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Nanocomputers: Technology, Design, and Implications

A Interactive Qualifying Project Report

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By

Brendan M. Smith

and

Mary A .Devlin

Approved:

William G. McGimpsey, Ph.D
WPI Project Advisor
Worcester Polytechnic Institute

1. nanotechnology
2. computers
3. society

Kristen Wobbe, Ph. D
WPI Project Advisor
Worcester Polytechnic Institute

ABSTRACT

The current technology used to construct computer microprocessors is quickly reaching its limits. The field of nanoelectronics may represent a new strategy for the computer industry to continue its rapid pace of increasing chip complexity and speed. This report provides a detailed overview of current research trends in this field to facilitate a broad understanding of the social and economic implications associated with the development of nanoelectronics and nanocomputing.

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PROBLEM STATEMENT

> "[Shockley, Bardeen, and Brattain] were awarded the Nobel Prize for physics for their invention, in 1947, of the point contact transistor. This device was not an instant success, because it operated over a limited range of frequencies, could amplify only to a limited degree, had limited stability, and was expensive to manufacture. It would have been difficult to predict at this point the shape of things to come. *[Rosenberg,* 1986]"

The feature sizes on the computer microchip have been steadily decreasing for the past thirty years while the fundamental operating principles behind them have not changed. As the semiconductor industry exhausts the capabilities of current technology, the field of nanoelectronics is being researched in order to continue the trend of smaller feature size and increased computing speed. It is the goal of this IQP to summarize current nanoelectronic research and to propose the possible implications of such technology if it becomes commercially available.

2. METHODOLOGY

2.1 INTRODUCTION AND LITERATURE REVIEW

The background information serves to educate our audience. The reader must have an in depth understanding of the history of computers and nanotechnology as well as the current innovations in the field of nanoelectronics before we can begin to tackle the enormous technological and societal implications such a technological advance could have on society.

Within this IQP, we have reviewed the existing body of literature concerning nanoelectronics and compiled a report upon its history of development, scientific foundations, current progress and probable implications. This has involved a thorough examination of periodicals, books, reports, opinions of those involved in the field, and of various other resources available on the world wide web. The majority of information on nanoelectronic technology under current development is available from scientific journals such as Nanotechnology, Science, Nature and Scientific American.

2.2 IMPLICATIONS

The probable implications of nanoelectronics has been researched through conventional library methods of books and periodicals, the world wide web, and various interviews, both personal and through e-mail, of relevant professionals - both scientists researching nanoelectronics and ethicists. There are a large number of references available in books, journals, and on the world wide web concerning the implications of the computer revolution. From this information, rational extrapolations on the effect of nanoelectronics can be made. In this paper we have balanced these projected impacts with the recorded ramifications of a computerized society.

2.2.1 EMAIL CONTACTS

We contacted the following professionals via email and solicited their opinions upon the implications of nanoelectronics with several questions (see Appendix A). We chose these professionals because of their work in the field of nanoelectronics, described below:

- **Jonathan P. Bird** (pird@asu.edu) - Associate Professor of Electrical Engineering at Arizona State University and member of ASU's Nanostructures Research Group (http://www.eas.asu.edu/~nano). Dr. Bird's research interests include studies of quantum transport in semiconductor nanostructures and of materials at ultra low temperatures and high magnetic fields. He has co-authored more than seventy publications in peer reviewed journals to date and his research is undertaken in collaboration with partners in the United States, Australia and Japan.

- **J. Storrs Hall** (josh@cs.rutgers.edu) - Senior scientist in the Laboratory for Computer Science Research at Rutgers University and moderator of the sci.nanotech usenet newsgroup. His research interests include computer architecture, artificial intelligence, particularly agoric and genetic algorithms as used in design, nanotechnology, and reversible computing.

- **David Ferry** (ferry@asu.edu) - Regents' Professor of Electrical Engineering at Arizona State University and member of ASU's Nanostructures Research Group. His research interests include quantum transport, quantum devices, and e-beam lithography.

- **Michael P. Frank** (mpf@.stockmaster.com) - Computer Science Ph.D. candidate in the EECS Department at MIT working in the Artificial Intelligence Lab under Professor Tom Knight on reversible computing. His paper, "Ultimate Theoretical Models of Nanocomputers," presented at the Fifth Foresight Conference on Molecular Nanotechnology in 1997, discusses asymptotic scaling issues and compares the performance of a variety of reversible and irreversible technologies.

- **James Tour** (tour@psc.sc.edu) - Professor in the Department of Chemisty and Biochemistry at the University of South Carolina. Dr. Tour researches new conjugated polymeric materials for incorporation into molecular-based electronic instrumentation. He has synthesized and tested the first functional molecular scale wires.

- **Calvin Quate** (quate@ee.stanford.edu) ~ Professor of Electrical Engineering and Professor of Applied Physics at Stanford University and inventor of the atomic force microscope. His research focuses on fabrication of microelectromechanical systems.

2.2.2 QUESTIONS

We formulated the following questions to probe the above authorities for their opinions on the probable emergence of nanoelectronics and the implications that might follow.

- The Mitre corporation's web site (www.mitre.org) predicts that nanocomputers could become commercially available between 2010 and 2020. This prediction is based upon an extrapolation from current electronic technology development using Moore's law, which states empirically that the feature size for devices on a semiconductor chip decreases by a factor of 2 every 18 months. In your opinion, is this an accurate, realistic prediction? If so, what do you anticipate will become available?

- Some operational nano-scale technologies currently in place in the research laboratory, such as those requiring atomic force microscopes or bulky lasers to read and manipulate data, require specialized, expensive and sophisticated equipment and therefore would be difficult to commercialize. Do you think it is reasonable to expect that commercialization of such nano-scale technologies will occur? What do you expect to become commercialized? Given a brief explanation of Drexler's rod logic, do you believe that such a mechanical system would be practical given the many systems under development utilizing molecular-scale transistors?

- No invention in history has spread so quickly throughout the world or changed so many aspects of human existence as the microprocessor. There are nearly 15 billion microchips of some kind in use today. Our microwaves, dishwashers, televisions, VCRs, stereos, and telephones - not to mention thousands of less obvious applications - would be rendered useless if we were to remove their microprocessors. There is no doubt that they have changed the way that we live. With this in mind, do you expect that the advent of even smaller and faster computing technology will have a dramatic impact on society? Given the integration of microprocessors into innumerable applications, how might nanocomputers affect other technologies?

- Particularly over the last decade, commercially available microprocessors have become an integral part of modern day life, especially those used for communication and information technology. Earlier technological breakthroughs such as the automobile and television have both improved and lowered our quality of life. Similarly, while technology such as the digital cellular phone has enabled modern man to communicate easily from virtually any place on earth, it has also compromised personal privacy. How do you think that dramatically smaller and faster computers could impact positively upon our society and economy? What do you foresee as negative implications?

- Given that many technologies are gradually introduced into society, do you think that the integration of nanocomputers will be noticeable to the average American? Do you think that less technologically developed countries will feel the impact of nanoelectronics? Would you expect that the technological and economic disparity between first and third world nations to increase? How?

2.2.3 PERSONAL INTERVIEWS

We also conducted face to face interviews with two professors at Worcester Polytechnic Institute. We chose these professors because of their expertise in impacts of new technologies and computer science. While the questions followed those related above, we also tailored them to suit the inclination of the person being interviewed. With Professor Shannon, we focused upon questions regarding the ethics of nanoelectronics and their probable effect. Our interview with Professor Gennert centralized upon the implications of multi-state logic devices upon programming languages and advantages of increased computing power.

