The Next Technological Revolution:
Predicting the Technical Future and its Impact on Firms, Organizations and Ourselves.

A paper prepared for the MIT Sloan School's 50th Anniversary Celebrations
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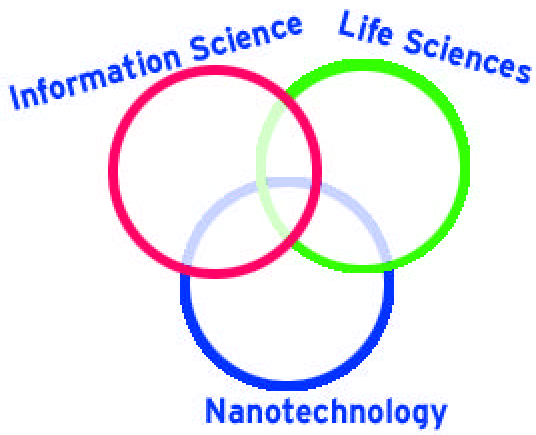
I. Introduction

Technology changes the world. Steam power, the railroad, electricity, the automobile – these technologies have changed how we work and how we live in irreversible ways. Within the last ten years, advances in telecommunications and computing have revolutionized communications, provided virtually unlimited data, and opened up new possibilities for products and services in nearly every industry.

In this brief essay, we draw on current MIT research to look forward: to explore how technology is likely to develop in the next twenty years and to begin to speculate on how these developments will change the commercial world. We sketch out the three areas in which we are likely to see the most progress – in information technology and communications, in the life sciences and in the science of the small, or "nanotechnology." Since each of these areas is far too large and far too complex to explore in any detail, we focus in depth on advances in medical technology, pervasive computing and water cleansing technologies for developing nations in an attempt to give the reader a sense for dramatic potential of current research. We also highlight developments in microelectro-mechanical devices to illustrate the ways in which current developments may interact with each other to create products and capabilities in ways that are almost impossible to foresee. Our goal is to give the reader a sense of the vibrancy, enormous potential, and sheer enthusiasm generated from the MIT research in these exciting fields. We hope to inform you, to pique your curiosity, and to provoke your thinking about the future.

II. General Trends

We are on the verge of the third industrial revolution -- the convergence of Information Technology, Life Sciences and Nanotechnology. *Information Technology* delivered the last technical revolution -- the Internet. The volume and creativity of current research guarantee that the pace of innovation in networks, telecommunications and computing will not slow. In fact, the rate of progress is probably accelerating. Advances in chemistry and biology in recent years have propelled *Life Sciences* to the forefront of scientific attention. New discoveries and improved understanding of cellular processes have spawned entirely new and exciting scientific fields such as proteomics, pharmacogenomics and genotyping. Each contributes to the real possibility of dramatically improving our health and extending the human life span. *Nanotechnology*, the study of matter at the atomic scale, promises to revolutionize our view of materials and offers unprecedented options for new machines and intermediate products. As the newest of the three, nanotechnology has achieved the fastest start from a funding perspective and is poised to surpass biotechnology and semiconductors in both scale and scope.



Information Technology

Look how far we've come! In the last 15 years, information technology and computer science have brought us into the Information Age with pocket telephones, email, automobiles that talk to us, laptops – a panoply of technical innovations that we take for granted but which were unheard of 10 years ago. New developments promise to continue at an aggressive pace. We can look forward to persistent computing and ubiquitous networks that sense conditions in our environment, control variable factors, analyze huge stores of information, and even predict the future. In a later section we focus on the impact of pervasive computing, but we offer highlights of a few compelling technologies here.

Network Grids

Computer network technology has evolved from loosely-connecting communication paths among computers, (i.e., sharing data via the Internet), to extremely tight coupling of multiple computers that create virtual super computers capable of sharing computational resources as well as data. These integrated systems will perform as a single machine, combining processing capacity and performance capable of solving some of the big scientific questions such as protein folding.

Neural Networks

Neural networks are software designed to mimic human brain activity and learning models. Neural networks are currently applied to a wide range of predictive computing applications, from sales forecasts based on historical data to mapping developments in cognitive science and neural biology. Prof. Amar Gupta of the MIT Sloan School uses neural networks in manufacturing operations analysis to minimize inventory requirements and optimize operational efficiency. Other applications include financial market forecasts, medical diagnostics (especially for tumor growth potential), and product market projections.

Quantum Computing

Although real applications are probably 20 years away, quantum computing is pushing the frontier of computational possibility. Scientists are beginning to harness the power of quantum mechanics to control and interpret atomic spin cycles that may solve currently-unsolvable problems such as the prime factoring of large numbers used in encryption. Prof. Issac Chuang, MIT Media Lab, has created a quantum computer and is leading multiple research projects to build powerful quantum computing architectures that aim to improve processing capacity, efficiency, and speed of classical computing.

