. It is said that when Archimedes got this idea, he jumped from the tub and ran naked on the street of Syracuse, shouting Eureka (I have found it).

Archimedes invented a pump for lifting of water (Waters and Aggidis 2015). It is essentially a screw that rotates inside the housing filled of water. The rotation of screw imparts rotational as well as axial velocity to the water. Due to axial velocity, the water moves and can reach at a height. Some believe that this device was already being used in Egypt for irrigation purpose and Archimedes only redesigned it with the sound foundation of theory. It is also believed that king of Egypt used it to pump water from the hull of the ship. Archimedes screw is used till today. It is used for pumping water, fish or food grains from one location to another. It is used during injection molding to deliver the compound material to the mould. The low rotation rate and lack of pressure required to move the material cause little or no damage to the fibers. Presently, research is going on to use the Archimedes screw as a turbine. The first of such devise was installed in Europe during 1994 and later introduced to UK in 2005 (http://www.westernrenew.co.uk/files/case_studies/river_dart.pdf).

Archimedes also built a famous planetarium that had single hydraulic mechanism, which moved several globes simultaneously. He also invented a hydraulic organ. With the help of ropes and pulleys, he moved a heavy ship. It essentially worked on lever principle. In his book entitled “On the Equilibrium of Planes”, Archimedes provided seven postulates, which in modern terms emphasize the balance of moment. A large force at one end of the lever can be balanced by small force acting at a larger distance from the fulcrum. The moment of both the forces will be equal about the fulcrum. The moment of a force about a point is the product of the force and perpendicular distance from the point. Archimedes was so confident about the law of lever that it is believed that he said, “Give me a place to stand on, and (I) will move the earth.”

Today even the school children are familiar with Archimedes’ principle that states that a body immersed in a fluid experiences an upward buoyancy force, which is equal to the weight of the displaced fluid. The principle applies to both floating as well as submerged bodies and to all fluids, i.e., liquids and gases. A body is able to swim if the upward buoyancy force is equal to the weight of the body.

Archimedes died in 212 BC. He was killed by a Roman soldier, when a long siege of Syracuse during the second Punic war (214–212 BC) was ended. It is said that the Roman commander, Marco Claudio Marcelo had ordered the soldiers not to kill Archimedes. When the Roman soldier approached Archimedes, he was solving a problem of mathematics and refused to accompany the Roman soldier. At this, the infuriated soldier killed him. Archimedes' tomb was constructed, where a sphere was drawn inside a cylinder as per the will of the Archimedes. In his work entitled "On the Sphere and Cylinder", he computed the volumes and areas of the sphere as well as cylinder and considered it as one of his greatest achievements.

Greek technology was at its zenith during and after some time of the period of Archimedes (300 BC–150 AD). The important innovations in this period include cranes, screws, gears, organs, odometer, wheelbarrows and roof tiles. The gears in Greek period used to have triangular teeth.

3.4 Hero of Alexandria

Hero of Alexandria, also known as Heron of Alexandria, was a Greek mathematician and engineer and was active in his native city Alexandria (http://www.britannica.com/biography/Heron-of-Alexandria). In his time, Egypt was under the control of Romans. There is a difference of opinion about the dates of his birth and death. Many believe that he was born circa 10 AD and died in circa 70 AD. He is credited for developing the first steam turbine called aeolipile (Papadopoulos 2007). It consisted of a spherical vessel from which the steam exited through two nozzles. The exiting steam provided a thrust to rotate the spherical vessel. There is no evidence that this turbine was used for any practical application.

Hero modified many inventions of his predecessors. Ctesibius (circa 285–222 BC) had invented hydraulics, which was essentially a water organ. Ctesibius is also called the father of pneumatics. Hero also developed wind powered organ and wind wheel. Marcus Vitruvius Pollio (born circa 80–70 BC, died after circa 15 BC), commonly known as Vitruvius, was a Roman author, architect, civil engineer and military engineer during the first century BC. He is known for his multi-volume work entitled *De Architectura*. Some of the inventions by Vitruvius are described in Hero's book Pneumatica. The book also describes working of a lot of toys such as singing birds, puppets and coin-operated machines. Hero was a lucid writer. The book also contains the working of siphon. Today, the working of siphon is easily explained with the help of Bernoulli's principle, which was published by Daniel Bernoulli in 1738 in his book *Hydrodynamica*. In his book *Automatopoietica*, Hero described automatic closing and opening of temple doors and statues that pour wine. This book can be called the first book on mechatronics; although there was no electronics in it, the approach was similar to mechatronics of today. He also developed a water clock. His book Dioptra describes a theodolite-like instrument used in surveying. Hero taught at Alexandria's Musaeum. Many believe that he acted as its Director and developed it as the first Polytechnic School or Technical Institute.

Hero has contributed a lot of books on geometry. The book Metric includes the derivation of Hero's formula (believed to be developed by Archimedes) for finding out the area of the triangle. The area of a triangle with sides a, b and c is given by

$$A = \sqrt{s(s-a)(s-b)(s-c)}, \tag{3.1}$$

where s is the sum of perimeter divided by 2, i.e., $s = (a + b + c)/2$. The book also contains an iterative method for approximating the square root of a number to desired accuracy. However, it is believed that this method was known to Babylonian circa 2000 BC.

Hero has contributed a lot to experimental mechanics. He recognized the value of experimental work. During the time of Aristotle, it was believed that nature abhors vacuum. Hero described an apparatus designed to show the existence of vacuum. It is a metal hollow sphere with a small hole with which a tube is attached. Hero argued that if one blows air into the sphere, then air enters in it and therefore, air must be compressible. One can also draw air out by inhaling and create a vacuum. In his book Mechanics, he described the theory of motion, statics, balance and a method for constructing three-dimensional shapes in proportion to a give shape using pantographs. He described the windlass (winch), the lever, the pulley, the wedge, the screw and the worm wheel. Hero is also credited with the construction of the first analog computer, a computing device based on gears and pins.

