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Perspectives

Coherence and divergence of megatrends in science and engineering*

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Abstract

Scientific discoveries and technological innovations are at the core of human endeavor, and it is estimated that their role will only increase in time. Such advancements evolve in coherence, with areas of confluence and temporary divergences, which bring synergism and that stimulate further developments following in average an exponential growth. Six increasingly interconnected megatrends are perceived as dominating the scene for the next decades: (a) information and computing, (b) nanoscale science and engineering (S&E), (c) biology and bio-environmental approaches, (d) medical sciences and enhancing human physical capabilities, (e) cognitive sciences and enhancing intellectual abilities, and (f) collective behavior and system approach.

This paper presents a perspective on the process of identification, planning and program implementation of S&E megatrends, with illustration for the US research initiative on nanoscale science, engineering, and technology. The interplay between coherence and divergence, leading to unifying science and converging technologies, does not develop only among simultaneous scientific trends but also along time and across geopolitical boundaries. There is no single way of development of S&E, and here is the role of taking visionary measures. Societal implication scientists need to be involved from the conceptual phase of a program responding to a S&E megatrend.

Introduction

Discoveries and advancements in science and technology evolve in coherence, with areas of confluence and temporary divergences. This dynamics bring synergism and tension that stimulate further developments following in average an exponential growth. Besides the societal needs of wealth, health, and peace, a key driver for discoveries is the intrinsic human need for intellectual advancement, to creatively address challenges at the frontiers of knowledge. Few of the most relevant discoveries lead to the birth of megatrends in science and engineering (S&E) after passing important scientific thresholds, then building up to a critical mass and inducing wide societal implications. After reaching a higher plateau, such discoveries spread into the main stream of disciplines and are assimilated into general knowledge. S&E megatrends always are traceable to human development and societal needs, which are their origin and purpose (Figure 1). We speak about S&E, because engineering skills provide the tools to implement scientific knowledge and the capability to transform the society.

Funding a megatrend means enhancing the chance of support of researchers moving into the respective field while maintaining most of the investment in the original research fields. The goals are: increasing the research outcomes of the total investment, obtaining the benefits sooner, and creating a suitable infrastructure for the new field in the long term. At

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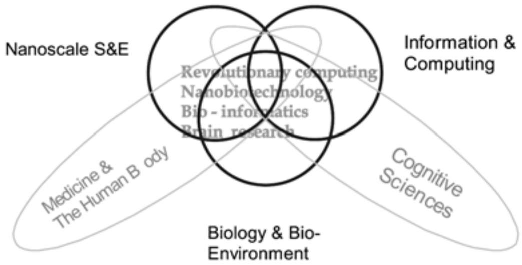

Figure 1. Coherence and synergism at the confluence of science and engineering streams.

times, groups of researchers argue that megatrends would present a threat to open science and technology advancement. We agree that it may present a threat for the uniform distribution of R&D funding, or maybe a real threat if the megatrend selection would be arbitrary. With proper selection with input from the scientific community, the primary purpose of a S&E effort at the national level is the big pay-off of the proposed novelty at the frontiers of science and of the synergism at interfaces. Without such divergent developments the entire S&E dynamics would be much slower, similar to the faster flowing fluids that are turbulent (with velocity fluctuations diverging from the mean velocity) and not laminar. I recall that the bicycle sketched by Leonardo da Vinci in 1493 (Figure 2) took about 400 years to be constructed, because only later the necessary materials were available. This illustrates the need for synergy and cooperative efforts between neighboring disciplines, and the need to bring a timely focus on the key contributing disciplines.

A megatrend is usually motivated by a challenge that may look unfeasible and even unreasonable to some people at the beginning, as it was ‘flying’, ‘landing on the Moon’, or ‘going into the nanoworld’. It must be sufficiently broad in goals and last sufficiently long to justify the national attention.

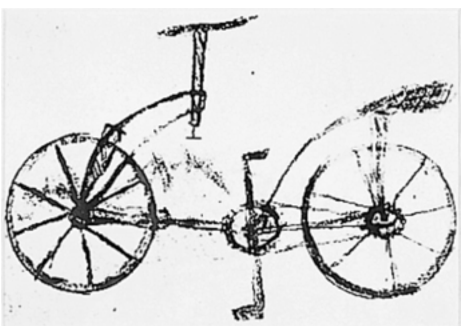

Figure 2. Schematic attributed to Leonardo da Vinci (1493).

An overview of what we see as key S&E trends in the US at the national level is presented in this paper. We will illustrate the identification process of a new trend with the recent ‘National Nanotechnology Initiative’ (NNI). Finally, the paper discusses the coherence and synergism among major S&E trends and the role of macroscale managing decisions.

