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Materials and Society - Impacts and Responsibilities

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ABSTRACT

The needs of today's advanced societies have moved well beyond the requirements for food and shelter, etc., and now are focused on such concerns as international peace and domestic security, affordable health care, the swift and secure transmission of information, the conservation of resources, and a clean environment. Progress in materials science and engineering is impacting each of these concerns. This paper will present some examples of how this is occurring, and then comment on ethical dilemmas that can arise as a consequence of technological advances. The need for engineers to participate more fully in the development of public policies that help resolve such dilemmas, and so promote the benefits of advancing technology to society, will be discussed.

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I. INTRODUCTION

It is indeed a privilege to be invited to present the 25th Annual Lecture offered by the TMS and ASMI on the subject of "Materials and Society." However, there is both good and bad new associated with this privilege. The good news is that one gets to enjoy the considerable learning experience of reading the preceding 24 lectures. The bad news is that one then has to find something to say that has not already been said, more insightfully and eloquently, by one's exceedingly distinguished predecessors.

They and many others have established the fact that the development of materials, from stone to bronze to iron to composite... and soon to designer nano-structures... has had, and will continue to have, a profound influence on the progress of civilization. And increasingly, for ecological and aesthetic reasons, society will impact the selection of materials to be developed, and the processes permitted to make them.

It is on this interplay between the needs and desires of society and the response of the materials scientist and engineer that I wish to focus today.

Albert Einstein was once asked to address the student body at California Institute of Technology. He commented that "It is not enough that you should understand about applied science in order that your work may increase man's blessings. Concern for man himself and his fate must always form the chief interest of all technical endeavors...in order that the creations of our mind shall be a blessing and not a curse to mankind. Never forget this in the midst of your diagrams and equations."[(1)]

The significance of this point came home to me a few years ago when I was serving as the "token engineer" on a state Humanities Council. The other council members were accomplished historians, sociologists, philosophers, etc., and the intellectual discourse that occurred during the proposal review process was brilliant; good ideas were generated at a furious rate. However, from time-to-time my engineering background would cause me to propose that some of these good ideas be "reduced to practice." In general, such suggestions were not warmly received, and eventually one of the more tolerant members of the Council explained to me that, "Just because you can do something, it does not follow that you should."

This was a salutary lesson, because it is true that not each and every concept or development that is advanced is necessarily a blessing. It does not follow that faster and cheaper is necessarily better (compare, for example, the Minute Waltz and Beethoven's Fifth Symphony). The decision to proceed with the development of any significant new technology likely to impact the community should expect to receive critical inputs from the affected parties in order to arrive at a socially acceptable agreement. Clearly economic, legal, political, ethical, and quality of life considerations are going to be as relevant as those concerned with technological advances.

Learning how to cope with this reality is a skill rarely introduced to young engineers. Yet experience teaches that political concerns often have a major impact on whether or not an otherwise useful project can proceed. This has led Augustine(2) to propose that, "For every engineering action, there is an equal and opposite social reaction," and to recognize that nowadays the profession of engineering might be better termed "Socioengineering," because to be successful at it one must be skillful not only in the traditional areas of engineering, but also in "written and oral communications, political science, economics and international relations."

Another important reality these days is "change." The French philosopher Alphonse Karr once commented that the more things change, the more they stay the same.(3) While, conceivably, this may be true for human nature, it certainly is not for technology. Nowadays, the more things change, the faster is their rate of change, this being especially true of the impact of technology on society.

A few years ago, a number of senior Japanese scientists and philosophers became concerned that rapid technological change was destroying the culture of their nation. So they wanted to decide which cultural elements absolutely must be preserved and passed on from generation to generation. In a sense, they wanted to define their cultural core competencies. They decided to organize a conference to discuss, first, "What does it mean to be human?," and later one to discuss, "What does it mean to be Japanese?." I was asked to contribute to the first of these meetings and, seeking advice, I asked Daniel Boorstein, noted American philosopher and, at that time, Director of the Library of Congress, how he might address the question, "What does it mean to be human?"

He replied, "There is no answer to this question... but it is very important that it be asked!" I suppose this response could be regarded as the philosophical equivalent of the Heisenberg Uncertainty Principle.

But there is no denying the fact that rapid advances in technology are changing our lifestyle in such significant ways that it becomes necessary for technically-literate citizens such as ourselves to pause from time to time and ask, "What is going on?" And, if we find the answer unsatisfying, then next to ask, "What should I be doing about it?" Am I really helping bring the benefits of advancing technology to society? Am I involved in the development of public policies that are based at least as much on scientific understanding as political philosophy? Am I taking the time to help Congressional staffers draft legislation that rationally incorporates such important realities as probability and risk. Why am I going along with our nation's development of comprehensive regulations to control radiation from nuclear plants yet not pushing for a complete ban on cigarette smoking which kills, I am told, 400,000 Americans each year?

It is important, of course, to keep in mind the limited role that scientific knowledge per se actually plays in real life. Harold Shapiro[4] once noted that, by 1 BC, just about every important form of machine gearing was known to the Greeks. Certainly an enormous technical achievement, yet one that appears to have had very little impact on Greek society. The Romans likewise developed the watermill, but did not use this device in anyway to enhance agricultural efficiency.

Thus then, as now, the mere availability of scientific knowledge does not of itself produce any improved quality of life or economic advantage. Other factors also are important, one of the most critical of which is the protection of real and intellectual property. In the medieval period, newly passed laws that provided protection from the arbitrary confiscation of land by a feudal lord (for example, laws emanating from the Magna Carta) led to real advances in agricultural technology with positive returns to the developers. Indeed, historian Lynn White has argued[5] that, given the then new political climate permitting the possibility of a real return on investment, the Renaissance itself may have been a consequence of a few, relatively modest technological advances which led in turn to a well fed and prosperous society... a society ready for the pursuit of intellectual challenge. He notes that the development of harness and the nailed-on iron shoe permitted the more energy-efficient horse to replace the ox as the draft animal of choice. This, together with the development of the deep-penetrating plow, and introduction of the three-field system of crop rotation permitted, in Europe, the massive cultivation of oats, peas and beans (possibly marketed as the world's first "health foods"?).

