Human-Technology Collaboration

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Abstract

The defining feature of the human species has always been that we employ technology to interact with nature. The modern case of human-computer interaction provides five distinct research and development approaches that could be applied to any field of engineering: (1) ergonomics, (2) cognitive modeling, (3) user-centered design, (4) value-sensitive design, and (5) technical culture. The felicitous "symphony orchestra" metaphor for social-technical systems also identifies widely applicable principles: (1) division of labor, (2) a harmony of scientific concepts, (3) the need for significant human expertise, (4) social cohesion of teams, (5) human guidance, and (6) properly defined general principles for decision making. Humanity may have reached a technological watershed at which the basis of much of the economy shifts from physical objects to information, but in any case innovation, will require new collaborations between fields of expertise, in service of human well-being.

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Introduction

Homo sapiens is said to be the tool-making species, yet it could just as well be described as tool-made, since our sociobiological evolution has been shaped by the technologies through which we exploit nature. Stonecutting tools survived from hundreds of thousands of years ago, yet many examples of ancient technology vanished over time, so often we can do little more than speculate, for example, to conjecture that the most important early tool was the bag, allowing a person to carry many other tools, a container that can symbolize convergence of technologies. Consideration of the relationships between tools and their makers over the full sweep of human history provides a background for understanding the dynamics today of the human-scale platform for convergence. This is the set of systems that enable convergence characterized by the interactions between individuals, between humans and machines, and between humans and the local environment. The current moment in human history resulted from the convergence of innumerable factors from our past, and we must now select from a divergence of potential futures, largely determined by human relationships with technology.

The Case of Human-Computer Interaction

A very large number of researchers and projects have in recent decades created a field called human-computer interaction (HCI), which offers many methods and ideas of value in understanding human-technology interaction in general. It should not be assumed that in the future all human-technology interactions will be mediated by electronic information-processing technologies, although current trends seem to be in that direction. Rather, we can draw lessons from this recently emerged field, apply them to other areas, and then consider what ways HCI may be insufficient as a general model. There are at least two very different ways HCI relates to science and technology convergence: (1) in its relevance to the professional practice in these technical fields and (2) as a key factor shaping the convergence of science and technology with society, facilitating both science education and the beneficial use of new technologies.

Consider a stereotypical scientist or engineer doing calculations around the year 1950, using a pencil, pad of paper, slide rule, and printed table of logarithms. Suppose that one step in data analysis or machine design required calculating an area of a rectangle, which could be done longhand, by multiplying the lengths of adjacent sides. The slide rule could give a quick estimate, perhaps accurate to three digits. Familiarly called “slipsticks,” slide rules were carefully made rulers in which one strip could be slid left or right between two others, in this example lining up a mark on the left end of the slider with the value on the stationary part of the ruler that represented one side of the rectangle, then looking along the slider for the number representing the adjacent side, and looking back on the stationary ruler to read out the area. This most common part of a slide rule had two identical logarithmic scales, so that multiplication could be performed as addition.

A multipage table of logarithms could do the same thing but with greater accuracy, allowing the user to calculate multiplication in a simplified form as addition, often through the use of a hand-operated mechanical adding machine. Slide rules also often had scales of trigonometric functions, and the typical scientist or engineer also possessed a printed book of sines, cosines, and tangents. Very few people ever learned the simple yet tedious methods for hand calculating square roots and cube roots or for calculating trigonometric functions, so slide rules and printed tables of functions were essential tools at that historical period.

Today, every civilized person owns a pocket calculator or computer that renders slipsticks and printed function tables utterly obsolete. The user does not even need to know whether the machine contains tables in its memory or calculates each result from scratch, so long as the answer comes immediately upon asking the machine a question. In some cases, a table of empirical data is required, for example, if one wishes to see how much $100 in the money of 1950 would be worth today, taking account of currency inflation. Yet one need never see that table. Online websites provide converters that are periodically updated with new data, and the Bureau of Labor Statistics website tells us that $100 of 1950 money was worth about $715 in 2000 and $989 in 2014.

The most impressive historical example is the Antikythera mechanism, a computer more than 2000 years old, in the form of a complex set of gears used to make astronomical calculations (Price 1974). It is not known how many such devices existed in the ancient world, but they must have been rare and required considerable expertise to operate. Yet now anyone interested in knowing about the positions of solar system objects from day to day can buy the computer-based virtual planetarium *Starry Night* for as low as $50 ($5 in 1950 money), which gets updates from the Internet as well as doing massive calculations inside itself and allowing the user to see the solar system from any position and point in time.

