A DEVELOPMENT OF EXPLICIT METHODS

IN TECHNOLOGICAL FORECASTING

by

Ralph Charles Lenz Jr.

A. E., University of Cincinnati
(1943)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

1959

Signature redacted

Signature of Author...
School of Industrial Management

Signature redacted

Certified by...
Faculty Advisor of the Thesis

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF INDUSTRIAL MANAGEMENT

ESTABLISHED UNDER A GRANT FROM
THE ALFRED P. SLOAN FOUNDATION, INC.

50 MEMORIAL DRIVE
CAMBRIDGE 39, MASSACHUSETTS

April 9, 1959

Mr. Ralph C. Lenz, Jr.
School of Industrial Management
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Mr. Lenz:

This letter is to give you permission to print additional copies of your thesis by the Multilith process and to submit to the School of Industrial Management a copy thus produced, in lieu of the typed copy normally required.

A copy of this letter is to be reproduced by the same process and is to be placed in each copy of the thesis immediately following its title page.

Sincerely yours,

Richard B. Maffei
Thesis Supervisor
School of Industrial Management

RBM:RS

Professor Alvin Sloane
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Sloane:

In accordance with the requirements for graduation, I herewith submit a thesis entitled "A Development of Explicit Methods in Technological Forecasting".

I also wish to express my appreciation, in this letter, for the counsel of Professors Forrester and Eastman during my preparation of the thesis. Their searching questions directed at the thesis drafts, and the corrections and revisions which they recommended, helped exceedingly to clarify concepts which otherwise would have remained vague and poorly expressed. I desire also to thank Professor Morison for his kindness in reviewing the early drafts and for his encouraging and constructive comments.

Sincerely yours,

Signature redacted

Ralph C. Lenz Jr.

ABSTRACT

A DEVELOPMENT OF EXPLICIT METHODS
IN TECHNOLOGICAL FORECASTING

Ralph C. Lenz Jr.

Submitted to the School of Industrial Management, Massachusetts Institute of Technology, on 4 May 1959, in partial fulfillment of the requirements for the degree of Master of Science.

     This thesis presents several methods of forecasting which may be used to predict rates of technological advance in terms of performance improvements of machines, extent of innovation, or numbers of inventions. 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 method of investigation included a search of the literature for references to principles of technological progress which might form a basis for prediction. Also included in the literature search was a review of methods which have been used for predictive purposes. On the basis of these findings, the several methods of forecasting presented in the thesis were developed.

     Each method 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, where such errors were found. In those cases in which the method is believed to be original, or has major elements of originality, the limitations governing its use are discussed.

     Each method is next presented in terms of the technique used to establish a forecast. The application of the method to typical forecasting problems is presented in abstract or general terms, followed by examples which demonstrate the use of the method in specific cases.

     Each of the methods presented offers the opportunity of making a forecast of progress which explicitly predicts quantitative improvements of technical performance which are 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 developed through 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 provide substantial improvement in long range planning activity not previously supported by carefully established forecasts.

Thesis Chairman: Jay W. Forrester
                 Professor of Industrial Management

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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 problem for investigation in this study is the development of specific methods for the prediction of the characteristics of technological innovations. The qualities sought for the methods of prediction are explicitness, expression in quantitative terms, definable accuracy of results, reproducibility of results, and derivation on a logical basis.

The prediction of invention, as defined for this problem, does not require that the invention be described, but rather the prediction that some type of innovation will occur, the probable timing of the innovation, and the probable effect of the innovation in continuing technological progress. The forecast of the future characteristics of a machine, or series of machines, implies the prediction of evolutionary trends in terms of secondary inventions and developmental activity. As in the case of primary invention, the description of the invention is not requisite to the forecast of the probability of a series of secondary

inventions, nor to the prediction of the fundamental charac-
teristics of the machine at given future periods.

Forecasting of the dimensions of a given class of
machines may be further defined as the quantitative des-
cription of significant dimensions which will be character-
istic of the machines at a specific future time, and in-
cludes prediction of the ultimate limits of these dimensions.
The forecasting of performance may similarly be defined as
the quantitative description of significant performance
capabilities at specific future dates, together with the
prediction of probable upper limits of performance. Fin-
ally, if the forecasting methods which are developed are to
have any significance, they must go well beyond forecasting
the characteristics, dimensions, and performance of machines
which can be assembled with present components, or which are
fully within the existing state-of-the-art, since such
"forecasts" are more properly placed in the category of
engineering design.

Effective methods of technological forecasting are
an essential element in the attainment of management goals
of profitable perpetuity for their companies. Such methods
are even more important to the larger segments of society,
i.e., industries, regions, and nations, in reaching deci-
sions which will guarantee their effective survival. In a

world in which machines are a dominant factor, the predic-
tion of the future characteristics of those machines is,
of necessity, an underlying factor in any projective action
in that world.

The most obvious use of the forecast is in plan-
ning. For any organization which has a major interest in
the production or utilization of machines, the technolog-
ical forecast is the first element in its long range
planning. Whether this forecast is implicit or explicit,
the final result of the planning activity can be no better
than the forecast on which it is based.

The forecast is also inherent in any process of
decision-making. In the decision to obtain any machine
which is expected to have a long useful life or in the
decision to commit resources to the production of machines
which have a long gestation period, an accurate technolog-
ical forecast is essential. If such decisions are the
responsibility of others, and the problem is one of influ-
encing the decision, then the technological forecast may
be used in support of the desired action.

As a method of review, the forecast is without
value unless it has been recorded and is available for
comparison with actual events. The recorded technological
forecast can be a most effective warning of the necessity

for changing plans, since the divergence of actual events
from the forecast upon which the plan was based is easily
noticeable. In contrast, a plan in which the original
forecast is unrecorded may often be adhered to in spite of
changing circumstances, since the divergence of the course
of events from the forecast situation cannot be detected.
Likewise, the recorded forecast may be useful in reviewing
major commitments at critical points. Divergence of actual
events from those forecast at commencement of an action,
may signal for the termination of the action at crucial
points and for the avoidance of further commitments. In
the absence of the recorded forecast as a standard for the
measurement of changing conditions, there is a strong ten-
dency for adherence to original decisions, and indeed there
is little reason to alter the original decision since the
magnitude of the change is difficult to determine in the
absence of a standard against which to measure.

The strongest reasons for development of explicit
methods of technological forecasting, however, are based
in the pervasive 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 real-
ity. In contrast, the implicit, or unrecorded forecast is

most often over-conservative and ignorant of possible actions of others, and leads to emotional defense of existing activity, rather than to reasoned and impassionate examination of the existing situation. The effective forecast removes barriers to objective thinking in pointing out where much greater progress is possible and desirable than has been planned, or conversely, in demonstrating the existence of lessened rates of progress. No better method of disturbing an inappropriate status quo exists than 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 progress trends, however, one of the most important functions of the accurate technological forecast is to insure that such decisions do not result in "too little--too late" nor in "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 in a progressive economy. Each projection requires careful consideration of the factors which will enable the achievement of the indicated progress, and apparent inconsistencies and barriers become evident, so that attention and effort may be focused on their removal. The necessity for innovation is projected well in advance so that the usual procrastination in introducing change may be overcome.

One further requirement for technological forecasting lies in the potential which it offers for the prediction of a competitor's probable activity. Any form of espionage or knowledge of competitive progress is of necessity, after-the-fact, and as such is useful only for corrective or countering action on a delayed basis. On the other hand, an accurate forecast of the maximum possible rate of progress which may be made by a competitor will provide a strong incentive for maximum effort to achieve the same degree of technological advance, and will destroy the complacency which may arise in the absence of exact knowledge of competitive developments.

It is not the intent of this study to provide the final definitive word on the subject of technological forecasting. Rather, an attempt has been made to provide a systematic presentation of related methods of forecasting, with the introduction of some elements and methods which are believed to be original and so, untried. Although examples are offered in support of the methods of prediction outlined, these are of necessity limited and cannot be claimed to demonstrate universal verities. No attempt is made to present an infallible, purely mechanical means of prediction, at least in part because this is not believed possible at the present time, but more because the investigation itself did not produce such a method. This

study is also limited in extent of coverage of the vast amounts of statistical data which might be used to support the findings herein, or to provide a basis for specific predictions in many technical fields. In the first case such data could only be obtained by a large staff, working exclusively to this purpose. In the second case, 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 extraction which could be presented in this study. In summary, this investigation is limited to an attempt to provide some measure of improvement in present methods of technological forecasting, with some suggested rules and procedures for making and testing such forecasts.

The investigation is composed in 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 individual chapters which describe each of the techniques; their application to the problems of predicting invention, characteristics, dimensions, and performance; appropriate examples; and suggestions on the limitations and capabilities of each method. In the third part the combination and correlation of results from collective considerations of the several independent techniques is discussed, with particular rela-

tionship 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 and probable consequences.

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, and the application of scientific methods has made few inroads against substantial opposition in many areas. Astrology even today probably has more practitioners than does astronomy, while "The Farmer's Almanac" weather predictions, even if not seriously believed, still command a wide printing. The claim of divine guidance for prophecy has seldom been voiced since biblical times, so that the predictor must rely upon repeated success in prediction, or demonstrated accomplishment in worldly affairs, as the source of his authority to prophecy. In those areas in which accurate prediction has been regularly repeated by mathematical methods, such as in the engineering design of structures, the practitioners have been quick to substitute euphemisms to avoid the words "prediction" or "forecast" in description of their work or results. Thus, even in those areas in which some measure of forecasting success has been obtained, as in business and economics, the technique is still suspect, and the terminology of prediction or forecasting introduces

immediate skepticism. The even less advanced art of fore-
casting invention, or the future state of technology, is
equally suspect.

Although the total history of forecasting bears
relationship to the subject of technological prediction,
it is not possible within the framework of this study to
outline that history. Today's methods of forecasting are
considerably more sophisticated than that ancient Roman
practice in which the augurs carefully examined the en-
trails of sacrificial sheep to determine whether or not
it would be favorable for the Popular Assembly to convene.
At the initiation of this study the author believed that
the secular forecasting procedures of population growth and
economics would provide useful analogies for the develop-
ment of trend forecasts in technology. Upon examination
however, of some of the accepted authorities in the field,
notably Pearl[1] and Kuznets[2], certain weaknesses become
evident, which require substantial correction if such meth-
ods are to be used as the basis for forecasting population
growth, economic increase, or technological progress. Most

---

[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).

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 unable to predict inflection points of the growth process, and provides accurate prediction only when maturity in growth is well established. Never-the-less, Pearl's treatment is useful in providing insight into growth processes in technological progress.

In Kuznet's work, the same weakness of arbitrary curve fitting is repeated, compounded by the indiscriminate application of the "growth curve" to many 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, while other sets of data represent only some fairly regular phenomena of accretion within expanding boundaries. To the extent that these weaknesses can be tolerated or overcome, useful analogies of these methods are

presented in later chapters. At the very least, the use of these methods forces the examination of prior rates of progress which provides substantial information on possible future rates of progress.

The works of S. C. Gilfillan[3, 4] on the sociology and prediction of invention are the best of the few references on the specific subject of technological forecasting. In "The Sociology of Invention", Gilfillan[5] specifies 38 social principles of invention which afford a potential framework for the prediction of technological progress. 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 of progress in any technical field.

In addition to the infinite number of implicit forecasts which might be developed by inference from the actions of individuals, businesses, and nations, there exist a finite, but very large, number of explicit forecasts on

[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.

12

technological progress abundantly scattered in the general
and technical literature. In most of such forecasts the
technique of development of the forecast is not defined and
may only be inferred. Such inference usually leads to the
conclusion that most of such forecasts are purely intuitive,
so that even when correct, no basis is available for repe-
tition of the methodology. In the rather substantial
remainder of predictive articles, some graphic or numerical
method is used to extend historic trends into the future.
The random choice of methods used in this manner, with
little evidence of any understanding of the implications of
the methods used, offers evidence of the absence of infor-
mation on the subject of technological forecasting. In the
field of aviation, Male has concluded from a study of over
200 forecasts 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] Even
though Male allowed substantial latitude in his definition
of valid trend and time elements, it is apparent from his
study that systematic methods capable of consistently
accurate prediction were not used by these forecasters.
Although Male's objective was "to study forecasting in avia-

---

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

tion with a view to improving the accuracy of future fore-
casts", he was unable to identify, by the results of his
study, any specific methods employed which might be recom-
mended for future forecasting.[7] Since Male does suggest
certain guides to long range planning which involve methods
of forecasting, the absence of identification of satisfac-
tory methodology may be the result of a corresponding
omission of the element "method-of-prediction" in his tabu-
lation of forecasts. Further study of his 200 examples of
forecasting, from the standpoint of this additional element,
might provide a correlation pointing toward the more accu-
rate methods of prediction.

The author's investigation arises thus, from the
absence in the literature of quantitative models or methods
of technological forecasting, from the inadequacies of
available analogies in biological and economic forecasting,
and from the evidence that previous and current forecasts
afford latitude for improvement in accuracy and content.

The sources of data used in the investigation, in
addition to those cited previously, were principally those
sources of statistical information which provide time-series
pertinent to the forecasting methods developed. Information

---

[7]*Ibid.*, p. 7.

relative to the general patterns of invention and innovation has been drawn from a few of the many books on this subject. For the chapter on dynamic forecasting, the works of Jay W. Forrester in the field of Industrial Dynamics have been relied upon in development of the methodology described.

