What Can Past Technology Forecasts Tell Us About the Future?

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ABSTRACT

Past forecasts of technical innovations include lessons that can be used in making forecasts today. A review of Herman Kahn and Anthony Wiener's "One hundred technical innovations very likely in the last third of the twentieth century," published in their 1967 book, The Year 2000, A Framework for Speculation on the Next Thirty-Three Years *found that fewer than 50% were judged good and timely, having occurred in the twentieth century. However, when the forecasts were grouped into nine broad technological fields there were wide variations in the judged accuracy of the forecasts. Forecasts in computers and communication stood out as about 80% correct, while forecasts in all other fields were judged to be less than about 50% correct. Sustained trends of increasing capabilities and declining costs of technologies used for computers and communication applications were apparent in 1967 and enabled accurate long term forecasts. To improve our current forecasts, we should look for sustained and continuing trends in underlying technologies, where increasing capabilities enable more complex applications and declining costs drive a positive innovation loop, lowering the cost of innovation and enabling wider learning and contributions from more people, thus sustaining the technology trends.*

Introduction

Forecasts of technology innovations are important in several ways, and making accurate forecasts improves the usefulness of forecasts. Long range technology forecasts are useful in government and social planning, helping policy makers determine future solutions to social problems, economic development, and military objectives. Shorter range forecasts, sometimes as short as a year or a few months are important in business planning. For example, technology roadmaps developed for strategic product planning depend on forecasts of technological capabilities. Product and technology planners must look for disruptive innovations that could change the technical and economic playing field in an industry. In some cases, entire industries must be on the lookout for disruptive technical innovations that could change the basis of competition. More accurate forecasts can improve planning in all of these areas.

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We can learn from technology forecasts made in the past and apply the learnings as we make our own forecasts in the present. This paper finds some lessons in the forecasts of technical innovations made by Herman Kahn and Anthony Wiener in *The Year 2000, A Framework for Speculation on the Next Thirty-Three Years* [1], published in 1967. Now that the Twenty First Century has arrived, their list of "One hundred technical innovations very likely in the last third of the Twentieth Century" can be reviewed for patterns and factors determining the quality of the forecasts. In this study, a small panel of reviewers found that fewer than half of the forecasted innovations occurred before the end of the century. However, forecasts in one topical area – computers and communication – stand out as far more accurate than others. More than 80% of forecasts in computers and communication were judged by the panel to have occurred. The characteristics of enabling technologies for computers and communications appear to have improved the accuracy of long-term forecasting in these areas. We can use this knowledge to improve today's forecasts, or at least to understand what areas can be forecast with greater accuracy.

The book, *The Year 2000, A Framework for Speculation on the Next Thirty-Three Years,* includes the forecasts of technical innovations reviewed here. The book presents scenarios for the future in economic, political and social dimensions as well as in technology. The authors "speculate far ahead" … "to try to predict conditions in reasonable detail and to evaluate how outcomes depend on current policy choices." The authors hoped to provide a framework for thinking that would anticipate future events and formulate policies that would lead to more desirable outcomes. The book is widely cited and continues to serve as a model for forecasters and scenario builders in government, academia and industry. The authors identify a number of long term trends in social, economic and political dimensions, and they introduce the concept of "Alternative Futures." They see "Accumulation of scientific and technological knowledge" as one of the 13 basic long-term trends; and the accompanying trend of "Institutionalization of change, especially research, development, innovation, and diffusion" captures their unstated, underlying assumption that technological innovations are perhaps the most important drivers of change.

Kahn and Wiener present their list of "One Hundred Technical Innovations Very Likely in the Last Third of the Twentieth Century" "in order to provide a quick impression of science and technology in the last third of the twentieth century." They maintain that each item has three characteristics:

1. "It is important enough to make, by itself, a significant change in the next thirty-three years."
2. "A responsible opinion can be found to argue great likelihood that the innovation will be achieved before the year 2000 – usually long before."
3. "Each warrants the description technological innovation, revolution, or breakthrough."

The list is presented as "deliberately eclectic and disordered" to avoid the "superficial appearance of order and understanding." But the list is not entirely randomly ordered. The authors present the list in three groups:

- "Most people would consider the first twenty-five as (largely) unambiguous examples of progress or human benefit."
- "The next twenty-five innovations would clearly have controversial consequences; many would argue that government policy might better restrain or discourage innovation here."
- "The last fifty items are included in part because they are intrinsically interesting and in part to demonstrate that it is fairly easy to produce a long list of items of innovation that entail nontrivial consequences."

The original list of 100 forecasts is reprinted in the appendix along with a listing of the topical area to which the current author has assigned each forecast.

REVIEWING THE FORECASTS

In this and in other reviews there are wide variations in the judgments of reviewers. This variation is a result of the reviewers' knowledge and frames of reference, and of ambiguity in the wording of the forecasts.

Reviews of forecasts are complicated by the difficulty of applying uniform standards and definitions. Forecasts are often worded in ways that allow for, or even require, interpretation on the part of the reader. This is true for many of the forecasts in this list, allowing considerable leeway in judging whether an innovation has occurred. For example, forecast number *7, "More reliable and long-range weather forecasting,"* can be seen by one reviewer as having occurred as a result of great improvements in weather forecasting, while another reviewer might judge it to have not occurred because weather forecasts are not yet perfect. How much improvement constitutes an innovation requires the reviewer's judgment.

Views of what constitutes an innovation rather than an invention or demonstration of concept also vary widely. A standard definition of innovation is "the introduction of something new." For this review, the definition is taken to mean new technology put into practice. In the list of 100 innovations, some have clearly occurred, for example, forecast number *70. Simple inexpensive home video recording and playing.* Other forecasts can be said to have been invented, but cannot be considered innovations because they have not been developed past the invention stage (*69. Individual flying platforms*), or are they have not seen widespread use because of undesirable side effects (*27. The use of nuclear explosives for excavation and mining*). Some innovations have arguably barely reached the invention stage even after massive investments (*79. Inexpensive and reasonably effective ground-based Ballistic Missile Defense*).