The comparison between a slide rule and a table of logarithms is instructive. Both are approximations of the mathematical functions they represent, but they perform this representation in a different way. In the language of modern computers, slide rules are *analog* devices, in which distance along the edge of a physical object represents magnitude along an abstract scale of real numbers. Log tables are *digital*, representing magnitudes as written symbols following a conventional notation system, typically in the decimal system, to some convenient number of digits.

For some decades, personal computers have functioned internally as digital devices but have used a combination of digital and analog methods for communicating with the human user. A computer's mouse is analog, at least as experienced by the user, moving the cursor across the display screen in a manner analogous to the movement of the mouse across its pad on the desk. The number pad on the keyboard, of course, is digital. Some game players use joysticks with their computers, and a very few users have trackballs rather than mice. Yet the standard combination of mouse and keyboard is physically awkward, and recent mobile devices dispensed with both, using touch screens instead, which can function either as analog or digital inputs, depending on their software. The classical idea of speaking with a computer, popularized in the original *Star Trek* series, has achieved some degree of success in recent years, but remains unreliable.

Given the complexity of the technology and the many ways it can be integrated into human life, researchers in human-computer interaction have developed a number of principles, potentially compatible with each other but often reflecting competing schools of thought. HCI research traditions overlap, following the principle of convergence, and the terminology is not distinct, yet it is useful to identify five approaches that have somewhat different emphases:

1. *Ergonomics* is a long-standing tradition in engineering design that emphasized the physical characteristics of the machine, the human, and the human motions required to operate the machine. In its early decades, ergonomics sought to improve the efficiency of manufacturing production, through *time and motion studies* to optimize human labor (Taylor 1911). More recently, the emphasis became the long-term physical well-being of the human, for example, avoiding work arrangements that would cause repetitive stress injuries. Today, not only are ergonomic principles applied to the design of information technologies, but computer simulation has become a tool for evaluating ergonomics of even such traditional tasks as truck driving and sheet metal work (Faraway and Reed 2007).
2. *Cognitive modeling* focuses on human perception, analysis, and planning during interaction with computers and other technological devices (Olson and Olson 1990). For example, much research focuses on visual search of a computer display to find words or images (Halverson and Hornof 2011). Results can improve the design and layout of computer displays but also provide deeper knowledge about how the human mind works that can be the basis for artificial intelligence systems that emulate it more accurately. For educational purposes and for designing graphic displays of scientific data for researchers, cognitive models can be crucially important to reduce errors as well as achieve efficiency (Börner 2010).
3. *User-centered design* directly involves users of the technology in the process of its development. A project might begin with focus group discussions with potential users and place a heavy emphasis on experimental usability studies as prototypes were being developed. Often, "users" are conceptualized as social groups rather than just individuals, as typically is the case for ergonomics and cognitive modeling. Ideally, the design process is iterative and extensive, cycling repeatedly through five evaluation phases: (1) assess the needs of the community, (2) select a technology plan for sociability, (3) test prototypes, (4) test sociability and usability, and (5) nurture the community (Abras et al. 2004). This approach has some affinity with the recent movement to involve nonprofessional volunteers in research teams, which is called *citizen science*.
4. *Value-sensitive design* seeks to fulfill the fundamental goals of the user or to frame the design in terms of an explicit set of goals that could reflect the needs of any of the participants in the production and use of the new technology. It ideally combines three qualities: (1) conceptualization comparable to a design

philosophy, (2) empirical research on the impact the design actually has on users, and (3) good performance of the technology itself (Friedman 2004). Akin to user-centered design, it gives representative stakeholders a role in the design process (Yoo et al. 2013). Individuals and groups differ in the values they hold dear (Hitlin and Piliavin 2004), and one study of computer games documented a long list of issues about how effectively the systems achieved the goals of different constituencies, including the educational goal to teach new values to the user (Flanagan and Nissenbaum 2014).

5. *Technical culture* defines the conceptual structure and historical tradition that develops a human-centered technology. For example, each computer programming language and operating system is similar to a culture, being a mixture of practically necessary features with logically arbitrary conventions (Rajlich 2004). At the same time, the wider culture provides a context that interacts with the narrower technical culture of the engineers doing the actual development work (Leidner and Kayworth 2006). The four approaches listed before this one give technology developers four clear methodologies to select from or to combine, while this approach seems more passive, observing the social-cultural system that innovates rather than controls it. However, studies that render the assumptions, values, and traditions of a technical culture more explicit may encourage innovators either to embody it more perfectly or to diverge from it in more radical episodes of transformation.

