Converging Technologies for Enhancing Human Performance: Science and Business Perspectives

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Abstract: Our goal is to provide a rough sketch of some of the possible implications (science and business) of *converging technologies for enhancing human performance* (Roco and Bainbridge, 2002). Converging technologies refers both to the simultaneous and rapid progress across seemingly separate areas of technology (e.g., nano-bio-info-cogno - NBIC) as well as to the increased inter-connectedness of these seemingly separate disciplines (perhaps leading to an ultimate unification as connections grow). Enhancing human performance refers to our individual (person) and collective (population) ability to achieve goals. The rapid, inter-connected progress characteristic of converging technologies results in better technological capabilities – a capabilities infrastructure – that can be broadly applied for many different purposes. These applications hold the promise to make people (individuals) healthier, wealthier, and wiser as well as to make organizations (collectives) more responsive (to customers), adaptive (improvement-oriented), and resilient (accelerating the rate of improvements in spite of the need for repeated transformational change). We will argue that in a very fundamental sense, ultimately it is information that matters to science and people that matter to business.

Section I: Introduction: Motivation and Goals

About 6% of the estimated hundred billion people who have ever lived are alive today, and given the exponential growth rate of world population, this percentage is increasing each year (Haub, 2002). Most people alive today live longer, have more possessions, and have greater access to information resources than at any previous point in history. Some would say that human performance, or our ability to achieve goals both individually and collectively, has been enhanced to all time highs. Others see many people who are being left out or see these advances as part of a vicious cycle of solving problems only to create new more complex and urgent problems, such as terrorism, pandemics, weapons of mass destruction, and global warming (Rischard, 2002; Glenn & Gordon, 2002). Meanwhile as the debate on the meaning of "real progress" rages on, we see that in the U.S., the Census Bureau (Barron, 2001) is reporting that life expectancy has risen from seventy years to seventy-seven years in just the past thirty years (ibid, pg. 73), median family incomes in current dollars have doubled in just the past twenty years (ibid, pg. 437), and internet usage (hours per person per year) has been nearly doubling each year since the middle of the last decade (ibid, pg. 704).

These trends in life expectancy, material wealth, and information access are part of a much longer progression going back some two million years. Over this time span, as the population of humans has grown providing the potential for collective performance enhancements, the performance potential of individuals has been enhanced through *biological and cultural co-evolution*. Biological evolution has changed our bodies and brains, from early *homo habilis* to *homo erectus* to today's *homo sapiens*. Cultural evolution has changed our social and physical environment, from simple stone tools empowering small bands of hunter-gathers to today's global communication, transportation, and distribution networks empowering many millions of knowledge workers in many thousands of interconnected businesses that form the global economy. It is truly amazing what a teenager or college student with a computer can accomplish in the world these days. Certainly global impact is not out of the question, as the story of Shawn Fanning unleashing the Napster genie suggests. Billion dollar media conglomerates and governments were needed to push that genie back just a little.

The term co-evolution originally referred to one organism evolving in tandem with another organism, such as butterflies and flowering plants (Ehrlich & Raven, 1964). Today, co-evolution refers more broadly to two or more *complex adaptive systems* (Alexrod and Cohen, 2000) that are ratcheting up their capabilities in tandem, a kind of cooperative arms race. Over a two million year period, the co-evolution of human biology (body and brain, genetics, nature) and human culture (language and artifacts, environment, nuture) have enhanced human performance to the point that we are even capable of sending some members of our species off the planet and into space.

The relative rates of change of two systems locked in an intimate co-evolutionary dance can vary greatly, as described by Deacon (2002) in his discussion of brain-language co-evolution:

> "Brain evolution takes place on a geological time scale. Even slight changes probably take hundreds of thousands of years to become widely represented in a species, and the basic architecture of the brains has been remarkably conserved since the origins of vertebrates. Languages, on the other hand, can become unrecognizably different within a few thousand years. Language evolution is probably thousands of times more rapid than brain evolution."

In the past few centuries especially in the U.S. and Europe, science, technology, and business seem locked in a three-way, co-evolutionary spiral that is accelerating and enhancing human performance. However, even as our individual and collective human performance has been enhanced, new problems are created and old problems aggravated (Wolfensohn, 2002; Stelle, 2002; Dahlman, 1999).

The motivation for this paper lies in the recognition of both the promise and the peril of accelerating progress, and the desire to better understand accelerating progress from the perspectives of science and business. Recently, the National Science Foundation and the Department of Commerce have co-sponsored a study of the ways converging technologies (Nanotechnology, Biotechnology, Information technology, and Cognitive technology - NBIC) may enhance human performance in the coming decades (Roco & Bainbridge, 2002; Roco, 2002). Converging technologies refers to a type of progress that is characterized by rapid advances across multiple areas of technology, accelerated by cross fertilization as the advances in one area speed progress in others (a type of inter-disciplinary co-evolution). The rapid, multi-front progress characteristic of converging technologies results in better technological capabilities which are faster and cheaper, and can be broadly applied for many different purposes.

In this paper, we explore applications of converging technologies for enhancing human performance, with the potential of making people healthier, wealthier, and wiser as well as making businesses more responsive, resilient, and adaptive. First, one of the key insights of some early pioneers focused on augmenting human performance will be discussed. Second, speculative frameworks for a science of convergence will be presented. Third, the business implications are considered, before fourth, concluding with a few final remarks on the importance of defining the human sciences in this endeavor. Our goal in this paper is to be provocative and stimulate others to provide improved frameworks for the science and business implications of converging technologies for enhancing human performance. We also hope that more organizations will invest in creating inter-disciplinary teams to develop common languages that span seemingly separate disciplines – this will improve the probability that significant critical interactions will not be overlooked (hazards) as well as paving the way for finding new connections (convergence opportunities).

Section II: Pioneers

The idea of enhancing human performance with technology augmentations stretches back to the very origins of our human-like ancestors. The ability to use an increasing variety of tools is a defining characteristic of *homo habilis* (Wells, 1949).   Nevertheless, only since the dawn of modern electronic information technologies around the middle of the last century has the notion of augmenting human thinking with information processing machines begun to be translated from the realm of science fiction into the realm of realistic visions of human-machine symbiosis.   Pioneers such as Vannevar Bush (1945) in "As We May Think" and J.C.R. Licklider (1960) in "Man-Computer Symbiosis" inspired many to think about the role information technology could play in accelerating scientific progress by empowering people to access, process, and store information more rapidly and flexibly. Vannevar Bush wrote about the problem that researchers face in staying abreast of advancements. Bush saw researchers using outdated methods. Significant information connections could become lost for a generation or more.

> "There is a growing mountain of research. But there is increased evidence that we are being bogged down today as specialization extends. The investigator is staggered by the findings and conclusions of thousands of other workers -- conclusions which he cannot find time to grasp, much less to remember, as they appear. Yet specialization becomes increasingly necessary for progress, and the effort to bridge between disciplines is correspondingly superficial.
>
> Professionally our methods of transmitting and reviewing the results of research are generations old and by now are totally inadequate for their purpose. If the aggregate time spent in writing scholarly works and in reading them could be evaluated, the ratio between these amounts of time might well be startling. Those who conscientiously attempt to keep abreast of current thought, even in restricted fields, by close and continuous reading might well shy away from an examination calculated to show how much of the previous month's efforts could be produced on call. Mendel's concept of the laws of genetics was lost to the world for a generation because his publication did not reach the few who were capable of grasping and extending it; and this sort of catastrophe is undoubtedly being repeated all about us, as truly significant attainments become lost in the mass of the inconsequential."

Later in this paper, Bush describes his proposed solution, Memex, Memex was conceived of as a highly instrumented desk. Memex could capture information and store it on microfiche. When viewing information, a lever could be used to control the rate at which information scrolled by the researcher.

While in the Navy, serving in the Phillipines, the second author happened to read Bush's article, and the seed of an idea was planted. Years later, as a radar technician he had seen how information could be displayed on a screen. He began to envision people sitting in front of cathode-ray-tube (CRT) displays, "flying around like aircraft" in an information space where they could formulate and portray their concepts in ways that could better harness sensory, perceptual and cognitive capabilities heretofore gone untapped. Then finally, people could communicate and communally organize their ideas with incredible speed and flexibility. This epiphany ultimately led to a characterization of the technical information problem (Bourne and Engelbart, 1958), a proposed framework for augmenting human intellect (Engelbart, 1962), and several years later a first public demonstration of some of those capabilities, in what has been referred to as the "Mother of all demos" (Engelbart and English, 1968). These ideas have continued to develop and now emphasize the importance of evolving improved human-tool capabilities infrastructures in organizations and society to address complex, urgent problems (See Appendix I).

Many people realized that human evolution was driven by adaptation of people to their environment. However, many of these people had not yet fully appreciated that the environment had gone through a very fundamental shift. The key insight of the pioneers was to understand that the first stage of human evolution was about nourishing (and protecting) the body in a natural environment, but now the second stage of human evolution was about nourishing the mind in an information-rich, human-made environment. Different environments lead to different goals, and selection pressures for different capabilities. In short, the pioneers realized that beyond people adapting to a changed environment, people were in fact (admittedly in the early stages) beginning to co-evolve with an information-enriched, human-made environment.