Today, of course, we use patent laws to protect our intellectual property rights, a practice first exploited in the 14th century by an English king interested in technology transfer.[6] He wanted to protect the knowledge-base of foreign craftsman imported into England to enhance the state of domestic productivity in such high technology areas as weaving and clock making. So, via letters patent, he granted royal protection from uncontrolled exploitation by others for a period of 14 years, this being the time required to graduate two generations of apprentices. In modern terms, this could be thought of as the time required to produce two or three generations of PhD's, the function of whom is to develop and exploit the knowledge base generated by their professor.

The needs of today's advanced societies have moved well beyond the requirements for food and shelter of earlier times, and now are focused on such concerns as international peace and domestic security, affordable health care, the swift and secure transmission of information, reliable transportation, the conservation of resources, and a clean environment. Progress in materials science and engineering is impacting each of these concerns, and it may be of interest to note some of the ways in which this is occurring. For convenience rather than parochialism I have tended to utilize examples generously provided by colleagues at Sandia National Laboratories. I appreciate that equivalent or possibly better examples could have been provided by researchers at other institutions.

II. SOME IMPACTS OF MATERIALS IN TODAY'S SOCIETY

A. Smaller, Cheaper, Cleaner: Modern society has become increasingly intolerant of the negative impacts of industrial productivity on the quality of life. Manufacturers must continue to meet the needs of society, of course, but will only be permitted to do so when using processes of high efficiency and minimal ecological impact. Research, therefore, must be directed towards processes that produce the desired product and little else, and products that are as small as possible, and are energy conserving in both manufacture and use. Some of the approaches now being applied to meet these ends include the use of computer-designed catalysts, near-net shape production processes and, eventually, nano-scale devices.

(i) Modern Catalysts: Many U.S. chemical and petroleum industries still produce up to five pounds of waste for each pound of marketable product, despite the fact that catalysts are used in 90% of their processes. These industries account for about $900 billion dollars of business each year, and consume about $2 billion dollars worth of catalysts, so that even modest improvements in catalytic efficiency could have significant effects on profitability. Accordingly, current research is focused on such topics as the theoretical modeling of chemical processes, atomic scale characterization of catalytic sites to better understand unit reaction processes, the development of new materials for catalysts, membranes, and supports, and the production of novel biological catalysts (enzymes).

Computer simulation of molecular structures and interactions now permit researchers to model desired reactions and to design molecules with a significant probability that they will exhibit useful catalytic capability. This is a far cry, for example, from the approach used to develop complex dye molecules only a decade or two ago. This involved making use of the empirical experience of a long-serving employee to guide the synthesis of a hundred or so new molecules each year, usually only one or two of which then exhibited the desirable properties of color and fade- and wash- resistance likely to result in a marketable product. Nowadays, computer simulation permits predictability of the likely functionality of a catalyst (or dye or drug) without the need to actually synthesize it.

This approach is now being used to generate catalysts for the conversion of natural gas into liquid fuels, for superior electrodes in fuel cells, and for the production of novel polymers, etc.[7] The porphyrin molecule shown in Fig. 1, for example, was developed to electrolytically reduce CO_2, the molecule shown at the top of the figure, to CO with a conversion efficiency of some 50%. In the absence of a catalyst, this reaction requires about +2.0V in water; with a porphyrin catalyst it can occur at ~ +0.52V. Under other experimental conditions, similar molecules can catalyse the formation of formic and oxalic acids, and formaldehyde.

The catalytic properties of certain metallic surfaces, e.g., of palladium, have been known and used for many years. Thus the possibility of producing catalysts that are of extremely high surface to volume ratio would seem the offer the promise of greatly increased catalytic power per unit mass of solid. This objective has now been demonstrated in experiments with nanoclusters, colloidal groupings of 10-1000 atoms, usually separated physically by a sheath of organic molecules (a micelle), and dispersed in a liquid medium. The highly-faceted surfaces of palladium nanoclusters can increase by factors of up to 1000 the efficiency with which this metal can hydrogenate pyrene (a classic process for evaluating catalytic efficiency). The possibility of achieving impressive and economical catalytic activity through the use of nanoclusters of very much cheaper materials; e.g. iron or iron sulfide, is now being pursued.[8]

In related developments, atomic force microscopy now permits the resolution of discrete reactions at surface sites, and recently developed spectroscopic techniques can follow the course of a catalytic reaction sufficiently well that the identity and concentration of its intermediates can be revealed.

(ii) Production of Near Net Shapes: Another way of minimizing waste and ecological impact is to produce the desired product or component in essentially final shape with little or no need for machining. If this can be done correctly the first and all succeeding times, production costs and impact can be much reduced.

Significant progress towards such ends is now being made in the area of investment casting through a combination of advanced computational and experimental techniques. In the past, the time from concept to "first article" for a complex investment casting, e.g., an automobile power steering assembly, could be as much as two years. However, through application of new computer-based approaches, engineers are now able to deliver a perfect casting, based on a solid model, in under two weeks, Fig. 2.[9]

Such processes involve several steps.[9,10] The first is to develop a three-dimensional computer model of the product and then to produce a finite-element mesh representation. Using the latter and other recently developed finite-element codes it is then possible to compute thermal distributions in the as-cast shape, the shrinkage distortions and stresses likely to result as it cools, and hence design an efficient casting strategy. Research in progress is aimed at predictive control of the microstructure, and real time, two- and three- dimensional x-radiography is being used to compare computer predictions and actual casting behavior.

Exciting progress has already been made in the development of such approaches, but the computations involved still require powerful computers and long run times. More efficient algorithms that can run on conventional computers are now required. In development is a Casting Toolkit, composed of software and a database that will be used by foundry personnel to select the optimum design of gates, risers, wall thicknesses and corner radii, etc., to produce a fault-free casting.

(iii) Small, Smart Things: Over the past century or so, industry has prospered by using materials such as steel, concrete and aluminum to make large structures, e.g., railroads, bridges, skyscrapers, steam turbines, cruise ships, automobiles and aircraft. In 1959, however, Feynman presented a talk to the American Physical Society in which he introduced the possibility of "manipulating and controlling things on a small scale." Later, in 1983, he presented a talk entitled "Infinitesimal Machinery," in which he conjectured the existence of such devices as micro-motors, and micro-robots the size of blood vessels that could be used as "swallowable surgeons."[(11)]

Today, the field of microengineering is growing rapidly. The auto industry, for example, already exploits devices of order of 100 μm in size to monitor the positions of moving vehicles, trigger air bags on collision, and optimize engine performance. The future of this field is indeed exciting. Over the past twenty years we have seen the scale of practical electronic devices reduced by factors of 10^4 (to ~0.5 μm), and of mechanical devices by 10^2 (from the smallest component of a Swiss watch to machines having dimensions of 100 μm). Likewise, the density of computer memory units on a chip has increased by about 10^4 (to 10^8 per cm^2), and so it is interesting to speculate on the possibility of developing devices that incorporate some or all of these advances, i.e., intelligent micro-electromechanical systems (IMEMS), with the specific capability to perform useful work perhaps a billion times more efficiently than do today's macro devices.

