THE FUTURE OF SCIENCE

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Of all scientists who ever lived, it has been said, ninety percent are living today. The same statement can probably be made about astronauts, pop singers, and Californians. It means simply that the scientific profession, except for a few pioneers, is a modern one. Its growth has been rapid, its methods multiplying, its purview expanding explosively.

We are still in the midst of this fascinating development, and it is certain that the future state of science will be utterly different from what it is today. Much of what might be said about its future has to be speculative; yet there are recognizable trends that give some substance to speculation. A few of these trends, and their expected implications for the third third of this century, are discussed below.

1. THE FUTURE SIZE OF THE SCIENTIFIC ESTABLISHMENT

A rough estimate of the number of scientists and engineers today is 2 million in the United States and 5 million world-wide. Population growth alone would raise

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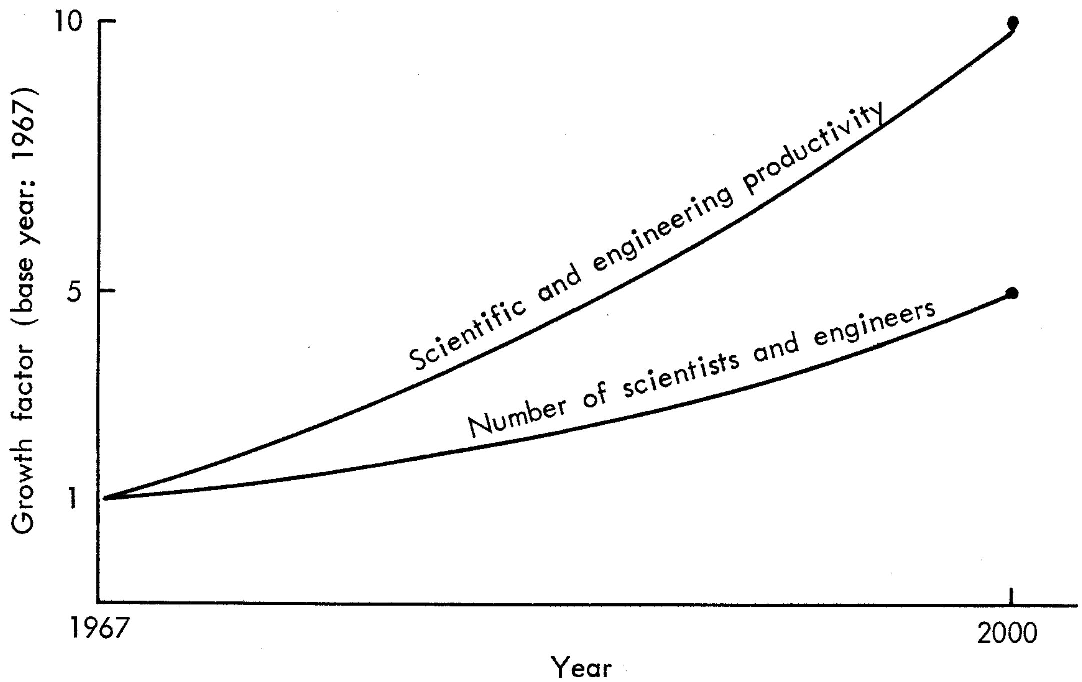

Fig. 1—Growth of scientific establishment

these figures to almost 4 and 10 million respectively by the year 2000. In addition, a doubling of the per-capita number of scientists and engineers has been observed to take place every 20 years thus far in this century. Even if this rate of increase slows down somewhat, we may expect by the year 2000 to have of the order of 10 million scientists and engineers in the United States and 25 million world-wide.

Another factor which contributes considerably to the output of the scientific community is the increase in what may be called the labor productivity of the individual researcher. This, of course, is a quantity which is only vaguely defined, yet there can be no doubt that its value, however imprecisely determined, has been rising rapidly due to the advent of high-speed computers and of scientific instruments of steadily increasing sophistication. I am firmly convinced, for reasons which at least in part will become clear in what follows, that we have not nearly reached the point in time where the rate of increase in this factor will begin to turn down. Taking, however, a very conservative view of the effect of this factor and assuming a mere doubling of per-capita researcher productivity between the present and the end of the century, we arrive at the estimate that the total scientific and engineering productivity will rise by a factor of 10 by the year 2000.