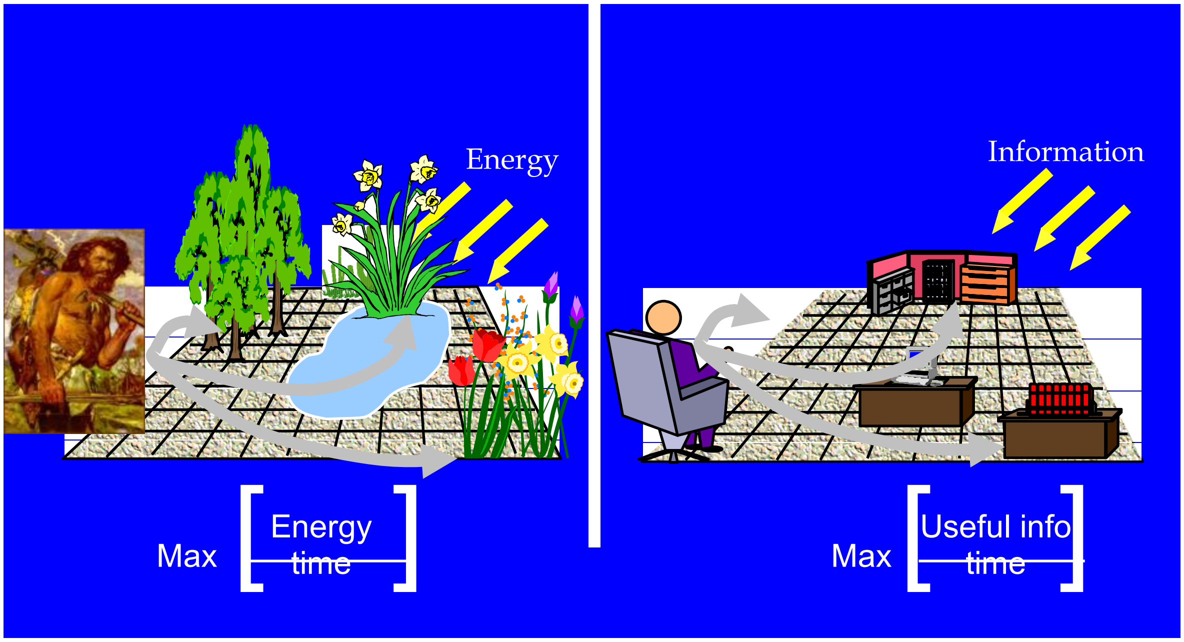


Figure 1: Humans as informavore (Miller, 1983) and information foraging (Pirolli & Card, 1999). Illustration (Pirolli, 2001).

Some might argue that this environmental shift really moved into high gear nearly 5500 years ago when the first large-scale human settlements were formed (Johnson, 2001):

> "Cities bring minds together and put them into coherent slots. Cobblers gather near other cobblers, and button makers near other button makers. Ideas and goods flow readily within these clusters, leading to productive cross-pollination, ensuring that good ideas don't die out in rural isolation. The power unleashed by this data storage is evident in the earliest large-scale human settlements, located on the Sumerian coast and the Indus Valley, which date back to 3500 B.C. By some accounts, grain cultivation, the plow, the potters' wheel, the sailboat, the draw loom, copper metallurgy, abstract mathematics, exact astronomical observation, the calendar – all of these inventions appeared within centuries of the original urban populations."

Although written records can be found as early as 7000 years ago, throughout most of human history information storage has been concentrated primarily in people, that is to say in large-scale human settlements. As the world population has grown, so has the information-richness of our environment (Museum National, 2001). In essence, population growth and information growth are locked in a positive feedback loop, and hence co-evolving. This tautologically true because people are information-rich, so the more people the more information. For example, information about fighting disease leads to more people surviving, and so often the right high-quality information leads to more people surviving, which in turn leads to more information, because people are information-rich. Information about what leads to survival and what leads to death, tends to be the kind of high-quality information that people pay attention to and furthermore actively seek out and teach to their children (who in turn respond skeptically until they have children of their own).

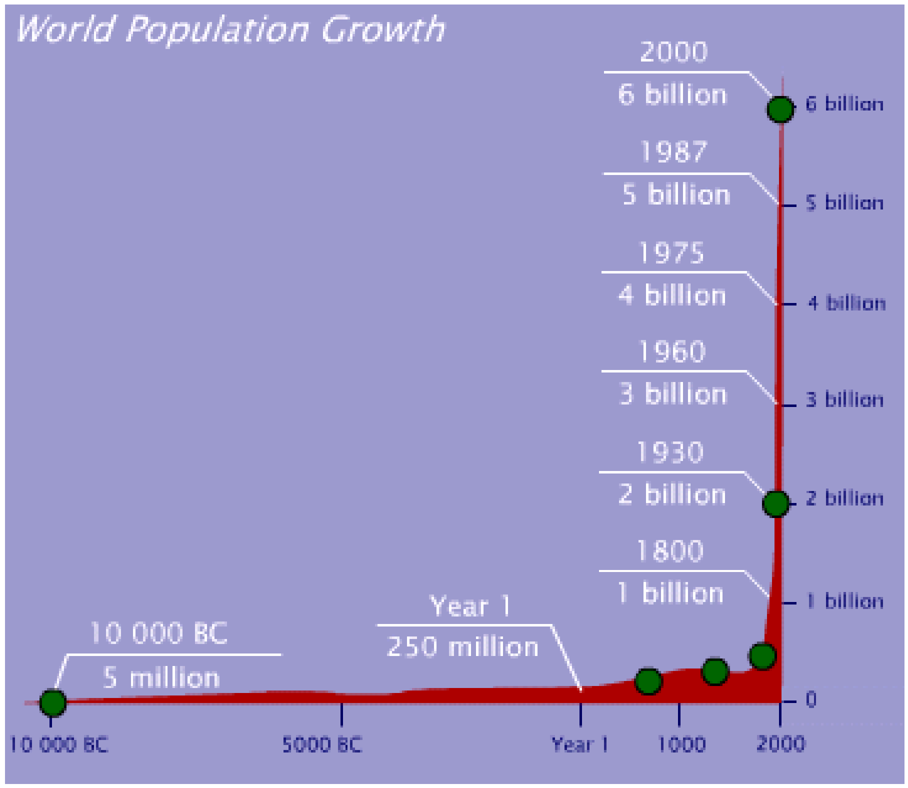
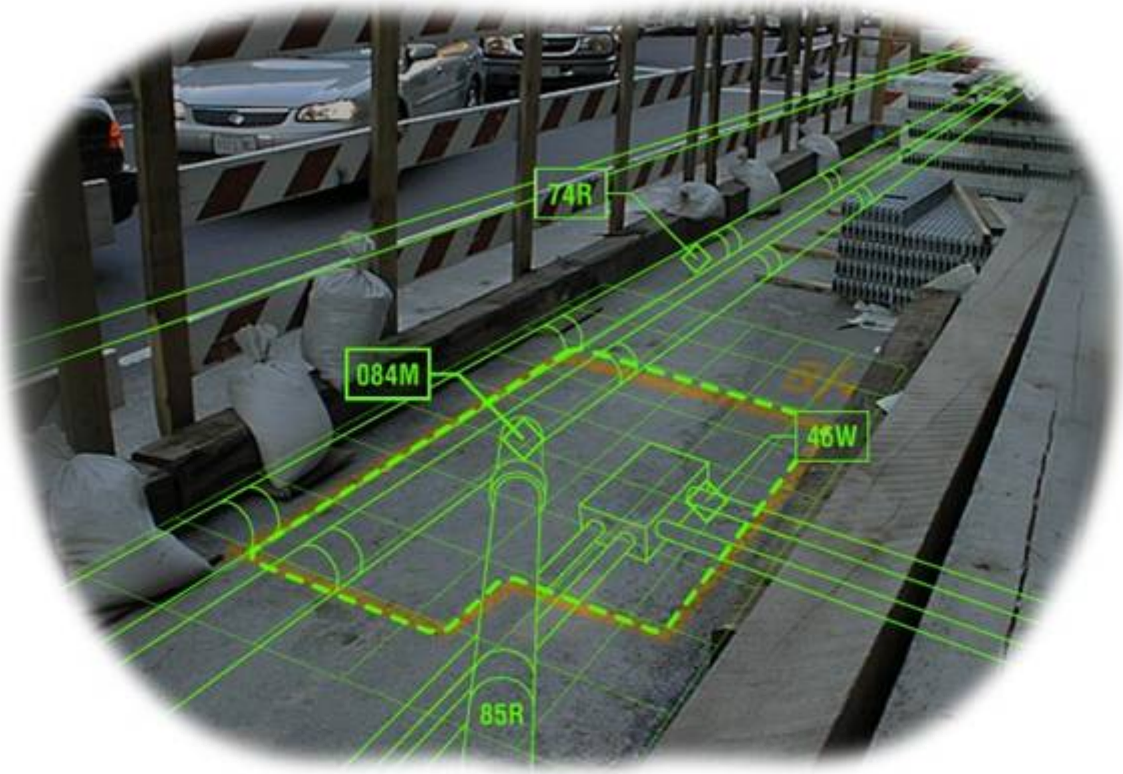


Figure 2: World population growth. From Musée de l'Homme, Muséum National d'Histoire Naturelle, Paris, France.