Such "small, smart things," devices that sense, think, and then act, do not yet exist. But techniques for the production of their component elements are being developed using the processes used to make silicon-based microelectronic devices. Progress is rapid. In 1994, the world's first "microsteam engine" was produced, Fig. 3.[(12)] Though not intended to do practical work, this little device, microgram for microgram, is about forty times more efficient than the engine that boosts the space shuttle into orbit. Since then, tri-level devices have been produced that permit the transmission of power, Fig. 4.[13] Because of their low mass, the cogs in the chain illustrated can be rotated at speeds of over 300,000 r.p.m.

Within the next year or so, power sources, sensors and computer memory will be grown on the chip surface nearby so that the mechanical device will be responsive to its environment, i.e., interactive and intelligent. The applications for such devices, some 10-100 of which can fit on the head of a pin, would seem to be limited only by our imagination. They will include medical sensors, pacemakers, smart tires, switches, gyros, secure munitions, auto navigators, and Feynman's micro-robots. A recent survey has predicted an annual market of $14 billion by the end of the century.

Where does materials science come into all of this? Well, clearly, for devices this small, corrosion takes on a whole new meaning, as do the phenomena of friction, lubrication and wear, and the technologies of joining, packaging and NDE. Thus, I suspect that the nano-scale world will provide mega-scale opportunities for challenging and important materials research!

Proceeding in parallel with the development of silicon-based micro devices is that of intermediate scale devices made from various materials by the LIGA process (a German acronym for Lithographic-Galvanoformung Abformung). This process involves directing synchrotron radiation through an x-ray mask on to a thick polymer resist cast on an electrically conducting substrate. The resist is then etched to dissolve the exposed or unexposed region, depending on the resist type. Metal is then deposited electrochemically to fill the gaps in the resist. After stripping, a final metal structure or a metal mold for subsequent replication is achieved.

LIGA exhibits a number of advantages over other microfabrication techniques. In particular, it is capable of fabricating high-aspect ratio structures millimeters thick but only microns wide, and also parts from various metallic alloys, plastics, glasses, ceramics and other materials. Research is now focused on developing superior polymer resist materials, and on understanding the micro-scale plating behavior of alloys. The LIGA process has already been used to produce gears, acceleration sensors, and fiber-chip couplers for integrated optical chips, as well as optical prisms and lenses, polymeric micro-pumps for such medical applications as drug delivery and chemical analysis systems, and a variety of devices for the aerospace and defense industries.[14,15]

B. Materials and Affordable Health Care: Most applications of materials to health care are inexpensive and in widespread use, contact lenses, artificial teeth and hip prostheses being obvious examples. However, the route to the futuristic bionic person, in whom every malfunctioning component has been replaced by some high-tech device, is proving to be very expensive. Already U.S. health care costs consume about 14% of the GDP, and recently these costs have been increasing at 10% p.a. Consequently, society is beginning to appreciate that the vision that every citizen should be entitled to the very best that medical technology can provide, regardless of cost, may be unrealistically Utopian.

Technology is frequently cited as the cause of rising health care costs, and it certainly plays a role. Clearly, if there were no magnetic resonance imaging machines, we would not have to buy them, and this would reduce costs... but at the cost of not saving lives. Considerations of such issues raise very culture-dependent answers to the question, what is the value of a human life? In practice, however, most technological developments show a positive return on investment over time, usually in terms of the ability of persons restored to health to contribute to the economy. For example, it has been estimated that the use of endoscopic surgery (often utilizing devices made from shape memory alloys and advanced thermoplastics) can reduce by 40% the cost of lost work days (an avoided cost benefit of ~ $340 million p.a. in the U.S.).

Biomaterials of various sorts are now used in some 2700 different medical devices and 2500 diagnostic products, the annual sales of which amount to $24 billion. Some of the most exciting work in this field is focused on the development of bioelastic polymers to replace muscle tissue, and for proteolytic gels for programmable drug delivery.[16] Another potentially important development, aimed at controlling the blood glucose content of the 14 million diabetics in the U.S., is a bioartificial pancreas.[17] This device, Fig. 5, consists of an acrylic housing that contains a coiled membrane (made of modified copolymer polyvinyl chloride and polyacrylonitrile (PAN)) surrounded by a chamber filled with porcine pancreatic cells. Blood flows through the membrane and is returned to the vascular system. The tubular membrane contains pores large enough to allow the transport of insulin into the blood, but small enough to provide barrier to cell diffusion. The device weighs only 80g and is intended to be implanted under the patient's skin. Animal testing by the W. R. Grace Corporation has demonstrated that this artificial pancreas can effectively control glucose levels for more than 6 months. If successful when tested in humans, it should not only greatly improve the quality of life of diabetics, but also reduce the cost of their health care, estimated to be of order $20 billion per year.

Advances in silicon micro devices have been mentioned earlier, but an especially intriguing development is a microtweezer for brain surgery. This device is about 500 μm square, and is opened and closed by a "smart" conducting polymer actuator. The object is to permit a surgeon to swiftly and precisely remove embolic materials introduced by an aneurysm. It is anticipated that this sensitive device could reduce operating time from four hours to one.

The use of titanium, cobalt and their alloys in hip prostheses is well known. However, problems still arise because of the intrinsically different mechanical response to stress of metals and bone, and because corrosion of the implant can cause it to become painfully loose. Hydroxyapatite coatings are being used to improve the durability of the metal-bone interface, but this problem has yet to be solved. Pure titanium seems to introduce the least problems, with nitrided titanium being especially resistant to galling and corrosion. Implants made from the latter material are likely to significantly outlast the durability of the patient, raising the bizarre possibility of their becoming family heirlooms.

