# The GWU Forecast of Emerging Technologies:

## A Continuous Assessment of the Technology Revolution

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## Abstract

*This article presents a method for the continuous assessment of major technological advances -- the George Washington University (GWU) Forecast of Emerging Technologies. Environmental scanning is used to identify emerging technologies (ETs), and a Delphi-type survey asks a panel of respondents to estimate the year each advance will occur, its associated probability, the potential size of its market, and the nation that will lead each ET. Eighty-five prominent ETs have been identified and grouped into twelve fields: Energy, Environment, Farming and Food, Computer Hardware, Computer Software, Communications, Information Services, Manufacturing and Robotics, Materials, Space, and Transportation. Results are presented from four survey rounds covering the past eight years and they then are compared longitudinally to estimate the range of variance. The data are also divided into three successive decades to provide scenarios portraying the unfolding waves of innovation that comprise the coming Technology Revolution.*

## Introduction

Revolutionary innovation is occurring in all scientific and technological fields. This wave of unprecedented change is driven primarily by advances in information technology (IT), but is much larger in scope that the Information Revolution – it is a Technology Revolution.

Science and technology are essentially accumulations of knowledge, and the Information Revolution is magnifying our ability to create and share technical knowledge. The result is that IT has become a major factor enabling unusually rapid technical developments, thereby accelerating advances in all fields. For instance, science has been transformed as networks of researchers are able to collaborate regardless of geography. Moreover, IT-enabled research organizations are evolving into new forms that speed up investigations: "All the lab equipment is connected to the network," says Mike Fannon, bioinformatics director at Human Genome Sciences. "We use the whole computational structure as a research tool."[1]

And because the knowledge in technical fields is often interconnected, advances in one area cut across others to accelerate the rate of development even further. Major advances in the field of information processing, for example, can have direct effects in others areas, such as managing the huge amount of data flowing from the Human Genome Project.[2] Advances in materials science pave the way for new forms of transportation, such as electric cars, and even a superconducting energy grid that might one day transmit solar or wind power from the deserts of Arizona to Alaska.[3] Science does not progress in a straight line. Change often occurs by accident or serendipity. Yet such changes encourage a spiral of cross-pollination that promises to increase the pace of innovation so greatly that modern societies may soon be transformed.[4]

At the same time that technical prowess grows, uncertainty over its social assimilation persists. Technological advances do not occur in a vacuum but are shaped by social forces. For instance, industry recognizes that the acceptance of new technologies is driven by consumer awareness, needs, lifestyles, values, and a host of other market factors.[5] National research and development funding is all too often subject to the whim of politics. Because of these confounding influences, the record of forecasting is poor.

Forecasts can often be overly pessimistic, and nowhere has this been more true than in information technology. Microprocessor development has proved so successful that chips are now three times faster than they were predicted to be in the early 1980s. It is as if we have in 1997 computers from the year 2000.[6] By some measures, computer performance has improved a million times since their invention fifty years ago.[7] The problem of pessimism is so notorious that the attitudes of prominent scientists often seem quaint in retrospect. In 1923, Robert Milikin, a Nobel Prize winner in physics, claimed "there is no likelihood man can ever tap the power of the atom." In 1895, Lord Kelvin, President of the Royal Society, said "heavier than air flying machines are impossible."

The flip side often reflects an optimism bordering on naiveté. Many people still recall predictions in the 1950s that the world would enjoy nuclear power "too cheap to meter." Or that we would fly personal jets to work and return from 20-hour workweeks to smart homes and robot servants that would prepare dinner automatically.

Optimism and pessimism are normal obstacles to forecasting, but they can be ameliorated through methodological rigor. Accidents, serendipity, and wild cards must also be dealt with to provide sound forecasts, and time horizons clearly play a crucial role. Forecasts of the next five to ten years are often so predictable that they fall into the realm of market research, while those more than thirty or forty years away are mostly speculation. This leaves a ten to twenty-year window in which to make useful forecasts. It is this timeframe that the GWU Forecast addresses.

## Goals and Methods

The GWU Forecast of Emerging Technologies integrates diverse methods, including environmental scanning, trend analysis, a Delphi-type survey, and scenario building. *Environmental scanning* is used to identify emerging technologies and to categorize them into different fields. *Trend analysis* guides the selection of the most important and influential advances for further study and organizes them into categories of emerging technologies (ETs). These ETs are then used to construct a modified *Delphi survey* for obtaining forecasts. Finally, the results are portrayed in time periods to build *scenarios* of unfolding technological change. By triangulating with a variety of methods instead of relying on a single approach, the Forecast produces more robust, useful estimates.

**Environmental Scanning**

For many years we have systematically scanned trade presses, popular magazines, science journals, and business literature to identify ETs. In addition, we conduct interviews and discussions with experts and practitioners to gain their insights on emerging technical trends. All these scanning data are clustered to spot ETs and estimate their potential. To enhance the meaning of these ETs, we then look for themes and patterns that aggregate them into larger clusters. The last time this process was conducted we identified the twelve fields reported in this article.

**Trend Analysis**

Within each field, six to ten of the most strategically important advances are chosen for further study based on trend analysis. For this latest survey conducted in 1996, eighty-five ETs were selected to represent the most crucial advances that can be foreseen. It should be noted that the number of ETs has changed slightly over the four survey iterations as new developments are identified and other ETs come of age. In addition , we periodically adjusted the questionnaire to clarify ambiguity and to reduce complexity and bias. This process dropped some items from earlier versions, added others in later versions, and produced some variations on similar questions. Despite these adjustments, the list has remained fairly consistent over the four revisions.