Six increasingly interconnected megatrends

There is a mutual interest for the S&E communities and society to advance major new areas of technological focus in response to objective opportunities, with the goal of accelerating the overall societal progress. Six increasingly interconnected megatrends in science, some closely followed by engineering and technology advancements, are perceived as dominating the scene for the next decades in the US:

(a) *Information and computing*: The bit-based language (0,1) has allowed us to expand communication, visualization, and control beyond our natural intellectual power. Significant developments beginning in the 1950s have not slowed down and there is the promise that we are continuing the exponential growth of opportunities in this area. The main product is in the form of ‘software’.

(b) *Nanoscale science and engineering*: Working at the atomic, molecular, and supramolecular levels allows us to reach directly at the building blocks of matter beyond our natural size limitation, that is orders of magnitude smaller than what we can see, feel, or smell. At this moment, this is the most exploratory of all megatrends identified in this list. The field has been fully recognized in the 1990s and it is just at the beginning of the development curve. The main outcome of nanotechnology is in the form of ‘hardware’, that is the creation of new materials, devices, and systems. The nanoscale promises to be the most efficient scale for manufacturing, as we know the nature now, with the smallest dissipation of energy, material consumption and waste, and with highest efficiency in reaching the desired properties and functions.

(c) *Modern biology and bioenvironmental approaches*: Studying the cells, their assemblies and interactions with their surroundings are uniquely challenging issues because of their unparalleled complexity. Biology introduces us to self-replicating structures of matter. It uses the investigative methods of information and nanoscale technologies. An important aspect is genetic engineering. Another important aspect is the connection between life and its environment, including topics such as global warming. Modern biology received its strength in the 1970s and its role is expanding.

(d) *Medical sciences and enhancing the human body*: The goals are maintaining and improving human physical capabilities. This includes monitoring health, enhancing sensorial and dynamical performance, using implant devices and extending capabilities by using human–machine interfaces. Healthcare technology is a major area of R&D, it has general public acceptance, and its relative weight is growing with the aging population.

(e) *Cognitive sciences and enhancing intellectual abilities*: It is concerned with exploring and improving human cognition, behavior, and intellect. Enhancing communication and group interaction are an integral part of improving collective behavior and productivity. This area has received less recognition even if increasing cognitive capabilities is a natural objective for a large section of population.

(f) *Collective behavior and system approach*: Use of architecture, hierarchical systems, chaos, and other concepts for studying nature, technology and society. It may describe a living system, cultural traits, reaction of the society to an unexpected event, or development of global communication, to name a few examples. Recognition of the system approach has increased in the late 1990s.

If one would like to model the evolution of the entire society, none of these six megatrends could be disregarded. The information, nano and bio S&E megatrends extend naturally to engineering and technology, have a strong synergism, and tend to move closer together. From these three trends, nanoscale S&E is currently more exploratory and it is a condition for the development of the other two. Information technology enhances the advancement of the other two. A mathematical formulation of the coherent evolution of research trends could be developed based on a system approach and time-delayed correlation functions.

Melding of human and S&E developments is noted. Bits (for computer and communication to satisfy the need for visualization, interaction, and control), genes and cells (for biology and biotechnology), neurons (for cognition development and brain research), atom and molecules (to transform materials, devices, and systems), and interactive component (part of system approach) are the basic scientific elements for the beginning of the 21st century. Human development, from individual medical and intellectual development to collective cultures and globalization, is a key goal.

A simplified schematic of this complex system is shown in Figure 1. The main trends are overlapping in many ways and their coherence and synergy at the interfaces creates new research fields such as bioinformatics, brain research, and neuromorphic engineering. Let's illustrate a possible path of interactions: information technology provides insights and visualization of the nanoworld; in turn, nanotechnology tools help measure and manipulate DNA and proteins; which contribute to uncovering the brain physiology and cognition processes; brain processes provides understanding of the entire system; then, the conceived system and architecture is used to design the new information technology; etc.

Unifying science and engineering

There are several reasons why unifying principles in S&E are arising now:

– Increased depth in understanding of physical, chemical, and biological phenomena revealing the fundamental common ground in nature.
– Significant advances are at the interfaces among disciplines in such a way that the disciplines are brought closer together, and, therefore, one can easily identify the common ground.
– There is a convergence of principles and methods of investigation of various disciplines at the nanoscale, using the same building blocks of matter in their analysis.
– There is a need to simulate complex, multiphenomena, and hierarchical processes where the known physico-chemical-bio laws are too specific for effective multiscale modeling and simulation. An obvious illustration is for modeling of many-body interactions at the nanoscale, where the laws are specific for each material, within bodies and the boundaries, at different environmental parameters, for different phenomena.