A number of medical devices now use advanced lithium batteries as power sources, e.g. pacemakers, drug delivery systems, and neuro stimulators (for pain reduction). Such batteries, based on the $Li-I_2$ cell, can now produce currents in the milliamp range for up to 7 years. One design uses a stainless steel case that also serves as an electrode, can be interrogated by telemetry, and weighs only 5g. Other batteries, for example those utilizing a lithium-silver-vanadium oxide (SVO) system, can provide pulses of up to 3 amps to power implantable defibrillators that shock irregular heart muscle contractions back to a normal rhythm.

The use of active implants for functional electrical stimulation (FES) to restore life to damaged spinal cords or other parts of the nervous system, is another exciting development.[(18)] Power is transmitted through the skin via a radio-frequency signal electromagnetically coupled to a receiving coil in the implanted stimulator. Since most spinal cord injuries tend to be suffered by people in their early twenties who otherwise possess a standard life expectancy, FES technology offers the possibility of some degree of independent motion, and of participation in normal life. Currently, FES systems are implanted in about 30 people around the world.

Unfortunately, problems arise when implants or other devices do not live up to the patient's expectations... which usually amount to absolutely trouble-free performance. All too often, the patient's response is to litigate against the device manufacturer or materials supplier for some large sum of money.

Now, whether the patient has been led to anticipate perfection, or simply hopes for it, causes expectations that most engineers recognize as unrealistic. In such a dynamically stressed and corrosive environment as the human body, the use of critical but delicate devices, or even of passive but psychologically supportive devices such as breast implants for women who have had cancer, will always involve the risk of failure. Thus, litigation in which only the lawyers emerge as winners is now having a chilling effect on the willingness of companies to supply materials or devices for many medical applications. Major companies such as Dow Chemical and Dupont, both of which have the research resources and the managerial desire to help provide engineering solutions to human health problems, are now withdrawing from this important endeavor, and are not permitting some of their materials to be used by device manufacturers. Materials no longer available for medical use include polyurethane for heart valves, polyethylene for artificial hips and knees, silicone for breast implants, and nickel/titanium alloys, surgical stainless steel and titanium for load-bearing implants.

The consequences of today's litigious environment are likely to include the diversion of R&D resources away from medical applications and, perhaps, the development and marketing of such devices by foreign companies in countries with a legal system that recognizes that progress is rarely made without risk, and that risk must be shared by the customer. Because engineers are fallible human beings, so are our products. Our research must always be as careful and rigorous as possible, but failure of any mechanical device will always be a possibility. Our nation's laws, and our lawyers interpretation of them, must accept this fact if progress in the application of materials technology to health care is to be sustained. Each of you could help bring more realism to this situation.

C. <u>Materials in Information Security</u>: Few technological developments have such a significant impact on society that its behavior is changed, but optical fiber technology is likely to be one such. Together with integrated circuits and computers, lasers and optical fiber communications have launched mankind into the Information Age. Optical fiber transmission systems are now employed in virtually every area of telecommunication, from undersea cables and intercity trunklines to inter-office networks.

The optical fiber has emerged as today's transmission medium of choice because it offers vastly superior capacity (bandwidth) at a lower cost than any other medium. The first optical fibers suitable for long distance communication, i.e. with a loss of $\ngtr$ 16dB/km, were produced at the Corning Glass Works in 1970 by ceramist Robert Maurer and his group. Maurer, et al. combined a doped fused silica core and a pure fused silica cladding to create the necessary difference in refractive index between core and cladding to "contain" the light beam within the fiber. They accomplished this by means of a flame hydrolysis process that deposited doped silica soot inside a pure fused silica cylinder, which was then drawn into a fiber. Subsequent research at Corning, Bell Labs and elsewhere solved other problems, such as how to achieve precise doping levels for tailoring graded indices for multimode transmission, how to produce chemical blocking layers for impurity containment, and how to eliminate water and hydroxyl ion impurities and so significantly reduce transmission losses.

The impact of this development is such that terms like the "Information Age" and the "Information Superhighway" have become symbolic of today's technical world. Its significance has led Patel[(19)] to compare the development of optical fibers with that of the jet engine. Both have made our world smaller and more accessible, but optical fibers have accomplished this at a much lower cost, with greater speed, and with less environmental risk. He has commented that the advent of multimedia and full bandwidth video conferencing using optical fiber communications may even, in time, make the development of optical fiber technology the more important of these two profound engineering accomplishments.

However, with advances come problems, and preserving the integrity of transmitted data is becoming increasingly important. Preventing hackers from breaking into an information system and siphoning off technical secrets, funds, medical records, or other data that one might wish to keep secure, is emerging as a non-trivial problem. The answer will probably lie in sophisticated cryptographic encoding, enabled by advanced semiconductor devices. Indeed, today's codes are sufficiently good that, to all intents and purposes, they are unbreakable. This is not entirely a blessing, however, since criminals may soon be able to encode the details of their nefarious transactions in ways that national security agencies are unable to decipher.

Preserving the surety of medical information is especially important, not only to prevent the fraudulent changing of records or digital images, but also to prevent misdiagnosis during real time, long distance, medical examinations. Whilst we are not quite ready for Star Trek-type instant medical diagnosis, sensor-laden devices that can transmit a portfolio of signals to a distant medical center for expert analysis are likely to be available in the next decade or two, but errorless and secure transmission of this data could prove critical to a patients survival.

Another area where materials science has and is playing an important role in information security is in the prevention of counterfeiting. Recent advances in copying technology led to the production of some $200 million worth of counterfeit bills in 1994. To reduce the likelihood of such bills being successfully used, a machine readable polymer strip that can be deciphered only in transmission is now embedded in large bills. And, beginning in 1996 with $100 bills, multilevel deterrence will be implemented. Notepaper will be printed with subtle variations in color density--a watermark--that is obvious to see yet challenging to reproduce. Iridescent, microprinted planchettes may also be distributed throughout the paper. Such polymer multilayers change color with viewing angle. Other interference micromirrors will probably be used in inks, also imparting angularly dependent vivid color to parts of the bill.

Of course, optical interferograms became common some time ago on credit cards. However, the holographic eagle still seen on many cards is now more of a tradition than a deterrent to fraudulent use. Indeed, the U.S. counterfeit card problem is four times larger than that for bills. Worldwide, credit card fraud exceeds $500 million, owing in part to organized crime: within 24 hours of a card theft in the U.S.A., a hundred copies can be available for use abroad. Typically these are magnetic copies, re-encoded from the original. Fortunately, very high coercivity (VHC) magnetic materials, which cannot be re-encoded at the necessary bit density without destroying the card itself, have just been developed.[20] The highest coercivity magnetic materials available are rare earth-transition metal compounds, the most common of which are samarium cobalt ($SmCo_5$) and neodymium iron boron ($NdFe_{14}B_2$). These materials have intrinsic coercivities around 14,000 Oe, this value being substantially greater than the few hundred Oe of iron oxide, or the few thousand Oe of the ferrite material used in today's "high coercivity" striped cards that can be re-encoded with a magnetic encoding head.