**Delphi Survey**

Once the fields and ETs are agreed upon, a Delphi-type survey is conducted. However, the type we use is modified because we do not use the traditional method of providing immediate feedback and requesting additional estimates to arrive at a consensus. Rather, our approach is to conduct another survey after an additional time period of about two years. That is, instead of two or more iterations occurring within a few weeks, we simply conduct one iteration every two years or so. While the traditional approach using multiple rounds does produce a tighter consensus, evaluations of the methodology show that the resulting consensus is not likely to be more accurate.[8] Thus, a one-round Delphi conducted every few years is believed to be equally accurate, far more practical, and it provides longitudinal data that traditional Delphis do not produce.

The survey is administered to a standing panel of approximately fifty authorities accompanied by results from the previous iteration. An introductory paragraph summarizing key data on each field is provided to remind participants of the status of each ET, changes that are occurring , and estimates of future trends. With this background in mind, the panel is asked to respond to four categories of survey questions for each ET: the *year* in which the event describing each ET is expected to occur, the *probability* associated with that estimate, the *market demand* for the ET, and the *leading nation* in which the ET will originate. For example, under Medicine, item 10.3 (Field 10, Question 3) reads: “Parents can routinely choose characteristics of their children through genetic engineering.” The aggregate response for this event produces an average at the year 2020, at a 53% probability, a demand of $21.3 billion, and suggests the U.S. as the leading nation. This means that the panel estimates there is a 53% chance that technical, regulatory, and attitudinal barriers will be overcome so that this event will occur in the year 2020, first in the United States, and that it potentially could generate a market of $21.3 billion.

Respondents include prominent futurists, forecasters, and technical experts. The panel has remained relatively consistent over the last eight years, with new members added to expand the pool and a few members leaving. Not all panel members respond each year, so there is some variation in both the number of responses and the composition of the panel for any given round. We allow a self-selection process so that participants only respond in fields which they feel a high level of confidence that they have sufficient knowledge to render an opinion.

The event defining each item is stated as precisely as possible using fuzzy logic. For instance, Table 1 defines the meaning we associate with "significant," "routinely," and so forth by specifying a percentage for each of these terms. This is particularly important for ETs that are developed and accepted over a long time period.

**Table 1 --**
**Fuzzy Variables:**

| | |
|---|---|
| "Significant" | 10%+ |
| "Commonly" | 30%+ |
| "Routinely" | 30%+ |
| "Majority" | 50%+ |
| "Most" | 80%+ |

### Scenario Building

The resulting data are then cross-sectioned by time periods to guide the construction of scenarios. While many different time periods are feasible, we have found that periods of one decade provide useful distinctions among the data. As the results will show, we have built scenarios for the decades 2001-2010, 2011-2020, and 2021-2030 using this approach. These scenarios consist of ET data arranged in chronological order of their estimated arrival, augmented with written comments.

### Validity of the Research Method

In designing the Delphi survey, we faced trade-offs. For example, some respondents felt the survey was too time-consuming, while others said it was too limited and narrowly focused on mainstream developments. This is an endemic issue for survey developers and reflects the need to weigh ample content against the respondent's attention span. We attempt to strike a workable balance.

A number of participants, including one of the originators of the Delphi method, questioned our treatment of year and probability. One of the techniques of a traditional Delphi is to assign a 50/50 probability rule to the anticipated year of an advance. That is, participants are usually asked to estimate the year when they would feel fifty percent certain that an advance would occur. While this approach may be more precise from technical considerations, more than a few participants felt that it presents a philosophical problem akin to the Schroederger's

Cat dilemma (where at any given moment the cat is either alive or it is dead but never in between). Many respondents pointed out that there are often circumstances in which a given advance would either take place with nearly 100% certainty or it would not take place at all. The belief is that there is no middle ground for some advances because they depend on regulatory changes, complementary breakthroughs, specific circumstances, competing technologies, the effects of standardization, or other binary "go, no-go" situations.

While our approach may not be statistically elegant because the probabilities associated with time forecasts may vary, we feel it is reasonable intuitively. Respondents provide their most likely estimate for time and the probability they attach to this estimate. Thus, our average figures produce the most likely overall time estimate and an estimate of the probability that this forecast is valid.

It should be obvious that the validity of our method hinges on implicit normal assumptions that no "wild cards" would occur in the next few decades, that our panelists were providing objective perspectives rather than trying to "swing" the data toward a pet technology or some other agenda, and so on.

In general, it must be remembered that, unlike hypothesis testing or other statistical measures, a forecast is not meant to provide a high degree of certainty. Rather, it is a rough estimate that only hopes to identify the right "ball park" within a few years. We contend that the methodology behind the GWU Forecast offers a practical approach to targeting the most important ETs within about a three to five year time span. This goal is completely adequate for the purpose of stimulating dialogue about the choices that must be made by planners, decision-makers, and society as whole in shaping technological developments and their social impact.

## Results

The following overview, Figure 1, provides a look at all 85 ETs with abridged definitions. Each ET has a designated item number that refers to the field and event number found in Appendix A. For example, item 11.2 refers to Field 11 (Space), and Item 2 ("A manned mission to Mars is completed"). The full text of each event with accompanying data is found in Appendix A.