- **Thomas Shannon** (tshannon@wpi.edu) - Professor of Religion and Social Ethics at Worcester Polytechnic Institute. His research interests include medical and professional ethics, ethical theory, and impacts of new technologies.

- **Michael Gennert** (michaelg@wpi.edu) - Associate Professor of Computer Science at Worcester Polytechnic Institute. Dr. Gennert is interested in Computer Vision, Image Processing, Artificial Intelligence, and Scientific Databases, with ongoing projects in biomedical image processing, application of fractal models to pavement analysis, VLSI implementation of median filtering, stereo vision, and very large spatio-temporal databases. He has authored or co-authored over 40 publications.

3. INTRODUCTION

No invention in human history has spread so quickly throughout the world or changed so many aspects of human existence as the microprocessor. The advantages of conventional microelectronic devices - their compact power, the flexibility and multitude of their applications, and the ease with which they are manufactured - has been and continues to be the key to the revolution in computer and information technology that has swept the world in the past half century. However, the most important characteristic of these solid-state circuits is how they have lent themselves to the miniaturization of electronic devices, especially computers.

For the past 40 years, computers have become more and more powerful as their basic component, the transistor, has decreased in size *[Muller and Kamins,* 1986]. Since the invention of the transistor in 1948 by Shockley, Brattain, and Bardeen, increasing numbers of these devices have been put onto a single integrated circuit, which incorporates transistors as well as diodes, resistors and capacitors interconnected into a functional circuit on a single chip of silicon. In the 1950's and 1960's, the solid state transistor replaced vacuum tubes and drastically reduced the size of electronic devices that initially had been invented and manufactured using tube technology. By the mid-1960s, successive generations of smaller transistors began replacing larger ones. This permitted more transistors to be packed into the same small space, resulting in greater computer memory and increased processing power.

Research is constantly underway to further reduce the size of electronic devices so as to obtain faster, more powerful processing. The smallest features on commercially available, state of the art integrated circuits - such as Intel's Pentium Pro and Pentium II processors - have linear dimensions of about 250 nanometers *[Focus: Moore's Law - Changing the PC Platform for Another 20 Years,* 1998]. A nanometer is one billionth of a meter, or about 10 atomic diameters. Intel has also reported a process using deep ultraviolet light lithography to produce a component with dimensions of 250 nanometers. A process that goes further into the ultraviolet spectrum is being researched that would allow components of 180 nanometer dimensions to be manufactured. Intel hopes to continue downsizing the scale of its components, achieving 130 nanometer scale with extreme ultraviolet, x-rays, and direct-write electron beam techniques [*Focus: Moore's Law - Changing the PC Platform for Another 20 Years,* 1998]. Although feature sizes on microprocessors have become increasingly smaller, the process whereby modern silicon computer chips are manufactured has theoretical physical limitations. Research predicts that once the smallest features of a transistor's design decrease to less than 100 nanometers, the devices will no longer function [*Frazier,* 1988; *Stix,* 1995]. At that point, small-scale quantum mechanical effects, such as tunneling of electrons through barriers, will begin to dominate the bulk effects that allow a semiconductor device to operate. This implies that continued reductions in size will require that present-day microelectronic devices be replaced with new nanoelectronic designs that capitalize on these dominating quantum effects. Such nanometer-scale electronic computers - i.e. nanocomputers - that contain molecular-scale components are likely to be 10,000 times more densely integrated than today's smallest microcomputers.

The idea of creating such devices that function on the nanometer scale is not new. Nearly 40 years ago, Nobel prize laureate Richard Feynman gave a talk entitled "There's Plenty of Room at the Bottom" at a meeting of the American Physical Society in which he predicted the increasing miniaturization of technology, including miniature machines so small that they would "manipulate at a nearly molecular scale."

> "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is

something, in principle that can be done; but in practice, it has not yet been done because we are too big." [*Feynman,* 1959].

Although Feynman's idea of building structures "atom by atom" sparked a great deal of interest in the scientific community, his proposals seemed out of reach for the time. "Wires... 10 or 100 atoms in diameter" sounded impossible and impractical to those listening in 1959. But to some attending the meeting, this seemed an obvious progression. After all, we are taught that the atom is the smallest unit of matter. All matter is made up of atoms, so why not build things with atoms? With his novel idea, Feynman sparked the scientific development and fabrication of nanometer-scale devices.

Interest in developing technology on the nanoscale arose in many different fields, especially the microelectronics industry. After the invention of the transistor in 1948 [*Holonyak,* 1992; *Kendall,* 1969; *Ridenour,* 1951; *Rockett,* 1948; *Sparks,* 1952] and the integrated circuit by Noyce, Kilby et al. in the late 1950s [*Quiesser,* 1988; *Rabaey,* 1996], digital electronic circuits continued to become progressively smaller. While only one transistor could be put on an integrated circuit in 1959 [*Meindl,* 1987], circuits could be made with a few thousand transistors only twenty years later [*Heath,* 1970; *Hittinger and Sparks,* 1965; *Noyce,* 1977].

The miniaturization of transistors and the increase in density of their solid-state circuitry appeared to follow an empirical trend. As observed by Gordon Moore, one of the founders of Intel Corporation, the feature size for devices on a semiconductor chip decreased by a factor of 2 every 18 months. This trend has continued through the present, and has come to be called "Moore's Law" [*Rabaey,* 1996; *Focus: Moore's Law - Changing the PC Platform for Another 20 Years,* 1998].

Through the 1980s, the number of transistors that could be placed on a computer chip continued to increase exponentially. By the mid-1980s, one million transistors could fit on a 1 centimeter square computer chip *[Meindl,* 1987]. The rapid increase of computing power sparked investigations into the theoretical limits of computation and processing of information *[Benioff,* 1980, 1982; *Bennet,* 1977, 1987, 1988; *Bennet and Landaur,* 1985; *Feynman,* 1982; *Fredkin and Toffoli,* 1982; *Landaur,* 1961, 1991]. This close examination of fundamental physical considerations led to the conclusion that computers based upon conventional solid-state transistors had functional limits that would soon be approached *[Keyes,* 1977, 1988, 1992,1993]. It became obvious that the next generation of computers would be based upon much smaller devices. These nanometer scale state machines might either function in a similar manner as the conventional transistor or utilize some novel technology *[Capasso,* 1985; *Carter,* 1982, 1987; *Claeson and Likharev,* 1992; *Frensley,* 1987; *Heiblum and Eastman,* 1987].

Advances in chemistry, molecular biology and physics in the 1960s and 1970s contributed towards the realization of such devices. These developments were aligned with Feynman's goal of manipulating matter atom by atom and molecule by molecule rather than in bulk. In 1974, Aviram and Ratner theorized about electronic circuit elements made from single molecules and showed in detail how they might function *[Aviram and Ratner,* 1974].

In the late 1970s and early 1980s, biochemists and molecular geneticists began taking advantage of naturally occurring biological processes to build and manipulate proteins and other molecules for medicinal and industrial purposes *[Cohen,* 1975, 1980; *Freedman,* 1991; *Gilbert and Villa-Komaroff,* 1980; *Hopwood,* 1981; *Ptashne and Gilbert,* 1970]. They discovered how to integrate short lengths of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) *[Creighton,* 1984; *Darnell,* 1985; *Felsenfeld,* 1985] into much longer sequences, often from completely different organisms, leading to the development of the molecular genetics industry. In 1983, Mullis developed a biochemical process known as the Polymerase Chain Reaction (PCR) *[Mullis,* 1990] that allowed the accurate exponential amplification of a few molecules of genetic material into macroscopically measurable quantities *[Ma,* 1995].