2. THE NEW ATTITUDE TOWARD THE FUTURE

It is only in the last few years that a wholly new attitude toward the future has become apparent among policy planners and others concerned over the future of our society, resulting in a new intellectual climate in many parts of the world. Customary planning horizons are being extended into a more distant future, and intuitive gambles—as a basis for planning—are being replaced by systematic analysis of the opportunities the future has to offer.

The research community, in particular, in view of the accelerating momentum of its capabilities, is realizing the enormous power and responsibility it has in selecting among the multitude of possible futures of our society those whose probability of occurrence it ought to influence through appropriate policy recommendations.

This rising social consciousness among scientists, based on a sense of urgency as well as a sense of their own strength, is propelling them in new directions that promise to relate their activities more closely to policy-making. The search for truth per se will thus be replaced or at least augmented, for better or worse, by a search for what is both morally right and attainable. The purists' motto of "science for science's sake" will carry less weight in the decades to come than the pragmatists' "science for society's sake."

To translate such new aspirations into fact will not come easily, however inevitable the commitment to this trend. The process will involve rather fundamental changes in method and quite noticeable changes in the routine behavior patterns of scientists.

3. CHANGES IN METHOD

During the next ten years or so the relative decay of fatalism will complete itself; the growing ability to do something about the future, from which the scientific community's new sense of social responsibility derives, will come to full fruition. The reason for this trend can be seen in two revolutionary developments that are currently unfolding.

One is what may be called the second computer revolution. It took just twenty years for the first computer revolution to be completed, from the mid-forties to the mid-sixties, during which time the computer grew up from being a bookkeeping device to becoming a highly versatile data processor and research tool. During that period the size and the cost of electronic computer components have gone down by factors of 100 and 100,000 respectively, and their speed has gone up by a factor of 100,000.