Life Sciences

> *We are in the midst of one of the most remarkable revolutions in the history of mankind. The revolution was sparked by scientific curiosity about life, but its consequences will be so far-reaching as to touch every aspect of society. It is an information revolution, unlocking databases of human heredity and evolutionary history. It is a medical revolution, holding the prospect that our children's children will never die of cancer. And it is intellectual revolution that may reshape – for better or for worse – our notions of human potential.*
>
> *I refer, of course, to the revolution in Genetics and Genomics.*
>
> *Dr. Eric S. Lander*
> *Director of the Whitehead Center of Genome Research*
> *Professor of Biology at MIT*
>
> *Millennium Evening at the White House, October 12, 1999*

Dr. Lander's prophetic comments heralded the dawn of a new age of possibility. With the completion of the human genome map, we suddenly face the prospect of understanding -- and possibly controlling -- the mechanisms of life itself. Scientists, governments and investors have responded with unprecedented fervor, launching a range of research designed to capitalize on these discoveries and propel our knowledge even further. Below are four examples of current life sciences research taking place at MIT.

- The Whitehead Institute, a non-profit, independent research laboratory affiliated with MIT, was one of the leading contributors to the recent mapping of the human genome. Current work includes projects exploring molecular genetics, cancer genetics, neurobiology, infectious diseases, X-ray crystallography, biomedical engineering and cell and developmental biology.

- DNA microarray techniques now test hundreds of thousands of compounds against a target field in a matter of weeks instead of the many months it used take to analyze only a few a hundred. More and better information is now available in a fraction of the time, raising hopes for the discovery of many new drugs.

- Will we someday be able to determine the genomic sequence of an individual while they wait in a doctor's office? Paul Matsudaira, professor of biology and bioengineering and member of the Whitehead Institute for Biomedical Research, is creating hand-held bioanalytic devices designed to identify human disease genes. Other forms include disposable, plastic "lab-on-a chip" platforms that can analyze a tiny amount body fluid (e.g., blood or saliva) for biomarkers to determine the health of an individual or the status of a disease process.

- Many promising drug therapies fail clinical trials due to high toxicity in a small number of patients. Because we can evaluate the genetic make-up of individuals, and therefore isolate risky candidates, many of these discarded compounds could be revived, potentially saving the lives of people who are genetically receptive to the treatments.

The Science of the Small

Much of the most interesting work at MIT today focuses on the "science of the small" – on machines, materials and processes constructed at very small scales. Broadly, this work can be divided into two: into "micromachines": structures that are tiny but still visible and into "nanotechnology": technology at the molecular level.

Micromachines

Microelectro-mechanical systems (MEMS) are tiny machines, often only a cubic centimeter in size, designed to interpret information about our physical world at a microscopic level and execute multiple tasks as sensors, computers, communications devices, and actuators. Highly sensitive electronic sensors interpret physical stimuli such as light, sound, etc. and produce electronic signal input to the device. After analog processing, signals are translated to digital signals and then reconverted to analog. At various stages, they initiate appropriate communications protocols to external optical or electronic devices, to on-board microchips, or to internal actuator mechanisms that compel a physical response such as mechanically moving or controlling something, displaying information, or generating electric power.

Over the last 15 years, the MEMS industry has grown to annually generate revenues of USD 4 billion with projections that it will approach USD 10 billion by 2005 (source: Electronic Business, III-Vs, Electronic Buyer News, Solid State Technology). Advances in fabrication technology such as Prof Emanuel Sachs' "three dimensional printing" have helped to generate a number of exciting developments. In addition to highly-specialized equipment such aeronautical components and medical diagnostics, MEMS devices are included in increasingly common consumer goods such as accelerometers that trigger automobile airbags, microfluidic inkjet printer heads, optical projection displays, and radio frequency devices in cell phone filters.

Many of the new developments in MEMS technology will be focused on biology, optics and power generation.

- <u>Health monitor</u> – Implanted microchip devices could relay the status of blood composition, hormone levels, and various pressures -- basically ubiquitous sensing that cannot be accomplished any other way. Information could be used to identify precursor conditions for disease or even provide early warning of a heart attack.

- <u>Power Generation</u> -- Researchers are focusing on energy generation and efficiency with a goal to design a miniature power source that can produce at least 10 watts of power for a few hours. This alternative to batteries, which are not good at small scale, could remove a key obstacle keeping electric cars from the mass consumer market: the large size and very heavy weight of enough conventional batteries to power a car for an acceptable distance.

- <u>Fuel Cells</u> -- The US Army is investing in research to develop a small fuel cell, literally a micro engine with a generator. They envision a day when a piezoelectric transducer is stored in the heel of a soldier's boot, which is connected (wired) to the rest of the uniform. Each step generates a charge, providing power to communication equipment and other devices carried by the soldier.

- Persistent Sensing – MEMS sensors could also be used for civil engineering projects (e.g., bridges, buildings, and roads) to identify small changes in structural integrity, providing an early warning system to maintenance engineers.

Nanotechnology

Nanotechnology is the study of matter at the nanometer scale – one billionth of a meter – the size of a single water molecule. Researchers have drawn from all scientific disciplines including biology, chemistry, physics and engineering, to develop techniques that isolate molecular components for study under unusual and complex conditions. Scientists are now capable of creating new materials with advantageous features not found in natural compounds and have discovered new properties and behaviors of existing matter when addressed at the molecular level. With the aid of new scanning probe microscopes, they can even isolate individual atoms, picking them up and rearranging them at will.

Theorists paint astonishing pictures of the possibilities of this new technology that is poised to change the world by creating a USD 1 trillion annual market within ten years. Some of the claims are almost certainly simple hype; some are very real. Scientific development and market creativity will define the winners over the next five to ten years. Here are a few possibilities.