CHAPTER II

FRAMEWORK OF THE TECHNOLOGICAL FORECAST

In developing a framework for technological forecasting it is useful to consider first some of the arguments offered against forecasting and their relationship to the problem of prediction. The most common argument advanced against any attempt at forecasting is that no one is able to foretell the future with certainty. In support of this argument is offered the opinion that most forecasts have been in error. , Lest this indictment appear too strong, the apologia is then offered that the course of events changes so rapidly that the probability of an accurate forecast is quite low. The man charged with administrative responsibility is tempted to argue that the forecast is unnecessary, since his decisions are concerned only with the action taking place here and now. Alternative arguments are that action based on predicted circumstances is extremely expensive, and that forecasts are a poor basis for trust or investment. Finally, the technique and practice of forecasting is frequently condemned on the paradoxical argument that the specific prediction in consideration is demonstrably false.

All of these arguments cited against forecasting may

best be answered by considering some postulated conditions
of no-forecast, their implications, and the errors associated with each. The simplest is of course the literal situation of no forecast what-so-ever, which really 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 may be practiced to a
limited degree in some organizations with transient managements. The obvious error of the condition of 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 adoption of the point of view that all external influences are the result of random processes, with the implication that decisions represent a gamble, even though some
knowledge of the odds and stakes exists. In business procedures the consequence is success when a favorable run is
experienced, and self-excused failure when the run is "unlucky". The forecast is apparent here in decisions implying that conditions will remain favorable, will change, or
will continue unfavorable, without assignment of any cause.

An infrequent avoidance of conscious forecasting is
the situation in which all action is based on an assumed
continuance of some prior set of circumstances, which no

longer exists. This situation is most evident when each action is on the basis of precedent. The implied forecast is that the "glorious past" is an accurate description of future expectations. The error of indiscriminate application of this method of forecasting is evident in any non-static society.

Much more commonly the implicit forecast is that the current circumstances will continue in the future. Most obvious signs of an unconscious forecast of this type are the continual attitude of crisis and abrupt reversals of previous decisions with each change in external circumstance. An example of this situation is the linking of research expenditures to a current sales or profit position. Even when this method of operation is explicitly stated as part of management policy or philosophy it is seldom recognized that this is actually a forecast.

Possibly the most popular of the unrecorded and unrecognized forecasts is the assumption that existing trends of change in circumstances will continue. The apparent justification for this tacit assumption is that measurement of the trend is rather inaccurate, so that recording of the trend as a basis for decision might prove embarrassing. Operations on the basis of this type of implicit forecast are evidenced by goals of the "higher, faster, further,

larger, better, and more" description. Failure to state
such a forecast in explicit recorded form does not make it
any less a forecast, but only introduces ambiguity as a
poor substitute for clearly defined limits and probabili-
ties. The errors of judgement that arise from the uncriti-
cal acceptance of such ambiguous forecasts are usually
unrecognized, in part because the unrecorded forecast is
difficult to reconstruct in the light of intervening changes
in circumstance.

Closely related to the assumption of the continua-
tion of present trends is the adoption of a course of action
based on an intuitive feeling toward the nature of future
conditions. Although this is the most submerged of the
various implicit forecasts, it is never-the-less very effec-
tive in guiding the actions of many successful men. The
existence of this type of forecast is easy to prove by the
existence of patterned decisions which anticipate future
situations, even though it practitioners may be most vocif-
erous in their opposition to defining and recording the
predictions involved. The greatest weaknesses of the meth-
od of action based on intuitive forecasts are that important
elements are easily overlooked, that it is impossible to
teach, and expensive to learn, and that it makes any process
of review impossible.

While the general case of forecasting has been considered here, the statements made are equally applicable to the special case of technological forecasting, which is of necessity an important part of today's managerial decisions. The race is one in which bets must be placed. There is no possibility of abstaining, and indeed most managers cannot even control the magnitude of their betting in this race, since it is closely linked to the total net worth of the segment of the economy over which each manager exercises control. Since some estimate of probable future conditions is inherent in each managerial decision or bet, the actual question is thus whether such a forecast should be made unconsciously as an implicit part of the decision, or should be arrived at deliberately and be stated explicitly. The first and foremost reason for an explicit forecast is to place the forecast in one of the categories detailed above, so that its general nature can be determined, and its general validity tested. Beyond this the explicit forecast offers the advantage of "bringing out into the light" all of the data, premises, and method used in making the forecast, and also affords a record against which actions may be compared and situational changes noticed.

If the premise is accepted that an explicit forecast is desirable, consideration needs be given to the subject of extrapolation since, if not inherent in forecasting, is at

least usually involved in some manner. The mistrust of
extrapolation is similar to and possibly inextricably a part
of the more general mistrust of forecasting. The dilemma of
the man who rejects the use of extrapolation in forecasting
consists in the fact that the other horn requires departure
from a point of position and time without knowledge of the
prior course, velocity, or acceleration involved in arriving
at that point. To the extent that continuity is involved in
any undertaking, the extrapolation (under an appropriate set
of rules) of information concerning the prior course of
events would appear to have greater validity than a forecast
which disregarded those events in predicting the future
course of similar events.

The selection of techniques to be used in develop-
ment of technological forecasting methods in this thesis was
based upon examination of the considerations which appeared
to govern those technical forecasts which have been made a
matter of record and also upon the techniques which have
been used for economic and biological forecasting. In many
of the instances in which inventions or technical progress
have been forecast, the actual method used by the forecaster
has not been stated, and indeed the process may have been
substantially intuitive. Never-the-less, examination of the
nature of the actual forecast usually reveals something of
the method used. In some instances the method of forecast-

ing progress is self-evident and explicit in the forecast,
such as by the use of graphs or the identification of uni-
form annual rates of increase, with extrapolation accom-
plished on the basis of some rule. However, an exact state-
ment of the rule of extrapolation is seldom given, and even
less often is any explanation or qualification offered for
the method used. Since, as previously stated, the purpose
of this study is not to examine and analyze prior forecasts,
no attempt will be made to cite specific forecasts from
which some consideration of techniques has been drawn, ex-
cept those for which the forecaster claimed an element of
originality or exclusiveness, or described his method and
the rationale therefore. Outside of these exceptions, the
examination of previous forecasts has served only in a most
general way in suggesting procedures useful for technologi-
cal forecasting.

Any general theory of forecasting must be based in
some manner upon that which has happened in the past. If
the forecast is one of the category 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 ex-
periments is permitted, with an attendant extrapolation of
the results expected. Similarly, as in weather forecasting,

when a given set of conditions has usually developed from a given prior set of circumstances, the forecast can be made on some probability basis that the same sequence of events will be followed in future occurrences. The problems then, in developing methods of technological forecasting, are to determine what prior circumstances are significant in terms of probable future occurrences and then to determine the techniques of extension, translation, or transformation which will convert the knowledge of prior circumstances into a prediction of the probable future.

The most obvious, and therefore most used, method of technological forecasting is based on the assumption that whatever has been happening in the past will continue to happen in the future, in the absence of any known or predicted cause for disturbance. The problems to be solved in using this technique consist principally in knowing and defining accurately just what has been happening in the past, and in determining the tolerable magnitude for disturbing influences. Implicit in the definition of what has been happening are the elements of rate of occurrences and rate of progress, together with the length of the period taken into consideration. The development of methods of forecasting by extrapolation, with due regard for the problems and elements noted above, 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 ad-
justment for such influences. However, these disturbing
influences, particularly those which tend to limit progress,
frequently loom so large in the mind of the forecaster as to
create greater errors in the forecast than would exist if
ordinary extrapolation formed the sole basis of the fore-
cast. Because of this, and because the forecast of unknown
disturbances is at least as difficult as the original prob-
lem, the use of analogies which offer a basis for estimating
the probable cumulative effects of many 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 econ-
omic 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.

---

[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).

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 over-all economic activity has frequently been used in economic forecasting. This has been extended in cyclical forecasting to the investigation and use of many patterns of events, many of which have only casual relationship. Use of this method for technological prediction on a secular basis is described in Chapter V.

The last of the methods which appear to have been used in technological forecasting is a logical extension of the preceding method. This method is based on prediction of the trend of a dependent variable as a function of the trends of two or more independent variables. This predictive technique has greatest utility for those cases in which the trends of the independent variables are well-established, easy to extrapolate, generally agreed upon, or 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. This use of interdependent relationships as a forecasting technique is also

developed in Chapter V.

Prediction of technological progress on the basis
of significant characteristics in trend curves offers sub-
stantial promise in extending the capabilities of the tech-
nological 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. In particular this method affords a basis for
prediction of the likelihood of new inventions, the proba-
bility of new industry arising, the types of new inventions
likely to be made, and a prediction of the pressures for in-
novation. This method of prediction is also useful in
determination of the probable performance which will be
achieved by inventive effort, and of shifts in relative sig-
nificance of various performance parameters. The use of
trend characteristics for prediction is described in the
final part of Chapter V.

The development of a method of technological predic-
tion based on the technique of "Industrial Dynamics" is des-
cribed in Chapter VI.[4] In this method the prediction of
technological progress is based upon mathematical expression

---

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

of the influence of those factors over which control may be exercised, such as 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, such as the number of trained individuals or dollars, to the quantities in which technological progress is measured, such as number of inventions or increase of maximum performance. 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 described. Such combinations may be used to provide a range of probable technical progress, if the resultant variation is sufficiently small enough to be a useful forecast. Alternatively the combination may provide a single, most probable, estimate of future progress. The use of variation in the results provided by the different

methods,to point toward additional research is also consider-
ed.   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 predic-
tion.

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, never-the-less 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, and many other forecasts are based on a conscious, although vague, process of mental extension of past experiences.

The underlying basis for this method of forecasting technical progress in our society possibly 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 relative increase of empiricism and the increasing number of scientific

---

[1]Pitirim A. Sorokin, *Social and Cultural Dynamics*, Vol. II (New York: American Book Company, 1937).

discoveries made each century since the 15th.[2] The contin-
uity of this pattern of scientific advance is an inherent
part of 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 by the
forecaster, it is still most likely to reflect the forecast-
er's inherent feeling that technological advance will follow
the patterns of the last four centuries.

Because this method of forecasting by extrapolation
of time series will continue to be used, and because it is
not without some validity, and further because other methods
of forecasting are derived in some measure from the same
underlying principles, it is desirable to give some thought
to development of the method. Key elements in such develop-
ment are the functional meanings given to the words "exten-
sion", "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 additional qualification before it may have meaning in

_____

[2]Ibid., pp. 38-39.

technological forecasting. Obviously, the quantity which composes the time-series must have technological signifi- cance, i.e., it must bear some relationship to the charac- teristics, dimensions or performance of a machine or class of machine. The greater the technological significance of the quantity is, the sounder will be the use of the time- series of the quantity for technological prediction. The converse is equally true, if the quantity is only indirect- ly 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, in the sense that it is unlikely to be influ- enced by whim, fancy, or other purely random factors. On the other hand, extension of the time-series of overall length of automobiles, which might be suggested as a basis for a forecast, would be highly 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

---

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

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 carefully selected to cover 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 as a useful device. 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. In any event, much better knowledge of all the forces which may affect the prediction may be secured by examining the entire time-series for forces which have affected it in the past.

The time-series, or the data which comprise it, can be meaningful for prediction only if care is taken that 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, that is, the passenger capacities of aircraft for feeder-

line service, of helicopters, and of inter-continental service aircraft, cannot be added indiscrimately to the data comprising the time-series.

Finally, qualification of the time-series should include appropriate consideration of the influence of the individual measurements whose sum comprises the quantity used for the time-series. In illustration of this point, the measurement of average maximum horsepower for passenger cars may be defined as the simple 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 actually 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 of the buyers. This qualification is particularly important where the measure of progress is any quantity which must be compromised in design by other important 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 distort the appearance of the data. Appropriate weighting in terms of averages of performance actually sold or delivered will usually provide a more useful time-series

for predictive purposes. In the illustration cited above, the average obtained by dividing the sum of the horsepower ratings of all passenger cars actually 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 review magazines are prolific sources of time-series composed of unweighted averages.

The meaning of the term "existing trends" in forecasting by extrapolation 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 assumed, 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 (except of randomness), 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. Similarly, a regular increase evidenced by a time-series may be used as a basis for forecasting a continuation of the same regular increase. If the total history of the time-series represents all the forces

which have influenced the trends evidenced, then the "best"
curve will be that which describes the influence of these
forces over the entire period.