[INSERT FIGURE 1, OVERVIEW]

If one scans the patterns formed by the display of ETs in Figure 1, a few broad trends stand out. First, a wave of major technological advances seems likely to arrive during the next three decades. Highly important technological innovations are occurring in all fields and they generally are estimated to arrive between the years 2003 to 2025, with a few more ambitious technologies maturing later in the century. One might argue about the number, significance, and likelihood of various ETs, but it seems clear that almost all fields of endeavor are undergoing a serious transformation that will in turn transform society. It is this three-decade long wave of technological change that we call the Technology Revolution.

The second major conclusion is that the four fields comprising Information Technology appear to lead this wave of innovation by roughly 5 years or so. This is in keeping with our previously stated proposition that IT serves as the principal factor now driving the Technology Revolution. Attention today mainly focuses on the Information Revolution, which in turn drives other fields a few years afterwards.

Finally, Space appears to be the lagging field. Some relatively simple space technologies are likely to arrive fairly soon, particularly the privatization of space efforts, but almost all serious technologies seem destined to wait about 30-60 years for their development and implementation. The reasons seem to involve the fact that space programs can be most readily postponed because the payoffs are uncertain and distant, and serious space exploration beyond the solar system will require technological breakthroughs that transcend our present knowledge of physics.

Detailed results are presented using three ways for organizing the data. The first cut provides complete 1996 data for all ETs using the survey form organized by 12 technical fields. While the implications of each ET could be examined in depth, here we look at only a few notable points. The second cut presents a longitudinal comparison of time forecasts across all survey rounds to estimate variations in the data. Finally, the third cut examines the larger pattern all these ETs form over time by constructing three successive decade-long scenarios that provide an integrated sense of how the Technology Revolution should unfold.

**Technical Fields**

In the four fields of Information Technology, advances are shown to be more conservative than conventional wisdom currently suggests.

For example, while the Internet continues to expand at phenomenal rates, results from the Information Services field show that we should not expect major changes in IT services very soon. The least conservative estimate -- entertainment on-demand (7.1) -- is not expected until 2003, while the most conservative -- half of all goods in the U.S. are sold through information services (7.5) -- arrives in 2018. Similarly, while search engine technology on the World Wide Web is advancing, we will not see intelligent software agents (5.5) in routine use until 2009. Personal digital assistants (PDAs) will not be adopted by the majority of people until 2008. Personal computers may soon be able to incorporate television, telephone, and interactive video (4.3), but our panel did not see this or a Web-TV (4.4) with telephone capabilities in wide use until 2005 or 2006.

Software also has a long way to go. Expert systems (5.2), once heralded as the undeniable decision-making software for the 1990s, have a 72% chance of finding routine use by 2010. Computer programs that can learn and adjust their own programming (5.8) will not be commonly available until 2012. Language translation software (5.4) has a similar fate, not achieving widespread practical use until 2012. A standard digital protocol (6.2), that would allow more advanced global networking applications, is not expected until 2006. And while U.S. citizens are heralding the Internet and the World Wide Web, most people will not have access to the information superhighway (6.3) until 2008.

The reason for this pessimism of the IT results is unknown, but we speculate that the distinction made earlier, between technological advance and its acceptance, suggests that most ETs will not become widely diffused into mainstream society until some time after their introduction. Panelists appear to think that major changes in lifestyle would need to occur before such changes replace present technologies. Furthermore, many of the questions refer to a more sophisticated version of a technology that is widely accepted into the mainstream. While some IT seems already available or just around the corner, such as electronic banking (7.4), today these advances are still in their primitive form or in limited usage.

In other fields, such as medicine, responses were more optimistic. Computerized medical information systems (10.1) including provisions for home and self-care could be commonly used in the general population by 2007. Holistic health practices (10.2) are becoming more accepted and will be well integrated in medicine by 2009. Gene therapy (10.4) will help eradicate inherited diseased by 2013. Organ replacement strategies will become routine, by growing genetically similar or cloned organs (10.5) or making synthetic organs (10.6), in the years 2018 and 2019, respectively.

In manufacturing, we are likely to see the mass customization of many products (8.3) around 2011. Automation (8.2) and Computer Integrated Manufacturing (8.1) should proceed such that the proportion of factory jobs will decline from its current percentage of about a third of the work force to less than ten percent by 2015. Material composites will replace traditional metals (9.4) in product designs by 2016. The helpful robot servants of the future (8.4) may or may not ever become a reality, with only a 64% likelihood of their arrival in 2016. Promising advances for the lie with the development of nanotechnology and microscopic machines (8.5) and their initial development in 2016. That could lead the development of self-assembling (9.6) and intelligent (9.7) materials around 2026 or 2027. Panelists think that the favorite technology of Tom Peters, “buckyballs” (9.5), will become instrumental in developing new materials by 2011. Advances in high-temperature superconductivity (2015) may finally see practical application in commercial applications by 2015.

By 2008, genetic engineering (3.1) and its accompanying regulatory regime should have changed to allow the routine production new strains of plants and animals. A number of years later, in 2015, the majority of farmers will have adopted organic or alternative farming methods (3.3) and the use of chemical fertilizers and pesticides will have declined by 2012 to at least one-half of current usage (3.2). New techniques, such as precision farming (3.6) and hydroponics (3.8) will be commonly used by 2015. More advanced technologies, such as automation of farming (3.5) and urban greenhouses or other intensive production systems (3.7) will not come about until 2020. One advance that panelists agreed was unlikely to occur was the consumption of artificial meats, vegetables, bread, and other foodstuffs (3.9). They gave this only a 39% likelihood of becoming common fare by 2022.