OTHER REVIEWS OF THESE FORECASTS

Many reviews of Kahn and Wiener's forecasts have been conducted, especially with the arrival of a new century when these innovations all should have materialized. The end of the millennium caused many popular reflections on forecasts made during the twentieth century, both favorable and unfavorable. Popular reviews tend to focus on the forecasting failures, but at the same time often highlight a few successes [2 -5].

More serious reviews range from positive to scathing. The list of forecasts as presented in the summer, 1967 issue of Daedalus, the Journal of the American Academy of Arts and Sciences are reprinted in the compendium, *Technology and the Future,* as a model of technology forecasting. There, the editor reviews the forecasts with a semi-positive assessment: "the forecasts tell us more about 1967 than 2000" [6].

In another review Paul Krugman [7,8] estimates that about a third of the forecasts materialized:

"If you go down the list, you will recognize such things as cell phones, the Internet and faxes. But Mr. Kahn's list contains all kinds of things that haven't materialized. Radical new building materials. Undersea cities. Medical cures for cancer and overweight. Only about a third of what he thought were surefire things have come to pass."

Finally, in an especially harsh review of the forecasts, Schnaars, in *Megamistakes,* ascribes the source of many of the forecasts to "technological wonder"[9]. He estimates as of 1989,

"only about 15 percent of the forecasts clearly proved correct – or look as though they will prove correct in the final decade of the century. Another 10 percent can be judged as partially correct if a more lenient yardstick is used to measure accuracy and if the most beneficial interpretation is given to the forecasts. Almost half of the forecasts were outright, clear-cut mistakes."

A REVIEW FOR LESSONS IN FORECASTING

Finding insights and methods to improve our own forecasts is our primary objective for this review. It is based on the judgments of an eight member panel chosen by the author, whose members are experienced in a range of scientific fields with a mix of industrial and academic backgrounds. The next section of this paper describes the review methodology. Next, an overall summary of the review is presented, followed by an analysis of the forecasts in several topical areas. A primary finding of the review is that forecasts in one area, communications and computers, were much better than the forecasts in any other area. Reasons for this difference are explored. First, sustained trends in enabling technologies that were apparent in the late 1960's enabled the forecasters to extrapolate trends with a high degree of accuracy. Several examples of enabling technology trends are presented. Second, the declining cost/capability trends lowered the threshold levels of investment required for innovation. This enabled contributions to science, technology and innovation by many people, continuing and speeding the advance of enabling technologies trends. A framework describing the positive feedback system sustaining long-term capability growth in computers and communication is described. Finally some lessons for current forecasting are derived.

Assessment Method

JUDGEMENT BY A PANEL OF EXPERTS

The list of 100 forecasted technology innovations was reviewed by a panel of eight "experts," people knowledgeable in technology and futures. Each panelist independently reviewed the forecasts. To reduce technical bias in the evaluation, the

panel included reviewers with backgrounds in several technology fields, and from industry and academia.

Each panelist was asked individually to rate each forecast on a five point scale:

1. *Bingo*: a truly remarkable prediction that has materialized.
2. *Okay*: a good prediction of innovation that has materialized.
3. *Not Yet*: a prediction that might occur, but hasn't happened yet.
4. *Oops*: just wrong
5. *What?*: As in: "What were they thinking? "

Forecasts were ranked by the average rating assigned by the panelists. For example if the panelists all agreed that a forecast was a truly remarkable prediction, the forecast's score was computed as 1, and if the forecast was viewed by all the panelists as truly wrongheaded, the forecast's score was 5.

FORECASTS BY TOPICAL AREAS

The present author grouped the forecasts into nine topical areas: Infrastructure and Transportation, Communications and Computers, Lifestyle, Health and Human, Defense, Materials, Aerospace, Environment, and Biotech and Agriculture. The appendix includes an indicator of topical area for each forecast. The categories and the number of forecasts in each area are shown in Table 1. The forecasts are unevenly distributed among the topical areas, perhaps based on the importance given each area at the time the list was created. The distribution also shows a 1960's emphasis (more than 40% of the forecast combined) on building infrastructure and on the then emerging areas of computers, electronics and communication. About 15% of the forecasts are related to Defense and Aerospace, reflecting the cold war and space race thinking of the time. About 15% of the forecasts are related to "lifestyle," showing the thinking of the time that technology could have strong influence on living standards and societal impact. On the other hand, Biotechnology and Agriculture and Environment together account for fewer than 10% of the forecasts. Were a similar list of forecasts made today, one would expect a higher percentage of these latter topics.

TABLE 1
Forecasts by Topical Area

Area	Forecasts
Infrastructure & Transportation	22
Communications & Computers	21
Lifestyle	16
Health and Human	13
Defense	9
Materials	6
Aerospace	5
Environment	5
Biotech and Agriculture	3

Results

In this section, the results of the panel's evaluation are presented. Each member independently reviewed the forecasts, assigning ratings as described.

THE BEST AND WORST FORECASTS

Table 2 shows the ten best forecasts as judged by the panel, ordered by the average score assigned by the panelists. The numbers associated with each forecast are those given by Kahn and Wiener. All but two of the best forecasts come from the second fifty forecasts, which the authors included to "demonstrate that it is fairly easy to produce a long list of items of innovation," and there is a notable lack of forecasts from the first twenty-five forecasts that "Most people would consider … as unambiguous examples of progress or human benefit." There was consensus among the panel members that the ten innovations listed have occurred, and these were the only ten that the panelists all agreed had occurred. All but one of the innovations in Table 2 are classified in the area of computers and communications, and the one exception (high altitude cameras) is strongly enabled by digital technologies.