3.5 Period After Hero and Before Galileo

During the time of Hero, Alexandria was a great learning center. One of the greatest astronomers in Alexandria was Ptolemy (circa 100–circa 170), who developed a geo-centric model of the universe, which is called Ptolemaic system. His most popular book is Almagest (Feke 2014). He published another book "Geography" that contains the first realistic atlas of the world. Ptolemy's geocentric model makes the following assumptions:

- Heavens move spherically.
- Earth is spherical.
- Earth is at the middle of the heavens.
- Earth is immobile.

Pappus (circa 290–circa 350) lived in the fourth century. According to some historians, he studied equilibrium and motion of a body along an inclined plane. He also studied center of gravity of a body and proposed a method of finding out the center of gravity of an irregular body by suspending it using several points of suspension (Oliveira 2014). His two theorems are very popular. Pappus set forth these theorems, which were restated by the Swiss mathematician Paul Guldinus in about 1640 AD (Shames 1997). The first theorem may be stated as follows:

> The surface area A of a surface of revolution generated by rotating a plane curve C about an axis external to C and on the same plane is equal to the product of the arc length s of C and the distance d traveled by its geometric centroid.

For example, when a line of length l is given full revolution about a parallel axis at a distance of r in the same plane, it generates the surface of a right circular cylinder of length l and radius r. Here, the arc length s is equal to l and in one rotation the geometric center of the line travels a distance of $2\pi r$. As per the first theorem of Pappus, the surface area of the cylinder is the product of the arc length and the distance travelled by the centroid. Hence, the surface area comes out to be $2\pi rl$.

The second theorem of Pappus may be stated as follows:

> The volume V of a solid of revolution generated by rotating a plane figure F about an external axis is equal to the product of the area A of F and the distance d traveled by its geometric centroid.

For example, when a rectangular of sides r and l is rotated by 360° about its one side of length, a right cylinder of length l and radius r is generated. The area of the rectangular is rl and its centroid travels a distance of $2\pi(r/2)$. Hence, by the second theorem of the Pappus, the volume of the cylinder is $\pi r \times rl = \pi r^2 l$.

After the period of Pappus, the growth of the mechanics slowed down. In the meantime, there was a great expansion in the Arab world. In the period of Arabian domination, mechanics showed low progress with other fields of physics such as optics being developed instead. The situation began to change in the thirteenth century. In this period, there was a lot of growth in science and philosophy including astronomy. Arabs translated many books from the Greek.

Jean Buridan (circa 1293–circa 1363) was a French priest who developed the concept of impetus (King 1955). The concept of impetus is closely related to the concept of momentum, which is the product of mass and velocity. Buridan studied and later taught at the University of Paris. Nicole Oresme (circa 1320–1382) was a French philosopher who also contributed to mechanics (http://www.britannica.com/biography/Nicholas-Oresme, accessed on October 18, 2015). William Heytesbury (http://plato.stanford.edu/entries/heytesbury/, accessed on October 18, 2015) was chancellor of Oxford University around 1371. His greatest contribution was the concept of acceleration, an unknown concept to Buridan and Oresme at the Paris School. At the beginning of the fourteenth century, an important social and cultural change took place in Italy, which is known as Italian Renaissance (Lee et al. 2010). In the fifteenth century, the Italian school of mechanics emerged (Pisano and Capecchi 2016). Notable personalities are Blasius da Parma (1327–1416), Nicholas of Cues (1401–1464) and Leonardo da Vinci (1452–1519). Blasius wrote a treatise on weights. He was also responsible for introducing statics and kinematics to Italian schools. He was professor of mathematics at the University of Padua, where he taught from 1382 to 1388. Nicholas of Cusa held, before the time of Copernicus and Newton, that the nearly spherical earth revolves on its axis about the Sun and that the stars are other worlds. Leonardo da Vinci lived in the period immediately before Scientific Revolution (circa 1550–1700). He was an engineer, artist, scientist and inventor. He studied the following problems related to mechanics:

- Concept of a moment of a force
- Rigid body motion in an inclined plane
- Solution of a system of force
- Energy of a body in motion
- Study of Earth's shape
- Theory of Center of Gravity
- The falling bodies
- Hydrostatics and hydrodynamics

Leonardo da Vinci (1452–1519) stated the two basic laws of friction (http://www.phy.davidson.edu/fachome/dmb/PY430/Friction/history.html):

(1) If the load of an object is doubled, its friction doubles.
(2) The areas in contact have no effect on friction.

He also stated that every frictional body has a resistance equal to one quarter of its weight. In other words, he suggested a Coulomb coefficient of friction of 0.25 for the bodies. This value is high considering most of the sliding bodies today; however, in Leonardo da Vinci's time, the tribological characteristics of the bodies were definitely inferior in comparison to present age. Leonardo da Vinci did not publish his theories on friction and he never got credit for it.

Leonardo da Vinci also studied strength of materials. He hanged a basket containing sand with an iron wire (Osakada 2010). The strength of the wire could be determined by measuring the weight of the sand when the wire broke. Unfortunately, this result was also not published in the form of a book and went unnoticed for a long time.

Nicolaus Copernicus (1473–1543) born in the Kingdom of Poland formulated a model of universe that placed Sun rather than earth at the center of universe. This was against the belief of the church. Copernicus was reluctant to publish his book because of the fear of church. Finally, the book was published when Copernicus was in his death bed. Later on, Galileo further developed the model of Copernicus with his telescopic observations.

3.6 Period of Galileo

Galileo (1564–1642) is called the father of modern science. Albert Einstein called Galileo "the father of modern physics—indeed of modern science altogether." Stephen Hawking has stated, "Galileo, perhaps more than any other single person, was responsible for the birth of modern science." Here, a brief biography and scientific contributions of Galileo are presented based on several references (Hofstadter 2009; Sharratt 1994; Næss 2005; Drake 1978; Grego and Mannion 2010). Vincenzio Galilei, the father of Galileo was born at Florence in 1520. He was a musician. In 1563, Vinczio married Giulia Ammanmati of Pescia and settled in the countryside near Pisa. Galileo was born on February 15, 1564 near Pisa. Galileo was first tutored by Jacopo Borghini after which he was sent to the Camaldolese monastery at Vallombroso to study grammar, logic and rhetoric. Galileo's father, Vincenzio wanted that Galileo should become a physician. He made arrangement with his friend Tedaldi for Galileo to live in Pisa, where he was enrolled at the University as a medical student in the autumn of 1581.

