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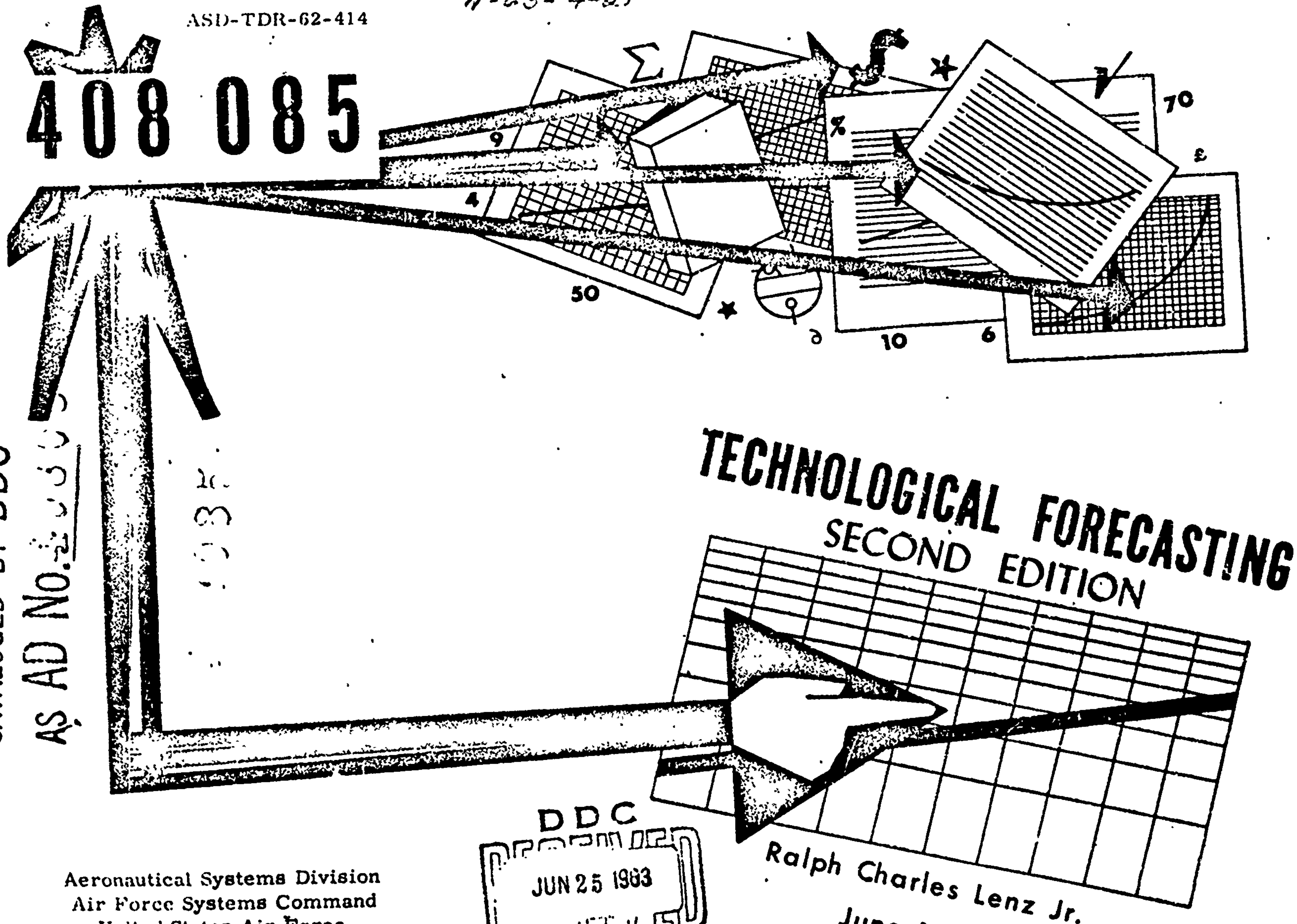

TECHNOLOGICAL FORECASTING
SECOND EDITION

Ralph Charles Lenz Jr.

June 1962

Aeronautical Systems Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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incl illus., tables.

Unclassified Report

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(over)

process of technological improvement. The investigation included a search of the literature for references to principles of technological progress which might form a basis for prediction. Included in the literature search was a review of methods which have been used for predictive purposes.

Each of the methods offers the opportunity of making a forecast of progress which explicitly predicts quantitative improvements of technical performance to be achieved at definite future times. The application of the methods presented should provide substantial improvement in long range plans not previously supported by carefully established forecasts.

1. Technological Forecasting (Methods)
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ABSTRACT

TECHNOLOGICAL FORECASTING

Ralph C. Lenz, Jr.

This study presents several methods of forecasting rates of technological advance. The methods include forecasting by extrapolation of existing rates; by analogies to biological growth processes; by precursive events; by derivation from primary trends; by interpretation of trend characteristics; and by dynamic simulation of the process of technological improvement. The investigation included a search of the literature for references to principles of technological progress and for methods which have been used for predictive purposes.

Each method of forecasting is first presented from the standpoint of the logic which supports its use for predictive purposes. This presentation includes a criticism of errors made in prior exposition or use of the method. Each method is next presented in terms of the technique used to forecast. The application of the method to typical forecasting problems is presented in general terms, followed by examples which demonstrate the use of the method in specific cases.

Each of the methods offers the opportunity of making a forecast of progress which explicitly predicts quantitative improvements of technical performance to be achieved at definite future times. The use of multiple methods for prediction of a single quantity offers confirmation of results, or alternatively, establishes a range of possible rates of progress. The forecasting methods in this investigation favor the conclusion that prediction of technological progress can be extended beyond the limits of purely intuitive processes. The application of the methods presented should substantially improve long range plans not previously supported by carefully established forecasts.

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CHAPTER I

INTRODUCTION

Technological forecasting may be defined as the prediction of the invention, characteristics, dimensions, or performance of a machine serving some useful purpose for society. The qualities sought for the methods of prediction are explicitness, quantitative expression, reproducibility of results, and derivation on a logical basis.

The prediction of invention does not require that the invention be described. Rather, the prediction is that a certain type of innovation will occur, the probable timing of the innovation, and the effect that it will have in continuing technological progress. A forecast of the characteristics of machines implies the prediction of evolutionary trends in secondary inventions and developments. As in the case of primary invention, description is not requisite to a forecast of a series of secondary inventions.

Forecasting the dimensions of machines may be defined as the quantitative description of significant dimensions of the machines at a specific future time, including prediction of the ultimate limits of these dimensions. The forecasting of performance may be defined as the quantitative description of performance capabilities at specific future dates, together with probable upper limits of performance. Finally, forecasting methods must go well beyond prediction of the characteristics, dimensions, and performance of machines which are possible within the existing state-of-the-art, since such "forecasts" are no more than engineering design.

Effective methods of technological forecasting are essential to the attainment of management goals. Such methods are even more important to society in general, in reaching decisions which will guarantee survival. In a world dominated by machines, the prediction of the future characteristics of those machines is a prominent factor in any projective action.

For any organization which has a major interest in the production or utilization of machines, the technological forecast is the first element in its long range planning. This forecast may be explicitly stated before the long range plan is derived, or it may be implied by the nature of the plan. In either case the final result of the planning activity cannot be better than the forecast on which it is based.

The forecast is inherent in decision-making. The decision to purchase a machine which is expected to have a long useful life, or the commitment of resources to the production of machines which have a long development period, require an accurate technological forecast.

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Forecasting is valueless for comparison with actual events unless it is recorded. The recorded technological forecast is a most effective warning that change is necessary. In contrast, a plan with an unrecorded forecast may be adhered to in spite of changing circumstances, since the divergence of actual events from the forecast is not detected. The recorded forecast is also useful as a standard in reviewing major commitments at critical points. Divergence of events from those forecast may be a signal for the avoidance of further commitments or the termination of the action.

The strongest reasons for development of explicit methods of technological forecasting are based on the broad influence which such forecasts have upon the minds of men. The accurate and convincing prediction of what can be done, or what will be done by others, is a most effective instrument for raising possibility to reality. In contrast, the implicit forecast is often overconservative and overlooks possible actions of others. Such forecasts lead to the emotional defense of existing activity, rather than to a reasoned examination of the actual situation. The explicit forecast removes barriers to objective thinking by pointing out where greater progress is possible and more desirable. Conversely, the explicit forecast may demonstrate lessened rates of progress. The best method of disturbing an inappropriate status quo is to produce a forecast which demonstrates the increasing untenability of such a situation. Since decisions usually tend to be made in the general direction of existing trends, one of the most potent reasons for technological forecast is to avoid the conditions of "too little--too late" and "too much--too soon."

The development and analysis of technological forecasts can be a most effective influence in the creative thought processes which are essential to dynamic management. Each projection requires careful consideration of the factors which will bring about the indicated progress. Apparent inconsistencies and barriers reveal themselves and attention may be focused on removing them. The necessity for innovation is projected well in advance and the usual procrastination is avoided.

One further advantage in technological forecasting lies in its potential for predicting a competitor's activity. Espionage or knowledge of competitive progress is necessary, but it is useful only for delayed corrective or countering action. On the other hand, an accurate forecast of the maximum rate of progress which may be made by a competitor can provide a strong incentive to achieve the same degree of technological advance.

Limitations and Arrangement

This study does not attempt to provide the final definitive word on technological forecasting. Rather, it attempts a systematic presentation of related methods of forecasting; along with the introduction of some elements and methods which are believed to be original. Although examples are offered in support of the elements and methods of prediction outlined, they are limited in number and cannot be claimed to demonstrate universal truths. No attempt is made to present an infallible, purely mechanical means of prediction, because this is not believed possible at the present time.

The study is also limited in extent of coverage of the vast amounts of statistical data which might be used to support the findings herein. For anyone who might desire to make technological forecasts in any field, the original sources of statistical data are more accurate, more voluminous, and more useful, than any quotation which could be presented in this study.

The investigation consists of three principal parts. The first part outlines the selection of the basic techniques which may be used in establishing technological forecasts. The second part consists of chapters which describe the various techniques of forecasting and their application to the problems of predicting the characteristics, dimensions, and performance of inventions.

In the third part is discussed the combination and correlation of results from the considerations of the several independent techniques. Particular attention is given to the range of variation, selection of the most probable prediction, and selection of the most useful prediction from the standpoint of its intended application.

History of Technological Forecasting

As is true of many fields of human endeavor, the technique of forecasting has been practiced as an art since before the dawn of history. The application of scientific methods has been slow due to substantial opposition. Astrology even today probably has more practitioners than does astronomy. Weather predictions of "The Farmer's Almanac" even though not seriously believed, still command a wide circulation.

The claim of divine guidance for prophecy has seldom been voiced since Biblical times. The "prophet" must still rely upon repeated success in prediction, or demonstrated accomplishment in worldly affairs, for his source of authority. Even in those areas in which some measure of forecasting success has been obtained, as in business and economics, the technique is still suspect. Thus, the very terms "prediction" or "forecast" raise immediate skepticism. The less advanced art of technological forecasting is even more suspect.

Although the history of overall forecasting has a relationship to the subject of technological prediction, it is not possible to outline that history within this framework.

At the initiation of this study, the author believed that the forecasting of population growth and economic trends would provide useful analogies for the development of technological forecasts. Upon examination, however, of some of the accepted authorities in the field, notably Pearl ① and Kuznets ②, certain

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① Raymond Pearl, The Biology of Population Growth (New York: Alfred A. Knopf, Inc., 1925).

② Simon S. Kuznets, Secular Movement in Production and Prices (Cambridge, Mass.: The Riverside Press, 1930).

weaknesses of theory became evident. Thus, these methods require substantial correction if they are to be used as the basis for forecasting population growth, economic increase, or technological progress. Most noticeable as a weakness in Pearl's work is the mechanistic method used in fitting a logistic curve to various sorts of growth processes. The values of the constants assigned to the equations of these curves are determined by a least squares fitting of the curve to the data points of the growth process. No attempt is made by Pearl to determine a logical variation of the constants from one growth process to another, nor to suggest a functional relationship of the formula to the growth process. For these reasons, the forecasting technique suggested by Pearl is completely inadequate in predicting inflection points of the growth process, and provides accurate prediction only when maturity in growth is well established. Nevertheless, Pearl's treatment is useful in providing insight into growth processes in technological progress.

In Kuznets' work, the weakness of arbitrary curve fitting is repeated, compounded by the indiscriminate application of the "growth curve" to phenomena which are not in any way analogous to the processes of growth. At best, many of the sets of data to which Kuznets applies the "growth curve" are only second or third derivative evidences of growth. Other sets of Kuznets' data represent no more than a fairly regular phenomena of accretion within expanding boundaries.

To the extent that the weaknesses can be tolerated or overcome, analogies of these methods are presented in later chapters. At the very least, the use of these methods forces an examination of prior rates of progress which provides information on possible future rates of progress.

The works of S. C. Gilfillan ③, ④ on the prediction of invention are the best of the few references on the specific subject of technological forecasting. In "The Sociology of Invention," Gilfillan specifies 38 principles of invention which afford a potential framework for the prediction of technological progress. ⑤ However, he makes no attempt to project this framework in a quantitative manner, suggesting, at the most, no more than the sequential order of events for progress.

An infinite number of implicit forecasts might be developed by inference from the actions of individuals, businesses, and nations. In addition, there exist a finite, but large, number of explicit forecasts on technological progress abundantly scattered in the general and technical literature. In most such forecasts the technique used for forecasting is not defined and may only be inferred. Such inference usually leads

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③ S. C. Gilfillan, "The Prediction of Invention," U. S. National Resources Committee, Technological Trends and National Policy (Washington, D. C.: U. S. Government Printing Office, 1937).

④ S. C. Gilfillan, The Sociology of Invention (Chicago: Follett Publishing Co., 1935).

⑤ Ibid., pp. 5-13.

to the conclusion that such forecasts are purely intuitive. Thus, even when the forecasts are correct, no basis is available upon which to build a methodology. In a rather substantial number of predictive articles, some graphic or numerical method is used to extend historic trends. The methods used for extrapolation show little understanding of the implications of the methods.

The random choice of predictive methods offers evidence of the absence of information on the subject of technological forecasting. D. W. Male has concluded from a study of over 200 forecasts in the field of aviation, that, "Of the predictions containing both a valid trend element and a time element, less than one-third were judged valid concerning the time element." ⑥ It is apparent from Male's study that systematic methods, capable of consistently accurate prediction, have not been used by aviation forecasters.

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⑥ Donald Warren Male, Prophecies and Predictions in Aviation (Mass. Inst. of Tech., Cambridge, Mass.: Unpublished Master's Thesis, 1958).

CHAPTER II

FRAMEWORK OF THE TECHNOLOGICAL FORECAST

In developing a framework for technological forecasting it is useful to consider some of the arguments offered against forecasting. The most common argument against forecasting is that nobody is able to foretell the future with certainty. In support of this opinion, it is argued that most forecasts have been in error. This indictment of forecasters is softened by the fact that events change so swiftly that the probability of an accurate forecast is quite low. Also, action based on predicted circumstances is extremely expensive, and is therefore a poor basis for trust or investment. Finally, forecasting is frequently condemned on the paradoxical argument that the specific prediction is demonstrably false.

These arguments cited against forecasting may best be answered by looking at some postulated conditions of no-forecast, their implications, and the errors associated with each. The simplest is the literal situation of no forecast, which implies that each action taken is unrelated to any past experience, present situation, or future intended action. The price of this insanity is non-survival, yet it is practiced to some degree in organizations prone to frequent changes in management. The obvious error in a "no-forecast" is that all action is random, limited only by the extremes of possible alternatives.

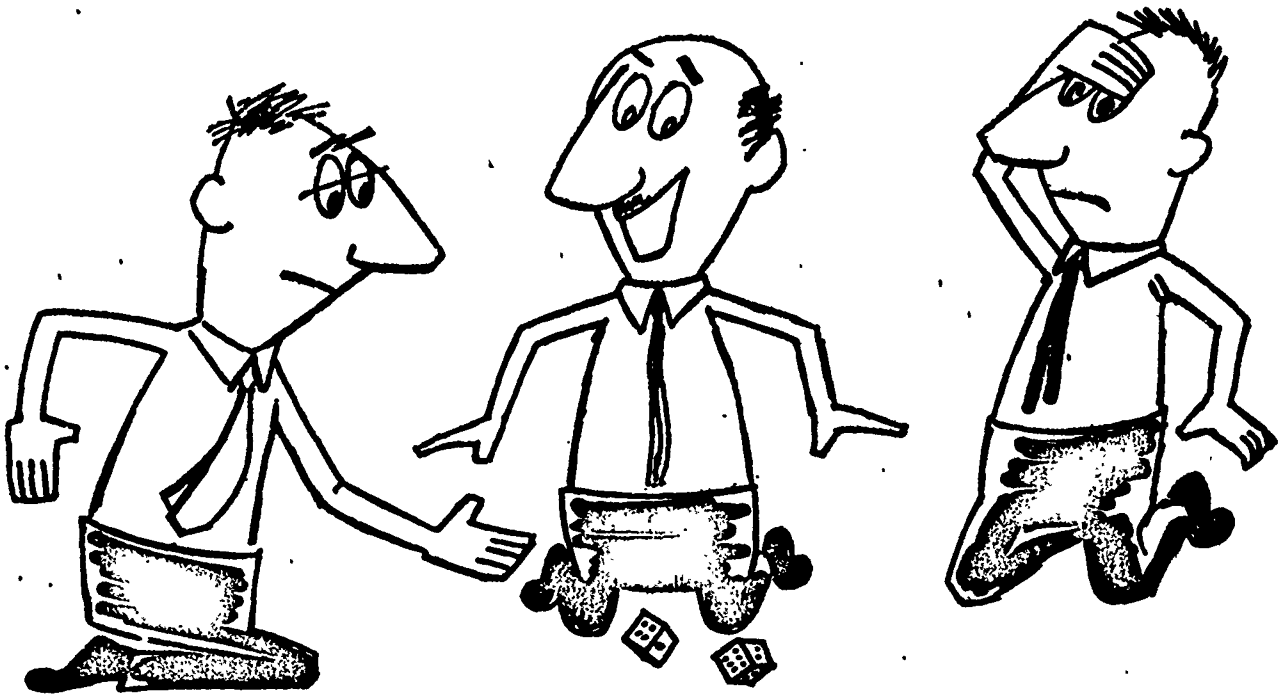
Closest to the literal situation of no-forecast is the point of view that external influences are random processes, with the implication that decisions represent a gamble, with some knowledge of the odds and stakes. In business the consequence is success when a favorable run is experienced, and self-excused failure when the run is "unlucky."

An occasional type of forecast is that in which action is based on an assumed continuance of prior circumstances, which no longer exist. This forecast implies that the "glorious past" is an accurate description of future expectations.

Much more common is the implicit forecast based on the assumption that current circumstances will continue. Obvious signs of an forecast of this type are the continual attitude of crisis, and abrupt reversals of decisions with each change in external circumstance. An example of this situation is the linking of research expenditures to a current sales of profit position. Even when this method of operation is explicitly stated as part of management policy, it is seldom recognized that this actually constitutes a forecast.

The most popular of the unrecorded and unrecognized forecasts is the assumption that existing trends of change will continue. Operations based on this type of implicit forecast are evidenced by goals of the "higher, faster, further, larger, better, and more" description. The errors of judgment arising from un-

Figure 1.



ANYTHING CAN HAPPEN

Figure 2.

Figure 3.

Figure 4.

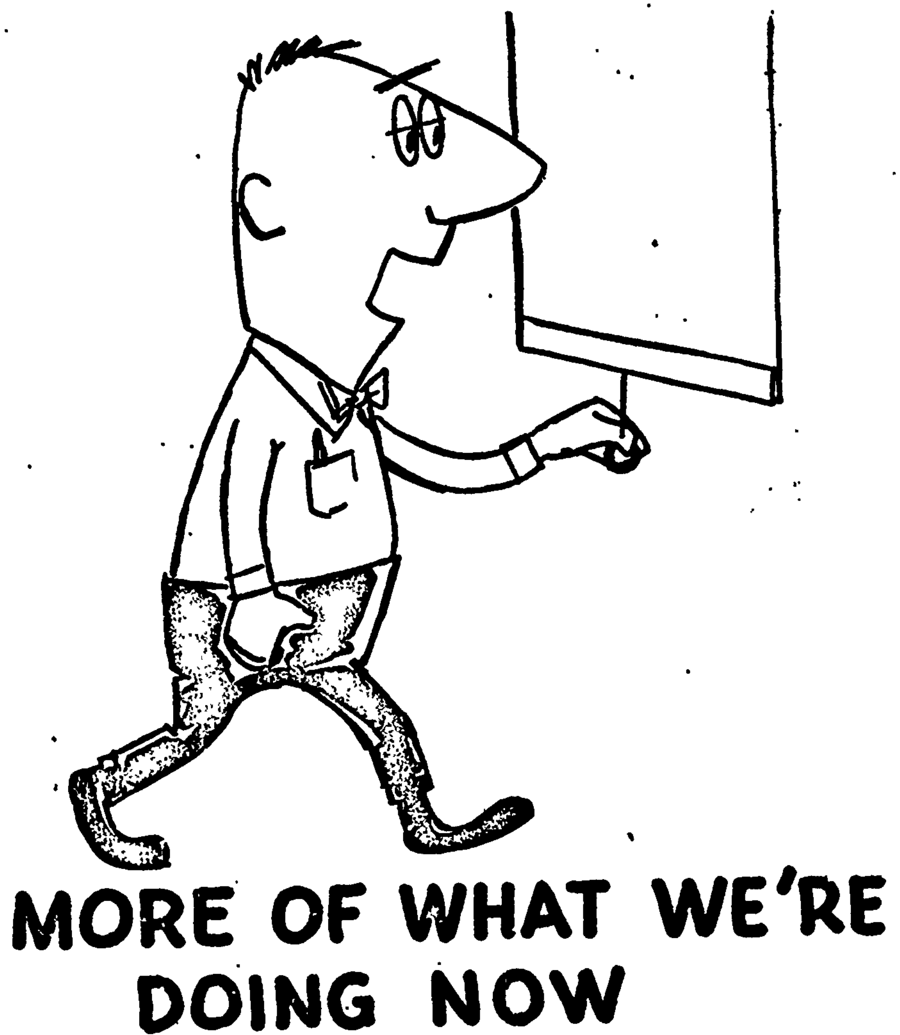
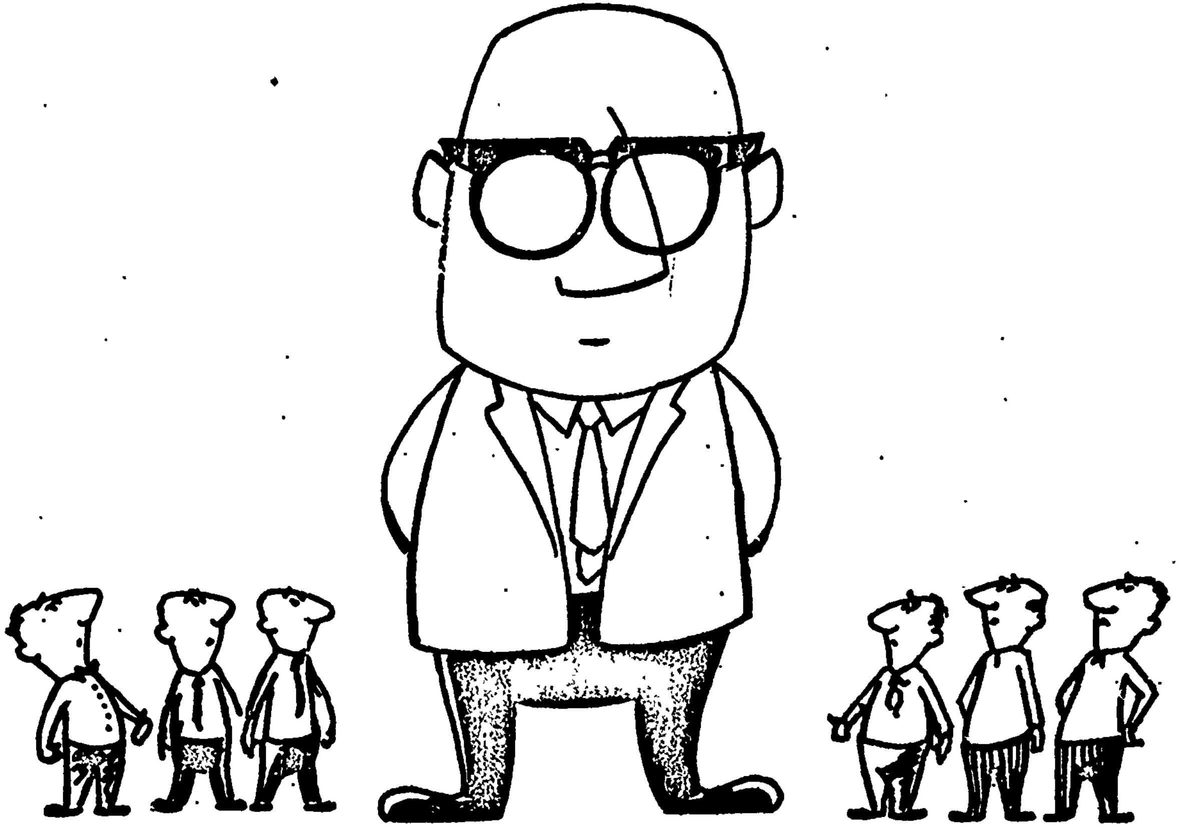


Figure 5.



GENIUS FORECASTING

Figure 6.

critical acceptance of ambiguous forecasts are usually unrecognized, because the unrecorded forecast is difficult to reconstruct after changes in circumstance have intervened.

Related to the assumption that present trends will continue, is the adoption of a course of action based on an intuitive feeling about future conditions. Although this is the most submerged of the various implicit forecasts, it is nevertheless effective in guiding the actions of many successful men. The existence of this type of forecast is easily demonstrated by a pattern of decisions which have anticipated future situations. However, practitioners of this type of forecasting may be vociferous in their opposition to defining and recording the predictions involved. Intuitive forecasting has great weaknesses that may be easily overlooked; it is impossible to teach, expensive to learn, and excludes any process of review.

While forecasting in general was considered here, the statements made are applicable to the case of technological forecasting. Effective forecasting of technical progress is a necessary part of today's managerial decisions. The race for progress is one on which bets must be placed, and from which there is no abstaining. Indeed, most managers cannot even control the magnitude of their betting, since it is closely linked to the net worth of the segment of the economy over which the manager exercises control. Since some estimate of future conditions is inherent in each managerial decision, the actual question is whether such an estimate should be made unconsciously as an implicit part of the decision, or whether it should be arrived at deliberately and stated explicitly. The principal reason for an explicit forecast is to place it in one of the categories detailed above, so that its validity may be tested. The explicit forecast offers the additional advantage of revealing the method, data, and premises used in making the forecast.