TABLE 2
10 Best Forecasts*

71.	Inexpensive high-capacity, worldwide, regional, and local (home and business) communication (perhaps using satellites, lasers, and light pipes)
74.	Pervasive business use of computers
82.	Direct broadcasts from satellites to home receivers
1.	Multiple applications for lasers and masers for sensing, measuring, communication, cutting, welding, power transmission, illumination, and destructive (defensive)
11.	Extensive use of high-altitude cameras for mapping, prospecting, census, and geological investigations)
29.	Extensive and intensive centralization (or automatic interconnection) of current and past personal and business information in high-speed data processors
76.	Other widespread use of computers for intellectual and professional assistance (translation, traffic control, literature search, design and analysis)
81.	Personal 'pagers' (perhaps even two-way pocket phones)
70.	Simple inexpensive home video recording and playing
72.	Practical home and business use of 'wired' video communication for both telephone and TV (possibly including retrieval of taped material from libraries) and rapid transmission and reception of facsimile

* Ranked by panelists' scores, best forecast first

Table 3 lists the ten worst forecasts, those that the panel agreed had not occurred. The list is ordered with the worst forecast last. Again, all but two of the worst forecasts come from the second half of the list. Of the ten worst forecasts, the panelists all agreed that the last nine forecasts had not occurred. One panelist thought that the first item on the list (individual flying platforms) had materialized, illustrating differing interpretations of the meaning of innovation. While there have been many demonstrations of individual

flying platforms using several technical approaches through the years (invention has occurred), there has been arguably insufficient use of the technology for it to be considered an innovation.

TABLE 3
10 Worst Forecasts*

69. Individual flying platforms
89. Widespread use of improved fluid amplifiers
94. Inexpensive road-free (and facility-free) transportation
48. Physically nonharmful methods of overindulging
87. Stimulated, planned, and perhaps programmed dreams
99. Artificial moons and other methods for illuminating large areas at night
19. Human hibernation for short periods (hours or days)
79. Inexpensive and reasonably effective ground-based BMD
27. The use of nuclear explosives for excavation and mining, generation of power, creation of high-temperature-pressure environments, or as a source of neutrons or other radiation
35. Human hibernation for relatively extensive periods (months to years)

PANELIST'S REVIEW

The panelists judged about 45% of the forecasted innovations to have materialized, that the innovations had occurred by the end of the century (rated as Bingo or Okay). Table 4 shows the ratings by panelist, ordered by the number of forecasted innovations judged to have occurred, along with the overall rating. Note that there is a wide range of viewpoints among the panelists. The most optimistic of the panelists judged about two-thirds of the forecasts to be correct, and the most pessimistic judged about three-quarters to be incorrect. The judgments of remainder of the panelists fall in the mid range of about half correct and half incorrect. Figure 1 shows the detailed scoring of the panelists, again ordered by the panelists' degree of optimism.

TABLE 4
Rating by Panelists

Panelist	Innovations Occurred	Innovations NOT Occurred
1	67	26
2	60	40
3	54	46
4	46	52
5	40	60
6	37	63
7	34	66
8	14	75
Average	45	55

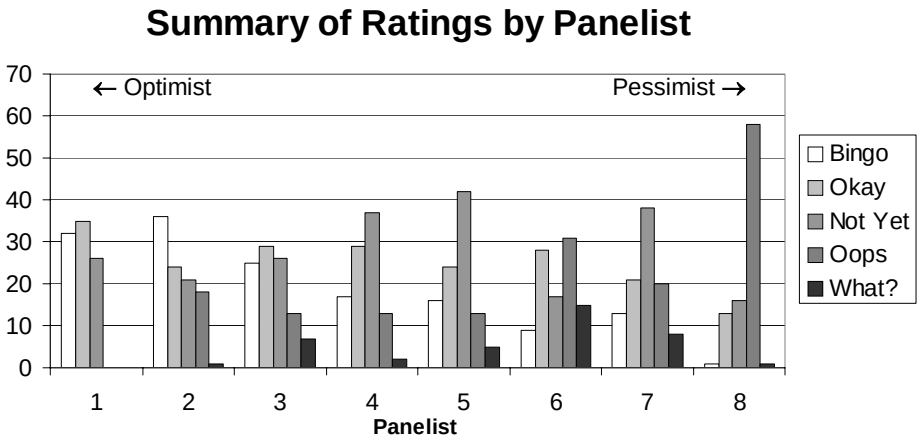

Figure 1. Ratings of the forecasts by the panelists ranged from optimistic to pessimistic

REVIEW BY TOPICAL AREA

Figure 2 summarizes the panelists' ratings of how many forecasted innovations materialized by topical area. The area of Communications and Computers stands out – with more than 80% of the forecasted innovations judged to have occurred. On the other hand, fewer than 20% of forecasted innovations in Aerospace were judged to have occurred. The 1960's were a time of great optimism for aerospace, but the great plans collapsed in the 1970's following the Apollo program. Only about 30% of forecasted innovations in Infrastructure and Transportation occurred, perhaps because the massive investments by single (mostly government) agencies needed in these areas were held up for financial, organizational or political reasons.

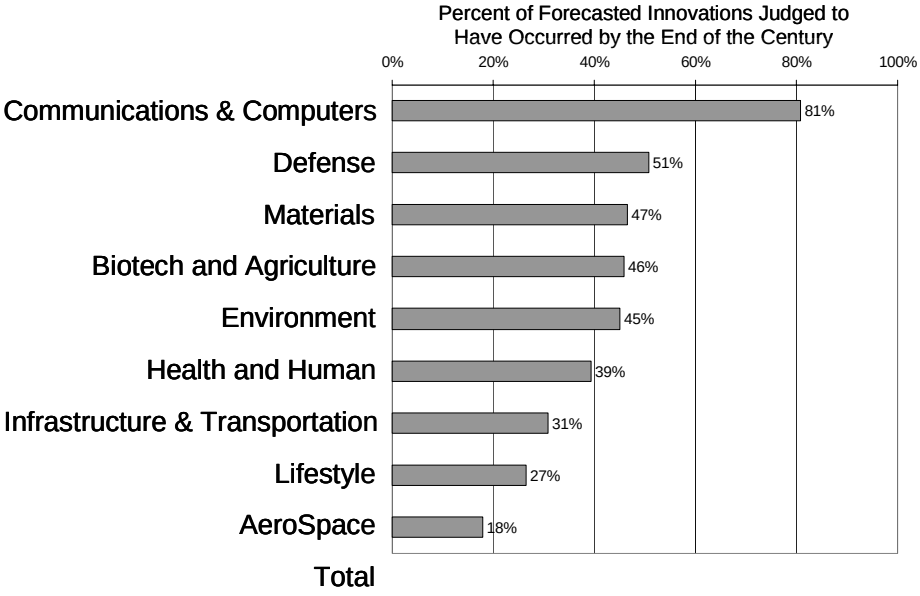

Figure 2. The quality of the forecasts varied widely across topical areas.