- Passive applications – materials that accomplish a task by virtue of their presence – are first to market and are available today in the form of impenetrable coatings for machine parts, protective clothing, and even the inside lining of tennis balls.

- Nanoelectronic circuits built from carbon nanotubes may some day break through the theoretical limits of silicon and allow production of a microprocessor with up to 5 billion transistors.

- Nanowire arrays built from nano-particle crystallization may potentially store trillions of bytes of data per square inch of storage medium.

- Fabricated nanomaterials that exceed the strength of steel at a fraction of the weight and cost may revolutionize many consumer goods and manufacturing processes.

- Nanoparticles called quantum dots reflect different waves of light depending on their size. They are used as biological markers and potentially as food coloring.

- Non-invasive diagnostics may be able to detect a tumor only a few cells in size when marked with nanoscale contrast agents.

Interactions across the Three Fields

Despite their differences, we believe that it is likely to be in the areas of overlap between technologies in all of three these areas – in IT, the Life Sciences and in the "Science of the Small" that the most dramatic advances are likely to take place. This is for two reasons. In the first place, all three fields face very similar challenges, and solutions that benefit one are likely to benefit the others.

- <u>Development of Tools</u> – progress in every field is dependent on the availability of interpretive tools that will measure, control, and diagnose the results of research. Appropriate tools are likely to be valuable across areas.

- <u>Fabrication</u> – successful implementation of many of these technologies requires new processes and factories to manufacture high volumes of precise machines at low cost. Again, progress in one area is likely to benefit the others.

- <u>Multi-purpose Use</u> – the viability of a technology will be determined by the variability and versatility of the applications it influences. Commercial success of a single development may depend on whether it can be integrated into multiple technologies or products.

- <u>Scale</u> – as technologies become more sophisticated, products often become increasingly smaller. Understanding the behavior of molecular particles and developing design techniques to harness them will be essential enablers of new technology.

In the second place, the most compelling and most important developments may well occur in the areas of overlap across the technologies. Below are just a few examples.

- Almost every facet of biotechnology generates massive amounts of data. A new field called bioinformatics, which crosses into the information technology realm, has evolved to address the particular requirements of storing and processing information generated from genome mapping, drug discovery and patient diagnostics.

- If we are to leverage the information provided by genotyping, we must understand the effect of gene expression at the cellular level. Kim Hamad-Schifferli, a Postdoctoral Associate in the MIT Media Lab, combined her knowledge of nanotechnology and biology to develop nano-scale bio-molecular tools that dehybridize DNA and ultimately regulate intracellular activity. This revolutionary invention allows researchers to "turn off" a particular gene -- without impacting the entire system -- to observe the impact on the cellular pathways.

- In the quest to achieve further miniaturization and increased capacity, semiconductor researchers have cultivated the realm of nanoelectronics and nanophotonics. Electrical engineers and computer scientists have come to rely not only on a new understanding of quantum physics for their work, but also to leverage the lessons biologists have learned from observing the pathways of various biomolecular devices.

- Biological computing – the pursuit of nanoscale circuits and wires built from biomolecules for computational purposes – lives right in the sweet spot. The burgeoning field of silicon biology draws from every hard science to develop biomolecular machines, field-effect biosensors, wireless biosensors, protein biochips and nanoelectronic devices.

III. Diving Deeper

With this "broad brush" overview of our technological future in mind, in this section we now focus in on a few particularly promising research programs. We have two goals. The first is to begin to put some flesh on the bones of our very general description. The second is to give the reader a sense of the uncertainty inherent in forecasting technological progress today with any precision. These technologies are fascinating, but they are also extremely complex. Trying to understand what may happen opens one up to the problem of the fractal: the more one understands, the more complex the phenomenon becomes.

We focus on four groups of technologies: on pervasive computing, on advances in medicine, and on two technologies designed for the developing world: water purification and instant eyeglasses. While the later two are much less "high tech" than the first, we include them deliberately since it seems to us one of the most important unresolved uncertainties of the next twenty years is that of the degree to which technological progress will benefit the poor and the disadvantaged.

Pervasive Computing

In 2015, the developed world will contain billions of micromachines capable of sensing, manipulating and communicating information about the environment, people, and objects. Buildings, homes and vehicles will become central computing platforms through embedded devices that interpret and modify conditions such as temperature, light, and sound, based on the pre-defined preferences of the individual using them. Convenient and powerful handheld devices will identify you and your preferences to the physical environment, provide the information you want, and allow you to communicate with your friends and colleagues. Wireless communications will facilitate all of these activities by connecting requests and creating sophisticated ad hoc networks as devices are moved throughout the network grid.

MIT's "Project Oxygen" is dedicated to realizing this idea through the development of integrated systems that are as available, accessible and useful to us as the air we breathe. Organized within the MIT Laboratory for Computer Science, Project Oxygen brings together world-renowned expertise in software, networks, hardware, knowledge management, artificial intelligence and security to create a new paradigm that weaves computing and communications into every aspect of our lives. The research focuses on four key technologies: on "environmental devices", or "E21s"; on handheld devices, or "H21s"; on networks, or "N21s"; and on work in knowledge and semantics.

