The Synergy of Human-Computer Evolution: Merging Biology and Technology in *Singularity*

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Abstract

This paper postulates that advances in technology are an integral component of human evolution. In particular, the author argues that without the need for conscious human awareness or intent the development of computer technology is evolution's approach to extending human intellectual capabilities. It is suggested that advances in nanotechnology and computing are moving along an evolutionary path toward a merging of biology and technology that is commonly referred to as *Singularity*. While recent advances in nanotechnology and intelligent digital computing are still at a primitive level they are nevertheless indicative of an evolutionary trend that will have a profound impact on human capabilities, life style, welfare, and concerns as humanity progresses on an accelerating path towards *Singularity*.

Introduction

The purpose of this paper is to draw attention to the exponential rate at which technology is advancing and to suggest that trends in digital computing during the past 50 years as well as developments in nanotechnology during the past 25 years are part of an evolutionary path. According to economist Norman Poire (2011), after a gradual start new technologies typically experience rapid growth for a period of about 50 years.

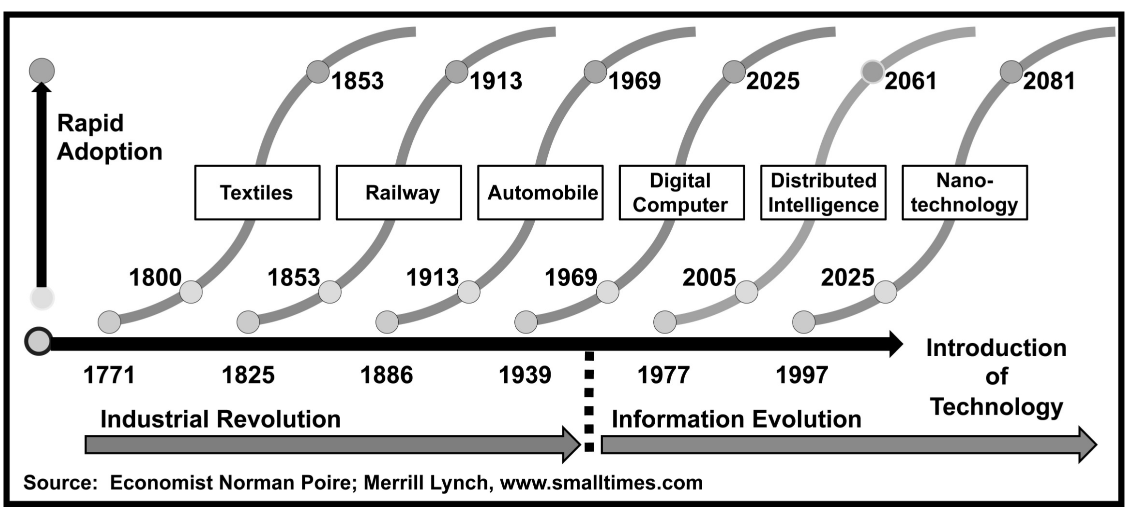

Figure 1: Technology innovation cycles (Source: Norman Poire – www.smalltimes.com)

Based on Poire's observation, as shown in Figure 1, we are nearing the end of the rapid development stage of digital computers and have just entered the rapid development stage of distributed intelligence. About the same time (i.e., 2025) that the rapid development stage of digital computing is expected to end the rapid development stage of nanotechnology is expected to start. It can be assumed with some certainty that the exponential rate of technological innovation is moving us along an evolutionary path that will require major adjustments in the way we have become accustomed to distinguish our human nature from technology.

The Human View of Technology

We human beings have always considered ourselves to be very different from anything that we have produced through the application of technology. Until recently the tools that we developed with our technological skills have been largely physical and in most cases mechanical in nature. Therefore, the distinction between what is human and what is the product of technological advances has been quite apparent and entirely logical. Human characteristics such as emotions, intuition, creativity, reproduction, and feelings are clearly not present in the products of technology.

So, how is it then possible for some of us to start talking about the merging of biology and technology? The tools that we developed in the past through our scientific and technical efforts were principally aimed at extending our physical capabilities such as the ability to travel with speed and comfort (e.g., by ship, rail, car, or air), to communicate without physical presence (e.g., by mail, telegraph, telephone, or computer), and to manufacture all kinds of products from the simplest utensils to very complex mechanical and electronic devices with great accuracy and efficiency. Yes, we also developed foods and drugs that are aimed at maintaining or restoring our biological performance. All of these scientific and technical endeavors are driven by our curiosity and innate intellectual capabilities.