The fields of energy and the environment are inherently difficult to separate, but there seems to be some convergence in environmental awareness and alternative energy use. For example, by 2010 or so we should expect manufacturers to adopt “green” methods (2.3), and a significant portion of energy usage will be derived from renewable sources and biomass (1.1 and 1.4). In these years consumers will recycle about half their household waste (2.2). Around 2016, additional improvements in fossil fuel efficiency (2.5) will reduce greenhouse gas emissions by one-half. At the same time, the majority of manufacturers may operate within industrial ecology parks (2.6) and use recycled materials for their products (2.4). Though the impact on society would be great, the likelihood of advanced energy systems such as hydrogen (1.7) and fusion (1.6) coming on-line in the 2020s is low.

The technologies that may have the most direct impact on the daily lives of individuals are in the field of transportation. Before people commonly drive advanced electric cars (12.3 and 12.4) in the 2010s, hybrid vehicles (12.2) combining the advantages of electric and internal combustion systems will be seen on the road by 2006. By 2017, high-speed rail systems (12.1) will connect major cities of the developed world, led by Japan. Around this time, we will see Automated Highway Systems (12.6) and Intelligent Transportation Systems (12.7) commonly used to reduce traffic congestion for commuters, take control of route planning and even do most of the driving. By the mid-2020s, short and long distance travel may be transformed. For short urban distances, personal rapid transit systems (12.8) may be installed, though this is given a low probability by the panel. They also gave a low probability to hypersonic aircraft (12.5) accommodating half of transoceanic passengers. These changes in transportation, coupled with changes in building codes, information technology and telecommuting, may lead to clustered, self-contained communities around 2023.

Space remains the most intriguing frontier to many people who envision the future. Advances here are also the most difficult to forecast since they require massive project planning, coordination with the government and the military, and, increasingly, international collaboration. Assuming a reduction of red tape, private corporations could perform the majority of space launches (11.1) by 2013. They will do this in part because the formation of new chemicals and compounds which are not feasible or possible on Earth can be developed in space (11.5). Many years later, the prospect of prospecting on Mars will begin with the completion of a manned mission (11.2) in 2029, only a year after a permanent moon base is established (11.3). Many years after that, in 2042, a spaceship or probe will be launched to explore a neighboring star system (11.4). We may even learn to approximate the speed of light by 2062 (11.6). This assumes that we do not contact intelligent life (11.7), which would be a major wild card with ramifications for all fields. The panel estimated that extraterrestrial contact would occur -- if at all -- around the middle of the 21st Century. The assumptions that are built into this forecast would be interesting to hear.

### *Longitudinal Comparisons*

The longitudinal data provides a perspective usually unavailable from traditional forecasting methods. This year, we are able to compare four sets of data ranged over the last eight years.

We expect that the farther distant an event, the greater the range. This seems to be generally the case, but the exceptions are surprising. To illustrate, the commercial use of fission power to provide half of the energy supply (1.5) has an anticipated year of 2018, with a range of four, that is, give or take two years, while the commercialization of fusion power (1.6) is expected in 2022 with a range of twenty years, or plus or minus ten years. Notice, however, that the estimates that arrive at both of these events are separated by only four years. Similarly, there seems to be remarkable consensus for many of the items in the field of Space, while Transportation tends to show wide variation. Some sources of variation in the range data may be explained by the revisions in the survey questions, the variations in the respondents, and the social and economic conditions of the times.

In looking over the range data, one may notice that some data are missing. Certain ETs were dropped, such as CD-ROM becoming the dominant form of storing information (anticipated in 1993 for 1999), because we estimated that this event has now occurred.

In other cases, ETs may lose interest or importance. Parallel processing (5.7), for example, may no longer hold as the model for supercomputing it once held because developments in distributed computing may be more feasible. Other earlier forecasts have been consolidated or split into separate targets. In 1990, we included an item for sentient computers, or artificial intelligence, in 2016, which many now think is impossible. Today, this idea is approached through more pragmatic ETs, such as computer sensory recognition (5.3), machine learning (5.8), and intelligent agents (5.5), anticipated by 2005, 2008 and 2009 respectively.

The longitudinal data show a strong consistency in the fields of Environment, Farming and Food, Space, and most of Information Technology. For example, for three rounds respondents said that private corporations will perform the majority of space launches as private ventures (11.1) in the year 2013. In contrast, there was wide disagreement regarding the likelihood that telecommuting will ever catch on, with estimates ranging from 2006 to 2023. The largest range was in the routine use of hypersonic aircraft for travel (12.5), once predicted to be routine as early as 1998, once as late as 2044.

Many individual ETs have remained consistent on the questionnaire over the four round. For instance, the ET for optical computers (4.5) remains and is now anticipated for 2007. Aquaculture (3.4), once looked at with high hopes of becoming a booming market by 2006 as predicted in 1990, was pushed back as far as 2020, though now is expected in 2014. Gene therapy (10.4) still holds a strong appeal for the cure or prevention of inherited diseases. People still expect to have personal robots (8.4) to handle routine aspects of life and work.