Physicists developed many new quantum constructs in the 1980s, including single electrons trapped in potential wells called "quantum dots" *[Eaves,* 1992; *Ekstrom and Wineland,* 1980; *Kastner,* 1993; *Reed,* 1993; *Sundaram et al,* 1991; *Turton,* 1995]. The design of scanning tunneling electron microscopes (STMs) and atomic force microscopes (AFMs) with which scientists could view and manipulate individual atoms *[Bedrossian et al,* 1989; *Binnig and Rohrer,* 1985; *Goss et al.,* 1987; *Hansma et al,* 1988; *Lyo and Avouris,* 1989; *Pool,* 1990] also took advantage of quantum effects. Feynman's vision of the creation and manipulation of molecular-scale structures and devices was given a physical scientific basis through these advances.

While biologists, chemists and physicists continued to explore their ability to manipulate matter on the nanoscale, conventional microelectronics technology was developing increasingly faster computers. These powerful new computers were used by scientists to model and "design" the properties and structures of atoms, molecules and solids, using semi-classical and quantum-mechanical approximations, such as the MM3 force field *[Allinger et al,* 1989; *Cohen et al,* 1982; *Comba and Hambley,* 1995; *Doucet and Weber,* 1996; *Lii and Allinger,* 1989a, 1989b; *Merkle,* 1991; *Wahl,* 1970]. Increasingly sophisticated and detailed computer graphics added to the interpretative power provided by the refinement of computer-based molecular scale modeling approaches *[Doucet and Weber,* 1996], The combination of these developments in diverse fields stimulated advances in the 1980s that put in place the scientific foundation for a true "nanotechnology." In 1974, Taniguchi introduced this term to refer to increasingly precise machining and finishing of materials *[Taniguchi,* 1974]. However, the term "nanotechnology" was first popularized in the 1980s by the scientist and visionary K. Eric Drexler in his book *Engines of Creation [Drexler,* 1986]. In his book, Drexler introduced the basic concepts and potential of nanotechnology in an extrapolation from a scientific paper he published at the beginning of the decade *[Drexler,* 1981]. According to Drexler, nanotechnology is the knowledge and means for designing, fabricating and employing molecular scale devices or "nanosystems" by the manipulation and placement of individual atoms and molecules with precision on the atomic-scale. Precise control of atomic structure would result in "effectively complete control of the structure of matter." In 1992, Drexler published *Nanosystems,* which used detailed analyses of quantum physics, chemistry and mechanical engineering to justify the nanometer-scale machinery - computers, robots, and self-assembling systems *[Drexler,* 1992] outlined in his previous book. Efforts to implement Drexler's ideas have served as inspiration for the new, interdisciplinary field.

In the 1990s, developments in physics, chemistry, biochemistry, electrical engineering and computer science are converging towards working nanoscale technology. A revolution is occurring in miniaturization. The engineering and manufacture of micron-scale machinery is one upon which the fabrication of further nanometer-scale technology can be based *[Angell et al.,* 1983; *Bryzek et al,* 1994; *Gabriel,* 1995; *Howe,* 1990; *Stix,* 1992; *Xu et al,* 1995; *Xu et al,* 1995]. There are methods in place for positioning single atoms *[Avouris,* 1995; *Eigler and Schweizer,* 1990; *Stroscio and Eigler,* 1991] and for making billions of copies of a few identical molecules as a routine laboratory process *[Ma,* 1995; *Mullis et al,* 1994]. Furthermore, great strides are being made in the self-assembly of more complex structures from molecular building blocks [*Kim and Whitesides,* 1994; *Kuhn,* 1994; *Lehn,* 1990; *Whitesides,* 1995]. Nanometer-scale quantum-effect devices, such as "artificial atoms" or quantum dots, have been transformed from laboratory curiosities to the most likely building blocks for the nanoelectronic industry [*Kastner,* 1992, 1993; *Seabaugh et al,* 1993]. Molecular electronic devices such as molecular wires are no longer solely theoretical. They have been synthesized [*Schumm et al,* 1994] and demonstrated [*Bumm et al,* 1996].

The computer and electronics industry is a particularly important focal point for these developments. There, practical elements of nanotechnology - especially new techniques for nanofabrication [*Jung et al,* 1996; *Tour et al,* 1995; *Whitesides et al,* 1995; *Xu et al,* 1995; *Xu et al,* 1995] - are growing in importance as the semiconductor industry develops circuits with feature sizes that approach 100 nanometers and the physical limits of conventional, bulk-effect microelectronic devices [*Frazier,* 1988; *Stix,* 1995]. It is hoped that nanometer-scale replacements will continue the trend towards miniaturization of computational and information storage elements to the molecular level, with the accompanying tremendous increases in circuit density, power and performance.

For these reasons, as well as the need for very small controllers to guide other micrometer-scale and nanometer-scale machinery, nanometer-scale computers are the paramount development in the emerging field of nanotechnology. The research focused on the fabrication of a functional nanocomputer is divided into several different approaches. These include both scaled-down reproductions of modern computer architecture, as well as novel designs to accommodate the various advantages and problems associated with nanostructures. Four distinct categories of research have evolved: chemical, mechanical, electronic, and quantum.

The area of chemical nanocomputing is a relatively new field. It is based upon the premise that chemical reactions can be used to compute using the rules of Boolean logic. Richard Adleman provided a breakthrough in chemical computation by solving a Hamiltonian graphing problem using DNA *[Adleman,* 1994]. Although his research showed that chemical reactions could solve difficult algorithms, it took four days to complete the calculations. Although the reactions themselves occur very rapidly, no technology exists for researchers to capitalize on their speed. Until such a breakthrough, Adleman's experiment exists only as an initial proof of a concept experiment that can not be utilized in a functional nanocomputer.

The area of mechanical nanocomputing also exists only as a conceptual idea. K. Eric Drexler pioneered the field by proposing a computer based upon 'rod' logic nanoscale switching devices that operate under purely mechanical means *[Drexler,* 1992]. The device would be similar to a Babbage adding machine constructed of nanoscale parts. When we asked scientists what they thought of Drexler's ideas, those surveyed agreed that by the time the capability exists to build such a device, simpler and faster devices utilizing microelectronics would be available. David Ferry, a nanoelectronics researcher at Arizona State University, went so far as to state that "Drexler's ideas are not worthy of discussion by serious people."

The professional nanotechnologists surveyed for this report all expressed similar opinions that the crucial breakthrough in nanoscale computing would occur in the field of electronic nanocomputers. We then focused specifically on this field and found a great deal of literature on both theoretical and experimental research. Since the field of quantum nanocomputing was found to be closely associated with nanoelectronics, it too is given an in depth explanation in this paper. To understand the impact that these research areas might have, the reader also needs an understanding of manufacturing techniques associated with them. After such an in depth overview it is much easier to understand the implications associated with nanocomputing.