The unifying science may manifest in three major ways:

– *Unifying the basic understanding of various phenomena, and bringing under the same umbrella various laws, principles and concepts in physical, chemical, biological, and engineering sciences*. For

example, in physics, there is an increasing awareness that weak, strong, electromagnetic, and gravitational forces may collapse into the same theory in the future (Grand Unified Theory). Mathematical language and other languages for improved communication at S&E interfaces, and the system approach offer general tools for this process.
– *Collective behavior in physics, chemistry, biology, engineering, astronomy, and society.* Theories are developed using the concepts of self-organized systems, chaos, and complex systems.
– *Convergence of the methods of investigation* describing the building blocks of matter at the nanoscale. The nanoscale is the natural threshold from the discontinuity of atoms and molecules to the continuity of bulk behavior of materials. Averaging approaches specific to each discipline collapse in the same multi-body approach.

Identifying and using unifying S&E has powerful transforming implications on converging technologies, education, healthcare, and the society in the long term.

Origin of national S&E funding trends

The foundation of a S&E trend is built up in time at the confluence of other areas of R&D, and it is brought to the front line by a catalytic development, such as, a scientific breakthrough or/and a societal need. For example, space exploration has grown at the confluence of developments in jet engine, aeronautics, astronomy, and advanced materials and was accelerated by the global competitiveness and defense challenges. Information technology has grown at the confluence of mathematics, manufacturing on a chip, materials sciences, media, and many other areas, and was pushed by the economical impact of improved computing and communication. Nanotechnology has its origins from scaling down approaches, building up from atomic and molecular levels, and better understanding chemistry, biosystems, materials, simulations and engineering, among others, and it is pushed by the promise to change almost all human made products. Biotechnology has developed at the confluence of biology, advanced computing, nanoscale tools, medicine, pharmacy and others, and has obvious benefits in health care and new products.

By developing these initiatives we have obtained additional funding. The last two national research initiatives are Information Technology Research (ITR) and NNI. For ITR we have a report from PITAC (President's Information Technology Advisory Committee), a committee with a significant participation from industry. This report shows new elements and expectations. According to this report the Internet is just a small token on the way for larger benefits. ITR was announced in 1999.

How one can get a new trend recognized for funding? There is no single process for raising a S&E trend to the top of the list of national priorities in the US. One needs to explore the big picture and in long term. It is important to identify a significant trend correctly; otherwise it is like either a gold mine that is not exploited, or wasteful path was chosen. We note that the major R&D initiatives are designed to receive only a relatively small fraction of the total research budget, because one must provide support for all fields including the seeds for the future major trends. Generally, one has to show a long-term, cross-cutting, high risk-high return R&D opportunity for justifying a funding trend. However, this may not be sufficient. From the above-listed six trends only the first two lead to multiagency national research initiatives, and there is *de facto* a national priority on health. Information technology and nanotechnology have received national recognition through the NSTC in 1999 and 2000, respectively. Another example is the support for global change, where a driving force has been international participation. We have summarized the main reasons of recognition for several programs in Table 1. A few years ago, NSF had proposed a research area on biocomplexity in environment, a beautiful and actual subject. This topic has not received so far equal attention by other funding agencies. A reason may be that no dramatic scientific breakthrough or surge of societal interest has been made evident at the date of proposal to justify reallocating funds at the national level. Cognitive sciences are key for human development and improvement, and it is expected that this area would receive an increased attention. Converging technologies starting from the nanoscale would be another area to consider in the future.

We could relate the S&E developments to the perception and intellectual ability of the contributing researchers. The left-brain handles the basic concepts and the right-brain looks into pictures and assemblies. 'Your left-brain is your verbal and rational brain; it thinks serially and reduces its thoughts to numbers, letters, and words. Your right brain is your non-verbal and intuitive brain; it thinks in patterns, or pictures, composed of "whole things"' (Bergland, 1985). Accordingly, the brain combines the reductionist elements with assembling views into a cooperative and

Table 1. Reasons for recognition: no unique process of identification of US national R&D programs (NSTC stands for US National Science and Technology Council; and PITAC for Presidential Information Technology Advisory Committee)

S&E funding trends in US	Main reason
'Information Technology Research' (1999–)	Proposed by PITAC; recognized by NSTC
'National Nanotechnology Initiative' (2000–)	Intellectual drive from bottom-up; recognized by NSTC
Medicine (NIH)	Public interest in health, and aging population; focus at the National Institutes of Health
Biology and bioenvironment	Distributed interest; NSF focus on biocomplexity
Cognitive	Not yet well recognized; included in education
Collective behavior	Not yet well recognized; not focused, part of others
Others in the last 50 years	
Nuclear program	National security
Space exploration	International challenge
Global change research	International agreements
Partnerships for a new generation of vehicles	Economical competitiveness; Environment

synergistic thinking approach. Those two representations of thinking may be identified as development steps for each S&E megatrend, as illustrated in Table 2.