Orchestration

A standard metaphor in discussions of technological convergence is the classical symphony orchestra.. The conductor must coordinate the actions of a large number of human beings, some like the violinists clustered in subgroups and others like the bass drum player taking unique roles. Each player uses a particular piece of technology, a musical instrument of a specific kind, and has gained extensive expertise operating it. While members of the audience may not be aware of the fact, each instrument is historically the result of systematic research in acoustics that could justly be called scientific. The coordination of instruments and players is accomplished most obviously by the human conductor, but the written musical score also plays a role, within the context of the particular cultural tradition to which the piece of music belongs. The performers have worked together for a considerable period of time and thus qualify as a cohesive social group. Each of these points applies in significant degree to other well-organized systems in which humans collaborate with technology and through technology collaborate with each other.

It is said that the first two abstract sciences that made sophisticated use of mathematics were astronomy and musicology. The Antikythera mechanism is remarkable to the point of being astonishing, yet it could not have been built without many years of systematic observation of the planets, in which their changing positions in the sky were noted with some degree of precision. We can thank the

Babylonians for much of the early progress in astronomy, even though the Antikythera mechanism is considered to be a Hellenistic Greek device. The Greeks were pioneers in musicology and acoustics and invented an especially complex precursor of the church organ, the hydraulus. This was a "water organ," and it should be remembered that the Greeks achieved some degree of accuracy in building clocks that operated with water. There were many varieties of hydraulus, typically each having multiple organ pipes just as today's church organs do, but apparently some used a hydraulic device to stabilize the pressure achieved by human pumping actions, so that the sound would be "fluid" rather than coming in a series of pulses.

Much ancient research concerned string instruments, in which the physics of producing sounds at different pitches can easily be studied (Helmholtz 1875). Long before the emergence of modern science, musicologists constructed a simple research device, like a two-string harp, using the same exact material for both strings. Both are tied at one end on a block fastened on a horizontal board, while the other end goes over but is not fastened to a bridge at the far end of the board, hangs down, and is held in position by a weight. Each string has a second bridge in the form of a small block that can be moved along the board, to define what length of the string is free to vibrate when it is plucked. Changing the weight changes the tension on the string, in a precisely measurable manner. This simple device allowed ancient researchers to determine the mathematical functions that define the musical intervals from which scales are assembled. A string that is exactly half the length of another will produce a tone that is an octave higher, so long as the tensions on the strings are the same. As the octave is the ratio 1 to 2, the perfect fifth is the ratio 2 to 3, and the perfect fourth is 3 to 4. With modern string instruments like the violin, the player instinctively knows this, because much of the work is setting fingers of the left hand at different distances along a string to produce different tones.

A grand piano is among the most complex machines devised by human beings, yet dates back three centuries, half that time in about its current form. Harpsichords, which are also complex, are about twice as old (Bainbridge 2012). Neither would have been possible without the invention of wiredrawing technologies that could create highly uniform, strong strings. Humans play both of these classical instruments by striking keys with the fingers, analogous to a computer keyboard, a set of levers constructed in such a way as to minimize noise and arranged in terms of the 12 musical tones per octave but organized to facilitate playing just the seven notes of a traditional scale. The mechanisms of both instruments include an escapement in the part that takes the action of the key and transfers it to the string. In the harpsichord, the escapement plucks the string when the key is depressed, but avoids plucking it a second time when the key is released. In the piano, the escapement hurls the hammer to hit the string, but then prevents it from bouncing to hit the string again. In both, a damper silences the string when the key is released, unless the player tells the machine not to do so. In fully evolved forms of both instruments, the strings achieve much of the range of tones by being in different lengths, but to avoid impractically long strings in the bass, the density of low strings is increased, having a greater thickness, being of brass rather than steel in harpsichords, or even in modern pianos winding a secondary wire around the primary one. Indeed, a full description of both instruments would require many chapters, some of which would focus on the huge variety of raw materials used in their construction and thus on the very elaborate supply chains required to manufacture them.