The medical curriculum at the University of Pisa was based on the works of Galen and Aristotle's book on natural science. Galileo noted that some laws of Aristotle are contrary to day to day observation. For example, according to Aristotelian theorem, the speed of a falling body is proportional to its weight. Aristotle had argued if the two bodies are dropped from a height, the heavier body will reach the ground faster. Galileo coined a paradox to refute this claim. The paradox is as follows. If a light and a heavy body are tied together, they will reach ground at the same time. Suppose an independent heavy body of mass m_h reaches the ground in time t_h and an independent light body of mass m_l reaches the ground in time t_l. When the two bodies are tied together, the composite body will reach in a time lying between t_h and t_l, because the heavy body will tend to drag the light body and the light body will tend to drag the heavy body. As a result, an intermediate speed will be attained by both the bodies. Now, if we look from a different angle, the mass of the combined body is $(m_h + m_l)$, which is more than m_h. Hence, as per the Aristotle's law, the combined body should reach in lesser time than t_h. Thus, there is a contradiction and it can be resolved only by assuming that speed of a falling body is independent of the mass.

Ostilio Ricci was a famous mathematician and military engineer during that period. In 1583, Galileo met Ricci and was fascinated by his lectures on mathematics. Ricci told Vincenzio that his son preferred mathematics to medicine and sought permission to instruct him. When Galileo returned to Pisa in the autumn of 1583, he devoted his time to mathematics and philosophy and absented himself frequently from required lectures. During Galileo's time, the teaching of mathematics at the University was poor. It had low status compared to general natural philosophy. Ricci introduced algebra and geometry to Galileo. He also made Galileo familiar with the work of Tartaglia, who was Ricci's own teacher and was recognized as the greatest mathematician of the sixteenth century. Tartaglia was first to find a general method for solving a cubic equation (Darke 1978; Næss 2005).

After leaving the University of Pisa without a degree in the spring of 1585, Galileo taught mathematics privately at Florence and Siena. He held some public teaching position at Siena during the academic year 1585–86. His first scientific treatise came out in 1586 and it was entitled La Bilancetta in Italian, whose English translation is the Little Balance. It described the construction and use of a device similar to Westphal balance. Westphal's balance is used to measure the specific gravity (or density) of liquids. Galileo did not claim its invention. In the little balance, Galileo proposes that Archimedes might have found the purity of the crown by measuring its specific gravity.

Later in 1586, Galileo began to compose a Latin Dialogue on certain problems of motion. In those days, the dialogue style was very popular in scientific writing. This book discussed the motion on an inclined plane. Galileo experimented with the motion of balls on an inclined plane. He observed that the velocity of the balls is not dependent on the size of the ball and is only dependent on the angle of inclination. After reaching the foot of the inclined surface, the balls keep moving on a straight path and finally come to rest because of friction. He proposed the law of inertia, which states that a body will preserve its velocity and direction so long as no force in the direction of its motion acts on it. Later on Newton presented it as the first law of motion in 1687, which states that everybody remains at rest or moves with constant velocity in a straight line, unless it is compelled to change that state by force acting upon it. In his book Dialogue, Galileo refutes the claim of Aristotelian scientists that earth does not move. In Italy, which is a peninsula, ships were very common. He provided the example of a ship's hull, where you cannot know if the ship is moving or not. Same is the case of the motion of earth. The law of Galilean relativity states that there is no physical way to differentiate between a body moving at a constant speed and a body at rest.

Galileo began his lectures as Professor of Mathematics at the University of Pisa in November 1589. During his time at Pisa, Galileo revised and completed his treatise De Motu (On Motion). There is story that Galileo dropped balls from the leaning tower of Pisa to demonstrate that all the bodies freely dropped from a height will reach the ground at the same time. Many people doubt the authenticity of this story.

At Pisa, on observing the motion of hanging lamps of the church, Galileo concluded that the time period of a pendulum is not dependent on the mass and amplitude of the pendulum. When initial amplitude is provided to pendulum, the pendulum starts oscillating. The amplitude keeps on reducing gradually because of friction, but the time period remains same. Galileo designed a pendulum clock on this principle. However, it could not be fabricated in his life time.

Galileo invented a basic type of thermometer in 1592–1593. It consisted of a sealed glass cylinder filled with clear liquid. In this liquid, a number of objects of different densities floated. Increasing temperature caused progressively less dense objects to sink at the bottom and engraving on the objects could be read to gauge temperature. The principle is very simple. With the increase in the temperature of the liquid, its density decreases. All the objects having densities more than the liquid will sink at that particular temperature. Some authors believe that Galileo did not invent this thermometer but only mentioned in his book.

In 1592, Galileo joined University of Padua. He gave the inaugural lecture on 7th December 1592. Galileo wrote a book on mechanics, which was composed for a course. Galileo developed a calculating instrument. He also developed a military compass. Galileo invented Pulsilogium in 1603. He constructed a pendulum, the length of which could be adjusted so that it swings in time with the patient's pulse. Now, the doctor could read a diagnosis directly from the length of the pendulum.

Galileo realized that the movement of a pendulum is also a kind of fall—a natural motion, not dictated by any outside force. From a modern perspective, it is not true because the pendulum is affected by the force of gravity. However, Galileo knew nothing of this. Galileo did experiments up to 9 m long pendulum. Time was measured by weighing the amount of water that had run into a container. He used the unit of time as 'tempo'. He observed that the time period is proportional to square root of the length of the pendulum. Today we know that the time period is given by

$$T = 2\pi\sqrt{\frac{l}{g}}, \tag{3.2}$$

where l is the length of the pendulum and g is the acceleration due to gravity. In the time of Galileo, the acceleration due to gravity was unknown. Galileo also observed that time of fall for a free-falling body from rest is proportional to the square root of the height it falls.

During the summer of 1607, Galileo turned his attention towards hydrostatics and strength of materials. Strength of Material formed the part of his book entitled Two New Sciences (Darke 1978). Galileo understood the parabolic nature of the paths of projectile. From 1609, he turned his attention towards astronomy with the help of his telescope.