The area of electrical nanocomputing is being pursued most vigorously. Research into the production of the electronic transistor has been ongoing for the past 50 years. This extensive background gives nanoelectronic researchers a wealth of information and very large industrial infrastructure with which to work [*Keyes,* 1992, 1993]. While the essential principles of the transistor itself have not changed, the majority of research aimed at increasing computing power is based upon increasing the density of transistors on an integrated circuit chip. [*Hittinger,* 1973; *Keyes,* 1992, 1993]. It is essential to be aware of the general concepts behind current semiconductor technology in order to fully understand its weaknesses and comprehend the changes associated with emerging nanoelectronic technologies.

The transistor is the basic building block of the central processing unit. It is a simple two-state switch that can be either "on" or "off," representing a 1 or 0 in binary code. By assembling several transistors together, an electronic logic gate can be formed. These gates perform simple Boolean logic functions such as AND, OR, and NOT. Logical transformations can then be executed by assembling several Boolean logic gates together.

The most common type of transistor in modern circuitry is the metal-oxide-semiconductor field effect transistor, or MOSFET. These transistors are fairly easy to fabricate and require very little power. A general understanding of the principles behind the MOSFET is necessary to understand its shortcomings. The problems that the MOSFET encounters when reduced to the nanoscale makes it necessary to research other possibilities of nanometer scaled switching devices.

The MOSFET is constructed on a surface of doped silicon and consists of two terminals called the source and the drain, sandwiching a third terminal called the gate. Dopants, such as arsenic or boron, are added to the silicon to create an excess or shortage of electrons. The most common type of MOSFET is dubbed the NMOS, in reference to the way different parts of the transistor are doped. The NMOS consists of two separated negatively doped (N-doped) regions, arranged on a positively doped (P-doped) substrate. The source and drain terminals lie on the N-doped regions with the gate placed between these two terminals and insulated from the P-doped surface by an oxide barrier. The area of P-doped silicon beneath the gate is called the channel [*Hittinger,* 1973]. Adjusting the voltage on the gate controls the flow of current between the source and the drain [*Pierret,* 1996; *Rabaey,* 1996].

If the voltage on the gate is below a certain point then no current can flow between the other two terminals because of the nature of P-doped silicon. However, if the voltage on the gate is increased, the positively charged "holes" in the P-doped silicon are repelled from the oxide insulator. This activity creates a very thin N-doped region within the channel between the source and the drain and allows current to flow between the two terminals [*Hittinger,* 1973; *Pierret,* 1996; *Raybey,* 1996].

That it is capable of being either conductive or non-conductive gives the MOSFET the properties of a two-state logic device. Additionally, the increase in conductivity attributable to a small change in voltage allows the MOSFET to act as an amplifier. The ability to amplify a small signal through a large series of logic gates is another reason why the MOSFET remains popular [*Keyes,* 1993].

It would seem logical to continue to reduce the MOSFET down to the nanoscale. But as minimum feature sizes of the MOSFET approach 100 nanometers it is expected that the

MOSFET will no longer function appropriately due to several factors including thermal noise, electron tunneling, loss of bulk effects, and heat dissipation [*Keyes,* 1988, 1992, 1993; Meindl, 1995].

The signal from a transistor must be larger than thermal noise. In other words, the amount of thermal noise present in a circuit would serve as a lower boundary for the voltages used in the operation of a MOSFET. This voltage would have to be applied over smaller areas as the overall size of the transistor is scaled down. The decreasing space between terminals would increase the electric field within. This greater electric field strength correlates to higher kinetic energies of the electrons traveling between the source and drain. If the electrons acquire enough kinetic energy they can knock free other electrons in the solid and therefore cause a surge of current through the transistor. The minimum 100 nanometer gate length of the MOSFET is therefore derived from the maximum electric field that can exist in the device before such a surge of current would occur [*Keyes,* 1992, 1993].

Another problem arises as the oxide insulator is scaled down to nanometer thickness. Classical physics says that if the total energy of an electron is less then the energy of a potential barrier then it cannot pass through the barrier. Quantum mechanics says that there is a large probability that if the barrier is thin enough, the electron is able to cross the barrier by a process called tunneling [*Atkins,* 1988, 1992; *Baggot,* 1992; *Ferry,* 1995]. This phenomenon occurs with increased exponential frequency as the thickness of the barrier is decreased and would render a transistor completely nonfunctional.

MOSFETs are bulk effect devices and therefore function according to the bulk principles of the atoms of which they are composed. As they are scaled down to the nanometer size, the quantum mechanical properties of the atoms become an issue [*Bate,* 1988]. This is because the ratio of dopant atoms to silicon is already very low. If scaled below 100 nanometers, a MOSFET's dopant atoms would number only in the tens or hundreds. Such a small number is not enough to change the properties of the silicon without quantum interference. Furthermore, the placement of such dopants will be statistically varied, possibly creating some areas with an abundance of dopants and others with a shortage.

Perhaps the largest problem facing the scaling of the MOSFET, as well as many proposed nanoelectronic switching devices, is heat dissipation. As more and more transistors are packed into smaller areas it becomes increasingly difficult for circuits to operate at room temperature. It has been pointed out that if the current trend of increased heat given off by enlarging the circuit density continues, then the heat given off by a nanoscale integrated circuit would be equivalent to that of exploding gunpowder [*Hall,* 1994]. Modern circuit architecture is therefore limited by the amount of heat that is dissipated [*Keyes,* 1970; *Keyes and Landaur,* 1970].

With so many problems facing the continued scaling down of the MOSFET transistor, new forms of switching devices are being investigated. Since nanometer scaling causes quantum interference that disrupts the field effect transistor, many researchers are looking at ways to harness such interactions. The area of nanoelectronics consists of devices that must be linked together with wires in much the same fashion as modern circuitry. Those switching devices utilizing quantum effects that are linked together in a wireless architecture are classified as quantum devices.

4. NANOELECTRONICS

Nanoelectronics can be divided into the two distinct fields of solid-state quantum effect nanoelectronics and molecular nanoelectronics. Solid-state quantum effect nanoelectronic devices function in a similar fashion to modern field effect transistors, but take advantage of the quantum interference that limits the scaling of the MOSFET. Although such devices can function at sizes close to 10 nanometers, they still rely on the bulk transport of electrons. Molecular nanoelectronic researchers want to use individual molecules that act as switching devices. They differ from solid-state devices because there is no need to etch or sculpt a solid to create the switching device. A molecular switching apparatus would be only 1-2 nm long, and would therefore allow for a very dense packing arrangement in a circuit.

The two basic types of solid-state nanoelectronic devices are the resonant tunneling devices and single electron transistors. Some literature places quantum dots in this category as well, but since the majority of quantum cell designs operate within a wireless architecture we have placed them in a separate category. Solid-state devices use an area of semiconductor or metal that has the ability to confine electrons. Such an area is very similar to the channel in the MOSFET.

The resonant tunneling diode, RTD, is the most elementary solid state nanoelectronic device. Unlike current transistors, which are made primarily of silicon, RTDs are made of semiconductor alloys such as gallium arsenide and aluminum arsenide [*Frensley,* 1987]. An RTD consists of two insulating barriers in a semiconductor with a gap of approximately 10 nm between them. This gap is a potential well for electrons [*Capasso,* 1992]. Quantum mechanics says that electrons between the two barriers are restricted to a limited number of quantized levels [*Atkins,* 1992]. The resonant tunneling diode operates on the principles of these quantization levels.

In order for an electron to pass through the insulating barrier it must undergo quantum mechanical tunneling. Electrons can only tunnel through the insulating barrier if they are at the same energy state as those electrons inside the gap. When this happens, the electrons on both sides of the insulating barrier are said to be "in resonance" and current can flow through the device. Thus, with current flowing through the insulated gap the device is in its "on" state. Non-resonant energy levels prevent current flow and the device is in its "off state.