By careful selection of some fraction of the time-
series, "trend curves" may be drawn which will support al-
most any predetermined conclusion. The most extreme cases
of this source of predictive error arise when the period
chosen as the basis for prediction is extremely short. The
enthusiast may take a year of rapid progress and project
that rate of progress into the future with great optimism.
Such predictions will then usually fail of accomplishment
in the time specified. The pessimist, or forecaster pro-
tecting a vested interest in a competitive area, will fre-
quently take a period so short as to exclude any rate of
progress whatsoever, and project the future as a simple
continuation of existing conditions. One of the most nota-
ble of such forecasts, in terms of forecasting effort ex-
pended, interest aroused, and support engendered, was "The
Great Delusion", authored by a Mrs. M. W. Acworth, under
the pseudonym "Neon", with the support of the British Ad-
miralty and British commercial shipping interests.[4] This
book, in 1927, predicted, among other things, that airplanes

---

[4]"Neon" Pseudonym for Mrs. M. W. Acworth, The Great
Delusion (London: Ernest Benn Limited, 1927).

would never be able to fly at night, that the internal com-
bustion engine had reached its limits of perfection, that
civil aviation would never become profitable, and that qual-
ifying facts or discoveries which might change these predic-
tions were highly improbable. Greater failures at predic-
tion are difficult to find, yet these predictions were ac-
cepted readily by the British press and much of the public
at that time.

In summary, if "existing trends" are to be used as
the basis of forecasting by extrapolation, they should be
carefully fitted to the entire time-series of the quantity
under consideration, and should evidence some characteristic
of regularity which may be projected into the future.

The consideration of the term "extension" follows
naturally from the definition of "existing trends" above.
In forecasting by extrapolation, any extension of an exist-
ing trend is limited by definition to simple extension, i.e.,
the introduction of causal factors of change, rules for
changes in trends, or the application of bias by the fore-
caster, introduces an entirely different method of forecast-
ing. As such, these additions may be perfectly 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 of a time-series, 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 the original extension had been relied upon. If the forecaster extends existing trends on the basis that the original forces which created these trends will continue, then any alteration that he makes must include the effect of all these forces; not merely his estimate of the influence of one of these forces. "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. Actually 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 produce the same pattern of progress than it
is to produce a different pattern. In the absence of actual
knowledge of some probable change in the controlling forces,
the first assumption is reasonable. Similarly, in the ab-
sence of actual 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 assump-
tions will become invalid. If it seems reasonable that
forces which have existed for a considerable length of time
are more likely to continue than forces which have existed
for only a short time, then it is reasonable to assume that
trends based on a long time-series may be expected to con-
tinue for a longer period of time than those which are based
on shorter time-series.

These definitions and limitations indicate the mean-
ing of forecasting by extrapolation as stated at the begin-
ning of the chapter. Acceptance and usage of this method
of forecasting probably is based on an intuitive feeling
regarding the nature of invention and progress 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 crea-

tions,.... An invention is essentially a complex of most diverse elements."[5] 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.

The parallelism of biological evolution and technological evolution requires further discussion if it is to be accepted as providing 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, just as evolution produces those functional changes in successive generations of the biological organism which will enhance its survival. Just as biological evolution produces changes in the appearance, size, and capabilities of a species, so may technological evolution produce changes

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

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 direc-
tion, so that observed patterns of change may be reasonably
expected to continue.

Using the evolutionary analogy as a basis for fore-
casting technological progress by the extension of existing
trends, the techniques of forecasting by extrapolation may
be considered. The first step required is the selection of
the quantity whose time-series is to provide evidence of
existing trends. The quantity selected must be technolog-
ically 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 because they have been achieved
under varying and arbitrary rulebook limitations which pena-
lize technical advances made in the "real world" where all
competitive forces operate freely. Hunsaker's prediction
in 1940 of aircraft progress on the basis of the trend of
world speed records for aircraft is an example of predictive
error occasioned by a time-series of "record" performance.[6]

---

[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).

In this example, while the actual technological improvement of aircraft was directed toward obtaining high performance at altitude, an arbitrary rule was imposed which required that the world speed record 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, which has been frequently noted by commentators on the subject of scientific and technical progress.[7] On this basis, the best procedure for identifying existing trends begins with plotting of the time-series on semilogarithmic graph paper. Then, that straight line which best fits the data of the time-series will represent

[7]Raymond Stevens, H. J. Rand, and others, cited in a presentation given by Professor Erwin H. Schell to the Sloan Fellows, August 5, 1958.

the existing trend of exponential progress. If no straight
line can be found which offers a reasonable approximation
to the time-series, then the validity of relationship of the
time-series to the type of scientific progress described
above may be questioned. In this situation the fitting of
some regular, but arbitrary, curve to the data cannot be
supported on the basis of the hypothesis of logarithmic
progress.

Having established the existing trend of the se-
lected time-series of technological progress, the first step
in forecasting is the extension of the existing trend into
the future. The regularity which is evidenced by a simple
exponential curve, representative of the existing trend,
affords easy projectability with assurance that the projec-
tion 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 fore-
casting technological progress, the forecaster who is aware
of the magnitude of effort required to achieve the future
performance indicated by the logarithmic curve will usually
conclude that the existing trend cannot be continued. Pres-
ent limitations are used to demonstrate that the rate of
progress in the future will be somewhat less than the current

rate. In the extreme case the conclusion is drawn that the rate of progress will become asymptotic to some near-term upper limit of capability. While either of these conditions may be true, they are inconsistent with the principles used in establishing the existing trend. Therefore, before proceeding further with a forecast divergent from existing trends, the forecaster must establish a new rationale, which includes a different explanation for the characteristics of the time-series, and which probably results in a change in the shape of "existing trends". If, however, 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. As will be shown later in this chapter, 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 forecast more accurate for as much as 30 years into future, than those 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.[8] Also, the prediction of E. H. Heinemann, in a

---

[8]Hunsaker, op. cit., p. 129.

paper presented at the Fifth International Aeronautical Con-
ference 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.[9] 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 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. Within
the framework of forecasting by extrapolation as indicated
herein, 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 used, 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, nor necessarily improbable, never-the-less it
seems that the probability of trend continuance is reduced
beyond this point where the time covered by prediction is

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

equal to the time covered by the history of the existing trend.

Application of the techniques outlined above is demonstrated by the examples in Appendix A. The forecasting of design characteristics is shown in Figure 1 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 2 of Appendix A. 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.

The prediction of the performance of a class of machines is shown in Figure 3, Appendix A. 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 continuous 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.

Since the method of forecasting by extrapolation requires a time-series of a characteristic, dimension, or performance parameter of a machine, thereby requiring the concurrent existence of the machine, it is not a particularly good method for prediction of inventions. In addition, since it admits only of continued extrapolation of current trends, it does not usually signal the invention of a machine to replace itself. Never-the-less this type of prediction can be used to forecast inventions. By the examination of forecasts of design characteristics, 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 this type of machine, or alternatively, that an invention already made will become sufficiently developed to displace the original machine on an operational basis. For example, as shown by Figure 1, as 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 replace the airplane.[10]

The prediction of invention on the basis of a forecast of machine dimensions may be made if the increase or decrease of a given dimension will force the invention or development of some other machine to accommodate the change of dimension. For example, the increase in gross weight of aircraft has forced the development (with some invention) 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 may be a fruitful use of forecasting by extrapolation. The usual objections offered 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,

----

[10]Of course the disappearance of the wing may occur at different times for different classes of aircraft.

when the propeller represented a limitation to continuance
of the trend of aircraft speed, the jet engine was developed
to provide a continuance, in spite of forecasts which ignor-
ed this possibility and predicted upper limits to the speed
of aircraft in the neighborhood of 550 mph. Lesser inven-
tions of this sort, such as the super-charger for continua-
tion of the altitude trend, may be found throughout the his-
tory 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. In addition,
many inventions of a corollary nature may be predicted quite
accurately by examination of the performance forecast. For
instance, when altitude performance of aircraft is predicted
to exceed 20,000 feet, by a given date, then the invention
of an oxygen breathing apparatus, a pressure cabin, or some
other device to solve the problem of human survival at that
altitude, can be predicted to occur at about that same date.

The limitations of the method of forecasting by ex-
trapolation 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 made to develop
such a theory in this chapter, since such attempts lead to
those modifications of this method of forecasting which are
presented in later chapters. Also this method affords no

opportunity to include changes in trends on a rational basis, even though changes in trends should be considered inevitable in the long run.

In spite of these limitations, including the necessity of accepting this method of forecasting on the basis of faith rather than reason, it 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. Adam's 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] Although the analogy drawn by Adams is quite poetic, he cites many ratios of increase in scientific progress, going back to the year 1400, to support the 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, as outlined in Chapter III, while gaining distinguished support, still lacks a fully developed theoretical explanation.

---

[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.

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 the specified field approaches "maturity". 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 is 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 (as indicated by weight increases of the rats). In each of these cases Pearl demonstrates that cellular increase obeys the formula developed in his

---

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

earlier work as follows:[3]

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

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". However, it is precisely this fitting ability which causes the greatest difficulty in use of the formula for forecasting growth, or by analogy, technical progress. 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 the shift is made to population forecasting or

___

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

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 exam-
ple 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 pre-
diction 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

---

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

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 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 general tendency of the forecaster is to set the upper limit too low. Unless some rational explanation

---

[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.

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. Then, the closer that the prediction approaches to this false limit, the more inaccurate the prediction becomes.

In spite of the arbitrariness of Pearl's equation for growth, the concept of population increase or technological improvement as a growth process offers several advantages to the forecaster. Comparisons may be made between biological growth and technical progress which offer insight into the processes of technical improvement, thus providing a basis for more accurate forecasting. Fundamental to this analogy is the concept of growth or 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.

Those aspects in which technical improvement is

---

[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.

considered by the author to be analogous to biological growth are detailed in Tables I and II, following. Table I gives the elements of analogy on the basis of cellular division in the biological process, while Table II gives the elements of analogy on the basis of paired, bisexual reproduction.

TABLE I

ANALOGUE SIMILARITIES OF BIOLOGICAL GROWTH AND TECHNICAL IMPROVEMENT, ON THE BASIS OF CELLULAR DIVISION.

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

TABLE II

ANALOGUE SIMILARITIES OF BIOLOGICAL INCREASE
AND TECHNICAL IMPROVEMENT, ON THE BASIS
OF PAIRED, BISEXUAL REPRODUCTION.

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

II. ANALOGY OF TECHNICAL IMPROVEMENT TO
GROWTH BY CELL DIVISION

The similarities between biological phenomena and technical improvement on each table offer opportunity for the development of several complex analogies. Full development of each of these is beyond the scope of this thesis. However, a useful contribution can be made by development of some of the simpler analogies, both for use in forecasting and to point the way toward further development. Such analogies are primarily useful in providing an interpretation of available statistics in terms of probable technological advancement. Additionally they serve to explain qualitatively some aspects of technical progress, which explanation may then serve for modification of quantitative forecasts.

Elements of the two analogies (cellular division and bisexual reproduction) are not exactly interchangeable, and certain confusion can be avoided by maintaining a separation of the two in all cases. The analogy based on cellular division is probably more useful in handling the growth of technology on a statistical basis, while the analogy of reproduction offers a more complete explanation of the process of invention.

The exponential growth of many technical areas may easily be explained if an unlimited process of cellular

division is accepted as a reasonable analogy to such process-es of technical improvement. Pearl explains the operation of the cell process in the 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 fin-ally 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]

This explanation provides a model for the growth of technol-ogy in a single area.

In the absence of cell death the increase in number of cells thus follows an exponential pattern. Similarly, as each idea or invention continues to give rise to other ideas or inventions, the number of inventions increases exponen-tially. 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, their differences, or the period required for cell division. Thus if the weight of the cell mass is known at two different

---

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

times, its weight can be predicted so long as the element of cell death is not introduced. Similarly, if one has a measure of the quantity of inventions in a given field at two separate times, and invention obsolescence has not yet occurred, then the increase in number 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 in the first 15 years of the history of such diverse technical fields as 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 the 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 for any purpose, this can be obtained by determining the average time required for the total number of inven-

---

[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.

tions to double in number. This of course 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 next 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. If cell division periods happened to be uniform, and if each cell had a uniform lifetime, then after a period equal to one lifetime, the rate of cell increase would show a sudden decrease equal to the number of initial cells. The increase thereafter, while continuing at the initial rate, would start from the level of cell population immediately after the death of the initial cells. For example, the series of cell populations, without death, of 1, 2, 4, 8, 16, 32, would become, with a lifetime equal to two periods, the series 1, 2, 3, 6, 12, 24. Since neither cell lifetimes, nor the useful lives of inventions, have a constant value, the effect of the mortality curve over an initial time equal to two or three average "lifetimes", is to produce the appearance of a declining rate of increase. Thus the series cited above might have the appearance 1, 2,

4, 7, 13, 24. Therefore, if the useful life of an invention
in a given technical field averages 15 years, the total num-
ber of inventions in that field will show a gradually declin-
ing rate of increase over a 30 to 45 year period, from this
cause alone. Since this is the total period over which the
history of many technical fields has been studied, it would
seem reasonable to take invention lifetime into account in
computing the trend of progress. While it is impossible to
determine "invention lifetime" precisely, an estimate of the
useful life of typical inventions, in a given technical
field, will give a more accurate basis for prediction than
will ignoring the "lifetime" effect.

A more important factor of increase than cell life-
time, is the "economic support for invention" which is anal-
agous to the nutrient media for cell increase. In the bio-
logical analogy, sufficient nutrient must exist 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 situa-
tion in which insufficient funds are available for exploi-
tation of the first invention, so that it lies dormant.
History records many cases of this kind, so that the anal-
ogy is not necessary to an understanding of the situation.
Never-the-less, the parallelism in this example emphasizes

the fact that while money alone can not produce inventions, neither can inventions to advance a technology be produced without money.