Credit for the invention of the telescope is attributed to the Dutch-German lens maker Hans Lippershey (1570–1619) of Middleburg, Zeeland in the Netherlands. Initially, it was having a magnification of 3X. News of this marvelous invention quickly spread around Europe and first reached the ear of Galileo in May 1609. Without any special knowledge of Lippershey's invention, Galileo figured out what kinds of lenses were required and built his first refracting telescope (Grego and Mannion 2010).

Galileo's first telescope only magnified about three times. Galileo wrote that his telescope consisted of a tube made of lead, two lenses both plane on one side but one spherically convex on the other side and the other concave. Galileo's second telescope constructed a few weeks later was of the same configuration but had a magnification of 10X. By November 1609, he had constructed a telescope with a magnification of 20X, grinding the lenses himself to his own specification in order to produce an instrument with higher magnification. It consisted of a 37 mm plano-convex objective lens with a focal length of 980 mm. The tube was of a wooden barrel-type construction made of long strips of wood glued together and consisted of two parts—the main tube to which the objective lens was attached and a small draw tube nesting inside it which housed eye lens.

In March 1610, Galileo published his amazing observations in Sidereus Nuncius (The Starry Messenger). It was a little book that made big impact. In addition to revelation about the Solar system, the Moon's cratered face and the moons of

Jupiter, the book included the observations of the milky-way, stars in Orion constellation, the bright Pleiades and beehive cluster.

Galileo's observations clearly showed that Earth was not located at the center of the Universe. Planet Venus showed phases just as the moon shows. Four star-like points were orbiting around Jupiter. They were named Galilean moons. None of these facts could be explained using the old geocentric Ptolemaic system. In terms of observing and recording astronomical phenomena, the period 1609–1612 was remarkable. Galileo's famous struggle with church began around 1612 (Grego and Mannion 2010). Those days, church used to carry out Inquisition if it suspected that anyone's activities were against the doctrine of church. In 1600, dissident thinker Giordano Bruno was convicted of heresy by the holy office and burned at stake. In 1612, Galileo offered his theory that the Sun revolves around its own axis. On February 26, 1616, cardinal Bellarmine warned Galileo not to hold, teach or defend Copernican theory. According to an unsigned transcript found in the Inquisition file in 1633, Galileo was also enjoined (prohibited) from discussing this theory either orally or in writing.

Galileo also invented a compound microscope. In his 1623 book, the Assayer, Galileo discusses a telescope modified to see objects very close. Originally called an Occhialino (small eye glass), the word 'microscope' was bestowed on this device by Galileo's fellow academician Johannes Faber. A telescope has a convex objective lens and concave eyepiece. In microscope, the eyepiece is convex and the objective lens is concave. Later on, a field lens was added at an intermediate position.

Galileo's battle with church culminated with a trial in April 1633, in which he was forced to abjure, curse and detest the heresy that he supported and taught, including the Copernician view that the Earth moved around a motionless Sun. He was placed under house arrest and forced to recite penitential psalms every day for 3 years. He was not even allowed out to walk in his garden.

During his final years, Galileo worked on his greatest book: Discourses on Two New Sciences. In this book, published in the Netherlands in 1638, he compiled all the observations and theories he had worked on over the previous 40 years. He developed kinematics and mechanics, describing the motion of bodies free from frictional forces. He was able to extrapolate from experiments that without the frictional forces, a body would keep on moving forever. The book also contains the topics on strength of material. By 1637, the eyesight of Galileo was failing. First he lost sight in his right eye. In December 1637, he was left blind. In his later years, Galileo was helped by Vincenzo Viviani, a 16 year old acolyte (assistant) who came to live with him in his home in Arcetri and who acted as his assistant and wrote his first biography (Grego and Mannion 2010). Galileo died of heart problem in 1642.

The other great scientist, during the period of Galileo was R. Descartes (1590–1650). He was a French philosopher, mathematician and scientist, who spent about 20 years of his life in Dutch republic. He is called the father of modern philosophy. He developed Cartesian coordinate system, which connected Euclidean geometry with algebra.

Johannes Kepler (1571–1630) provided three laws of planetary motion based on the data of Tycho Brahe (1546–1601). The laws of Kepler are as follows:

1. All planets move in elliptical orbits, with the Sun at one focus.
2. A line that connects a planet to the Sun sweeps out equal areas in equal times.
3. The square of the period of any planet is proportional to the cube of the semi-major axis of its orbit.

Brahe made all the observations with naked eye. Kepler worked for sometime as an assistant of Brahe. After Brahe's death he got access to the huge data left by Brahe.

Another great researcher of that period was Stevinus (1548–1620). He provided the law of parallelogram for forces that is expressed in the following form:

> The two forces acting on a particle may be replaced by a single force, called their resultant, obtained by drawing the diagonal of the parallelogram, which has sides equal to the given forces.

He also provided a principle of hydrostatics that the pressure of the fluids is proportionate to their depths.

3.7 Period of Newton

The year in which Galileo died, Newton was born. He was born into a forming family of Woodthorpe Manor on 25th December 1642 and named after his father—Isaac Newton. His mother's name was Hannah. When Newton was only three year old, his mother married a prosperous minister from a nearby village. Newton remained with his grandmother, Margery, at Woodthorpe. Newton entered Trinity College of Cambridge University. He got a degree from Trinity College in 1665. Royal Society of London was formed in 1662. Newton became its member in 1672 at the age of 30 and served as its president between 1703 and his death in 1727 (Grego and Mannion 2010).

Newton came across the Robert Hooke's famous book Micrographia that was published around 1964. Robert Hooke is famous for providing the law of elasticity in 1660. It states that for relatively small deformations of an object, the displacement or size of the deformation is directly proportional to the deforming force or load. It is said that Hooke got this idea while working with Robert Boyle (1627–1691) on whose name is a law that states that for a fixed amount of an ideal gas kept at a fixed temperature, pressure and volume are inversely proportional. In 1678, Hooke described the inverse square law to describe planetary motion. Later on Newton provided a universal law of gravitation that is stated as follows:

> Every object in the Universe attracts every other object with a force directed along the line of centers of the two objects. This force is proportional to the product of their masses and inversely proportional to the square of the distance between the centers of mass of two objects.