Techniques of Forecasting

In explicit forecasting, extrapolation is usually involved in some manner. Any general theory of extrapolation is obviously based in some manner upon that which has happened in the past. If the extrapolation is called engineering design, dependence on the past is expressed in forecasting that the repetition of certain acts will produce the same result as those same acts have produced in prior experiment. A reasonable extension of the quantities used in prior experiments is permitted, with an attendant extrapolation of the results expected. Similarly, as in weather forecasting, when certain conditions have usually developed from a given prior set of circumstances, the extrapolation can be made that the same sequence of events will probably occur again. The problem in developing methods of technological extrapolation is to determine what prior circumstances are significant to probable future occurrences; and then to determine what extension, translation, or transformation of the prior circumstances will convert them into a prediction of the probable future.

The most obvious method of technological forecasting is to assume that whatever has been happening in the past will continue to happen in the future, provided there are no disturbances. The problems to be

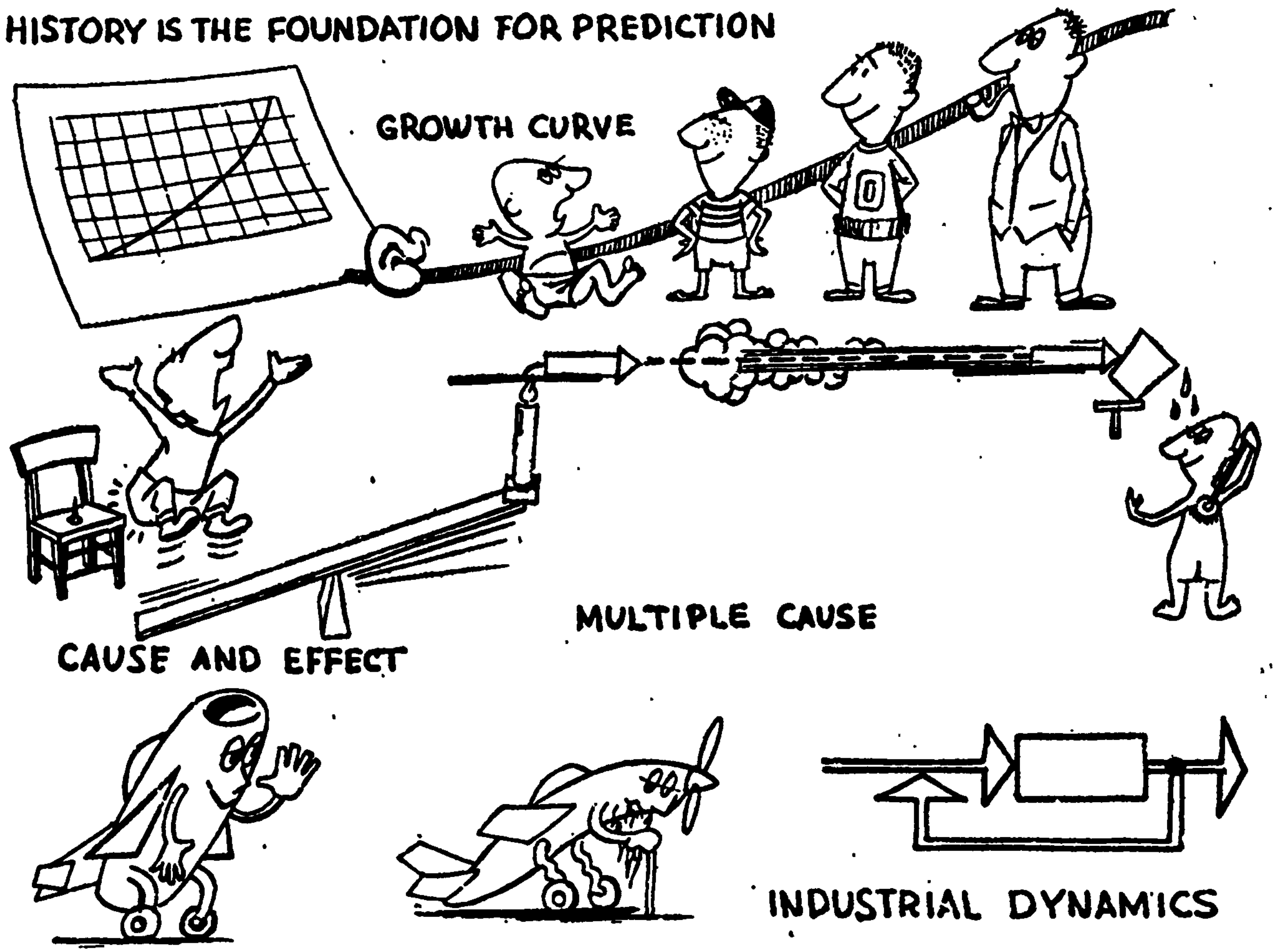

HISTORY IS THE FOUNDATION FOR PREDICTION
GROWTH CURVE
0
CAUSE AND EFFECT
MULTIPLE CAUSE
INDUSTRIAL DYNAMICS

Figure 7.

solved in using this technique consist principally in knowing and defining accurately just what has happened in the past, and in determining the tolerable magnitude of disturbing influences. Implicit in the definition of what has happened are the rate of occurrences and the rate of progress during a period of time. The development of methods of forecasting by extrapolation, is contained in Chapter III.

Because there are disturbing influences which change the course of events from the trend of the past, the logical first step in improvement of the simple forecast is the adjustment for such influences. However, disturbing influences frequently loom so large in the mind of the forecaster as to create greater errors than would exist if extrapolation formed the sole basis of the forecast. Because of this, and because the forecast of unknown disturbances is at least as difficult as the original problem, the use of analogies to estimate the cumulative effects of future disturbances is often suggested as a basis for prediction. The work of Pearl ① in the biology of population growth has been cited by Kuznets ② as an analogy for secular movements in production, and by Dewey and Dakin ③ in an exposition of methods of economic prediction. The application of these analogies to the problem of technological forecasting, together with notes on the limitations of the method, is explained in Chapter IV.

Causal Relationships Between Events

In further development of the forecasting framework, the employment of causal relationships between two courses of events may be considered next. The use of this method of forecasting has been thoroughly described in most studies of cyclical economic movements. For example, the influence of the inventory accumulation cycle upon the level of overall economic activity has frequently been used in economic forecasting. A logical extension of this method is prediction of the trend of a dependent variable as a function of the trends of two or more independent variables. This technique has greatest utility when the trends of the independent variables are well established, easy to extrapolate, generally agreed upon, or are simply available in the form of statistical data. In contrast, the trend of the dependent variable may be of recent origin, of irregular nature, controversial, or not easily acquired from conventional sources of information. The use of interdependent relationships as a forecasting technique is developed in Chapter V.

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① Raymond Pearl, The Biology of Population Growth (New York: Alfred A. Knopf, Inc., 1925).
② Simon S. Kuznets, Secular Movements in Production and Prices (Cambridge, Mass., The Riverside Press, 1930).
③ Edward R. Dewey and Edwin F. Dakin, Cycles--The Science of Prediction (New York: H. Holt and Company, 1947).

Significant Characteristics in Trend Curves

Prediction of technological progress on the basis of significant characteristics in trend curves offers substantial promise in extending the capabilities of the technological forecaster. The characteristics of trends as natural limits to progress are approached, and as rates of progress decline, signal the approach of major changes in technology. This method affords a basis for prediction of the likelihood of new inventions, the probability of new industry arising, the types of new inventions likely to be made, and a prediction of the pressures for innovation. These uses of trend characteristics for predictions are described in the final part of Chapter V.

The development of a method of technological prediction based on the technique of "Industrial Dynamics" is described in Chapter VI. ④ In this method of prediction technological progress is based upon mathematical expression of the influence of those factors over which control may be exercised. These factors include the numbers of people trained for a given research and development function, the number of people employed to perform that function, and the facilities provided for experiment. The effect of each of these factors, and the feedback relationships, are combined in equations which provide a prediction of the technological progress to be obtained from a given input of the factors involved. The greatest difficulty in this method of technological forecasting is the determination of the transfer coefficients which relate quantities of the input factors to the quantities in which technological progress is measured. In most cases the transfer coefficients will necessarily be based on the empirical relationship which has existed in the past between the input and output factors.

The framework for technological forecasting is completed in Chapter VII, by considering the combination of the various means of prediction. Such combinations may be used to provide a range of probable technical progress, if the resultant variation is sufficiently small. Alternatively the combination may provide a single, most probable, estimate of future progress. The way in which large variations in predictions by different methods may be used to determine the possibility and nature of sudden changes is developed to some extent. Finally, consideration is given to selection of methods of prediction on the basis of the purpose of the forecast.

The six methods of forecasting, and the combined use of these methods, as described in the following chapters, provide a consistent development of technological prediction.

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④ Jay W. Forrester, "Industrial Dynamics--A Major Breakthrough for Decision Makers", Harvard Business Review, Vol. 36, July--August 1958.

CHAPTER III

FORECASTING BY EXTRAPOLATION

A most common method of forecasting is the extension of some form of time-series on the basis that existing trends will continue. Although it may be argued that this is not a very accurate method of forecasting technological progress, nevertheless it is, and will probably continue to be, widely used. Most of the intuitive forecasts of progress are probably based on subconscious versions of this method of prediction.

The basis for this method of forecasting technical progress in our society may be found in the characteristics of our culture, defined by Sorokin as follows; "For the last four centuries we have had a rising tide of the truth of senses, the contemporary scientific truth." ① Sorokin continues on from this point to show a correlation between his measurements of the increase of empiricism and the increasing number of scientific discoveries made each century since the 15th. ② The continuity of this pattern of scientific advance is inherent in the background of anyone with enough knowledge to attempt a technological forecast today. Therefore it is almost inevitable that the forecaster operating without conscious method will predict progress in the future as an extension of progress in the past. Furthermore, even if the method of forecasting is consciously selected, it is still likely to reflect the forecaster's inherent feeling that technological advance will follow the patterns of the last four centuries.

Definitions. The method of forecasting by extrapolation of time series will continue to be used, it is not without validity, and other methods of forecasting are derived in some measure from the same underlying principles. For these reasons it is desirable to give some thought to development of the method. Key elements in such development are the functional meanings given to the words "extension," "time-series," "existing trends," and "continue."

The generic definition of "time-series", as being a series of measurements of a quantity over a period of time, needs qualification before it may have meaning in technological forecasting. Obviously, the quantity which composes the time-series must have technological significance, i.e., it must bear some relationship to the characteristics, dimensions or performance of a class of machines. The greater the technological significance of the quantity is, the sounder will be the use of the time-series for technological prediction.

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① Pitirim A. Sorokin, Social and Cultural Dynamics, Vol. II (New York: American Book Company, 1937).
② Ibid., pp. 38-39.

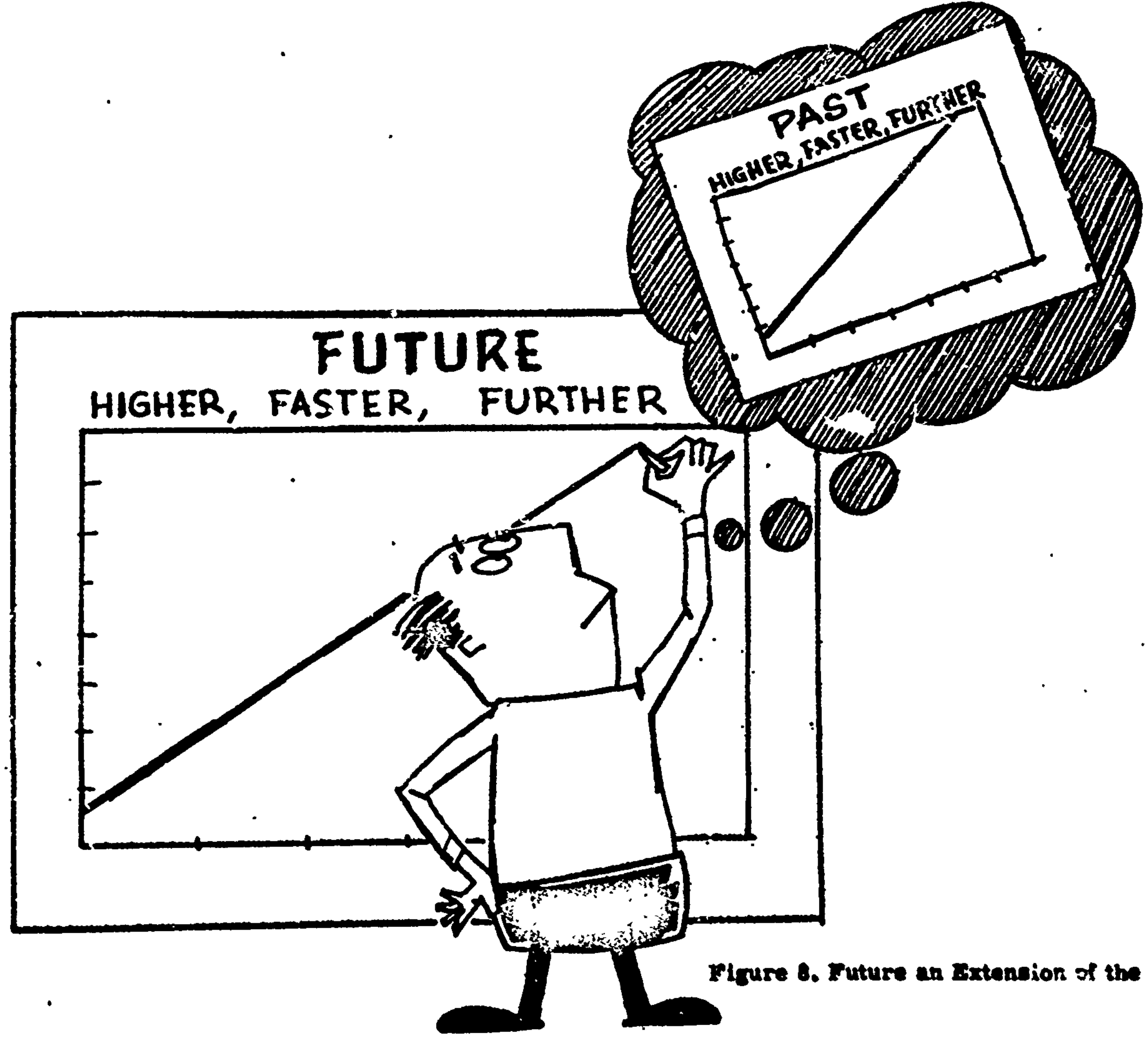

Figure 8. Future an Extension of the Past

"EXTENSION"

"TIME SERIES"

"EXISTING

TRENDS"

"CONTINUE"

Figure 9.

The converse is equally true, if the quantity is only indirectly related to technical progress, its time-series will not provide a good basis for prediction. For example, as long as increasing locomotive power provides economic benefits, the time-series of locomotive horsepower will provide a sound basis for forecasting the future trend of locomotive horsepower, since it is unlikely to be influenced by whim, fancy, or other random factors. On the other hand, the time-series of overall length of automobiles, which might be suggested as a basis for a forecast, would be unreliable, since it depends upon the fashion preferences of the buying public and of the producers, which are subject to abrupt reversal. ③

Further qualifications of the usage of time-series for prediction include the limitation that the time-series must be reasonably complete. A time-series which includes only some fraction of the total history of the quantity involved may give spectacularly misleading impressions. For instance, a prediction of automobile horsepower based on a time-series covering the decade 1948 to 1958, which represented the period of the "horsepower race", would give results substantially different from those predicted on the basis of a time-series covering the entire period of development of the automobile. To the extent that increased "horsepower" has been a response to demands for greater utility, the longer time-series provides the better basis for prediction. Much better knowledge of all the forces which affect the prediction may be secured by examining the entire time-series for forces which have affected it in the past.

The time-series can be meaningful for prediction only if the entire time-series describes the same sort of universe. For example, the time-series for the passenger capacity of aircraft used for commercial transport originally covered only those transports designed for carrying passengers between major cities on the trunk-line routes. If this time-series is to be meaningful for prediction, it must continue to be limited to aircraft designed for the same purpose. Therefore, the passenger capacities of aircraft for feederline service, of helicopters, and of inter-continental service aircraft, cannot be added indiscriminately to the data comprising the time-series.

Qualification of the time-series should also include consideration for the influence of the individual measurements whose sums comprise the time-series. In illustration of this point, the measurement of average maximum horsepower for passenger cars may be defined as the average obtained by dividing the sum of the horsepower ratings of all models by the number of models. This will strongly over-state the average horsepower selected by the buying public, since the high-horsepower models selected by few buyers have the same influence on the average as the medium and low horsepower models selected by the large majority. This qualification is particularly important where the measure of progress is a quantity which must be compromised in design by other quantities. In such cases, a few freaks can always be designed or built which would maximize one quantity at the expense of others. The inclusion of this performance in a time-series, on the false assumption that it represents technological progress, can seriously

③ Dwight E. Robinson, "Fashion Theory and Product Design," Harvard Business Review, Vol. 36, No. 6, (November-December 1958), pp. 135-137.

distort the trend. Appropriately weighted averages of performance actually sold or delivered will provide a more useful time-series for predictive purposes. Using the previous illustration, the average obtained by dividing the sum of the horsepower ratings of all passenger cars sold, by the number of cars sold, will provide a more reliable time-series of average horsepower than the method previously cited. If this seems so obvious as not to require comment, it may be noted that trade journals and technical magazines are prolific sources of time-series composed of unweighted averages.

The meaning of the term "existing trends" is closely related to the meaning of the term "time-series," to which it applies. If all the limitations assigned previously to time-series are accepted, then "existing trends" means that curve which "best" describes the data comprising the time-series. "Best" for the purposes of prediction must include some regularity which will enable extrapolation. A curve perfectly fitted to all points, which has no apparent pattern, is useless for prediction since it cannot be projected. A repetitive cyclical pattern, although not of major interest in technological forecasting, is an example of regularity useful in forecasting. A regular increase evidenced by a time-series may be used as a basis for predicting a continuation of the same regular increase. If the total history of the time-series represents all the forces which have influenced the trends, then the "best" curve will be that which describes the influence of these forces over the entire period.

Consideration of the term "extension" follows naturally from the definition of "existing trends." In forecasting by extrapolation, any extension of an existing trend is limited by definition to a simple extension. Thus the introduction of causal factors of change, rules for changes in trends, or the application of bias by the forecaster, constitute different methods of forecasting. As such, these additions may be valid, but the forecast may no longer be considered the result of trend extrapolation. It is the author's impression that many forecasts which started out to be a simple extension of the existing trend, have been subsequently altered by the forecaster on one of the bases noted above. Such alterations have frequently caused greater errors in the prediction than would have resulted if reliance had been placed on the original extension. "Extension," then, is defined as projection of a regularity in the existing trend of a time-series of some technological parameter of progress.

Finally, in this definition of forecasting by extrapolation, the meaning of the word "continue" needs to be considered. In technological forecasting no guarantee can be given that even the most regular pattern of progress will continue indefinitely. However, the question to be answered by the forecaster does not require this guarantee, desirable as it might be. The forecaster is required to predict that rate of progress which, on the basis of available evidence, is more probable than any other. In forecasting by extrapolation, two basic assumptions are made. One, that those forces which created the prior pattern of progress will be more likely to continue than to change. Two, that the combined effect of these forces is more likely to extend the previous pattern of progress than it is to produce a different pattern. In the absence of knowledge of some probable change in the controlling forces, the first assumption is reasonable. Similarly, in the absence of knowledge of the relationships among the controlling forces, the second assumption is the best that can be made. As the forecaster extends his projection of existing trends farther and farther into the future, the greater becomes the probability that one of these two assumptions will become invalid.

These definitions and limitations indicate the meaning of forecasting by extrapolation. Acceptance and usage of this method of forecasting probably is based on an intuitive feeling regarding the nature of invention and progress. This feeling has been expressed by Gilfillan as follows, "What is called an important invention is a perpetual accretion of little details, probably having neither beginning, completion, nor definable limits, ... An invention is an evolution, rather than a series of creations, ... An invention is essentially a complex of most diverse elements." ④ The evolutionary accretion of details, arising from a complex of diverse elements, suggests a regularity of technological progress which might be expected to continue so long as no major events occur to disturb such progress.

Technique. The parallelism of biological evolution and technological evolution provides a rationale for the use of extrapolation in forecasting. In this analogy, the introduction or "invention" of a major machine, such as the automobile, may be considered the equivalent of a mutation which produces a new species. In this case, the progenitor of the automobile mutation might be considered to be the steam locomotive. Then subsequent improvements in the machine would follow the path of evolution, with continued improvement in the functional characteristics of the parts of the machine. This improvement occurs in a manner analogous to that by which evolution produces functional changes in successive generations of the biological organism so as to enhance its survival. Biological evolution produces changes in the appearance, size, and capabilities of a species. In a similar manner technological evolution produces changes in the characteristics, dimensions, and performance of a class of machines. In both cases the forces which produce the changes will tend to act continuously in the same direction, so that observed patterns of change may be reasonably expected to continue.

Using the evolutionary analogy as a basis for forecasting technological progress the techniques of forecasting by extrapolation may be considered. The first step is selection of the quantity whose time-series is to provide evidence of existing trends. The quantity selected must be technologically significant, and accurate data covering the period of development must be available. Unfortunately, one of the most accurate sources of performance data, the national or world records of performance, are frequently useless for technological predictions. Such records are achieved under arbitrary rulebook limitations which penalize technical advances made in the "real world," where competitive forces operate freely. For example, while the actual technological improvement of aircraft has been directed toward obtaining high performance

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④ S.C. Gilfillan, The Sociology of Invention (Chicago: Follett Publishing Co., 1935), pp. 5-6.

INVENTION IS EVOLUTIONARY

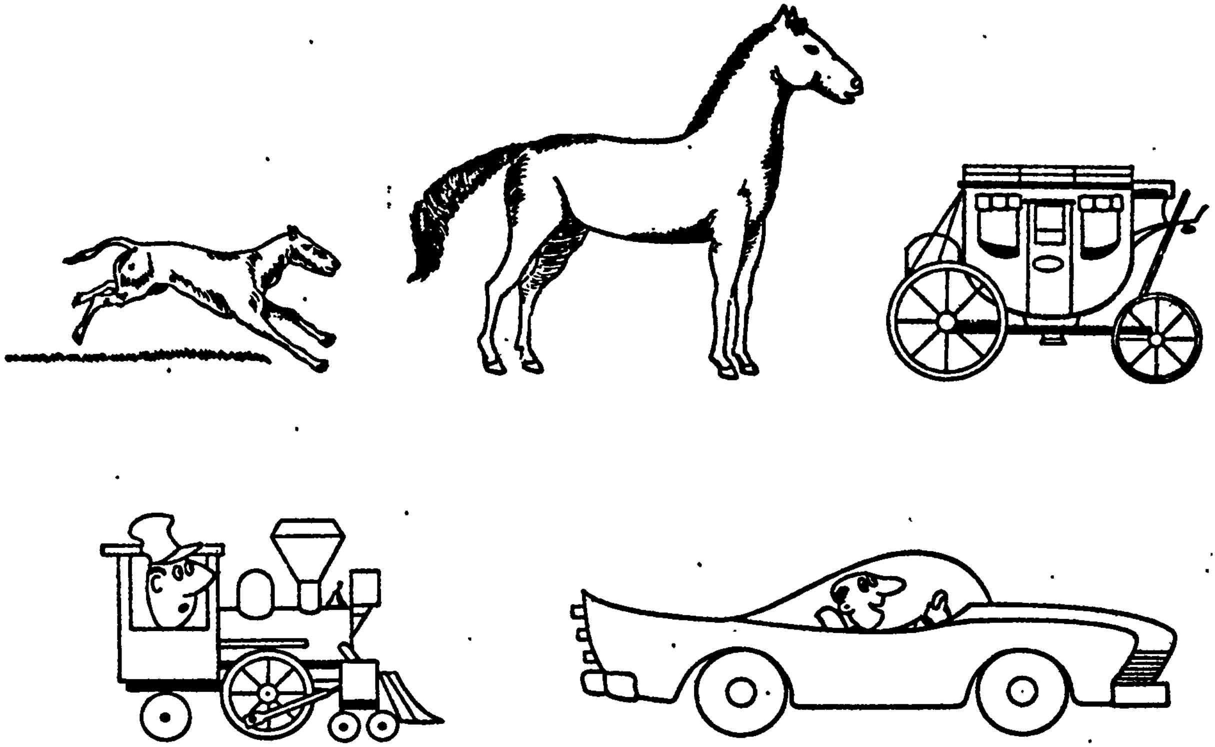

Figure 10.

at altitude, an arbitrary rule was imposed requiring the world speed record to be set on the basis of sea-level conditions. In spite of this fact, and others which limit the utility of world speed records for aircraft as a measurement of existing trends of aeronautical progress, this time-series has been used repeatedly for predictions in the field of aviation.

After the time-series has been selected, the next step is the identification of existing trends. In a society which is expanding exponentially, the accretion of technological details appears also to occur exponentially. In turn this logarithmic accretion of details is apparently responsible for a similar geometric increase in the rate of technological advance. This geometric rate of advance has been frequently noted by commentators on the subject of scientific and technical progress. On this basis, the best procedure for identifying existing trends begins with plotting of the time-series on semi-logarithmic graph paper. Then, the straight line which best fits the data of the time-series will represent the existing trend of exponential progress. If no straight line can be found which offers a reasonable approximation to the time-series, then the relationship of the time-series to the type of scientific progress described above may be questioned. In this situation the fitting of some arbitrary curve to the data cannot be supported on the basis of the hypothesis of logarithmic progress.

Having established the existing trend of the selected time-series, the first step in forecasting is the extension of the existing trend into the future. The regularity of a simple exponential curve affords easy projectability, with assurance that the projection is actually a continuation of the existing trend. The use of semi-logarithmic graph paper for plotting the time-series adds mechanical simplicity, since the straight line, representing exponential increase, may simply be extended to represent continuation of the trend.

At this point in forecasting technological progress, the forecaster who is aware of the effort required to achieve the future performance indicated by the logarithmic curve will usually conclude that the existing trend cannot be continued. Present limitations will be used to demonstrate that the rate of progress in the future will be less than the current rate. In extreme cases, the conclusion will be drawn that the rate of progress will become asymptotic to some near-term upper limit of capability. This situation has been described by F.H. Clauser in the following manner:

"In years gone by, studies aplenty have been made foretelling the future trends of speed and size of aircraft, powers and weights of engines, range and capabilities of radars, and so on. Occasionally, some devilish individual takes the trouble to go back and compare past predictions with later reality. Invariably, he finds that engineers and scientists are a conservative lot in their predictions. The immediate problems that confront them appear so formidable that they flinch from predicting ever-accelerating progress and conjure up visions of a natural barrier ahead which will cause the curve of progress to flatten off much as a biological population comes into equilibrium with its environment." ⑤

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⑤ F.H. Clauser, Magnetohydrodyamics: A Prophecy, an informal paper, NAS-ARDC Special Study Group, National Academy of Sciences, 1957.