After cell division has occurred the first time, then twice as much nutrient is required to permit the development of both cells once again to the point of division. The third generation requires four times the amount of nutrient, and so on, the amount of required nutrient proceeding in geometric fashion with the geometric increase in number of cells. In the analogy, economic support for invention proceeds in a like fashion, with each increase in number of inventions requiring an equal increase in economic support if the process of development of "new" inventions is to continue. If nutrient or economic support is supplied in quantities insufficient for development of every cell or invention, then cell division or invention will proceed only at the rate at which nutrient or economic support is provided. Retardation of this nature has frequently been confused with "maturity" by exponents of the growth theory for forecasting economic expansion or technological advance.[11]

---

[11]For example, Kuznets (op. cit., Kuznets, 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.

The availability of funds for research and development in any given technical field permits the conditional forecast of limits to progress in that field. If, over some prior period of time, a given rate of funding has produced a given number of inventions, then the projected rate of funding will give the limit of the number of inventions which may be expected. Even if the number of inventions may not be quantified, the proportion of future inventions to past inventions will not be greater than the ratio of projected funds to past funds, for equal periods of time. This relationship may then be used, as will be shown later, to give a conditional prediction of progress, when progress can be measured in units other than number of inventions.

Two considerations frequently curtail economic support of invention below the level necessary for exponential growth. First is the failure to grasp the essential facts of the analogy just presented. Few men with 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, with the later imposition of "ceilings" of constant expenditure, which are revised when they become patently unrealistic. The second consideration, which is more realistic, is the competition of other technical fields

for economic support. This is, of course, analogous to the
competition of two cell masses for a limited nutrient. When
the technical field (or cell mass) is small its needs for
economic support (or nutrient) are also small, and exponen-
tial growth is possible. As the size of the technical field
(or cell mass) grows, its economic (or nutrient) needs began
to impinge upon the needs of other technical fields, and a
consequent limitation is imposed upon economic support. This,
in turn, results in a reduction of the previous rate of
growth.

If the growth pattern of a given technology is to be
described in terms of growth toward "maturity", then the
limits of economic demand for invention need to be examined
in terms of their analogy to volume limits of cell masses.
The volume limits of cell masses vary greatly, ranging in
type from the artificial limits of laboratory containers for
collections of cells, to the evolutionary limits of the size
of the human animal, and ranging in size from plankton to
whales. The difficulties presented by this variation help to
explain the problem faced by forecasters who work with
"growth" curves which assume some limit of "maturity". If,
in the biological analogy, the predictor should examine the
growth of an animal of an entirely new species of which no
prior knowledge existed, then as the animal grew at varying
cyclical rates, the prediction of ultimate size would fluc-

tuate 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 maturity would be stated to have been achieved. Many "growth" predictors of the late 1930's and 1940's were willing to concede "maturity" to the U. S. economy, and most of its segments, 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 useful analogies may be developed which will help in determining the upper limits of a given technology. If in the biological case, the animal of the new species is similar to some existing species, then the growth curve of the new animal may be matched to the known growth curves for the existing species. If an early similarity is noted, then some reason exists for predicting maturity limits of the new animal which are close to the limits of the old species. Similarly if two fields of technology, one old and one new, are similar in nature, then the pattern of growth to technical maturity of the new one may be predicted on the basis of comparison with the older field. In both the biological and the technological case, the predictor must be reasonably certain that the old and the new species, or technologies, are indeed similar.

The characteristics of maturity also offer promise in prediction of the limits of growth. In the biological analogy, as the animal approaches maturity, parts of the cell mass become more specialized and more organized. Similarly, as a technology becomes more specialized, and as greater standardization occurs, 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".[12] Thus the appearance of substantial standardization and specialization may well indicate that limits to further technological improvement might be predicted with some accuracy.

To complete the biological cell division analogy, the elements of size of the cell mass, and the relationship of size to the strength characteristics of an organized cell mass, need to be considered. These elements relate analogically to statistics which are usually presented as indications of "growth" in technology.

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, and

_____

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

is seldom thought of in terms of the number of cells. Since the size of the cell mass is proportional to the number of cells, then if the number of cells grows exponentially, the weight and significant linear dimensions will also grow 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 the manner that the dimensions of some major part of the cell mass are proportionate to equivalent dimensions of the total mass. Thus, observed growth of a major part of the mass (number of patents) may be used to estimate proportionate growth of entire mass (total number of existing inventions).

While size of the mass is usually emphasized as the measurement of growth in the biological part of the analogy, the emphasis is shifted to strength or performance as the measure of growth on the technological side. This is primarily because of the relative ease of measurement in each case. For an organized cell mass the strength of the mass may be measured by the ability to lift, to cover a certain distance in a given time, to raise its own weight given distances in given times, and by similar measures of performance. Each of such capabilities will increase in some

manner roughly proportionate to increases in the size of the
cell mass. Such performance might therefore be used con-
sciously as an approximate measure of growth, or wrongfully
be interpreted as growth itself. This is quite parallel to
the usual measurements of "growth" in technology.

Since performance measures are easier to obtain than
measurements of the number of inventions, performance usual-
ly is accepted as the measure of growth of the technological
field. A principal difficulty involved in this method of
measurement is that inventions may accumulate without a
demonstration of performance over a given period, just as
cell growth may occur without being exercised in a demon-
stration of strength. Thus the absence of demonstrated im-
provements in performance capability may be wrongfully
interpreted as cessation in growth of invention in a given
field. Then when some call is made for improved perform-
ance, the result of the accumulation of inventions appears
as a steep rise in the performance curve.

Gross errors are frequently made when other charac-
teristics roughly related to growth of the cell mass, or
technology, are used as measures of the technology itself.
For instance, the increase in consumption of coal is fre-
quently cited as a measure of the growth of power technol-
ogy. In the biological analogy, this is equivalent to
stating that the increase in consumption of a given nutrient

represents the growth of the cell mass. That the consumption
of coal (or specified nutrient) may be proportionate to the
growth of the technology (or cell mass), is certainly true,
yet the gradual shift to another energy source (or nutrient)
is not necessarily related to a decline in growth and should
not be so characterized.

On the positive side, the growth analogy description
of performance capabilities may be used for technological
prediction, if evidence exists of a continuous effort toward
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 princi-
ples of biological growth, the projection may be presumed to
have some validity as a prediction.

To summarize, the analogy of cell division to tech-
nological improvement may be used for prediction in the fol-
lowing 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 the increase in economic support for invention to

the rate of increase of invention, to show that exponential
increase in invention is not likely to be maintained without
exponential increase in the economic support thereof; (3) By
indicating the lessened rate of progress induced by the ob-
solescence of inventions, over an initial period in the tech-
nology equivalent to two or three invention "lifetimes"; (4)
By projecting the growth curve to "maturity", with a con-
stantly diminishing rate of increase in progress, where, and
only where, the limits of demand for invention in a given
field can be reasonably determined; and (5) By relating in-
creases in performance capabilities to growth curve charac-
teristics which will enable projection of performance capa-
bility.

III. ANALOGY OF TECHNICAL IMPROVEMENT TO THE
HIGHER REPRODUCTIVE PROCESS

The biological process of paired, bisexual reproduc-
tion offers a detailed analogy to the process of development
of a single invention. This process, as outlined in Table II,
page 56, was disposed of as a simple cell division in the pre-
ceding case.

As the starting point of this analogy, it is assumed
that an existing invention or discovery, communicated to the
receptive mind of an inventor, will bring about the origina-
tion 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. Insofar as this analogy holds, the resultant offspring in the technical case is always of the male gender, being a new invention or discovery.

After the origination of the new idea, or conception, embryonic development of the idea 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 growth 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 directly only for the inventor, as in the analogy, nutrition needs to be provided only for the female parent. The period required for invention is equivalent to the period of gestation in the biological analogy. 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 higher species of animals, such as man. Second, the period required for invention will be governed to some extent by 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 greatly by adequate support, only the inventor can
actually produce the new idea; just as excellent medical
care may aid the birth of an infant, but only the female
parent can actually bear the infant.

Using the above elements of the analogy, it can be
shown that the number of forthcoming inventions cannot sig-
nificantly exceed the number of inventors, for any period of
time equal to the average period required for invention.
Thus, in order to predict the number of inventions which will
be made in the future, the forecaster needs first to fore-
cast the number of inventors. This is relatively easier than
to predict than 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, and lesser inventors
can be assumed to be present on some regular basis in pro-
portion to the total population. Then, with an assumption
as to the average period required for an invention, the num-
ber of inventions over that period can be predicted not to
exceed the number of inventors existing at the beginning of
the period. For any given technology, the determination of
an average period for invention, leading to a prediction of
number of inventions, is easier than might be supposed. For
example, an average of the number of patents obtained by

inventors with multiple patents in a given field, divided by
the average working lifetime of such inventors minus the
average time spent on development and exploitation, would
give an estimate of the average time required per individual
invention.

Continuing the analogy, the next step is disclosure
of the invention or idea, which is analogous to birth in the
biological sense. Disclosure represents the first complete
evidence of the existence and nature of the idea. It is
worth noting that the "idea" represents the second genera-
tion male parent at this point. Unlike most 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 equiva-
lent to nutrition for the biological infant. To the extent
that economic support is not provided for development, the
idea or invention dies. In prediction of technological
progress, therefore, the projected availability of develop-
ment funds can be used to determine the number of inventions
which can be supported. So long as this number does not
exceed the number of inventions made, then availability of
development funds will determine the number brought to oper-
ational use. Thus it can be predicted that a constant flow

of development funds will produce not greater than an arithmetic rate of increase in total number of inventions.

The time required for reducing 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 normal death in the biological case. The analogy up to this point is sufficiently natural that the biological expressions are frequently employed in describing the inventive process, for instance, "birth of the idea", "conception of the invention", and "embryonic idea". However, little use has been made of the analogy in determining and describing the quantitative relationships of nutrition, parenthood, and growth periods, to their counterparts in the technical improvement process.

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

capability achieved by the total number of operational inventions is equivalent to the total strength of the work force in the biological analogy.

To use this analogy in predicting technological progress, the ideal method would be the complete development of quantitative relationships at each step of the analogy. However, the statistics to support such a development are not available. Never-the-less, if the analogy is accepted, then various regression analyses, supported by cause-and-effect relationships, may be used for predictive purposes. Thus, if performance capability is a function of the total number of operational inventions, which is a function of economic support for development and numbers of inventors, then growth in performance capability can be related directly to economic support and numbers of inventors. Then, 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. It is important to note that this analogy places a limit upon the rate of advance, regardless of number of inventors and amount of development funds, by including gestation and development periods in the model.

To summarize, the analogy of paired, bisexual reproduction to technical improvement may be used for prediction

in the following ways: (1) By forecasting the number of in-
ventors working in a given area, with due allowance for the
time required for invention, the number of future inventions
may be predicted; (2) By forecasting the availability of
development funds, the number of inventions which can be
brought to operational use may be predicted: (3) By deter-
mining prior relationships of growth in performance charac-
teristics to numbers of inventors and economic support, the
forecaster may predict performance characteristics as a con-
sequence of scheduled economic support and education of in-
ventors.

(

CHAPTER V

FORECASTING BY TREND CORRELATION

Some events occur as a direct result of events which have already happened. Other events follow the pattern of preceding events, without discernible causative influence. In a third case, events which are difficult to predict directly, may be related to other events whose future occurrence is easier to predict. Such circumstances offer a useful basis of prediction for the technological forecaster. Prediction by this method requires the selection of the technical parameter which is to be forecast, the finding of a related set of events, the determination of the relationship between the technical parameter and the related events, and finally the projection of these three elements.

The 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 for the next twenty years, when he states that "The major events that determine the future have already happened--irrevocably".[1] Although

---

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

logical, this type of prediction does require a certain
blitheness of spirit in ignoring the possibility of major
mishaps which might materially alter the expected causal
relationship. This type of prediction is also helped by a
certain ignorance of historical trends, since such trends
frequently seem to be at variance with simple cause-and-
effect relationships.

In making a forecast of the causal relationship
variety, only one factor need be considered in selecting
the technical parameter which is to be the object of the
prediction. This factor is whether progress in the tech-
nical parameter is indeed dependent on a single controlling
class of conditions. For example, if all of the scientific
discoveries which are necessary to permit technical advance
in a given area have been made, and no political barriers
have been imposed, then one might consider that economic
conditions have constituted the only restraint upon progress
in that area. The technical advance thus singly restrained
would then be a suitable subject for cause-and-effect fore-
casting. As a specific illustration, passenger carrying
capacity of the automobile, unlimited by technical or legal
restrictions, is related to the maximum number of passengers
which the average purchaser expects to transport reasonably
frequently, that is, the number of passengers in his family.
Thus in the field of 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 selection of the specific set of events which has a definite effect upon the object of prediction. For example, if the length of the maximum single span of bridges is considered unlimited by political or narrow economic barriers, then the possible technical limits may be scanned for a specific controlling variable such as the maximum tensile strength of materials reasonably available for bridge building.

When a controlling variable is found, then the prediction of technological events 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. It may be observed that many notable inventors succeeded principally because of an intuitive understanding that limiting barriers had been removed, and consequently, what had been impossible before,

was now predictably possible. For example, the steamship involved no new discovery on Fulton's part, but simply the recognition that steam-engines had reached the point of efficiency which made their application to ship propulsion feasible.