Devices

The Oxygen researchers envision environmental devices called "E21s" will be embedded within the physical structures of "intelligent spaces". They will serve as the nerve center, directing communications requests, completing computational tasks, and managing network connectivity. E21s will interpret presence and activity in open spaces and facilitate seamless communication among people and the central network through microphones, cameras and computational interfaces. Human communication with E21s will be as simple as a voice command or a waving arm gesture.

Mobile handheld devices called "H21s" will provide the personal link for users to communicate with the E21 platform. They will also provide functions like telephone service, Internet access, streaming video, and voice recognition. The network and communication pathways used by the H21s will be dynamic and self-changing, because the devices will determine their function and choose the device or network interfaces that are most appropriate to meet the needs of a particular user in a particular time or place. For example, your verbal request to see budget spreadsheets you created last week would prompt your H21 to connect to the company intranet, conduct a search for the appropriate files, and display them in a logical order.

Networks

Communication among these devices will be controlled by networks called N21s that will configure themselves based on the changing requirements of the E21s, H21s, and people in the room. In addition to managing network traffic and authentication, N21s will create and control ad hoc networks called collaborative regions, comprised of a group of devices gathered for a particular purpose or timeframe. N21s will enforce security and access policies, and they will support multiple communications protocols that will adapt as applications and device standards evolve.

Knowledge and Semantics

E21s, H21s and N21s will not reach their full potential without the move from an information source that requires human interpretation to one that embeds meaning within the data itself, so that machines can navigate and solve problems independently. The evolution of our current World Wide Web to this kind of "Semantic Web" is the vision of its inventor, Tim Berners-Lee, and represents a critical component of Oxygen.

The Semantic Web will provide a structural framework that will define data and guide automated processing by identifying the data type, defining potential uses, proposing logic, and imposing rules related to the information. Specifically, the Semantic Web will use RDF language that documents the relationships between objects. Objects have meaning, and the relationships between the objects (semantic links) have meaning as well. By documenting the meaning of data and the links between data, applications can merge or interconnect disparate data from other applications. In this environment, software agents will be able to understand relationships between objects and perform work on our behalf.

The Future of Pervasive Computing

If these technologies are successfully developed they will have dramatic implications. The following business conference scenario developed by the Project Oxygen team provides one possible example:

> Hélène calls Ralph in New York from their company's home office in Paris. Ralph's E21, connected to his phone, recognizes Hélène's telephone number; it answers in her native French, reports that Ralph is away on vacation, and asks if her call is urgent. The E21's multilingual speech and automation systems, which Ralph has scripted to handle urgent calls from people such as Hélène, recognize the word "décisif" in Hélène's reply and transfer the call to Ralph's H21 in his hotel. When Ralph speaks with Hélène, he decides to bring George, now at home in London, into the conversation.
>
> All three decide to meet next week in Paris. Conversing with their E21s, they ask their automated calendars to compare their schedules and check the availability of flights from New York and London to Paris. Next Tuesday at 11am looks good. All three say "OK," and their automation systems make the necessary reservations.
>
> Ralph and George arrive at Paris headquarters. At the front desk, they pick up H21s, which recognize their faces and connect to their E21s in New York and London. Ralph asks his H21

where they can find Hélène. It tells them she's across the street, and it provides an indoor/outdoor navigation system to guide them to her. George asks his H21 for "last week's technical drawings," which he forgot to bring. The H21 finds and fetches the drawings just as they meet Hélène.

Advances in Medicine

The right medicine for the right patient at the right dose at the right time.

Current research in genetics and in materials technology have the potential to dramatically improve the range and effectiveness of existing biomedical treatments. Here we touch briefly on three exciting developments: on the use of single nucleotide polymorphisms, or SNPs, to find new drugs, on new techniques for controlled drug discovery and on recent advances in tissue engineering.

Personalized Medicine: Using Individual Phenotypes to find New Drugs

The Human Genome Project produced a consensus DNA sequence map of the human genome that describes 99.9 percent of the genetic composition of individuals. The remaining 0.1 percent – one in every 1,000 letters – describes the characteristics that make an individual genetically unique and also determines predisposition to or protection from disease. These variations are called single nucleotide polymorphisms (SNP).

On the clinical side, information from SNPs can be used to map a patient’s genetic makeup, sometimes referred to as genotyping. Knowing a patient’s genotype will allow doctors to better diagnose diseases and prescribe medicines accordingly. On the drug development side, pharmaceutical companies can take advantage of SNP information to develop drugs that act with more potency and fewer side effects on patients with specific genetic profiles.