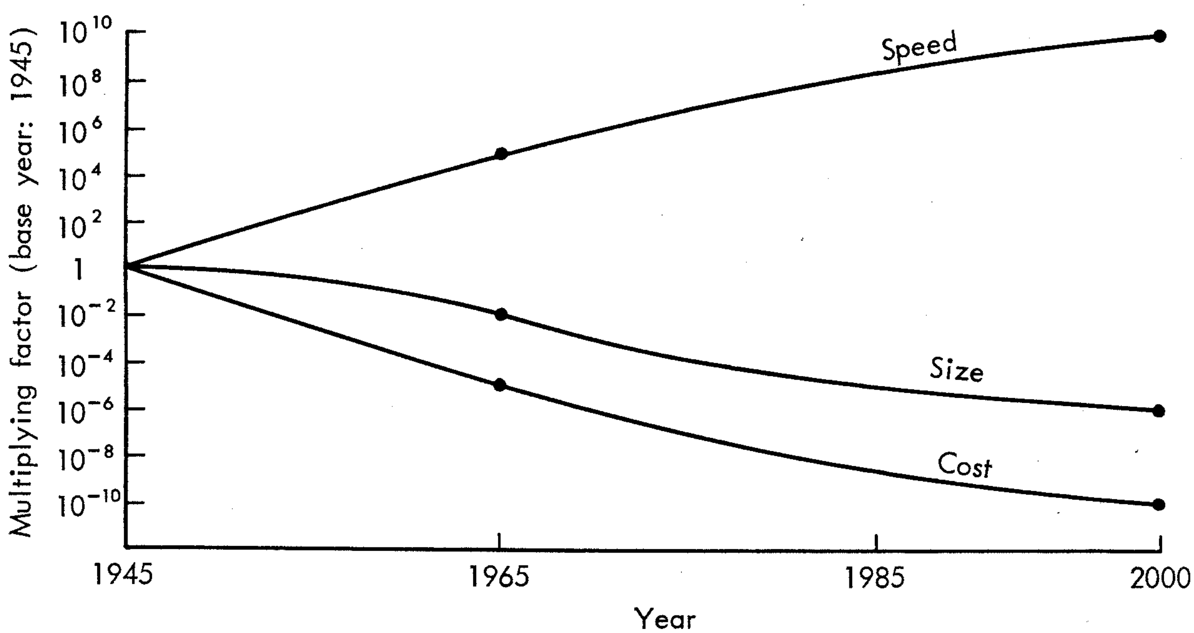

Fig.2—Computer characteristics

While these trends will continue for some time and, together with long-distance time-sharing arrangements, will account during the next decade for a continued annual doubling of the amount of computer power in the world, the second computer revolution will add a significantly new flavor to this national resource of ours. It will consist of the amalgamation of two separate trends, which in combination promise to have a powerful impact on planning processes generally. They are (i) the relative automation of the computer, in the sense of doing away with many of the cumbersome aspects of computer programming and thereby facilitating direct communication between the individual researcher and the computer; and (ii) the invention of numerous highly versatile display devices, coupled directly to the computer, that permit a designer to construct visual and, when necessary, moving images of his ideas as he develops them. These two trends, which are well under way, will constitute the beginning of a true symbiosis between man and machine, where in a very real sense man's intelligence will be enhanced through collaboration with a computer.

The other revolution in the making, that will add to our control over the future, is of a very different kind; it is more subtle and potentially even more influential. I am referring to the reorientation that is beginning to take place within the so-called soft sciences.

The traditional methods of the social sciences are proving inadequate to the task of dealing effectively with the ever-growing complexity of forecasting the consequences of alternative policies and thereby furnishing useful planning aid to high-level decision makers in the public or private sectors. This lack of policy orientation is now beginning to be effectively overcome. Rather than continue the futile attempt to emulate the physical sciences, researchers in the social-science area are realizing that the time has come to emulate physical technology instead.

They are beginning to do this by seeking an interdisciplinary systems approach to the solution of socio-political problems. They will accomplish this by transferring the methods of operations research from the area of physical technology to that of social technology.

The potential reward from this evolving reorientation of some of the effort in the social-science area toward social technology, employing operations-analytical techniques, is considerable; it may even equal or exceed in importance that of the achievements credited to the technologies arising out of the physical sciences.

Operations analysis was first brought into being through the exigencies of World War II; it has since continued to develop and become a widely accepted tool, not only in the peacetime management of military affairs, but throughout the operations of commerce and industry.

Among the principal operations research techniques that have proven themselves in these areas and that show great promise of being transferable to that of social technology are the construction of mathematical models, simulation procedures, and a systematic approach to the utilization of expert opinions—the latter a subject on which I will presently add a few more words. All of these techniques—it is almost needless to say—are greatly aided and continually refined through the availability of the computer, and the second computer revolution which I described may well add another order of magnitude to their potency. In particular, automated access to central data banks, in conjunction with appropriate socioeconomic models, will provide the soft sciences with the same kind of massive data processing and interpreting capability that, in the physical sciences, created the breakthrough which led to the development of the atomic bomb.

Among the new pragmatic approaches taken by operations analysis, that I mentioned, is the systematic utilization of the intuitive judgment of groups of experts. A method developed, and still being refined, for the purpose of obtaining a consensus of informed opinions has become known as the Delphi Technique. This technique* uses a series of questionnaires interspersed with information and opinion feedback derived from previous questionnaires. Some of the questions directed to the participating respondents may, for instance, inquire into the reasons for previously expressed opinions, and a collection of such reasons may then be presented to each respondent in the group, together with an invitation to reconsider and possibly revise his earlier estimates. Both the inquiry into the reasons and subsequent feedback of the reasons adduced by others may serve to stimulate the experts into taking into due account considerations they might through inadvertence have neglected, and to give due weight to factors they were inclined to dismiss as unimportant on first thought.

The Delphi approach derives its importance from the realization that projections into the future, on which public policy decisions must rely, are largely based on the personal expectations of individuals rather than on predictions derived from well-established theory. Even when we have a formal mathematical model available—as is the case, for example, for various aspects of the national economy—the input assumptions, the range of applicability of the model, and the interpretation of the output all are subject to the intuitive intervention by an individual who can bring the appropriate expertise to bear on the application of the model. In view of the absence of a proper theoretical foundation and the consequent inevitability of having, to some extent, to rely on intuitive judgment, we are faced with two options: we can either wait indefinitely until we have an adequate theory enabling us to deal with

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*Discussed in more detail in Erich Jantsch's article in the same issue.

socioeconomic and political problems as confidently as we do with problems in physics and chemistry, or we can make the most of an admittedly unsatisfactory situation and try to obtain the relevant intuitive insights of experts and then use their judgments as systematically as possible. The use of the Delphi approach represents an effort to proceed along the second of these alternatives.