A device very similar to the MOSFET can be created from the resonant tunneling diode by placing a gate over the insulated gap. Such a device is termed a resonant tunneling transistor, or RTT [*Capasso,* 1992]. The gate of an RTT functions in very similar manner as that on a MOSFET. By adjusting the voltage on the gate, the flow of electrons across the gap can be controlled. Once again a small voltage change on the gate results in a large current flow through the device. This allows the RTT to act both as an amplifier and a switching device.

The RTT has one large advantage over conventional transistors besides its very small size. Modern transistors are two-state devices and therefore operate under binary code. RTTs and RTDs are capable of having multiple switching states since electrons can have more than one quantized energy level. For example if the voltage on the gate of an RTT is zero then the device is off, representing a "0". When the voltage on the gate is increased to allow the first energy level to come in resonance the device would be considered on, representing a "1". If the voltage is increased past this first energy level the device would be switched off unless the voltage is significant enough to bring a second energy level into resonance. If the second energy level is brought into resonance the device would be switched on again, but this time representing a "2".

This multi-state switching allows the device to represent a higher level of logic states. A device that represents more logic states allows a logic gate to be constructed with fewer transistors. This translates into an increase in the logic density of an integrated circuit since more multi-state logic gates could be placed into the same area than possible using two-state devices [*Mikkelson, et al;* 1994].

The construction of RTTs is extremely difficult due to the complexity of the devices of such remarkably small size and the sensitivity of the quantum interactions they rely upon. This has prompted researchers, such as Seabaugh et al., to propose hybrid technology transistors. Such devices employ conventional field effect transistors that have nanometer scale RTDs built into the drain. This design allows the MOSFET to exhibit multi-state switching. Thus an increase in the density of logic could occur without having to increase the number of transistors. This hybrid technology would also represent a gigantic step towards the development of purely nanometer scale transistors.

Another proposed solid state nanoelectronic switching device is the single electron transistor. Single electron transistors, SETs, are devices that capture or release a single electron from a larger pool of electrons [*Kastner,* 1992; *Likharev,* 1988]. A SET consists of a source and a drain similar to a conventional MOSFET. An insulated 'island' lies between the source and drain and electrons are able to tunnel from the drain through the insulator onto the island. A limited number of electrons are able to occupy the island at one time due to its size. The electrostatic repulsion of those electrons residing in the island prevents other electrons from tunneling through. This repulsion is called a Coulomb blockade [*Chou and Wang,* 1992; *Devoret et al,* 1992; *Fulton and Dolan,* 1987; *Kastner,* 1992,].

A third electrode called a gate is placed near the source and island. An increase of voltage on the gate allows an electron to overcome the Coulomb blockade and tunnel through. It subsequently tunnels through to the drain. This process is repeated on the scale of 10^7 times per second, creating a measurable flow of current from the source to the drain. Increasing the gate voltage further allows one more electron to remain stable on the island than the previous resting state. This pattern repeats itself as voltage on the gate is increased. The SET therefore also has the ability to operate as a multi-state switching device, with the added advantage of amplification of the gate signal across the island similar to that seen in the MOSFET.

The biggest problem encountered with the SET is surrounding temperature. The temperature of surrounding material could easily provide enough energy to overcome the Coulomb blockade. The majority of SETs fabricated must be immersed in liquid nitrogen to retain the capability of creating a Coulomb blockade. A group of Japanese scientists recently created a SET 30nm across capable of creating a Coulomb blockade at 150° Kelvin, twice the boiling point of liquid nitrogen [*Nakajima et al*, 1994]. This is a significant breakthrough towards the goal of creating a SET that operates at an average room temperature of 300° K.

Although solid state nanoelectronic switching devices such as the resonant tunneling devices and the single electron transistor are on the nanometer scale, they still rely upon the bulk effect principles of their macromolecular structures. Such devices have to be etched in a similar manner to modern circuits.

Unlike solid state nanoelectronics, the field of molecular nanoelectronics is concerned with individual organic molecules that are able to act as switching devices and wires. Individual molecules are on the scale of a single nanometer or smaller and can potentially be produced in large quantities via organic synthesis. Several different classes of molecular nanoelectronic switching devices have been proposed. The two most promising fields are electric field controlled molecular switching devices and electromechanical molecular switching devices. Electric field controlled molecular switching devices employ quantum confinement in a similar manner as modern transistors and proposed RTDs and RTTs. Electromechanical molecular switching devices apply electrical or mechanical force on a molecule to change its conformation.

Electric field controlled molecular switching devices utilize quantum interference between atoms of a single molecule. The majority of researchers have suggested using the ideas behind devices such as the resonant tunneling diode and transistor, and creating a molecule that acts as an electronic switching device [*Tour,* 1996, 1997; *Reed,* 1997].

A good example of this research is the molecular resonant tunneling diode. The device is a single molecule that uses benzene rings as the source and drain. A third benzene ring insulated by a methylene group on either side acts as the island. This arrangement allows the molecule to create a potential energy barrier similar to that of a solid-state RTD [*Tour,* 1997]. Electrons in resonance with those on the island benzene ring can tunnel across the methylene barriers. Reed has already demonstrated a working molecular RTD [*Reed,* 1997]. Structures for molecular RTTs have also been proposed, but these have yet to be fabricated [*Tour,* 1996].

One of the disadvantages to this technology is the difficult task of achieving resonance with the source and drain simultaneously. Another difficulty facing researchers is the large charging energy in a potential well as small as a single benzene ring. This energy could be more than that spacing the different energy levels of the electrons in the molecule. The flexibility of organic structures, however, gives researchers many tools with which to attack such problems.

To avoid such problems, some molecular nanoelectronic researchers are examining the field of electromechanical nanoelectronic switching devices. Electromechanical devices are very different from previously discussed switching devices. The majority of the nanoscale electrochemical switching devices function like a MOSFET transistor. However, electromechanical devices are more closely related to Drexlers's rod logic.

The molecular shuttle switch synthesized by Bissel *et al.* consists of a 'bead' of benzene rings that slides along a strand of molecules [Bissel et al., 1994]. The strand that the bead slides upon has two molecules of differing charge that act as stations. By removing an electron from one station the bead shifts to the second. Return of the electron causes the bead to return back to the first station. Although such a molecule has been synthesized, little work has been done on developing a method of probing the state of the bead molecule. This is a major roadblock for a feasible nanoscale electromechanical switching device.

A device similar to the molecular shuttle is the atom relay mechanism. The atom relay switch was developed and simulated by researchers at Hitachi [*Wada et al,* 1993]. It uses a mobile atom to open and close the flow of current through a molecular wire. Such a device would only be functional at extremely low temperatures to prevent the evaporation of switching atoms off of their substrate. Logic gates using this theoretical proposal would be limited to two-dimensional architecture unlike the three-dimensional possibilities of other nanocomputing proposals.

Joachim and Gimzewski have proposed using buckyballs as electromechanical switching devices [*Joachim,* 1991; *Joachim and Gimzewski,* 1995]. They reported a 50% reduction of current through a buckyball when it was pressed and deformed by a scanning tunneling electron microscope. This process was shown to be reversible; however it would be very impractical to use an STM to operate every switch on a circuit. It was then proposed to use a piezoelectric gate to produce an effect similar to the STM. However, the prototype for this device performed at an undesirably slow rate of speed.