FORECASTS IN COMPUTERS AND COMMUNICATION

Forecasts in communications and computers stand out from forecasts in other areas in their apparent quality. Table 5 lists these forecasts in order of their score, with the forecasts judged best listed first. All but the last three innovations on this list were judged by the majority of the panel to have occurred.

TABLE 5
Forecast Innovations in Communications and Computers

1	Multiple applications for lasers and masers for sensing, measuring, communication, cutting, welding, power transmission, illumination, and destructive (defensive)
29	Extensive and intensive centralization (or automatic interconnection) of current and past personal and business information in high-speed data processors
70	Simple inexpensive home video recording and playing
71	Inexpensive high-capacity, worldwide, regional, and local (home and business) communication (perhaps using satellites, lasers, and light pipes)
72	Practical home and business use of 'wired' video communication for both telephone and TV (possibly including retrieval of taped material from libraries) and rapid transmission and reception of facsimile
74	Pervasive business use of computers
76	Other widespread use of computers for intellectual and professional assistance (translation, traffic control, literature search, design and analysis)
81	Personal 'pagers' (perhaps even two-way pocket phones)
82	Direct broadcasts from satellites to home receivers
57	Automated universal (real-time) credit, audit and banking systems
84.	Home computers to "run" household and communicate with the outside world
88.	Inexpensive, rapid, high-quality reproduction; followed by color and high-detailed photography reproduction-perhaps for home as well as office use
90.	Conference TV
28.	General use of automation and cybernation in management and production
85.	Maintenance-free, longlife electronic equipment
86.	Home education via video, computerized, and programmed learning
83.	Inexpensive (less than $20), long-lasting, very small battery-operated TV receivers
54.	Automated grocery and department stores
20.	Inexpensive design and procurement of 'one of a kind' items through the use of computerized analysis and automated production
24.	Three-dimensional photography, illustrations, movies, and television

CONSENSUS VIEWS

There is considerable variation in the reviews of individual forecasts among the panelists. Some forecasts were viewed in very much the same way by the panelists, and some forecasts were viewed remarkably differently. Table 6 shows the forecasts with the greatest and least degrees of consensus among the panel, as measured by the standard

deviation of the panelists' ratings. For each forecast, the table shows the number of panelists that assigned each rating. In the upper half of the table, the forecasts with a high level of agreement among the panelists are relatively precisely described, while in the lower half, the forecasts with the lowest level of agreement are worded in ways that demand interpretation by the reader. One simple lesson for forecasters, simple to state but difficult to carry out, is to state forecasts in an unambiguous, precise way.

TABLE 6
Forecasts With the Greatest Consensus

Forecast	Bingo	Okay	Not Yet	Oops	What?
71. Inexpensive high-capacity, worldwide, regional, and local (home and business) communication (perhaps using satellites, lasers, and light pipes)	8	0	0	0	0
34. Practical use of direct electronic communication with and stimulation of the brain	0	0	8	0	0
74. Pervasive business use of computers	7	1	0	0	0
82. Direct broadcasts from satellites to home receivers	7	1	0	0	0
13. Major reduction in hereditary and congenital defects	0	1	7	0	0
1. Multiple applications for lasers and masers for sensing, measuring, communication, cutting, welding, power transmission, illumination, and destructive (defensive)	6	2	0	0	0
11. Extensive use of high-altitude cameras for mapping, prospecting, census, and geological investigations	6	2	0	0	0
29. Extensive and intensive centralization (or automatic interconnection) of current and past personal and business information in high-speed data processors	6	2	0	0	0
76. Other widespread use of computers for intellectual and professional assistance (translation, traffic control, literature search, design and analysis)	6	2	0	0	0
81. Personal 'pagers' (perhaps even two-way pocket phones)	6	2	0	0	0
42. Genetic control or influence over the 'basic constitution' of an individual	0	0	6	2	0
51. Permanent manned satellite and lunar installations-interplanetary travel	0	0	6	2	0

Forecasts With the Least Consensus

Forecast	Bingo	Okay	Not Yet	Oops	What?
100. Extensive use of 'biological processes' in the extraction and processing of minerals	2	0	3	1	1
37. New and relatively effective counterinsurgency techniques (and perhaps also insurgency techniques)	0	3	1	4	0
43. New techniques and institutions for the education of children	0	3	1	4	0
95. New methods for rapid language teaching	0	3	1	4	0
14. Extensive use of cyborg techniques (mechanical substitutes for human organs, senses, limbs)	2	1	2	2	1
93. Inexpensive worldwide transportation of humans and cargo	2	1	2	3	0
66. New techniques for keeping physically fit and/or acquiring physical skills	0	5	0	3	0

36. Cheap and widely available central weapon systems	0	3	1	2	2
83. Inexpensive (less than $20), long-lasting, very small battery-operated TV receivers	4	0	4	0	0
26. Widespread use of nuclear reactors for power	2	1	0	5	0

Lessons from the Forecasts

Forecasts in communications and computers were judged to have been much better than any of the other areas. Two key drivers of the greater accuracy of forecasts in communications and computers stand out. First, sustained trends in enabling technologies for communications and computers were apparent in the 1960's and have continued to the present, allowing forecasters to extrapolate capability and cost trends with a high degree of accuracy. Performance capability has grown exponentially, enabling ever more sophisticated applications of technology. Second, the scale of investment required for innovation with enabling technologies of communications and computers was driven down by the declining costs of the enabling technologies. This allowed contributions by many people, working in industry, academia, and independently to advance the field. Many small decisions and technology innovations resulted, and relatively few massive infrastructure changes were required for successful innovation (going beyond invention). The activities of many innovators enabled fast and sustained industry learning.