The growth of the human population and available information in the environment has grown hand-in-hand, specifically including key transitions (good ideas) brought on by the rise of agriculture, colonial expansion and *laissez faire* economics, scientific method, industrialization and democratic political reforms, universal education, improved healthcare, global transportation and global communication networks, as well as rapidly improving information technologies. One can ask, "What are possible next steps in the evolution of even more information-rich environments for people?" WorldBoard (Spohrer, 1999; see Figure 3) is one such vision, for providing contextual learning via a planetary augmented reality system that helps "put information in its place." There are many other ideas about next steps (Rheingold, 2002).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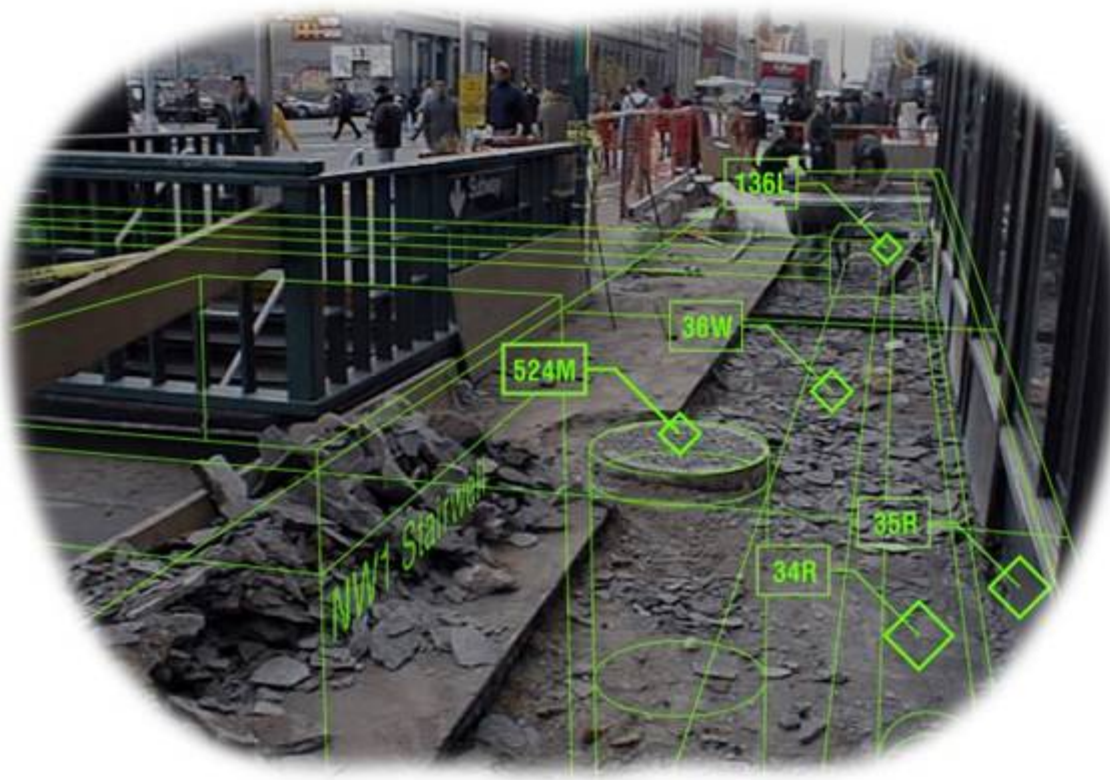
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Figure 3: WorldBoard, a vision of a planetary augmented reality system. Artwork by Ian Bruce (1998).

In sum, pioneers such as Bush and Licklider saw that people were adapting to, and in the early stages of co-evolving with, an increasingly information-rich, human-made environment. They also realized that advanced information technologies would both accelerate the co-evolution and ultimately lead to a human-machine symbiosis, both individually (person) and collectively (organization or business), further accelerating the storing, processing, and replication of information.

Section III: The Science of Nano-Bio-Cogno-Socio-Techno (NBCST) Convergence

Converging technologies is the term we use to describe a kind of co-evolutionary progress, wherein progress in one area accelerates progress in multiple other areas. The scientific goal underlying the study of converging technologies is very ambitious, and may not be achieved for many decades. Nevertheless, the study of converging technologies seems to present an opportunity *to unify scientific models across a range of separate disciplines into a single model*. As we will see, the unification opportunity presents itself, if and only if the models in separate disciplines can all be recast in terms of information processing for co-evolving complex adaptive systems that must store (encode), process, and replicate information. Others have suggested similar unifications (Watts, 2003; Wolfram, 2002; Wright, 2002; Laszlo, 1996). A brief review of the scientific method will help clarify the notion of unifying scientific models across a range of separate disciplines.

The scientific method has been described as a five step process: observation, speculation, prediction, experimentation, and argumentation (Holton 1973, Crump 2001; Gallambos 2000). *Observations* of the world are recorded as data. Today this data is uniformly stored, processed, and shared as bits of information inside computers. *Speculations* give rise to theories or models that must describe and ultimately explain the data. People create and understand the models, which are often based on assumptions that are combined with certain knowns and extended by methods of logic. These models constitute the central knowledge shared by members of the scientific community within a specific discipline. *Predictions* based on the models posit future data that might someday be observed under proper conditions. *Experimentation* is then used to confirm the predictions, thereby eliminating models that do not make accurate predictions or cannot make the full range of predictions of a more general model. The technologies and methodologies that members of the scientific community use to create favorable conditions for gathering experimental data constitute another key body of knowledge shared by members of the scientific community within a specific discipline. Often these tools and techniques lead to inventions that harness science for practical purposes, and commercial ends. Finally, *argumentation* (favoring simplicity, Occam's Razor) is used to discard overly complex or inelegant models when there exist multiple models that all agree with experimental results or simply remain beyond the sensitivity of current measurement technologies. Additionally, if two or more separate models can be replaced by a single model, then unification is said to have occurred. For example, Maxwell's equations unified electricity and magnetism in terms of electromagnetism. Efforts to create a unified field theory are an attempt to replace what once were multiple separate models with one single, overall model (set of equations). Unifying science across a range of separate disciplines can be accomplished both by shared models across the disciplines as well as shared technologies and methods for experimentation.

The scientific study of converging technologies, which again is a special type of co-evolutionary progress driven by inter-disciplinary cross pollination, suggests that we ask the following question: Can we understand and control to suit our purposes the different mechanisms for storing (encoding), processing, and replicating information across multiple systems? Currently, the multiple systems are the province of separate scientific disciplines, with some cross disciplinary interconnects. The two primary systems are the natural systems and the human-made systems, and the five secondary systems are the physical, living, cognitive, social, and technological systems (Laszlo, 1996):

Natural Systems: The natural environment that people exist in

Information in Physical Systems: Matter and energy from the sub-atomic to the universe.

Scientific Disciplines: Physics, Astrophysics, Nanotechnology, etc.

Information in Living Systems: From the molecular basis of life to population dynamics in ecosystems (relating living to physical systems).

Scientific Disciplines: Biology, Chemistry, Ethology, Embryology, etc.

Information in Cognitive Systems: From neuron to brain to knowledge of the natural world and the human-made world.

Scientific Disciplines: Cognitive Science, Psychology, Neuophysiology, Child Development, etc.

Human-Made Systems: The human-made or cultural environment that people exist in.

Information in Social Systems: From two people to family groups to organizations to civilizations, our languages, economies, and laws.

Scientific Disciplines: Sociology, Ethnology, Linguistics, Economics, Political Science, Organizational Behavior, etc.

Information in Technology Systems: From stone tools to modern information technology, the artifacts we surround ourselves with.

Scientific Disciplines: Technology Design Science, Human Computer Interactions, Human Factors, Bionics, etc.

When we refer to converging technologies in this paper, we are specifically referring to nano-bio-cogno-socio-techno (NBCST) convergence, or simply convergence (see Table 1).   NBCST is a suggested reformulation of NBIC (Roco and Bainbridge, 2002). Convergence is related to a systems view, and a systems view has been advocated by many (Miller, 1978; Laszlo, 1996; Alexrod & Cohen, 2001; Johnson, 2001). A systems view invites us to perform a thought experiment concerning the limits of the scientific method.   The thought experiment asks about the feasibility of acquiring all data, all models, and all capabilities, and project forward as some writers have suggested to the extremely controversial notion of the end of science (Horgan, 1999) or project backwards to determine what portion of all the data is available today or likely to be available over the coming decades (Burke, 2001). A time machine would settle the debate in this kind of thought experiment. We will return to this thought experiment in the concluding remarks section.

	System	**Store**	**Process**	**Replicate**
Nano	Matter (Nature)	Atoms & Molecules	Universe to Atoms	Galactic, Stellar, Planet

				Evolution
Bio	Life (Nature)	DNA	Cells to Ecosystems	Evolution
Cogno	Thought (Nature/Human)	Brains	Neural Nets	Evolution - Culture
Socio	Culture (Human)	People (special. role, commit.)	Organizations	Evolution - Culture
Techno	Technology (Human)	Bits, Tools, and Artifacts	Computers	Design-Factories

Table 1: A *unified information systems framework* as the basis of a unified view of science: Nano-bio-cogno-socio-techno (NBCST) convergence in terms of the five key information storage, processing, and replicating systems. Each of these is an evolving complex adaptive systems – a system with a well-defined history that we only have partial visibility onto.

Convergence spans multiple systems capable of information storage, processing, and replication. Table 1 summarizes five such systems, two of which correspond primarily to natural processes (nano-bio), two of which correspond to primarily human-made processes (socio-techno), and one that connects the two with blended natural and human-made processes (cogno). As a rough sketch, the description of the five systems in Table 1 suggests a unified way to view the five systems as information storage, processing, and replicating systems. However, much work remains to be done to firm up these notions and make them rigorous. Ultimately, one must show that the laws governing information storage, processing, and replication are the most general laws in the universe, superceding or fully encompassing the current formulation of many of natural laws. We term this the *unified information systems framework* of science. The examples below provide some grist for this effort.

The first example is one that begins with the assumption that a type of interdisciplinary cross-pollination is already accelerating and being accelerated by a unified information system framework view of science. This is just a long way of saying that different scientific disciplines are getting better at leveraging each others' results because new information allows connecting the dots between systems previously studied separately. The information about DNA is being connected to the information about brain development, which is being connected to information about human behavior, which is being connected to information about animal behavior in other species. For example, the story of FOXP2 gene illustrates this for the bio-cogno-socio area, connecting observations across the levels of DNA, brains, species, and populations (Walton, 2002). The story begins with the observation that some members of a family in Scotland were afflicted with slurred speech, while other members of the same family were not. Molecular biologists from London took DNA samples from those with the slurred speech and those with normal speech in the family, and isolated the genetic difference to genes they labeled the FOXP2 genes. Meanwhile, independently, in Cambridge, embryologists studying genes that influence brain development, had identified the same gene location as being connected to influencing the development of the brain associated with controlling the muscles of speech articulators. Furthermore, in Germany researchers comparing early human DNA to modern DNA had located the same region as one area of genetic difference. Other researchers studying primate and human differences had identified the same area as significant. Many predict that the next decade will see many breakthroughs connecting genetics to human behavior (Ridley, 2003).