The successor to the credit card is the "smart card." An onboard microchip can transact finances with potentially great surety. Not only can it cipher a sophisticated cryptographic key, the key itself might be biometric, such as a thumbprint. To enhance the surety of smart cards, designers have borrowed the "protected volume" concept from nuclear weapons security. A protected volume is a "burglar alarm" that senses any tampering or intrusion. If this occurs, the card is automatically disabled, the information it holds being erased in a split second.

D. Materials in Transportation: (i) Automobiles: Public transportation consumes about 27% of the total energy used in the U.S., and most of this is petroleum-derived. Energy use for transportation is predicted to grow by about 25% from now through the year 2010. This is about the same rate of growth as that noted during the period 1978-1993 (~ 1.5% p.a.). It is somewhat daunting to recognize, however, that during the latter period, average auto weights declined by 20-25%. It follows that if we are to hold transportation energy consumption growth to less than 1.5% p.a., not only must we continue to reduce auto weights by similar amounts, but also find other ways to increase fuel use efficiency. Such actions may permit us to reduce U.S. dependence on foreign oil, the reliability of this source presently requiring a multi-billion dollar p.a. investment in military presence. It is possible that this scenario could be significantly changed by the increased use of telecommunications and work-at-home policies. Reducing the number of day's in a work week, on the other hand, is likely to result in increased leisure driving and fuel consumption.

These and other considerations have led the Federal Government and the major automakers to establish the Partnership for a New Generation Vehicle (PNGV), one objective of which is bringing about an average reduction in weight of about one third from that of today's mid-size car, and to increase its fuel efficiency to about 80 mpg while retaining its performance, space, comfort and safety.

Achieving such bold goals will require the development of superior materials for almost every auto application, from tires through engine and power trains, to interior accoutrements and body work. Current approaches include the use of plasma-sprayed coatings on pistons and aluminum engine blocks to permit higher operating temperatures; cast and welded aluminum space frames; optimized induction heat treatments of drive shafts to increase their strength and to reduce mass by 15%; the use of glass or carbon fiber reinforced composite materials for bodies and flywheels (breakthroughs to reduce processing costs are required); the development of new types of batteries and fuel cells; plastic instead of glass windows; foam core body panels and seats; and perhaps new types of smart tires, the frictional behavior of which self adjusts to rolling versus accelerating/braking conditions; etc.

Evident consequences will be that the need for steel and petroleum will decline, but opportunities will arise for companies to develop and produce new types of structural and energy conserving materials.

(ii) <u>Aerospace</u>: The aerospace industry currently uses about 2.2×10^9 kg of materials annually. This is only of order 1% of the total amount of structural materials produced (cement and steel constituting some 90% of the gross), but the industry is by far the largest user of superalloys, high strength aluminum and titanium alloys, and (for now) various types of advanced composites.[21]

Historically, the principle drivers for the use of advanced materials in the aerospace industry have been performance enhancement and weight reduction. Reducing the weight of an aircraft by 1 kg can save several thousand dollars in fuel costs over its life, while the same action can provide additional payload capacity valued at about $1500 per kg for a launch vehicle. However, while the traditional aerospace requirements for materials that exhibit strength, low density, toughness, and corrosion and fatigue resistance remain, another requirement is becoming increasingly important, namely, affordability. With this objective in mind, a current goal of the U.S. Air Force technology development program is to reduce by 2005 both the structural weight and the cost of an aircraft by 50%, while still meeting all relevant performance and design-life criteria. In addition, they have issued a challenge to the U.S. aerospace industry to reduce the cost of launching 1 kg of payload from about $1500 to $150.

One trend well underway to reduce costs via near-net shape production while simultaneously increasing performance/weight characteristics, is the development of materials of ultra fine microstructure. These are then shaped by superplastic forming.

Looking a decade or so in the future, one may conjecture that, by then, high performance structural materials will consist of a matrix whose chemical composition has been selected through the use of quantum mechanical calculations to optimize its strength (interatomic bond strength) and ductility (crystal structure), and will contain a homogeneous distribution of different types of submicron sized particles selected to add specific preferred properties, such as toughness, conductivity, photo-sensitivity, or resistance to stress corrosion cracking in a particular environment. Furthermore, the component's macrostructure and design will have been application-tailored via computer simulation to minimize any likelihood of premature failure.

Returning to the present, consideration of some of the criteria involved in the design of a next-generation regional airliner can be illuminating. Such a vehicle is likely to be designed for a life of 25 years that will involve 60-80,000 flying hours and 250,000 miles of travel on the ground! Clearly, fatigue and corrosion phenomena will continue to be of concern for some time.

The past few years have seen some impressive developments in materials for aerospace and aircraft, not the least of which are the new Al-Li alloys. These materials are of interest to aerospace designers because the addition of 1 w/o Li to Al produces both a 3% reduction in density and a 10% increase in stiffness-to-density ratio. The Weldalite™ series of alloys (Al - ~ 1 Li - 4.5-6Cu - 1.5 Mg + Ag + other elements), are of particular interest because modest variations in composition or heat treatment can produce a wide variety of useful combinations of high strength, toughness, corrosion resistance, and weldability.[22] This family of alloys was designed to meet the need for a weldable Al-Li alloy for the fuel tanks of lifting vehicles. However, an unexpected bonus arose when it was discovered that they could also exhibit strengths of more than 700 MPa (100Ksi), primarily because of the presence of an extremely fine and homogeneous distribution of the intrinsically stiff T-1 (AlCuLi) phase. Morphologically, this phase is about 0.1 micron in dia., but only one unit cell in thickness. The fracture toughness of certain Weldalite™ alloys also increases with decreasing temperature. This means that expensive cryogenic property testing can be replaced by room temperature tests knowing that, whatever results are obtained, the low temperature properties will be better.