It is relevant to keep track of this connection when developing a new research program. For example, the basic concepts originated in the left-brain allow individuals and groups to develop representations further from their primary perception. Let us consider the human length scale. Initially, humans used their hands and developed representations at their natural length scale; then, they used mechanical systems and their representation move towards the smaller scale of exact dimensions of those mechanisms; later, optical tools helped us move into the microscale range, from where electron microscopes and surface probes helped us move into the nanoscale range and nuclear physics, and so on. In a similar manner, abstract concepts handled by the left-brain has helped us move into larger scales: first the design of a building and geography of a territory; later the Earth representation (useful in sustainable development and global change R&D), then the universe representation (needed in space exploration). The left-brain would favor reductionism analysis and depth into a single field, which may contribute to the 'divergent' advancements. And for finite time intervals such advancement tend to develop faster, to diverge, to take a life of their own. Meantime, the 'whole think' approach is favored by the right-brain activities. It is the role of the right-brain to assemble the vision and global picture for each initiative, and see the coherence among them. This coherence leads to unifying concepts and converging technologies.

Table 2. S&E megatrends as related to human representation

Left-brain focus	Right-brain focus	S&E trend
DNA, cell (from natural environment)	Biosystems, organisms	Modern biology
Atom, molecule (from natural environment)	Patterns, assemblies	Nanoscale S&E
Bits (chosen language)	Visualization, networking	Information and computing

The societal feedback is the essential and ultimate test for establishing and assimilation of S&E megatrends. There are clear reasons: increasing wealth and improving health care, protecting a sustainable environment, enhancing the culture and the national security. That means, the scientific communities, government and society at large have the same goals when one looks from the national point of view and in the long term, even if the R&D funds for a megatrends favor some S&E communities in the short term.

Reasons, preparation, and approval process of the National Nanotechnology Initiative

Few reasons are defining this initiative:

- *The need for fundamental research* that may lead in the long term to systematic methods of control of matter at the nanoscale. All living systems and man-made products work at this scale. This is because all basic building blocks of matter are established and the basic properties are defined in the range between one and hundred molecular diameters. The first organization in biosystems is in the same nanometer range. For example, our body cells include typical nanobiomotors converting energies to the forms needed, such as chemical, electrical, mechanical, and vice-versa. The typical size of the organelles (see Figure 3) in a cell is 10 nm, which correspond approximately to 10 molecules of water. Such fundamental understanding may change our long-term strategies concerning health care, the way we mange the environment and do manufacturing. This is the first initiative at national level motivated and focused on fundamental research.
- *Nanotechnology promises to become the most efficient length scale for manufacturing*. While we know that the weak interactions at the nanoscale

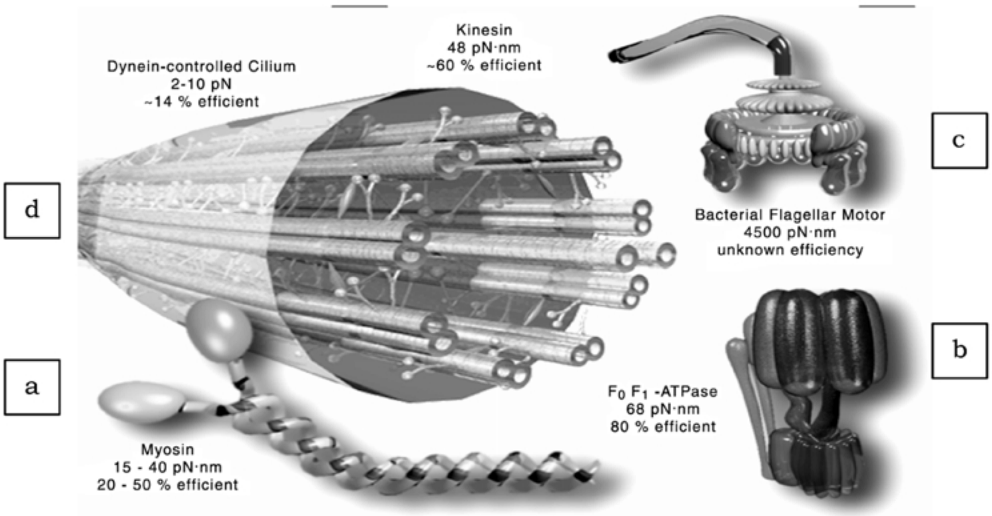

Figure 3. All living systems work at the nanoscale – illustration of cellular nanomachines (after C. Montemagno, 2001): (a) Myosin, the principle molecular motor responsible for muscle movement (characteristic dimension L about few nm); (b) ATP synthase, a chemical assembler (L about 10 nm); (c) Bacterial flagella motor (L about 20 nm); (d) A dynein-microtube complex assembled to form a cilia (L about 50 nm).

would require a small amount of energy for manufacturing, that precise assembling of matter would lead to products with high performance and without waste, we do not have systematic and manufacturing methods for economic production at the nanoscale. This is a reason we need to focus on fundamental research.