Figure 3 illustrates how these factors reinforce themselves in a positive loop. Declining cost/capability enables lower investment for innovation, which enables contributions by more and more people. And the competition and learning involving many contributors sustains the enabling technology advances.

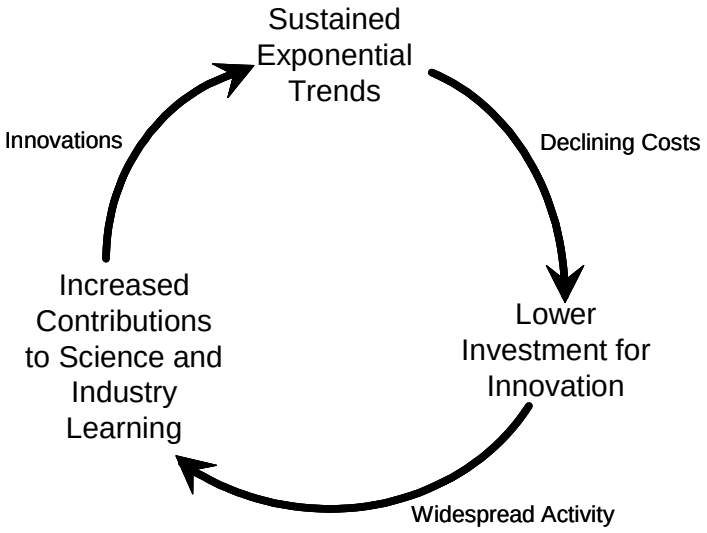

Figure 3. Sustained technology trends lower investment, creating a positive innovation loop.

SUSTAINED TRENDS IN ENABLING TECHNOLOGY

Sustained trends in technologies underlying innovations in computers and communications have enabled predictable, long-term growth. These trends include exponential advances in semiconductor performance/cost, computing capability, storage capacity/cost, and optical transmission capacity. These trends were largely apparent at the time Kahn and Wiener made their forecasts, and have continued for as long as 40 – 50 years.

Trends in semiconductor density and performance/cost have shown exponential growth for several decades. Figure 4 shows the experience curve for semiconductor Dynamic Random Access Memory (DRAM) beginning in 1964. The graph on the left shows a plot of the average selling price per bit versus the cumulative volume of bits produced on a log-log scale. In 1964 the average price for storage of a single bit was just over 10 cents, while today the price has fallen below 1/10000 of a cent. The experience curve has a 70% "slope," indicating that with a cumulative doubling of volume the average selling price per bit declined to 70% of what it was. This trend has been sustained by many technology innovations, and has continued through significant changes in industry structure. For example, the curve dips below the long term trend during the late 1980's – when charges of Japanese dumping were made. But the trend returned to track soon afterwards. To illustrate how sustained trends are used in forecasting, Figure 4 also shows a plot of the price per bit data by year. The time plot on the right also shows the targets for price per bit published in 1999 International Technology Roadmap for Semiconductors. This forecast is one of a series of semi-annual technology roadmaps created by the semiconductor industry with the leadership of Sematech [10]. One can see how the industry has used the trend to set its targets, thus sustaining the advances.

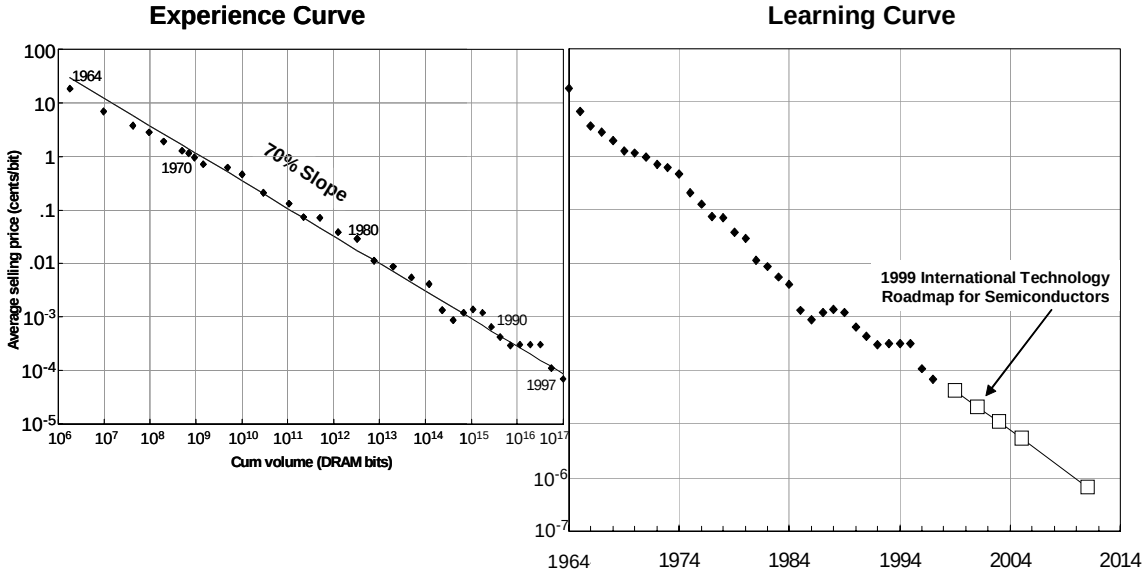

Figure 4. Experience Curve and Learning Curve for Semiconductor Dynamic Random Access Memory shows the sustained exponential growth that enables forecasting.

Another forecast of semiconductor performance advance is commonly referred to as "Moore's Law." Based on early experience in integrated circuit development, Gordon Moore forecast in 1964 that the number of transistors on a chip would double every eighteen months [11]. This forecast was available to Kahn and Wiener at the time they made their forecasts of technology innovations, and could have enabled them to estimate the application capabilities of electronic processing and storage in the future.