The greatest difficulty in predicting future events as the consequence of known causal events lies in the rapid advance of science today. The exploitation of each new discovery is so swift that such a forecast is essentially short range, seldom exceeding the length of time required to design and produce a system or 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 is valid. Thus Drucker forecasts the progress of automation partly on the basis of the predictable ratio of total population to working population in the U. S. over the next twenty years.[2]

Prediction on the basis of an observed sequential relationship between two time-series, without proof of a causal relationship, is a useful but somewhat dangerous method of forecasting. This method has frequently been used in economic forecasting, so that examples of its use

_____

[2]Ibid., pp. 3-5, and p. 33.

and misuse may be readily drawn from that source.

One such example of the economic theories of prediction based on an observed sequential relationship is the "sunspot" theory, in which the 11-year cycle of sunspot activity is presumed to influence economic behavior to follow a similar cyclical pattern.[3] By the use of adjustable "lag" times, "smoothing", "averaging", and the imposition of major and minor cycles, practically any economic time-series with random motion may be shown to follow some cyclic phenomena. This adaptibility is a frequent source of error in the use of sequential relationships in cyclical situations where cause-and-effect is not clearly demonstrated. Even though a similar cyclical pattern is observed in two time-series, it is impossible to determine from the patterns alone, which series actually "precedes" the other. Thus either series might be used to predict its own movement, but nothing is gained by using one of the series to predict the movement of the other.

Most of the difficulties of sequential forecasting, as cited above, may be avoided in technological forecasting if its use is limited to non-cyclical relationships. Since

---

[3]Edward R. Dewey and Edwin F. Dakin, Cycles--The Science of Prediction (New York: H. Holt and Company, 1947) pp. 141-145.

most of the patterns of technological advance are patterns
of continuous increase, with cyclical variation appearing
only in the rate of advance, it is frequently possible to
discern situations in which one measurement of technical
progress consistently lags another by a constant length of
time. Where this is true, and especially where some nat-
uralness appears in the relationship, it is possible to use
the leading measurement to predict the status of the fol-
lower over a length of time equal to lag period. If the
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.

Forecasting on this basis requires the search for
two technological time-series, one of which has consistent-
ly preceded the other. If the relationship between the two
series is a natural one, then some confidence in the fore-
cast may be expressed. If the relationship is strained,
the possibility of error in the forecast is in some propor-
tion to the technical difference between the two series.
For instance, the maximum dimension of radar "dishes" might
follow the maximum wing-span of aircraft, yet the use of
this relationship for prediction would introduce a consider-
able possibility of error, since no similarity exists in the
forces affecting the development of the two objects.

An example of effective use of a sequential relation-

ship may be found in the correlation of the maximum speed of military aircraft to the maximum speed of commercial aircraft. As shown by Fig. 4 of Appendix A, 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. Although reasons may be suggested to explain this lag period, almost equally good reasons may be advanced to show that a different relationship should exist. Therefore the predictor can only state that this is the observed relationship, that the forces which established the relationship have not changed, and that he therefore expects the relationship to continue. On this basis; 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 somewhere 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.

In forecasting by the correlation of two series of events, use may be made of the fact that, of any two series of events which have either a cause-and-effect relationship or simply a demonstrable similarity, one of the two may be

easier to forecast. In such a case, even if the two series are related concurrently, a forecast of the easier series may be used as the basis for forecasting the more difficult series. This is the basis for many forecasts of economic time-series, in which a forecast of the Gross National Product is used as the primary series. Regression analysis of the prior relationship between the two series is used to obtain an expression of the second series in terms of the GNP. Then projected values of GNP are converted by this expression into projected values of the second series. Although the forecast of the second series will reflect any error in the forecast of GNP, such error may well be less than that incurred by projecting the second series separately.

To establish a technical forecast of this nature, a forecast of the primary time-series is obtained, and the relation between this series and the one of interest for prediction is determined. These two elements are then combined to forecast the series of interest. An example of such a forecast when the primary series is a controlling factor, is the prediction of the aerodynamic forces acting upon a pilot escaping from a disabled aircraft. 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 from aerodynamic laws. 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 situations exist in which secondary
technical requirements are established as a result of ad-
vances in major performance characteristics. Thus, this
method of forecasting, on the basis of concurrent projection,
is particularly useful in establishing research requirements
for secondary inventions.

I. USE OF INTERDEPENDENT RELATIONSHIPS
FOR PREDICTION

Correlation of trends may be extended to the use of
two or more primary trends which then define a third course
of events. This method of prediction offers three principle
advantages over the simple relationship between two vari-
ables. First, the trend of a given technical parameter
which is complex and difficult to predict by itself, may
sometimes be easily expressed as the result of a relation-
ship between two or more other trends. Second, any two pri-
mary trends, related to the same technical area, may, if

extended on their existing course, result in a physically impossible situation. Examination of this situation for alternate consequences may then give rise to useful predictions. Third, either of two primary trends might be extended by any of several types of invention, yet the mutual requirements of these trends may indicate that only one or two courses of invention would actually be followed.

In using two or more trends to determine a third, the predictor must have available a number of primary trends which significantly relate to the technical field of interest. To these he must add a knowledge of probable relationships that might arise from combinations of such variables. With these two elements 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 of the techniques of the preceding chapters which appear appropriate, followed by projection of the unknown variable on the basis of the relationship between the primary variables.

As an example of this type of forecast, the relationship between "passenger capacity", "load factor", "total passenger miles", and "total plane miles flown", for commercial aircraft in domestic trunk line service, may be examined. 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 Depart-
ment of Commerce statistics, as shown in Figure 5, Appendix
A.[4] 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. However, 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 2½% per year in 1980. Also since 1947, the "load
factor" has remained essentially constant between 60% and
70% and may be most reasonably projected to continue at 65%.
Meanwhile the passenger capacities of new aircraft added to
the trunk airline fleets since 1953, and to be added in the
future, have continued to increase in a manner consistent
with the past rate of increase of passenger capacity. The

_____

[4]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 statisti-
cal 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 be combined to give a meaning-
ful figure. The average figure obtained by the method indi-
cated, is a fair representation of the hypothetical "average"
aircraft used by the airlines.

consequence of lower rates of increase of "total passenger miles", combined with physically increased "passenger capacity", and constant "load factor", is that "total plane miles", as the dependent variable in this situation, will not continue at its 1930-1957 rate of increase after 1960.

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; giving no hint of probable diminishment in the rate of increase, and no basis for predicting any rate of increase other than the existing rate. Thus a forecaster using "trend data" for "total plane miles" might project quite inaccurate estimates of airway traffic, with attendant errors in prediction of the equipment needed to support that traffic.

In concluding this example, the prediction of "total plane miles" is obtained by transposing the equation for "passenger capacity" so as to solve for plane miles on the basis of the other three variables. The diminution of the rate of increase of "total passenger miles" may be assumed to remain constant to 1980, although support for this assump-

tion represents a separate problem in forecasting. Load factor , as already indicated, has stabilized at 65%. For the remaining variable, "seating capacity", two choices may be made, providing two solutions to the equation as limiting values for the prediction of "total plane miles". The upper limit 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. This assumption implies that the higher capacity jet aircraft currently being introduced have more passenger capacity than is warranted, and that they will tend to lower the average "load factor" in trunk airline operations. 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 prediction for "total plane miles" shown in Figure 5, Appendix A. Thus the prediction is 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 selection and modification of one of the limiting conditions to obtain a most probable

value. Such selection is not necessary, however, in this demonstration of the technique used in prediction.

A second example of the use of interdependent relationships in forecasting may also be taken from the domestic trunk airline situation previously described. In this case the forecaster is interested in trends which appear mutually contradictory. In the domestic airline situation, the forecaster (ignoring the results presented in the discussion of prediction of "total plane miles") 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). However, if he then continues by solving the equation previously given for "seating capacity",

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

he will obtain the curve labeled "false prediction" on Figure 5, 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 such a circumstance is not physically impossible, it would require cancellation of nearly all present airline orders for new aircraft, and gradual 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 by the predictor for the possibility of alternate consequences. The most obvious of such alternates is the correction of "total plane miles" as outlined in the preceding example. The search for other alternates is the responsibility of the forecaster in each situation. However, one alternate may be cited in demonstration of the method. By examining the lower limit curve of "total plane miles", projected on the basis of the long-term trend in seating capacity, it may be noted that this curve 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. The alternate to this situation would be that aircraft size would stop increasing in 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 then 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 which must be provided for.

The example of trunk airline operations also may be used to demonstrate the use of trend correlation to predict the probable course of invention. If the prediction cited

in the previous paragraph is valid, then a basis exists for
predicting the improvement pattern for airways traffic con-
trol equipment. Since the total number of flights is pre-
dicted (in this example) to increase only slightly over
present levels, then traffic control equipment will not re-
quire major improvements in terms of volume of traffic
handled. Research and development should therefore be di-
rected primarily to improvements necessitated by increased
speeds and greater precision required by jet aircraft oper-
ating characteristics.

These predictions are cited only as examples of pos-
sibilities of this method of forecasting, and are not neces-
sarily valid. In making any technical forecast, many more
possibilities should be examined. The greater the amount of
correlation which is employed, the more likely is the pos-
sibility that the forecaster will successfully describe the
future course of events.

II. PREDICTION ON THE BASIS OF
TREND CHARACTERISTICS

The methods of technological forecasting described
in the preceding chapters have been concerned with extending
time-series to provide a quantitative measure of future
events. These time-series may be used in quite a different
way for prediction if account is taken of characteristics

in the trend curves of the time-series. These characteristics
may occur in that part of the trend curve which represents the
known situation, or they may be observed in the projection of
the trend curve.

The use of trend characteristics in forecasting de-
pends upon recognition of the forces which produce the ob-
served shapes of time-series, upon the consequences of con-
tinuation of those forces, and upon possibilities for change
as a result of these consequences. Some of the more obvious
characteristics may be pointed out, and examples may be given;
however, the skillful use of this technique depends upon con-
siderable knowledge of the technical field in which forecast-
ing is being attempted, and practice in using trend curves for
prediction.

One of the simplest situations for prediction on the
basis of trend characteristics is the one in which a well-
established exponential rate of progress will, if extended,
intercept some known physical limit. Since, by definition,
progress cannot be extended beyond this limit, only two pos-
sibilities exist. The first possibility is that progress
will indeed stop at this point, and that such a situation will
be satisfactory to all concerned. The second possibility is
that a new technology will be developed which will permit the
extension of progress on some equivalent basis, beyond the

limits previously known. It is this second possibility which offers opportunity for prediction. If the old technology is one which has filled a definite need of society, and if its advance in performance has also been useful, then an innovating society is unlikely to let progress cease, if a substitute technology can be found. Thus a pressure for discovery is created to bring about the necessary invention. One may predict that the intersection of the exponential trend with the physical limit is the logical time for an invention or discovery which will produce a new technology to extend performance beyond the previous limit. A further predictable characteristic of this situation is that the required innovation becomes more and more likely as the intersection approaches. Also, if invention does not occur at the time of intersection, the pressure for innovation will become greater as it becomes obvious that progress has ceased. If the invention occurs before the limit of progress is reached, it is likely to be closely related to the existing technology. If the invention is delayed, the new technical possibilities will be different from the old in some degree roughly proportionate to the length of the delay.

In predicting invention on the basis of intersection of the trend with a known limit, it may not be possible to specify exactly what the invention will be. However, some characteristics of the invention may be guessed at by the

nature of the barrier imposed, and by the physical possibil-
ities lying outside of the barrier.

Although the word "breakthrough" has been used
rather loosely to characterize almost any invention, it
would appear that an invention which overcomes a clearly dis-
cerned barrier to exponential progress, is one which actually
deserves the title "breakthrough". Most such "breakthroughs"
do not provide great steps ahead, but rather enable contin-
uation of exponential rates of progress. If the new tech-
nology created by the breakthrough is closely related to the
old, it is likely that the new rate of progress will be a
continuation of the prior rate. If the new field is sub-
stantially different from the old field, it is probable that
a new rate of progress will be established, intersecting the
old rate at its intersection with the previous limit.

As an example of this type of prediction, the maxi-
mum speed of military aircraft as shown in Figure 3, Appen-
dix A, may be examined. 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 predictors of aeronautical progress at that
time predicted that aircraft speed performance would not

exceed such limits. These limits were 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, replacing the propeller, would become an operational innovation in 1944 or 1945, enabling a continuation of the speed trend at its prior exponential rate. Such a prediction 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 it offers an indication that what could have been predicted by the method cited herein, actually did happen in a manner consistent with the principles cited.

If this example is used to make a prediction of the future, it may be observed from Figure 3, Appendix A, that extension of the speed trend 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. These

developments will be equivalent in some manner to the innovation of jet propulsion. Thus it may be predicted that the structural and materials developments necessary to provide an airframe capable of operation at the 800° F surface temperature of Mach 4 speeds will be invented not later than 1965-66. This example offers no more proof than the first examples, that the method of prediction is valid, but is cited to show that a forecast may be established by the method given.