A first major application of the Delphi technique to long-range forecasting was carried out three years ago under the auspices of The RAND Corporation; excerpts from its outcome are presented later in this article. A second such study is currently under preparation.

Another context in which this approach may have some utility is that of real or simulated decision-making situations. Many readers, no doubt, are familiar with some forms of business games. The decisions called for at various points in such exercises, like those in corresponding real-life situations, are usually based on intuitive judgment. Whenever it is desirable to rely on such occasions on the judgment of more than one person, a consensus can be formed through an application of the Delphi technique.

There are other operations research methods that can be transferred from the physical to the social domain, but I believe that the two I mentioned particularly--simulation and the systematized use of informed opinion--while lacking the elegance and cohesiveness of a scientific theory, represent effective, though crude, tools for exploring the future and thereby aiding the planning process. The newly discernible willingness to examine the applicability and refine the use of such tools in the social-science area, together with the computer capabilities already on the horizon, convince me that we are entering an era of potentially remarkable social progress.

4. NEW FORMS OF PROCEDURE WITHIN THE SCIENTIFIC ESTABLISHMENT

Along with the epistemological reorientation indicated above we may expect substantial changes in the procedural side of scientific transactions. These will profoundly affect some of the traditional behavior patterns within the scientific profession.

Conferences: The utility of conferences began to deteriorate decades ago; now, when attendance by thousands has become the rule, we are faced with a situation that is absurd and ludicrous. Scientific congregations have to be reduced to reasonable proportions, and new ways have to be found to make more constructive use of the talents and knowledge of those who do congregate. Novel conference styles are beginning to be experimented with, and it may safely be predicted that, particularly with the aid of electronic computing and display devices, new forms of conference workshops will evolve in which the participants' role will have been changed from that of passive spectators to interactive contributors.

Researcher-computer symbiosis: As a result of the second computer revolution referred to earlier, the use of a console tied to a (time-shared) computer and to banks of data and of mathematical models will become part of the scientist's daily routine. The computer's role will thus rise to that of a quasi-colleague, and this man-machine team's productivity may be expected far to exceed that of today's scientist. (I earlier gave a factor of 2 as a highly conservative estimate.)

Interdisciplinary teams: There are signs today of widespread recognition that the complex problems involved in shaping the future of our society are multidisciplinary in character and that their solution requires the collaboration of scientists and technologists from many different fields. Yet thus far little more than lip-service is being paid to this need for interdisciplinary cooperation, partly because effective methods for encouraging and facilitating such joint attacks on problems are still in the explorative stage. However, such quasi-experimental techniques as operational gaming and other simulation workshop approaches offer great promise in this direction. Not only has it been demonstrated that a simulation laboratory environment facilitates cross-disciplinary communication; but a participant's interaction with persons representing viewpoints different from his own, that is induced by the demands for (simulated) decisions, presents him with new insights into the problem structure that might otherwise have eluded him. Based on today's promising beginnings, organized interdisciplinary team approaches to major problems will become common modes of operation, especially when such interaction among specialists—even in geographically distinct locations—can take place through a computer acting as an intermediary and simultaneously providing access to a central data bank.

University reform: The universities are unable to spearhead this movement toward true interdisciplinary cooperation, largely because of the incentive structure that discourages scholars from devoting too much time to enterprises that do not find their rewards within the departmentalized promotion system. While this situation, by default, has left it primarily to industry and to government-sponsored nonprofit corporations to carry out interdisciplinary pioneering work, there are strong indications that the universities will undergo the necessary administrative and curriculum reforms to enable them to resume the lead in this type of research.

Publications: Scientific and technical publications, like conferences, have gotten completely out of hand, and through sheer volume they have become self-defeating. There are two principal motivating forces for publishing articles in the technical journals: the incentive structure (where again the universities are the main, but not the only, villains), and the genuine need for communication with the rest of the scientific community. In this latter regard we may, fortunately, expect some radical changes—although it may well take another decade to see real progress. Eventually, the traditional form of communication through the printed word will here be replaced by placing a record of the material to be communicated in a central data bank and making this material available to other researchers through highly sophisticated data retrieval devices.