In performing a piano concerto, the pianist and orchestral conductor are partners in directing the social organization, and the leader of first violins also plays a leadership role, especially when tuning up prior to the performance. Pianos are usually not tuned by their owners, because this is a highly technical task, but by a professional every few months. Violins must be tuned immediately before a performance, by the player, with all violins in the orchestra tuned to the same pitches. Modern pianos are tuned to an equal temperament scale, in which intervals like perfect fourth and fifth are not exact, because mathematically the full set of tone intervals has a complex pattern. But during performance, violinists tend to adjust their pitches closer to the perfect intervals, by exactly where their finger presses on a string. Brass instruments naturally produce a series of pitches in the overtone scale, illustrated by a sequence of ratios 1 to 2, 3, 4, 5, and so forth. The introduction of valves into brass instruments, about two centuries ago, added to their capabilities but did not free them entirely from the overtone sequence. The exception among brass instruments is the trombone, which like the violin can produce any frequency of vibrations within its range.

The point of reviewing these details is to make the very general point that the mathematics of any human-centered technology may start with simple principles, but quickly becomes complicated, having different implications for different tasks within the technological and social system. We could say that the violin and trombone are analog devices, in which the user adjusts the frequency of vibration by directly changing the physical length, while the harpsichord and piano are digital devices. If the instruments are the hardware of an orchestra, the software is the musical score.

Tantalizingly inscrutable fragments of musical score survived from the ancient world, so apparently musicians long sought to write down the music of their songs as well as the words. The dominant form of musical notation today derives from Europe and evolved primarily in the medieval period. In some ways, it is intuitive, for example, in that "high" notes are placed higher than "low" notes on the five-line staff, the notes are written in a linear sequence representing time, and an orchestral score has a different staff for each set of instruments. Yet there are arbitrary elements as well, for example, that adding a flag to a quarter note transforms it into an eighth note and reduces its duration in half. However, this does not mean that musical notation is "unscientific." Mathematical notation is also a mixture of intuitive and conventional principles, as, for example, a summation sign that may be annotated with the range over which the sum should be calculated. Computer programs were traditionally written by humans, but interpreted by computers, and the human readability of programs is a major issue for open-source software projects, in which many humans must read, edit, and expand a program that must run properly on machines.

Cultural conventions exist within the context of the fundamental features of human cognition, and nothing represents the subtleties of this interaction better than the history of written language. As Ancient Egyptian hieroglyphics most famously illustrate, writing began as pictures of objects or actions and then evolved into a more abstract representation of the sounds of spoken language. In the case of Chinese writing, the pictographs lost their visual representational quality, without becoming simply symbols for phonemes. Modern Japanese expresses fundamental contradictions of human nature by combining four different systems: (1) nearly 3,000 *kanji* characters borrowed from Chinese, (2) about 50 *hiragana* characters representing all the different syllables in spoken Japanese, (3) *katakana* similar to hiragana but used for foreign words, and (4) a great diversity of modern symbols introduced from global culture, from Arabic numerals to stylized outlines of human hearts. English speakers should hesitate to criticize Chinese and Japanese for failing to adopt simple alphabets, because they should remember that the spelling in their own language is very far from uniform. More pertinent to the theme of this chapter, hieroglyphics have been reborn as icons on computer screens, suggesting they were not simply obsolete but served particular cognitive functions in the past, as they do again today.

Several competing explanations may be offered about why the written languages of major Asian nations did not become simply alphabetic. One is that human cognition fundamentally involves manipulation of concepts, rather than consonants and vowels. Another is that complex forms of writing confer added status on the educated classes in society. Another is that language functions differently in various spheres of life and the apparent simplicity of alphabets may work best in short-term commercial exchanges, while computer icons facilitate quick selection of a software choice. For science and technology, spoken language is useful but inadequate and must be supplemented with many other forms of documentation and communication. Graphs are visual analogs expressing relationships between continuous variables. As this handbook amply illustrates, conceptual charts are also valuable. A large fraction of patent applications include diagrams of machines. In many sciences, specimen collections are essential, as are research instruments, so physical objects are important for science as they are for engineering.

For two centuries, music theorists have debated the extent to which music embodies the fundamental processes of human thought, having cognitive as well as emotional elements, the development of complex themes over time, and communication as well as expression, relying upon a diversity of technologies (Meyer 1994). Recognizing the complexity of science, technology, and society, any brief list of principles is bound to be at best an approximation, yet six related insights can be drawn from the example of a symphony orchestra:

1. *A division of labor with technological specialization marks every large-scale technological activity*. That is to say, every large-scale human project has the qualities of a system, and thus knowledge of the type of system and its common dynamics would be useful.
2. *Complex social-technical systems depend upon a symphony of scientific concepts*. Harmony between system components, as in music, does not mean unison but compatibility and resonance. If the components had been identical, then

most of them might have been superfluous, yet they could not be dissonant with each other without endangering the system.