At the same time, we have become very much aware of the benefits that can accrue from our intellectual capabilities. Efforts to exploit and improve these capabilities have been centered on education. Our formal education starts at the early age of five or six years and progresses through stages of increasing intensity and specialization for 12 to 20 years depending on aptitude and stamina. Yet we readily admit that we continue to learn in an informal manner through work experience and communication until the end of our lives. In other words, we have created for ourselves an environment in which our inherent biologically-based intellectual capabilities are progressively developed through formal and informal learning processes. This is an environment that is based on the principle that every human being has certain inherent intellectual capabilities that can be unleashed and enhanced only through the acquisition of knowledge by a progression of learning activities.

From this point of view the concept of *Singularity* is difficult for us humans to even comprehend, let alone accept. It suggests that human intellectual capabilities can be dramatically extended through implants that contain knowledge and information processing capabilities. In other words, a merging of biology and technology. However, we are beginning to see the very primitive beginnings of *Singularity* with artificial limbs that are connected to nerve fibers and the control of external devices by thought processes. Although these achievements are certainly at the very forefront of scientific and technological advances, they are nevertheless primitive when we consider what is required to be accomplished to achieve a more substantial merging of biology and technology.

Requirements of Singularity

Ray Kurzweil defines *Singularity* as "… *a future period during which the pace of technological change will be so rapid, its impact so deep, that human life will be irreversibly transformed*" (Kurzweil 2005, 7). This definition foreshadows the dawn of a period in human evolution when computation as well as the assembly and self-replication of devices is performed at the molecular level. Accordingly, *Singularity* is inextricably linked with nanotechnology and both are dependent on autonomous computation capabilities (Figure 2).