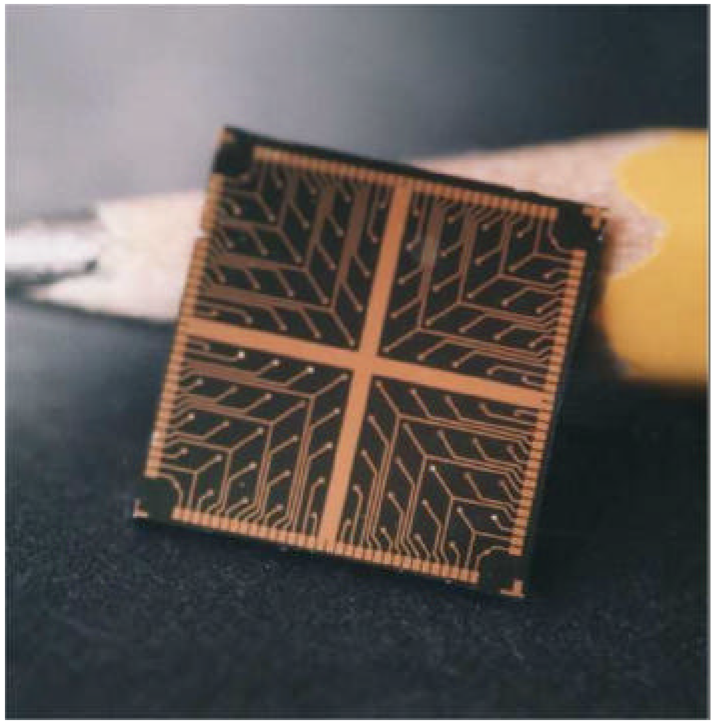
Many researchers see SNPs as the genomic keys that will open the doors to personalized medicine. SNPs may help explain why individuals respond differently to the same drug. As we learn more about the influence that human genetic composition has on the disease process, we will understand more about the metabolism of medicine. Once these pathways are further understood, targeted gene expression and protein synthesis may be controlled to achieve optimal individual reaction to a drug.

Herceptin, produced by Genentech, is a successful example of this type of personalized therapy. Herceptin (Trastuzumab) is the first targeted, humanized monoclonal antibody for treatment of women with HER2 (human epidermal growth factor receptor 2) positive metastatic breast cancer. Herceptin is designed to target and block the function of HER2 and is only effective on the subset (about 20%) of breast cancer patients who have a genetic profile of HER2 overexpression. A genetic test to determine whether the patient over-expresses HER2 is needed before Herceptin is prescribed.

Controlled Drug Delivery

To date, most malignant brain cancers were largely untreatable due to two complications. First, although the brain tumor is localized, the vast majority of chemotherapy drug therapies are delivered systemically, and significant doses of chemotherapy must be frequently administered. This exposes the entire body to the action of the drug and results in potentially significant side effects and substantial patient discomfort. Second, the blood-brain barrier prevents a variety of blood-born chemicals from penetrating the brain and reaching brain cancer cells.

Dr. Robert S. Langer, Kenneth J. Germenshausen Professor of Chemical and Biological Engineering at MIT, has changed the way brain cancer is treated. His approach offers new hope to patients with this severe, life-threatening disease. Langer collaborated with Dr. Henry Brem, currently Director of Neurosurgery at Johns Hopkins, to design a biodegradable polymer that releases medicine at a controlled rate. About the size of a dime, the surface-degrading wafer is impregnated with cancer chemotherapeutic drugs. The wafers are implanted during the tumor removal surgery. The chemicals are released locally, directly to the tumor site, in high concentrations over a period of 2-3 weeks. Consequently, the drug is contained within the brain where it is needed and therefore does not cause the systemic toxicity typical of anticancer drugs that often result in liver, kidney or spleen damage. In clinical trials, the wafer has been shown to significantly prolong patient survival while improving the quality of life. Approved in 1996 by the FDA, the wafers became the first new treatment for brain cancer in 25 years. This is the first polymer-based treatment to deliver chemotherapy directly to a tumor site, and this kind of approach is already proving useful in the treatment of other cancers, in the development of polymer-drug coated stents and a variety of other conditions.



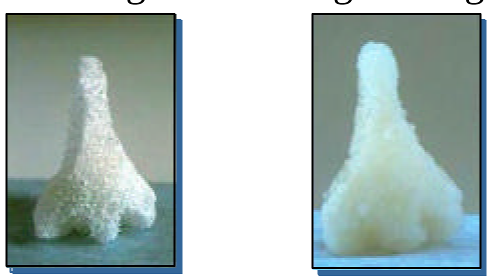
(Photograph by Carita Stubbe, provided courtesy of MicroCHIPS, Inc.)

Langer has also pioneered research in remote-control systems for drug delivery. The rate at which the drug is released can be controlled using ultrasound, electric pulses, or external magnetic fields. Eventually, the drug release can be controlled and activated on demand by a biosensor to create a smart delivery system. An implantable "pharmacy-on-a-chip" was recently prototyped in Langer Lab. The microchip is made of silicon and contains multiple (up to 1000) drug reservoirs. Scientists in the Langer Lab hope that someday doctors will be able to monitor a patient's vital statistics and blood chemistry as well as administer appropriate medicine remotely. In addition to potentially treating diseases such as prostate cancer, ovarian cancer, endometriosis, and severe bone infections, the same type of slow and controlled-delivery system may someday be applied to insulin, growth hormones, gene therapy agents, and vaccines.

Tissue Engineering

Dr. Langer is also a pioneer in tissue engineering, developing methods for synthesizing artificial cartilage, skin, liver, nerves and blood vessels for human transplant. Langer's method is to build biodegradeable polymer matrices in an appropriate shape and infuse them with bio molecules, often cells from the patient’s own body, to create replacement tissue. This approach provides tremendous flexibility in design and application and can be applied to a wide variety of structural requirements. Langer and Joseph Vacanti created the tissue engineering field because there were not methods to treat patients dying of liver failure such as those being treated by Vacanti, a transplant surgeon. Their studies could also lead to new ways of growing cartilage, for example for patients without ears. In one study, after preparing the matrix in the approximate dimensions, a tissue engineered ear was implanted on the ear of a rabbit for incubation. It will someday be grown to the appropriate size for a child.