The next generation high speed commercial transport (HSCT) will require lightweight alloys for wing surface structures capable of withstanding temperatures of around 150-200°C. Most current aluminum alloys are not useful at such temperatures, but Weldalite™ alloys are now exhibiting ultimate tensile strengths of over 500 MPa at 200°C. Such values exceed the strength of 2219 at room temperature, Fig. 6. The ultrafine microstructure of Weldalite™ also permits superplastic forming, facilitating the production of complex shapes by slow pressing or forging at elevated temperatures.

Candidate materials for applications at elevated temperatures include titanium alloys, metal matrix composites, and a variety of intermetallics, e.g. the aluminides. For example, the material currently selected for the skin of proposed National Aerospace Plane (NASP or X-30) is a SiC fiber reinforced titanium alloy B-21S (Ti-15Mo-2.7Nb-3Al-0.2 Si). The matrix of this composite provides two significant advantages over competitor materials, (i) it can be reduced in thickness by 80-90% without an intermediate anneal, and so can be readily be made into foil, and (ii) in consequence, it is much cheaper to manufacture than aluminide-based composites. B-21S also exhibits good oxidation resistance and is relatively tolerant to hydrogen.

The stability of the SiC-Ti interface may present some concerns, however, since titanium has a well known tendency to pick up carbon and become embrittled. For this reason, an alloy development approach based on the principle of using only hardening entities known to be thermodynamically stable with respect to the matrix has some merit. Potentially such a material could be welded without markedly influencing the size, distribution and chemistry of its hardening phases, a property supportive of manufacturability and structural reliability. A process that permits such advantages, based on the self-propagating synthesis approach, has now been developed by Brupbacher et al.[23] Known as the XD™ process, it has been used to produce "designer" titanium aluminide microstructures containing hard boride phases for strength, softer phases for toughness, and nitride whiskers for creep resistance.[24] The mechanical properties of such materials are promising. For example, at 800°C the UTS of the TiAl matrix is 630 MPa, but the addition of 7% XD-TiB_2 increases this to 1050 MPa. The latter value is comparable with the properties of the best nickel base alloys, but the aluminides are of lower density. Fracture toughness is > 25 MPa$\sqrt{m}$.[24] Another advantage of using the XD™ process to produce aluminide matrix composites is that the fine dispersion of second phase particles inhibits grain growth, and the consequence is superplastic capability.

One of the most important areas for technology development in the aerospace industry in the '90s will be smart structures, i.e. structures with the capability of monitoring external and internal conditions and of responding swiftly and automatically to control their influences.[25] Smart structures will be able to sense loading conditions and detect the onset of cracks or excessive fatigue damage; to monitor and dampen flutter and vibration; and to adjust surface optical properties to absorb (become stealthy) or reflect radiation as desired. Accomplishing these capabilities will require the use of embedded sensors and actuators connected (probably) by optical fibers and electro-optical linkages to an on-board computer. The materials requirements for such developments are diverse, ranging from shape memory alloys and piezoelectrics to optical fibers, electrorheological fluids, stress-and photo-sensitive polymers, electro-optic devices, and, of course, IMEMS.

The benefits anticipated from smart structures are impressive: increasing the lift to drag ratio of an aircraft via adaptively controlled surfaces should produce a 50% increase in range or 30% increase in payload; reducing helicopter blade vibration and twist should produce a 25% increase in speed and significantly reduced noise.

E. Materials, International Peace and Domestic Security: (i) Military Defense: Developments in materials traditionally have been translated into improved weapons, e.g., sharper swords, tougher and lighter armor, bigger guns with more penetrating shells, quieter submarines, faster planes, and nuclear weapons. And, in spite of the end of the cold war, the availability of weapons of mass destruction (WMD) continues to serve to reduce the threat of significant offensive action against the U.S. by some other state. Increasingly, however, this form of "ultimate defense" is becoming seen as a diplomatic tool by certain nations with less than desirable intentions. Consequently, detecting and countering the proliferation of WMD's is now a matter of real concern. The acquisition of intelligence on who is doing what, where, and how with biological, chemical and nuclear weapons is a major challenge today, and sensor capabilities are, as yet, marginal. Space based sensors and fixed seismic devices can reveal various types of weapons testing, but the detection of underground production operations still presents difficulties. Consequently, the development of new classes of tiny chemical sensors is being investigated, sensors that can sniff, observe, listen, analyze and transmit information. One objective is to be able to mass produce these so cheaply that they can be spread like "seeds" by stealthy aircraft over a suspicious area.

Such devices are likely to consist of a chemical or biological film adsorbed or bonded on to a semiconductor device. Changes in the electrical properties of the film, induced by interaction with active molecules in its environments, change the nature of its interaction with the semiconductor surface, and so can be detected and analysed by the semiconductor device. The present state-of-the-art is that sensors are now available that can detect toxic organic effluents such as trichlorethylene, certain illegal drugs, hydrogen and other gases, and critical species in certain manufacturing processes. It is ironic to note that much R&D effort was expended in the past to prevent changes in the functioning of semiconductor devices by chemical interaction with their environments!

Actually, the portfolio of possible detectable changes in physical properties induced by chemical interactions is quite extensive, including variations in dielectric coefficient, work function, surface charge, dipole moment, refractive index, surface acoustic wave behavior, modulus, and electron/hole concentration and distribution,[26] so there are plenty of phenomena to be exploited, and significant potential to be developed. Recently developed Pd-SiO_2 - Si detectors, 10^{-3} cm^2 in size, can sense the presence of a mere 100 hydrogen atoms, and a change in hydrogen pressure of order 10^{-9} Torr. Even so, this feat is still several orders of magnitude less impressive than the detecting capability for certain biological molecules of a moth!

Another issue of concern to the DoD is the aging nuclear weapons stockpile. Nuclear weapons were designed to last about 20 years, but with the cessation of production, the few remaining will have to last much longer. The question is, can they do so reliably? When will components degrade sufficiently that they simply must be replaced? And replaced with what? Many of their components were designed 30 years ago, and are no longer available.

Predicting when a component needs to be replaced is an emerging challenge for materials scientists, and this capability will be required for a number of critical but aging systems, e.g., aircraft, nuclear reactors, telecommunications infrastructures, etc. Moreover, it is not always the critical device itself which degrades, but rather its polymeric container, or the solder connections between its electronic components.