Computing capability has seen sustained exponential growth since the first general purpose computers were developed during the 1940's. Figure 5 shows the performance of the fastest computers of the time in terms of operations per second (a FLOP is a Floating Point Operation per Second) [12, 13]. This exponential performance trend has been sustained with innovations in basic technologies used for switching and processing – from relays to vacuum tubes to transistors to integrated circuits, and with innovations in fundamental architectures – from single processors to parallel processors to massively parallel architectures. The trend in processing capability was evident during the 1960's, and was known and used by Kahn and Wiener for their forecasts.

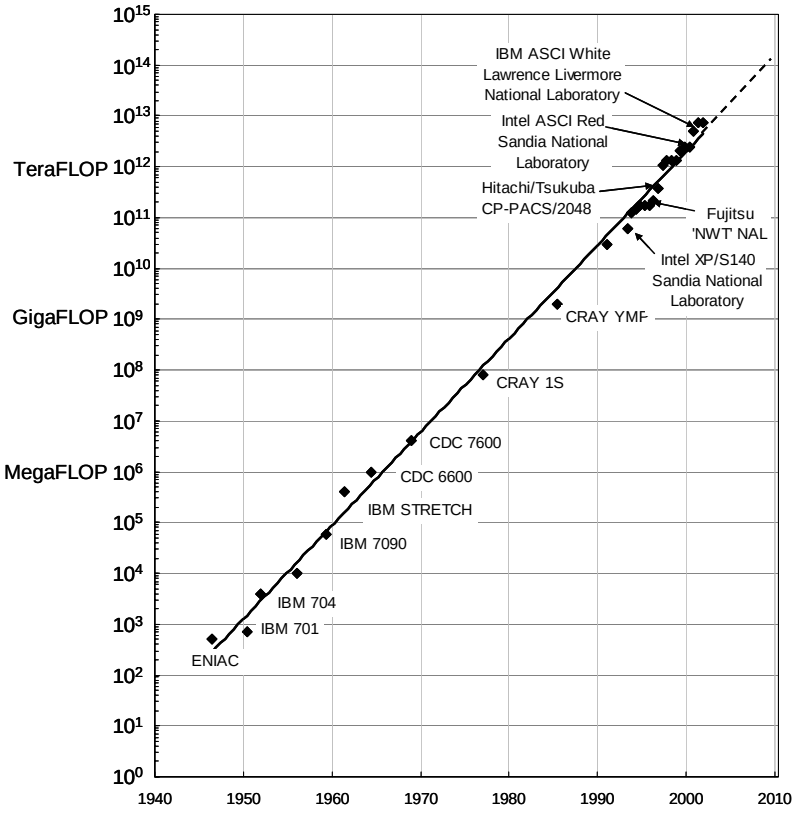

Figure 5. The power of the fastest computers has grown exponentially since the 1940's

Electronic storage capability has also seen exponential growth for an extended period of time. Figure 6 shows the cost/capability experience curve for rigid disk drives, charting the exponentially declining cost of storage versus the cumulative number of

bytes of storage produced during the 1990's. The chart shows the average price per gigabyte of rigid disk drive storage versus the cumulative disk storage capacity shipped [14]. The curve has a 50% slope, indicating that the price per bit of storage halved with a cumulative doubling of volume produced. In recent years, volume has about doubled annually, with the result that disk drive capacities have doubled each year while prices per drive have remained roughly constant.

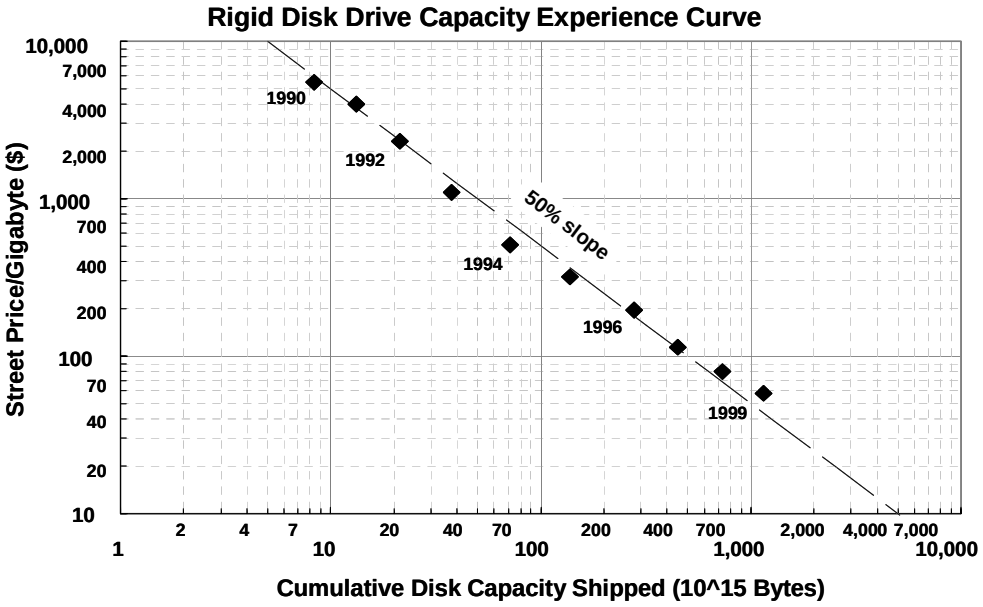

Figure 6. Rigid Disk Drives have sustained capacity growth and cost declines.

Optical communication capability has also experienced sustained exponential growth. Figure 7 shows exponential growth in transmission capability of a single optical fiber over the last twenty years [15]. The trend was sustained for much of the period by increasing the bit rate transmitted using a single wavelength of light (growing about 1.5 times each year); but as technologies for transmitting multiple wavelengths of light on a fiber were developed during the 1990's, the rate of growth increased to about 2 times each year. The early indicators of optical technology were available to Kahn and Wiener in the late 1960's – the laser had been invented and early experiments in optical transmission were underway—enabling them to extrapolate capabilities for their forecasts. Recently the theoretical capacity of a single fiber has been shown to be limited to about 100 terabits/second (10^{14} bits/second) [16], placing an upper bound on single fiber capacity that could be reached within a decade at recent growth rates (about a doubling of capacity each year). Continued growth in optical communication system capacities will require multiple fibers, and the exponential growth rate beyond the single fiber limiting point will have to be reconsidered.