Mathematically, the gravitational force F_g is given by

$$F_g = G\frac{m_1 m_2}{r^2}, \tag{3.3}$$

where m_1, m_2 are the masses of the objects, r is the distance between the centers of masses and G is the universal gravitation constant. The value of G is 6.673×10^{-11} $\text{m}^3/\text{kg s}^2$. If the two masses of 100 metric ton mass are having their mass centers separated by a distance of 10 m, they will attract each other with a force of about 6.67 mN, a small value. Hence, in machine design, this force is neglected between two elements of the machine.

In 1666, Newton invented calculus. In 1687, Newton published his famous book "Principia Mathematica Philosophia Naturalis", which is famous by the name of Principia. It contains three laws of motion (Kumar 2003):

Law 1: Each and every body perseveres in its state of rest or of uniform motion in a right line unless it is compelled to change that state by forces impressed there on.

Law 2: The alteration (acceleration) of motion is ever proportional to the motive force impressed and is made in the direction of right line in which the force is impressed.

Law 3: To every action, there is always opposed an equal reaction or the mutual actions of two bodies upon each other are always equal and directed to contrary parts.

The first law is essentially Galileo's law of inertia and it defines the term force. The second law relates force to mass and acceleration. If the concept of force is taken from elsewhere, then the first law can be derived from the second law. For a rigid body, the third law can be derived from the second law but not for the deformable bodies. Hence, the third law is an independent law, in general.

In 1704, Newton published his book Opticks. It included inflexion of light (diffraction). Using a glass prism, Newton investigated the refraction of light and performed elaborate experiments that enabled him to discover measurable patterns in light. He investigated 7 colors in the spectrum of light—red, orange, yellow, green, blue, indigo and violet. Newton proposed a theory that light is made of particle. On the other hand, Dutch physicist and astronomer Christian Huygens (1629–1695) proposed the wave nature of light. Albert Einstein (1879–1955) showed the particle nature of light in his 1905 paper of photoelectrical effect. Today light is considered to have a dual nature. In 1717, Newton observed a phenomenon in which an interference pattern is created by the reflection of light between two surfaces—a spherical surface and an adjacent flat surface. Due to it, circular dark and white bands are created. These are now called Newton's ring. They are produced based on the principle of interference and form the basis of many measuring instruments.

The famous mathematician Leonhard Euler (1707–1783) provided the laws of motion for a rigid body. Euler's as well as Newton's laws are valid in an inertial frame of reference. A frame of reference which is at absolute rest is an inertial reference frame. A reference frame that is moving with respect to this frame of reference at a uniform linear velocity is also an inertial reference frame. An accelerating frame is a non-inertial frame of reference. In an inertial frame of reference, following are the Euler's two laws:

First law: The rate of change of linear momentum (mass of the body multiplied by the velocity of center of mass) is equal to the net impressed force on the body.

Second law: Given O is a fixed point on the inertial reference frame, the rate of change of the angular momentum of the body about O is equal to net moment of forces acting on the body about O.

Euler also provided the equations for hydrodynamics. Euler used differential calculus to express Newton's second law.

During the time of Newton, Bernoulli family contributed a lot to engineering. Jacob Bernoulli (1655–1705) along with his brother Johann Bernoulli (1667–1748) founded the calculus of variations. With the help of calculus of variations, one can find an integrand function that minimize or maximize an integral. For example, consider the following integral expression (called functional, i.e., function of functions):

$$I = \int_0^l \left\{ \frac{1}{2} EA \left(\frac{\mathrm{d}u}{\mathrm{d}x} \right)^2 - q(x)u \right\} \mathrm{d}x. \tag{3.4}$$

Suppose also that u is 0 at $x = 0$. The expression in Eq. (3.4) represents the total potential energy of a rod of cross-sectional area A and length l, whose Young's modulus of elasticity is E. The function u provides the displacement of the rod, when the load of intensity $q(x)$ is applied on the rod, i.e., the load per unit length is $q(x)$. One can substitute many possible functions u such as $\sin(x)$, x^2 or any such function that is 0 at $x = 0$. For different functions, the value of functional I will be different. Out of all possible functions, the function which minimizes the value of I represents the exact displacement field for the elastic rod. However, it is not possible to evaluate I for all possible function values. Calculus of variations provides an easy way. It finds out that the function u that minimizes I satisfies the following differential equation:

$$\frac{\mathrm{d}}{\mathrm{d}x} \left(EA \frac{\mathrm{d}u}{\mathrm{d}x} \right) + q(x) = 0; \quad \text{with } u = 0 \text{ at } x = 0. \tag{3.5}$$

Solution of Eq. (3.5) can be obtained by any standard method for solving second order ordinary differential equation. It is also possible to carry out the reverse process, i.e., given a differential equation of Eq. (3.5), the corresponding integral form of Eq. (3.4) can be obtained by using calculus of variations.

Calculus of variations seems to have started by solving brachistochrone (shortest time) problem. In 1696, Johann Bernoulli posed the following problem. "Find the shape of the curve down which a bead sliding from rest and accelerated by gravity will slip (without friction) from one point to the other in the least time." It is said that Newton solved this problem the very next day. The solution is a segment of cycloid. Later on many mathematicians solved this problem in different ways.

Another great mathematician and physicist during the time was Daniel Bernoulli (1700–1782), son of Johann Bernoulli. His excellent work titled “Hydrodynamica” was published in 1738. Bernoulli’s principle for incompressible, inviscid, steady and laminar flow is the basis for the design of a number of measuring instruments and machines. The principle states that the total mechanical energy associated with flowing fluid comprising the energy associated with the fluid pressure, the gravitational potential energy of elevation and the kinetic energy of fluid motion remains constant. It is based on the principle of energy conservation.

3.8 Classical Mechanics After Newton

Nine years after the death of Newton, Charles-Augustin de Coulomb (1736–1806) was born in France. He has contributed a lot to electricity and magnetism. Coulomb was a military engineer who turned to physics later on. In mechanics, he is known for his following laws on friction:

1. The maximum force of friction is independent of the magnitude of area in contact between the surfaces.
2. The maximum force of friction is proportional to the normal force on the area of contact.
3. The maximum force of friction is less and practically constant at low velocities of sliding than that at the state of impending motion.