### *Scenarios of Technological Evolution*

The most intriguing social, technological, and economic developments arise when the paths of emerging technologies intersect. Since none of the advances included in the 1996 survey were anticipated to occur before the end of the 1990s, this leads to a convenient partitioning of the data. Thus, we present the future here as a series of time intervals organized by forecast year and condensed into three time span horizons, or scenarios, portraying the First, Second, and Third Decades of the 21st Century. Of the eighty-five events in the survey, twenty-seven occur in the years 2001 to 2010, forty-six occur between 2011 and 2020, and twelve occur from 2021 and beyond.

In the tables below, "ref.#" reflects the convention used throughout this study referring to field and item. Year, probability, and demand represent the means of those categories for all respondents. Standard deviation (s.d.) indicates the variation of responses about the associated year.

**Decade 1: 2001 to 2010**

| *ref.#* | *Event* | *Year* | *s.d.* | *Prob.* | *Demand* |
|---|---|---|---|---|---|
| *7.1* | Entertainment On-Demand | 2003 | 4.6 | .84 | 90.0 |
| *7.2* | Videoconferencing | 2004 | 4.3 | .83 | 44.5 |
| *4.3* | PC Convergence | 2005 | 6.4 | .84 | 111.4 |
| *4.4* | Entertainment Centers | 2006 | 7.4 | .83 | 108.6 |
| *7.7* | Distance Learning | | 5.2 | .78 | 41.5 |
| *2.1* | CFCs are Replaced | | 5.7 | .77 | 52.2 |
| *4.6* | Advanced Data Storage | | 8.5 | .75 | 43.6 |
| *6.2* | Standard Digital Protocol | | 5.2 | .70 | 70.0 |
| *12.2* | Hybrid Vehicles Common | | 5.4 | .69 | 87.0 |
| *6.1* | PCS Gains Markets | | 4.1 | .56 | 42.1 |
| *10.1* | Computerized Self-Care | 2007 | 3.3 | .82 | 87.0 |
| *6.4* | Groupware Systems | | 4.6 | .75 | 33.3 |
| *5.3* | Computer Sensory Recognition | | 6.2 | .73 | 34.3 |
| *5.1* | Modular Software | | 5.7 | .72 | 47.1 |
| *4.2* | Parallel Processing Computing | 2008 | 10.2 | .80 | 63.6 |
| *6.3* | Information Superhighway | | 5.5 | .78 | 74.3 |

| | | | | | |
|---|---|---|---|---|---|
| *3.1* | Genetically Produced Food | | 5.1 | .75 | 66.8 |
| *4.1* | Personal Digital Assistants | | 6.3 | .75 | 53.8 |
| *2.2* | 1/2 Household Waste Recycled | | 5.9 | .74 | 53.2 |
| *5.5* | Intelligent Agents | 2009 | 9.5 | .79 | 28.5 |
| *5.6* | Ubiquitous Computing Environment | | 7.2 | .75 | 32.5 |
| *6.5* | Broadband Networks | | 5.6 | .70 | 103.3 |
| *7.4* | Electronic Banking/Cash | | 7.1 | .70 | 69.0 |
| *10.2* | Holistic Health Care | | 4.2 | .61 | 55.0 |
| *1.1* | Alternative Energy Sources | 2010 | 10.7 | .77 | 45.6 |
| *2.3* | "Green" Environmental Methods | | 10.0 | .73 | 90.0 |
| *5.2* | Expert Systems | | 7.9 | .72 | 59.3 |

As the information revolution proceeds into the 21st Century, major advances in information technology will occur. As the IT fields mature, the effects will begin to permeate all fields and industries.

Multimedia interconnectivity will be the theme for the first decade, allowing people to interact seemlessly across information mediums and geographic borders. Virtual reality and large flat panel displays will take the place of the computer monitor, allowing simultaneous viewing of several applications at once, virtual meetings, and group collaboration. On-line communities will have grown from text-based chat-rooms to three-dimensional, real-time realities. Education, entertainment and virtual tourism will enter a new era, and the consumer will have nearly unlimited choices. Electronic commerce and banking will be the currency of choice in developed countries as the cashless society is realized.

Sophisticated software will aid consumers and professionals by providing intelligent agents to filter news and mail. Expert systems may finally see routine use as surrogate doctors, lawyers, and other professionals. These systems will be remotely accessed, not bought as stand-alone software, and updated continuously. Software will run on microprocessors imbedded in household products, walls and automobiles. Modular programming and a common language for computer communication will lead to ubiquitous computer-enhanced environments.

While the amazing advances in information technology will steal many headlines, medical breakthroughs will compete for the news. Genetic science discoveries and access to vast banks of human genetic information will allow medical researchers to seriously tackle gene therapy. At the same time, the medical community will have accepted the validity of holistic health care. Even today, according to David Eisenberg, M.D., of the Harvard Medical School, Americans make approximately 425 million visits annually to alternative medical practitioners, compared to the more than 388 million visits made to regular physicians. New strains of plants and animals will allow for designer foods and new farming processes. Farmers will have begun to widely adopt organic and "green" farming methods, partly due to genetic manipulation of plants that make them resistant to pests and spoilage. Pollution control and highly effective recycling efforts will become normal in developed countries, which may allow developing countries such as China to leapfrog "dirty" industrialization in favor of "clean" and sustainable development.