The deeper our understanding of information storage, processing, and replication across these systems the more interdisciplinary cross-fertilization we can expect to see. Adopting this unified information systems framework view, many future studies present themselves as well. For example, it would be interesting to look at the relative abundance of skills (as defined by occupation types perhaps) in the human population throughout human history, and relate them to the physical characteristics of the Earth where human population exists (terrain, weather, seashore populations, mountain populations, etc.) as well as to level of sophistication of technology. One might expect to see the rise in sophisticated technology as leading to a decoupling of skills from geography over time. Of course, many existing studies that examine political, economic, linguistic, and organizational behavior interactions with geography, technology, and other factors can be leveraged to make this notion of an information framework as the basis of a unified model of all sciences more rigorous.

Nevertheless, a unified information systems framework must be more than just a simple causal connection between levels, such as DNA leading to brains leading to behavior. As important as these causal connections are, and they are *very* important, causal connections are not enough to truly understand the short term (developmental) and long-term (evolutionary) histories of complex adaptive systems. As Watts (2003, pg. 245) explains:

> "History… has a tendency to ignore the things that *might* have happened but did not. Obviously, what actually happened is more relevant to our current circumstances than what didn't. But we have an additional predisposition to assume that the actual outcome was somehow *preferred* over all other possibilities, and this is where our perceptions of the world can misconstrue arbitrariness for order. From a scientific point of view, therefore, if we want to understand what might happen in the future, it is critical to consider not only what did happen but also what *could have* happened."

Complex adaptive systems are complex. Sometimes small things get amplified all out of proportion – like rolling a snowball downhill, some ideas rapidly gain size and strength. Sometimes big things get rapidly dissipated to nothing – like rolling a boulder uphill, some ideas go nowhere fast. For example, many college students have written small pieces of code to help a friend, very few of these turned into anything like Napster. On the flip side, many large companies have invested millions to launch a new product that did well in trials but fizzled in the market. Why do some new configurations of information set off a cascade – like DNA – that set up a whole new level in the unified information systems framework? Even when we understand how each system included in the unified information systems framework stores, processes, and replicates information, and how they are causally connected across levels, we may still not understand the various networks implicit in each of the systems (latent network potentials) that at the slightest provocation set off new cascades, amplifying small actions all our of proportion. Perhaps some of these cascades can even set off new levels. Looking at the history of the universe can help shed some light on when and how new levels (types of complex adaptive systems that store, process, and replicate information) are created. Again, the skeptic in us says that these levels are just one of the unfolding possibilities of levels (courses of evolution for the universe), and other levels might have occurred – though all would have had to possess information storage, processing, and replication capabilities. People spend far too much time speculating about which levels are conscious, so we'll ignore that question.

Tables 2a and 2b provide a chronological (evolutionary, unfolding) perspective on a possible unified information systems framework underlying all sciences. All of the dates are very approximate and open to some debate, nevertheless the tables concisely represent some of the key advances in the history of the universe, life on our planet, and humans that lead to new capabilities enabling the environment to be enriched to the level that allowed the next advancement/new capability to appear. By some estimates 12 billion years ago the big bang created the energy-matter-space-time (EMST) that comprises our universe. Some time later as the galaxies and stellar systems form, the variety of atoms increases over time (it would be interesting to have a time-line of the relative abundance of different types atoms over time). About 4.5 billion years ago the Earth formed, and provided a stable environment for the formation of molecules (again it would be interesting to have a time-line of the relative abundance of different molecules, and look for events that caused a great increase or decrease in the relative abundance of particular molecular forms (Sneden and Cowan, 2002)). About 3.5 billion years ago the earliest bacteria and simple single celled organisms appear in the fossil record (Bloom, 2000). Fortunately for us, fossils are a form of information storage, and radioactive decay and the relative abundance of different isotopes of atoms provides a useful chronometer, leaving a time-stamped information trace in history that allows us to speculate about the past and build models to explain the available data. About 2.5 billion years ago, sponges and some of the earliest multi-cellular organisms can are observable in the fossil record. A giant leap forward occurred a mere 0.7 billion years ago, clams were some of the earliest organisms to not only have separate organs but a nervous system to coordinate their interactions with each other and the environment, allowing sophisticated behaviors to develop with numerous survival advantages over other species competing for the same resources and searching for appropriate environmental niches. Brains first appear about 0.5 billion years ago in the early sea creatures known as trilobites, and again the inventory of behavioral capabilities is expanded (along with the information storage, processing, and replicating capabilities of the species). Swarm, or collective intelligence, emerged in flying insects (bees) about 0.2 billion years ago – and new levels of distributed information processing in a supra-organism became possible. Some 0.065 billion years ago, mass extinctions occur and the die was cast for the emergence of a new order of life on earth. A mere 0.002 billion years ago on the savannahs of Africa a new species appears with powerful new capabilities enabled by a larger than average brain, the ability to use rudimentary spoken communication and stone tools. The early human story begins with a powerful new means of replicating information in both speech and tools.

Billion Years Ago	**Advance**
12	Big Bang (EMST)
11.5	Milky Way (Atoms)
8	Sun (Energy)
4.5	Earth (Molecules)
3.5	Bacteria (Cell)
2.5	Sponge (Body)
0.7	Clams (Nerves)
0.5	Trilobites (Brains)
0.2	Bees (Swarms)
0.065	Mass Extinctions
0.002	Humans Tools & Clans Co-evolution

Table 2a: Billion year view of the evolving capabilities of physical and biological systems, and dawn of the human systems: cognitive, social, technological systems.

Generations Ago	**Advance**
100,000	Speech
750	Agriculture
500	Writing
400	Libraries
40	Universities
24	Printing
16	Accurate Clocks
5	Telephone
4	Radio
3	Television
2	Computer
1	Internet/e-Mail
0	GPS, CD, WDM

Table 2b: A generation view of the evolving capabilities of cognitive, social, and technological systems, and the accelerating pace of advancement.

Compared to the billion year view of physical and biological evolution, the human story of cognitive-social-and-technological evolution is best told in units of generations – again an approximate measure closer to fifteen years in the beginning of Table 2b and stretching to about twenty years by the end of Table 2b. About 750 generations ago, agriculture allows some hunter-gathers to establish larger permanent settlements that allow for the emergence of enhanced information storage, processing, and replication in early villages that eventually lead to the rise of cities (Johnson, 2002). Approximately 500 to 400 generations ago, written languages and libraries arise further enhancing the information storage and replication capabilities of humans (Boorstin, 1983). About 40 to 24 generations ago the rise of first universities that have persisted to present day as well as printing provide a much more complete picture of the evolution of capabilities than at any previous point in human history. About 16 generations ago, the first accurate chronometers allow much less risky global navigation, colonization, resource exchange to occur, and for the first time the human species spans the planet with global networks connecting all the continents. Insurance companies, an organizational evolution, also provide new risk management capabilities. At this point, the pace of advancement explodes as illustrated in Figure 1. A population explosion begins that is still raging forward. In the modern period (our grandparents to the present), advancements such as the telephone, radio, television, computer, and internet have further enhanced our information storage, processing, and replication capabilities. In the last decade the rise of cell phones, global positioning systems (GPS), CD and DVDs for information storage and replication, wave division multiplexing (WDM) of signals for fiber-optic broadband global communication networks, etc., amply demonstrate the real impact of accelerating change on the way we individually and collective store, process, and replicate information. Before presenting a framework for summarizing these advancements, consider the development of GPS briefly. Often information is not available when and where we need it, in some sense the information is tacit or hidden. Developments like GPS allow one to know location (longitude, latitude, elevation) explicitly, in some sense making hidden information observable. This is one of technology's real strengths – making hidden or tacit information explicit.

Table 3 presents the *outside-inside framework of human performance enhancements* (Spohrer, 2002), which summarizes improvement areas that have enhanced human performance over the past two million years. The outside-inside framework, as its name suggests, divides improvement areas that have enhanced human performance as either external to the human body (environmental and personal) or inside the human body (temporary and permanent). External-environmental enhancements include new materials (stones, bricks, wood, cloth, paper, plastics, etc.), new agents (animals with skills/uses, organizations with governance or social development capabilities, businesses with product and services capabilities, people with skills/occupations, information bots on the web, etc.), new places (a building with a purpose, a place in cyberspace with a purpose, information enhanced places that take on new affordances in augmented reality, etc.), new tools (utensils, machines, computers, etc.). External-personal enhancements include things that can be easily carried with a person or that a person can be carried in (clothes, watches, weapons, cell phones, personal digital assistants (PDAs), jewelery, cars, vehicles, specialized suits for specific occupations, etc.). Internal-temporary includes all ingestibles that are consumed and pass through the body as well as temporary physical and mental states that have survival or performance advantages (foods, medicines, sleep, etc.). Internal-permanent enhancements include organs (natural organs, replacement organs, implants, etc.), skills (child development, new learning, new uses of old sensor effectors, etc.), and new genes (variations that lead to advantages, up to an including new species designation). The outside-inside framework is an extensible framework intended to help concisely organize and categorize the many different ways of enhancing individual and collective human performance that have arisen throughout time.