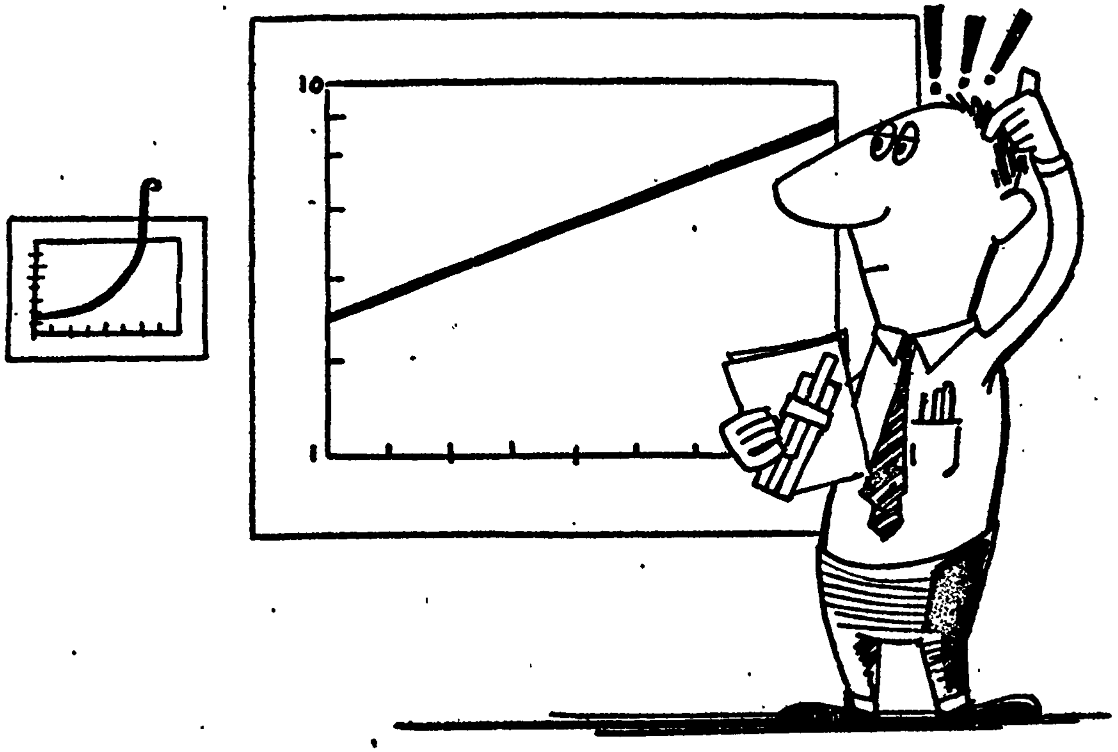

Figure 11. Exponential Progress

However, if the forecaster will adhere to a prediction based on the continuation of existing trends, he will find that the supposed limitations are often overcome, and that the past rate of advance is indeed continued. If predictions of the maximum speed of aircraft are used as an example, then adherence to the existing trend at any time after 1930 would have produced a more accurate forecast than those forecasts which were based on knowledge of the limitations to be overcome. For example, the predictions by Hunsaker in 1940, of world speed records for aircraft, were exceeded by 67 mph in 1945 and by 90 mph in 1948, even though these records did not actually represent maximum aircraft performance at the time they were established. ⑥ Also, the prediction of E.H. Heinemann, in a paper presented at the Fifth International Aeronautical Conference in June 1955, of airplane high speed vs. time, was exceeded by 250 mph in 1958, on the basis of the world speed record of 1404 mph set by the Lockheed F104. ⑦ If forecasts based upon limitations to the continuance of existing rates of progress cannot be relied upon even when made by men of such eminence as those cited, then the case against the use of such limitations in forecasting is fairly complete.

If then, extension of a simple exponential curve, representative of the existing trend, is taken as the basis for prediction of technological progress, the remaining element is the extent of continuation of the trend. No rule for "cutoff" of the prediction can be given. A forecast further into the future than the length of time covered by the time-series, would imply a continuance of the forces which created the existing trends for a period longer than their previous existence. While this is not impossible, nevertheless it seems that the probability of trend continuance is reduced beyond this point where the time covered by prediction is equal to the time covered by the existing history of the trend.

Application of the techniques outlined above may be demonstrated by the following examples. The forecasting of design characteristics is shown in figure 12 by the example of the trend of the ratio of wing-span-to-length for U.S. Army and Air Force aircraft. This trend is significant in that it demonstrates the evolutionary nature of aircraft design as the wings become less and less prominent. The forces producing this evolution include increases in power which make large wings less necessary to sustain lift, accompanied by the drag penalty of large wings as maximum speeds are increased.

The forecasting of the change in dimensions of a class of machines over a period of time is shown in figure 13. In this case the gross weight of single-place fighter aircraft is shown as a function of time. The trend of this dimension is a significant indication of the increasing complexity of this type of airplane and also of the evolution of the machine under the force of high performance requirements.

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⑥ Jerome C. Hunsaker, "Research in Aeronautics," National Research Council, Research -- A National Resource Vol. II Industrial Research Sect. III. (Washington, D.C.: U.S. Government Printing Office, 1941)

⑦ E.H. Heinemann, Design of High Speed Aircraft, Preprint No. 563 (New York: Institute of the Aeronautical Sciences, 1955).

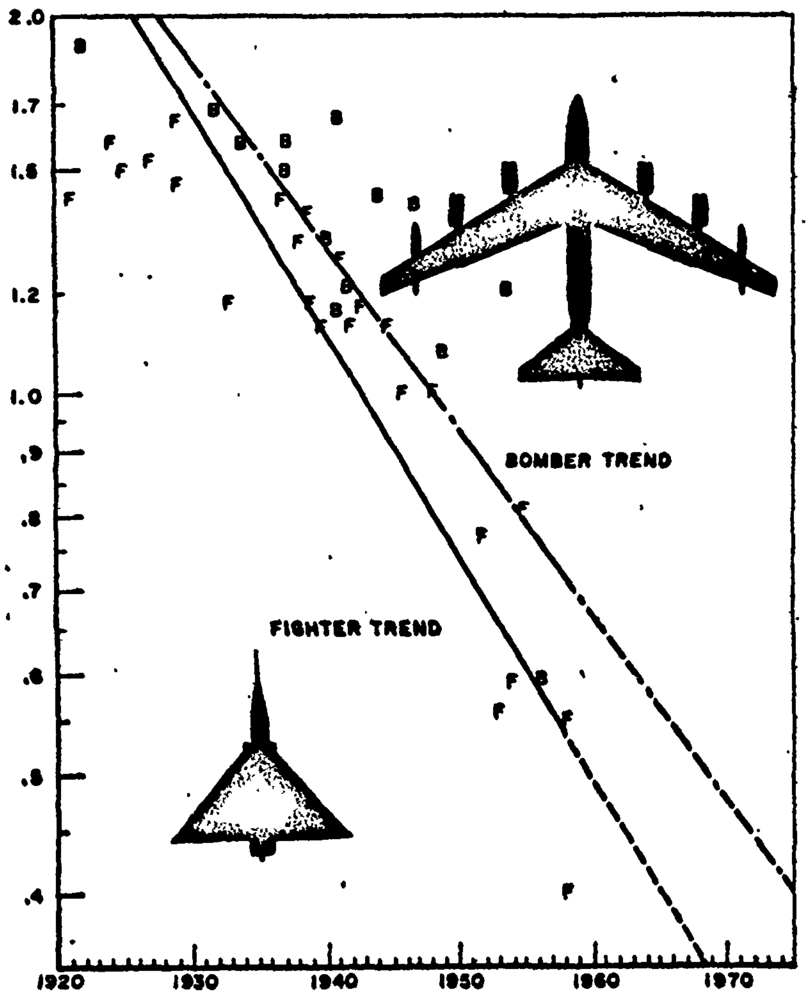

Figure 12. Ratio of Wing-Span-To-Length for U.S. Combat Aircraft

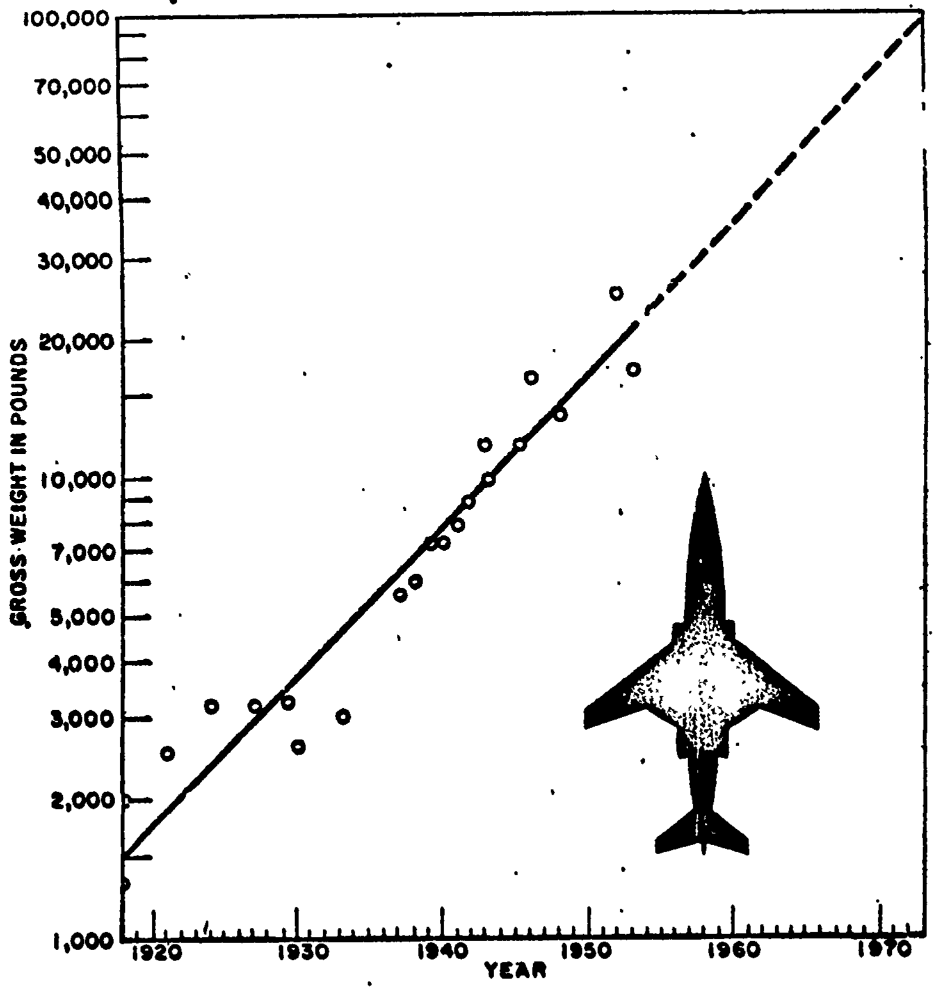

Figure 13. Gross Weight of U.S. Single-Place Fighter Aircraft

The prediction of the performance of a class of machines is shown in figure 14. In this instance the speed trend of operational fighters and bombers of the U.S. Army and Air Force is shown and predicted. Since improvement in this parameter of performance has continuously represented a major objective of aircraft design, it demonstrates very well the exponential increase in progress arising from the accretion of detail inventions. Even the introduction of the jet engine as a propulsion force did not disturb the apparent trend, but instead contributed to its continuation.

Prediction of Invention - This type of prediction can be used to forecast inventions through the examination of forecasts of design characteristics by which an estimate may be made of the time at which evolution will produce a substantially different type of machine. As this time approaches and passes, the probability increases that a major invention will produce the different type of machine. Alternatively, an invention already made may become sufficiently developed to displace the original machine on an operational basis. For example, as shown by figure 15, when the wing becomes a smaller and smaller part of the airplane, the airplane more and more closely resembles a ballistic rocket. Thus it may be predicted that, at the point of virtual disappearance of the wing, that the ballistic rocket as an operationally successful invention will completely replace the airplane. ⑧

The prediction of invention on the basis of a forecast of machine dimensions may be made if the change of a given dimension will force the invention of some other machine to accommodate the change. For example, the increase in gross weight of aircraft has forced the development of new types of ground-handling equipment. The importance of prediction in this respect is that the dimensional trend may signal for the occurrence of the invention well before it actually becomes a necessity.

The prediction of invention on the basis of performance forecasts offers a fruitful use for forecasting by extrapolation. The usual objections to the extension of existing trends are those limitations of the present technology which would prevent such extension. This offers opportunity for predicting that those inventions will be made which will remove the present limitations. For example, when the propeller represented a limitation to continuance of the trend of aircraft speed, the jet engine was developed to provide a continuance. The invention occurred in spite of forecasts which ignored this possibility in predicting upper limits to the speed of aircraft in the neighborhood of 550 mph. Lesser inventions of this sort, such as the super-charger for continuation of the altitude trend, may be found throughout the history of aviation. A significant fact is that the ground work for these inventions was usually laid long before the actual need existed, so that continuance of the existing trend appears to have a certain inevitability.

Limitations - The limitations of forecasting by extrapolation lie principally in that it is not supported by a carefully developed theory of the reasons why progress should occur in this fashion. No attempt is

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⑧ Of course the disappearance of the wing may occur at different times for different classes of aircraft.

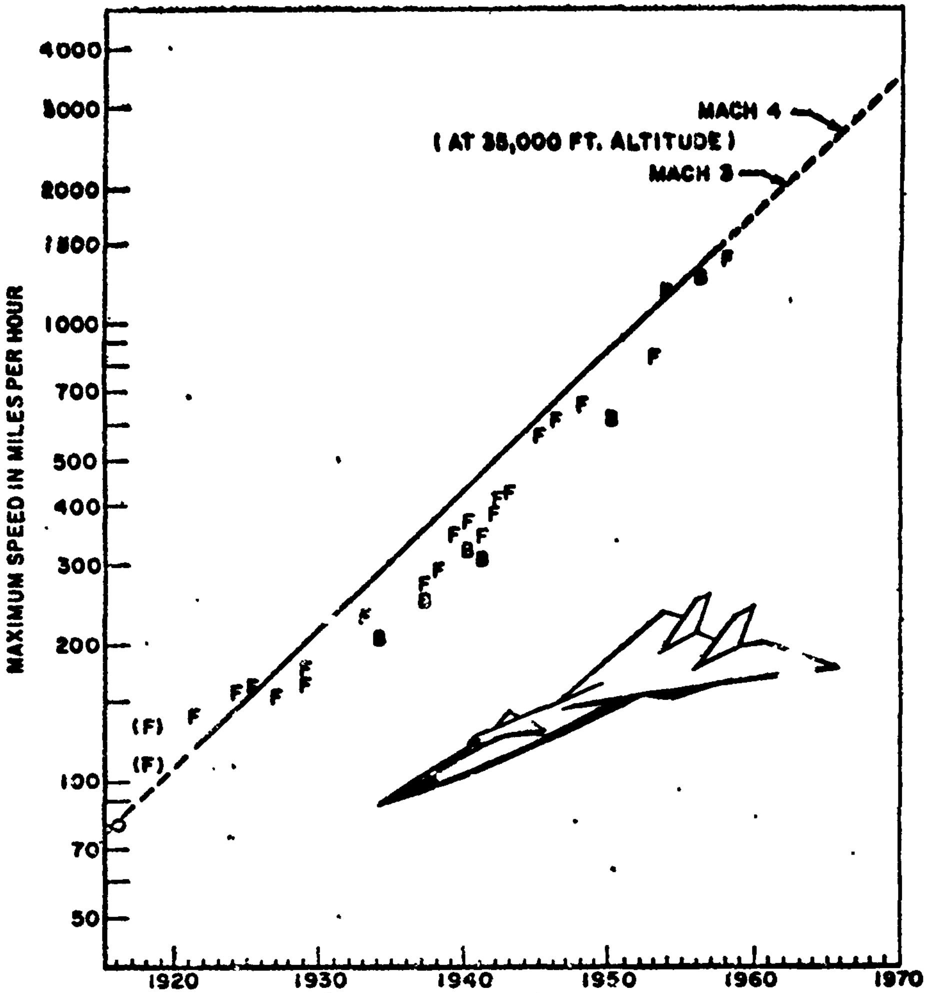
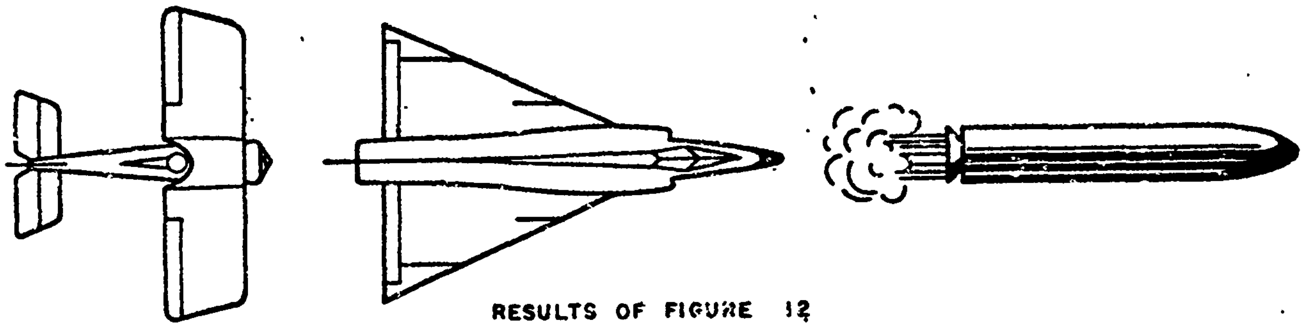
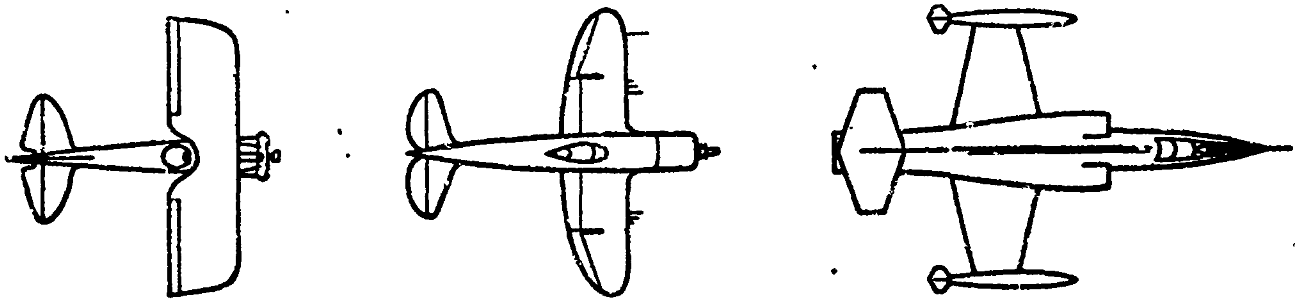


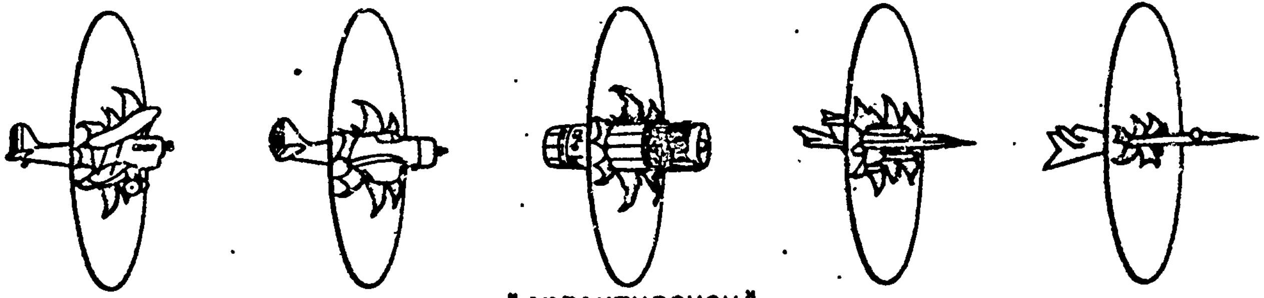
Figure 14. Speed Trend of U.S. Military Aircraft



RESULTS OF FIGURE 12



RESULTS OF FIGURE 13



"BREAKTHROUGH"
RESULTS OF FIGURE 14

Figure 15.

made to develop such a theory in this chapter, since such attempts lead to modifications of this method of forecasting which are presented in later chapters. In spite of these limitations, this method still offers a better basis of forecasting than the random application of methods having even less rationale and very little correlation with records of progress. In a world in which measured trends appear to exhibit the characteristics of logarithmic increase more often than any other characteristic, this method of forecasting seems reasonably appropriate.

CHAPTER IV

FORECASTING BY GROWTH ANALOGIES

Attempts to develop a theory explaining why technical progress should proceed in an exponential manner date back at least as far as 1907 to the theory advanced by Henry Adams. Adams' law of acceleration for progress assumed that a new mass, introduced on earth into a system of forces previously in equilibrium, is induced to accelerate its motion until a new equilibrium is established. ① Adams cites many ratios of increase in scientific progress, going back to the year 1400, to support his theory that progress follows the same principle of exponential increase as does the law of acceleration under the influence of gravitational forces. However, Adams fails to identify either the masses or the forces in his formula in quantitative terms. Therefore, forecasting by extension of exponential trends, while gaining distinguished support, still lacks a fully developed theoretical explanation.

In further attempts at explanation of the nature of progress, many writers have proposed analogies to the phenomena of biological growth. Most have noted that the initial advance is exponential, followed by a continued diminution of the rate of advance as "maturity" is approached. The synthesis of many of these fields of progress, each occurring at different intervals, may still result in the exponential advance cited by Adams for the total progress of society.

I. RELATIONSHIP OF PROGRESS TO GROWTH

Pearl's work on the analogy of population increase to the growth of biological organisms has been cited by writers in the field of population forecasting, economic forecasting and technical forecasting. ② Pearl's thesis if that the increase of population in a given area follows a pattern similar to the increase of biological cells confined within limits. As examples Pearl includes the rate of increase of fruit flies within a bottle; the rate of increase of yeast cells in a given environment; and the rate of cell increase within white rats. In each of these cases Pearl demonstrates that cellular increase obeys the formula developed in his earlier work as follows: ③

$$y = \frac{L}{1 + ae^{-bx}}$$

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① Henry Adams, The Education of Henry Adams (Boston: Massachusetts Historical Society, 1918). Edition cited, published in New York by the Modern Library, 1931, pp. 489-498.

② Raymond Pearl, The Biology of Population Growth (New York: Alfred A. Knopf, Inc., 1925).

③ Raymond Pearl, Studies in Human Biology (Baltimore: Williams Wilkins Co., 1924), pp. 558-583.