**Decade 2: 2011-2020**

| *ref.#* | *Event* | *Year* | *s.d.* | *Prob.* | *Demand* |
|---|---|---|---|---|---|
| *8.3* | Mass Customization | 2011 | 6.1 | .73 | 330.0 |
| *12.3* | Electric Cars are Common | | 9.2 | .70 | 102.0 |
| *1.4* | Organic Energy Sources | | 7.8 | .60 | 43.0 |
| *9.5* | Buckyballs and Buckytubes | | 2.0 | .59 | 20.0 |
| *8.1* | CIM Used in Most Factories | 2012 | 6.1 | .73 | 124.0 |
| *5.8* | Machine Learning | | 9.0 | .67 | 31.0 |
| *5.4* | Computer Language Translation | | 6.2 | .65 | 40.9 |
| *3.2* | Farm Chemicals Drop 1/2 | | 6.6 | .60 | 27.5 |
| *10.4* | Gene Therapy | 2013 | 5.1 | .63 | 63.3 |
| *7.3* | On-Line Publishing | | 7.1 | .60 | 65.8 |
| *10.8* | Major Diseases Cured | | 9.8 | .58 | 116.0 |
| *9.2* | 1/2 of Autos Recyclable | | 5.3 | .58 | 51.0 |
| *4.5* | Optical Computers | 2014 | 10.5 | .64 | 67.1 |
| *9.1* | Ceramic Engines | | 9.0 | .58 | 49.0 |
| *3.4* | Aquaculture | | 6.7 | .56 | 52.4 |
| *10.7* | Computerized Vision Implants | | 4.4 | .56 | 31.7 |
| *3.6* | Precision Farming | 2015 | 10.9 | .69 | 71.4 |
| *8.2* | Factory Jobs Drop to 10% | | 6.6 | .67 | 150.0 |
| *5.7* | Neural Networks | | 9.9 | .61 | 28.5 |
| *3.3* | Alternative/Organic Farming | | 9.8 | .57 | 76.0 |
| *9.3* | Superconducting Materials | | 5.8 | .56 | 43.0 |

| | | | | | |
|---|---|---|---|---|---|
| *2.6* | Industrial Ecology | | 9.4 | .55 | 48.0 |
| *3.8* | Hydroponic Produce | | 8.7 | .53 | 40.0 |
| *8.5* | Nanotechnology | 2016 | 10.2 | .66 | 31.3 |
| *2.4* | Recycled Goods | | 11.8 | .66 | 126.0 |
| *8.4* | Sophisticated Robots | | 9.4 | .64 | 130.0 |
| *1.2* | Energy Efficiency | | 10.0 | .61 | 49.2 |
| *2.5* | Fosssil Fuels Cut Greenhouse Gas | | 9.5 | .59 | 46.0 |
| *12.4* | Fuel Cell Electric Cars | | 13.7 | .58 | 116.0 |
| *12.7* | Intelligent Transportation Systems | | 6.4 | .58 | 90.0 |
| *9.4* | Material Composites | | 5.8 | .53 | 100.0 |
| *12.1* | High-Speed Maglev | 2017 | 9.5 | .58 | 120.0 |
| *4.7* | Biochips | | 10.7 | .54 | 57.8 |
| *1.3* | Fuel Cells | | 11.1 | .53 | 61.2 |
| *11.5* | New Materials from Space | 2018 | 5.0 | .57 | 21.5 |
| *7.5* | 1/2 of Goods Sold Electronically | | 13.0 | .55 | 208.3 |
| *12.6* | Automated Highway Systems | | 5.0 | .55 | 70.0 |
| *10.5* | Cloning/Organ Replacement | | 9.8 | .53 | 62.7 |
| *11.1* | Private Space Ventures | 2019 | 6.1 | .62 | 60.0 |
| *10.6* | Synthetic Body Parts | | 10.9 | .58 | 68.3 |
| *7.6* | Telecommuting | | 7.5 | .56 | 468.0 |
| *3.5* | Farm Automation | 2020 | 9.7 | .60 | 82.4 |
| *3.7* | Urban Greenhouses | | 11.4 | .53 | 55.0 |
| *10.3* | Genetic Engineering | | 9.9 | .53 | 21.3 |
| *1.7* | Hydrogen Energy | | 12.2 | .50 | 102.0 |
| *1.5* | Fission Power | | 20.1 | .46 | 26.3 |

The early 2010s will witness the most striking technological advances in terms of number and scope that our civilization has seen. Information technology will be taken for granted and IT-enabled activities involving working, learning, shopping, publishing, and leisure will become a way of life, much the way automobiles became a way of life a few decades after their introduction. Computers themselves will begin to emulate the human brain in sensory recognition and thought processing. Neural networks, biochips, and artificial intelligence may finally reach fruition as computing speeds and parallel architectures are applied and exploited.

The interconnections of technology during this decade will transform developed societies in ways similar to the agrarian and industrial revolutions. This will be the decade of information technology diffusion. Specific information will be immediately available to people and computers on demand. Academic research will be performed anywhere, at any library, with any colleagues. Travelers can know where they or their baggage are at any given moment through satellite global positioning networks. Much of travel and tourism itself will become virtual, and thus environmentally benign. Computers will know personal details of consumers and production capabilities and be able to customize almost any product to individual needs. Automation in manufacturing will increase to the point where such jobs will fall to less than 10% of the workforce, as they did a century before with farm labor. Information technology innovations will allow parents to check on their kids, farmers to check on their crops, states to check on their criminals, and meteorologists to check on the weather. Our ability to manipulate matter will change, as nanotechnology becomes the new enabling technology for the remainder of the century.