Popularization of science: Despite the expected continuation of the explosive growth in scientific knowledge, which might on first thought seem to widen the gap of understanding between scientist and non-scientist, I venture to predict that during the 1980s, at the latest, we shall enter a new era of popularization of science. For one thing, the scientists themselves, in order to be able to communicate effectively across disciplinary boundaries, will require a certain amount of popularization of what their colleagues in other fields are doing. This process will be greatly aided by computer-controlled instruction and advanced data retrieval systems that will make it increasingly possible to extract information about an area without already having to be an expert in that area. Once such facilities are generally available and many households are equipped with consoles tied to central computers and data banks, the general public—with its expected increase in leisure time—will be ready to accept the acquisition of popularized scientific knowledge as a new hobby. This trend toward public enlightenment will be reinforced by the scientific community's desire, discussed earlier, to be more policy-oriented in its activities; for, a more thorough analysis of future societal options on their part will remain ineffective unless there is a better informed public that can exercise these options intelligently through the democratic process.

5. FUTURE SCIENTIFIC DEVELOPMENTS AND BREAKTHROUGHS

There are many substantive developments in the sciences whose occurrence can be predicted with a good deal of confidence; it is not so easy, however, to attach estimates of dates to them at which such occurrences will take place. Reproduced on the next page is a chart representing part of the outcome of an attempt to forecast such dates, which was carried out three years ago under the auspices of The RAND Corporation by T. J. Gordon and the author. These results were obtained through an application of the Delphi technique, using a panel of about twenty respondents prominent in various fields of science. The graphical display shows both the medians of their final responses and the interval containing the middle fifty percent of them (the so-called interquartile range). For example, with regard to Item 13 (creation of artificial life), one quarter of the respondents thought that this would first occur before 1979, another quarter between 1979 and 1989, a third quarter between 1989 and 2000, while the remaining quarter thought it would occur later than 2000 if at all. (The same respondents, if reinterviewed today, would no doubt wish to revise some of their estimates, particularly those referring to items where significant progress or failure has been evident in the intervening years.)

There can be little doubt, in looking over these forecasts, that in the opinion of the experts participating in that survey great stress would be placed in the next few decades on these three areas of scientific development:

- Biomedicine,
- Cybernetics,
- Resources technology.

In addition, in view of the expected reorientation within the social sciences, we may anticipate (or perhaps I should say, we may hope that we may anticipate) that

- Organization theory

may come into its own, where by this term I mean the general discipline concerned with human interactions in decision-making situations. Taken in this sense, organization theory is a direct extension of the so-called theory of games, an extension which we must urgently seek to achieve in order to deal with social conflict situations that the present theory has been unable to resolve. Any form of social intercourse, be it among persons or business firms or states, can be viewed as a game we are playing, or rather a continuing series of games, in which in some sense we strive to maximize our individual or corporate or national utilities. The next great breakthrough in the social sciences, comparable in significance to such physical-science breakthroughs as the creation of artificial life or the taming of thermonuclear energy, may well be the construction of a theory of organizations that succeeds in dealing rationally with situations of interpersonal or international conflict.