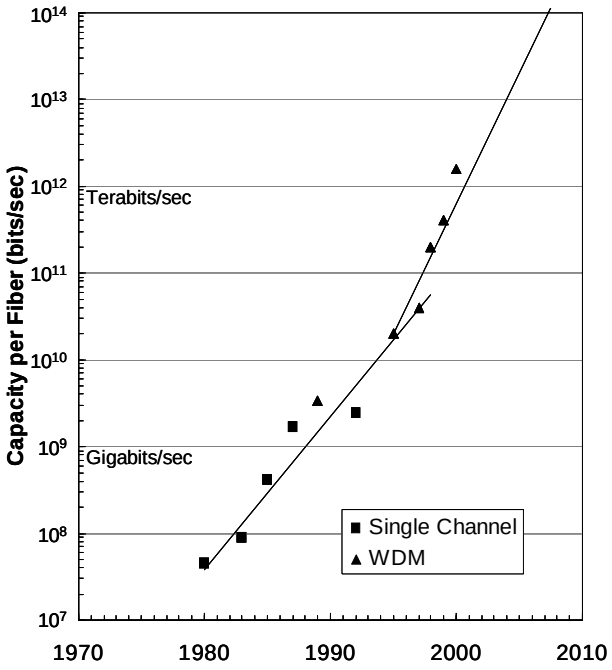

Figure 7. Optical transmission capacity has grown exponentially for 20 years. Recent research indicates the theoretical capacity limit is about 100 terabits/second (10^{14} bits/second).

MANY INNOVATIONS ENABLED

Each of the trends in enabling technology results in continued declining costs for technology applications. Declining costs stimulate increased innovation in two ways. First, lower capital requirements allow more people to use the technologies for innovation. Second the communication and exchange of ideas among those innovators has been enabled by the very processing and communication technologies they are developing.

Declining costs of technology allow increasingly elaborate applications. Declining semiconductor costs enable applications using greater amounts of stored data and more complex algorithms for processing. For example, steady increases in the abilities of chess playing computers tracked the advances of the fastest computers of the day shown in Figure 5 to the point that computers now compete at the hightest level. Voice processing, a complex processing challenge, is becoming practical in compact, often portable electronics with the use of low cost memory and digital signal processing. Lower cost electronic processing is also replacing mechanical functions in automobiles and other large equipment.

The lower costs of enabling technologies allow more people to be involved and to collaborate in new ways. The innovations of many technology start-up corporations are possible due to lower costs and reduced financial risks. The open source movement in software development that emerged in the 1990's has been enabled by low cost, widely available global communications of the internet, low cost powerful computers, and

widely available software – allowing rapid contributions to innovative software systems and rapid application and improvement by many individuals.

Using the Lessons for Forecasting

How can the lessons from this study be applied? The lessons from this review suggest that we look for areas with capability growth patterns that will be sustained for long periods in the future or for areas where the growth in enabling technologies, such as information technologies, will have an impact.

The trends for semiconductors, computing, storage, and optics described in this paper will continue for some time, allowing continued accurate forecasts in computers and communication. To improve forecasts in other areas, we should look for similar sustained trends. While trends in other areas may not be so fast, they can help ground our forecasts in the realm of the possible, helping us avoid Schnarr's trap of technological wonder – where we forecast the impossible.

New growth areas may be impacted by the trends that are driving computers and communication. We should look for areas where these trends will have an effect. Replacement of mechanical functions by electronics, computers and algorithms is one area where this impact can be readily seen. New growth areas will include nanotechnology, which will benefit from many of the technology innovations that drive computers and communication. Fabrication methods are similar and can be quickly adapted from the semiconductor industry to new nanotechnology applications. Information technology is currently being applied in biotechnology and genomics and may make synthesis and uses of new compounds more targeted and predictable, resulting in sustained advances in these areas.

This review has shown that with careful study and analysis, it is possible to find strong underpinning trends for many of our technology forecasts, resulting in better forecasts and improved decision making by policy makers and business leaders. The study also indicates that to find areas that can be accurately forecasted, we should look for positive innovation loops where declining technology cost/capability trends enable lower investment for innovation, allowing contributions by greater numbers of people, which in turn sustain the cost/capability trends.

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Appendix

One hundred technical innovations very likely in the last third of the twentieth century

(Forecasts are listed in the original order and with original numbering. The Area is the forecast area assigned for this study.)

Area Legend

Infrastructure & Transportation	I	AeroSpace	S
Health and Human	H	Biotech and Agriculture	B
Materials	M	Environment	E
Defense	D	Lifestyle	L
Communications & Computers	C		

Forecast	Area
1. Multiple applications for lasers and masers for sensing, measuring, communication, cutting, welding, power transmission, illumination, and destructive (defensive)	C
2. Extreme high-strength and/or high-temperature structural materials	M
3. New or improved superperformance fabrics (papers, fibers, and plastics)	M
4. New or improved materials for equipment and appliances	M
5. New airborne vehicles (ground-effect machines, VSTOL and STOL, superhelicopters, giant and/or supersonic jets)	S
6. Extensive commercial application of shape-charge explosives	D
7. More reliable and long-range weather forecasting	E
8. Expansion of tropical agriculture and forestry	E
9. New sources of power for fixed installations (e.g., magnetohydrodynamic, thermionic, thermoelectric, and radioactivity)	I
10. New sources of power for ground transportation (storage battery, fuel cell, electromagnetic fields, jet engine)	I
11. Extensive use of high-altitude cameras for mapping, prospecting, census, and geological investigations)	D
12. New methods of water transportation (large submarines, flexible container ships, automated single-purpose bulk cargo ships)	I
13. Major reduction in hereditary and congenital defects	H
14. Extensive use of cyborg techniques (mechanical substitutes for human organs, senses, limbs)	H
15. New techniques for preserving and improving the environment	E
16. Relative effective appetite control	L
17. New techniques and institutions for adult education	L
18. New and useful plant and animal species	B
19. Human hibernation for short periods (hours or days)	L
20. Inexpensive design and procurement of 'one of a kind' items through the use of computerized analysis and automated production	C
21. Controlled and/or supereffective relaxation and sleep	L
22. More sophisticated architectural engineering (geodesic domes, 'fancy' stressed shells, pressurized skins, and esoteric materials)	I
23. New and improved uses of the oceans (mining, farming, energy)	I
24. Three-dimensional photography, illustrations, movies, and television	C
25. Automated or more mechanized housekeeping and home maintenance	L
26. Widespread use of nuclear reactors for power	I
27. The use of nuclear explosives for excavation and mining, generation of power, creation of high-temperature-pressure environments, or as a source of neutrons or other radiation	I
28. General use of automation and cybernation in management and production	C