In the paper submitted to French Academy of Science in 1784, Coulomb showed the results of torsion test of iron wire.

Jean-Baptiste le Rond d’Alembert (1717–1783) published a book entitled Treatise of Dynamics in 1743. It contains d’Alembert’s principle. Using d’Alembert’s principle one can convert a dynamics problem into a statics problem. It introduces a concept of inertia force. The inertia force of a particle is the negative mass times acceleration. Thus, Newton’s law states that force on a particle is mass times the acceleration, whilst d’Alembert’s principle states that the particle is balanced under the action of applied force plus inertia force. Thus, $\boldsymbol{F} = m\boldsymbol{a}$ expression for Newton’s second law becomes $\boldsymbol{F} + (-m\boldsymbol{a}) = 0$ as d’Alembert’s expression. Although it is just algebraic expression, it is helpful in solving the complicated problems of dynamics. When a dynamics problem is converted into a statics problem, the well-established methods of statics can be applied.

Gaspard-Gustave de Coriolis (1792–1843), a mechanical engineer, introduced the concept of Coriolis force and acceleration. Suppose that a particle is moving on a link with velocity of magnitude v and the link itself is rotating with an angular velocity ω, then the particle will experience a Coriolis acceleration of magnitude

$2\omega v$, which is in addition to other acceleration viz., centrifugal, tangential and sliding accelerations. Coriolis effect comes in a non-inertial frame. In a proper inertial frame, the effect does not exist (Goldstein et al. 2002).

In 1768, Lavoisier demonstrated the law of conservation of mass, which can be stated as follows:

> The total mass of a closed system stays constant for any physical-chemical transformation to which it can be submitted.

The experiment consisted of boiling water over a period of 101 days, measuring the weight of whole system before and after the operation. It was observed that the total weight remained constant.

Alternative formulation to Newton's 2nd law was provided by Joseph-Louis Lagrange (1736–1813). He defined a Lagrangian L as

$$L = T - V, \tag{3.6}$$

where T is the kinetic energy and V is the potential energy. Lagrange showed that for a conservative system (in which the potential energy can be expressed as a function of position), the following equation holds good:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = 0, \qquad j = 1 \text{ to } n, \tag{3.7}$$

where q_j represents the jth independent coordinate that is used for specifying the position of the system, which has n degrees-of-freedom. For an n-degree-of-freedom system, there will be n equations. For getting an idea about this approach, consider a spring-mass system subjected to a force F. Keeping one end of the spring, a mass is attached with the other end and the mass is pulled with a force F. The position of the mass can be specified by a coordinate x. At $x = 0$, the stretch of the spring is zero. The kinetic energy T of the system is

$$T = \frac{1}{2}m\dot{x}^2 \tag{3.8}$$

and the potential energy is

$$V = \frac{1}{2}kx^2 - Fx. \tag{3.9}$$

Hence, the Lagrangian is given by

$$L = \frac{1}{2}m\dot{x}^2 - \frac{1}{2}kx^2 + Fx. \tag{3.10}$$

Now applying Eq. (3.6):

$$\frac{\mathrm{d}}{\mathrm{d}t}\left\{\frac{\partial\left(\frac{1}{2}m\dot{x}^2-\frac{1}{2}kx^2+Fx\right)}{\partial\dot{x}}\right\}-\frac{\partial}{\partial x}\left(\frac{1}{2}m\dot{x}^2-\frac{1}{2}kx^2+Fx\right)=0, \tag{3.11}$$

which provides

$$m\ddot{x}+kx=F. \tag{3.12}$$

This could have been obtained by applying Newton's second law, but in more complicated systems, Lagrange's method is convenient to apply. Lagrange was born in Turin, Italy and his book on Analytical Mechanics was published in 1788 (Oliveira 2013).

By using the calculus of variations, the integral form of Lagrange's method can be obtained. This is known as Hamilton's principle (Goldstein et al. 2002). It can be stated as follows:

"The motion of a conservative system is such that the line integral (called the action or the action integral)

$$\int_{t_1}^{t_2} L\ \mathrm{d}t, \tag{3.13}$$

where $L = T - V$, has a stationary value for the actual path of the motion."

In the late eighteenth century and early Nineteenth century, a lot of work was done in the area of strengths of materials. S.D. Poisson (1781–1840) worked in many areas of mathematics. One material property is named after him as Poisson's ratio. It is the ratio of the proportional decrease in a lateral measurement to the proportional increase in length in a sample of material that is elastically stretched. It can be shown that for isotropic materials, the upper bound on the Poisson's ratio is 0.5 and the lower bound is −1. Suppose a 1 m long steel rod of square cross-section of 10 mm side is stretched by 1 mm and its Poisson's ratio is 0.3, then its sides will be shortened by 0.003 mm. Claude Louis Marie Henri Navier (1785–1836) was an engineer and has designed several bridges including suspension bridge. However, the suspension bridge was a failure. He has contributed a lot in solid and fluid mechanics. He is well-known because of Navier-Stokes equations which are the momentum balance equations for a viscous fluid. George Gabriel Stokes (1819–1903) has contributed a lot to hydrodynamics. A. Cauchy (1789–1857) started 3 by 3 matrix notations of the stress components. Cauchy stress tensor refers to force per unit of deformed area. G. Lame (1795–1870) also contributed to strength of materials and is well-known for Lame's constant for an elastic material. Thomas Young (1773–1829) has studied the elastic behavior of the material and provided a constant E in 1807 that is known as Young's modulus of elasticity. It is the ratio of change is stress to change in strain during the elastic range. It is said that Giordano

Riccati has used it in 1782 and Leonhard Euler published it in 1727. In mechanics, George Green (1793–1841) is well-known for providing a measure of strain in his name.