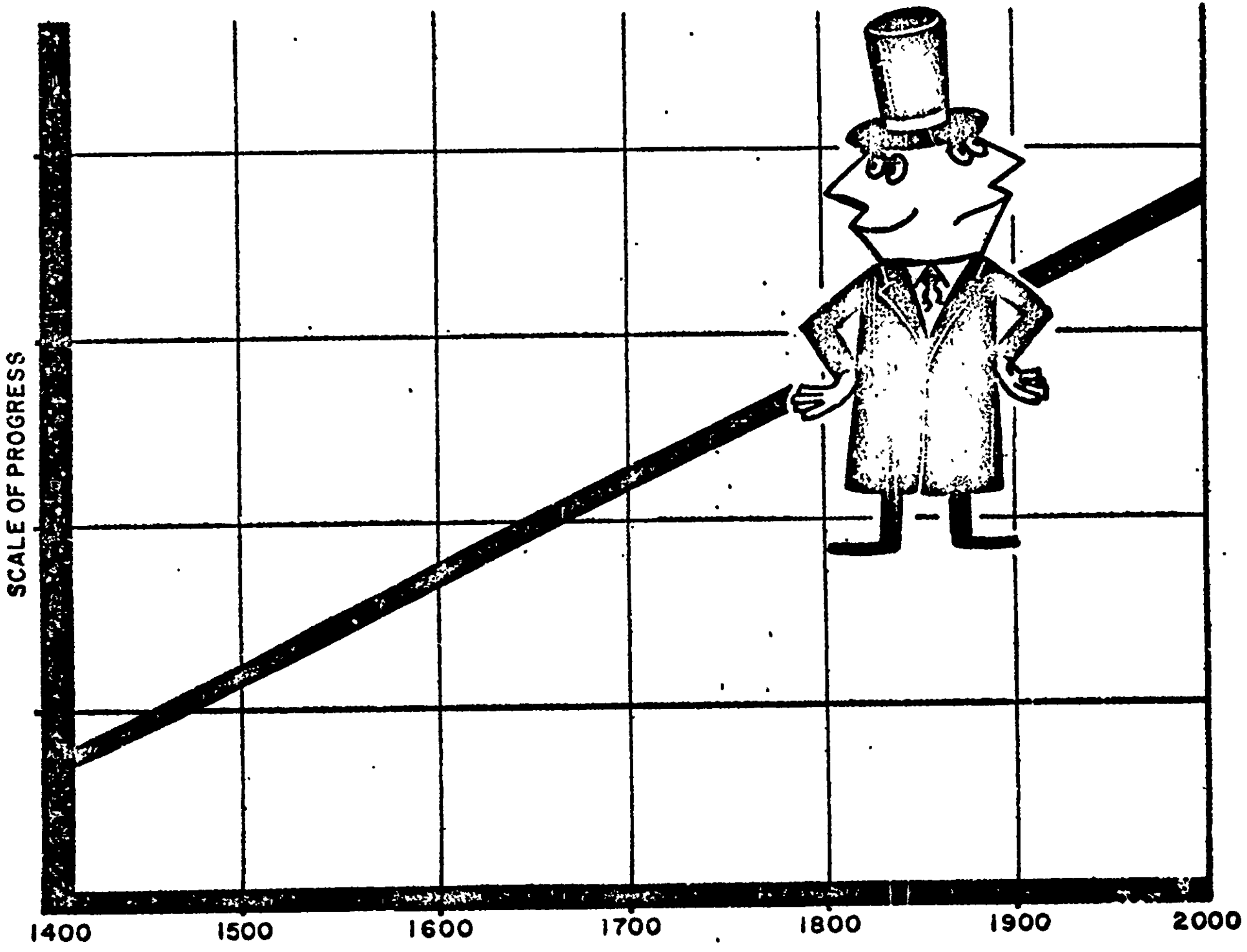

Figure 16, Adams' Law of Acceleration

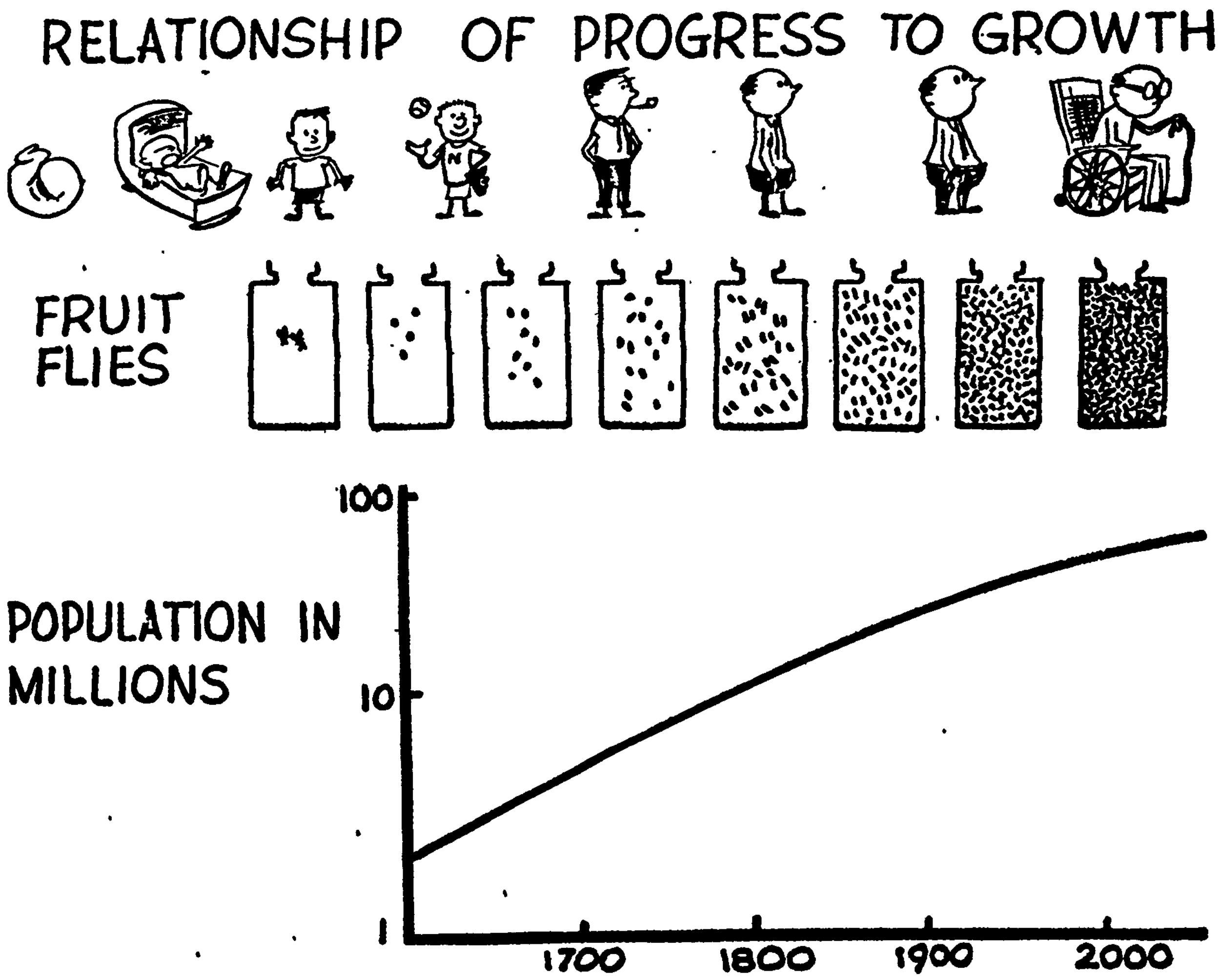
RELATIONSHIP OF PROGRESS TO GROWTH
FRUIT FLIES
POPULATION IN MILLIONS
100
10
1
1700
1800
1900
2000

Figure 17.

In this formula ''y'' is the unit of cellular increase, ''L'' is the upper limit of that increase, ''x'' is the unit of time, and ''a'' and ''b'' are constants.

Pearl's formula for growth can be made to fit many cases of cellular increase by proper selection of the constants ''L'', ''a'', and ''b''. If the constants are developed for a single species by measurement of the growth of several specimens, then these same constants may be transferred to other specimens of that species for prediction of growth. For example, if the relationship of ''y'', in terms of body weight, to ''x'', in terms of years, is known for a young child, then with the application of constants ''a'' and ''b'' for human beings, the future growth pattern and maturity limit ''L'' for growth of the child may be predicted.

When Pearl's formula is applied to population forecasting or to the forecasting of technical progress, the categorization of the objects of forecasting into similar classes is much more difficult than the classification of species. Thus the determination of the constants is made on the basis of using the least squares method to fit a curve to whatever data exists for the single specimen which is the object of the forecast. Because points of data covering the early history of any individual specimen may have a rather wide scatter, the constants developed for forecasting may vary considerably from those which later describe the entire curve.

Pearl's forecasts of population growth are an example of both the capabilities and weaknesses of this method. In 1925 he predicted a limit of population for the United States of 197 million, with predicted populations of 148.7 million in 1950, and 159.2 million in 1960. ④ The 1950 prediction was within 3 million of the actual 1950 census count of 151.7 million, but the 1960 prediction of 159.2 million will be in error since U.S. population in July 1958 was already approximately 174 million. Current estimates of U.S. population also indicate that Pearl's upper limit of 197 million will be surpassed in the 1960's, with population expected to go considerably beyond the 200 million mark in later decades. The greatest weakness of Pearl's formula lies in the strong influence of the upper limit ''L''. ⑤ In the curve fitting method used by Pearl, values of each of the constants, including ''L'', are assumed so as to obtain a first approximation to the growth curve. Then these constants are adjusted by the least squares method to obtain a better fit with the existing data. The initial value chosen for ''L'' is not greatly affected in

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④ Pearl, op. cit., Biology of Population Growth, p. 589.

⑤ As Pearl himself says ''it is apparent that the accuracy of determination of the upper asymptote of the curve will depend in part directly upon the number of observed ordinates from which the fitting must be done, and their location relative to whole growth cycle. Thus if all the observed points lie in the first half of the curve (below the point of inflection) we shall evidently get a less reliable estimate of the upper asymptote than if the observations cover say three fourths or more of the whole cycle.''
op. cit. Studies in Human Biology, p. 581.

PEARL'S METHOD OF POPULATION FORECASTING

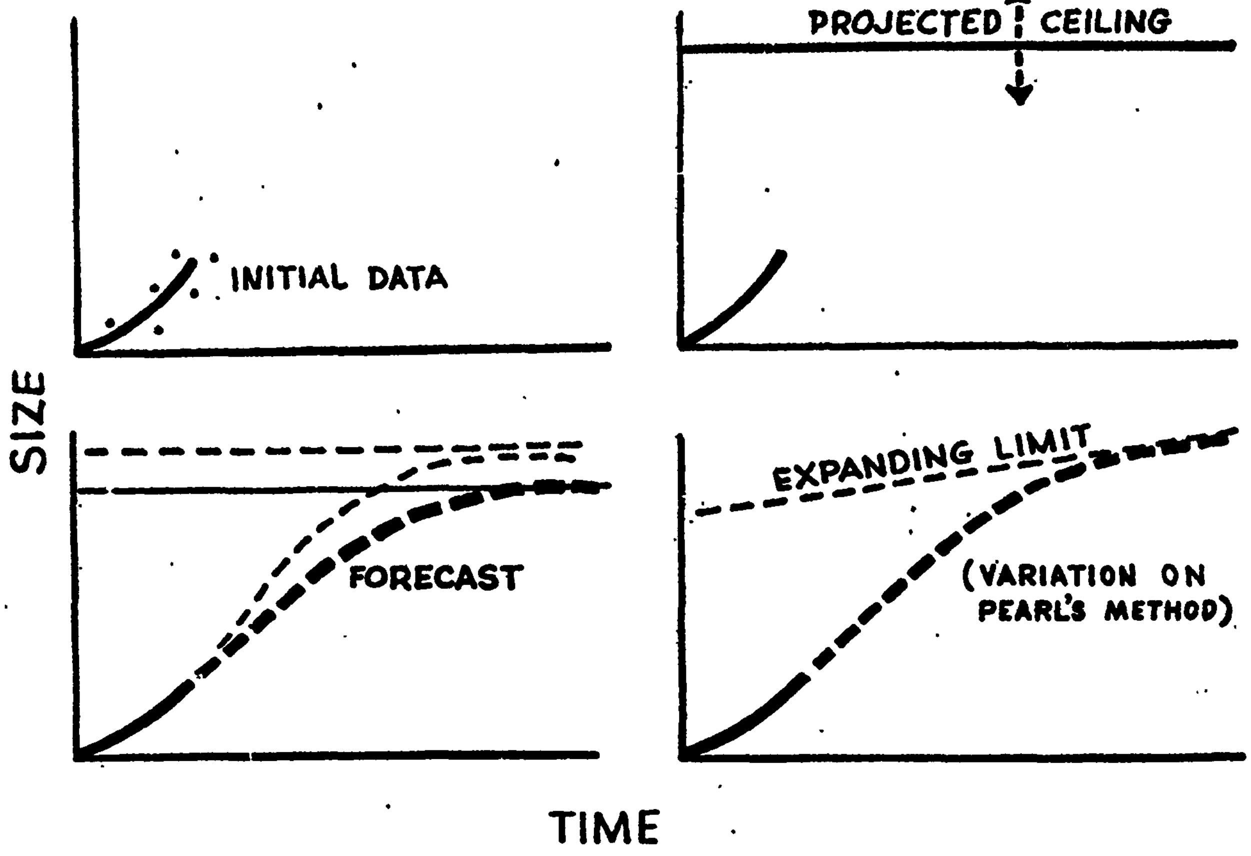

Figure 18.

this process, although the appearance of mathematical accuracy is given to the original assumption. Thus an initial value of the limit "L", erroneously chosen, will bring about increasing error in the prediction as the limit is approached.

If the entire concept of an upper limit for population growth or technological improvement is not invalid, at least the determination of the upper limit is extremely difficult. The forecaster generally tends to set the upper limit too low. Unless some rational explanation exists for the upper limit, such as the action of a determinable level of food production in limiting population increase, the predictor has little basis for choice of an upper limit. ⑥ To the predictor operating without a known upper limit, a short term decrease in the rate of growth falsely signals for lowering of the upper limit.

In spite of the limitations of Pearl's equation for growth, the concept of technological improvement as a growth process offers several advantages to the forecaster. Comparisons between biological growth and technical progress offer insight into the processes of technical improvement, thus providing a basis for more accurate forecasting. Fundamental to this analogy is the concept of increase by reproduction, either by cellular division or by paired bisexual reproduction. Both of these processes proceed on an exponential basis in the absence of restrictive forces.

II. ANALOGY OF TECHNICAL IMPROVEMENT TO GROWTH BY CELL DIVISION

Exponential growth of many technical areas may easily be explained if an unlimited process of cellular division is accepted as a reasonable analogy to the process of technical growth. Pearl explains the cell growth of an adult individual as follows:

> "Every living thing starts its separate, individual existence as a single cell----- What subsequently happens in the case of a higher multicellular organism, like man say, is that the single cell divides into two, then four, eight, sixteen, and so on to a number which finally becomes unaccountably large. But in this process all the cells remain in contact with and attached to each other, the whole mass forming the growing and differentiating individual. This process of growth goes on at different rates, but without interruption or cessation, until the complete development of the adult has been attained." ⑦

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⑥ In technical improvement, this limit might be determinable from the existence of some physical set of circumstances. For example, an upper limit for altitude performance of aerodynamically-supported aircraft may be related to the existence of an upper limit to the earth's atmosphere.

⑦ Pearl, op, cit., Biology of Population Growth, p. 5.

This explanation provides a model for the growth of technology in a single area, as shown in Table 1.

When there is no cell mortality, the increase in number of cells follows an exponential pattern. Similarly, as ideas or inventions continue to give rise to other ideas or inventions, the number of inventions increases exponentially. The problem of quantifying cell increase is usually handled statistically by determining the weight of the cell mass, without regard to the weight of the individual cells. If the weight of the cell mass is known at two different times, its weight can be predicted, waiving any cell mortality. Similarly, if the quantity of inventions in a given field is known for two separate times, with invention obsolescence excluded, then the increase of inventions in that field may be predicted on an exponential basis. This situation holds nearly true for the cumulative number of U.S. patents issued during the first 15 years of the history of many diverse technical fields. Examples of such technical growth include cotton machinery, weaving machinery, spinning machinery, the aeroplane, the automobile (for the period commencing in 1901), the typewriter, the sewing machine (after 1853), and radio (for its first 10 years).⑧,⑨

While "patents" are not inventions, they are a useful measure of the degree of activity in a given field, and in many cases probably bear some uniform relationship to the number of inventions actually made in that field. ⑩ If the average "time required for an initial invention to initiate 'new' invention" is desired, it may be obtained by determining the average time required for inventions to double in number. This does not identify any given "new" invention with a specific primary invention, nor does it set limits on the time involved in any single case.

The analogy of cell division may be extended to those factors which cause a departure from the initial exponential rate of improvement. Of first consideration is the effect of cell lifetime, or normal cell death, on the size of the cell mass. In the corresponding technical analogy, the effect of obsolescence upon the total of existing inventions must be considered. For example, the series of cell populations, without death, of 1, 2, 4, 8, 16, 32, 64, would become, with a lifetime equal to two periods, the series 1, 2, 3, 5, 8, 13, 21. ⑪ After the perturbation introduced by the initial death, this series represents growth at a lower exponential rate. In a similar fashion, the obsolescence of inventions will bring about a lessened rate of increase in the number of useful inventions. While it is impossible to determine "invention lifetime" precisely, an estimate may be made of the average useful life of inventions in a given technical field. Such an estimate will give a more accurate basis for prediction than if the "lifetime" effect is ignored.

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⑧ Simon S. Kuznets, Secular Movements in Production and Prices (Cambridge: The Riverside Press, 1930), pp. 54-56.

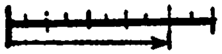
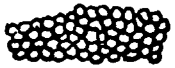
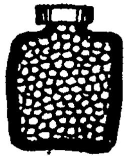
⑨ Robert K. Merton, Fluctuations in the Rate of Industrial Invention. The Quarterly Journal of Economics, 1935, pp. 454-474.

⑩ Ibid., p. 455.

⑪ This series has the formula $P_n = 2x_n - 1 - (x_{n-1} - x_{n-2})$

Table 1

Cellular Analogy

BIOLOGICAL GROWTH		TECHNICAL IMPROVEMENT
Initial Cell		Initial Idea or Invention
Cell Division		Inventive Process
Second Generation Cell		"New" Idea or Invention
Cell Division Period		Time required for Initial Invention — to Initiate "New Invention
Nutrient Media		Economic Support for Invention
Cell Lifetime		Useful Life of Invention
Cell Death, Normal		Obsolescence of Invention
Cell Mass		Technical Area or Machine Class
Volume Limit of Cell Mass		Limits of Economic Demand for Invention in a given Technical Area
Size of Cell Mass		Total of Existing, Non-Obsolescent Inventions in Technical Area
Strength of Cell Mass		Performance Capability

''Economic support for invention'' is analagous to the nutrient media for cell increase. In the biological analogy, sufficient nutrient must be provided to enable individual cells to increase in size up to the division point. If sufficient nutrient does not exist for the first cell to reach the division point, no increase in number of cells will occur. This is equivalent to a technical situation in which insufficient funds are available for exploitation of the first invention, so that it lies dormant. This example emphasizes the fact that while money alone can not produce inventions, neither can inventions be produced without money.

After the first cell division has occurred, twice as much nutrient is required for the development of both new cells to the point of another division. The third generation requires four times as much nutrient, and so on; the process is a geometric one. By analogy, economic support for invention proceeds in a like fashion. Each increase in number of inventions requires an equal increase in economic support if the development of ''new'' inventions is to continue. If the nutrient or economic support is insufficient for the development of inventions, the rate of technological growth will be slower. Retardation of this nature has frequently been confused with ''maturity'' by those who use the growth theory for forecasting economic expansion of technological advance. ⑫

Economic support of invention is frequently curtailed below the level necessary for exponential growth. Few men who have the power of economic decision can readily accept, and even less readily forecast, the necessity of a research program which expands exponentially without limit. Therefore, economic support is usually provided initially on a scale permitting exponential advance, but later ''ceilings'' are imposed. These ''ceilings'' are revised only when they become patently unrealistic.

Economic support is also limited by the competition for resources with other technical fields. This is analogous to the competition of two cell masses for a limited nutrient. When the technical field is small, its needs for economic support are also small, and exponential growth is possible. As the size of the technical field grows, its economic needs impinge upon the needs of other technical fields, and an economic limitation is imposed, and a reduction of the previous rate of growth occurs.

If a given technology is to be described in terms of growth toward ''maturity,'' the limits of economic demand for inventions must be examined in terms of their analogy to volume limits of cell masses. The volume limits of cell masses range in type from the artificial limits of laboratory containers for collection of cells, to the evolutionary limits of the size of the human animal, and range in size from plankton to whales. The difficulties presented by this variation help to explain the problem faced by forecasters who

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⑫ For example, Kuznets (op. cit., Kusnets, Secular Movements in Production and Prices, pp. 85-89) fits a Gompertz ''growth curve to the time series of anthracite coal output in the U.S. That this curve gives a good fit cannot be argued; however, the use of growth characteristics as an explanation is less convincing than an explanation based on gradual diversion of production funds to competing fuels.

work with "growth" curves which assume some limit of "maturity." For example, in the biological analogy, the predictor might examine the growth of an animal of an entirely new species of which no prior knowledge existed. Then, as the animal's growth proceeded at varying rates, the prediction of full growth size would fluctuate widely as the curve was fitted to each added point of growth data. The temporary effect of sickness on growth of the animal might result in such a severe lowering of the apparent growth rate that one might think maturity has been achieved. Many "growth" predictors of the late 1930's and 1940's were willing to concede "maturity" to the U.S. economy on the basis of the effect of the depression, or "sickness" of the economy during the thirties.

On the other hand, if caution is used, some analogies may be developed which will help in determining the upper limits of a given technology. If, in the biological case, the new species is similar to an existing species, then the growth curve may be compared to the existing species. If an early similarity is noted, then the maturity limits of the new animal should be close to the limits of the old species. If two fields of technology, one old and one new, are similar in nature, then the growth to technical maturity of the new field may be predicted by comparing it with the older field.

In the biological analogy, as the animal grows, body members become more specialized in function. Similarly, as a technology becomes more mature and thus specialized, and standardized, a lessening of growth may be noted. Gilfillan notes among his 38 "Social Principles of Invention" that "the standardization which tends to accompany wide organization obstructs inventions which would require changing the standard form." ⑬

To complete the biological cell division analogy, the size of the cell mass, and the relationship of size to the strength characteristics of an organized cell mass, need to be considered. For an organized cell mass, such as man, the size of the mass is usually defined in terms of the weight of the collected cells, or some linear dimension of the mass. Since the size of the cell mass is proportional to the number of cells, then if the number of cells increases exponentially, the weight and significant linear dimensions will also increase exponentially. Thus weight and height are conventional measurements of growth for biological samples. No such easy measurement exists for determining the totality of invention in a given technological area. However, the number of patents in a given field is usually proportionate to the total of inventions in that field, in a similar manner that a dimension of a major part of the cell mass is proportionate to an equivalent dimension of the total mass. Thus, the observed growth of the number of patents may be used to estimate the total number of existing inventions.

While size of the mass is usually the measure of growth in biology, the emphasis is shifted to performance as the measure of growth in technology. This is primarily because of the relative ease of measurement in each case. For an animal, performance may be measured by the ability to lift, to cover a certain distance in a given time, or by similar measures. Such performance might be used consciously as an approximate measure of growth, or wrongfully be interpreted as growth itself.

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⑬ S. C. Gilfillan, The Sociology of Invention (Chicago: Follett Publishing Co., 1935), p. 9.

PREDICTION ON THE BASIS OF GROWTH, CASE I

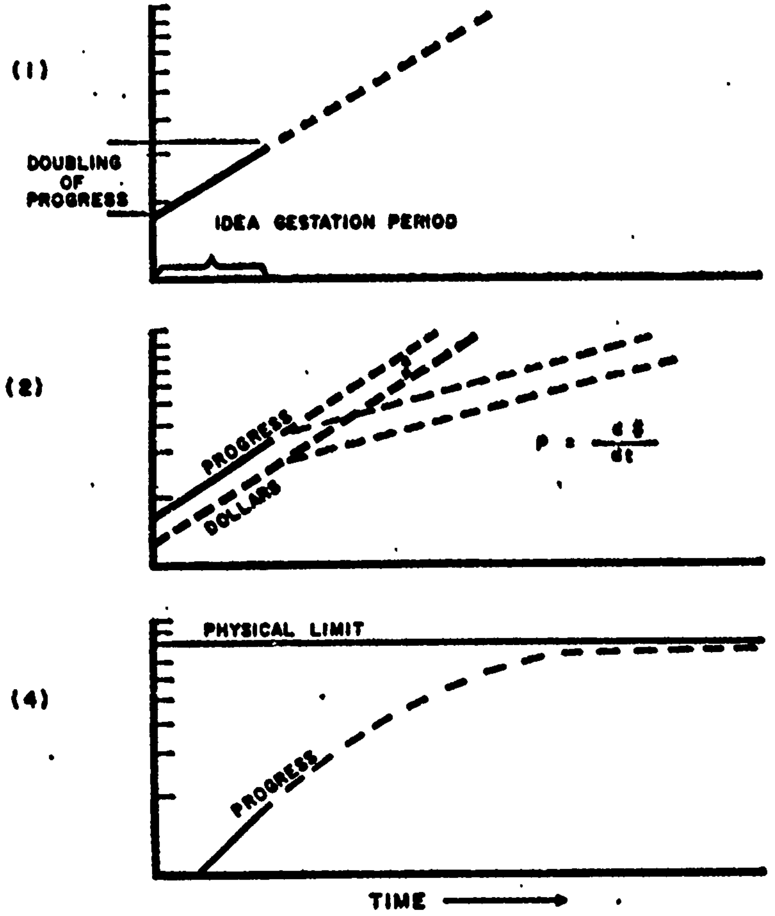


Figure 19.

Since performance measures of inventions are easier to obtain than measurements in number, performance usually is accepted as the measure of growth in technological fields. The fallacy of this method of measurement is that inventions may accumulate without a demonstration of performance over a given period. The absence of demonstrated performance may be erroneously interpreted as cessation of invention. However, when a call is made for improved performance, the accumulation of inventions results in a steep rise in the performance curve.

The growth analogy of performance may be used for technological prediction, if there is evidence of a continuous effort in improved performance. The curves of measured performance will usually exhibit the characteristics of exponential growth, of insufficient nutrient or economic support, and of maturation. If then, the curve of performance in a given technology, such as the maximum speed of aircraft over a period of years, is projected in accordance with the principles of biological growth, the projection will have some validity as a prediction.

To summarize, the analogy of cell division to technological improvement may be used for prediction in the following ways: (1) By identification of the average period required for ideas to be generated from prior inventions, and use of this time period as the basis for predicting the doubling of technical progress over each such period; (2) By relating economic support of invention to the rate of increase of invention, to show that exponential increase in invention is not likely without exponential increase in the economic support; (3) By indicating the lower rate of progress caused by the obsolescence of inventions; and (4) By projecting the growth curve to "maturity," with a constantly diminishing rate of increase in progress, where the limits of demand for invention in a given field can be reasonably determined.

III. ANALOGY OF TECHNICAL IMPROVEMENT TO THE HIGHER REPRODUCTIVE PROCESS

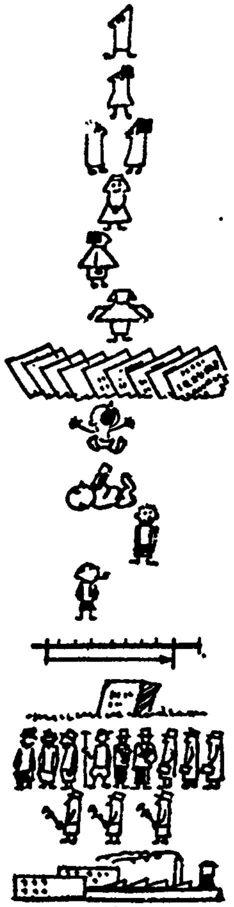
The biological process of paired, bisexual reproduction offers an analogy to the development of invention, as outlined in Table 2.

For the starting point of this analogy, it is assumed that an existing invention, communicated to the receptive mind of an inventor, will bring about the origination of a new idea. This is equivalent to the biological situation in which the male parent, the opportunity for fertilization, and the receptivity of the female parent, combine to produce conception of a new individual.

Following the origination of the new idea, an embryonic development takes place. The development of the idea, like embryonic growth, is hidden, usually in the mind of the inventor and sometimes without his knowledge. Although evidence of the idea may be available, such as notes, sketches, and models, it may be assumed for the purposes of the analogy that such elements do not constitute disclosure. During this period economic support is needed only for the inventor, as in the analogy, nutrition needs to be provided only for the female parent. The period required for invention is analogous to the period of gestation.

Table 2

Bisexual Reproduction Analogy



BIOLOGICAL INCREASE	TECHNICAL IMPROVEMENT
Male Parent, or Parent Cell	Existing Invention or Discovery
Female Parent	Inventor
Opportunity for Fertilization	Communication of Knowledge
Conception	Origination of Idea
Embryo	Evidence of Growth of Idea
Embryonic Growth	Development of Idea
Gestation Period	Period Required for Invention
Birth	Disclosure of Invention
Nutrition	Economic Support
Maturation Period	Reduction to Practice
Maturity	Operational Use of Invention
Lifetime	Period from Disclosure to Obsolescence
Death, Normal	Obsolescence
Total Male Population	Total Inventions Disclosed Minus Obsolete Inventions
Total Work Force	Total Operational Inventions
Total Strength of Work Force	Performance Capability

At this point in the analogy, certain elements useful for prediction appear. First, it would seem that simultaneous multiple inventions from a single inventor are as rare as simultaneous multiple births in the human species. Second, the period required for invention will be related to the complexity of the idea; just as the gestation period is usually related to the complexity of the individual of the species. Third, although development of an idea may be aided by adequate support, only the inventor can actually produce the new idea; just as medical care may aid the birth of an infant, but only the female parent will actually bear the infant.