Solder joints usually fail by thermomechanical fatigue. The effects of thermal and stress cycling is sometimes evident in the microstructure of a typical Pb-based solder as a thin, coarse-grained band Fig. 7.[27] This band, being softer than the matrix, deforms preferentially, leading to crack initiation, propagation, and interconnect failure. This problem can be alleviated by selecting off-eutectic compositions and alloys that have higher solidus and liquidus temperatures. Thus, recently developed Sn-based, Pb-free solders now provide excellent thermomechanical fatigue resistance.[27]

Beyond ensuring their immediate reliability, the next challenge for nuclear weaponry is the "Self Aware Weapon." Such a weapon would be inherently safe; know where it is at all times; be capable of diagnosing and communicating its state of health and location (e.g. I am in Albuquerque, and am sensing hydrogen in compartment B that is coming from a corroding aluminum fixture); be tamper proof; could not be armed until its target has been located; and could not be detonated until it has received and verified the fire command, etc. Such a weapon will rely on a whole portfolio of different sensors, radiation-hardened microelectronics, optoelectronic interconnects for high data rate communications, and microelectromechanics devices to sense tampering, etc., Fig. 8.[28]

(iii) Non Lethal Weapons: An important trend in the opposite direction is, however, the development of non-lethal weapons. Nowadays, a policeman or a soldier facing a violent adversary with a weapon has little choice but to use his or her gun. However, less lethal approaches would clearly be better, and materials for deterring aggressive citizens, for gluing an aircraft to its runway, or for disabling a tank's treads are now being developed. One of the earliest forms of conflict deterrent was the smoke screen. Today's arsenal of deterrents include superslick coatings, adhesives, sticky nets, beanbags, high level sound, and aqueous or polymeric foams.

Foams are attractive as dispensable barriers. Polymeric foams can have expansion ratios of 50:1, and aqueous foams of 25,000:1. Recently, guns to shoot sticky foams distances of up to 30 metres have been developed and, as one might expect, being covered in goo swiftly discourages aggressive tendencies. Fig. 9.[29] In Somalia recently, the U.S. Marines dispensed sticky foam on concertina wire, making the wire extremely difficult to cut.

Essentially ordinary soapsuds can also be amazingly effective. A person immersed in such foam, Fig. 10, cannot see or hear, and quickly becomes disoriented. The possibility of seeding such foams with oleoresin capsicum 6 (the active ingredient in pepper sprays) and using them for riot control is a consideration. Presumably, a sneeze would indicate involvement. Polymer stabilized foams can exist for hours, and so could be used for temporary barricades. Appropriate amounts of an aqueous foam can also reduce the overpressure from a high explosive some ten fold, so such foams may find application in the protection of federal buildings.

Clearly, if our police used only non-lethal weapons, then their role as preservers of the peace in the community might be more realistically performed. One consequence might be that criminals also would go non-lethal, so reducing today's horrendous murder rate. Meanwhile, defusing a riot by making the ground too slippery to stand on, stopping a getaway car by electronically disabling its computer, or wrapping a knife-wielding man in a sticky net, each have the potential of reducing the societal consequences of confrontation, making our neighborhoods safer and more pleasant places in which to live.

These are some of the many ways in which materials can and will impact society.

IV. TECHNOLOGY AND ETHICS

The introduction of any advance in technology is not without risk, and wise human choices require us to have some appreciation of the competing risks of alternative options... the risk to use it vs. the risk of not using it. For example, the vaccine for whooping cough can cause serious side reactions in about one in ten thousand cases. When this fact became known in England some years ago, public outcry led to abandonment of the requirement for vaccination. The number of deaths caused by whooping cough rose so swiftly that the vaccination program was promptly re-instated. Koshland[30] has noted that the pros and cons of this decision are intriguing. One might argue, "Use the vaccine, more people will be saved." Alternatively, one might say, "We are not responsible for nature's scourges, but we are for any deaths caused by our vaccines." Koshland comments that "morality should state that errors of omission are as important as errors of commission," and that today we need a "morality that does least harm to the most people." I would add that doing the most good to the most people might be an even better maxim.

You may be aware that one's health is more likely to be affected by radiation introduced into the atmosphere by burning coal to generate electricity, than from the radiation customarily emitted from a nuclear power plant. And that more miners die each year extracting coal than do nuclear plant operators going about their daily operations. Yet today's public is strongly opposed to nuclear power, in part because of the perceived risk of human error in causing another Chernobyl. But when a modular and intrinsically-safe reactor is developed, perhaps within the next decade, what then shall be our decision regarding the use of nuclear power generation?

What are some other technological developments that may produce ethical dilemmas in the next few decades or so? Prediction is difficult, of course, but perhaps we can do better than the revolutionary Trotsky, of whom it was said that, "he was so far sighted that, as yet, none of his predictions have come true!"

Certainly we shall see major advances in medical diagnosis, brought about by coupling advanced scanning technology with massive computational and analytical capacity. Our dilemma will be the same as today. Given the tremendous cost of operating such a new system, who will be able to make use of it... only the very wealthy... and the (subsidized) very poor? This will not be a permanent dilemma, of course, because no doubt within 25 years improved versions of such machines will be as common, and as inexpensive to operate, as are x-ray machines today.

How about the human genome project? This initiative should provide information permitting the early diagnosis of certain genetic disorders, allowing biomedical engineers to know which part of your DNA to remove and replace. The challenges of choice here are several, ranging from religious concerns... are we playing God... to the hazards of unequal opportunity. If, for example, it were known that the candidate for a job is likely to become debilitated sometime in the future by multiple sclerosis, would he or she be hired? How should we adjust our equal opportunity laws? Should we require affirmative action plans related to chromosome design?

For how many years should we design a human to live? Should our policy on this be concerned with quality of life, so that we should build in a self-destruct mechanism triggered when some reduced level of physical or intellectual vigor is reached? For example, when you can no longer run 100 yards in 20 seconds, or solve a non-linear differential equation, then should it be time for you to say farewell? Incidentally, would anyone be seriously interested in working until they were 165 years old?

Personal computers and networks will soon permit us to access the whole world's information database. We shall then have both access and excess. Who then shall prioritize what is important and what is not? If, one day, we teach computers to think, should we believe the answers? Could they lie? Should we allow computers to become creative, or should we pass laws limiting imagination to humans?

Given telephones that permit us to be reached anywhere in the world, and location indicators that reveal exactly where it is that we are, will privacy be possible or even permitted? Or will seeking it be regarded as unsociable and therefore unlawful behavior?