The work on plasticity also started during this period. F.J. Gerstner (1756–1832) applied the load to a piano wire of 0.63 mm diameter and 1.47 mm in length with a series of weights till plastic deformation and drew stress-strain curve (Osakada 2010). As early as 1856, Maxwell (1831–1879) studied the occurrence of the yield. Maxwell showed that the total strain energy per unit volume could be resolved into two parts—the strain energy of uniform tension or compression and strain energy of distortion. He apprehended that the distortion energy part was responsible for the plastic deformation. Henri E. Tresca (1814–1885) carried out the experiments on metal forming processes such as punching, extrusion and compression starting from 1864. Tresca graduated from Ecole Polytechnique at the age of 19, but started publishing academic papers quite late (at the age of 50). The Tresca yield criterion is well-known in the plasticity. The Tresca criterion states that whenever the maximum shear stress at a point reaches the critical value, the yielding starts at that point. This also implies that hydrostatic stress (mean stress) does not affect the yielding.

In 1871, French mathematician and engineer Barre de Saint-Venant (1797–1886) wrote a paper on elasto-plastic analysis of partly plastic problems, such as the twisting of rods, bending of rectangular beams and pressurizing of hollow cylinders. Sain-Venant considered the following assumptions:

(1) The volume of material does not change during plastic deformation.
(2) The directions of principal strains coincide with those of the principal stresses.
(3) The maximum shear stress at each point is equal to a specific constant in the plastic region.

Saint-Venant is famous for his principle in the strength of material that states that except in the immediate vicinity of the points of application of the load, the stress distribution may be assumed independent of the actual mode of application of the load as long as loadings are statically equivalent. This principle is conveniently used to find out the stresses far away from the load. In the immediate vicinity of the load, the stresses can be determined using advanced theoretical or experimental methods (Beer et al. 2004). Von Karman carried out compression test on marble under high pressure and results were published in 1911.

Johann Bauchinger (1833–1893) found that the yield stress in compression after plastic deformation was significantly lower than the initial yield stress in tension. Bauchinger conducted a lot of uniaxial loading experiments with his own designed extensometer. The lowering of the yield stress in reversed loading is caused by the residual stresses (at the microscopic scale) left in the material after unloading. In many metals, this effect is small.

A criterion alternative to Tresca criterion is von Mises criterion. In terms of principal stresses, this criterion states that at the onset of yield,

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_Y^2. \tag{3.14}$$

This criterion was first proposed by M.T. Huber (1872–1950) in 1904; however it was unnoticed for about 20 years as it was written in Polish language. Huber has developed this criterion based on a number of experiments. In 1913, Richard von Mises (1883–1953) developed this criterion on the basis of mathematics. R. von Mises was born in Lemberg (now in Ukraine) and graduated in mathematics from Vienna University of Technology. Hencky (1924) introduced the paper of Huber and derived the yield criterion on the basis of distortion energy. In 1925, Lode conducted experiments on thin tubes subjected to internal pressure as well as axial force. The materials chosen were iron, copper and nickel. The effect of intermediate principal stress on the yielding was studied. It was observed that the yielding behavior of metals is closer to von Mises criterion, whilst Tresca criterion is more conservative. In 1933, G.L. Taylor and H. Quinney also conducted experiments on thin tubes subjected to axial load. However, they applied twisting moment instead of internal pressure. The materials chosen were steel, copper and aluminum. They also confirmed that material behavior in yielding is more closely represented by von Mises criterion. In 1937, Arpad L. Nadai (1883–1963) showed that this criterion could be stated as follows: The yielding occurs when the shear stress on the octahedral plane in the space of principal stresses reaches a critical value. An octahedral plane is equally inclined to all the principal planes. Nadai was born in Hungary and graduated from Budapest University of Technology.

Tresca and R. von Mises criteria are for isotropic materials. In 1948, Rodney Hill provided a quadratic yield criterion for anisotropic materials. A special case of this criterion is von Mises criterion. In 1979, Hill proposed a non-quadratic yield criterion. Later on several other criteria were proposed including Hill's 1993 criterion. Rodney Hill (1921–2011) was born in Yorkshire, England and has tremendous contribution in the theory of plasticity.

Apart from yield criterion, one is interested in the constitutive relations. In the elastic constitutive relation, the stress is related to strain; however in the plastic constitutive relation stress can be related to strain-rate or strain-increment. In 1872, M. Levy used an incremental constitutive equation, which was later proposed by von Mises. Levy's paper was not known outside France. Levy-Mises relation considers that the increments of plastic strain increments are in proportion to deviatoric components, i.e.,

$$\frac{\mathrm{d}\varepsilon_1^p}{S_1} = \frac{\mathrm{d}\varepsilon_2^p}{S_2} = \frac{\mathrm{d}\varepsilon_3^p}{S_3}, \tag{3.15}$$

where S_i are the principal deviatoric stress components. Prandtl (1924) developed the relations including elastic part for plane strain case and Reuss (1930) did it for the general case. It is assumed that total increment in strain is the sum of increments in elastic and plastic strain. Thus,

$$d\varepsilon_i = d\varepsilon_i^p + d\varepsilon_i^e. \tag{3.16}$$

Inversion of Prandtle-Reuss equations was carried out by Hill in around 1950.

Apart from macroscopic observations, attempts were being made to understand microscopic behavior of plasticity. In 1923, Percy Williams Bridgman (1882–1961) invented a method to make a single crystal of metal by pulling it out of molten metal. He extensively studied the behavior of metals under high hydrostatic pressure. In 1946, he received the noble prize in physics for his work on high pressure physics. Taylor (1934), Polanyi (1934) and Orowan (1934) independently proposed the sliding mechanism by crystal defects, i.e., dislocations. The existence of dislocation was proved in 1950, after electron microscopy was invented. First person to recognize it experimentally was K. Yamaguchi. M. Polanyi (1891–1976) made contribution to crystallography. In 1938, he formed the Society for the Freedom of Science.