Cartilage Tissue Engineering



BEFORE
cell seeding

AFTER
2 weeks in culture

(Photo courtesy of Dr. Robert S. Langer)

For blood vessel engineering, Langer and Laura Niklason, a former Postdoctoral Associate in the MIT Chemical Engineering department and now a Professor at Duke University, took a similar approach. They have achieved artificial structures that exhibit all the characteristics and strengths of natural blood vessels. A polymer structure is coated with cells that mirror the cellular structure of a natural blood vessel: smooth muscle cells on the outside, endothelial cells on the inside. Although endothelial cell cultures can be grown from a variety of sources, Shulamit Levenberg, another MIT Postdoctoral Associate, showed that human stem cells provide the greatest efficacy. After the structure is cultivated to the desired dimensions, the vessel is pulsated with an electric pump that propels fluid at an ideal rate and pressure.

Langer, always searching for new applications of his technology, is working with Julie Andrews, the singer, to develop new repair techniques that will restore the delicate tissues of damaged vocal cords. In collaboration with physicians at the Massachusetts Eye and Ear Infirmary, researchers at the Harvard Medical School, and Mariah Hahn, an MIT graduate student in computer science and electrical engineering, Langer is considering three approaches to solving the problem: injection of an elastin or collagen to improve elasticity, introducing engineered material to replace portions of the vocal cord tissues, or "growing" a new vocal cord via introduced matrices.

Dr. Shuguang Zhang, Associated Director of the Center for Biomedical Engineering, is tackling similar problems using biological scaffolds rather than polymer matrices. The self-assembly properties of human proteins were discovered in 1993, and stimulated the research that led to the discovery of synthesized peptides that create a biological matrix scaffolding for cell attachment and cell-based transplants for regenerative medicine. The peptide gel is about 98% water with very high viscosity for good support. It allows cells to move freely and combine in 3D structures just as they would in nature. "Cartilage gel," the first application, may repair damaged cartilage, potentially providing relief to weekend athletes as well as osteoarthritis patients. John Kisiday, a graduate student in the Biomedical Engineering Division, is hoping to create a gel which will transport living cartilage cells directly into the joint and provide a supportive environment while the implant takes hold. After it is no longer needed, the extraneous material will simply erode away.

Clean Water for a Billion People

Today, over 1.1 billion people do not have access to safe, clean drinking water. Two and a half billion people do not have access to sanitation services. Each year, 2.2 million people, most of them children, die of illness related to unclean water, poor hygiene or unsatisfactory sanitation.[i] These are typically the poorest citizens of developing countries. With global population expected to increase by 20% to 7.1 billion by the year 2015, the problem will only get worse.

In addition to the high mortality rate, waterborne illnesses claim close to half the population in the developing world at any given time.[ii] Diarrhea, Ascaris, Dracunculisis, Hookworm Schistosomiasis and Trachoma are responsible for severe malnutrition that leads to stunted physical growth, impaired cognitive development, and blindness. Poverty manifests as a continual negative spiral for underserved communities – poor people cannot easily pay for access to clean water that will improve their health because they are too sick to work and earn income.

Susan Murcott, Lecturer in the Department of Civil and Environmental Engineering, founded the Nepal Water Project to provide onsite water analysis and household cleansing solutions to people that need it. Her graduate students conduct research and design experiments during the academic year and spend at least a month in the field, testing and applying their theories and solutions. Last year, Murcott's students won three separate awards: the MIT IDEAS Design Competition for colloidal silver ceramic filters for Nicaragua; the Lemelson international prize for microbial/arsenic treatment system in Nepal; and the MIT $1k Business Idea Warm-Up Competition for very low-cost chlorine manufacturing for water treatment systems in Haiti.

In addition to providing the technology solutions that will clean household water, Murcott and her students are interested in helping people become self-sufficient in their water cleansing efforts. For example, local potters are engaged in clay vessel and filter design and production. Similarly, community leaders are trained in appropriate hygiene behavior and learn about the dangerous health effects of contaminated water so they can provide education and local support throughout the year.

Murcott emphasizes that no single technical solution will work for all regions. Sustainable treatment programs must address the specific purification needs of local water and support the cultural norms of the community. However, all solutions share the following characteristics:

- Perform well technically – consistent particle removal to reduce turbidity and microbial (bacteria, virus, protazoa, helminth) removal at acceptable levels
- Low-cost – not more than USD 3-15 per household per year
- Socially acceptable – gender sensitive, acceptable taste, e.g., minimal chlorine residue
- Locally available and appropriate – parts and systems from acceptable materials that can be easily distributed, especially to rural areas
- Simple to use – transferable to illiterate users
- NO ELECTRICITY REQUIRED![iii]

One of the difficulties of treating water in the field is identifying the composition and level of contaminant in the water. Typical diagnostic processes depend on incubating water with a substrate for at least 24 hours. Most incubators require plentiful electricity, which violates the most emphatic rule.

To solve this problem, Murcott teamed with Amy Smith, who won the Lemelson-MIT Student Prize for Innovation and Invention for her laboratory incubator. Smith's design maintains temperature via phase-change material without the need for electricity or electronic parts.