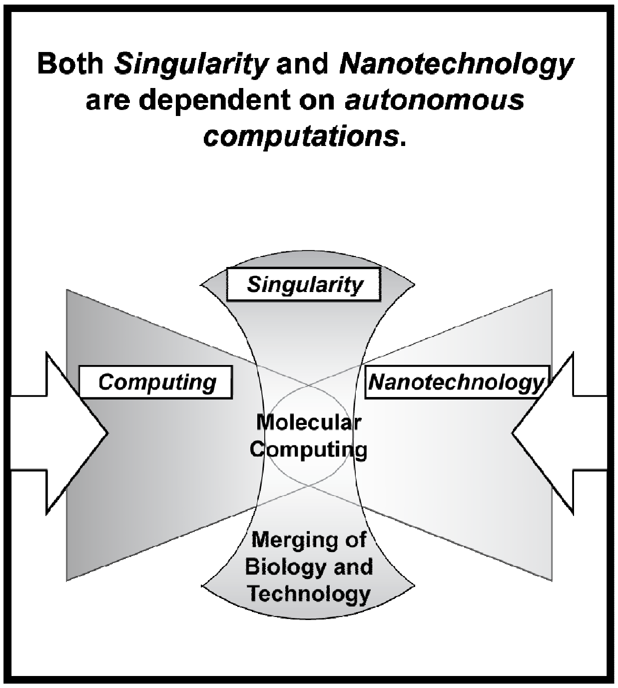

Figure 2: Nanotechnology and Computing are *Singularity drivers*

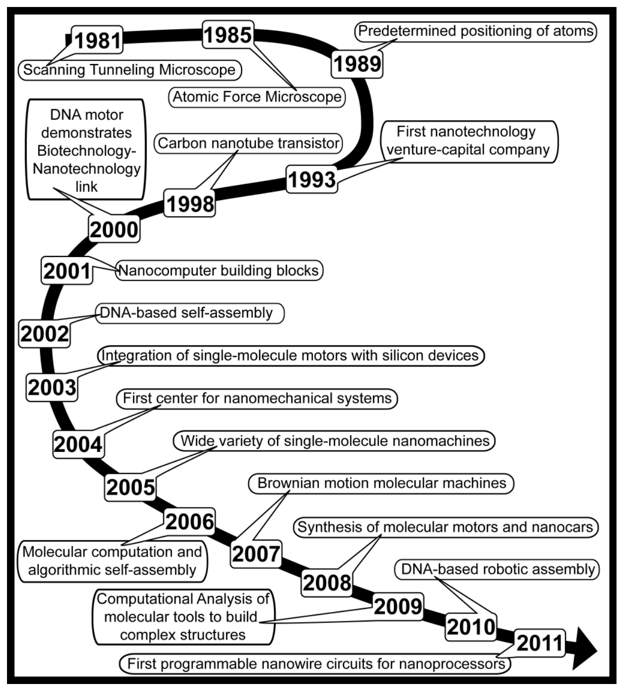

Figure 3: Historical nanotechnology milestones

Although the first mention of the feasibility of nano-scale operations was made by Nobel laureate Richard Feynman in a 1959 lecture (Feynman 1959), it was the writings of Eric Drexler and his colleague Chris Peterson at MIT in the 1980s that proposed the initial concepts for molecular nanotechnology (Drexler 1986, Drexler et al. 1991). From a brief historical perspective (Figure 3), with the invention of the Scanning Tunneling Microscope in 1981 and the Atomic Force Microscope in the mid-1980s it became possible to manipulate individual atoms (Jacoby 2000). In 2000, collaboration between Lucent Technologies, Bell Labs and Oxford University produced the first DNA motor (Lucent 2000). This was followed in quick succession by the first DNA computing devices (NY 2001), logic circuits made of carbon nanotubes (Humer 2001), and an individually addressable molecular-scale transistor (Bell 2001). A 2002 press release of the American Association for the Advancement of Science (AAAS) boldly announced that due to the increased rate of new discoveries nanoelectronics and nanocomputers, orders of magnitude faster than silicon-based digital computers, were likely to come to the industrial production stage years earlier than previously anticipated (AAAS 2002).

While these may be viewed as strong indications that the field of nanotechnology is advancing at a rapid rate, the ability to construct motors and computers at a molecular granularity does not in itself lead to the kind of merging of biology and technology that is envisioned by *Singularity*. A core component of the state of *Singularity* is superhuman intelligence made possible through the seamless augmentation of biological human intelligence with the knowledge and capabilities stored on non-biological, nano-scale devices. An example of such a device would be a chip implant containing information that is accessible to the brain through human thought and reasoning processes.

So, what is really required for a knowledge implant containing for example an entire language to be useful? The daunting task lies in the construction of the interface between the implant and the human brain. How and exactly where should the implant be connected to our nervous system, which consists of millions of neurons and billions of synapses? To answer those two questions with some degree of certainty we need to know a great deal about how the human brain works, what areas of the brain we need to interface with, and how the knowledge in the implant can be transferred into or made accessible to our brain. While we already know in general terms and in some cases in more specific terms how our brain functions, much more will need to be known to achieve even a modicum of *Singularity*. However, evolutionary trends that are suggesting that we are on the path to merging biology with technology are already discernable.

Research into surgical retina implants that is aimed at deciphering the coding of visual object recognition in the biological brain is still in its infancy (Poggio 2001, Humayun et al. 2000, Sung and Poggio 1998). More headway has been made with inner-ear cochlear implants because the human auditory-processing system is less complex than the visual-processing system. By studying the specific neuron types and synapses that are involved in the interpretation of auditory signals, Watts and his colleagues have been able to build a computer simulation of a significant portion of the human auditory-processing system (Watts 2003). The simulation models the transformations that take place during neural information processing rather than the individual neurons and synapses.

It is impossible to predict with any degree of accuracy how quickly or slowly progress will be made in scientific and technical fields such as nanotechnology that involve quantum leaps in knowledge and capabilities. The necessary discoveries are made by many individuals and research groups that depend on resources in the form of funding, facilities and equipment. The availability of these critical resources is in turn dependent on government policies and commercial interests. Distractions due to major natural disasters, economic recessions, wars, and unfavorable political agendas can at least temporarily significantly retard the rate of progress, while favorable circumstances can create an environment that accelerates progress.

Data, Information and Knowledge Immersion Trends

As we enter the Information Age the difference between the learning processes that we have had to rely upon in the past to apply and enhance our intellectual capabilities and the additional processes that will become available in the future are gradually revealing themselves. It is certainly not being suggested that the process of learning is something of the past that will gradually disappear as a formal activity, but rather that learning in an era of *Singularity* will be significantly different. Rather than building knowledge in our brain mostly through interaction with our external environment and formal instruction, we will increasingly augment these processes with knowledge immersion techniques.