Using the above elements of the analogy, it can be shown that the number of forthcoming inventions cannot significantly exceed the number of inventors, for any period of time equal to the average period required for invention. Thus to predict the number of inventions which will occur, the forecaster needs first to forecast the number of inventors. This is relatively easier than to predict the number of inventions, since a certain amount of training is required for most inventors. Even such rare individual discoverers as Newton, LaPlace, and Einstein, occur with some statistical regularity, while lesser inventors can be assumed to be present on some regular basis in proportion to the total population.

For any given technology, the establishment of an average time period of invention, which might be used in forecasting inventions, is easier than might be supposed. For example, if one determines the average number of patents obtained by inventors who have multiple patents in a given field, and divides this by the average working lifetime of these inventors minus the average time spent on development and exploitation, the average time required per invention is obtained.

The next step in the analogy is disclosure of the invention, which is analogous to birth in the biological sense. Disclosure of the idea is the first complete evidence of its existence and nature. The "invention" itself represents the second generation male parent. Unlike infants in the biological analogy, it is capable of bringing about the origination of a third generation almost immediately after disclosure or "birth."

Economic support for the infant invention is necessary. If economic support is not provided for development, the invention dies. In predicting technological progress, therefore, the projected availability of development funds can be used to determine the number of inventions which will be supported. For example, it can be predicted that a constant level of development funding will produce a constant number of inventions in a given time period, which will limit the total number of inventions to an arithmetic rate of increase.

The reduction of an invention to practice is equivalent to the maturation period in the biological analogy. Operational use is equivalent to maturity. The period from disclosure of invention to obsolescence is equivalent to biological lifetime, while obsolescence is equivalent to death in the biological case. This analogy is so natural that expressions such as "conception of the invention," and "embryonic idea," are frequently used to describe the inventive process. However, little use has been made of the analogy in relating the quantitative aspects of nutrition, parenthood, and growth periods, to their counterparts in the technical improvement process.

The final step is the extension of the analogy to the characteristics of a population built up from an initial single pair. In this extension, the total of inventions disclosed, minus the total of obsolete inventions, is equivalent to a total male population. The number of operational inventions is equivalent to the total work force. This leads to the concept that the performance capability achieved by the total of operational inventions is equivalent to the total strength of the work force in the biological analogy.

To summarize, if performance capability is a function of the total number of operational inventions, which is a function of numbers of inventors and economic support for development; then growth in performance capability can be related directly to economic support and numbers of inventors. The forecaster can predict values of economic support and numbers of inventors, and derive from this information a prediction of the rate of technical progress.

CHAPTER V

FORECASTING BY TREND CORRELATION

Determination of the future as the consequent result of known events is most appealing to the logical mind. This is the type of prediction used by Drucker in forecasting the future of the United States when he says, "The major events that determine the future have already happened--irrevocably." ① Although logical, this type of prediction does require a certain blitheness of spirit in ignoring the possibility of major mishaps which might alter the expected causal relationship.

In forecasting on the basis of causal relationship, only one factor need be considered in selecting the technical parameter which is to be predicted. This factor is whether progress in the technical parameter is indeed dependent on a single controlling condition. For example, if all of the discoveries which are necessary for technical advance in a given area have been made, and no political barriers have been imposed, then economic conditions might constitute the sole restraint upon progress in that area. The technical advance thus singly restrained would be a suitable subject for cause-and-effect forecasting. To illustrate: the passenger carrying capacity of the automobile, unrestrained by technical or legal restrictions, is related to the maximum number of passengers which the average purchaser expects to transport, i.e., the number of members in his family. Thus in automobile design, the predictor would select passenger-carrying capacity as a parameter which might be forecast on the basis of statistically significant changes in family size.

The second step of forecasting on the basis of causal influence requires the selection of a set of events which has a definite effect upon the object of prediction. For example, if the maximum single span of bridges is not limited by political or narrow economic barriers, then possible technical limits may be scanned for a specific controlling variable. Such a variable might be the maximum tensile strength of materials available for bridge building.

When the controlling variable is found, then the prediction may be completed by determining the effect of the current status of the controlling variable upon the controlled parameter of progress. If this seems trivial, it may be noted that the first practical steam engine clearly forecast the ultimate invention of the steamship and the steam locomotive; and that Goddard's success in liquid rocket experimentation was a necessary precursor to the ICBM and satellite successes. Many notable inventors succeeded principally because of their recognition that limiting barriers had been removed, and that consequently, what had been impossible before, had become predictably possible.

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① Peter F. Drucker, America's Next Twenty Years (New York: Harper & Brothers, 1955), p. 2.

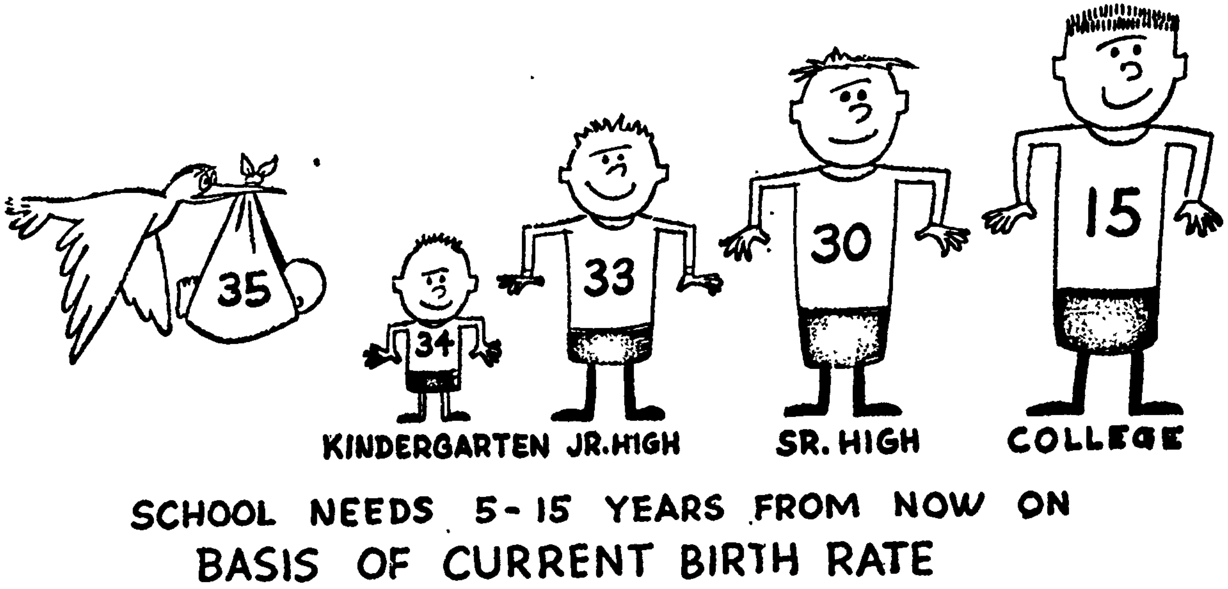
35
34
33
30
15
KINDERGARTEN
JR.HIGH
SR.HIGH
COLLEGE
SCHOOL NEEDS 5-15 YEARS FROM NOW ON
BASIS OF CURRENT BIRTH RATE

Figure 20.

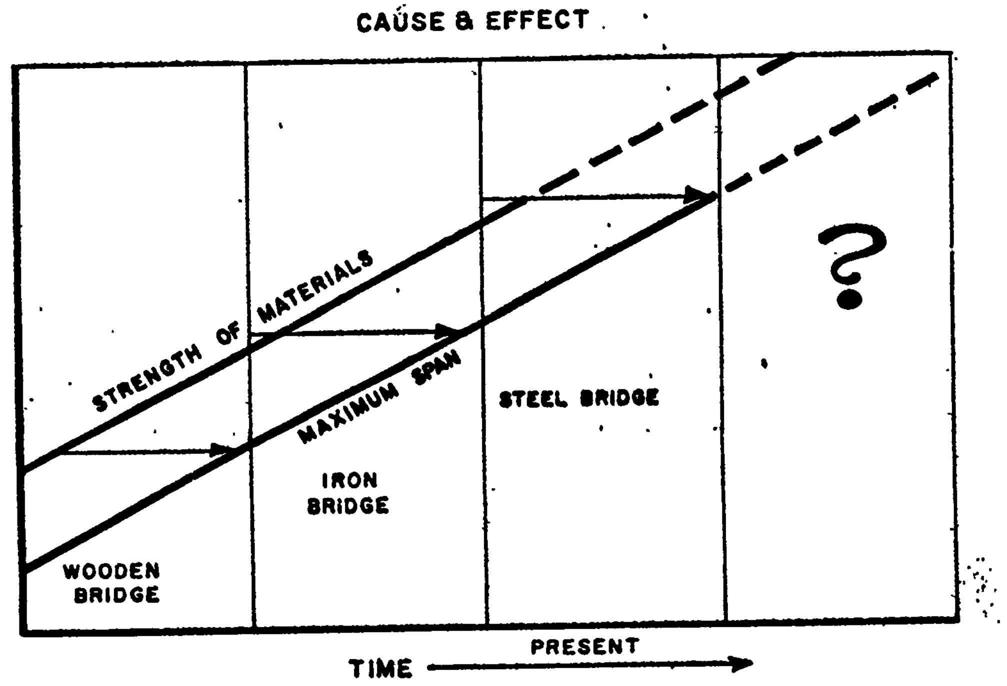
CAUSE & EFFECT
STRENGTH OF MATERIALS
MAXIMUM SPAN
WOODEN BRIDGE
IRON BRIDGE
STEEL BRIDGE
?
TIME
PRESENT

Figure 21.

The greatest difficulty in predicting future events as the consequence of known causal events lies in the rapid advance of science. The exploitation of each new discovery is so rapid that such a forecast is essentially short range; seldom exceeding the time required to design and produce the mechanism using the discovery. Sometimes, however, when the limiting factors are economic, political, or social, the changes are sufficiently gradual that a longer range forecast could be valid.

Since technological advance usually follows a pattern of continuous increase, situations frequently occur in which one measurement of technical progress lags another by a given length of time. Where this is true it is possible to use the leading measurement to predict the status of the follower over a length of time equal to lag period. If the time lag is short, only a short-range forecast results; if the lag is as long as a decade, a useful long-range forecast is possible.

An example of sequential relationship may be found in the correlation of the maximum speed of military aircraft to the maximum speed of commercial aircraft. As shown by figure 22, the speed of commercial aircraft has consistently followed the speed of military aircraft. The period of lag has increased from six years in the 1920's, to eleven years in the 1950's. On the basis of the trend, commercial aircraft with speeds of Mach No. 2 may be expected to be introduced not later than 1970. If such aircraft are not introduced at this time, then aircraft with a speed of Mach No. 3 will be introduced somewhat near 1976. In such a case, the prediction simply says that there is a logical time for the introduction of Mach No. 2 aircraft. If other forces cause this time to be passed over, then this performance range will also be passed over.

The prediction of the aerodynamic forces acting upon a pilot escaping from a disabled aircraft may be used as an example of a sequential forecast where the primary series is a controlling factor. In this case, the time-series of maximum aircraft speeds is the primary forecast, and the relationship of the aerodynamic forces acting on the escaping pilot, to aircraft speed, is easily determined. With this information the time-series for aerodynamic forces acting on the pilot is easily established. Then, with knowledge of the limits of tolerance of the human anatomy to acceleration and wind blast, the need for, and probable invention of, ejection seats and capsule escape devices can be predicted. Such a forecast may be made well before the aircraft speeds necessitating these devices have actually been attained. A large number of similar situations exist, in which secondary technical requirements are established as a result of advances in major performance characteristics. Thus, this method of forecasting is particularly useful in establishing research requirements for secondary inventions.

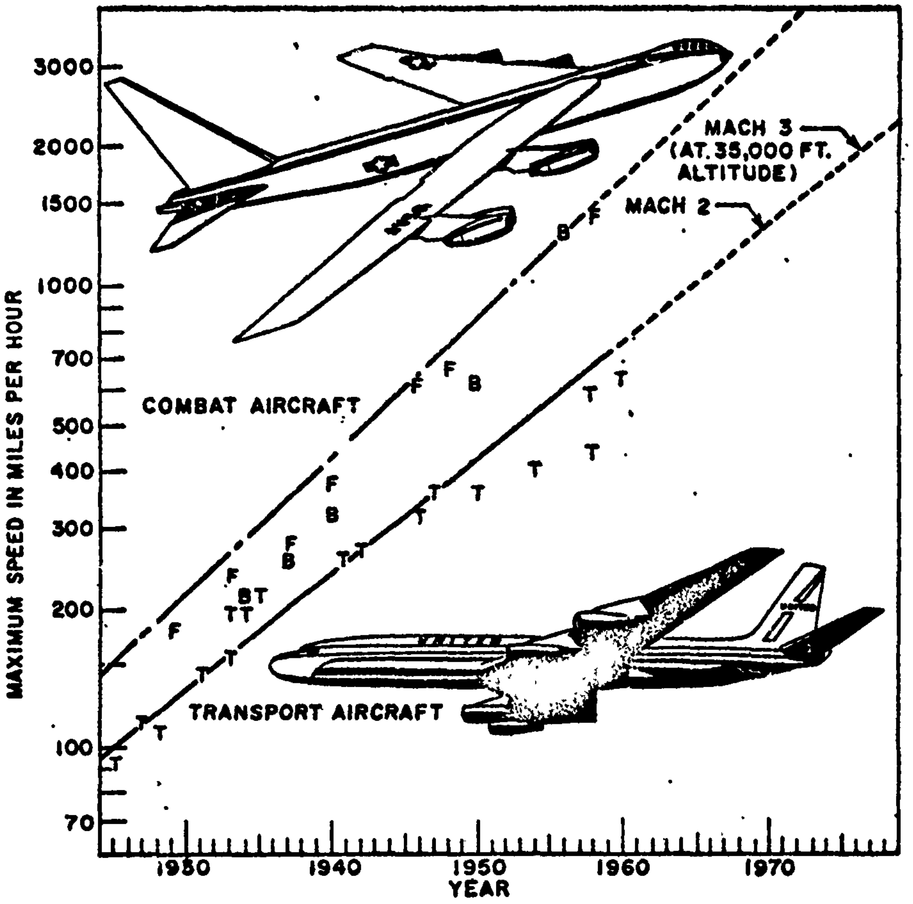

Figure 22. Comparative Speed Trends of Combat and Transport Aircraft

I. USE OF INTERDEPENDENT RELATIONSHIPS FOR PREDICTION

The trend of a technical parameter which is complex and difficult to predict by itself may sometimes be more easily expressed as the result of a relationship between two or more other trends.

In order to use two or more trends to determine a third, the predictor must have available a number of primary trends which are related to the technical field of interest. To these he must add a knowledge of probable relationships that might arise from combinations of such variables. The predictor may then select the relationship and the primary variables which influence the desired technical improvement. The trends of the primary variables may be projected on the basis of any techniques which appear appropriate. The prediction is then completed by projection of the unknown variable on the basis of the relationship between the primary variables.

An example of this type of forecast is the relationship between "passenger capacity," "load factor," "total passenger miles," and "total plane miles flown," for commercial aircraft in domestic trunk line service. If "passenger capacity" is defined as "total passenger miles" divided by "total plane miles" times "load factor," the four variables may be established from available Department of Commerce statistics. The time-series for these four quantities are shown in figure 23. ②

Until 1957, "total passenger miles" increased at a greater rate than did the combination of "plane miles" times "load factor;" and "passenger capacity" continued to increase as shown by the curve for this variable. Beginning in 1947, the rate of increase of "total passenger miles" has steadily declined from 24% per year in 1947 to 12% per year in 1957. If this rate of increase of "total passenger miles" continues to diminish in the same manner (halving every 10 years), it will become 10% per year in 1960, 5% per year in 1970 and 2 1/2% per year in 1980. Since 1947, the "load factor" has remained essentially constant between 60% and 70% and may be projected to continue at 65%. Lower rates of increase of "total passenger miles," combined with physically increased "passenger capacity," and constant "load factor," will cause "total plane miles," to have less than its 1930-1957 rate of increase after 1960.

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② Although the dependent variable in this situation is actually "total plane miles" it is necessary to obtain "passenger capacity" as an average figure from the statistical data for the other 3 variables. This necessity arises because of the wide variety of passenger capacities actually used by the airlines in various configurations and models of aircraft, which can scarcely by combined to give a meaningful figure. The average figure obtained by the method indicated, is a fair representation of the hypothetical "average" aircraft used by the airlines.

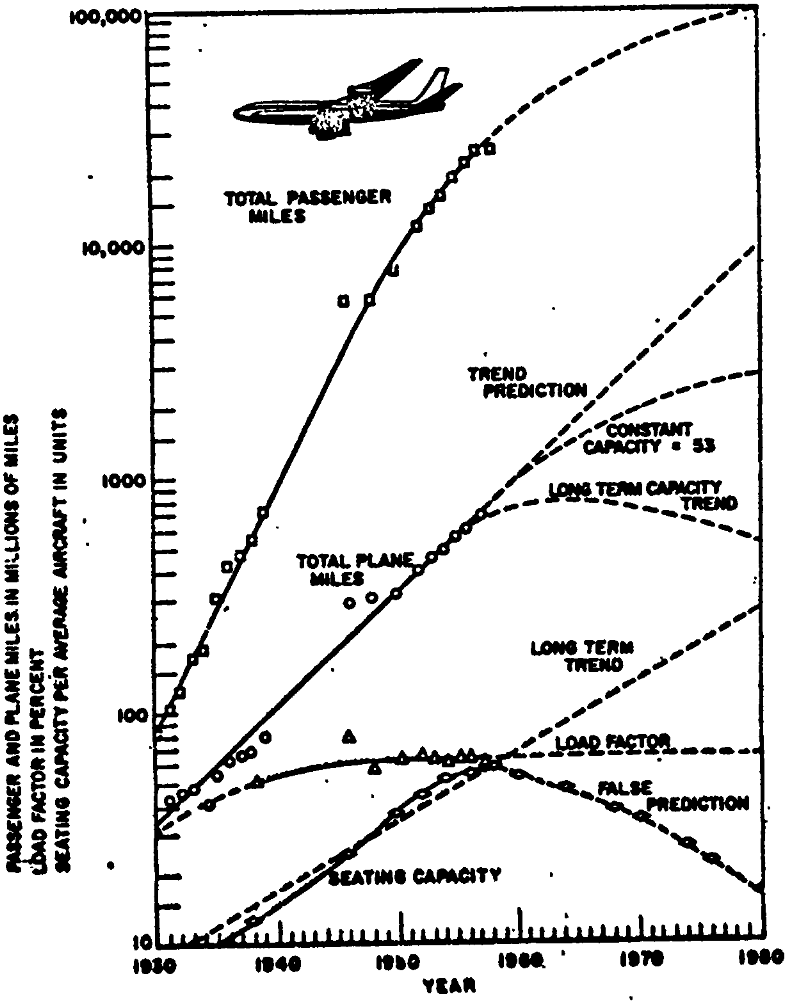

Figure 23. Domestic Trunk Airline Operations

The observation that "total plane miles" will not continue to increase at its prior rate, and the possibility of predicting "total plane miles" on the basis of trends in three controlling variables, is the essence of this example. If the data for "total plane miles" is examined separately, it may be observed to follow a quite constant rate of increase up to 1957. Thus this single set of data gives no hint of probable lowering the rate of increase other than the existing rate.

To conclude this example, the prediction of "total plane miles" is obtained by transposing the equation for "passenger capacity" so as to solve for plane miles. The diminution of the rate of increase of "total passenger miles" may be assumed to remain constant to 1980. Load factor, as indicated, has stabilized at 65%. For "seating capacity, "two choices may be made, providing two solutions to the equation for the prediction of "total plane miles." The upper limit solution is obtained by assuming that "seating capacity," which has shown a sharply reduced rate of increase since 1950, is economically at its most practical value, and will not continue to increase in the future. The lower limit is obtained by assuming that the long-term trend of passenger capacity is valid. This assumption implies the introduction of substantial numbers of 200-passenger aircraft between 1968 and 1975, and some 300-passenger aircraft as early as 1974.

The solution of the equation, for upper and lower limits, gives the two predictions for "total plane miles" shown in figure 37, Appendix A. The predictions are that "total plane miles" will be not less than 740 million in 1970, and 550 million in 1980; and will not be greater than 2.0 billion in 1970, and 2.8 billion in 1980. Because this spread is quite large, the final prediction requires modification of the limiting conditions to obtain a most probable value. Such selection is not necessary, however, to demonstrate the technique.

A second example of the use of interdependent relationships in forecasting may also be taken from the domestic trunk airline situation. In this case the forecast is derived from trends which appear mutually contradictory. In this second example, the forecaster might initially accept the apparent trends of "total passenger miles" (percentage rate of increase halving every ten years), "total plane miles" (constant percentage rate of increase), and "load factor" (constant at present level). The equation for "seating capacity,"

$$\text{seating capacity} = \frac{\text{passenger miles}}{\text{plane miles} \times \text{load factor}}$$

will then produce the curve labeled "false prediction" on figure 37, Appendix A. This curve indicates that the seating capacity of individual, trunk-line aircraft will decline after 1960, reaching a level of 16 seats per aircraft in 1980. While this circumstance is not impossible, it would require cancellation of most airline orders for new aircraft, and replacement of present equipment with smaller models. Since this would run counter to sound economic operation of the airlines, the apparent contradiction should be examined for the possibility of alternate consequences. The most obvious of such alternates is the correction of "total plane miles'' forecast, as outlined in the preceding example. At least one other alternate may be cited in demonstration of the method. The lower limit curve of ''total plane miles,'' projected on the basis of the long-term trend in seating capacity, reaches a maximum in 1964, and thereafter declines. This implies that after 1964 fewer flights would be scheduled by the trunk airlines, with resulting lessened passenger convenience. Alternatively, aircraft size might remain constant after 1964, so that the increase in ''total plane miles'' thereafter would be at the same rate as the increase in ''total passenger miles.'' Such a prediction, if consistent with other evidence, would afford a good basis for design of the next ''generation'' of aircraft in terms of seating capacity, and would also indicate the rate of increase of airways traffic.

These predictions are cited only as examples of possibilities of this method of forecasting. In making any technical forecast, many more possibilities should be examined. The greater the amount of correlation, the more likely is the possibility that the forecast will actually describe the future course of events.

II. PREDICTION ON THE BASIS OF TREND CHARACTERISTICS

The methods of technological forecasting previously described have been concerned with the extension of time-series to provide a quantitative indication of future events. Time-series may be used in quite a different way for prediction by taking account of characteristics in the trend curves of the time-series.

One of the simplest situations for prediction on the basis of trend characteristics is one in which the extension of a well-established exponential rate of progress intercepts a known physical limit. Since, by definition, progress cannot extend beyond this limit, only two predictive possibilities exist. The first obviously is that progress will indeed stop at this point. The second is the development of a new technology that will permit the extension of progress on some equivalent basis beyond previously known limits. If progress in the old technology has filled a definite need, then an innovating society will not let progress cease, when a substitute technology can be found. Thus a motive for discovery is created to bring about the necessary invention.

One may predict that the intersection of the exponential trend with the physical limit indicates the logical time for an invention which will produce a new technology extending performance beyond the previous limit. If the invention does not occur at the time of intersection, the pressure for innovation will become greater as it becomes obvious that progress has ceased. When the invention occurs prior to the limit of progress, it is likely to be closely related to the existing technology. If the invention is delayed, the new technical possibilities will in some degree be different from the old proportionately to the length of the delay.

In predicting invention on the basis of intersection of a trend with a known limit, it may not be possible to specify the exact nature of the invention. However, some characteristics of the invention may be indicated by the nature of the barrier imposed, and by physical possibilities lying outside of the barrier.

The word "breakthrough" has been used rather loosely to characterize almost any invention. However, an invention which overcomes a clearly discerned barrier to exponential progress actually deserves the title "breakthrough." Most such "breakthroughs" do not provide great steps ahead, but rather enable continuation of exponential rates of progress. If the new technology created by the breakthrough is closely related to the old, it is likely that the new rate of progress will be a continuation at the prior rate. If the new technology is substantially different from the old, it is probable that a new rate of progress will be established, intersecting the old rate at its intersection with the previous limit.

The maximum speed of military aircraft as shown in figure 14 is an example of this type of prediction. In the period 1938 to 1940 it was obvious to most aeronautical engineers that the maximum speed feasible for propeller-driven aircraft was something less than the speed of sound in air, and that the probable practical limit was between 550 and 600 miles per hour. Therefore, most forecasters of aeronautical progress at that time predicted that aircraft speeds would not exceed this limit. The limit was readily accepted even though jet engine principles were well known and had been undergoing development for aircraft propulsion since the 1920's. If, at that time, the exponential trend of aircraft speeds from 1908 to 1938 had been extended, it would have intercepted the 550-600 m.p.h. barrier in 1944 or 1945. Thus, the prediction could have been made that the jet engine, or some similar propulsion device, would become operational in 1944 or 1945. Further, it might have been predicted that the innovation would enable a continuation of the speed trend at its prior exponential rate. Such predictions would have fitted very well with the historical facts as they actually came about. Of course, prediction after the fact is quite easy, and this example is not cited as a proof of the predictive method. However what could have been predicted by the method cited herein, actually did happen in a manner consistent with the principles cited.

This example may also be used to make a prediction of the future. Extension of the speed trend on figure 14 indicates military aircraft speeds of Mach No. 3 (at 35,000 feet altitude, 1990 m.p.h.), in 1962; and Mach No. 4 (at 35,000 feet altitude, 2660 m.p.h.) in 1966. If military aircraft continue to operate within the atmosphere, these speeds will require structural and materials developments which have not yet been achieved. Thus it may be predicted that the structural and materials developments for an airframe capable of operation at the 800°F surface temperature of Mach 4 speeds will occur not later than 1965-66. This example does not offer proof that the method of prediction is valid, but is cited to show that a forecast may be established by the method given.

Many inferences may be drawn from the characteristics of trend curves. For instance, if a steady decline in rate of progress has been observed in a given technical field, then an increasing exodus of engineers from that technical field may be predicted. This occurs because of the natural drift of engineers away from the "old," fields towards the "new." This exodus will hasten the decline of progress in the older technical field.