3. *Significant human expertise is required in all the domains that comprise the system*. Some of that expertise is required during specific stages of the work, such as a violinist's fingering expertise during the performance and a piano tuner's skills beforehand; thus, the diversity of coordinated contributions is distributed across time as well as space and instrumentation.
4. *A degree of social unity is required of the people working together, but not uniformity*. This cohesion can be structured, in large collective efforts, with subgroups like the second violins functioning as a unit distinct from first violins and suppliers of parts for an aircraft manufacturer dispersed at different geographic locations, yet the people should share common goals and ideally a sense of connection with each other.
5. *Direction in the form of human leaders is essential, but not dictatorship*. As modern theorists in management science have long observed, under most normal conditions, leaders are most effective if they help followers see how doing what the organization needs will also serve their own personal goals (McGregor 1960).
6. *Obeying properly defined general principles is fundamental to creative freedom*. In 1776, the American Declaration of Independence enshrined "the consent of the governed" as a key principle of government, but in 1780 the constitution of the Commonwealth of Massachusetts proclaimed "a government of laws and not of men." In convergence with each other, these two apparently contradictory principles assert that leadership should serve the personal needs of those who are led, yet be guided by abstract principles rather than the personal desires of the leaders. Another way to look at this creative tension is to note that human freedom can flourish best, when humanity has the fullest possible comprehension of the rigid laws of nature.

The Information Civilization

The examples of slide rules and symphony orchestras illustrated very general principles that apply today, yet concerned the technologies of the past. We may well ask how different our current era is from past periods of history, both in terms of the problems we face and the opportunities we may exploit. At each point in human history, it was too easy to be pessimistic, too risky to be optimistic, and too hidebound to be realistic. Imaginative vision is an essential motivator for convergence, so long as we invest the effort required to render its products feasible and judiciously criticize possible harmful unintended consequences (Bainbridge 2007). A good example for human-technology collaboration is the virtual orchestra shown in Fig. 1.

Each of the ten performers depicted in Fig. 1 is both real and virtual, an actual human being operating an avatar in the Internet-based computer game, *Lord of the Rings Online* (LotRO). They are performing in public to an audience of a couple

Fig. 1 An international orchestra playing in Tolkien's middle earth

dozen other avatars, not shown, in the virtual city Bree, in front of the Prancing Pony tavern, a center of informal LotRO social life. The two short avatars in the front are hobbits, and the woman hobbit playing a drum is the organizer and conductor of the group. The person operating her lives in Europe, as do most of the others, but two are in the United States, each communicating through a personal computer. They play music for about an hour, perfectly coordinated by the technology and the human leadership, an online convergence of geographically distributed individuals, and a convergence of technology with the arts.

Although the musical instruments and the performers' costumes are merely images produced by computer graphics, the players needed to do considerable work to acquire them. They also needed to learn the rather complex software system that produced the music, frankly quite separately from the graphics. If the sound of each instrument had been produced where the player was located, it would have been difficult to get the sounds of all ten to fit together, given Internet latency which introduces irregular delays. Therefore, each person in the audience and each player hear music synthesized on their own computers, following a score downloaded and controlled in real time over the Internet. The scores were orchestrated expertly by the conductor and one of the players, using an alphabetic notation system simply called ABC, which also can play music produced by artificial intelligence systems (Oliwa 2008; Cheng 2012).

The orchestra performance was coordinated through a nicely programmed piece of amateur open-source software called Songbook, which required each player to download the right ABC files prior to the performance. The conductor communicated with the players through a private text chat channel built into LotRO, while using a public channel to tell the audience which song came next. She also could talk with her performers through an online voice communication system called Mumble, run separately but in parallel with LotRO. This very successful performance was held in the spring of 2014, and in the summer a LotRO music festival called Weatherstock VI brought together the avatars of fully 487 people.