Two prominent aspects of the Information Age are readily apparent, namely: global connectivity that allows us to communicate without concern for distance and cost; and, instant access to data and information. The concept of *presence* is being redefined in the Information Age. We have begun to see the gradual acceptance of a new concept of *presence* that does not require the physical relocation of persons. Major sporting events and entertainment shows are more conveniently viewed remotely on television from the home. Typically, in the case of sporting events, the quality of the televised presentation of the competition is greatly improved by technical enhancements such as instant replays and close-up shots of particularly skillful maneuvers, explanations and analyses by informed commentators, and short profile films of the best competitors.

At the same time we are inundated with data. When we use search engines to find some information on the Internet, we typically receive more links to potential information sources (i.e., hits) than we care to look at. We have learned from experience that many of the hits will be disappointing because they do not lead to the information that we are seeking. Soon after the terrorist attacks on the United States in September 2001, much evidence was found that several warnings of a planned attack were contained in the routinely collected intelligence data, but had been overlooked. The military are so inundated with sensor data from satellites, unmanned aerial vehicles, and land-based sources that they cannot possibly analyze in near-real time. These are all symptoms of a rapidly escalating data deluge problem.

The amount of data that is being collected by our global digital infrastructure far exceeds our human ability to interpret, analyze, draw conclusions, and act upon under even less than time-critical conditions. This is not a problem that occurs only under special circumstances, such as relief operations after a major national disaster. Rather, the data deluge problem is clearly becoming more pronounced. The reason is quite simple; - while the volume of data is increasing exponentially our human ability to interpret the data is increasing linearly. Clearly, if we continue to apply the same methods to this problem then we are destined to fall further and further behind.

The Beginnings of an Evolutionary Path

The initial societal drivers that led to electronic computation were the need for greater calculation speed, accurate numerical solutions, and analyzing large data sets such as astronomical charts and census data. Warfare and the need for navigational accuracy figured prominently in these initial drivers. Later it became apparent that the ability of computers to process large volumes of data was a very useful and potentially even more important capability. With the miniaturization of electronic components both the power and data storage capacity of computers has increased over the past two decades by factors of six and four every three years, respectively. Today, an electronic mass storage device (i.e., disk drive) with a storage capacity of two terabytes (i.e., two thousand billion bytes) can be purchased for less than $250 (US 2012) at a local retail store. The enormity of that data storage capability becomes clear when we consider that the millions of books in the US Library of Congress collection will require a data storage capacity of less than 20 terabytes.

During the later half of the 20th Century computation speed increased from the ENIAC's clock rate of 0.1 MHz in 1946 to 4,000 MHz for a typical laptop computer in 2012. Similarly, as shown in Figures 4 and 5, the density of a single computer chip increased more than a hundred thousand fold in a 15-year period from 5,000 transistors in 1974 (i.e., Intel 8080 chip) to over 700 million transistors in 2008 (i.e., Intel four core i7 chip).

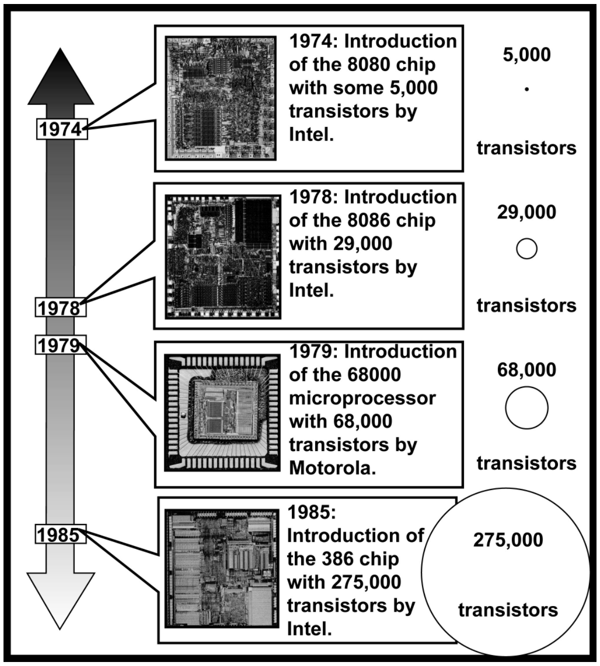

Figure 4: Computer chip density (1970-1990) (from 5,000 to 275,000 transistors)