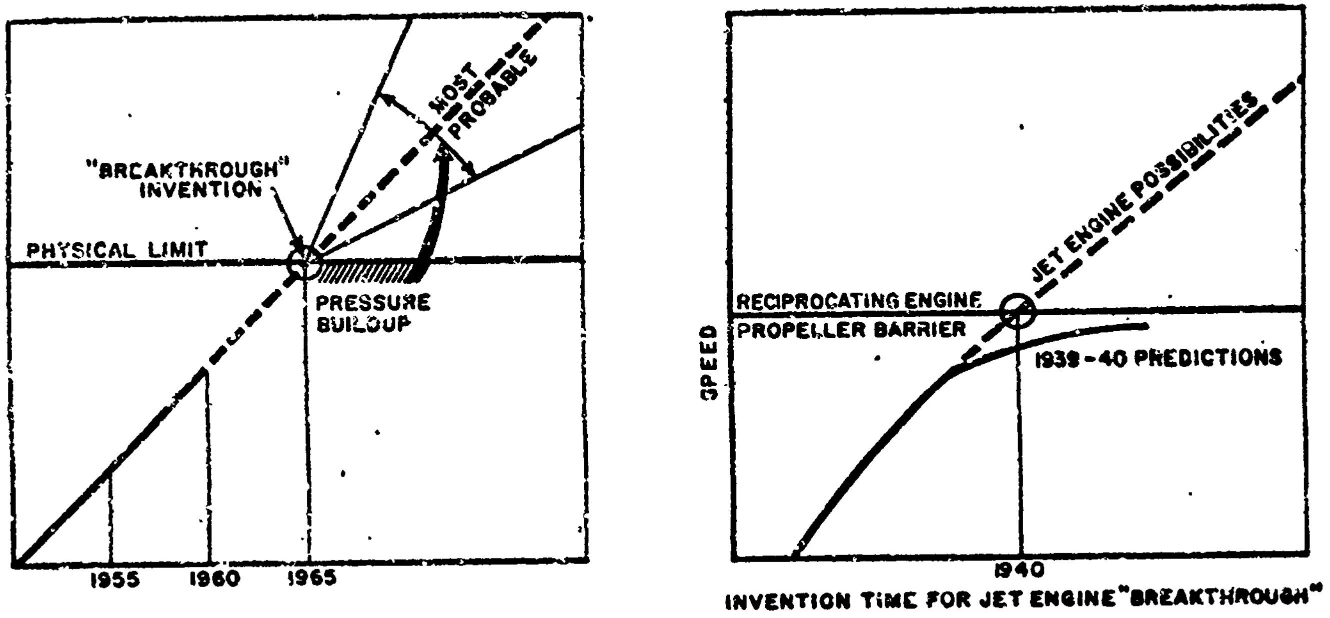

Figure 24. "Breakthroughs".

CHAPTER VI

DYNAMIC FORECASTING

The title "Dynamic Forecasting" is derived from the term "Industrial Dynamics," used by Professor Jay W. Forrester to connote a method of decision making for industrial managers in which complex business operations are simulated on a digital computer. ① By varying the information fed into the computer, the effect of management decisions on future operations may be determined. A similar method may be used for technological forecasting by the effect of various policies on technical progress may be estimated.

The forecasting of technological progress by dynamic simulation requires a model which describes the manner in which technical progress is achieved. The model should represent the elements which produce technical progress, described in terms of a dynamic system which includes information feedback control. In most cases technologies have progressed at exponential rates, so that the model must encompass the possibility of "excursion" or "divergence."

A dynamic model, to represent the development of a technology, has been constructed. Since the model is related to the dissemination of knowledge and to the progress which results therefrom, it is designated the "knowledge-progress system."

Either of two paths might have been followed in the development of this model. As a first alternative, the model might have described a complete cultural system within which the processes of discovery, invention, and innovation could take place. Such a model would be very useful in identifying all of the factors which influence progress. However, such a complete model would require more information about economic and social forces affecting innovation than are currently available. A second alternative was the development of a simple model using a limited number of factors pertaining to education in technology and the progress which is obtained. Such a model has the advantage of conceptual simplicity to aid in understanding its operation, will operate with information currently available, and can be modified as conditions warrant. Such a model may serve for the testing of concepts, policies, and decisions concerning technological progress.

The second alternative is the one represented by the model shown in figure 25. The simplicity of this model is such that tabular computation may be used, without recourse to computer facilities.

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① Jay W. Forrester, "Industrial Dynamics--A Major Breakthrough for Decision Makers," Harvard Business Review, Vol. 36, July--August 1958.

The flow diagram of the knowledge-progress system is as shown in figure 25. A similar diagram, coded in terms of the equations for the dynamic behavior of the system, is given by figure 36, Appendix B; followed by the equations in table B 1, and identification of the variables and constants in table B 2.

The upper section of the diagram represents a system in which personnel are trained in a technology, and after training, are employed either to teach others, to do research, or to do other work. Information feedbacks are employed in this part of the model as a system control, together with information and decisions which are independent of the system. The lower part of the diagram represents technological progress as it is controlled by the number of personnel and the facilities available for research and development.

The starting point for the model is the population bracket of ages 18-21. Variations in the number of people in this bracket will determine the number seeking training, and therefore affect later portions of the system. The size of this reservoir of "population eligible for training" may be determined from census statistics. If a major variation occurs in the size of this 18-21 age bracket it should be taken into consideration. The addition of war veterans to the usual 18-21 age group in 1946 and 1947 is an example of a major variation.

Equation 1R determines the rate of flow of individuals from the total 18-21 age group into the "population" available for training. This rate of flow is actually controlled by a multitude of individual decisions as to the desirability of training. The factors affecting these decisions are statistically collected in terms of information about the number of teachers available; the number of "eligible" individuals; and the current employment ratio in the technical field involved. A proportionality constant, relating the number of potential students to the eligible population under given conditions of the three decision factors, was derived from historical data. During the last 50 years, the number of individuals desiring to enter training has remained a fairly constant proportion of the product of the eligible population times the number of teachers. Adjustment is also necessary for the fact that potential students in the 18-21 age bracket become eligible only once during the three year period, but appear three times in the total. Therefore the total count of the 18-21 population is divided by three so as to reflect only the entry rate of new eligibles.

The flow of individuals making the "choice to accept training" creates a reservoir of individuals available for training, as indicated by equation 2L. The quantity in this reservoir is normally low, representing those individuals desiring to accept training who have not yet been able to enter training. The outflow of the reservoir consists of those who are "received for training", and those who are "diverted from training." Equation 4R indicates the rate of diversion as a function of the length of time which each individual is required to defer his entrance into training. The equation states that one-third of the individuals who are required to wait one year will be diverted; that of the remainder who wait two years, one-half will be diverted; and that all the remainder will be diverted after waiting three years.

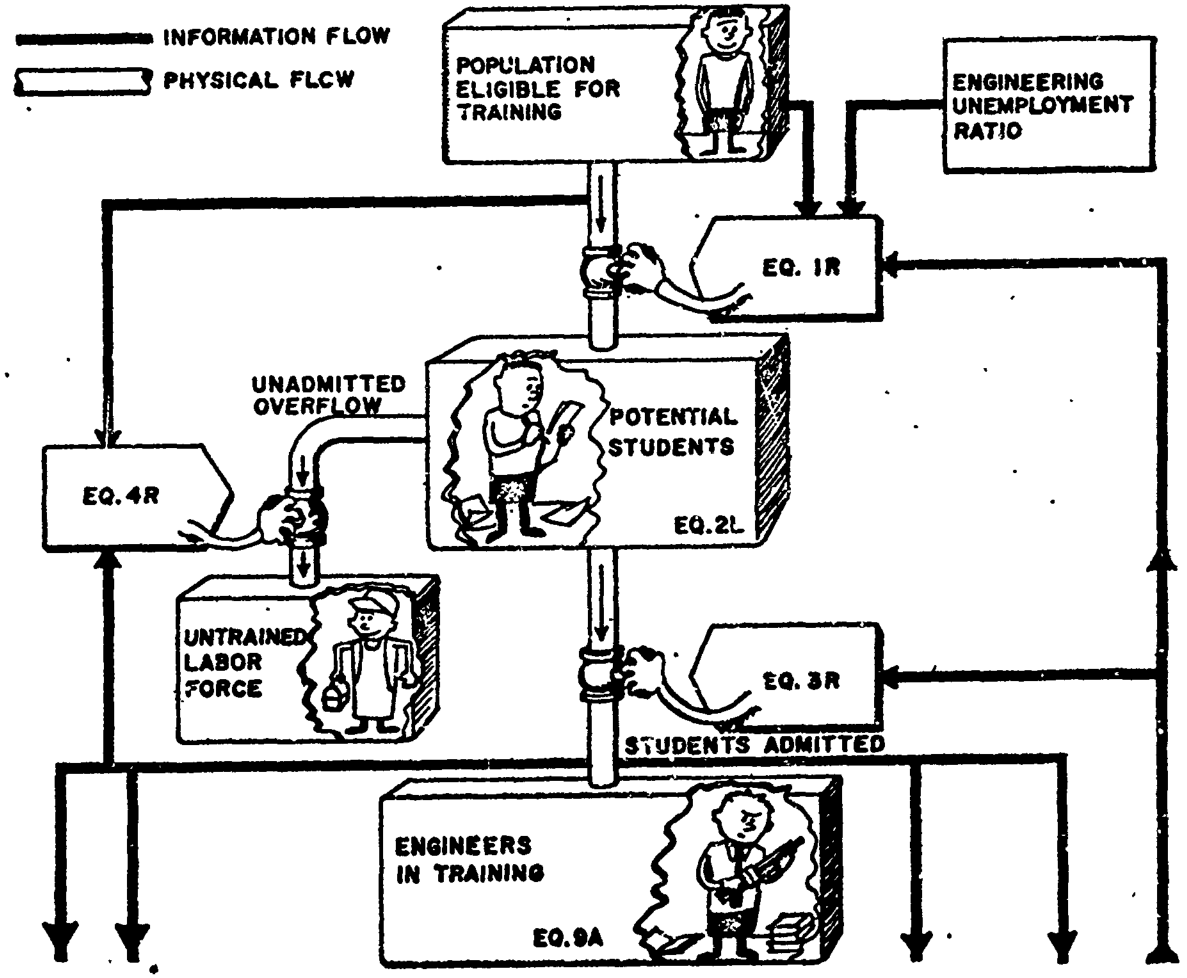

Figure 25. Flow Diagram for Knowledge-Progress System

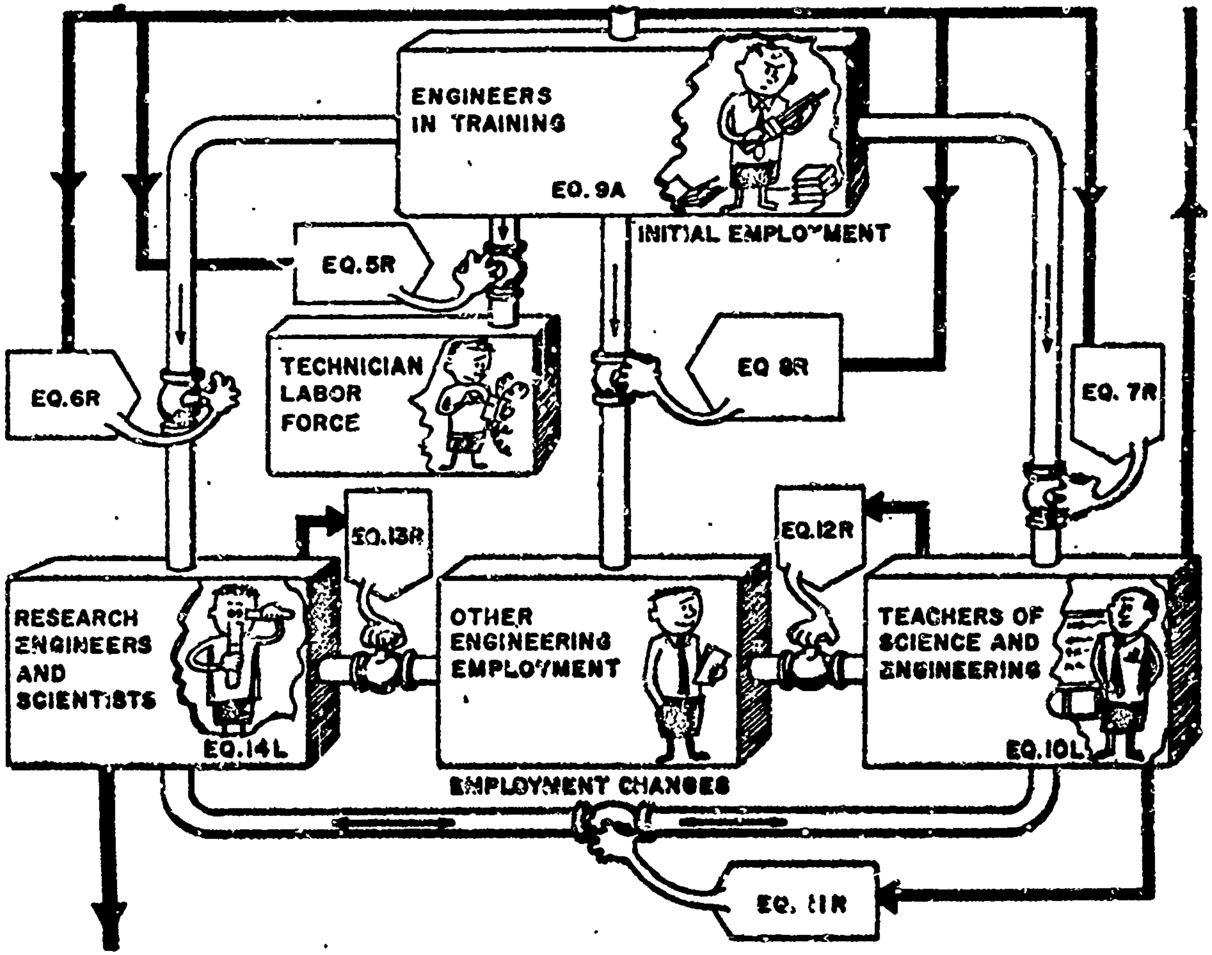

Figure 25. (Cont'd)

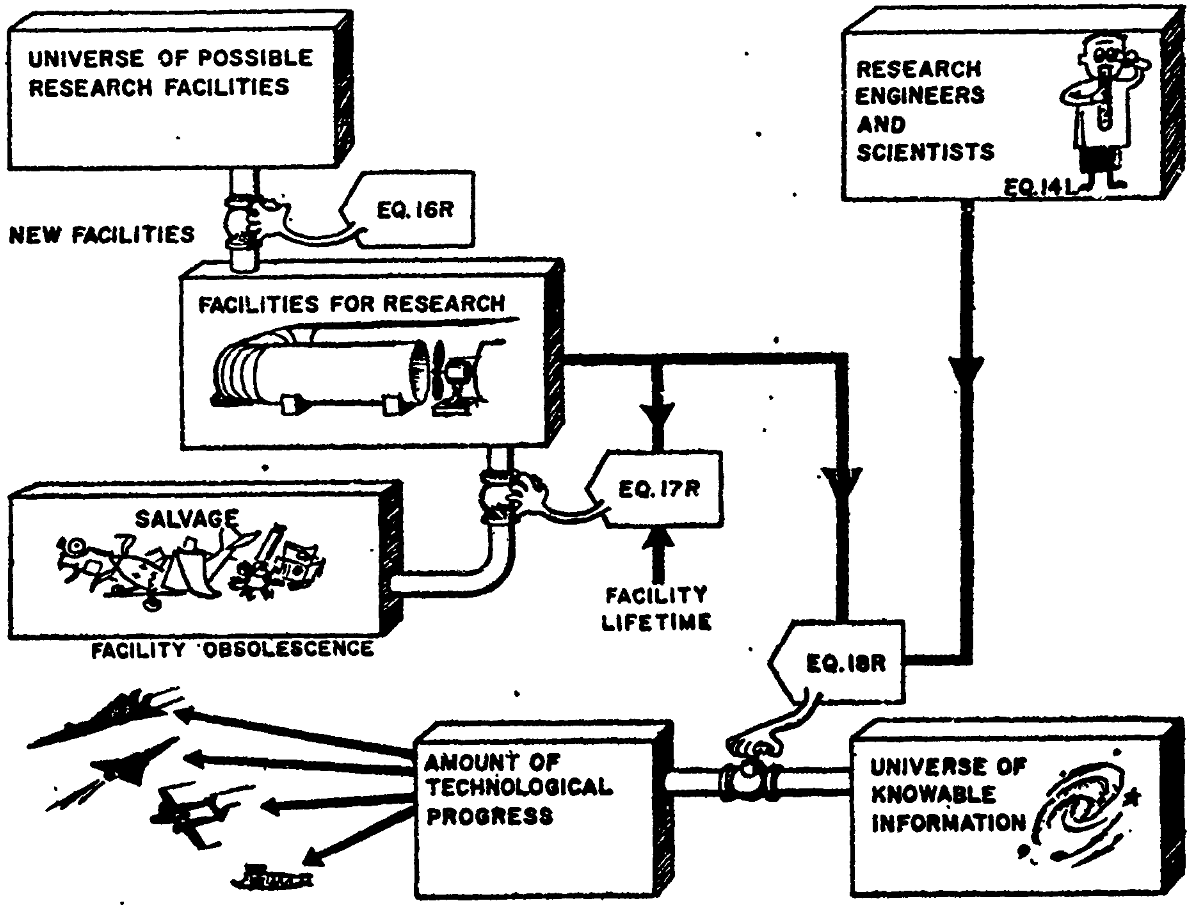

Figure 25.(Cont'd)

Equation 3R represents the rate of flow of individuals "received for training," as a function of the previous rate of acceptance and of additions to the teaching staff. In the absence of additions to the teaching staff the equation states that prior levels of initial enrollment will be maintained. If the teaching staff is augmented, initial enrollment will be increased by the product of a proportionality constant describing "student load per teacher" times the number of teachers added. This constant has been given the value of 15, consistent with the ratio of engineering students per teacher in 1950.

A reservoir of "minds in training," is created by the flow of individuals received for training. This reservoir, as described by equation 9A, contains the individuals in training in the past period, plus the inflow, minus the individuals who fail in training, and minus the individuals who complete their training.

Equation 5R describes the outflow of individuals who fail, in terms of various failure rates times the size of the entry flows for appropriate prior periods. A failure rate is assigned for the first year in which a given flow of students enters, another rate is applied in the second year for the remaining students, and so on to the fourth years. The equation thus is the summation of failures occurring in any given period.

The outflow of individuals who complete their training is described in equations 6R, 7R, and 8R. Each equation describes a portion of the total outflow in terms of the destination of the individuals involved. For example, in equation 6R, the outflow of individuals "available for research" is defined as the proportion of graduates going into research, times the number of graduates expected from the entry class of the fourth prior period. Each entry class is fully accounted for by an equal total outflow by the time that the training period is completed.

Under the actual present day conditions proportions of graduates going into the separate fields of research, teaching, and other employment are determined without regard for the dynamics of the system, or information available from the system. This is the reason for defining the three factors as constants as given in table B2. These values are in accord with present proportions for each field. Other values may be assigned to these constants, representing changes in incentive for entry into each field, in order that the effects of such changes may be observed.

Equations 10L and 14L represent reservoirs of "teachers available to teach engineering," and "research engineers" respectively. The level of each of these reservoirs is a function of its prior level plus the inflow of newly-trained individuals, plus the algebraic addition of flows from or to the other reservoir and to or from the reservoir of engineers in other activities. Information about the number of teachers affects the flow of individuals received for training, as indicated previously. The number of research engineers is a controlling factor in the flow of progress, as will be shown later.

The equations for cross-flow of trained individuals between the reservoirs are 11R, 12R, and 13R. Each of these equations describes the flow from one of the reservoirs to another as a function of the relative "compensation" offered in each area and of the level of the reservoir from which the flow is occurring. The equations indicate that the rate of flow from one field of employment to another is proportional to the difference between the compensations of each field, divided by the sum of the compensations, multiplied by the total employment in the losing reservoir. This represents a reasonable approximation to the actual process of movement between employment fields.

The equations for cross-flow present the "compensations" as constants, determined outside of the system. Since existing compensation policies are almost completely irrational in the larger sense, "compensation equations" would be difficult to establish. However, values for the constants may be obtained by measurements of existing rates of flow, which arise from the relationship of differing compensations in each of the fields. Then the model may be used to test the effect of variations in compensation policy upon the operation of the system.

Since progress in technology requires laboratories, equipment, and other physical facilities, as much as it requires researchers, the model includes provision for these items. Equations 15L, 17R, and 18R represent this element of the system. The rate of construction of "new facilities for research" is determined largely by decisions made independently of information from the model. Operation of the model, therefore, is based on assumptions concerning the rate of facility construction. Assumptions may be made on the basis of available knowledge concerning rates of construction; or a variety of assumptions may be made, so that the effects of each may be determined.

The units of measurement for facility construction are determined by the way in which this term is used in later equations. This requires that research facilities be described in units each of which is equal to the amount of facilities required by one researcher. Determination of the quantity of such units on the basis of information about dollars spent in construction is not simple. However, even a rough estimate is more meaningful than a precise measurement of physical or dollar quantities of facilities which is unrelated to adequate matching of facilities and researchers.

Equation 15L defines "plant or facilities available for research" as the total facilities existing in the prior period, plus new facilities added, less facilities which have become obsolete. "Obsolescence of research facilities" is defined by equation 17R as a third-order delay function of the quantity of existing facilities. This assumes that, for any given input of new facilities, no part of such facilities will become obsolete immediately, but that the rate of obsolescence will rise slowly, reach a peak value somewhat in advance of the average facility "lifetime," and then decline slowly.

The final part of the "knowledge-progress system" relates research facilities and the number of research workers to the rate of "flow of elements of technical progress." Equation 18R describes this flow as a function of the product of the level of "research engineers and scientists" and the level of research facilities, divided by the sum of these quantities. Thus, if the research workers have the proper amount of facilities, the rate of technical progress will be proportionate to the number of researchers. If only half of the required facilities are available, the rate of progress will be reduced by one-third. If twice the required facilities are available, the rate of progress will be increased by only one-third.

The flow of technical progress is equivalent to the release of knowledge from an infinite universe of knowable information. Both the quantity and the variety of this knowable information are infinite. For example, progress in aeronautics might depend upon such varied elements as improvements in aerodynamic theory, refinement of fuels, and better metallurgy. A single unit to describe equal increments of progress in each of these fields would be impossible. The model has been constructed, therefore, so that specification of the units of progress is not necessary at this point.

Equction 19L completes the model by describing total progress in terms of some "desired parameter of technical performance." The equation states that the level of performance which is possible now, equals the level of performance which was previously possible plus the increment of performance achieved by progress. The increment of performance is the product of a proportionality constant times the flow of elements of technical progress. Since the units of output from the combination of research workers and facilities were not converted to units of technical progress, the constant in equation 19L converts the units of output into increments of performance improvement. Thus measurable quantities of research workers and facilities may be related to a measurable performance improvement, even though the intermediate step of "technical progress" is unmeasurable. The constant which relates performance improvement to the number of researchers and research facilities may be determined by the relationship of these factors over some prior period.

The "knowledge-progress system" model may be used for technological forecasting in several ways. If a given technological field is well established, the relationships between the different parts of the model may be determined. Then future operation of the system may be computed on the basis of these relationships, and the resulting improvements in technical performance may be forecast. If the existing relationships are well known, it is possible to use the model for experimenting with changes in the relationships, or with the decisions which bring about the observed relationships. Thus, the effect of such changes on technical performance may be forecast.

In the development of a new technology, the various ways in which the model might operate may be explored. Then decisions may be made which will achieve desired objectives in the operation of the system. Resulting technological improvement may be forecast shortly after the system is put into operation, since the characteristics of system operation will be known. An example of this use of the model is given by Cases 1 and 2 in Appendix B.

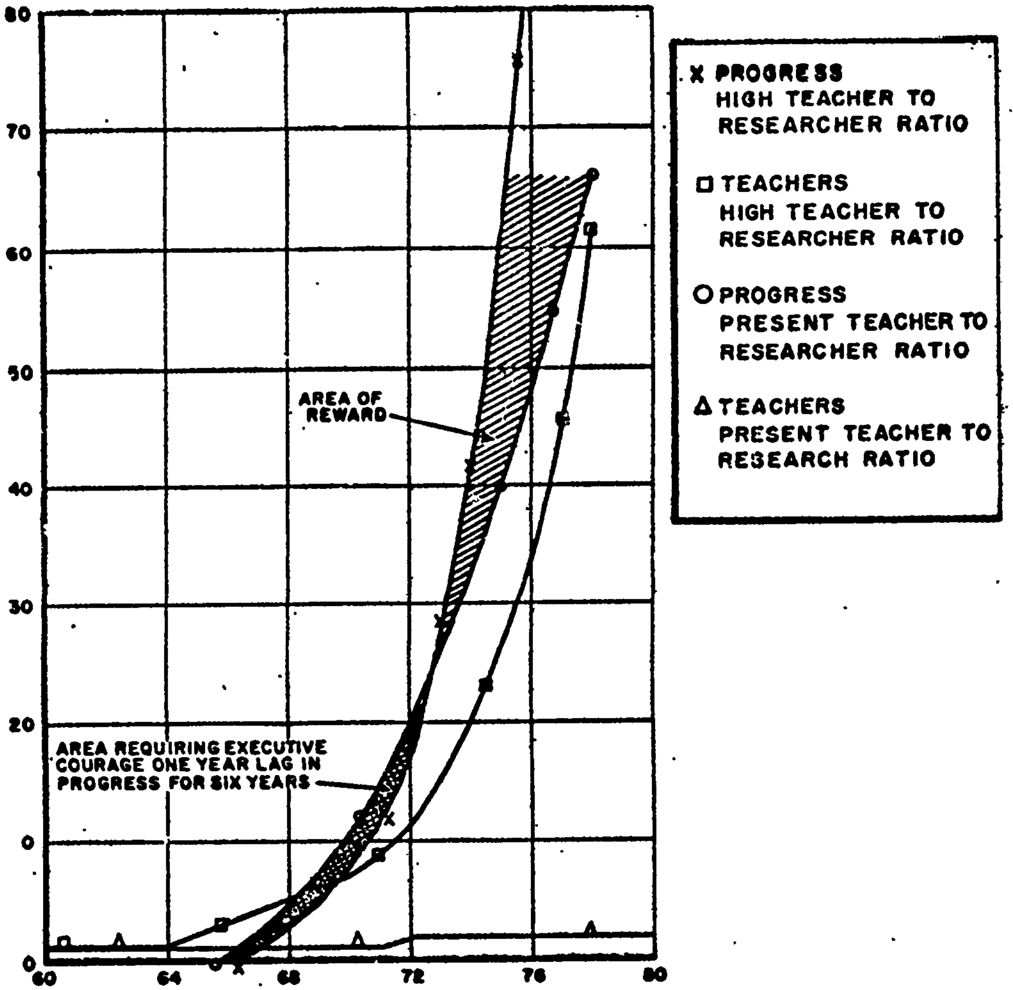

Figure 26. Knowledge-Progress Model

Case 1, Appendix B, demonstrates the development of a new technical field, starting with a single teacher as the originator of the technology. The ratio of graduates going into teaching and into research is set equivalent to existing ratios for all technical fields in the U.S. In this case, the curve depicting the rate of improvement of technical performance is strikingly like the curve of improvement in many technological fields, as cited by Hornell Hart, Kuznets, and others. ②, ③. Thus the characteristic decline in the rate of increase of performance improvement may be due primarily to the ratios between technological training and research and development.