Relative Position	**Improvement Areas**
External (outside the body; environmental)	Materials - Cost, Affordances, Dynamics
	Agents – Societies, Organizations, People, Bots, Animal
	Places – Real, Virtual, Mixed
	Tools – Utensils, Machines, Connectors
External (outside the body; personal)	Tools – Wearables, Mobile Tools
Internal (inside the body; temporary)	Ingestibles – Medicines, Foods
Internal (inside the body; permanent)	Organs – Implants, Sensor & Effectors
	Skills – Learning, New Uses of Old
	Genes – New Species, Devel. Process

Table 3: The inside-outside framework, for summarizing improvement areas that enhance human performance.

Table 4 again presents a by-generations view of key advances in human history, as well as some predictions for the future. The table also provides annotations for each advance, showing relevant outside-inside framework categories as well as unified information system framework categories for each advance. Table 4 provides a summary of advances, but a great deal of information is left out, both in terms of important advances in human history not shown, but more importantly the many relevant infrastructures needed to support the advances that are not shown. For example, let’s consider accurate clocks (Sobel, 1996). The opportunities and complex urgent problems of that era that lead to the development of accurate clocks contributed as well to the origins of banks and insurance companies – which are new organizations (agents in the outside-inside framework terminology). English land owners were mortgaging their properties to support emerging import-export and colonization businesses. The risks associated with inaccurate navigation that lead to lost ships, goods, and people led to both insurance companies and accurate clocks. These new businesses relied on the creation of new skills and new occupations that are not reflected in Table 4, but should be. Table 4 places undue emphasis on technology for enhancing human performance, and not enough emphasis on the social systems that enhance human performance. For this reason, the over emphasis of the technology and the under emphasis of the organizations and occupations in the science perspective, the next section on the business of convergence will do more to highlight the importance of businesses in enhancing human performance. .

Generations	Advance	Improvement Area	Information Model
-100,000	Homo habilis	New Agent	store, process, replic.
	Speech	New Skill	process, replicate
-500	Writing	New Tool, Skill	store, replicate
-400	Libraries	New Place, Agent	store, replicate
-40	Universities	New Place, Agent	store, process, replic.
-24	Printing	New Tool, Skill	store, replicate
-16	Accurate Clocks	New Tool, Skill	store, replicate
-5	Telephone	New Tool, Skill	replicate
-4	Radio	New Tool, Skill	store, replicate
-3	Television	New Tool, Skill	store, replicate
	TV - stories	New Skill	process
-2	Computers	New Tool, Skill	store, process, replic.
-1	Internet	New Tool	store, replicate
0	GPS	New Tool, Skill	store, replicate
+0.5	On-demand e-business	New Agent	store, process, replic.
+2?	NBIC - Sustainable	New Material	replicate
	NBIC - Bionics	New Sense	process
	NBIC - WorldBoard	New Tool, Place	store, replicate
	NBIC - Bots	New Agent	store, process, replic.
+5?	Utility Fog	New Material	replicate

Table 4: Generations view of advances that have enhanced human performance, annotated with outside-inside framework categories as well as unified information systems framework categories.

Before turning more fully to a business perspective on convergence, note that Table 4 makes several predictions (positive values for generations). The first predicted enhancement for the future is referred to as an *on-demand e-business*. On-demand e-businesses are more responsive, resilient, and adaptive than businesses are today, in part because more of their processes are automated. In general, businesses serve the purpose of efficiently replicating products and services required by people, other businesses, or agents (as proposed in the outside-inside framework). Other predicted advances in the next couple of generations include environmental friendly materials, enhancing sustainability, as well as bionics (artificial cochlea, retina, organs, neural pathways, etc.), WorldBoard (or planetary augmented reality systems providing overlaid information in locations), bots (or artificial intelligence agents with natural language capabilities allowing conversational access to information stored on our computers, in our businesses, or on the web). Finally, an ultimate advance, if it were ever to be realizable which seems doubtful by today's standards, is utility fog – or the ability of microscopic particulars to self-assemble to create material products on demand (Hall, 1993).

In sum, the science perspective on convergence is best summarized in two goals: (1) to find a unified model underlying all empirical sciences that accounts for all data, and (2) to understand and control to suit our purposes the different mechanisms for storing, processing, and replicating information across multiple systems. To address the first goal, a number of proposals have already been made, such as complex adaptive systems (Alexrod & Cohen, 2000), holistic systems (Laszlo,1996), automata evolving patterns (Wolfram, 2002), and network science (Watts, 2003). In this section, we alluded to a unified information systems framework that might be developed over time into a more completely fleshed out model – as the specific information storage, processing, and replication processes of the five main systems are elucidated. The data required is a more complete accounting of the origins and development of capabilities across the five systems. Ultimately, all five of these models may be shown to be largely isomorphic. To address the second goal, we will need to better understand the processes at work in nature and combine them with our human-made methods. Specifically, work in the areas of nanotechnology, embryology, neurophysiology, child development, organizational behavior, and related disciplines are revealing naturally evolved methods for creating materials and organisms, and these techniques will inform our consciously-designed, human-made methods for more efficiently and sustainably creating materials and machines. In the next section, we present some of the business implications of convergence.

Section IV: Business

What is the "reason for being" of business (Haeckel, 1999)? Businesses exist to address the needs and wants of *people*, individually (consumers) and collectively (other businesses and organizations), with *profitable* products and services. Business is a game we play collectively because it benefits people (consumers) and creates profits (benefits producers). A win-win outcome is possible when more value is created than expended, according to some mutually agreed upon framework of accounting. One can view business either through the lens of profits or through the lens of people. We consider each of these in turn, as well as the relationship of business to science.

Most people focus on the word "profitable" in the definition of business instead of the word "people," in part because profits provide the incentive (and measure of success) for the owners of a business who assume the risks associated with operating the business. Thus, when comparing business and science, it is not surprising that many equate the importance of business methods for increasing profits to the importance of scientific methods for increasing knowledge – if knowledge (or information) is fundamental to science, then certainly profits are fundamental to business. Given a focus on profits, one can ask what business methods can be used to increase profits? Increasing profits can be achieved in six relatively fundamental ways:

(1) Innovation (new products and services with larger markets and/or higher margins).
(2) Cost reduction (same output for less cost – out sourcing, off-shore, optimization, automation).
(3) Productivity improvements (more output for the same cost – human incentives, improved skills, improved tools, optimization, automation).
(4) Consolidation and monopoly control (buy out or eliminate competitors, or move into markets with no competition).
(5) Industry cost removal (collaborate with competitors to remove cost from an industry and improve overall margins – enlightened self interest).
(6) Industry market expansion (collaborate with competitors to increase the size of the market – a rising tide lifts all ships).

If NBCST convergence is accelerating innovation as we have argued, then businesses that can best tap into abundant innovation for increasing profits should have advantages.

A business perspective on convergence, or rapid innovation derived from interdisciplinary co-evolution, suggests focusing on people as the best way to increase profits. Table 5 summarizes a multi-layered relationship that exists between the worlds of science and business that is mediated by technology. Because the purpose of business is to bring to market products and services that address the needs and wants of people, Table 5 highlights the human sciences which range from genetics to the social sciences. Advances in the human sciences produce vast amounts of data, from genomics data that doubles in volume about every six months to purchasing pattern data at the other end of the human sciences spectrum. The data both drives the expansion of information technologies (storage, processing, replication), and also underlies the development of new products and services, which in turn drives the growth of business. As can be seen by the businesses highlighted in Table 5, fundamentally people are interested in businesses (products and services) that help make people healthy (including secure), wealthy, and wise. In fact the U.S. Census website (Barron, 2001), defines quality of life metrics for people that touch on these and others areas. In the limit as businesses become more and more automated, businesses must compete on the value they deliver to people, individually (consumers) or collectively (other businesses). In addition, as traditional businesses become more automated, new levels of business will expand including derivative businesses, creating even more opportunities for people to invest (not just with capital) in businesses and share in the returns.

	Science	**Technology**	**Business**
Group	Social Science, Economics, Org. Behavior	Science produces Data; Data drives Information Technology; Technology underlies new Products & Services; New Products & Services drive Business.	Financial Services, Legal, Insurance, Government
Individual	Cognitive Science, Child Development		Education, Communication
Brain	Neurophysiology		Healthcare, Public Sector
Cell	Proteomics		Healthcare, Industrial Sector
Gene	Genomics, Embryology		Healthcare, Distribution Sector

Table 5: The business of people: healthy, wealthy, and wise.

Technology mediates the co-evolution of science and business along with the evolving wants and needs of people, individually and collectively. In the remainder of this section, some of the business implications of convergence are considered.

How will convergence make people healthier? Personalized pharmaceuticals that are custom developed to best meet an individuals needs are foreseeable. Table 6 shows the progression from genes to messenger RNA to proteins to metabolic pathways to phenotype, which provides a road map leading ultimately to personalized medicines. By some estimates, three hundred terabytes per person times six billion persons yields almost two trillion terabytes of data to provide a detailed biological map of everyone alive today. Rational drug development requires managing enormous complexity. Pharmaceutical companies are beginning to differentiate themselves on the power of their information technology platforms. Historically, two hundred and twenty targets have generated $3 trillion of value. Industrialized genome sequencing has created a target rich, lead poor environment that will slowly reverse over the next several years as *in-silico* biology drives the discovery of new lead compounds. Beyond personalized pharmaceuticals, convergence should lead to improved sensor technology that will allow monitoring the body 24x7 to detect potential problems early. Convergence will drive the development of custom drugs, personalized medicine, and new approaches to health care. In terms of the inside-outside framework, new ingestibles will be one of the key enhancements.