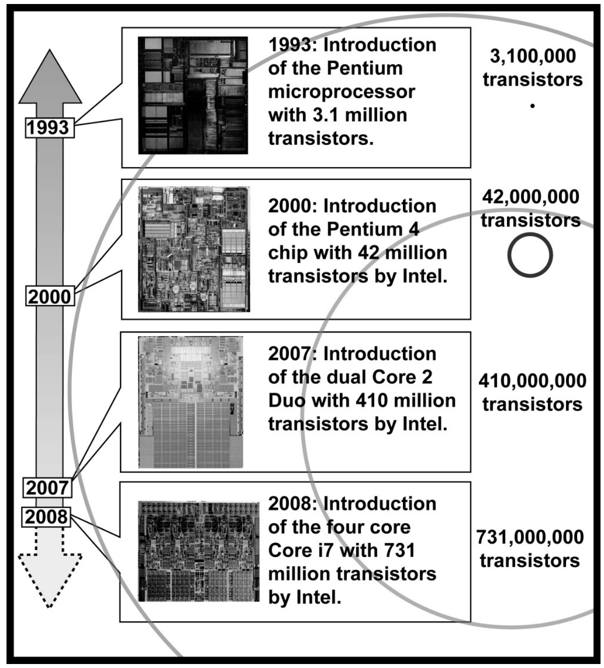

Figure 5: Computer chip density (1991-2008) (from 3.1 to 731 million transistors)

During the same period the principal utilization of computers has shifted from mathematical calculations to data processing and information management. In the commercial world the transformation of business practices and processes was more gradual but nonetheless significant with: automated tabulation of interest and depreciation rates in the 1960s; automated accounting and payroll record keeping and improved productivity with cost control software in the 1970s; functional integration and organizational restructuring in the 1980s; ordered archiving of data to facilitate productivity and marketing analysis with analytical on-line processing tools in the 1990s; and, increasing business intelligence applications in a global e-commerce environment in the 2000s. As global connectivity facilitated remote customer-vendor accessibility, the automated identification of market trends and customer preferences became a prerequisite for sustaining competitiveness and market share.

Clearly discernable in this historical sequence is the human desire to exploit the advances in technology with the objective of becoming more competitive through increased efficiency and the early identification of market and consumer trends. However, as the volume of available data increased to the point where it became overwhelming the focus shifted from data management to the automated extraction of information in preparation for predictive analysis and planning. In this we see a fairly rapid shift from the reliance on manual analysis techniques in the 1970s and 1980s to an increasing expectation that these tasks will be automated. In fact, the automation was not confined to the analysis process but soon encompassed the continuous collection and monitoring of the data so that market changes and trends could be detected in near real-time.

This evolution proceeded along several parallel paths as it created an increasing human reliance on computer-based communication and information management systems and capabilities. Two of these paths are particularly relevant to the theme of this paper. First, the manner in which the human user could access the computer changed significantly as the computing pervaded almost every aspect of human activity. Batch-processing gave way to remote access through interactive time-sharing of centralized computer facilities, only to be replaced by personal computers and then by ubiquitous wireless access to virtually unlimited computing capabilities (i.e., cloud computing) through global networks (i.e., Internet) with very small highly portable devices (e.g., smart phones).

Second, the need for more intelligent software became a predominant factor. With the increased need for the computer to automatically extract useful information from an overwhelming volume of data the importance of context was recognized (Figure 6). It became clear that for a computer to interpret data it requires an information structure that provides at least some level of context. This can be accomplished utilizing an ontology of objects with characteristics and a rich set of relationships to create a virtual version of real world situations and provide the context within which agent logic can automatically operate (Pohl 2004). The term ontology is loosely used to describe an information structure, rich in relationships that provides a virtual representation of some real world environment (e.g., the context of a problem situation such as the management of a transport corridor, the loading of a cargo ship, the coordination of a military theater, the design of a building, and so on). The elements of an ontology include objects and their characteristics, different kinds of relationships among objects, and the concept of inheritance (Figure 7).