Typically, household water cleaning systems that meet these qualifications are contained within simple, spigot vessels, usually produced locally from plastic or pottery. Filtration systems are comprised of at least two containers that hold various sand aggregates or fibrous material that trap impurities as the water transfers from one well to the other. Most sand filters are easily maintained by simply stirring the top 5 cm of sand, breaking up the biofilm layer that forms through use, and replacing the highly turbid water that results with relatively clean water. There is no incremental cost or labor associated with filter cleaning.

This arsenic removal system is comprised of three vessels. Contaminated water is poured into the top portion containing course sand and iron nails. The water flows to the second stage containing fine sand and charcoal. Finally, the clean water is collected in the bottom chamber. This relatively simple and elegant design meets the core criteria and effectively removes 98% of arsenic concentrations of 300 parts per billion, bringing the level to internationally-accepted levels of 0 to 5 parts per billion.

Solar disinfection systems use solar ultraviolet and thermal radiation to purify water in clear plastic bottles that are filled and left in the sun for at least 48 hours. Estimating that each person requires 10 liters of water per day, a family of five will have 75 1-liter bottles in transit over 3 days. While a bit cumbersome, this method is simple, inexpensive and requires no chemicals. Murcott's students are concentrating on the variations in diurnal temperatures in different climates as well as whether bottle materials can be enhanced through insulation or other materials to increase the temperature of water in the bottles.

Chlorine is an effective water cleanser. A few drops added to a bucket of contaminated water will clean it to acceptable drinking levels in a few minutes. Residual chlorine taste and availability of the chlorine itself are the greatest obstacles to this method. In Nepal, powdered chlorine bleach is available only as an import from India, making an inexpensive and consistent supply nearly impossible.

However, a portable machine that generates sodium hypochlorite from local salt and tap water may provide an acceptable solution and build a cottage industry for local communities. Because the machine requires an adequate supply of electricity, production facilities should be established in central locations, probably cities. Establishment of supplier and distributor networks is planned to ensure efficient delivery to local and remote dealers, NGOs, hospitals, and centralized water treatment plants, thus creating an economic boost while solving a social problem.

Low Cost Eyeglasses

Saul Griffith, doctoral candidate in the MIT Media Lab and technology history buff, solved a nagging problem using technology that is over 140 years old. While on a volunteer mission to provide people with free glasses in Guyana, Central America, Griffith and his colleagues felt with increasing frustration that their efforts weren't really solving the problem. "We could determine the right prescription using portable diagnostic equipment and that was okay. But then we had to search through boxes of donated glasses to find something close to the solution."

Previous attempts to solve this problem had focused on creating water-filled lens that are pressurized to achieve the desired refraction, but these proved unsatisfactory because of the high manufacturing complexity and weight of each pair of glasses, as well as the fact that the multiple interfaces led to many internal reflections in certain lighting conditions. The range of correction was also limited and would not correct for astigmatic error. Griffith reversed the standard approach such that the complex flexible surface became the mold, not the final product. Modifying this technique he was also able to produce arbitrary mold surfaces programmatically that included astigmatic and even progressive lenses. All of this was fitted into a portable device that produces a plastic lens of uncompromised quality to specification in about 10 minutes.

He partnered with two Harvard Business School students to found a company called Low Cost Eyeglasses and won the HBS Social Enterprise Business Plan Contest in March 2001. The business model aims not only to improve the vision of billions of people but also to create entrepreneurial opportunities for people who live in developing economies.

Forecasting the Impact of Advancing Technology

These brief descriptions leave unanswered the question of exactly how and when these kinds of technologies will impact the impact the commercial world. Many of these technologies – perhaps half – will never reach the market at all. They will prove to be technically infeasible, or there will, in the end, be no real need for them. Unfortunately we have no way of knowing, ex ante, which half will prove to be the ones that do make it to the market. Predicting their likely impact is even harder. Recall ADL's famous prediction that the entire world market for the computer was likely to be less than ten units – or the skepticism with which the telegraph was initially greeted. Really important, world changing technologies have a history of being used in ways that no one – least of all their inventors – really expected. Who would have predicted that the teenage market would be critical to the development of wireless communications?

Nevertheless, we speculate below on the four ways in which we believe that these technologies will change the world: on their implications for the firms and industries for whom these technologies are likely to be "disruptive", for the privacy and security of individuals, for the global structure of production and distribution and finally, for the changing strategic role of technology inside the firm.

The disruption of firms and industries

The technologies that we have discussed are likely to have their most obvious impact on those individual firms whose business models and product lines they threaten to replace. While the collapse of the Internet bubble has made it less fashionable to worry about "disruption", significant technological shifts have a history of creating very significant problems for established firms. IBM and Digital Equipment did not make the money from the PC revolution: Intel and Microsoft did. Even in the much maligned case of the Internet, it is clear that many industries – notably travel and financial services – will never be the same again. The kinds of advances in IT, in the life sciences and in nanotechnology that we have discussed above are likely to have similarly dramatic competitive consequences.

In IT, it is already clear that a move to embedded, mobile computing based around an open architecture presents the business models of many of the current industry leaders with tremendous challenges. The collapse in telecommunications stocks and Microsoft's announcement of its ".NET" architecture are symptoms of this uncertainty.