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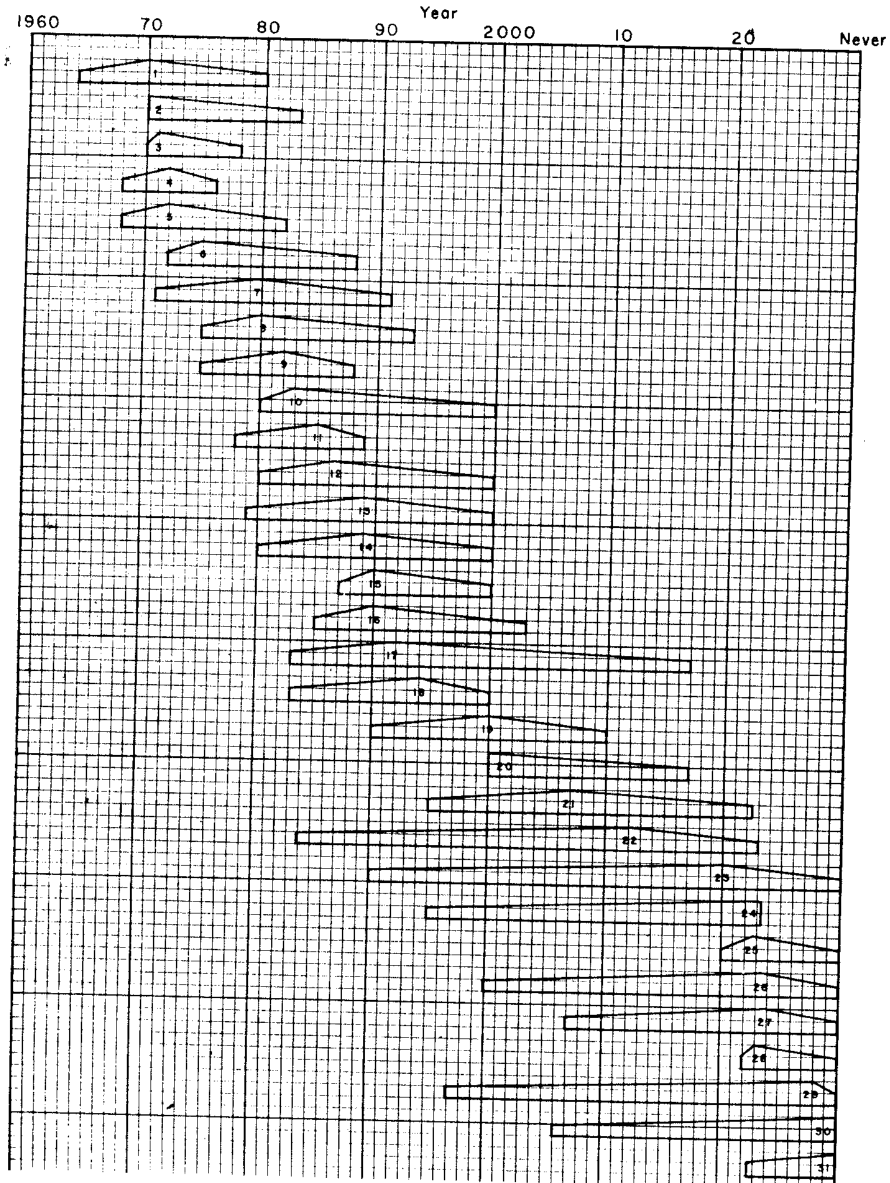

Fig. 3—Expert consensus on scientific breakthroughs
(medians and quartiles)

1. Economically useful desalination of sea water
2. Effective fertility control by oral contraceptive or other simple and inexpensive means
3. Development of new synthetic materials for ultra-light construction
4. Automated language translators
5. New organs through transplanting or prosthesis
6. Reliable weather forecasts
7. Operation of a central data storage facility with wide access for general or specialized information retrieval
8. Reformation of physical theory, eliminating confusion in quantum-relativity and simplifying particle theory
9. Implanted artificial organs made of plastic and electronic components
10. Widespread and socially widely accepted use of nonnarcotic drugs (other than alcohol) for the purpose of producing specific changes in personality characteristics
11. Stimulated emission ("lasers") in X and Gamma ray region of the spectrum
12. Controlled thermo-nuclear power
13. Creation of a primitive form of artificial life (at least in the form of self-replicating molecules)
14. Economically useful exploitation of the ocean bottom through mining (other than off-shore oil drilling)
15. Feasibility of limited weather control, in the sense of substantially affecting regional weather at acceptable cost
16. Economic feasibility of commercial generation of synthetic protein for food
17. Increase by an order of magnitude in the relative number of psychotic cases amenable to physical or chemical therapy
18. Biochemical general immunization against bacterial and viral diseases
19. Feasibility (not necessarily acceptance) of chemical control over some hereditary defects by modification of genes through molecular engineering
20. Economically useful exploitation of the ocean through farming, with the effect of producing at least 20% of the world's food
21. Biochemicals to stimulate growth of new organs and limbs
22. Feasibility of using drugs to raise the level of intelligence (other than as dietary supplements and not in the sense of just temporarily raising the level of apperception)
23. Man-machine symbiosis, enabling man to extend his intelligence by direct electromechanical interaction between his brain and a computing machine
24. Chemical control of the aging process, permitting extension of life span by 50 years
25. Breeding of intelligent animals (apes, cetaceans, etc) for low-grade labor
26. Two-way communication with extra-terrestrials
27. Economic feasibility of commercial manufacture of many chemical elements from subatomic building blocks.
28. Control of gravity through some form of modification of the gravitational field
29. Feasibility of education by direct information recording on the brain
30. Long-duration coma to permit a form of time travel
31. Use of telepathy and ESP in communications