Although it is unlikely that a functional nanocomputer will take advantage of electromechanical technology, the research performed in this area is beneficial to nanotechnology as a whole because it allows for the development of nanoscale technologies that could become very useful in other areas of research. The established infrastructure of the computer industry is based upon electrical switching devices. It would therefore be an easier transition for the industry to develop nanoscale computers based upon the conventional theory of electricity.

Perhaps the innovation in molecular electronics that will most likely be used in the development of a functional nanocomputer is the molecular wire. Whether single molecules could conduct electricity had been a question of considerable debate that cast a shadow of doubt over proposed molecular switching devices. Opponents to molecular electronics argued that research on the subject was useless if the devices would not conduct electricity.

The debate was finally put to rest by James Tour in 1997. Tour fabricated a molecular wire composed of *n* bonded benzene rings and annealed one end of the chain to a gold electrode. Using the tip of a scanning electron microscope as the second electrode, Prof. Tour passed a measurable current through the molecular chain *[Schumm et al,* 1994, *Bumm et al.* 1996]. Tour and Reed then placed thiol groups at the ends of the molecular wires and adsorbed both ends to gold electrodes. The wire once again proved to be a conductor *[Reed,* 1996] with the addition of the thiol groups advantageously acting as 'alligator clips' because they were easily attached to metal substrates *[Bain and Whitesides,* 1989; *Tour et al,* 1995; *Bumm et al,* 1996]. This ease of attachment correlates to fabricating circuits with the wires by connecting molecular embedded transistors.

Tour's molecular wire design relies heavily on the % bonds that connect each benzene ring. The **7i**-electrons above and below the structure interact with each other creating a single orbital the length of the structure that permits mobile electrons to travel through the wire.

The Tour and Reed model is not the only proposal for a molecular wire, although it is the only model that has been proven to conduct electricity. Researchers have proposed the fullerenes known as buckytubes as potential molecular wires. The molecular tubes would be filled with a more conductive material so the tube itself would act as a support structure. Preliminary research has shown that it is very difficult to obtain different tubes with identical conductive properties. Several other carbon-based polymers have also been proposed as potential molecular wires [*Beck,* 1992; *Cai,* 1992; *Wu,* 1994]. Most proposals arise from the development of a novel synthesis technique for a nanometer size fiber.

5. QUANTUM NANOCOMPUTING

The majority of research in the field of quantum nanocomputing is devoted to quantum dots. Quantum dots are small potential wells that electrostatically isolate a well-defined number of electrons from their surrounding environment [*Bakshi et al,* 1991; *B'alasingam and Roychowdhury,* 1994; *Bandyyopadyay et al,* 1994; *Lent et al,* 1993; *Lent et al,* 1994]. The electrons are confined to a small 'island' region composed of metal or semiconductor insulated from the surrounding material. The dot-like island can range from 30 to 100 nanometers in size and hold from zero to hundreds of electrons. It can consist of small deposited or lithographically defined regions [*Tarucha et al,* 1996], small, self organized droplets [*Yusa,* 1995; *Notzel,* 1996], or nanocrystallites grown *in situ* or deposited in a film [*Bawendi et al,* 1990; *Klein et al,* 1996].

Quantum dots are constructed with islands that are short in all three dimensions, confining the electrons with zero classical degrees of freedom so that electronic states are quantized in all three dimensions [*Goldhaber-Gordon et al,* 1997]. Making an island short in all three dimensions leads to widely spaced quantum energy levels for an electron on the island. The energy of repulsion is also large because the island's size does not allow a pair of electrons to get far from each other. Therefore, the flow of current through the dot is affected by both the interaction between the electrons on a quantum dot and the energy levels for each individual electron. Consequently, the quantum dot can act as a multi-state device. The current jumps to a discrete value when electrons can first travel through the island one at a time, and further quantized jumps herald the ability of electrons to go through two, then three at a time. The smaller and more frequent jumps occur when an electron can travel across the dot not just in the island's lowest-lying vacant quantum state but also in one or more excited states. The more paths available for electrons, the greater the current flow.

In the category of quantum dots, we include individual dots ('artificial atoms') *[Reed,* 1993; *Turton,* 1995] as well as coupled dots ('quantum-dot molecules') *[Randall,* 1993] and a kind of composite device called a 'quantum dot cell,' in which four or five quantum dots form a single two-state device *[Lent et al,* 1993; *Lent,* 1995; *Korotkov,* 1995; *Lent,* 1997].

Quantum dots differ from single-electron transistors in that the dots rely on specific quantum effects among a few electrons in logic circuits. Since the resistance of such devices is low, the precise number of electrons in the device is not known, and cannot be used to store and retrieve information. However, interactions between or among dots can. One quantum dot may affect another dot even if the two are not wired together. Two dots, separated by a large potential energy barrier, can influence each other through their long-range repulsive interactions. For example, the electric field of the electrons in one quantum dot can change the number of electrons in another nearby quantum dot *[Lent,* 1992; *Lent et al,* 1993; *Lent,* 1993; *Peterson,* 1994].

Adding an electron to one quantum dot will cause an electron to vacate a nearby dot, so long as the exciting electron can escape to a nearby location, such as a drain or an empty quantum dot. The electron that started this chain of events must have tunneled into the first quantum dot from a nearby reservoir. Used in this way, a quantum dot can be thought of as a two-state device with each state corresponding to the occupancy of the dot by zero or one electron. Two such devices placed next to each other would tend to take on opposite states, given that the electrons have a path of escape.

Lent, Tougaw and Porod [*Lent et al.,* 1993; *Lent et al.,* 1994] propose a variant of the arrangement of nearby quantum dots like those described above. By simply introducing more quantum dots to serve as the electron reservoirs, they suggest a five-dot "cell" that holds two electrons. The full set of five quantum dots is fabricated onto a single insulating square constructed around them. Since the two electrons in each five-dot cell repel each other, they automatically move to opposite corners of the cell. The two such electron configurations possible represent the two states of the device.

Boolean logic functions can be implemented by setting up appropriate patterns of the Lent-Porod quantum dot cells. Since these quantum dot cells communicate via their electronic fields and not through the flow of current they are the basis for a new form of "wireless" electronic computation.

Difficulties associated with their fabrication present the primary obstacles to the implementation of computers based upon quantum dot cells [*Montemerlo et al.,* 1996]. In order to compute without numerous errors, the location and size of the dots must be precisely controlled. The structures also must be carefully designed and prepared to minimize undesired tunneling of electrons across or out of cells. Also, as with single-electron transistors, the maximum operating temperature increases as the dots are made smaller, and any small background charge near a cell can permanently lock the cell into one position, ruining the computation.

6. MANUFACTURE OF NANOCOMPUTING DEVICES

Today's integrated circuits, such as Intel's Pentium microprocessor are manufactured using photolithography. This process uses light to etch a pattern onto a silicon wafer coated with a photosensitive material. Manufacturers favor photolithography because it lends itself to mass production very easily. A large area of silicon can be etched at one time, allowing for a large number of chips to be produced in one exposure. This process was first carried out using light in the visible spectrum. Since the wavelength of light used in photolithography is the limiting factor of feature size, the decrease in transistor size has exhausted the capabilities of visible spectrum photolithography.