- *Large societal pay-offs are expected in long term in almost all major areas of the economy* (see Roco and Bainbridge, 2001). The properties and functions are adjustable and are a function of size, shape, and pattern at the nanoscale. Thus nanoscale sciences created a tremendous scientific interest. However, this would have not been sufficient to start a national research initiative. It has become of national interest only in the last two years because of the increased ability to manufacture products with structures in the nanometer range. This possibility promises a new industrial revolution leading to a high return on investments and to large benefits for the society.
- *Nanoscience and nanotechnology development is a necessary contributing component in the overall advancements in S&E* including digital revolution and modern biology, human sciences and collective behavior. The creation of 'hardware' through control at the nanoscale is a necessary square in the mosaic. The future will be determined by the synergy of all six research areas, and at the beginning between information, nano-, and bio-sciences starting from the molecular length scale. The developments as a result of the convergent technologies will be significant, but are difficult to predict because of discontinuities.

NNI was the result of systematic preparation. It was done with a similar rigorosity as used for a research project, and the documents were prepared with the same rigorosity as for a journal article. In 1996–1998, there was an intellectual drive to define nanotechnology in a broader sense, and reach a consensus with various S&E communities. In the interval 1997–2000, we have prepared the materials answering to the defining questions:

– What are the research directions in the next 10 years? (answered in 'Nanotechnology Research Directions' – a vision for the next decade, 1999; see http://nano.gov)
– What is the international situation? ('Nanostructure Science and Technology' – a worldwide study; 1999; see http://nano.gov)
– What are the societal implications? (Societal Implications of Nanoscience and Nanotechnology, 2000; see http://nano.gov)
– What is the vision and implementation plan for the government agencies? (NNI, Budget request submitted by the President to Congress, NSTC, 2000; see http://nano.gov)

– How we inform and educate the public at large about nanotechnology? (Nanotechnology – Reshaping the World Atom by Atom; see http://nano.gov)

Approval process began with various S&E communities and advanced with the positive recommendation of the Presidential Council of Science Advisory and Technology and the Office of Management and Budget. The President proposed NNI on January 21, 2000 in a speech at the California Institute of Technology. The proposed budget was then approved by eight Congressional committees including those for basic science, defense, space, and health related issues. Finally the Congress appropriated \$422m for NNI in fiscal year 2001 (see Roco, 2001).

The role of macroscale management decisions

It is essential that we take time for exploring the broad S&E and societal issues, for looking and planning ahead. This activity needs information at the national level and includes macroscale management decisions, which must be sufficiently flexible to allow for creativity and imagination to manifest during their implementation. Predictions are difficult because of the discontinuities in development and synergistic interactions in a large system. We learn about successes of macroscale visionary ideas and corresponding decisions in industry. One example is General Electric, where Jack Welsh has adopted a clear vision and measures structured at the level of the whole company for ensuring a long-term success. The R&D activities depend on the decisions taken at the macroscale (national), S&E community (providers and users), organization (agency), and individual levels. In addition, the international situation is increasingly affecting the results in individual countries. An international strategy would require a new set of assumptions as compared to the national ones (Roco, 2001b).

(a) *Macroscale measures at the national level.* The measures at the national level have broad and long implications. Different visions and implementation plans may lead to significantly different results.

(1) We will illustrate with an example. NSF collects information on the evolution of sources of R&D funding like the one shown in Figure 4. One observes that federal funding is relatively constant from 1992 to 1998. In the same interval, private R&D funding has increased and approximately doubled as compared to

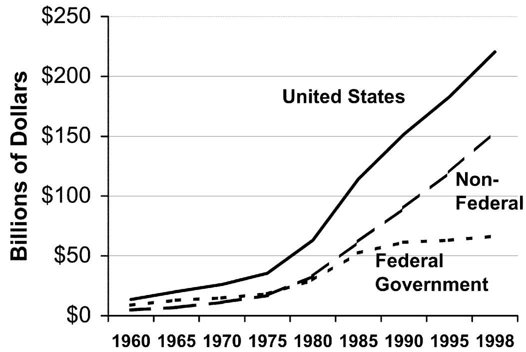

Figure 4. National R&D funding by source (NSF, 2000).

the federal government funding. Federal government share of support for nation's R&D decreased from 44.9% in fiscal year 1988 to 26.7% in fiscal year 1999. Also, more funds in industry are dedicated to funding development and applied research. Government needs to direct its funding more on complementary aspects: fundamental research (see the Bohr's quadrant in Figure 5) and mission-oriented projects that encourages depth of understanding, synergism and collaboration among fields (see the Pasteur's quadrant). Frequently, the focus in this last quadrant is on developing a generic technology.