3.9 Relativistic and Quantum Mechanics

Relativistic and quantum mechanics do not find much application in conventional mechanical engineering. Here, they will be discussed very briefly. Albert Einstein (1879–1955) showed that Newtonian mechanics has its limitation. He observed that speed of light is same for all inertial observers regardless of their velocity or the velocity of the source of light. The implication of this is that events that occur simultaneously for one observer can occur at different times for other observers. Prior to Einstein, it was agreed that distance between the places of events depends on the observer, but not the time. Einstein discovered that there is no absolute time. It also depends on the state of motion. In Newtonian mechanics, space and time are totally unrelated concepts. In relativistic mechanics, they are related. Some interesting consequences of relativistic mechanics are as follows. An object cannot exceed the velocity of light in vacuum, which is 3×10^8 m/s. As the velocity of an object increases, it appears shorter. Its mass increases and hence it becomes difficult to accelerate such an object. Time clock also moves slower in an inertial frame moving with high velocity. These effects will be experienced only when an object approaches the velocity of light. For most of the practical situation, Newtonian mechanics is good enough.

For very tiny objects, such as electron, quantum mechanics is needed. Max Planck (1858–1947) is considered as the father of quantum mechanics. Salient point of quantum mechanics is that all matters and energy exhibit both wave-like and particle-like properties. If the size of the object is large, its wavelength will be too small to be observed. Also, there is a famous uncertainty principle that states that as one makes more precise measurement of the position of an object, the uncertainty in its momentum increases.

3.10 Conclusion

It is observed that in the beginning studies in the mechanics were concerned with rigid body dynamics. Aristotle pioneered to develop the theoretical foundation of dynamics. However, most of his theories are proven wrong now. Archimedes contributed to statics including fluid-statics and his many findings are still valid. Aristotelian mechanics was uprooted by Galileo. However, the proper laws of mechanics were put forth by Newton. After Newton, rigid body mechanics reached almost saturation and focus shifted to strength of materials including plasticity theory. In the beginning of twentieth century Newtonian mechanics was challenged by relativistic mechanics and quantum mechanics, but these could not overthrow Newtonian mechanics. For practical range of sizes and velocities, Newtonian mechanics is good enough.

References

Armytage, W. H. G. (1961). *A social history of engineering*. Massachusetts: The MIT Press.

Assis, A. K. T. (2010). *Archimedes, the center of gravity, and the first law of mechanics: The law of lever* (2nd ed.). Montreal: C. Roy Keys.

Barnes, J. (2003). *Aristotle: A very short introduction*. New Delhi: Oxford University Press.

Beer, F. P., Johnston, E. R., & Dewolf, J. T. (2004). *Mechanics of materials* (3rd ed.). New Delhi: Tata McGraw-Hill.

Ceccarelli, M. (2014). Contributions of archimedes on mechanics and design of mechanisms. *Mechanism and Machine Theory*, *72*, 86–93.

Coxhead, M. A. (2012). A close examination of the pseudo-Aristotelian *Mechanical Problems*: The homology between mechanics and poetry as *technē*. *Studies in History and Philosophy of Science, 43*, 2012.

Drake, S. (1978). *Galileo at work: His scientific biography*. New York: Dover Publications.

Feke, J. (2014). Meta-mathematical rhetoric: Hero and Ptolemy against the philosophers. *Historia Mathematica, 41*, 261–276.

Goldstein, H., Poole, C., & Safko, J. (2002). *Classical mechanics* (3rd ed.). Singapore: Pearson Education.

Grego, P., & Mannion, D. (2010). *Galileo and 400 years of telescopic astronomy*. New York: Springer.

Hofstadter, D. (2009). *The earth moves: Galileo and the Roman Inquisition*. New Yourk: W.W. Norton & Company.

Kahn, C. H. (1996). *Plato and the socratic dialogue: The philosophical use of a literary form*. Cambridge: Cambridge University Press.

King, P. (1955). *Jean Buridan's logic—the treatise on supposition, the treatise on consequences*. Tokyo: D. Reidel Publishing Company.

Kumar, K. L. (2003). *Engineering mechanics*. New Delhi: Tata McGraw-Hill.

Lee, A., Péporté, P., & Schnitker, H. (2010). *Renaissance? Perceptions of continuity and discontinuity in Europe* (pp. c.1300–c.1550). Boston: Brill.

Næss, A. (2005). *Galileo Galilei: When the world stood still*. Berlin: Springer.

Oliveira, A. R. E. (2013). Lagrange as a historian of mechanics. *Advances in Historical Studies, 2*(3), 126–130.

Oliveira, A. R. E. (2014). *A history of the work concept: From physics to economics*. New York: Springer.

Osakada (2010). History of plasticity and metal forming analysis. *Journal of Materials Processing Technology, 210*, 1436–1454.

Papadopoulos, E. (2007). Heron of Alexandria (c.10–85 AD). In M. Ceccarelli (Ed.), *Distinguished figures in mechanism and machine science* (pp. 217–245). Netherlands: Springer.

Pisano, R., & Capecchi, D. (2016). *Tartaglia's science of weights and mechanics in the sixteenth century: Selections from Quesiti et inventioni diverse: Books VII–VIII* (Vol. 28). Dordrecht: Springer.

Satyawadi, S. (1994). *Proto-historic pottery of indus valley civilization: Study of painted Motifs*. New Delhi: D.K. Printworth.

Shames, I. H. (1997). *Engineering mechanics—statics and dynamics*. Singapore: Pearson Education.

Sharratt, M. (1994). *Galileo: Decisive innovator*. New York: Cambridge University Press.

Tuominen, M. (2009). *The ancient commentators on Plato and Aristotle*. Stocksfield: Acumen Publishing Limited.

Waters, S., & Aggidis, G. A. (2015). Over 2000 years in review: Revival of the Archimedes screw from pump to turbine. *Renewable and Sustainable Energy Reviews, 51*, 497–505.

Winter, T. N. (2007). *The Mechanical Problems in the Corpus of Aristotle*. Lincoln: University of Nebraska.

Retrieved October 17, 2015, from http://www.britannica.com/biography/Heron-of-Alexandria.

Retrieved October 18, 2015, from http://www.britannica.com/biography/Nicholas-Oresme.

Retrieved October 20, 2015, from http://www.phy.davidson.edu/fachome/dmb/PY430/Friction/history.html.

Retrieved October 18, 2015, from http://plato.stanford.edu/entries/heytesbury/.

Retrieved August 20, 2015, from http://www.westernrenew.co.uk/files/case_studies/river_dart.pdf.