This has resulted in a shift to shorter wavelength ultraviolet light. Ultraviolet lithography does not lend itself to nanometer scale production. The limit of feature size using UV lithography is approximately 250 to 300 nanometers. A further refinement to UV lithography makes use of x-rays and therefore has the possibility of producing nanoscale features. The small wavelength of x-rays would allow for a lithographic technique capable of characteristics in the range of 50 to 100 nanometers [*Smith and Schattenburg,* 1993]. Several laboratories are currently working to refine the area of x-ray lithography; however, it is a very expensive process [*Stix,* 1995] and the high energy of the x-rays causes significant damage to the surrounding substrate.

From the previous discussion it is clear that proposed devices for nanocomputing would require new methods of fabrication. Conventional lithography techniques are reaching their limits of fabrication with the MOSFET. New approaches to lithography have been proposed as well as novel methods of nanosynthesis.

Several research groups have been refining a technique that uses an electron beam to etch out structures on a substrate. This is a technique very similar to the prevailing UV lithography. The small size of the electron beam used allows for the ability to produce features in the tens of nanometer range [*Cambell,* 1996; *Gentili et al,* 1994; *Huang et al,* 1993; *Marrian et al,* 1994]. The nature of the beam used in electron-beam lithography allows for extremely precise structures to be sculpted, but the high energy of the electrons also causes damage to surrounding substrate. Researchers are looking at ways of lowering the intensity of the electron beam without sacrificing a great deal of precision [*Campbell,* 1996].

Unlike lithography techniques, the fabrication process of molecular beam epitaxy deposits molecules instead of removing them. Molecular beam epitaxy, MBE, uses a low-pressure beam of molecules directed at a heated crystal surface to create layers of deposited molecules [*Cambell,* 1996; *Cho,* 1994; *Panish,* 1994]. Current techniques of MBE cannot adequately create useful nanometer scale structures. Refinement of the technique is leading to atom lithography, where single atoms are built upon one another on a substrate. Atom lithography is very similar to the core nanotechnology ideas of Feynman and Drexler. Researchers have already shown that individual atoms can be manipulated using a scanning tunneling electron microscope, STM, or an atomic force microscope, AFM.

The impracticality of using expensive and large machines, such as the STM and AFM, to build a great number of nanostructures has provided additional attention to the usefulness of chemosynthesis. Molecular electronics hold the most promise for reliable and economical fabrication by taking advantage of chemical self-assembly. A large number of identical molecules can be created through organic synthesis. The major obstacle to such technology is that the synthesized molecules must then be positioned into logic gates. A possible solution would be synthesizing the molecules so that they are already positioned on a substrate. The research group of George Whitesides at Harvard University has developed a method of fabricating self-assembled monolayers of molecular devices [*Gorman et al.,* 1994; *Kim and Whitesides,* 1994; *Kumar et al,* 1994]. Such a method has an advantage over conventional solution-based synthesis techniques, because it is much easier to etch such a surface than assemble a circuit by positioning one molecule at a time.

7. IMPLICATIONS OF NANOELECTRONICS

It has been about thirty years since Gordon Moore's observation, now known as Moore's Law, that microchip complexity doubles approximately every 18 months. Moore's Law holds true even today and adherence to its predictions is a driving force behind the semiconductor microchip industry's vigorous pace to produce increasingly complex circuits [*Meieran,* 1998]. However, as chip complexity has increased, the fundamental science behind how the transistors are manufactured has remained the same.

The ease with which the MOSFET has lent itself to scaling has undoubtedly allowed the semiconductor industry to maintain the pace first identified by Gordon Moore, but the continued scaling down of the transistor is not enough to allow adherence to Moore's law. Chip size increases at a rate similar to the scaling of the transistor. The scaling of the transistor permits more transistors to occupy a smaller area, while an increase of chip size provides a greater area for these smaller transistors to occupy. These two factors combined contribute to the semiconductor industry's adherence to Moore's law. However, once the limits of the MOSFET have been reached, simply increasing chip size using such transistors will not suffice to keep pace with Moore's prediction.

Michael Frank, a nanocomputing researcher at MIT stated that "as soon as we reach the limits of semiconductor technology, Moore's law can be expected to slow down for a while." With the exception of researcher James Tour, nanotechnology researchers surveyed for this paper echoed similar sentiments. Jonathan Bird, a member of the nanostructures research group at Arizona State University, stated that "Moore's law will continue to hold until new paradigms for computing are needed." The authors of this paper strongly agree with such a prediction.

Such a shift in basic computer architecture, as mentioned by Bird, would be necessary once the limits of current transistor technology have been reached. This includes the enormous change that would also occur with the introduction of multi-state devices. Researchers such as Brar and Kulkarni are researching hybrid transistors, that utilize both conventional and nanoscale technology *[Brar,* 1998; *Kulkarni et al.,* 1998]. Such technology may not ease the transition towards total nanoscale computers to the degree that many researchers would hope. Hybrid technology transforms binary silicon transistors into multi-state devices. The computer industry has built an infrastructure around binary logic devices and relies upon this to develop more advanced integrated circuits and continue adherence to Moore's law [Mieran, 1998]. Since the infrastructure is centered upon binary logic, it is useless to the advancement of multi-state logic.

J. Storrs Hall, a senior scientist in the Laboratory for Computer Science Research at Rutgers University, believes that nanoscale microprocessors will follow Moore's law, but that the first functional nanocomputers will be relatively simple at first. This is directly related to the industry not having the infrastructure with the capability of producing complex microprocessor architecture. We infer such a conclusion since Hall further predicts that several years after the development of the first nanocomputers, their architecture will become increasingly complex and such microprocessors will be much cheaper than conventional silicon electronics. Once the semi-conductor industry overcomes the inherent developmental difficulties of seeing nanocomputing technology through its infancy, in much the same way that was previously done with MOSFET architecture, the production of computers that exceed conventional microelectronic technology is possible.

David Ferry, another member of the nanostructures research group at Arizona State University, also alludes to a slow down of Moore's law similar to that mentioned by Michael Frank. Both researchers predict that Moore's law will stall once the limits of current semiconductor technology have been reached. The authors share the opinions of those interviewed that the future abatement of Moore's Law will be attributed to the microchip industry's need to design new methods of manufacturing for devices that deviate from the previous architecture used for computer microprocessors.

The development of such manufacturing methods is an extremely expensive venture. The facility costs for semi-conductor manufacture is currently increasing on a semi-log scale. This trend is now known as Moore's Second Law. It comes of no surprise that the semiconductor industry does not wish to follow such a trend [*Meieran,* 1998]. However, in breaking this trend, chip manufacturers must be careful not to devote all of their resources to streamlining conventional manufacturing processes. The investment into the development of new manufacturing technologies will allow for a smoother transition towards the inexpensive manufacture of emerging nanocomputing devices. Such an investment would also favor our economy, because "the U.S. semiconductor industry has undergone phenomenal growth during the 1990s and added more value to the U.S. economy than any other manufacturing industry *[Weir and Andrey,* 1998]." The possibility of another country developing better manufacturing capabilities is a real threat and should serve to reinforce the U.S. semiconductor industry's need to fund such research.

Once the nanocomputing industry has established itself and has the capabilities of producing functional machines, the implications of such technology would be felt by society.