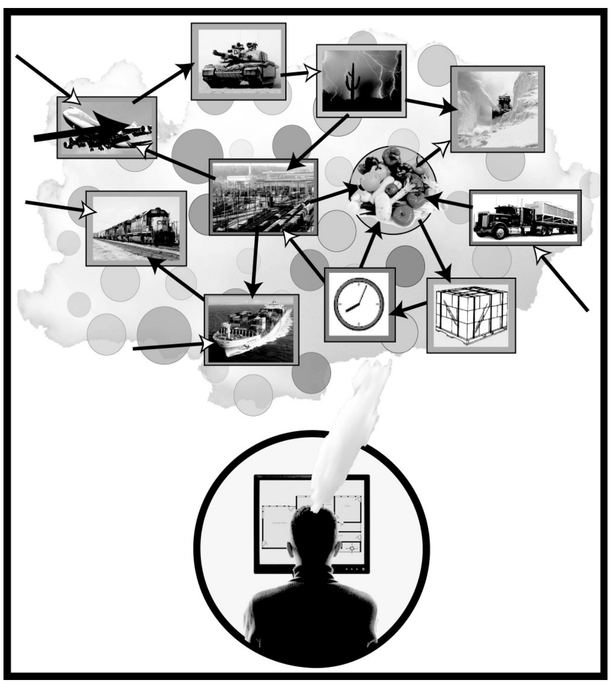

Figure 6: Virtual model of real world context

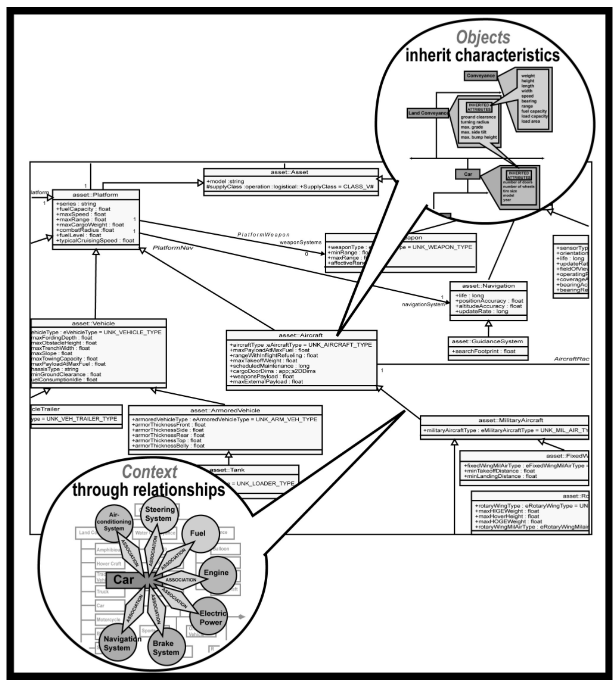

Figure 7: Machine readable ontology

The ability to construct a virtual software model of real-world context is of special significance and therefore warrants further discussion. As shown in Figure 7, the lines between the objects that are represented by boxes indicate different kinds of relationships that exist among those objects in the real-world. The ontology is constructed in a language (e.g., Unified Modeling Language (UML) or Web Ontology Language (OWL)) that allows these relationships to be automatically interpreted by software (Warner and Kleppe 1999, Hebeler et al. 2009). The expressiveness of the ontology is largely dependent on the granularity of the context model and the power of the analysis patterns that it incorporates (Fowler 1997). The context of a real-world situation can be modeled in terms of: time; location; physical environment such as climate, topography, and current weather conditions; identity; culture; activity; urgency; and, history. In this way the computer gains a level of understanding of the context within which the data should be interpreted. Arguably, this constitutes a significant advance in that it provides the means for elevating the computer from rote data-processing to information management in a collaborative partnership with the human user.

While still far distant from the concept of *Singularity*, the context provided by an ontology does open the door to a collaborative human-computer relationship at the semantic level. This is an essential requirement for the ability to interface for example a knowledge chip implant with human brain functions. The chip must interface not only physically to the appropriate neurons, but also semantically to enable the human brain to process and take advantage of the information stored on the chip. The complexity of this interface is almost beyond our human comprehension at the current state of technology.

By analogy we might consider the difficulties that are faced by national intelligence and homeland security agencies in listening in on millions of concurrent cell-phone conversations to identify dispersed terrorist planning activities and potentially imminent public security threats. Neural processing like global cell-phone communication is highly dynamic. Therefore, the interface between the implanted chip and the human brain must be adaptable to changing conditions both in the physical and semantic domains. From a physical point of view it is unlikely that a static interface will suffice. More likely the interface will need to be able to replicate part or all of its components as the need for new neural connections arises. This is the realm of nanotechnology with its three fundamental objectives: positioning of molecules in a predetermined order; self-replication of molecular systems; and, assembly of molecular components into devices (Drexler et al. 1991, 293-4). From a semantic point of view the interface must be able to detect changes in neural processing, evaluate the impact of those changes in respect to the type or intent of the implant, autonomously develop a plan for effectively adapting to the changed conditions, automatically implement the plan, and continuously monitor the effectiveness of the current interface environment.