**Decade 3: 2021 and beyond**

| ***ref.#*** | ***Event*** | ***Year*** | ***s.d.*** | ***Prob.*** | ***Demand*** |
|---|---|---|---|---|---|
| *3.9* | Artificial Foods | 2022 | 9.1 | .39 | 74.8 |
| *12.9* | Clustered Communities | 2023 | 12.4 | .53 | 85.0 |
| *12.8* | Personal Rapid Transit | 2024 | 10.8 | .43 | 62.5 |
| *12.5* | Hypersonic Air Travel | 2025 | 12.6 | .48 | 91.0 |
| *9.7* | Intelligent Materials | 2026 | 11.4 | .57 | 66.0 |
| *1.6* | Fusion Power | | 8.7 | .50 | 113.3 |
| *9.6* | Self-Assembling Materials | 2027 | 12.5 | .56 | 82.0 |
| *11.3* | Permanent Moon Base | 2028 | 11.5 | .55 | 32.5 |
| *11.2* | Manned Mars Mission | 2037 | 15.4 | .59 | 30.0 |
| *11.4* | Stellar Exploration | 2042 | 21.9 | .51 | 47.5 |
| *11.7* | Extraterrestrial Contact | 2049 | 22.5 | .33 | 45.3 |
| *11.6* | Near-Light Speed Achieved | 2062 | 28.2 | .43 | 75.5 |

The third decade of the 21st Century will see expansion into new frontiers. These frontiers will be in space, biology, and global ethics. The genetic revolution will have moved beyond curing diseases of the mind and body and will have turned to the last taboo of modern society, the improvement of the human genetic code.

At the same time, the need for the world to collaborate on large engineering projects will become imperative if we are to afford an advanced space program. Other global initiatives will require huge resources that no one nation will be able to provide. The challenges we will face in this and subsequent decades will be global, and only a global consensus will allow for progress on problems of population, environmental sustainability, space development, and human bioengineering.

These new frontiers and the imperatives of international cooperation will raise questions for all societies. Nations will find themselves with increasingly less influence than virtual communities or multinational corporations. World religions may need to seek unity in diversity. Humanity's penchant for violence will need to be understood and controlled. The perceived need for people to be able to live in unnatural environments such as the moon or Mars or the ocean seabed may demand new genetic designs for these pioneers. The bioethical concerns we face today will be eclipsed by those of tomorrow. Such changes will demand an exploration of global ethics if we are to settle new environments. That we will have the resolve to explore these new frontiers is less certain than the fact that we will have the necessary tools to do so.

History suggests that it is important not to understate changes that lie ahead, and that the result of change is not always positive. Hope exists in a better understanding of cultural dynamics and interpersonal relations. Advances in such "spiritual" disciplines might provide future generations with a solid awareness of the process of change, so by 2050 or so, society could emerge into a period of rapid, but manageable, evolutionary growth. Though new technologies will continue to come at breathtaking speed, they will not have the same chaotic, transformational effects as earlier technologies. A number of events could derail this progress: a global war, a major plague, a religious upheaval, an asteroid strike or other environmental catastrophe. However, assuming these things do not take place, humankind could enter into an age of new challenges that will probe our ability to adapt and achieve.

## Discussion

The GWU Forecast is in the process of continuous improvement. It has been pointed out by some that the survey is too long, the evaluation terms are too vague, and it is unclear whether the scope covers the United States, developed countries, or the entire globe. Often participants were asked to provide a “leading nation” where such a question was inappropriate, or there were larger dynamics at work, such as the tendency of the U.S. to pioneer a new technology but another country to develop and distribute it. When we referred to “industrialized countries” a number of people wondered if we meant those currently or those in the future. Some advocated a more international focus for the survey.

In the next round, we will decide whether this forecast should restricted to a U.S. version. This could provide international comparisons with forecasts from other counties. Given the existence of Delphi-type surveys in Japan and Europe, a more U.S.-centric survey would provide a basis for cross-cultural or comparative studies. This would have the benefits of illuminating cultural bias as well as the effect of geography leading to more multi-dimensional results.

In developing the ET parameters, we faced several hurdles. The “market demand” section was particularly tricky, and the numbers it yielded ranged broadly. This is the most difficult category for respondents to anticipate and has the widest variation. One panelist commented: “This is stretching the capabilities of even the most prescient prognosticator. What, in 1980, would even the most respected of economists have predicted for market demand ten years down the line for personal computers?” While we recognize the limitations of anticipating an emerging, this component provides at least some indication of the relative impact of the event. It attempts to put a dollar figure on an ET to provide some concept of the potential risks and rewards associated with a particular development.

The effect of technology hype or “millennium madness” for skewing the results did not go unnoticed by our panelists. One panelist even asked if the Delphi approach actually measures “the effectiveness of propaganda more than the likelihood of technological innovation." Another panelist thought that we would have many forecasts clustered around the year 2000. We see no signs of this effect in the data.

A number of panelists suggested expansions or innovations to the survey section. One might be to use pair-wise comparisons to assess the relative likelihood of events. "For example," said one panelist, "I would say that routine use of expert systems is twice as likely as neural nets on parallel computers and three times as likely as language translation, yet the Forecast shows them all to be about the same likelihood." Separating out specialists from generalists was seen as a needed improvement, and one participant suggested inviting independent financial analysts who follow high-technology trends to participate in the study.