Case 2 shows the development of a new technical field, changed from Case 1 by adjusting upward the proportion of graduates entering teaching, relative to the graduates entering research work. In Case 2, the level of performance is less than in Case 1 for the first seven years. Beyond this seven year period, Case 2 shows very little decrease in the rate of performance improvement, while Case 1 shows the rapid decline which many writers have cited as "maturity."

It may be noted that many writers support the premise that progress is proportional to the number of individuals trained and employed in the process of technological improvement. Since this proposition is fundamental to the "knowledge-progress system," the views of some of these writers will be cited.

Gilfillan (paraphrased), states that individual genius has not been essential to any important invention; that invention comes only at the hands of inventors, and in proportion to their numbers, intelligence, time expended, and mechanical equipment available to them; and that invention is aided by the specialization of labor which results in the specialized occupation of professional inventor. ④

Brozen states, with regard to the differences in profitability of industries, which are related to differences in their research efforts, that there are two reasons why research effort did not grow more rapidly in previous years: First, trained personnel were not available, and second, the science base was inadequate. ⑤ Both of these reasons for the limited increase in research effort are closely related to the dynamics of the "knowledge-progress system" model.

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② Hornell Hart, "Logistic Social Trends," American Journal of Sociology Vol. L (1945) pp. 337-352.
③ Simon S. Kuznets, Secular Movements in Production and Prices (Cambridge: The Riverside Press, 1930).
④ S.C. Gilfillan, The Sociology of Invention (Chicago: Follet Publishing Co., 1935). After stating his 38 principles of invention, Gilfillan develops the reasoning behind each principle in his later chapters, which may be reviewed for further support of the contentions advanced.
⑤ National Science Foundation, Scientific Manpower--1957 (Washington, D.C.: U.S. Government Printing Office, 1958). Scientific Advance as a Factor in Economic Change, Yale Brozen, P. 10.

CHAPTER VII

COMBINATIONS OF FORECASTING METHODS

No one of the methods of forecasting cited in the preceding chapters is unquestionably superior to the others. Therefore the best prediction for a given purpose may require several forecasts using alternate methods. The several forecasts may provide a range of probable developments; they may be combined to give a single estimate of the future; or they may provide a choice of predictions according to the purpose for which it is to be used. Variation among the several forecasts may signal a change in the trend of events, or may emphasize the need for additional predictive effort.

The combination of forecasts should start with the extrapolation of existing exponential trends. If these trends are well established, and if artificial restrictions have not limited progress, then continued exponential progress is the maximum rate of progress likely to be achieved. To obtain a more rapid rate of progress, drastic changes are necessary; either in the procedures which have produced past progress, in the technology involved, or in the objectives toward which progress is directed. For example, the maximum speed of aircraft increased exponentially, doubling every ten years, so long as the technology was limited to manned aerodynamic vehicles and air-breathing propulsion systems. Speed increases greater than this rate were achieved only by the changes in technology and objectives represented by the unmanned ballistic missile with rocket propulsion.

After the exponential rate of progress has been established, then other rates may be forecast by biological analogies, by use of correlative techniques or by use of dynamic forecasting methods. The smallest rate of progress predicted by these methods represents the minimum probable rate of progress.

The maximum and minimum rates of progress enclose the area of probable progress. If this area is too broad, the forecasts may be examined to determine a single, most probable rate of progress. Although no logic supports the averaging of predictions, an average may be used if there is no evidence that any one of the predictions is more accurate than the others. Any technique of averaging may be used to obtain a forecast, but the forecaster should not assume that a major improvement in forecasting has thereby been obtained.

The "average" forecast may be used simply for the convenience of dealing with a single set of values representing future progress. A further advantage of a single forecast lying between the extremes occurs when the forecast is used by a large number of individuals to guide a variety of decisions. If it cannot be predetermined that such individuals would use the most appropriate forecast for their decisions, the least damage will be done by providing only a single, average forecast.

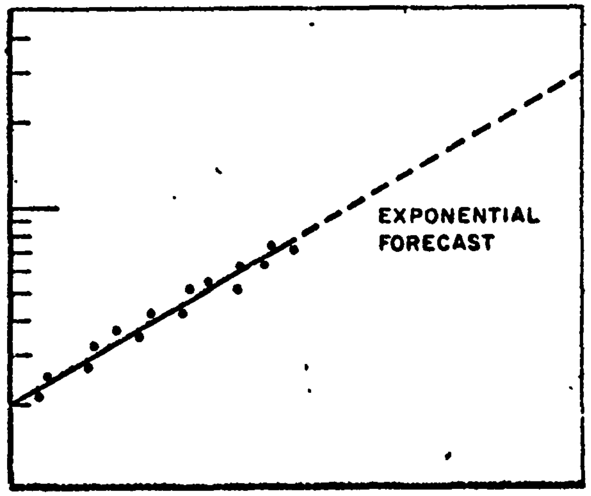

Figure 27. BASIC FORECAST

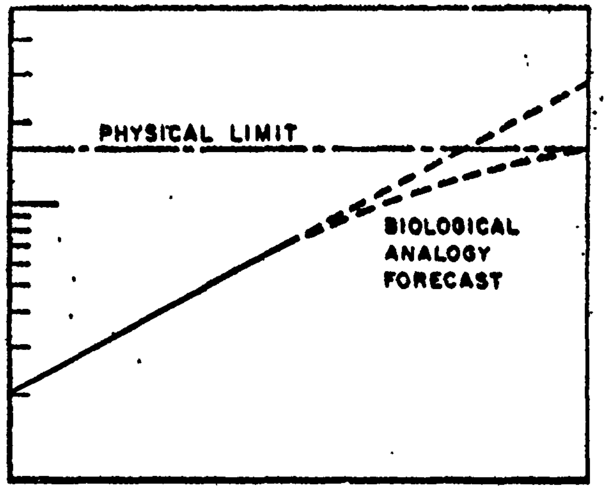

Figure 28. MODIFIED FORECAST

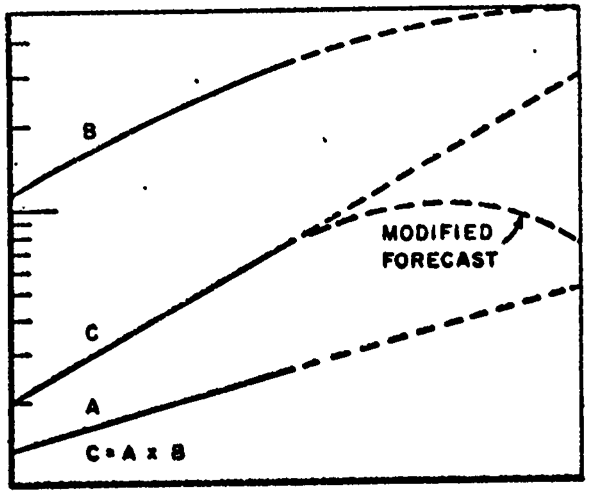

Figure 29. DEPENDENT FACTOR MODIFICATION

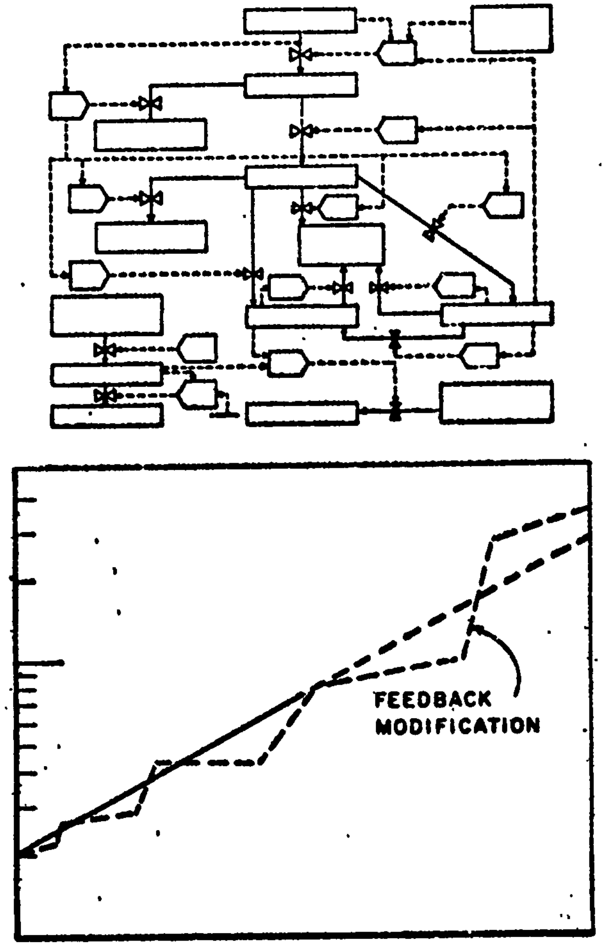

Figure 30. DYNAMIC FORECASTING MODIFICATION

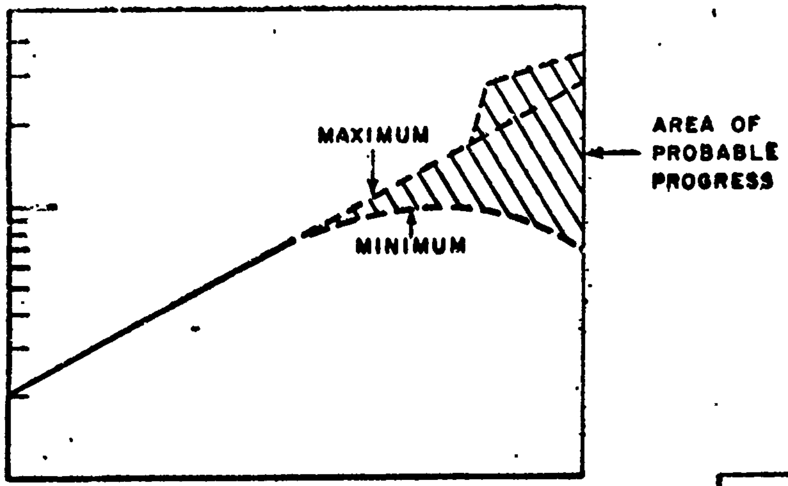

Figure 31. LIMITS OF PROBABLE PROGRESS

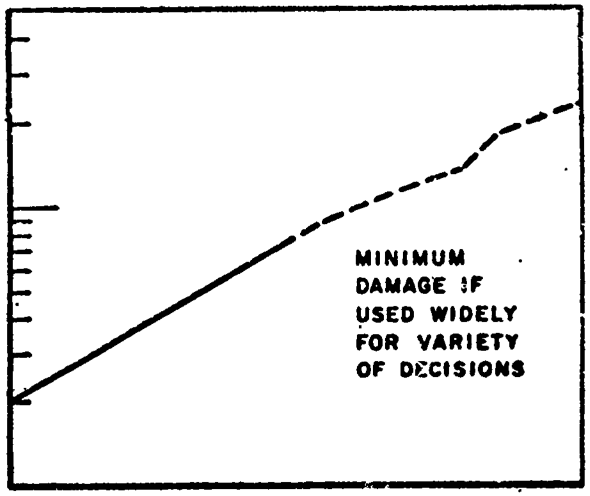

Figure 32. AVERAGE FORECAST

If several different forecasts of the rate of progress of some parameter of technical performance have been developed, each of these forecasts may be used as a basis for separate actions or decisions. Such use of different forecasts does not imply inconsistency, but rather reflects the relative consequences of actions based on the different forecasts. As an example, if the decision concerns the rate of investment in research in a competitive situation, then a prediction that competitors will continue an existing exponential rate of progress is more conservative than one which assumes a lessened rate of progress. On the other hand, if the decision concerns investment in an old technology competing against a newer technology, a forecast of "maturity," or a declining rate of increase, in the old technology will be more conservative.

A wide variation in forecasts may indicate that significant changes in the technology are about to take place. For example, a prediction by dynamic forecasting may indicate that the rate of progress in technology "A" will rapidly diminish in the near future. At the same time exponential extrapolation may indicate a far more rapid rate of progress. Under these conditions the forecaster may well look for a new technology which will take over the burden of progress formerly born by technology "A".

Systematic forecasting offers a high probability of disclosure of changes, and frequently points to causal factors. Thus an entire body of evidence supporting such changes is highlighted for detailed examination.

The variation in two forecasts of technological progress may indicate that the lower rate of progress will prevail, unless substantial changes are made in the supply of resources. In such a case, the variation signals for a managerial decision, either to increase the resources, and thereby the rate of progress, or to accept the lower rate of improvements. Thus the possibility of "decision-by-default" is reduced when the facts are made clear by difference between two predictions.

Most forecasters may be well pleased with the results of a single forecasting attempt, since it is an "obvious" and "unambiguous" prophecy. If, however, a second or a third method is used, which produces a different forecast of equal credibility, then the "obvious" becomes subject to closer scrutiny. Additional investigation will usually disclose significant information leading to a better forecast; and will lead to greater knowledge of the factors involved in achieving further progress.

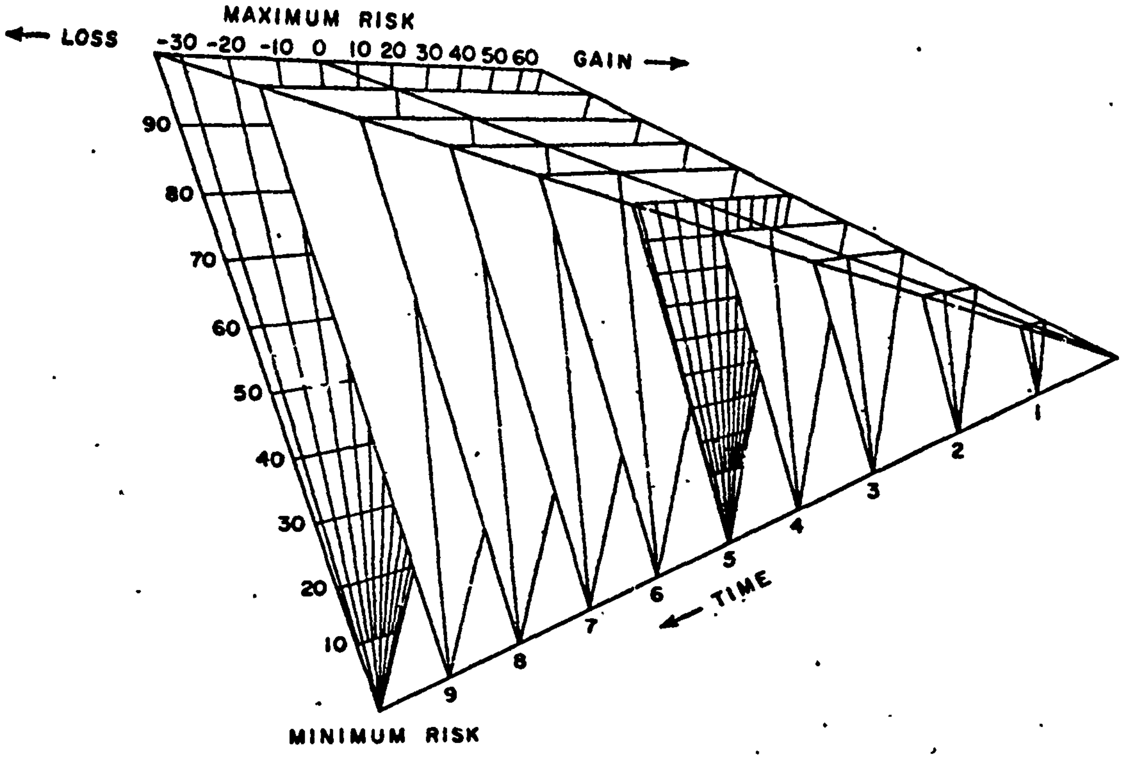

Figure 33. MINIMAX PYRAMID

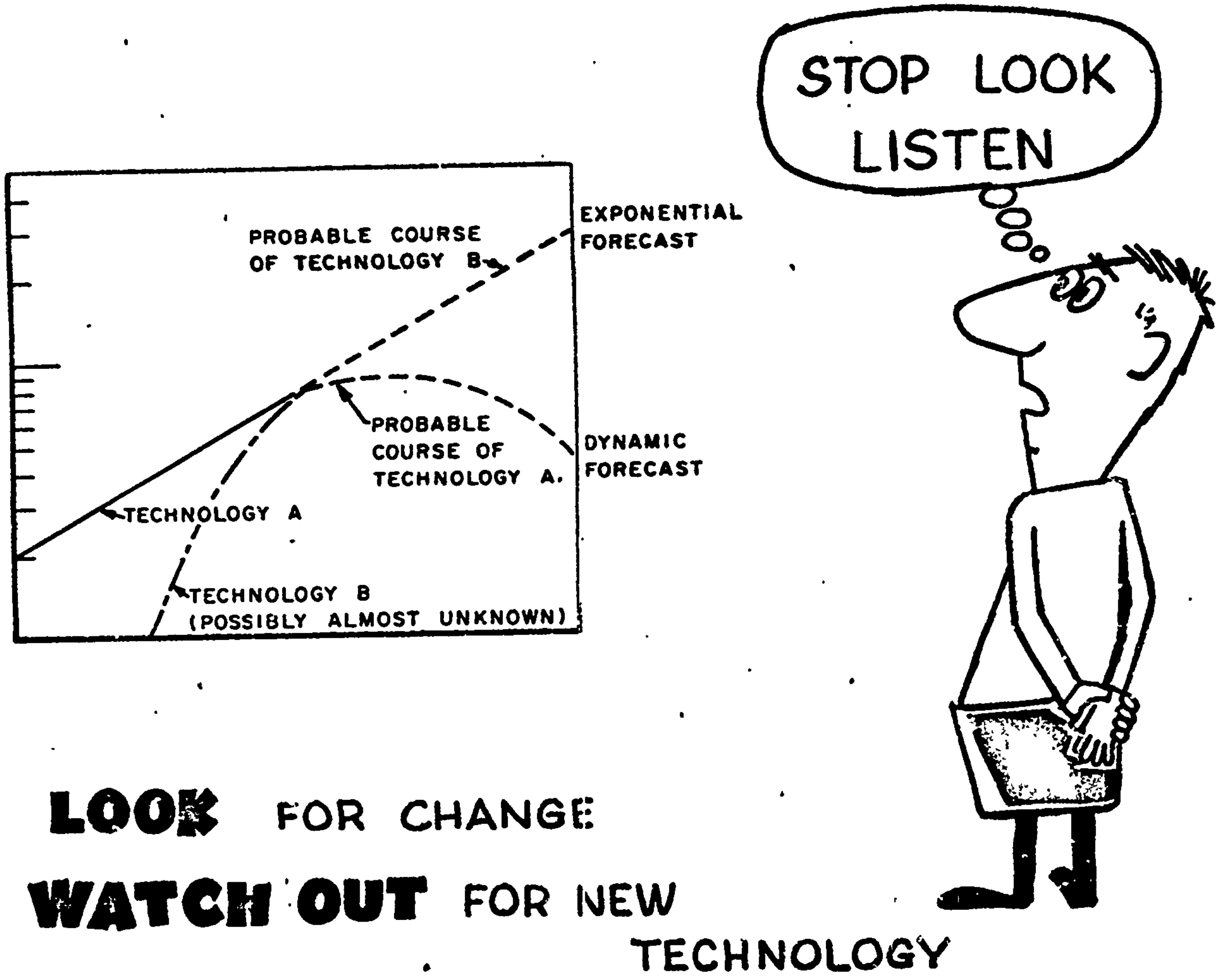
STOP LOOK LISTEN
PROBABLE COURSE OF TECHNOLOGY B
EXPONENTIAL FORECAST
PROBABLE COURSE OF TECHNOLOGY A.
DYNAMIC FORECAST
TECHNOLOGY A
TECHNOLOGY B (POSSIBLY ALMOST UNKNOWN)
LOOK FOR CHANGE
WATCH OUT FOR NEW TECHNOLOGY

Figure 34.

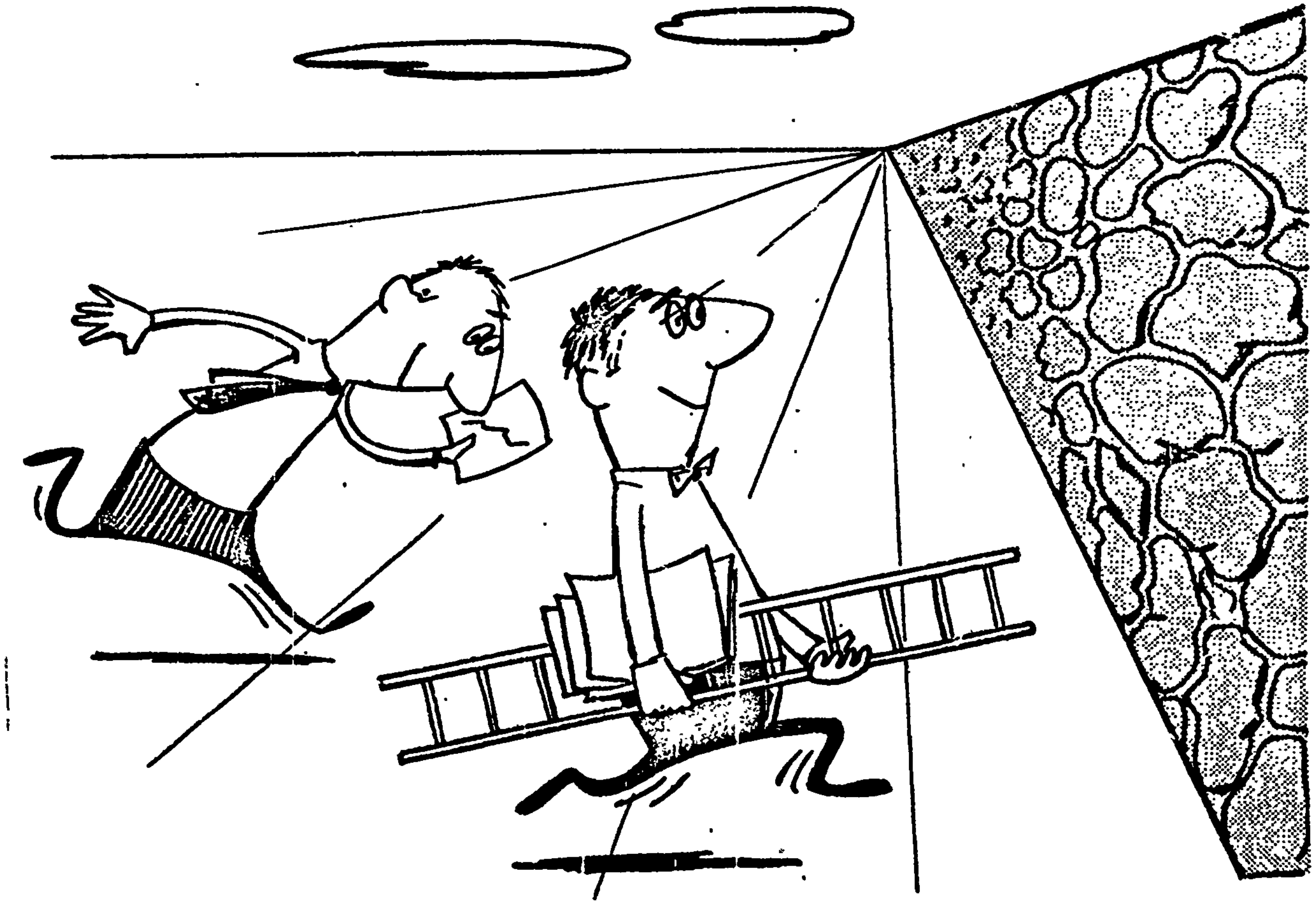

Figure 35. The Value of Additional Investigation

CHAPTER VIII

SUMMARY

The several methods of technological forecasting developed in the preceding chapters indicate the possibilities of predicting technical innovation on a systematic basis. The several methods enable the projection of progress by the use of regular rules and procedures. Each of the methods affords a forecast of quantitative improvements of technical performance to be achieved at definite intervals of time. The procedures permit reproducibility of results by independent investigators, subject to agreement upon initial conditions and the specific method used. Each technique has been developed on the basis of logical premises, which may be examined to determine the credibility of forecasts made by that technique.

Effective technological forecasting is essential to long range planning in any organization where technology plays a major role. Prediction of the probable rate of future progress is necessary in order to plan effective research and development. Ultimately the forecast provides the basis for plans to make use of the technological progress which is predicted.

The extrapolation of exponential rates of progress, outlined in Chapter III, is the simplest method of forecasting consistent with historical patterns of technological advance. This method conforms to the pattern of progress in Western civilization over the last four centuries, and is likely to provide successful forecasts of progress in major technical fields.

The analogy of biological growth to technological progress offers a logical extension to prediction by simple extrapolation. The biological analogy developed in Chapter IV predicts exponential advance in the early stages of a given technology, followed by diminution of the rate of advance as the technology becomes "mature." The analogy of biological growth has been loosely applied in explanation of progress in many economic and technological fields. In many of these applications the analogy has been erroneously used, with consequent failure in prediction. However, if the growth analogy employs factors and relationships which are truly analogous, then credible predictions of future progress are possible.

Correlation of progress in a given technical field with the similar advance of some related factor, as developed in Chapter V, is an effective method of forecasting if the known factor has a causal or consistent relationship with the progress to be predicted. If the known factor has sufficient lead-time over the unknown factor, this method provides a long-range forecast which is particularly acceptable.

The use of relationships between two or more factors which jointly determine the rate of technical improvement is also described in Chapter V. Interdependent relationships in forecasting may also be used when the extension of two or more trends would result in an impossible or improbable situation.

Patterns in trend curves may be used to predict certain events by the use of techniques described in the concluding section of Chapter V. This method of forecasting may be used to predict rather accurately the probable occurrence of major inventions, and the development of new technologies.

"Dynamic Forecasting" employs the principles of information feedback control to describe the operation of a dynamic system for producing technical progress. This offers an effective method for prediction of irregular advances in technology. The technique, described in Chapter VI, employes a dynamic model to simulate the relationship of such factors as the number of teachers of a given technology, the number of potential students, the number of researchers, and the extent of research facilities, to the rate of technological progress. This method may be used to test the effect of alternate courses of action upon future progress.