Federal government provides funds for industry only under limited programs such as SBIR (Small Business Innovative Research), STTR (Small Technology Transfer), and ATP (Advanced Technology Program at National Institute of Standards and Technology) or for special purposes as DARPA (Defense Advanced Research Program Agency). By supporting applied research often means that a large number of exploratory research could not be funded if the total funding is constant.

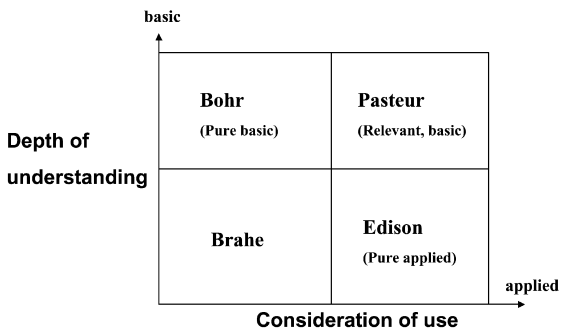

Figure 5. Pasteur's Quadrant (schematic after Stokes, 1997): redirecting R&D investments with a new role for engineering.

(2) Another example is the following. The proportion of life sciences in the R&D federal research funding has increased by about 13%, while the engineering sciences have decreased by the same percentage since 1970 in US. Funding in physical and chemical sciences have relatively decreased, too. This has changed not only the research outcomes, but also the education contents and the overall infrastructure. One way to address this imbalance is to prepare national initiative in complementary areas in such a way a balancing act takes place.

(3) The measures need a collective discipline and flexibility in implementation. A 'bio-inspired' funding approach of the major NNI research areas has been adopted. The funding agencies have issued solicitations for proposals addressing relatively broad R&D themes that were identified by panels of experts according to the agency missions; then, researchers respond with specific ideas in their proposals to those solicitations in a manner suggesting a bottom-up assembling process of projects for each theme.

(4) The coherence among various S&E areas should be evaluated periodically in order to create conditions for convergence and synergism. Figure 6 suggests that the major trends identified in this paper will play an increased role, beginning with the synergism of nanoscience, modern biology, information technology, and neuro-cognitive sciences. These four areas would provide new basic approaches, integrated from the molecular level up, with the main purpose of enhancing cognitive, human body, and social performance. This would create an unprecedented role for innovation that is envisioned acting as a transforming tool.

(5) Macroscale measures should address the increased role of the partnerships between the government sponsored research providers and industry.

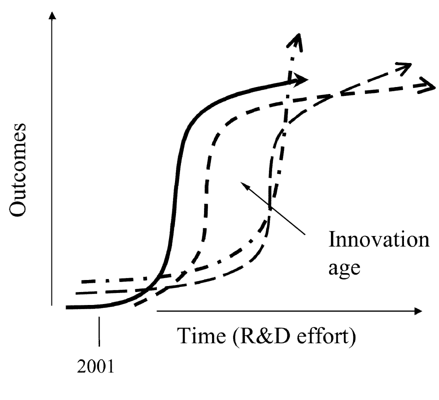

Figure 6. The 'Innovation age'(nano-bio-info-cognition).

Table 3. Nanotechnology in the world: comparison for industrialized countries' estimated government sponsored R&D in $millions/year (estimation Dec. 2000)

Financial year	1997	2000	2001
Western Europe	126	200	est. 225
Japan	120	245	est. 410
USA	116	270	422
Total triade	362	715	1057

(6) The measures should encourage international collaboration based on mutual interest. The US investments in the areas of nanoscience and nanotechnology represent about 1/3 of the global investment made by government organizations (see Table 3).

At NSF, support is made available to investigator initiated collaborations and through activities sponsored by the foundation. For example, periodical overview workshops with topics of mutual interest in nanoscience and nanotechnology are organized between the US and Swiss researchers (see Table 4). Future activities are in planning.

(7) National and cultural traditions will provide the diverse support for a creative society, and their role appears to provide also the continuity and stability necessary to a prosperous society.

(8) The role of taking visionary measures is essential to the long-term development of S&E in US. The speed of development, the coherence of various S&T trends, rate of implementation and utilization, are affected by macroscale managing decisions. The chief aim is to create the knowledge base and institutional infrastructure necessary to accelerate the beneficial use of the new knowledge and technology and reduce the potential for harmful consequences. To achieve this, the scientific and technology community must set broad goals, involve all the participants including the public, and creatively envision the future. The implementation

Table 4. Bilateral Swiss–US nanoforum events

Nanoforum in Zurich, September 1999	Focus on experimental and simulation tools (Co-sponsored by the Swiss Academy of Engineering Sciences, Swiss NSF, Swiss Association for Nanoscience and Technology, MINAST and US NSF)
Nanoforum in Princeton, December, 2000	Focus on nanobiotechnology and pharmaceutical processes at nanoscale (Co-sponsored by the US NSF, NASA, Swiss Academy of Engineering Sciences and Swiss NSF)

plans must include measures for stimulating the convergence and beneficial interaction among the S&E megatrends, including coordinated R&D activities, joint education, and infrastructure development.