One may well ask why people would want to play music online and at a great distance from each other, rather than together at the same place. One reason is that the LotRO orchestra consisted of people who loved the *Lord of the Rings* mythos created by J. R. R. Tolkien, a rare but deep cultural orientation. While not strictly speaking a scientist, Tolkien was a scholar of historical linguistics, who perhaps ironically held rather negative views of modern technology. Thus, LotRO is a good example of the interplay between convergence and divergence. Sociologist Claude Fischer (1975) long ago explained that the large populations of big cities allow people with unusual preferences to band together, producing a much greater diversity of subcultures than can be found in low-population areas. These subcultures not only differentiate from each other but interact and thereby produce even more subcultures, hybrids that result from their creative convergence. The Internet is a virtual city with a population not of a million but a billion, thus enabling vastly more subcultures, some of which will take on very real significance in the wider world.

Yet each technology requires some expertise for human beings to operate it, as well as infrastructure investment, so technologies compete against each other to determine which one will dominate in any particular area of human life. Government agencies and corporations experimented extensively with the nongame online virtual world *Second Life* as a venue for group meetings (Bohannon 2011), but most withdrew eventually. One reason was that *Second Life* like LotRO is optimized for use by numerous individuals, interacting more or less equally, at multiple locations, in real time, via low-bandwidth connections. Often a corporation or government agency uses the Internet in three ways quite different from this: (1) connecting two groups situated in the high-bandwidth teleconferencing rooms of two separate branches, rather than many completely separated individuals, (2) broadcasting primarily one-way communications from leadership to the general personnel of the organization, and (3) telecommuting in which individuals contribute their labor asynchronously from multiple locations, including while traveling in the field, with little interaction between them.

Many technologies, perhaps even most, can be used by individuals as well as groups. To continue with the example of virtual worlds like LotRO, which can stand in for many other forms of technology, these environments can be training schools that teach forms of science and engineering to individuals. For example, many future-oriented computer games have the human player interact with robots or other complex machinery that does not yet fully exist here on Earth (Bainbridge 2011b). Consider the *Star Wars* mythos, where two of the prime characters were robots, interacting as partners with humans. The National Robotics Initiative calls such machines *co-robots*, because they collaborate with humans and have a degree of autonomy, without challenging human authority. Many online gameworlds, LotRO among them, allow players using some kinds of avatar to operate *secondary avatars* as well, for example, a hunting bear to help a lore-master in LotRO (Bainbridge 2011a). In the classic but now terminated virtual world, *Star Wars*

Fig. 2 A droid engineer and her creations in a virtual universe

Galaxies, an engineer avatar could collect raw materials, set up component factories, and make a huge variety of robots, as illustrated in Fig. 2.

Every one of the robots in the picture was constructed by the woman engineer avatar standing near the middle. She mined virtual resources from the surrounding environment, set up factories and small production facilities, assembled modules, and in some cases programmed the resulting robots to speak or act in certain ways. A typical battle robot could be given or sold to another player, even if that player's avatar lacked the skills to construct robots, who could then program it to patrol a specific area and give it moment-to-moment commands during a battle. While the system was far from realistic, it did simulate many of the steps required to build real robots and thus had an educational quality.

A debate currently rages over whether robots and other forms of smart technology will erode employment opportunities for humans, especially people who are not especially adept at operating advanced technology (Brynjolfsson and McAfee 2011). The use of simulated robots and other secondary avatars in online games illustrates one of the real-world problems. In undertaking combat missions, often the computer-generated enemies are too formidable for a single player to defeat, but a player with a team of secondary avatars may triumph even without human teammates. Thus, we often turn to machines because human beings are not available to help us, yet getting in the habit of doing so devalues humans. As information technology leverages the abilities of technically competent people, it may reduce the total number of jobs available, especially for people who lack the education or innate abilities to compete in terms of technical competence. Economists have long argued that technological innovation is *creative destruction*, destroying old jobs while inventing new jobs, but there is little reason to trust that the new jobs will automatically be numerous enough to offset the destructive part of the process (McKnight and Kuehn 2012).

Conclusion

The prime antidote to despair is innovation. We must do our best to anticipate unintended negative consequences of new technology, but often the proper response is a mixture of improving the technology and fine-tuning other components in the social-technical system. If world population stabilizes, per capita wealth can increase indefinitely, not by giving each person more food and heating each home hotter, but by providing new cultural services that require human artistic creativity but may use little if any additional natural resources. Playing a three-century-old wooden Stradivarius violin does not require chopping down a living tree, and the energy costs of online communication are more than offset by the reduced need for physical travel. Hopefully, there will be ample employment for everyone who wants to work, in jobs that are interesting as well as useful. This probably requires radical rethinking of the relationships among the arts, humanities, and sciences, indeed using the technology to create entirely new forms of human expression.

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