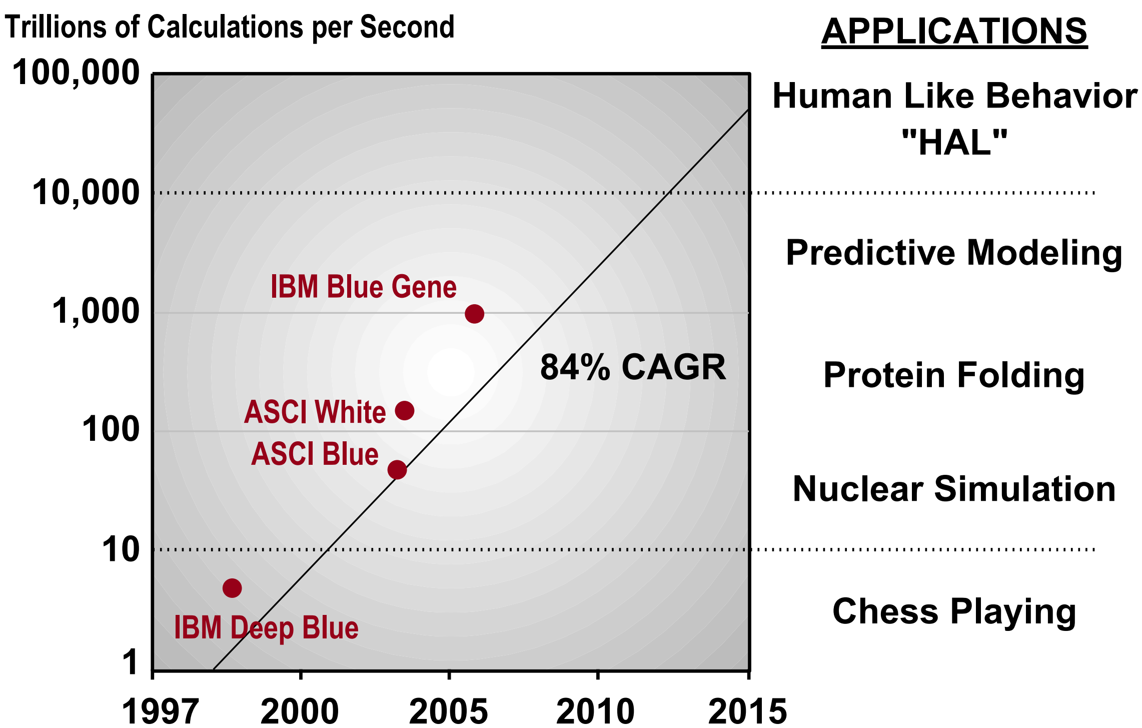
6,000,000,000 phenotypes (people)	Hundreds of millions of pathways influenced by the environment and stochastic processes create 6 billion different individuals. Individuals interact.
100,000,000 metabolic pathways	1.5 million proteins interacting in complex networks create hundreds of millions of metabolic pathways.
1,500,000 proteins	Post translational modification turns 500,000 messages into 1.5 million proteins.
500,000 messenger RNA	Alternative splicing turns 40,000 genes into 500,000 messages.
40,000 genes	40,000 genes (approx.100 million bases) represent less than 3% of the genome (approx. 3 billion bases). The function of the remaining 97% remains elusive.

Table 6: The steps building up to personalized pharmaceuticals (numbers approximate).

How will convergence make people wealthier? A recent back of the envelop calculation (Rees, Testemale, and Wackernagel, 1995) indicates that for all six billion people on Earth to live at the material standards of U.S. citizens, the resources of two additional planets would be required. Cheaper, stronger, lighter, more durable and sustainable materials are needed for everything from computers to vehicles to roads to housing to furniture to clothing to food (Hawken, Lovin, and Lovin, 2000). Roll-to-roll electronics, stain resistant fabrics, chromatically active and polymorphic materials are just some of the new directions that are emerging (Trivedi, 2002). Convergence will drive the creation of new materials and perhaps someday a universal material that is cheap, strong, and adaptive to many contexts. In terms of the inside-outside framework, new materials will be one of the key enhancements.

How will convergence make people wiser? As illustrated in Figure 1, information as a commodity is a fundamental consumable for modern humans. In Figure 4, the increasing information processing capabilities of computers is plotted in terms of trillions of calculations per second over time. The right hand side of Figure 4 shows the emergence of new capabilities as processing power increases. By 2015, it is conceivable that natural language access to the world wide web will be possible. When this capability is combined with voice recognition and wide spread use of cellular telephones, conversational interfaces to all human knowledge become a possibility. The implications of everyone with a personal genius just a phone call away are quite staggering. Could this lead to a wiser population? It is also worth noting that by 2015, the cost of storing all the audio and video in someone's life, as well as the bandwidth to send audio-video from a cellular phone to a "life cache server" should be cost effective for most people. The vision of storing a person's (or a societies) entire life history has been around for a while

(Gelertner, 1988), but has received a recent boost with the announcement of DARPA's LifeLog program (Gage, 2003). Convergence will drive the creation of new information processing components and systems with the potential to augment human senses, memory, decision making, and communications capabilities. In terms of the inside-outside framework, new agents will be one of the key enhancements.



Source: ACSI Roadmap www.llnl.gov/asci, IBM Brain ops/sec: Kurzweil 1999, The Age of Spiritual Machines

Figure 4: Increasing information processing capabilities leading to human like behavior.

If more people become healthier, wealthier, and wiser as a result of convergence, then what will happen to business? How will collective human performance be impacted? How will business organizations evolve? Via the selection pressure imposed by profitability (survival), businesses are evolving to be more responsive (to customers), adaptive (improvement-oriented), and resilient (accelerating the rate of improvements in spite of the need for repeated transformational change).

Every business process is composed of four components: (1) people (human system), (2) technology (tool system), (3) external services (provided by other businesses - organizations), and (4) external regulations (mandated by governments - organizations). In general, the cost of people is rising, the cost of technology is dropping, the cost of external services is dropping, and the cost of external regulations is rising. In the early stages of human history, most businesses served the needs of individual people. Today some of the most interesting businesses that serve consumers are using new technologies to support the collection and utilization key human sciences data with commercial value. For example, consider the recommendation system at Amazon (which recommend books that buyers may want), the reputation system at e-Bay (which tracks the quality of buyer and seller interactions), or the content quality filtering systems at Slashdot (which ensures a high quality level even when posting at the website are open to the public). Across the whole range of human sciences the amount of useful data with business applications is increasing. However, increasingly businesses serve the needs of other businesses, as the pace of business evolution accelerates.

Other key types of organizations that have evolved with businesses are governments, cooperatives, and non-profits. Often it is these institutions that ensure that more people, and not just those living in the developed nations of the world, derive benefit from the rapid science-business co-evolution that convergence seems poised to further stimulate. In fact, Table 4 should be redone to include the evolution of organizations, as it is Table 4 over emphasizes the importance of technologies, but ignores most of the new organizations, skills and professions that were needed to produce and use the new technologies. Governments have evolved, from towns to city-states to empires to nations, with rulers claiming authority based on wisdom, military might, birth right, divine designation, and election (Grun, 1975,; Gallambos, 2000). The significance of government regulations to business evolution, including taxes, incentives, trade rules, and employer-employee rules, are significant. Also, government R&D laboratories are a key source of innovation impacting business evolution. Cooperatives evolved to protect people from early industrial age businesses, ranging from the first successful cooperatives of Robert Owens (1844), to those of Charles Fourier, the Granger Movement, collective farms, and communes (Greenhall and Levey, 1983). Two key types of non-profits that have impacted business evolution are universities (a source of skilled labor as well as innovation) and industry non-profits (a source of standards and often a trusted intermediary). Moschella (2003, pg. 81) summarizes six customer-led business patterns of the past, including ASCAP, Visa, SABRE, ATMs, EDI, and Bar Codes, and suggests that one of the most noteworthy aspects of the list is that only one (SABRE) is still run by a for-profit company.

Throughout human history new skills (cognitive), new organizations (social), and new technologies (technical) have been co-evolving - three key aspects of human-made culture. Recently, in the last twenty generations of human history, science and business have begun rapidly co-evolving, or ratcheting each other up faster than any other two social systems. Even more recently, in the last ten generations of human history, new forms of government have emerged that foster science and business. The co-evolution of science and business provides the potential for making people noticeably healthier, wealthier, and wiser with each passing generation. Innovations jump the science to business gap more rapidly. Governments and other organizations provide incentives and inhibitors further shaping the co-evolution. Finally, the system responds to itself, as individuals and organizations tap into an increasingly powerful societal capabilities infrastructure (see Appendix I), the potential for mischief is increased as well. High tech criminals and terrorists organizations are just two examples of mischief, which make watching 007 movies somewhat less entertaining. In sum, convergence is not only accelerating inter-disciplinary cross-pollination in the sciences, but also the evolution of businesses with the potential to enhance human performance and enhance the potential for mischief.

Section V: Concluding Remarks & Future Directions

This paper has explored the notion of converging technologies for enhancing human performance from a science and business perspective. *Converging technologies* or simply *convergence* refers to a type of co-evolutionary progress that is characterized by rapid advances across multiple areas of technology, accelerated by inter-disciplinary cross fertilization. *Enhancing human performance*, or said another way, enhancing our human ability to achieve goals both individually and collectively, has been progressing for nearly two million years since our earliest human-like ancestors, *homo habilis*. The early phase of human evolution was characterized by hunter gathers seeking food (energy) to nourish their bodies, and the later phase of human evolution has been increasingly characterized by knowledge workers seeking information to nourish their minds.

From a science perspective, convergence may mean a unification of five levels of systems into a unified information systems framework -- physical (atoms & molecules), biological (DNA), cognitive (brain & symbols), social (organizations), and technical (tools). The framework ultimately must explain the way that information storage, processing, and replication processes operate in each of the five systems. The framework must account for the origins, development, and selection of variability at each level, both what historically happened as well as well as what might have happened. Imagine plotting the relative quantity of atoms, molecules, types of DNA (species), symbols (words), occupations, and tools over time. A unified model underlying all the separate sciences is the grand challenge of convergence.