All of the preceding methods may be used to predict technological progress. Multiple methods tend to confirm forecasts of progress if essential agreement is obtained from all of the methods. A "most probable" estimate, or a range of possible rates of progress, may be established from multiple forecasts which do not agree. Wide variation in forecasts may signal that major changes in technology are imminent, or that further investigation is needed.

The development of these methods of forecasting indicates that prediction of technological progress need not be on a purely intuitive basis. The methods presented herein, if applied to the forecasting of technological development, should substantially improve long range planning activity not previously supported by careful forecasting.

An implied conclusion of each of the forecasting methods except the method of "dynamic forecasting," is that a certain determinism governs the rate of technical progress. From this conclusion, it is often erroneously argued that since the rate of progress is inevitable, then it need not be forecast, since actions necessary to such progress will occur without being planned. If world society is taken as the framework within which progress is being made, then this deterministic view is probably valid. However, achievement of the projected progress is not inevitable for smaller segments of society. Those countries, industries, and companies which fail to anticipate the probable rate of progress will be overtaken by the course of events. They will become followers rather than leaders in technical progress. On the other hand, if small segments of society attempt to exceed the deterministic rates of advance they will usually fail because such rates derive from the basic technological developments which support the whole society.

The methods of technological forecasting presented herein are recommended for use in long range planning. Each of the techniques has advantages for certain types of forecasting problems, which may be determined only by experience and actual trial. Forecasts which indicate a continuous rate of progress are recommended in preference to forecasts of discrete levels of progress to be achieved at specific intervals. The continuous forecast shows clearly at all times the gap between performance actually achieved and the predicted performance. In contrast, the forecast which describes events at widely separated intervals permits complacency during the interim. The continuous forecast of technical improvement indicates that the penalty of tardy achievement is substandard performance.

Male's recommendations that relate forecasting to the long range planning function are repeated below since they are pertinent to the techniques developed in this study: ①

(1) Forecasting should be established as clear and distinct from long range planning, for which it forms a major basis.

(2) The elements of economic development and technical development should be separated when forecasting is done so that "possible" technical improvements are not confused with "probable" developments under limiting economic conditions.

(3) Research efforts should be monitored to detect significant discoveries which may forecast the probable direction of technical advance.

(4) Long range forecasts should be reviewed and brought up to date at regular intervals.

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① Donald Warren Male, Prophecies and Predictions in Aviation (Cambridge: Unpublished Master's Thesis, 1958) pp. 43-48.

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APPENDIX A

Forecast Examples

Table A 1

Ratio of Wing Span to Length
for U.S. Combat Aircraft

Year of First Delivery	Airplane	Span (Ft)	Length (Ft)	Ratio $\left(\frac{\text{Span}}{\text{Length}}\right)$
1921	Boeing MB-3A	28.6*	20.0	1.43
1922	Curtiss NBS-1	81.5*	42.7	1.90
1924	Curtiss PW-8	35.8*	22.5	1.58
1925	Curtiss P-1	34.6*	22.9	1.51
1927	Boeing PW-9C	35.2*	23.0	1.53
1929	Curtiss P-6	34.6*	23.5	1.47
	Boeing P 12	33.0*	20.0	1.65
1932	Keystone B-4A	82.2*	48.9	1.68
1933	Boeing P-26A	28.0	23.9	1.17
1934	Martin B-10B	70.5	44.8	1.57
1937	Boeing YB-17	103.9	68.3	1.51
	Douglas B-18	89.5	56.7	1.58
	Seversky P-35	36.0	25.1	1.43
1938	Curtiss P-36A	37.4	28.5	1.31
1939	Lockheed YP-38	52.0	37.9	1.37
	Curtiss P-40	37.4	31.8	1.18
1940	North American B-25	67.5	51.1	1.32
	Bell F-39C	34.0	30.1	1.13
1941	Martin B-26	65.0	56.0	1.16
	Convair B-24D	110.0	66.3	1.65
	Republic P-43	36.0	28.5	1.26
1942	Martin B-26B	71.0	58.3	1.22
	Republic P-47D	40.8	36.0	1.13
	North American P-51A	37.0	32.3	1.14

* Equivalent Monoplane Span

Fahey, James C., U.S. Army Aircraft 1908-1946 (New York: Ships and Aircraft, 1946).

Table A 1 (Cont'd)

Year of First Delivery	Airplane	Span (Ft)	Length (Ft)	Ratio $\left(\frac{\text{Span}}{\text{Length}}\right)$
1943	Bell P-63A	38.3	32.7	1.17
1944	Boeing B-29	141.3	99.0	1.43
1945	Lockheed P-80A	39.0	34.6	1.13
1946	Republic YP-84	36.9	36.5	1.01
1947	Convair B-36	230.0	163.0	1.41
1948	North American F-86A	37	37	1.00
1949	Boeing B-47A	116	107	1.08
1952	Republic F-84F	33.5	43.4	.77
1953	Convair F-102A	38.0	68.3	.56
1954	Boeing B-52A	185.0	152.8	1.21
	McDonnell F-101C	40	67.5	.59
1955	North American F-100A	38	47	.81
1956	Convair B-58	57	97	.59
1958	Republic F-105B	35	64	.55
	Lockheed F-104A	22	56.8	.40

Table A 2

Gross Weight of U.S. Single-Place Fighter Aircraft		
Year of First Delivery	Airplane	Gross Weight (Thousands of Pounds)
1918	(Nieuport 27 C.1)	1.3
1918	(Spad XIII C.1)	2.0
1921	Boeing MB-3A	2.5
1924	Curtiss PW-8	3.2
1925	Curtiss P-1	2.8
1927	Boeing PW-9C	3.2
1929	Curtiss P-6	3.2
1930	Boeing P-12B	2.6
1933	Boeing P-26A	3.0
1937	Seversky P-35	5.6
1938	Curtiss P-36A	6.0
1939	Curtiss P-40	7.2
1940	Bell P-39C	7.2
1941	Lockheed P-38	15.3
	Republic P-43	7.8
1942	Republic P-47D	14.5
	North American P-51	9.0
1943	North American P-51B	11.8
	Bell P-63A	10.0
1945	Lockheed P-80A	11.7
1946	Republic YP84	16.5
1948	North American F-86A	13.8
1952	Republic F84F	25.0
1953	North American F-86F	17.0

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Table A 3

Speed Trend of U.S. Military Aircraft		
Year of First Delivery	Airplane	Maximum Speed (MPH)
1909	Wright Bros. B	42
1916	Curtiss JN-4	80
1918	(Nieuport 27 C.1)	110
1918	(Spad XIII C.1)	135
1921	Boeing MB-3A	141
1924	Curtiss PW-8	161
1925	Curtiss P-1	163
1927	Boeing PW-9C	158
1929	Curtiss P-6	180
1929	Boeing P-12	171
1933	Boeing P-26A	234
1934	Martin B10-B	212
1937	Boeing YB-17	256
	Seversky P-35	281
1938	Curtiss P-36A	300
1939	Curtiss P-40	357
1940	North American B-25	322
	Bell P-39C	379
1941	Martin B-26	315
	Republic P-43	350
1942	Republic P-47D	420
	North American P-51A	390
1943	North American P-51B	436
1945	Lockheed P-80A	578

(See footnote on following page.)

Table A 3 (Cont'd)

Year of First Delivery	Airplane	Maximum Speed (MPH)
1946	Republic XP-84A	619*
1948	North American F-86A	671*
1950	Boeing B-47A	600
1953	Convair F-102A	860
1954	McDonnell F-101C	1200
1956	Convair B-58	1330
1958	Lockheed F-104A	1404*

Fahey, James C., U.S. Army Aircraft 1908-1946 (New York: Ships and Aircraft, 1946).

Performance after 1953 from Aviation Week Vol. 70, No. 10, (March 9, 1959) p. 186.

*World Record Performance.

Table A 4

Comparative Speed Trends of Combat and Transport Aircraft*

Year of First Airline Operation	Airplane	Maximum Speed (M.P.H.)	Military Designation
1925	Fokker F-IV	95	T-2
1927	Fokker Trimotor	116	C-2
1928	Ford-Stout 4-AT-B	111	C-3
1931	Ford-Stout 5-AT-B	148	C-4A
1933	Curtiss Condor T-32	161	YC-30
1933	Boeing 247D	200	C-73
1934	Douglas DC-2	202	C-33
1935	Douglas DC-3	220	C-47
1941	Curtiss-Wright CW-20	264	C-46
1942	Douglas DC-4A	275	C-54
1946	Lockheed 649	329	C-69
1947	Douglas DC-6	370	C-118
1950	Lockheed 1049	370	
1954	Douglas DC-7	409	
1958	Lockheed Electra	450	
1958	Boeing 707	610	
1960	Boeing 720	649	

*Speeds of Military Aircraft from table 3 and figure 3.

Fahey, James C., U. S. Army Aircraft 1908-1946 (New York: Ships and Aircraft, 1946).

Table A 5

Domestic Trunk Airline Operation				
Year	Total Passenger Miles (Millions)	Total Plane Miles (Millions)	Load Factor %	Seating Capacity
1930	84	34	33	8
31	106			
32	127			
33	173			
34	188			
35	314			
36	436			
37	477			
38	558	83	50	13
39	736			
1946	5903	305	79	25
1948	5822	316	58	
1950	7766	327	63	38
1952	12121	411	67	46
53	14298	467	65	
54	16246	497	63	52
55	19217	564	64	
56	21643	622	64	54
57	24500	711	62	
58	24435	700	60	58
	-----	Prediction	--	--
		"Trend"		"False"
1960	34000	1000	65	53
1964	47000	1560	65	46

Table A 5 (Cont'd)

Year	Total Passenger Miles (Millions)	Total Plane Miles (Millions)	Load Factor %	Seating Capacity
		Prediction "Trend"		"False"
1968	60000	2440	65	38
1970	67000	3000	65	34
1974	80000	4800	65	26
1976	86000	6000	65	22
1980	96000	9600	65	16

$$\text{Seating Capacity} = \frac{\text{Passenger Miles}}{\text{Plane Miles X Load Factor}}$$

APPENDIX B

Diagrams and Equations for Dynamic Forecasting

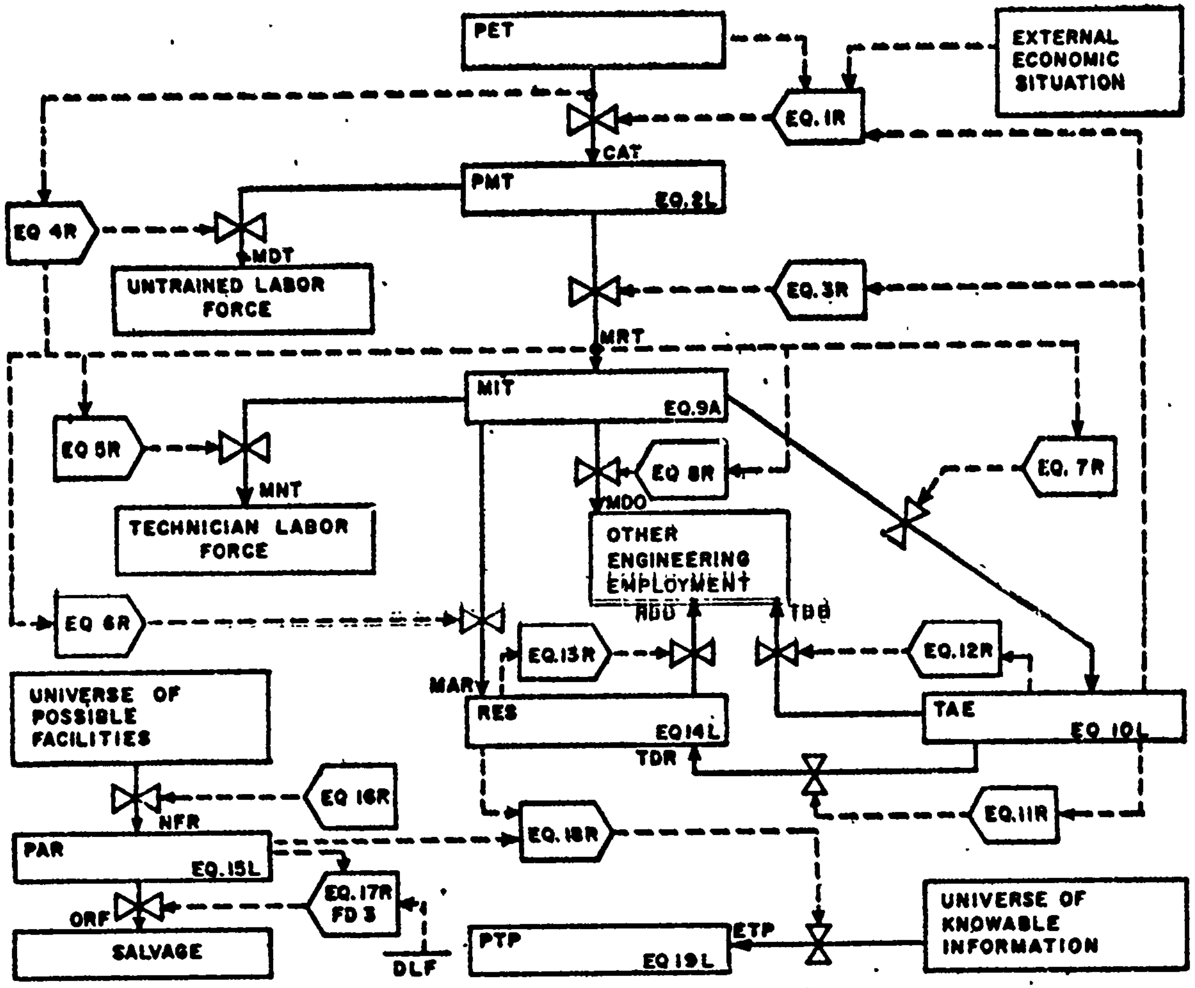

Figure 36. Flow Diagram for Knowledge-Progress System

Table B 1

Knowledge-Progress System Equations

DT = 1 Year	Eq. No.
$\mathrm{CAT.KL} = \mathrm{APT} \times \frac{\mathrm{PET.K}}{3} \times \left[\frac{\mathrm{ESE.K}}{\mathrm{ESA.K}}\right]^3 \times \mathrm{TAE.K}$	(1R)
$\mathrm{PMT.K} = \mathrm{PMT.J} + \mathrm{DT}(\mathrm{CAT.JK} - \mathrm{MRT.JK} - \mathrm{MDT.JK})$	(2L)
$\mathrm{MRT.KL} = \mathrm{MRT.JK} + (\mathrm{AST})\,(\mathrm{TAE.K} - \mathrm{TAE.J})$	(3R)
(Note: DT(MRT.KL) cannot exceed PMT.K + DT(CAT.KL)	
$\mathrm{MDT.KL} = 1/3\left[(\mathrm{CAT.IJ} + \mathrm{CAT.JK} + \mathrm{CAT.KL}) - (\mathrm{MRT.IJ} + \mathrm{MRT.JK} + \mathrm{MRT.KL})\right]$	(4R)
$\mathrm{MNT.KL} = (\mathrm{AFL})\,(\mathrm{MRT.HI}) + (\mathrm{AFT})\,(\mathrm{MRT.IJ}) + (\mathrm{AFS})\,(\mathrm{MRT.JK}) + (\mathrm{AFF})\,(\mathrm{MRT.KL})$	(5R)
$\mathrm{MAR.KL} = (\mathrm{AGR})\,(\mathrm{AGE})\,(\mathrm{MRT.GH})$	(6R)
$\mathrm{MAT.KL} = (\mathrm{AGT})\,(\mathrm{AGE})\,(\mathrm{MRT.GH})$	(7R)
$\mathrm{MDO.KL} = (\mathrm{AGO})\,(\mathrm{AGE})\,(\mathrm{MRT.GH})$	(8R)
$\mathrm{MIT.K} = \mathrm{MIT.J} + \mathrm{DT}(\mathrm{MRT.JK} - \mathrm{MNT.JK} - \mathrm{MAR.JK} - \mathrm{MAT.JK} - \mathrm{MDO.JK})$	(9A)
$\mathrm{TAE.K} = \mathrm{TAE.J} + \mathrm{DT}(\mathrm{MAT.JK} - \mathrm{TDR.JK} - \mathrm{TDO.JK})$	(10L)
$\mathrm{TDR.KL} = \frac{\mathrm{ACR-ACT}}{\mathrm{ACR+ACT}} \times \mathrm{TAE.K}$	(11R)
$\mathrm{TDO.KL} = \frac{\mathrm{ACO-ACT}}{\mathrm{ACO+ACT}} \times \mathrm{TAE.K}$	(12R)
$\mathrm{RDO.KL} = \frac{\mathrm{ACO-ACR}}{\mathrm{ACO+ACR}} \times \mathrm{RES.K}$	(13R)
$\mathrm{RES.K} = \mathrm{RES.J} + \mathrm{DT}(\mathrm{MAR.JK} + \mathrm{TDR.JK} - \mathrm{RDO.JK})$	(14L)
$\mathrm{PAR.K} = \mathrm{PAR.J} + \mathrm{DT}(\mathrm{NFR.JK} - \mathrm{ORF.JK})$	(15L)
NFR.KL = Rate of facility construction, determined outside of the system	(16R)
$\mathrm{ORF.KL} = \mathrm{FD3}(\mathrm{PAR.K}, \mathrm{DLF})$	(17R)
$\mathrm{ETP.KL} = f(\mathrm{RES.K}), (\mathrm{PAR.K})$ Assume $= \frac{\mathrm{RES.K} \times \mathrm{PAR.K}}{\mathrm{RES.K} + \mathrm{PAR.K}}$	(18R)
$\mathrm{PTP.K} = \mathrm{PTP.J} + \mathrm{ARP}(\mathrm{ETP.JK})$	(19L)

Table B 2

Variables and Constants for Knowledge Progress System

1. ACO = ConstAnt, Compensation of engineers for Other purpose
2. ACR = ConstAnt, Compensation of Researchers
3. ACT = ConstAnt, Compensation of Teachers
4. AFF = Proportionality constAnt of Failures, First year = $\frac{7}{32} \approx .2$
5. AFS = Proportionality constAnt of Failures, Second year = $\frac{5}{32} \approx .2$
6. AFT = Proportionality constAnt of Failures, Third year = $\frac{4}{32} \approx .1$
7. AFL = Proportionality constAnt of Failures, Last year = $\frac{3}{32} \approx .1$
8. AGE = Proportionality constAnt of Graduates to size of Entry class from which that group of graduates is drawn = $\frac{13}{32} \approx .4$
9. AGO = Proportionality constAnt of Graduates going into Other activity, normally = $0.347 \approx 0.38$
10. AGR = Proportionality constAnt of Graduates going into Research & development, normally = $0.630 \approx 0.60$
11. AGT = Proportionality constAnt of Graduates going into engineering college Teaching, normally = $0.023 \approx .02$

Note: AGO + AGR + AGT must equal 1.00

12. APT = Proportionality constAnt of Population desiring to enter Training, per teacher, under full employment conditions = $\frac{.026}{13000} = 2 \times 10^{-6}$

Table B 2 (Cont'd)

Variables and Constants for Knowledge Progress System

13. ARP = Proportionality constAnt relating performance improvement to input of Researchers and research Plant.
$= \frac{PTP.J - PTP.I}{RES.I \times PAR.I}$ (Determined on the basis of actual relationship for some prior period)

14. AST = Proportionality constAnt, Student load per Teacher = 15

15. CAT = Choice to Accept Training

16. DLF = Delay, Lifetime of research Facilities (average lifetime, or D, = 10 years)

17. ESA = Engineers and Scientists Available (determined outside of the system)

18. ESE = Engineers and Scientists Employed (determined outside of the system)

19. ETP = Flow of Elements of Technical Progress

20. MAR = Minds Available for Research & development

21. MAT = Minds Available to Teach engineering

22. MDO = Minds Diverted to Other purposes

23. MDT = Minds Diverted from Training

24. MIT = Minds In Training

25. MNT = Minds Not Trained successfully

26. MRT = Minds Received for Training

27. NFR = New Facilities for Research

28. ORF = Obsolescence of Research Facilities

29. PAR = Plant or facilities Available for Research

30. PET = U.S. Population Eligible for Training, ages 18-21

31. PMT = Potential Minds for Training

32. PTP = Desired Parameter of Technical Performance

Table B 2 (Cont'd)

Variables and Constants for Knowledge Progress System

33. RDO = Research engineers & scientists Diverted to Other purposes

34. RES = Research Engineers & Scientists

35. TAE = Teachers Available to teach Engineering

36. TDO = Teachers Diverted to Other purposes

37. TDR = Teachers Diverted to Research & development

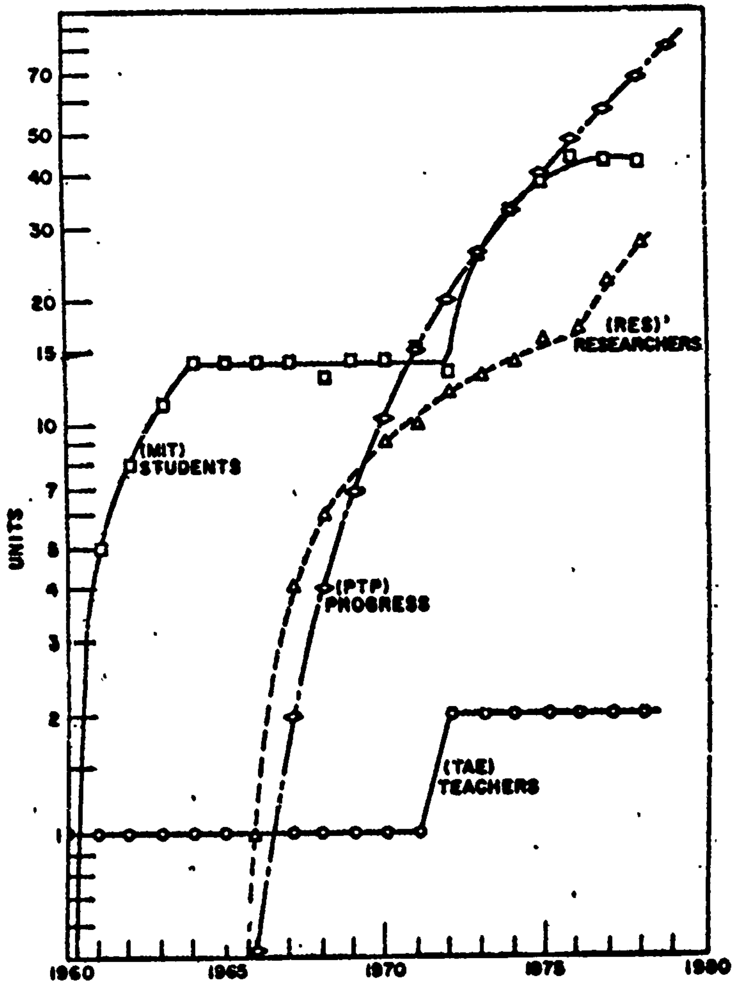

Figure 37. Knowledge-Progress Model: Case 1
New Technical Field, Present Teaching vs. Research Ratio

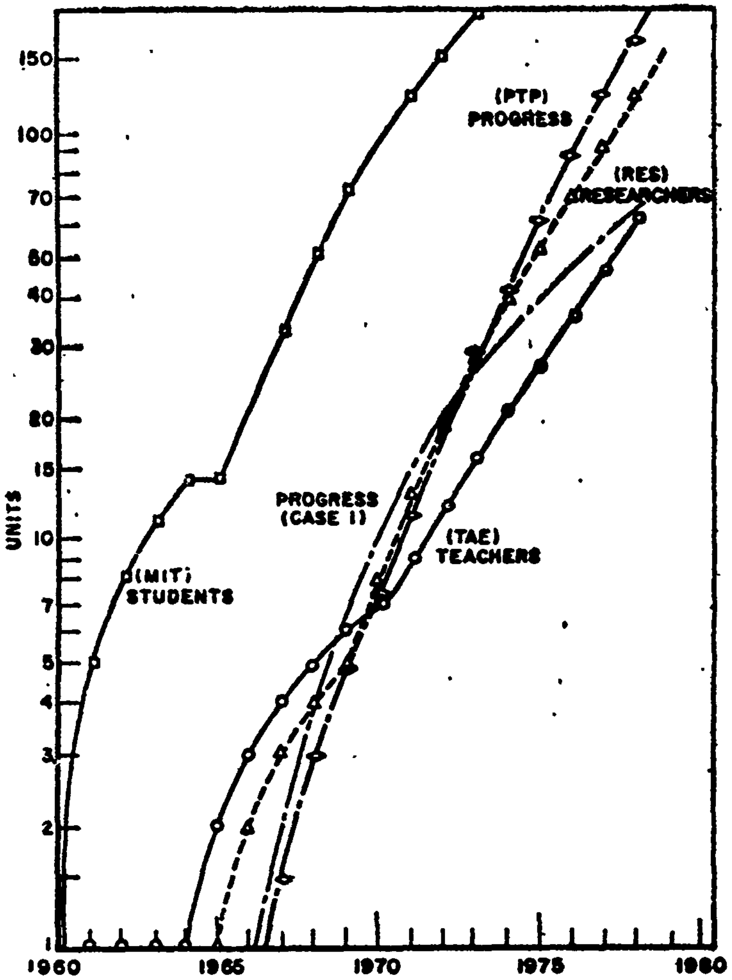

Figure 38. Knowledge-Progress Model: Case 2
New Technical Field, High Teaching vs. Research Ratio

Aeronautical Systems Division, Dir/Plans,
Wright-Patterson AFB, Ohio.
Rpt Nr ASD-TDR-62-414, TECHNOLOGICAL
FORECASTING. (Second Edition) Jun 62, 106p.
incl illus., tables.

Unclassified Report

This study presents several methods of forecasting to predict rates of technological advance. The methods include forecasting by extrapolation of existing rates; by analogies to biological growth processes; by precursive events; by derivation from primary trends; by interpretation of trend characteristics; and by dynamic simulation of the

(over)

process of technological improvement. The investigation included a search of the literature for references to principles of technological progress which might form a basis for prediction. Included in the literature search was a review of methods which have been used for predictive purposes.

Each of the methods offers the opportunity of making a forecast of progress which explicitly predicts quantitative improvements of technical performance to be achieved at definite future times. The application of the methods presented should provide substantial improvement in long range plans not previously supported by carefully established forecasts.

1. Technological Forecasting (Methods)
I. R. C. Lenz, Jr.

Aeronautical Systems Division, Dir/Plans,
Wright-Patterson AFB, Ohio.
Rpt Nr ASD-TDR-62-414, TECHNOLOGICAL
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