> "The main thing.. .is to remember that technology manufactures not gadgets, but social change. Once the first tool was picked up and used, that was the end of cyclical anything. The tool made a new world, the next one changed that world, the one after that changed it again, and so on. Each time the change was permanent. *[Burke,* 1998]"

In humankind's history, few other inventions are more notable than the computer. The computer is more important than the technological breakthroughs of electricity, automobiles and telephones simply because of its programmability to perform a multitude of tasks. While the first computers consisted of an entire room filled with vacuum tubes, they performed the same basic mathematical computations as a modern handheld calculator. Microprocessors are now small and diverse enough to be integrated into watches, telephones, cameras, microwaves, and comparatively tiny computers. Indeed, "as we are able to make computers smaller and smaller, we will undoubtedly find more uses for them *[Gennert,* 1998]."

Modern life has come to depend on computers. Although it has become increasingly difficult to avoid exposure to computers either directly or indirectly, it is not necessary to know the intricacies of how they work or how to program them. Their adaptability to many applications - from word processing to controlling traffic lights - as well as their ease of use has made them increasingly useful to society. But "while bringing many benefits to society the revolution [computers and electronics] will also bring problems, tension, and disbenefits *[Fisher,* 1990]." There exists a simple dichotomy between the view that computers are a neutral, even useful, tool and the view that it can create serious problems.

As the size of the transistor decreases with innovations in nanoelectronics, the increased integration of microprocessors that follows will undoubtedly aggravate and alleviate these benefits and conflicts in modern society. What follows is a comparison of probable impacts that smaller, faster computers will have upon areas where the prevalence of computing technology has already been felt.

Although computers were initially designed to assist in numerical calculations, the most important uses currently are as communication engines, such as the Internet and email, and control mechanisms such as those in robotics and system monitoring. Both are related to the manipulation and dissemination of information. Communication of information instantaneously and to multiple recipients is made possible by the Internet, and increasingly we are a networked nation. Because of this, simple extrapolation allows speculation that the integration of nanocomputers into society would increase the tendency to communicate using computers.

Computer mediated communication is a new form of communication and has raised issues of integrity, verifiability and accountability. Communication is instantaneous and ubiquitous with the use of the Internet. One can communicate with one person or with thousands with the click of a button, and it is not necessary to know with whom you are communicating. Thus social status is leveled since cues are removed because of the lack of face-to-face contact. Therefore, there is more equality in contact; the content of what is written is more important than who is writing it. How then can the authenticity and quality of data be reassured? It is equally simple to propagate anti-semitism on the Internet as it is to distribute pictures of your favorite celebrity. Furthermore, such potentially destructive information is given verifiability simply because it exists on the Internet.

Thus, the advantages of this increased communication must be weighed with the disadvantages. Recently, a study conducted by researchers at Carnegie Mellon's Human Computer Interaction Institute concluded that "use of the Internet is likely to increase depression and be detrimental to the psychological well being of users *[Feeling Depressed?,* 1998]. They found that rather than enhance relationships for users, use of the Web was resulting in less satisfactory relationships with existing friends and relations. Furthermore, increased use of the Net tended to result in more stress and less communication within existing social networks. One could speculate that this is the result of the user's isolation from "facemail" contact between actual human beings.

Currently, there are estimated to be 151 million people on the Internet worldwide *[Nua Ltd.,* 1998]. Nanoelectronics will undoubtedly increase that number as computers become smaller and therefore more portable. Email will become an increasingly used form of communication. In a poll by Ernst & Young, 36 percent of respondents said they use email more frequently than any other communication tool verses 15 percent who said they preferred the face to face communication of a meeting *[Morgan,* 1998]. As computers become even more ubiquitous as means of communication, people may find themselves feeling more isolated from their fellow human beings.

Probably the most frequent charge leveled against computers is that they rob us of our privacy *[Rosenberg,* 1992]. Indeed, aggregation of databases make possible detailed matching of individual characteristics that may end privacy as we know it. However, this is a foregone conclusion as nearly all transactions from buying gas with a credit card to borrowing a book from the public library is computerized. When we asked James Tour, who synthesized the first working molecular wire, what he believed to be negative implications of nanocomputers, he foresaw that there could be "more danger that government and consumer groups will know too much about us and our private lives." Another prominent nanotechnologist, David Ferry believes that "[nanocomputers] have the power to restore that personal privacy through encryption.. .the technology is there for personal privacy, whether on the internet or in cellular communications."

The increased ubiquity of tinier, cheaper computers may further strain the relationship between humans and humanity by raising the issues of humankind's meaning and purpose. The experience of using computers may cause us to devalue calculation and logical reasoning, placing a higher value on emotions and defining what it means to be human *[Turkle,* 1984]. Joseph Weizenbaum suggests that computer-based data will become so important that we will neglect our cultural traditions and fail to explore non-technological areas of human experience. Echoing the theme of the Promethean myth, he fears that our fascination with the power of the computer to let us design and control imaginary worlds will lead us to tragedy in the real world of social cooperation and conflict *[Weizenbaum,* 1976; *Perrolle,* 1987]. In her book, *Life on the Screen: Identity in the Age of the Internet,* Turkle interviews a college student who states "[real life] is just one more window, and it's usually not my best one *[Turkle,* 1997]." This student considers the time he spends in on-line worlds as real as life, and significantly more interesting and important. In this way, society could become slaves to its machines as people continue to live vicariously and virtually through their computers.

The most serious and complex problem associated with the impact of computers on society has to do with work. While the increased manufacture of nanocomputers for an expanding number of applications would surely create jobs, the applications themselves may destroy jobs. In *The Social Impact of Computers* (1992), Rosenberg states that "the introduction of computers, office networks, telecommunication systems, and fax machines has as its goal a major improvement in office productivity, but also fewer jobs." When asked how he thought dramatically smaller and faster computers could impact upon our society, Jonathan Bird expressed that "large scale unemployment is... .an obvious concern." As computers ensure that information becomes synonymous with power, journeyman craft skills are becoming less valued than abstract, symbolic knowledge.

Although society is affected by every technological innovation, whether the impact is positive or negative is in the hands of humanity. This was the sentiment echoed by the majority of the scientists that we surveyed. J. Storrs Hall stated that "it depends on what people do with it, not on how it works." Similarly, David Ferry believes that "there will always be negative implications as long as there are [those] who feel they have to define how others should live" and Jonathan Bird stated that "an important future social challenge will be to adapt to the changes and opportunities that technology presents."

When the first room-sized computers were constructed, it was thought that the computing requirements of the entire world could be serviced by only one or two of the immense machines. The potential advantages of the first transistor developed by Shockley, Bardeen and Brattain in 1947 were equally impossible to anticipate. Although we can predict some of the implications of nanocomputers, we suspect that the majority of their repercussions are as obscure to us as were the ramifications of transistor technology.

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LETTER USED IN CONJUCTION WITH QUESTIONS

As one of our degree requirements as seniors at Worcester Polytechnic Institute, we are carrying out a project to investigate the impact of nanotechnology on society.

As part of this project we have developed and extensive bibliography of scientific papers dealing primarily with the development of nanostructures with potential applications in the area of nanoelectronics and nanocomputing. In contrast to the growing body of literature in this new field, there has been little attention paid to the potential impact that nanoscale will have on the economy and society as a whole.

Our search in both the scientific literature and the World Wide Web has shown us that your research activities are focused in part on nanotechnology. We were wondering if you could spend a few minutes and give us some feedback on the potential societal impact of nanotechnology. We have included several questions below but if these do not adequately address your thoughts on the issue please feel free to just add your own comments.

We note that this is not a survey or a mass mailing. We have chosen only about a dozen people to contact. In our written report, we plan to reference your responses unless you indicate a preference to the contrary. We greatly appreciate any small amount of time you could spend on this. Thank you in advance.