The use of trend characteristics for prediction may be extended to those situations in which the rate of increase in performance is steadily diminishing. Such a decrease may be due to a diminution in the rate of increase of research funds, or to a maturity in the technical field as represented by an asymptotic approach to physical limits. In either case, the possibility for prediction is similar to the possibility given by the relationship of exponential progress and known physical limits. In the case of a diminishing rate of increase, it is apparent that some forces, which may or may not be discerned, are tending to bring progress to a halt. If these forces are competitive and newer, they may be expected to continue the advance of progress in some related manner. For example, if the production of coal should show a steadily diminishing rate of increase, this may mean only that the production of oil has been expanded to maintain an

exponential increase of the total energy supply. In such a situation, it may be forecast that the older technology will be replaced by the newer, and that the rate of progress in the new field will compensate for the loss in the older technology. The use of such a forecast enables the predictor to search for unknown competitive fields, and to determine the growth rate of such competitive fields before they are well established.

If limited funding for research is the force which is depressing the rate of progress, then a pressure of possible discoveries increases in proportion to the departure of the trend curve from the established exponential rate. This pressure is a potential force to bring about entry of another organization which may achieve the exponential rate of progress. This pressure also increases the possibility of entry of a new technology offering a substitute rate of progress.

If the forces depressing the rate of progress represent maturity of the technical field as physical limits are approached, this is a special case of the intersection of exponential progress with a known physical limit. In this special case the physical limits, which may be unknown, are observed to be hindering further progress. Therefore it may be predicted that, as the rate of progress approaches the limiting value, the development of a new technology becomes

increasingly probable.

In each of the situations cited above, the forecast may be made more specific by noting the amount and rapidity of divergence from the exponential trend. If the divergence is small, no prediction may be warranted. If the divergence is large and increasing rapidly the probability of innovation is also large. When the rate of increase drops either to zero, or below some natural limit (such as the rate of population increase, for the case of a consumption product), innovation becomes almost inevitable. If this drop to a zero rate of increase can be predicted, then the innovation can be forecast to occur somewhat before the time that the rate becomes zero.

Many other inferences may be drawn from the characteristics of trend curves. A few of these may be cited as examples, with the assumption that others may be developed through the knowledge of the individual forecaster. For instance, if a steady decline in rate of progress has been observed in a given technical field, then an increasing exodus of engineers and innovators from that technical field may be predicted. This is because of the natural inclination of innovators towards a "new" field. In turn, this exodus will hasten the decline of the rate of progress in the older technical field, so that decline, once started, proceeds at a

rapid rate in many cases.

Kuznets cites the decline in output per worker in
the situation of exhaustion of natural resources.[5] By anal-
ogy, the output of innovation per engineer might be expected
to decline as the exhaustion of theoretical possibilities is
approached in a given technology. Thus, even an exponenti-
ally increasing "work force" of engineers will produce a
lesser rate of increase of progress as technical limits are
approached.

[5]Simon S. Kuznets, Secular Movements in Production
and Prices (Cambridge: The Riverside Press, 1930), pp. 38-
39-40.

CHAPTER VI

DYNAMIC FORECASTING

The title, "Dynamic Forecasting", which is used to identify the method of forecasting described herein, is derived from the term "Industrial Dynamics", as used by Jay W. Forrester to describe the time-varying behavior of industrial and economic systems.[1] Professor Forrester uses the title "Industrial Dynamics" to connote a method of decision making for industrial managers in which complex business operations are simulated on a digital computer. By varying the information provided to the computer, the effect of various management decisions on future operations can be determined. A similar method may be used for technological forecasting; by which the effect of various policies on technical progress may be estimated.

The forecasting of technological progress by dynamic simulation requires a model which describes as accurately as possible 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

---

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

includes information feedback control. Since, in most cases, the rate of technological progress has increased exponentially over a considerable period of time, the model must encompass this possibility of "excursion" or "divergence". Also, since most technologies show the characteristic of limited increase after some period of time, the model should be capable of producing such a situation as a result of appropriate inputs.

A dynamic model, purporting to represent the development of a technology, has been constructed as a part of this thesis. Since the model represents that part of the system which related to the dissemination of knowledge, and the progress which results therefrom, it will be referred to as 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 been made to describe a complete cultural system within which the processes of discovery, invention, and innovation might take place. Such a model might be very useful in identifying all of the factors which influence progress. However, this complete model would have been beyond the scope of this thesis, and would have required more information about economic and social forces affecting innovation than will be available for many years. Because of these factors, the second alternative for a knowledge-progress model was chosen. This

alternative was the development of simple model, using a limited number of factors pertaining to the process of education in technology and the resultant progress which is obtained. Such a model has the advantage of conceptual simplicity which aids understanding of its operation; can be made to operate with information which is currently available; and can be modified as conditions warrant. As the simple model is improved it might eventually encompass all of the significant factors influencing innovation. Meanwhile, it is capable of serving as a useful, working model for the testing of concepts, policies, and decisions concerning technological progress.

The simple dynamic model which was developed for this thesis contains relatively few factors, a limited number of feedback relationships, and a nearly equal number of relationships determined externally to the system. The simplicity of the model is such that it may be computed in tabular fashion without recourse to computer facilities. No simultaneous equations are used, consistent with the restrictions imposed by the Industrial Dynamics method of solution; however the equations describing the model do imply a simultaneity of information which is incompatible with the "Dynamo" programming of the IBM 704 Computer.[2, 3] Because of this factor, the

_____

[2]Jay W. Forrester, Formulating Quantitative Models

computations for testing the model were accomplished by
tabulation.

A flow diagram of the knowledge-progress system is
shown in Figure 1 on page 105 following. A similar diagram,
coded in terms of the equations for the dynamic behavior of
the system, is given by Figure 1, Appendix B; followed by
the equations in Table 1, and identification of the vari-
ables and constants in Table 2.

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

---

of _Dynamic_ _Behavior_ _of_ _Industrial_ _and_ _Economic_ _Systems_,
Part _I_ (Cambridge: Unpublished Memo: D-16 Mass. Inst. of
Tech., 1958), p. 24.

[3]The first step in improvement of the model might
well be the revision of those equations which imply simul-
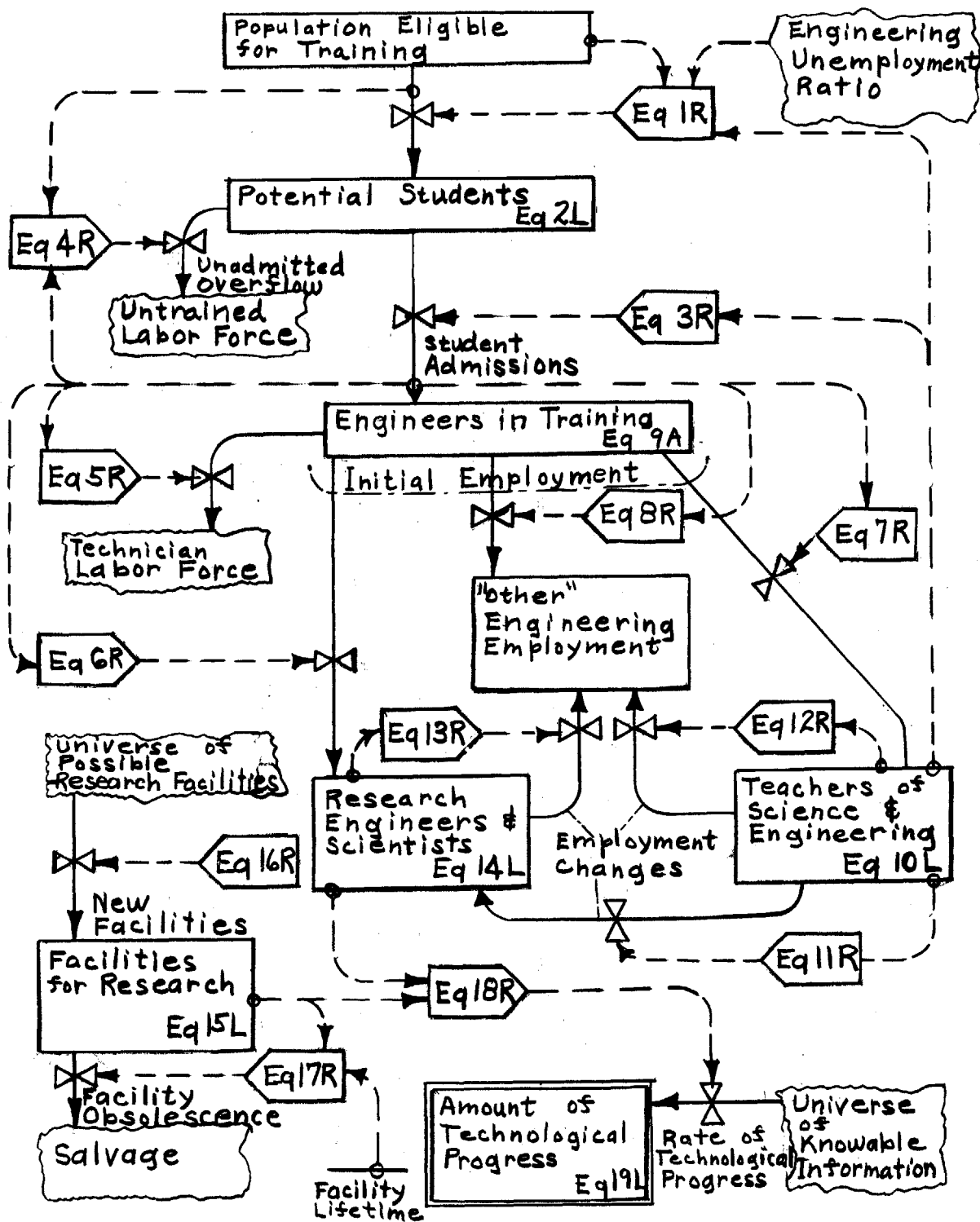taneity of information.

Figure 1.   Flow Diagram for Knowledge-Progress System.

The starting point of the model is the segment of population in the age bracket of 18-21. The size of this segment of the population is not controlled by information feedback from the rest of the system. Never-the-less, variations in the size of this segment affect the number of people seeking training, and therefore affect later portions of the system. For any given period of time the size of this reservoir of "population eligible for training" may be determined from census statistics. If major variants occur in the population eligible for training, such as the addition of war veterans to the usual 18-21 age group in 1946 and 1947, then such variations should be included in determining the size of the reservoir.

Equation 1R defines the rate of flow of individuals from the "eligible" group into a select group of individuals potentially available for training. In a democratic society this rate of flow is controlled by a multitude of individual decisions as to the desirability of training. In this simple model these decisions are considered to be statistically controlled by information about the number of teachers available (as reflected in promotional efforts of the institutions affording training); by the number of "eligible" individuals (as previously defined); and by the current employment ratio in the technical field involved (reflecting job opportunities). A proportionality constant, relating the number of

potential students to the size of the eligible population under given conditions of the three controlling factors, was derived from historical data. If sociological conditions change, this proportionality constant may also change. However, on the basis of the historical data dovering the last 50 years, the number of individuals desiring to enter training has been a fairly constant proportion of the product of the eligible population times the number of teachers. An additional adjustment is made 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 to reflect only the entry rate of new eligibles.

The flow of individuals making the "choice to accept training", as described above, creates a reservoir of individuals potentially available for training, as indicated by Equation 2L. The quantity in this reservoir is normally low, representing only those individuals desiring to accept training, who have not yet been able to enter training. The outflow of the reservoir is in two parts, those who are "received for training", and those who are "diverted from training". Equation 4R indicates the rate of diversion as 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 of the final remainder will be diverted after waiting three years.

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 an amount equivalent to 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. The rate of flow of individuals "received for training" cannot exceed the rate of flow of individuals "choosing to accept training" plus any accumulation of individuals "potentially available for training".

A reservoir of individuals, or "minds in training", is created by the flow of individuals received for training. This reservoir, the level of which is 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 rate of 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 year. The equation thus represents the summation of the 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. Each outflow is described as a proportion of the product of the number of individuals entering training at the appropriate prior period, multiplied by a fraction indicating the percentage who complete the training. For example, in Equation 6R, the outflow of individuals "available for research" is defined as the proportionality constant of graduates going into research, times the number of graduates expected from the entry class of the fourth prior period. The equations are established so that each entry class is accounted for in terms of an equal total outflow by the time that the training period is completed.

The proportions of graduates going into the separate fields of research, teaching, and other employment are believed by the author to be determined without regard for the dynamics of the system, and also with little regard for information available from the system. This is the reason for defining the three factors as constants. Values have been given in Table 2 for each constant. These values accord with present proportions for each field. However, other values may be assigned to these constants, representing changes in incentive for entry into each field, so that the affects of such changes may be observed. The broadening of the model to include factors influencing these rates of flow would involve most of the economic and social structure of society, so that such a modification must be excluded for the present purpose.

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 level of teachers is a factor in decisions affecting the flow of individuals received for training, as indicated previously. The level 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 by work in each area and also as a function of the level of the reservoir _from_ which the flow is occurring. As written, 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 of each, and multiplied by the level of total employment in the losing reservoir. This is believed to represent a reasonable approximation to the actual process of movement between employment fields.