From a business perspective, convergence may mean an acceleration of new innovative products and services drawing on five levels of human sciences – gene, cell, brain, individual, and group. Advances in each of these areas holds the promise of making people healthier (personalized pharmaceuticals), wealthier (sustainable materials), and wiser (learning conversations). The co-evolution of science and business is accelerating, as the time from scientific innovation to business impact is decreasing. In addition, the co-evolution of science and business is transforming businesses as well, and the fittest businesses are becoming more responsive, resilient, and adaptive.

Considerable work remains to firm up the ideas suggested in this paper, and provide a more complete framework for studying human performance enhancements and the human sciences. Broadly defined, the human sciences encompass the totality of knowledge of individual and collective human experience that is accessible via the scientific method. To an order of magnitude, the Population Reference Bureau (www.prb.org) and others have estimated that about 100 billion members of the family homo (species homo erectus, homo habilis, and homo sapien) have lived (in the roughly two million year history of this human family). This means that about 6% of everyone who has ever lived is alive today, and of course this percentage is increasing. The average life expectancy of most of these people was short, according to Haub (2002):

"In any case, life was short. Life expectancy at birth probably averaged only about 10 years for most of human history. Estimates of average life expectancy in Iron Age France have been put at only 10 or 12 years. Under these conditions, the birth rate would have to be about 80 per 1,000 people just for the species to survive. Today, a high birth rate would be about 45 to 50 per 1,000 population, observed in only a few countries of Africa and in several Middle Eastern states that have young populations."

So by some measures the totality of human experience is roughly 10**19 seconds worth of experience – all of language, all of culture, and all artifacts. The percentage of directly observable human experience is on the rise (because more of us are alive, living longer, with more instruments to measure more of human individual and collective experience exist). This year alone, an estimated 10**17 seconds of that experience could be observed if we could only capture it. We are capturing lots of interesting pieces of it.

One can ask how much of this estimated totality of human experience can ever be known (without assuming time travel!)? A large number of different sciences are working on pieces of the problem:

Ethnology: The study of humans in the context of their natural and human-made (cultural) environment, including origins, development, and functioning.
Psychology: The study of human behavior, both hidden and observable.
Sociology: The study of collective human behavior.
Linguistics: The study of human language and communications.
Economics: The study of how humans produce, allocate, distribute, and consume commodities and goods.
Political Science: The study of the processes, institutions, and activities of government.
Organizational Behavior: The study of collective human behavior as embodied in organizations.
Managerial Psychology: The study of strategies and incentives for aligning collective human action for business purposes.
Anthropology: The study of the origins, development, and varieties of humans.
Archeology: The study of the remains of human culture.
Child Development: The study of the learning and early development phases of children.
History: The study of past events.
Semiology or Semiotics: The study of human cultural products as a formal systems of signs with meanings.

Many other sciences of animals and living systems shed considerable light on humans as well:

Neurophysiology: The study of neurons, nervous systems, and brains.
Embryology: The study of reproduction and development.
Genetics: The study of heredity, both traits (expression) and DNA (encoding).

Molecular Biology: The study of life at the molecular level.
Cytology: The study of cells.
Histology: The study of tissues.
Anatomy: The study of living structures.
Physiology: The study of living functions.
Bionics: The study of hybrid living (natural) and electro-mechanical (human-made) systems.
Sociobiology: The application of evolution to the study of animal and human behavior.
Ethology: The study of animal behavior.
Biology: The study of life.
Zoology: The study of animal life.
Botany: The study of plant life.
Bacteriology: The study of bacteria.
Ecology: The study of the inter-relationships of organisms (individual and collective populations) and their environments.

These represent just a few of the many relevant sciences that are shedding some light on the totality of human experience, directly or indirectly.

So again, how much of the 10**19 seconds of human experience can ever be known? This is an interesting question for many reasons, including the fact that *each of these sciences is just people whose thoughts and actions are creating knowledge, so these sciences are in fact part of the totality of knowledge of individual and collective human experience*. This may not remain as true for long, when machines start generating more of the information, and we must distinguish between machine generated knowledge and human generated knowledge. One area sure to contribute interesting insights to the study of the human science of geneology is genetics. Accurate genetic information about people in families will probably be very helpful in identifying specific ailments associated with a particular family, but this data may also reveal some surprising discrepancies with recorded family history.

Also, we might ask if *any of these sciences are close to being done* – much as Horgan (1996) has inquired of the physical sciences. When will a particular science have compiled all knowledge of their subject area as currently defined, or more generally what would it mean to compile all the knowledge of their subject area, and how close are they to having either complete knowledge or as much as will ever be accessible by the scientific method? Before getting into the issue of knowledge that the scientific method can reveal that is not directly observable or indirectly observable via appropriate technologies, let's look at knowledge that can be described as measurements of human experience to see how much we can get directly by measurement without more sophisticated models or inference techniques. Also, this analysis will look at just straight measurement, not sophisticated models, just the vanilla measurements for this particular thought experiment.

Let's start by revisiting the human genome. Human DNA has an estimated 40,000 genes (approx.100 million bases) that represent less than 3% of the genome (approx. 3 billion bases). The function of the remaining 97% remains elusive. Alternative splicing turns 40,000 genes into 500,000 molecular messages inside cells. Post translational modification turns 500,000 messages into 1.5 million proteins. The 1.5 million proteins interacting in complex networks create hundreds of millions of metabolic pathways that keep a human functioning normally in a wide range of contexts. Finally, hundreds of millions of pathways influenced by the environment and stochastic processes create 6 billion different individuals. This represents about 10**24 bytes of data for everyone alive today, and some estimates predict that DNA sequencing of an individual will be done in minutes by 2020, when the population may be well over 10 billion people.

Next, let's consider neurophysiology, and specifically the wiring of individual human brains. Number of neurons in human brain: 10**14. Each neuron makes between 1000 and 10,000 connections with other neurons. So, this leads to about 10**19 neural connections, times 10 billion people, this is 10**29 neural connections. However, probably more interesting than having the neural connectivity maps of all human brains is understanding the function of the human brain during various tasks. In the last few decades several techniques have been developed for producing images of brain metabolism. The idea is to find out which parts of the brain are working hardest (most metabolism) during various cognitive tasks. The three most commonly used metabolic imaging techniques are: regional cerebral blood flow (rCBF), positron emission tomography (PET), and functional magnetic resonance imaging (fMRI). While none of these have been reduced to wearable devices, and some require inert radioactive gases or other tagged substances to be entered into the blood stream, and they do not have sufficient spatio-temporal resolution to get an individual neural connections, nevertheless in getting an estimate, like the human genome, as to how much data we are talking about for all the people alive at any time, we are clearly talking about not only the 10**29 neural connections in a 10 billion person population, but also the time-resolution required is on the order of milliseconds – meaning about 10**10 time slices per year, or 10**39 measurements for 10**19 connections for 10 billion people and about 10 billion measurements per year. That's a very large finite number. Recall the number of particles in the universe is estimated to be around 10**80 (Ball, 2002).

Next, let's consider embryology, and specifically the development of humans from conception through birth. Before considering humans, it is worth noting that fruit fly and mouse embryology are areas of intense study – well in advance of human embryology. The position within an embryo where the various organs (head, brain, heart, lungs, arms, legs, etc.) will develop is controlled by a set of genes known as the homeotic genes (Johnson, 2001; Ridley, 2003). Homeotic genes initiate pattern formation in the embryo as different genes switch on in specific spatio-temporal patterns. Given the trillions of cells in the human body, and the nine months gestation period, the numbers are a couple orders of magnitude greater than the brain firings for one years worth of behavior. So let's suggest about 10**31 measurements for a human embryo from conception to birth, and times 1 billion new people over some period, this is about 10**40 measurements. This is another very large finite number.

These first three sciences (genomics, neurophysiology, and embryology) lay the foundations for psychology and sociology. Psychology will be measurements for a life-span (say 100 years, or 10**12 milliseconds in a life), though one has to measure all the stimuli from the environment – which includes all the sense, sight, hearing, smell, taste, touch, as well as internal kinesethics. Note that in some sense this is already covered by neural activity, but the actual stimulus, rather than the internal response also needs to be captured to truly do psychology, including the interaction of the person with the environment. Sociology is more than just the neurophysiology and psychology measurements for all people. While we glossed over it in psychology, sociology as the science of collective human experience forces us to start modeling linguistics (information), economics (value), and political science (authority and law) – or the emergent abstractions that cause collective behavior to have the various forms it has. It is not clear what right measurements are here. In some sense, we do a pretty good job of recording mass communications, financial information for businesses, and government and legal actions, already. All of these extra phenomena are embodied as things, both concrete and abstract in the human-made environment. So, while we safely skirted representing the natural environment in all the previous areas, it is hard not to represent the cultural environment when one gets to sociology, and all the other sciences that deal with collective human behavior, since other people and other aspects of our culture are part of the complete picture for sociology – especially if we describe this as enthnology – the study of humans and their inter-relationship to culture. The good news is that culture is finite because is has been created in finite time, by a finite number of people. The bad news is that much of culture is historical in origin, and so now we need to measure history. Here's where the real problems begin (beyond refining our measurements of the "now" which may turn out to be impossibly hard for various reasons), so let's return to the scientific method.

In sum, considerable work remains to be done to complete a model of the human sciences, and then to integrate that model into a unified information systems framework for science to complement a model of the natural sciences. Even more work is required to understand the business implications of a unified information systems framework for science. In fact, as human endeavors themselves, the co-evolution of science and business would have to be part of that framework.