Given that most manufacturing and other energy-consuming tasks such as gardening will be done by robots, how shall we release and control the energy previously consumed by such activities? Is there more to life than jogging, golf, and surfing the World-Wide Web? Should we pass laws requiring everyone to work not less than 4 hours a day?

Will the emerging availability of smart, all-seeing and all sensing satellites, and an unmatched arsenal of brilliant and totally accurate weapons, cause the U.S. to decide to become the world's policeman? Or should we turn over these capabilities to the United Nations and work towards "One world, under a variety of Gods, with liberty and justice for all?"

Someone said recently that modern technology is marvelous. It has enabled man to gain control over everything except modern technology. More to the point is Wenk's[31] comment that "Whoever controls technology, controls the future." The question is then, who will control the technology?

V. THE SOCIOENGINEER

Mortimer Adler once commented to Bill Moyers on television that "There is knowledge, there is understanding, and there is wisdom. Scientists and engineers generate knowledge; some even seek understanding; but they tend to leave wisdom to the philosophers." Unfortunately, the situation is actually worse than this because, nowadays, most philosophers also are disconnected from the policy-making process. Today, most important decisions are made by politicians, many of whom began their careers as lawyers. So should we rely upon lawyers to make the decisions? No. The function of lawyers is to tell what you cannot do, not what you can. Through laws they establish the lowest common denominator for what society will permit its citizens to do, what is allowed... but not what is achievable. Policy should point the way to the achievable, and set standards or goals for a preferred quality of life.

How about the industrialist? No. In a capitalist society the need for a prompt and significant return on the financial investment will always be a primary consideration. So decisions will usually be reactionary, and focused on the near-term.

The humanist then? No. Because most contemporary humanists are not sufficiently technically astute to perceive either the potential benefits or bedevilment's of fast-moving technologies.

Well, how about the engineer? Unfortunately not... because most contemporary engineers are too busy working on today's challenges to be concerned about the ramifications of yesterday's results. Questions regarding "values" are likely to elicit a response in terms of the speed of the latest supercomputer.

So much for the problem; how should we approach its solution? I am told that Arnold Penzias was once asked what motivated him to become a scientist. He said it was his mother, because every evening when he came home from school, she'd say, "Well, Arno, what good question did you ask today?" I'm concerned that, today, few engineers in industry or academe are asking the good questions. Not merely questions about how to do their job better, but such questions as, "Should this job actually be done," and "What might be the (unexpected) consequences of doing it?" What are the consequences of such an unquestioning approach? First, if you don't know why you're doing what you're doing, you can't prioritize it in the scheme of things. It's hard then to develop a proper balance in your life... job vs. family responsibilities, and of these vs. the need for physical, sociocultural, and political activities. In other words, an appropriate concern for value as well as action. Second, if you don't ask "Why am I doing this job?", you will fail to investigate the potential second and third order consequences of what you're doing... what might be termed the "So what's!". In this regard, Senator Daniel Moynihan once noted that, "In the course of human history, it was very important that man invent the wheel. But it was equally important that, soon after, someone invent the brake!"

The person who, when asked what he or she does, proudly says, "I am a materials engineer," may be missing out on much of what life has to offer unless, before they say this, they think: First: I am an intelligent and contributing human being. Second: I am a citizen with civic responsibilities. Third: I have gained some scientific knowledge. And, finally, I have some expertise to offer in one small segment of the universe of technology, namely, materials engineering. Perhaps pursuing the inverse of this sequence is the formula for a useful life. Perhaps we must lose expertise to gain perspective and wisdom.

How then to start? Let's assume that all of us are rightfully concerned with meeting the needs of society, and with maximizing the benefits that technology can bring to it. But let us first take heed of Sagoff's[32] comment that we maximize the benefits of technology only "When we bring economic activity into a sustainable relationship with nature... for example... by renewing the resources we deplete... and by maintaining the functioning of the ecological systems on which we depend." Thus, we must remember to take into account the total life cycle impact of any product we develop. Our mission must be to develop cost-effective, energy-conserving, ecology-preserving, wealth-generating technologies... that improve the quality of life of the maximum number of human beings today, and into the future. Given wealth, distributed appropriately through intelligent public policy (which, of course, we shall henceforth help develop), we shall be able to support education, research, the arts and humanities, health, music, transportation, etc., and all of those things besides engineering that make life worthwhile. So much for the engineers.

What should we ask of the humanists? Well, it's time for them to come out of the library and learn something about the workings of the physical world. They should stop talking to themselves about such incremental issues as to whether or not they should teach the literary canon (the masterpieces of the dead white males), or only the works of living black females. Instead, they should start talking to engineers, to lawyers, industrialists, and everyone else, about the important things in life, the values beyond survival that make life truly work living. They should focus on explaining the importance to our society of such grand concepts as truth (defined by Bronowski[33] as "The cement that holds society together"), and about goodness, dignity, duty, responsibility, justice, tolerance, and reason... speaking in terms that politicians, engineers and ordinary citizens can understand and act upon.

Thus, much as the challenge to the engineer is to reduce the great physical concepts to practice, so the challenge to the humanist is to reduce the great philosophical concepts to practice. And the approach to this challenge is the same for both practicing humanists and technologists, namely: To apply to our emotions and imaginations, facts; to our facts, values; and to our values, action to reduce the facts and values to practice... via rational public policy.

Clearly what this increasingly complex world needs now is technically literate humanists, visionary lawyers, patient capitalists, and socioengineers, who together will develop public policies that are based on the highest values of our culture, rather than on physics, politics, and rhetoric. Each of us has a role to play in the decision making process: The engineer must decide can it be done? The economist must advise on whether or not we can afford to do it.

The lawyer should recommend on whether society will permit us to do it. And the humanist must help answer the question... but should we do it... will it truly improve our quality of life, both now and in the future?

The engineer who can help decide which problems to solve, then set about solving some of them, and finally work with other citizens to reduce the solutions to socially acceptable practice, will have a career and a life that is both intellectually challenging and emotionally rewarding. Hopefully, many of our profession will consider applying this "value-added approach" to their careers. If so, we may confidently anticipate a future in which we shall have the time to contemplate not so much the questions "what," or even "so what," but the more fundamental question, "why?" As Boorstein sagely noted, we shall not find the answer to this question, of course. But only by seeking solutions to technological problems of sufficient import as to raise ethical concerns, and then helping define rational policies that permit society to handle such concerns, shall we help the "nation choose the futures it wants, and deter those it does not."(31)

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