Forecast	Area
29. Extensive and intensive centralization (or automatic interconnection) of current and past personal and business information in high-speed data processors	C
30. New and possibly pervasive techniques for surveillance, monitoring, and control of individuals and organizations	D
31. Some control of weather and/or climate	E
32. Changes or experiments with the overall environment (increase in C-14, carbon dioxide)	E
33. New and more reliable educational and propaganda techniques for affecting human behavior-public and private	L
34. Practical use of direct electronic communication with and stimulation of the brain	H
35. Human hibernation for relatively extensive periods (months to years)	L
36. Cheap and widely available central weapon systems	D
37. New and relatively effective counterinsurgency techniques (and perhaps also insurgency techniques)	D
38. New techniques for very cheap, convenient, and reliable birth control	H
39. New, more varied, and more reliable drugs for control of fatigue, relaxation, alertness, mood, personality, perceptions, fantasies, and other psychobiological states	H
40. Capability to choose the sex of unborn children	H
41. Improved capability to 'change' sex of children or adults	H
42. Genetic control or influence over the 'basic constitution' of an individual	H
43. New techniques and institutions for the education of children	L
44. General and substantial increase in life expectancy, postponement of aging, and limited rejuvenation	H
45. Generally acceptable and competitive synthetic foods and beverages	B
46. 'High quality' medical care for underdeveloped areas	H
47. Design and extensive use of responsive and supercontrolled environrnents for private and public use (for pleasurable, educational, and vocational purposes)	I
48. Physically nonharmful methods of overindulging	L
49 Simple techniques for extensive and 'permanents cosmetological changes (features, 'figures," perhaps complexion and even skin color)	L
50. More extensive use of transplantation of human organs	H
51. Permanent manned satellite and lunar installations-interplanetary travel	S
52. Application of space life systems or similar techniques to terrestrial installations	S
53. Permanent inhabited undersea installations and colonies	I
54. Automated grocery and department stores	C
55. Extensive use of robots and machines 'slaved' to humans	L
56. New use of underground 'tunnels' for private and public transportation and other purposes	I
57. Automated universal (real-time) credit, audit and banking systems	C
58. Chemical methods for improving memory and learning	L
59. Greater use of underground buildings	I
60. New and improved materials and equipment for buildings and interiors (e.g., variable transmission glass, heating and cooling by thermoelectric effect, and clectrolumineseent and phosphorescent lighting)	I
61. Widespread use of cryogenics	L
62. Improved chemical control of some mental illnesses and some aspects of senility	H
63. Mechanical and chemical methods for improving human analytical ability	H
64. Inexpensive and rapid techniques for making tunnels	I
65. Major improvements in earthmoving and construction equipment	I
66. New techniques for keeping physically fit and/or acquiring physical skills	L
67. Commercial extraction of oil from shale	I
68. Recoverable boosters for economic space launching	S
69. Individual flying platforms	S
70. Simple inexpensive home video recording and playing	C
71. Inexpensive high-capacity, worldwide, regional, and local (home and business) communication (perhaps using satellites, lasers, and light pipes)	C
72. Practical home and business use of 'wired' video communication for both telephone and TV (possibly including retrieval of taped material from libraries) and rapid transmission and reception of facsimile	C
73. Practical large-scale desalination	I
74. Pervasive business use of computers	C

Forecast	Area
75. Shared time (public and interconnected?) computers available to home and business on a metered basis	C
76. Other widespread use of computers for intellectual and professional assistance (translation, traffic control, literature search, design and analysis)	C
77. General availability of inexpensive transuranic and other esoteric elements	M
78. Space defense systems	D
79. Inexpensive and reasonably effective ground-based BMD (Ballistic Missile Defense)	D
80. Very low-cost buildings for home and business use	I
81. Personal 'pagers' (perhaps even two-way pocket phones)	C
82. Direct broadcasts from satellites to home receivers	C
83. Inexpensive (less than $20), long-lasting, very small battery-operated TV receivers	C
84. Home computers to "run" household and communicate with the outside world	C
85. Maintenance-free, longlife electronic equipment	C
86. Home education via video, computerized, and programmed learning	C
87. Stimulated, planned, and perhaps programmed dreams	L
88. Inexpensive, rapid, high-qualitv reproduction; followed by color and high-detailed photography reproduction-perhaps for home as well as office use	C
89. Widespread use of improved fluid amplifiers	M
90. Conference TV	C
91. Flexible penology without necessarily using prisons (bv use of modern methods of surveillance, monitoring, and control	I
92. Common use of individual power source for lights, appliances, and machines	I
93. Inexpensive worldwide transportation of humans and cargo	I
94. Inexpensive road-free (and facility-free) transportation	I
95. New methods for rapid language teaching	L
96. Extensive genetic control for plants and animals	B
97. New biological and chemical methods to identify, trace, incapacitate, or annoy people for police and military uses	D
98. New and possibly very simple methods for lethal biological and chemical warfare	D
99. Artificial moons and other methods for illuminating large areas at night	I
100. Extensive use of 'biological processes' in the extraction and processing of minerals	M