(b) *Second level: strategic planning at the national level for the R&D providers and users of a S&E megatrend*. I will exemplify with the strategy adopted by the NNI. The main goal of NNI is to fully take advantage of this new technology by a coordinated and timely investment in ideas, people, and tools. A coherent approach has been developed for funding the critical areas of nanoscience and engineering, establishing a balanced and flexible infrastructure, educating and training the necessary workforce, promoting partnerships, and avoiding unnecessary duplication of efforts. Key investment strategies are:

– *Focus on fundamental research:* This strategy aims to encourage revolutionary discoveries and open a broader net of results as compared to development projects for same resources.
– *Policy of inclusion and partnerships:* This applies to various disciplines, areas of relevance, research providers and users, technology and societal aspects, and international integration.
– *Recognize the importance of visionary, macroscale management measures:* It includes defining the vision of nanotechnology, establishing the R&D priorities, and interagency implementation plan, integrating short-term technological developments into the broader loop of long-term R&D opportunities and societal implications, using peer review for NNI, developing a suitable legal framework, and integration of some international efforts. Work done under NSTC (White House) has allowed us to effectively address such broader issues.
– *Prepare the nanotechnology workforce*: A main challenge is to educate and train a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology. The concepts at the nanoscale (atomic, molecular, and supramolecular levels) should penetrate the education system in the next decade in a similar manner how microscopic approach made inroads in the last 40–50 years.
– *Address broad humanity goals:* Nanoscale S&E will lead to better understanding the nature, improved wealth, health, sustainability, and peace. This strategy has strong roots, and may bring people and countries together. An integral aspect of broader goals is increasing productivity by applying innovative nanotechnology for commerce (manufacturing, computing and communications, power systems, energy).
– *Identify and exploit the coherence with other major* S&E trends.

As part of a S&E megatrend, one may address a scientific and technological 'grand challenge' at the national level.

(c) *The 'organization level' is concerned with optimum outcome in each department, agency, national laboratory, or other organization.*

(d) *The 'individual level' addresses issues related to education, motivation, productivity, and personal involvement.*

Common ground for the 'science community' and 'society at large'

(a) We vision the bond of humanity driven by an *interconnected virtual 'brain'* of the Earth's communities searching for intellectual comprehension and conquest of nature (Roco, 1999). In the 21st century, we estimate that scientific and technological innovation will outperform for the first time the societal output of the physical activities separated by geographical borders. Knowledge and technologies will cross multiple institutional boundaries on an accelerated path before application, in a word dominated by movement of ideas, people, and resources. National and cultural diversity will be a strength for the new creative society. The interplay between information, nano-, bio-, and health-care technologies, together with cognitive sciences and cultural continuity will determine the share to progress and prosperity of national communities no matter their size.

(b) *Researchers need the big picture of different disciplines.* The current focus on reductionism and synthesis in research will be combined and partially overtaken by better understanding of complexity, crossing the streams in technology, crossing the national and cultural borders, and recognition of various aspects of unity in nature. The ability to see complex systems at the molecular and atomic level, will bring a new 'renaissance'. Leonardo da Vinci, equally brilliant in the art of painting as in mechanical, hydraulic, military, and civil engineering, expressed the quintessence of the known renaissance. The laboratory investigations started in the 17th century led to researchers on different reductionism paths. Nowadays, all disciplines discover the ability and are ready to work at the molecular and nano length scales using information and biology concepts: the reductionist divergence of S&E seems to regroup again and find a confluence. The collective, multiphenomena and multiscale behavior of systems between single atoms and bulk become the center of attention in order to extract new properties, phenomena and function – like a new alchemy. This 'big picture' approach would require depth in each discipline, and good communication across disciplines.

(c) *Visionary R&D planning pays off*, and it is essential to take the time to courageously look into the future. 'The best way to predict the future is to create it' according to Alan Kaye, Xerox Park. Technological progress may be accelerated by a wise structuring of S&E, and helping the main trends (or megatrends) be realized sooner and better. Why do we all of this? We cite Allen Greenspan (1999), the US Federal Reserve Chairman, who is responsible for establishing the interest rates, credited the nation's 'phenomenal' economic performance to technological innovation that has accelerated productivity. 'Something special has happened to the American economy in recent years... a remarkable run of economic growth that appears to have its roots in ongoing advances in technology'. We have seen in the last twenty years, that the industrial productivity has increased. This is the key reason why the US economy is growing. One may prove that there is a connection between science, engineering, and development. Productivity growth rate has increased from 0.8% during Carter years, to 1.6% during Reagan, 1.7% during Bush, and 2.1% during Clinton presidency. These increases are attributed to the technological innovation. Several case studies show that investment in research at the national level also brought about 20% additional benefits in private sector and 50% in social return. There is no single or proven way of development of S&E, and here is the role of taking visionary measures. The coherence and synergism of various S&E trends, and the rate of implementation and utilization are affected by the macroscale managing decisions. The measures must be based on good understanding of the global societal environment and long-term trends. A professor does not leave his students to do everything they like in the academic research. On the contrary, if a research goes well more resources are guided in that direction. The idea of setting priorities and providing the infrastructure to major promising projects should be held true at the national level, where one has additional advantages such as synergistic and strategic effects.