We end by asking one final question that arose during the writing of this paper. What would the world be like if converging technologies actually converged? One vision of this ultimate convergence is based the versatility of the cell which makes up the bulk of the biomass on this planet, including ourselves. What if all human-made things, such as clothes, buildings, furniture, vehicles, and computers, might someday be made out of smart, self maintaining, modular building block material, not unlike the cell? What if this building block material could be grown like cells and could easily operate inside a human body? What if this building block material could be individually and collectively intelligent? This modular building block material begins to sound somewhat like a hypothetical practical version of a cross between utility fog (Hall, 1993) and the noosphere (de Chardin, 1955). Even before such a material might be practical, it may be possible to simulate worlds which contain materials with these properties. Ultimately, exploring possible answers to questions like this last one may very well be addressed using simulations.

Acknowledgements: While this paper provides more speculations than answers, the authors are indebted to many colleagues who asked probing questions. The authors wish to thank colleagues from Bootstrap.org, EOE.org, NSF, NBIC Workshops, and IBM Almaden Research Center. The authors have benefited from conversations with James Burke, Martin Haeberli, Bill Daul, Joseph Hentz, Rick Lempert, and Sally Kane.

Appendix I: Evolving Capabilities

As further examples for the interested readers, this appendix presents three key concepts about evolving human-tool capabilities infrastructures for organizations and society. Figure I.1 illustrates that the co-evolution of the human system and tools system results in an enhanced (cheaper, faster, better, etc.) capabilities infrastructure. People and organizations tap into the societal capabilities infrastructure to enhance their performance and achieve goals.

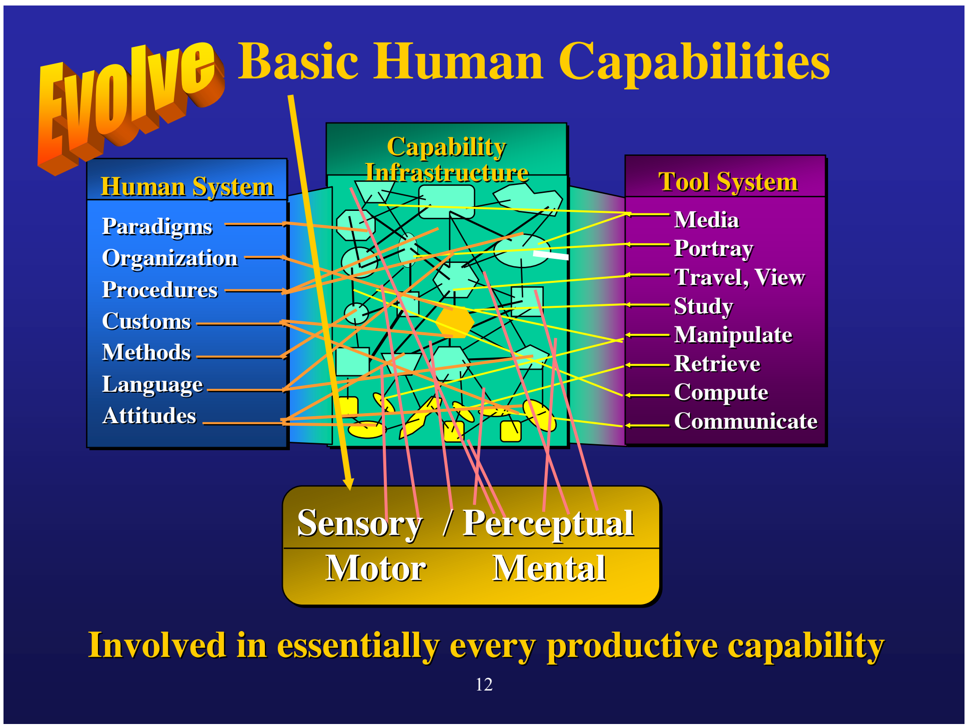


Figure I.1: Human System and Tool System Co-Evolve to Enhance the Capability Infrastructure.

When organizations tap into the capabilities infrastructure as they perform activities to achieve goals, many factors contribute to which capabilities they are able to access and use. Organizations can be compared and contrasted based on the capabilities they use and don't use, as suggested in Figure I.2. Benchmarking business processes is the current jargon for comparing how organizations do things to achieve goals.

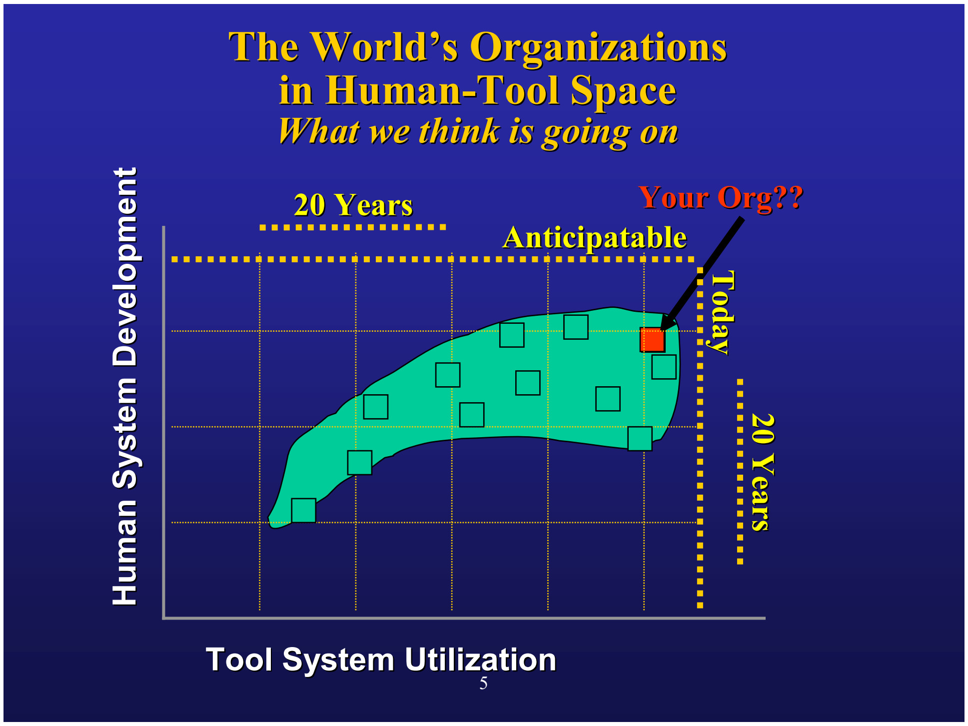


Figure I.2: The World's Organizations in the Human-Tool Space

As organizations attempt to improve their capabilities, there are three activity areas to consider, referred to as A, B, and C activities in Figure I.3. The A activity serves the customers, the B activity improves the product cycle time and quality, and the C activity *improves the improvement* cycle time and quality (like compound interest!). Some organizations simply perform A activities with no view to improvement - or as James March would say, they exploit what they have in hand. Many organizations perform some level of B activity as well to improve their products – or as James March would say, they explore for what might be at hand. Some organizations perform the C activity, but many more rely instead on external organizations or industry organizations to perform the C activity and only adopt the new capabilities, rather than invest in the development of these C level capabilities. To perhaps better comprehend the significance of as well as the unfortunate under investment in the C activity, it is worth considering the words of Abraham Lincoln: "If I had only an hour to chop down a tree, I would spend forty-five minutes sharpening my axe."

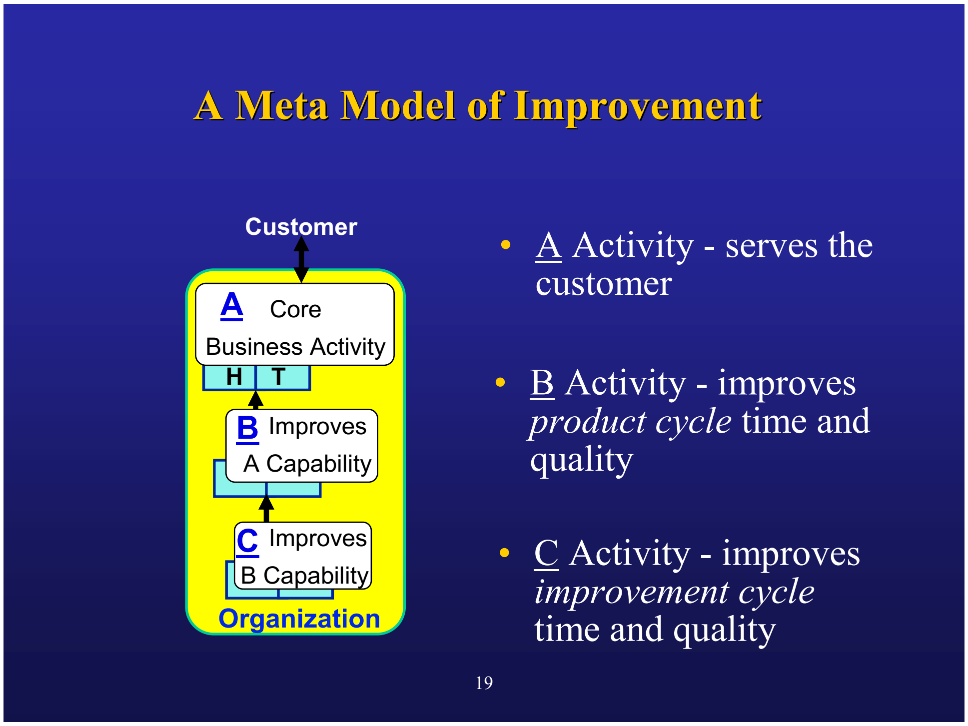


Figure I.3: A Meta Model of Improvement

The interested reader can find more information on the co-evolution of the human system and the tool system, societal capability infrastructures, the meta-model of improvement, and related topics at http://www.bootstrap.org.

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