The ability of the interface to perform these semantic functions will require a similar level of artificial intelligence at the molecular scale of computing that is currently emerging in digital computer software. What will take the place of ontologies and agents to provide the required intelligence in nanocomputers is not known at this time? Even though the objectives are similar, the approach for embedding intelligence in nano-scale components may be quite different. For example, the two-way interface between an implant and the human brain could utilize electric signals combined with chemical agents to link seamlessly into the electric impulses and biochemical reactions that govern neural behavior. Under these circumstances the implant side of the interface will be required to not only compute in real-time the amount and timing of the electric impulses and chemical agents, but also control their release with nano-scale precision. Such an electro-chemical emulation of neural synaptic functions is of course very different from current software intelligence approaches. Nevertheless, it may be argued on a conceptual basis that advances in intelligent software on digital computers are at the very beginning of an evolutionary path toward achieving the kind of intelligence that will be required at the molecular level for knowledge chip implants.

Conclusion

Although there is already an emerging body of knowledge, some encouraging research findings, and an increasing volume of publications in the field of nanotechnology, it is still difficult not to be skeptical about the concept of *Singularity*. Our human vision of the future is limited by the biological basis of our intelligence and cognitive processes. We acquire most of our knowledge by interaction with our physical environment and even though we have the ability to build on this knowledge through reasoning, we remain *situated* in our environment (Brooks 1990, 3-7). In other words, we are immersed in our environment to the extent that it is almost impossible for us to reason about anything that is not in some way related to our past or current experience, or for us to come to conclusions that are not at least partially verifiable within our environment.

At the same time we are curious about the future and drawn to speculation for two largely self-serving reasons. First, we tend to be fearful of the future because we recognize that our past experience may not prepare us for a different set of future conditions. Therefore, we try to formulate contingency plans for alternative future conditions in an effort to protect ourselves. Interestingly enough in most cases our speculations about future conditions tend to be significantly off the mark. Second, we are competitive in nature and try to gain an advantage over others by preparing for possible events or changes in our environment. This mindset is particularly prevalent in the realm of business and politics, where the phrase *"… looking out of the box"* has a decidedly positive connotation.

The advocates of *Singularity* point to historical trends and in particular the exponential rate of technological advances to counter the intrinsic human skepticism toward technology-driven changes that are far beyond the current boundaries of human vision (Kurzweil 2005, Mulhall 2002). For example, who would have believed 100 years ago, in 1912, that the following technological advances will be possible?

- Moving pictures of events around the world (i.e., television), in near real-time, in every home.
- Instantaneous, wireless global communication (voice and data) on a small hand-held device (i.e. smart phone) that also serves as a camera, navigation device, and computer.
- Portable computing devices that can store trillions of words and execute billions of instructions per second.
- Surface and air transportation at high speed for everyone.
- The human Genome deciphered.
- A human landing on the Moon and an international manned space station.

Similarly, it should be plausible in 2012 that the following technological capabilities will be achieved during the next 100 years:

- Nano-scale devices that can travel in our bloodstream and cleanse our arteries of life threatening deposits.
- Implants that augment human memory and facilitate thought control of external devices.
- Self-replicating robots with touch sensitivity, vision, hearing, and intelligence that rival humans.

- Replacement of agriculture with synthesized food production.
- Tunnel transportation between major cities at supersonic speed.
- Carbon nanotubes from Earth to the geosynchronous orbit for access to space homes.

While it is almost certain that all of these advances and more will be achieved by 2112, a more precise estimate of the advent of any one of these capabilities is likely to be misleading. As mentioned in an earlier section of this paper, there are a host of social and environmental factors and events that could impact the rate of change. Apart from major wars and epidemics there is always the possibility that we cannot prevent an asteroid from colliding with Earth, wiping out a significant percentage of animal and plant life, infrastructure, and human population. Research and innovation could be stalled for decades as we rebuild our environment.

References

AAAS (2002); 'New World of Nanoelectronics May Arrive in the Near Future, AAAS Speakers Say'; American Association for the Advancement of Science Press Release, 14 February: on-line at www.eurekalert.org/pub_releases/2002-02/aaft-nwo020602.php

Bell (2001); 'Bell Labs Scientists Build the World's Smallest Transistor, Paving the Way for Nanoelectronics'; Bell Labs Press Release, 8 November.