In the life sciences, a move to personalized medicine and the development of therapies that are targeted to an individual's genotype would run directly counter to the pharmaceutical industry's current focus on the development of "blockbuster" drugs. Will the major pharmaceutical firms be able to cover their research and development costs if there are many more drugs, each selling to a much smaller population? Will the considerable skills they have developed in marketing and sales be rendered obsolete by the new technologies? Will diagnostic laboratories be disintermediated when lab-on-a-chip technology provides immediate feedback on a patient's condition?

The new materials and the move to nanotechnology open similar questions. Du Pont, for example, has announced a major commitment to "biologically based materials" as a long term replacement for their petrochemically based business, but such a switch will make many of their existing competencies obsolete, and presents the firm with very significant organizational challenges.

The flip side of these concerns, of course, is that the new technologies will open up enormous opportunities for newly founded, entrepreneurial firms. Truly ubiquitous computing coupled with the widespread deployment of integrated micro sensors will probably lead to an order of magnitude increase in the amount of available information. The ability to instantly obtain this information will launch new service lines and may even create new industries in manufacturing, distribution, data mining and analytics and a wide range of security and privacy applications.

The Impact on individuals

These technologies are also likely to have a very significant impact on us all as individuals. The initial rumblings as to the importance of individual privacy that have surfaced around the Internet and around the increasing consolidation of commercial data banks are likely to become a shout. The technology will soon be available to link nearly every data base on earth: to have that information instantly available at any point: to track every transaction, and even every movement of every "connected" individual. Such power has an obvious potential for abuse. How much do you wish others to know about you? How vulnerable is your life if much of it is instantly visible to possibly unauthorized eyes?

Advances in medical technology will raise similar concerns. There has already been much discussion about the pros and cons of genetic screening: do you want your employer to know that you have a genetic susceptibility to depression? If a company knows an employee is predisposed to a fatal illness, can it compel that person to undergo preventative therapy? But it will very soon be possible to implant a sensor that will transmit detailed data about your moment to moment physiological condition to… your employer? Your estranged wife? The technologies of the next twenty years are not "out there". They will not happen "somewhere else." Their small size and their ubiquity will make them truly pervasive, and this ubiquity will bring with it either a vigorous and sustained conversation about the appropriate use of information or an extension of control and the associated opportunity for abuse that will have transforming implications for our society.

From a more optimistic perspective, these new technologies have the potential to significantly increase our quality of life. Better therapies will bring obvious benefits, but it may be that the biggest benefit we can expect is that local, embedded, micro sensors will give us a better idea of where our time is going and of how we are reacting, physically, to what we are doing. Perhaps the next wave in technological development will help us become a significantly less stressed, more aware society.

The Global Structure of Production

Thirdly, there is the possibility that these technologies will change the very structure of firms and organizations. We have already seen that recent advances in telecommunications have made it possible for ten person firms to become truly global in a way that would have been unthinkable twenty years ago. It may be that the new technologies will only accelerate this trend. As products and machines become very small, production and distribution may become very local. This may preclude the need for large-scale and expensive factories and could encourage companies to establish a larger number of smaller facilities. Will organizations become more decentralized and therefore smaller? They might.

However, implementation of the Semantic Web and corresponding device development will allow companies to control ever increasingly large volumes of information, support huge employee bases and potentially capture even greater market share. Will emerging economies of scale in data management remove the limits to growth and encourage formation of monolithic companies? Will we see a world in which the consolidation of economic power into a few very large firm continues? We might.

There is also a real possibility that these new technologies may open up qualitatively different development paths for some of the developing economies. Does the move toward small scale, low energy products open up the potential for broader application? Will developing countries exploit future research, development and production opportunities to leapfrog over the established competition? We know that cellular phone technology in South America and wireless infrastructure in China exceeds the US standard. In many ways, developing countries are well positioned to participate in the next wave of technological innovation and production. The move toward small scale, and low energy products may open up the potential for broader applications, further expanding the potential market. New fabrication facilities to manufacture new devices and tiny machines will be built in areas with low cost land and labor forces. Research, development and production opportunities abound. A significant percentage of nanotechnology researchers, for example, are from rapidly developing economies. If they return en masse to their countries, expertise in advanced technology will migrate with them. Can the new technologies have a significant impact on the quality of life for the billions of the world's inhabitants who are so much less fortunate than we are?

A Changing Strategic Role for Technology?

Lastly, we predict that the days when technology could be safely left in the hands of R&D are over, if they were ever here. The work that is in the labs now has truly startling potential. If there are real interactions between the three streams of work: between advances in computing, biology and the "science of the small" – and the beginnings of such interactions are already visible – then they will have advances that no one can predict. The innovative networks that we see now between the public and private sectors and between large and smaller firms are likely to become increasingly important and increasingly pervasive. Making decisions as to which technologies to invest in internally, which externally and which to simply "watch" will become increasingly costly and increasingly important. The returns to managing technology strategically: to being fully aware of what is likely to happen and to having thought through how the organization will respond to the future while simultaneously maintaining the ability to run "conventional" businesses continuously in an appropriate way will be enormous.

Some organizations are already experimenting with the appointment of a "Chief Innovation Officer" and with integrating technology much more closely into the strategy of the firm. These are clearly important steps and we expect that they will become commonplace. However we suspect that they may not be enough: that twenty years from now sophisticated technological literacy will be as central to the CEO's job as financial literacy is now, and that technology will have transformed the world in ways in which we have not even begun to imagine.

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