(d) *The risk of S&E developments should be evaluated in the general context of potential benefits and pitfalls in the long term.* Significant S&E developments inevitably have both desired and undesired consequences. Dramatic discoveries and innovations may create a tension between societal adoption of revolutionary new technologies in the future and our strong desire for stability and predictability in the present. Important research findings and technological developments may bring undesirable negative aspects. Bill Joy has recently raised such issues with the public. He went further and presented scenarios that would imply that nanoscale science engineering may bring a new form of life, and its confluence with biotechnology and information revolution could even place in danger the human species. According to one scenario, human species could have been enslaved by nanorobots. In our opinion, raising the general issue was very important, but several scenarios are speculative starting from unproven assumptions on nanorobots (see comments from R. Smalley, 2000) and other extrapolations. Also, the general reaction of society was underestimated. We had bacteria causing anthrax and chicken cholera as discovered by Pasteur about 100 years, but there was no systematic poisoning of our waters, air, etc. using these microorganisms that may destroy human species. However, one has to treat these aspects with responsibility. For this reason we have done studies and we tasked coordinating offices at the national level to track and respond to the potentially unexpected developments including the public and legal aspects. So far we all agree, that we do not have to stop building cars because cars may accidentally kill people on the street. While all possible risks should be considered, the need for economical and technological progress must be counted in the balance. We underline that the main aim of our national research initiatives is to develop the knowledge base and to create an institutional infrastructure to have broader benefits for the society in the long term. For this purpose it is very important to involve the entire community from the beginning including social scientists, to have a broader vision and be able to choose which way to go.

(e) *Contributions to the broader vision and its goals are essential* at any level of activity, including organizational and individual levels. Researchers and funding agencies need to recognize the broad societal vision and contribute to the respective goals in a useful and transforming manner, at the same time allowing the unusual (divergent) ideas to develop for future discoveries and innovations. The funded megatrends provide temporary drivers that seem to be part of the overall dynamics of faster advancements in S&E. In a similar manner, one needs to observe the international trends and respond accordingly. Internationalization with free movement of ideas, people, and resources makes impossible long-term advances only in one country. The cultural and national diversity is an asset for the creative, divergent developments in S&E.

In a system with R&D management structured at several levels (macroscale, single S&E trend at the national level, organization, and individual), the macroscale measures have large implications, even if they are relatively less recognized by the S&E community that is more focused on specific outcomes at the organization and individual levels and on distributing the funds. The recognition system centered on individual projects in R&D universities and other research organizations may be part of the reason for the limited recognition of the role of macroscale measures.

(f) *Maintaining a balance between continuity and 'new beginnings' (such as funding S&E megatrends) is an important factor for progress at all levels*. The coherence and convergence are driven by both the intrinsic scientific development (such as work at the interfaces) and societal needs (such as the focus on health care and increased productivity). The divergence tendencies are driven also by both internal stimuli (such as special breakthrough in a scientific and engineering field) and external stimuli (such as political reasons – see medieval age or communist age, religious, and military). We need to stimulate the convergence and allow for temporary divergences for the optimum societal outcomes, using for example the mechanisms of R&D funds allocation and enhancing education based on unity in nature. Such activities need to be related to the individual capabilities, where the left-brain (new beginnings) and right-brain (coherence) have analogous dual roles as the drivers of S&E trends.

(g) *The societal importance of innovation*, defined as 'knowledge applied to tasks that are new and different', is growing. In many ways, S&E has begun to affect our lives as an essential activity because of the innovation that motivate, inspire, and reward us. While the ability to work has been a defining human quality, and increasing industrial productivity was at the motor of the 20th century, we see innovation as being the main engine and joining other key humanity drivers in the 21st century. The coherence and divergence of major S&E trends is an intrinsic process that ensure faster progress in science and technology, enhancing human performance and improving the quality of life. We envision the S&E trends converging towards an '*innovation age*' in the first half of the 21st century. Current changes are at the beginning of that road. They are triggered by the inroads made in understanding the unity of nature manifested equally at the nanoscale and in broad complex systems, by reaching a critical mass of knowledge in physical and biological sciences and their interface, and by the increased ability to effectively communicate between the S&E fields.

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