Bell G. (1990); 'The Human Genome: An Introduction'; in Bell G. and T. Marr (eds.) Computers and DNA, Proceedings Volume VII, Santa Fee Institute, Studies in the Sciences of Complexity, Advanced Book Program, Redwood City, California (pp. 3-12).

Brooks R. (1990); 'Elephants Don't Play Chess'; in Maes P. (ed.) Designing Autonomous Agents, MIT/Elsevier, Cambridge, Massachusetts (pp. 3-7).

DeLisi C. (1990); 'Computation and the Human Genome Project: An Historical Perspective'; in Bell G. and T. Marr (eds.) Computers and DNA, Proceedings Volume VII, Santa Fee Institute, Studies in the Sciences of Complexity, Advanced Book Program, Redwood City, California (pp. 13-19).

Doolittle R. (1990); 'What We Have Learned and Will Learn from Sequence Databases'; in Bell G. and T. Marr (eds.) Computers and DNA, Proceedings Volume VII, Santa Fee Institute, Studies in the Sciences of Complexity, Advanced Book Program, Redwood City, California (pp. 21-31).

Drexler K. (1986); 'Engines of Creation: The Coming Era of Nanotechnology'; Doubleday, New York, New York.

Drexler K., C Peterson and G. Pergamit (1991); 'Unbounding the Future: The Nanotechnology Revolution'; Quill William Morrow, New York, New York.

Feynman R. (1959); 'There's Pleanty of Room at the Bottom: An Invitation to Enter a New Field of Physics'; American Physical Society lecture, California Institute of Technology (Cal Tech), 29 December: on-line at www.physics.umn.edu/groups/mmc/personnel/pete/There....html.

Fowler M. (1997); 'Analysis Patterns: Reusable Object Models'; Addison-Wesley, Boston, Massachusetts.

Hebeler J., M. Fisher, R.Blace and A. Perez-Lopez (2009); 'Semantic Web Programming'; Wiley, Indianapolis, Indiana.

Humayun M., ?? (2000); 'Human Neural Retinal Transplantation'; Investigative Ophthalmology and Visual Science, 41(10), September (pp. 3100-6).

Humer C. (2001); 'IBM Milestone Could Lead to Smaller Chips'; Los Angeles Times, 27 August (pp. C2).

Jacoby M. (2000); 'New Tools for Tiny Jobs'; Chemical & Engineering News, 16 October: on-line at www.pubs.acs.org/cen/nanotechnology/7842/7842instrumentation.html, 15 August 2001.

Kurzweil R. (2005); 'The Singularity Is Near'; Viking (Penguin Group), New York, New York.

Lucent (2000); 'Researchers from Lucent Technologies' Bell Labs and University of Oxford Create First DNA Motors'; Lucent Technologies Press Release, 9 August.

Mulhall D. (2002); 'Our Molecular Future: How Nanotechnology, Robotics, Genetics, and Artificial Intelligence will Transform Our World'; Prometheus Books, Amherst, New York.

NY (2001); 'Scientists Build Tiny Computer Using DNA Molecules'; New York Times on the Web, 27 November.

Poggio (2001); Information Science and Technology Colloquium Series; 23 May: on-line at http://isandtcolloq.gsfc.nasa.gov/spring2001/speaker/poggio.html.

Pohl J. (2004); 'Interoperability and the Need for Intelligent Software'; Proceedings Office of Naval Research (ONR) Conference on Collaborative Decision-Support Systems, Quantico, Virginia, 8-9 September (pp. 1-26).

Poire N. (2011); 'The Great Transformation of 2021'; Lulu (on-line at www.smalltimes.com).

Rieffel E. and W. Polak (2011); 'Quantum Computing: A Gentle Introduction'; MIT Press, Cambridge, Massachusetts.

Sung K. and T Poggio (1998); 'Example-Based Learning for View-Based Human Face Detection'; IEEE Transactions on Pattern Analysis and Machine Intelligence, 20(1) (pp. 39-51): on-line at http://portal.acm.org/citation.cfm?id=275345&dl=ACM&coll=GUIDE.

Warner J. and A. Kleppe (1999); 'The Object Constraint language: Precise Modeling with UML'; Addison-Wesley, Boston, Massachusetts.

Watts L. (2003); 'Visualizing Complexity in the Brain'; in Fogel D. and C. Robinson (eds.) Computational Intelligence: The Experts Speak, IEEE Press/Wiley, Hoboken, New Jersey (pp. 45-56): on-line at http://www.lloydwatts.com/wcci.pdf.