Generally, there was a strong consensus of the usefulness of the forecasts. In an effort to continually improve the relevance and interest of the survey, clarifications and revisions will be incorporated into future rounds.

Since the most recent Forecast was conducted, new events have overtaken some results. Examples are the possible evidence of life on Mars, the discovery of water on the moon, cloning, growing excitement over the building of Internet II, and uncountable permutations in the computer and communications industries. Through it all is the pervasive sway of information technology. One comment highlighted the changes we can anticipate as IT begins reaching all industries and fields: "The communication technologies will have a more profound impact on our society than the combined effects of the invention if the automobile, nuclear power and even electricity." Some see IT as a harmful element to civilization. For example: "Already tenuous interpersonal relationships will disappear altogether because human relationships are very inefficient compared to creating new impressions and realities on command. It is an opium for the masses which will lead to highly informed non-persons engaging in self-indulgence." Another commentator stated, "We are in the process of creating a highly sophisticated venue for handing the fate of humanity over to depersonalized, socially insulated masses."

We noted earlier that public acceptance of new technologies often presents more of a limiting factor for many advances, as well as regulatory barriers, international competition, changes in demographics and consumer needs, and changes in long held practices and attitudes. Although we ask respondents to take these considerations into account, one participant pointed out, "Social impact requires a study of its own. Who predicted that Ford's Model-T would change courtship and sexual mores? Someone could have, but I'll bet no one was asked." For example, one panelist discussed the likelihood of fission power supplying half the world's electricity supply (1.5): "There are several trends at work. In the short term, fossil fuels are not becoming expensive so rapidly as many expected or hoped. The politics and economics of nuclear power do not look good. In the longer term, the competition from cleaner coal with new technology and with solar will become increasingly important, and problems with issues like terrorism and proliferation are likely to make the political problems even worse." Medicine and health care is an area particularly beset by non-technology related struggles. Regarding self-care, "The driving force will not be higher self-awareness, but sheer financial load of assigning all health related issues to the medical industry." Additionally, holistic health faces more of an attitudinal barrier than a structural one.

The social impact considerations may be the reason that the IT results appear to be too conservative. One participant put it this way: "A basic human property collides with technology -- people want to slam the door of a new car, see and feel clothing, squeeze the tomatoes -- but to the extent that people are willing to buy something not physically inspected, they will buy most things by 2020 through some kind of remote process." In reference to on-line publishing (7.3), one panelist said, "People like to hold books in their hands." With regard to electronic shopping (7.5), he said, "People like to try things on." One participant pointed out: "A survey of U.S. teenage girls shows more than 90% list 'shopping' as their favorite activity."

Two manufacturing and material technologies that have enormous promise are nanotechnology (8.5) and buckyballs (9.5). Buckyballs have been called the most promising technology of the future, with uses ranging from microball bearings, cancer therapies, to ultralight batteries.[9] Some of the respondents simply asked, "what are buckyballs?" Combining intelligent materials and micro-machines with the diversity of uses represented by buckyballs, or Carbon-60, shows another crossroads of technology that has the capability to transform our lives and environments. These may one day give us the ability to create hypothetical but corporeal environments on demand.

## Conclusion and Next Steps

The survey participants were extremely helpful in suggesting improvements and next steps for the project. Such comments from the panel and the WFS conference provided depth and meaning to the survey results. While the forecast years can give one an initial impression of the vast changes facing us, these comments give life to the numbers.

Follow-on studies may include examining and developing models of societal adoption of technology innovation. A complementary piece to this study might consider these ‘soft’ aspects by taking a social science perspective to change, seeing social forces not only as barriers but also as enhancers of ETs. The main thrust of such a paper would be to see the larger picture and to explore the wave of technology sweeping over us. We hope that some researchers will use the results of this survey to conduct forecasts of socio-cultural consequences. Studies such as these would enlarge the reach and relevance of the Forecast.

The next steps of this study are to conduct the 1998 Forecast, to organize a conference on the theme of emerging technology, and develop an interactive website. We are in the process of refining the panel of authorities, improving the clarity and focus of the questionnaire, and developing the method of analysis to examine the data in more sophisticated ways. At this time we plan to convene a biennial conference in which representatives of industry, academia, and government converge to discuss the results and implications of this and similar technology forecasts. Sponsors are currently being sought for these efforts. This project has previously been conducted by the authors without affiliation to any funding organization. To date, sponsors for the project have served in an advisory capacity only. In developing the project plan and its implementation, we had to be aware of these constraints. However, the strong potential and relative acceptance of this method suggests additional resources could improve its development. Contact information is listed below.

The next manifestation of the forecast may be entirely different from its predecessors. In addition to minor changes, such as separating out the specialist responses from the generalist responses, the format may change entirely. We are developing a World Wide Web page to either replace or complement the round-by-round approach with a continuous stream of data. Individuals on the Web would enter their estimates and these would be compared with the "experts." Our expert panel, in this case, would be able to log into the system at anytime to make or revise their estimates. Qualified panelists would be added or subtracted as they wished, and the research team would be involved with formulating good ETs and serving as the system gatekeepers. We forecast this advance by the end of 1997.

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# Appendices

### *Appendix A: Delphi survey full text*

[INSERT DELPHI SURVEY WITH RESULTS HERE]

### *Appendix B: Comparisons of Delphi Forecasts*

[INSERT LONGITUDINAL DATA HERE]

### *Appendix C: Participant List*

[INSERT PARTICIPANT LIST HERE]

ENDNOTES

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