The equations for cross-flow represent the "compensations" as constants, determined outside of the system. Since the rates of monetary compensation are set by a different group of individuals for each field of employment, they are essentially unrelated to each other. Also, the existing compensation policies are almost completely irrational in the larger sense, so that "compensation equations" would be difficult to establish. Values for the constants may be obtained by measurements of existing rates of flow, which represent the relationship of the total compensation in each

field. Then the model may be used to test the effect of variations in compensation policy (however arrived at), upon the operation of the system.

Since progress in technology requires laboratories, equipment, and other physical facilities, just as much as it requires researchers, the model must include some provision for these items. Equations 15L, 16R, and 17R are therefore included to represent the "plant or facilities available for research". The rate of construction of "new facilities for research" is determined largely by decisions made independently of information from the model. Therefore Equation 16R, describing this quantity, has not been made definitive.

The flow of new research facilities might be described as a function of the number of researchers diverted to the proposing, designing, and construction of such facilities, and of the number of individuals in training and the number of researchers currently available. However, information about the determinants of the rate of facility construction is not sufficient to permit adequate expression of this quantity. Operation of the model, therefore, is accomplished by making assumptions about the rate of facility construction. Such assumptions may be based on 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. These require 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 information about the number of research workers and research facilities 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. Units for the measurement of the rate of technical progress are not specified, because they are basically indeterminable at this point in the system.

The flow of technical progress is conceived as the rate at which knowledge is released from an infinite universe of knowable information. Both the quantity and the variety of this knowable information are infinite. Thus the flow is composed of a mixture of some of the knowable facts about the physical universe.[4] For example, progress in

---

[4]In a more complex representation of the system, the infinite reservoir of knowable information would constitute the first of a series of reservoirs. Each succeeding reservoir would be filled by a flow of knowledge released by research work from the preceding reservoir. For example, "basic research" would provide "fundamental knowledge" from the physical universe. Then "applied research" would release "fundamental knowledge" to fill a reservoir of "technical information". The last stage of this process would release

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, as will be shown.

Equation 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 research facilities were not converted to units of technical progress, the proportionality constant in Equation 19L converts the units of output into increments of performance improvement. Thus measurable quantities of research workers and research facilities may be related to a measurable item of performance

---

"technical information" to produce "progress". The present model implies either that none of the reservoirs in the complex process are empty, or that the number of researchers at each step in the process is such as to maintain a uniform flow.

improvement, even though the intermediate step of "technical progress" is unmeasurable. The proportionality constant which relates performance improvement to the number of researchers and research facilities may be determined on the basis of the relationship of these factors over some prior period.

The "knowledge-progress system" model may be used for technological forecasting in several different ways. First, if a given technological field is well established, the relationships which exist between the different parts of the model may be determined. Then the 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 also possible to use the model for experimenting with changes in the relationships, or with the decisions which bring about the observed relationships. In this manner 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 those decisions may be made which will achieve desired objectives in the operation of the system. The technological improvement which will result 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.

In Case 1, Appendix B, the development of a new technical field, starting with a single teacher as the originator of the technology, is shown. The ratio of the flows of graduates 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 rather strikingly like the curve of improvement in many technological fields, as cited by Hornell Hart, Kuznets, and others.[5,6] Thus the characteristic decline in the rate of increase of performance improvement may be due primarily to the pattern adopted by society for technological training versus research and development leading to production improvements.

Case 2 shows the development of a new technical field, which is changed from Case 1 only by adjusting the proportion of graduates entering teaching upward, relative to the number of graduates entering research work. In Case

[5]Hornell Hart, "Logistic Social Trends", American Journal of Sociology Vol. L (1945) pp. 337-352.

[6]Simon S. Kuznets, Secular Movements in Production and Prices (Cambridge: The Riverside Press, 1930).

2, the level of performance is less than in Case 1 for the first seven years after initial progress is made. 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 evidencing "maturity".

Such experiments with the model provide an understanding of the operation of the system under given conditions, which in turn enables prediction of probable rates of progress.

In conclusion, it may be noted that many writers support the premise that technological 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" described herein, the views of some of these writers will be cited for substantiation.

Gilfillan (paraphrased), states among his 38 principles of invention that: (No. 26) Individual genius has not been essential to any important invention, and the progress of invention appears impersonal to the student of sociology; (No. 27) Invention comes only at the hands of inventors, and in proportion to their numbers, intelligence, time expended, and mechanical equipment available to them; and (No. 17)

Invention is aided by the specialization of labor which re-
sults in the specialized occupation of professional inven-
tor.[7]

Brozen states, in relationship to the differences in
profitability of industries, which are related to differ-
ences in their research efforts, that there are two reasons
why research effort did not grow more rapidly in previous
years; first, that trained personnel were not available, and
second, that the science base was inadequate.[8] Both of these
reasons for the limited increase in research effort are
closely related to the dynamics of the "knowledge-progress
system" model.

---

[7]S. C. Gilfillan, The Sociology of Invention
(Chicago: Follett 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.

[8]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

None of the methods of technological forecasting cited in the preceding chapters are unquestionably superior to the others. Therefore the best prediction for a given purpose may require the development of several forecasts by alternate methods. The several forecasts may provide a range of probable developments; or they may be combined to give a single, most likely, estimate of the future; or they may simply provide a number of predictions from which one may be chosen according to the purpose for which it is to be used. Variation among the several forecasts may be used to signal the possibility of changes in the trend of events, or to emphasize the need for additional predictive effort.

The combination of forecasts to obtain a probable range of values should start with the extrapolation of existing exponential trends as outlined in Chapter III. If these trends are well established, and if artificial restrictions have not limited progress, then the forecast of continued exponential progress will represent the _maximum_ rate of progress which is likely to be achieved. To obtain any 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 in-
creases greater than this rate were achieved only by the
changes in technology and objectives represented by the un-
manned ballistic missile with rocket propulsion.

After a maximum rate of progress has been established,
then lesser rates of progress may be forecast by the biolog-
ical analogies of Chapter IV, by use of the correlative
techniques of Chapter V, or by use of the dynamic forecasting
methods of Chapter VI.[1] The smallest rate of progress which
is predicted by these methods represents the minimum rate to
which progress is likely to be limited. If, however, the
smallest rate of progress is inconsistent with other evidence,
then the next smallest rate of progress may be chosen as the
minimum rate of progress. If the rates of progress intercept

----

[1]The rates of progress predicted by these methods will
ordinarily be less than present exponential rates if the pre-
vious qualification, restricting drastic changes in proce-
dures, technology, or objectives, is adhered to. This qual-
ification is not as serious as it might appear, since the
assumption of changes in any of the three factors is suffic-
ient grounds for an entirely separate set of predictions.

each other, the forecaster may choose the envelope of small-
est rates as the minimum rate of progress, or may select
that rate which seems most appropriate at each successive
period of time.

The maximum and minimum rates of progress enclose
the area of probable progress. If this area is sufficiently
narrow to satisfy the predictor's objectives, any further
effort is best directed at improving the accuracy of the pre-
dictions which form the limits of the area.

If the area of prediction obtained by this method
affords too broad a choice of rates of progress, the combina-
tion of forecasts may be examined to determine a single, most
probable rate of progress. Although no logic supports the
averaging of two or more predictions, the average is occas-
ionally used in the absence of evidence that any one of the
predictions is more accurate than the others. If the predic-
tor believes that one of the predictions is somewhat more
accurate, then some method of "weighting" the average in favor
of the "better" forecast is usually employed. Akin to aver-
aging, is the selection of that one of several forecasts
which appears to be a rough average of the others. Any simi-
lar technique of averaging may be used to obtain a forecast,
so long as the forecaster does not assume that a major im-
provement in forecasting has thereby been obtained.

In many situations the "average" forecast may be
used simply for the convenience of dealing with a single
set of values representing future progress. In such cases
the use of average values is qualified, either by implica-
tion or specifically, by limits of variation which may be
constant, or increasing, with time. An "average" forecast
is most likely to be demanded by individuals who do not
desire the confusion of extraneous "facts", and who are
disturbed by alternate choices. One further advantage of a
single forecast lying between the extremes is where the fore-
cast is made available to a large number of individuals who
may employ it to guide a variety of decisions. If it cannot
be predetermined that such individuals would use the most
appropriate limiting values for their decisions, the least
damage will be done by providing only a single, average,
forecast for their use.

The selection of a forecast on the basis of the pur-
pose for which it is to be used is better than the use of
an average forecast. After several different forecasts of
the rate of progress of some parameter of technical perform-
ance have been developed, each of these forecasts may be used
as a basis of separate actions or decisions. Such use of
different forecasts concerning the same thing does not imply

inconsistency or indecision, but rather reflects the relative consequences of actions based on the different types of forecasts. As an example, if the decision is one which governs the rate of investment in research in a competitive situation, then the prediction that competitors will continue an existing exponential rate of progress is more conservative than one which assumes a lessened rate of progress. If, on the other hand, the decision concerns investment in an "old" technology competing against a newer technology, then a forecast of "maturity", or a declining rate of increase, in the old technology will be more conservative.

In planning research for a technology in which progress has been exponential, decisions which give priority only to projects with the potential to maintain this rate will eliminate many wasteful "knob-polishing" improvements. For example, improvements on reciprocating engines might have been deemphasized at an early date, in favor of equivalent effort on turbine engines.

In decisions involving the choice of technical approach, product design, products to be manufactured, or product "mix", those predictions which indicate exponential increase for new technologies, coupled with declining rates of increase for old technologies, will generally be the better choice. On the other hand, if expansion of capability is

possible quickly and with little expenditure when the need
is demonstrated, then the forecast of the lowest rate of
progress will be the most useful for guiding decisions. The
prediction giving the lowest rate of progress is particularly
required when the cost of over-capacity is high compared with
the cost of adding capacity as needed.

The use of alternate predictions for comparing the
relative costs of various actions belongs in the field of
operations research, and is beyond the scope of this thesis.
However, it may be noted that alternate predictions of tech-
nological progress may provide essential information for
statistical models of the decision process based on a range
of probable future events.

A wide variation in forecasts may indicate that sig-
nificant changes in the technology are about to take place.
For example, a prediction by the dynamic forecasting model
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 "B", which will take over, in some
fashion, the burden of progress formerly born by technology
"A". In many cases, similar conclusions might be drawn from
other evidence, so that this use of forecasting seldom con-

stitutes a unique method of discovery of changes in technology. However, systematic forecasting offers a high probability of disclosure of changes, and frequently points to the causal factors. Then the entire body of evidence supporting such changes is highlighted for detailed examination.

The variation in two forecasts of the same parameter of technological progress may indicate that the lower rate of progress will prevail, unless substantial changes are made in the supply of resources (or "nutrient" in the biological analogy of Chapter IV). In such a case, the variation signals for a "positive" managerial decision, either to increase the resources, and thereby the rate of progress, or to accept the lower rate of improvement. The essential element is that the possibility of "decision-by-default" is reduced when the facts are made clear by the difference between two predictions.

Disagreement between predictions emphasizes the desirability of making more than one prediction. Most forecasters may be well pleased with the results of a single forecasting attempt, since it is an "obvious" and "unambigous" 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. The requirement for additional investigation will usually disclose significant information leading to a better forecast; and will in any case

lead to greater knowledge of the factors involved in achieving further progress.

CHAPTER VIII

SUMMARY

The development of the several methods of technological forecasting in the preceding chapters has indicated the possibilities of predicting technical innovation on a systematic basis. Taken as a whole, the several methods enable the projection of progress in any given technical field by the use of regular rules and procedure. Each of the methods affords the opportunity of forecasting 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 of prediction has been developed on the basis of logical premises, which may be examined to determine the degree of credibility to be placed in 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 action leading to the orderly accomplishment of research and development, with adequate provision of required resources. Ulti-

mately the forecast provides the basis for plans to make use of the technological progress which is predicted.

The methods of technological forecasting which have been developed in the preceding chapters are summarized in the following paragraphs. Each of these methods may be used for the prediction of innovation and its effects in the continuation of technological progress.

The extrapolation of exponential rates of progress, as outlined in Chapter III, is the simplest method of forecasting which has any consistent relationship to historical patterns of technological advance. This method is related to the pattern of progress in Western civilization over the last four centuries, and has a high probability of success when used to forecast the advance of major technical fields.

Use of the analogy of biological growth to technological progress offers a logical extension of prediction by simple extrapolation. As developed in Chapter IV, the biological analogy predicts exponential rates of advance in the early stages of a given technology, followed by a diminution of the rate of advance as the technology progresses toward "maturity". The analogy of biological growth has been loosely applied in explanation and prediction of progress in many economic and technological fields. In many cases the analogy has been ill-conceived and erroneously applied, with

consequent failures in prediction. However, if the growth analogy is used carefully, with proper determination of factors and relationships which are truly analogous, then credible predictions of future technical progress may be made.

Correlation of progress in a given technical field with a 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 to the progress which is to be predicted. If the known factor precedes the unknown by a sufficient length of time, this provides an effective method of long-range forecasting which is particularly acceptable to the logical mind.

An extension of the method of simple correlation is the use of relationships between two or more factors which determine the rate of progress of technical improvement. This method of forecasting, also described in Chapter V, is useful in forecasting progress which does not follow exponential trends or growth patterns. This technique does, however, require that those factors which control the rate of progress be easily and reasonably predictable, since small errors in the controlling variables may produce large errors in predicting the rate of progress. Another use of interdependent relationships in forecasting arises when the

extension of two or more established trends would result in
a physically impossible or improbable situation. In this
case, the forecaster is guided toward a search for alternate
predictions, such as, modification of the established trends,
or of major innovations which would alter the significance
of the existing trend relationships.

Characteristic patterns in trend curves may be used
to predict certain types of events by the use of techniques
described in the concluding section of Chapter V. This meth-
od of forecasting is the least quantitative of the various
techniques, although it may be used to date rather accurate-
ly the probable occurrence of major inventions, the intro-
duction of important innovations, and the development of new
technologies.

"Dynamic Forecasting" employs the principles of in-
formation feedback control to describe the operation of a
dynamic system for producing technical progress. This offers
an effective method for explaining and predicting irregular
advances in technology. The technique, described in Chapter
VI, employs 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 tech-
nological progress. This method has the advantage of deter-

mining the effect of alternate courses of action upon proba-
ble future progress. This advantage of "conditional" fore-
casting is not easily encompassed by other methods of tech-
nological prediction.

All of the preceding methods may be used to predict
progress in any field of technology. Multiple methods, used
in the prediction of a single quantity, tend to confirm any
given forecast 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
examination of multiple forecasts which do not agree. Wide
variation in forecasts may signal either that major changes
in technology are about to occur, or that further investiga-
tion of the technical parameter or data used to measure
"progress" is needed.

The development of the several methods of technolog-
ical forecasting which have been described supports the con-
clusion that prediction of technological progress need not be
on a purely intuitive basis. The methods developed herein,
if applied to the forecasting of future technological develop-
ment, should substantially improve long range planning activ-
ity not previously supported by careful forecasting.

The conclusion may also be drawn that "proof" of the
validity of any method of technological forecasting is

impossible if the primary pattern has been one of continuously increasing progress. For instance, proof may be attempted by demonstrating that use of the method at some prior period would have produced a prediction which later came true. This "proof" may justly be criticized on the basis that the method was developed in accordance with the total historical pattern and therefore proves nothing. If the attempt at proof is made by actually predicting the future, the test of the method must wait until the future arrives. Even then, after the method has proved valid for one period of time, no assurance exists that the same method will produce a valid prediction under the changed conditions of future periods. Therefore it is concluded that acceptance of any method of technological prediction must be based on logic used in its development, and on its apparent relative merit over other forecasting techniques.

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. Being thus deterministic, the rate of progress cannot be greatly affected by conscious action. From this conclusion, it is often erroneously argued that if the rate of progress is inevitable, then it need not be forecast, since everything necessary to such progress will occur without planned action. 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 nearly so 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 follow-
ers rather than leaders in technical progress. On the other
hand, if smaller segments of society attempt to exceed the
deterministic rates of advance, they will usually fail be-
cause such rates are based upon the entirety of complex
relationships which constitute the whole society. The
smaller segment of society is unable to duplicate or con-
trol all the factors in the larger society which are neces-
sary to the achievement of greater rates of advance.

The methods of technological forecasting which have
been developed in this study are recommended for use in long
range planning. Each of the techniques has advantages for
certain types of forecasting problems, which may usually be
determined only by experience and actual trial.

Forecasts which indicate a continuous rate of prog-
ress 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 performance

improvement which was predicted. In contrast, the forecast of progress which describes events at widely separated intervals permits complacency during the time between the predicted events. The continuous forecast of technical improvement indicates that the penalty of tardy achievement is substandard performance. The discrete, or interval, forecast indicates failure to progress in terms of units of time. Because of this, the effects of lateness of achievement, and the effort required to return to the forecast level of progress, are often overlooked with the interval forecast.

Certain of Male's recommendations relating forecasting to the long range planning function may well be repeated in concise form because of their pertinence to the use of the techniques developed in this thesis.[1] These recommendations (paraphrased), are as follows:

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

(2) The elements of economic development and technical development should be distinguished in forecasting, so that "possible" technical im-

---

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

provements are not confused with "probable" developments under limiting economic conditions.

(3) Research efforts should be monitored to detect significant discoveries and inventions which may be used in forecasting the probable direction of technical advance.

(4) Long range forecasts should be reviewed at regular intervals in the light of new developments which may give reason for alteration of the forecast.

If comprehensive reference works were available to provide a background and framework for technological forecasting, then the development of particular methods might be accomplished separately and in greater detail. To the extent that this thesis provides such a general background, it is suggested that the methods presented, or others, may be suitable subjects for further study and more thorough development. On the other hand, to the extent that the present study fails to furnish a complete background and framework, it is suggested that effort be directed toward development of a unified reference work on technological forecasting.

Two of the methods of forecasting offer particular promise for further investigation. The biological analogy,

if developed in further detail, may explain how technologies
function as viable organisms, capable of being "born", grow-
ing at predictable rates, and subject to "maturity" and
"death" in a competitive society. The quantitative charac-
teristics of this analogy might be improved by further study
of the biological phenomena of growth which determine the
size of individuals and species.

Further development of the dynamic model of the
knowledge-progress system would be helpful in explaining the
process of technological advance. The resultant understand-
ing of the process would measurably improve the techniques
of forecasting. The study and use of the method of dynamic
forecasting offers the possibility of changing the social
patterns which presently impose a strong deterministic limit
upon the progress of most technologies.

BIBLIOGRAPHY

BIBLIOGRAPHY

A. BOOKS

Adams, Henry. The Education of Henry Adams. New York: The Modern Library, 1931.

Dewey, Edward R., and Edwin F. Dakin. Cycles--The Science of Prediction. New York: H. Holt and Company, 1947.

Drucker, Peter F. America's Next Twenty Years. New York: Harper & Brothers, 1955.

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

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

Kuznets, Simon S. Secular Movements in Production and Prices. Cambridge, Mass.: The Riverside Press, 1930.

Neon (Pseudonym for Mrs. M. W. Acworth). The Great Delusion. London: Ernest Benn Limited, 1927.

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

Pearl, Raymond. Studies in Human Biology. Baltimore: Williams Wilkins Co., 1924.

Sorokin, Pitirim A. Social and Cultural Dynamics. New York: American Book Company, 1937.

B. GOVERNMENT PUBLICATIONS

Brozen, Yale. "Scientific Advance as a Factor in Economic Change," Scientific Manpower--1957. National Science Foundation. Washington: Government Printing Office, 1958.

Gilfillan, S. C. "The Prediction of Invention," Technolog-
ical Trends and National Policy, United States National
Resources Committee. Washington: Government Printing
Office, 1937.

National Research Council. Research--A National Resource,
Vol. II, Industrial Research. Washington: Government
Printing Office, 1941.

National Science Foundation. Science and Engineering in
American Industry. Washington: Government Printing
Office, 1956.

National Science Foundation. Scientific Manpower--1956.
Washington: Government Printing Office, 1957.

C.   PERIODICALS

Brozen, Yale. "Determinants of the Direction of Technolog-
ical Change," American Economic Review, Vol. 43,
(May, 1953), 288-302.

Forrester, Jay W. "Industrial Dynamics--A Major Break-
through for Decision Makers," Harvard Business Review,
Vol. 36, No. 4, (July--August, 1958), 37-66.

Gilfillan, S. C. "Prediction of Technical Change," Review
of Economics and Statistics, Vol. 34, (November, 1952),
368-385.

Hart, Hornell. "Logistic Social Trends," American Journal
of Sociology, Vol. L, (1945), 337-352.

Merton, Robert K. "Fluctuations in the Rate of Industrial
Invention," The Quarterly Journal of Economics, Vol.
XLIX, (May, 1935), 454-474.

Robinson, Dwight E. "Fashion Theory and Product Design,"
Harvard Business Review, Vol. 36, No. 6, (November--
December, 1958), 126-138.

Siegel, Irving H. "Technological Change and Long-run Fore-
casting," Journal of Business of the University of
Chicago, Vol. 26, (July, 1953), 141-156.

Snyder, Carl. "The Problem of Monetary and Economic Stability," The Quarterly Journal of Economics, Vol. XLIX, (February, 1935), 173-205.

D. UNPUBLISHED MATERIALS

Drysdale, Taylor, Col. USAF. "A National Posture in Four Dimensions." Unpublished Thesis, Air University Maxwell Air Force Base, Alabama, 1955.

Forrester, Jay W. "Formulating Quantitative Models of Dynamic Behavior of Industrial and Economic Systems, Part I." Cambridge, Mass.: Unpublished Memo: D-16, Mass. Inst. of Tech., 5 April, 1958.

Forrester, Jay W. "Production--Distribution System." Cambridge, Mass.: Unpublished Memo: D-23, Mass. Inst. of Tech., 22 October, 1958.

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

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

Schell, Erwin H. "The Changing Environment of Management." Presentation given to the Sloan Fellows at Massachusetts Institute of Technology, August 5, 1958.

Wells, Howard A. "The Allocation of Research and Development Resources." Unpublished Master's thesis, Ohio State University, Columbus, Ohio, 1958.

APPENDIX A

TABLE I   143

RATIO OF WING SPAN TO LENGTH
FOR U.S. COMBAT AIRCRAFT

Year of First Delivery	Airplane	Span (Ft)	Length (Ft)	Ratio ($\frac{Span}{Length}$)
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 P-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
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	34.5	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	58.8	.40

* Equivalent Monoplane Span.

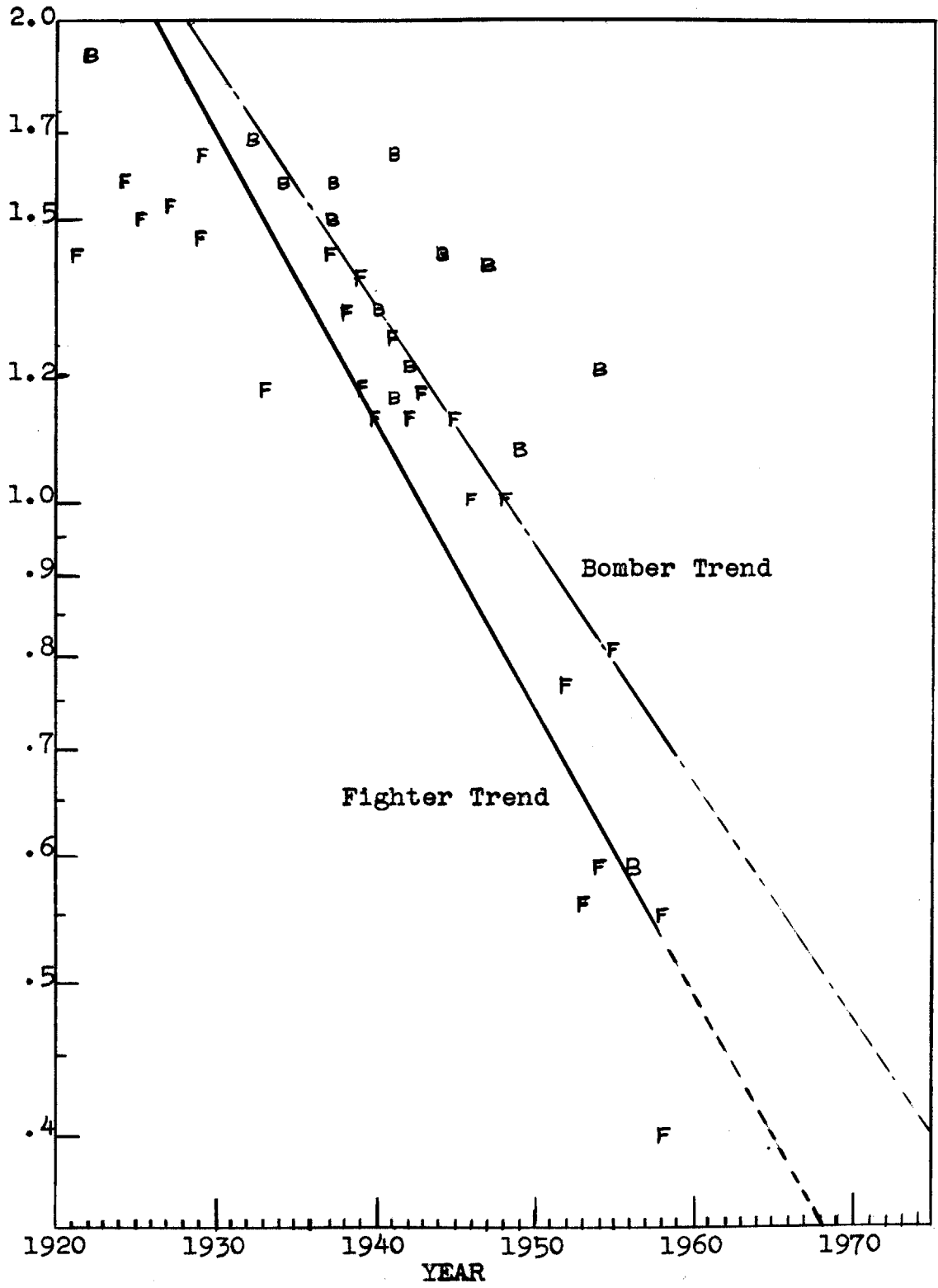Fahey, James C., U.S. Army Aircraft 1908-1946 (New York: Ships and Aircraft, 1946.

Figure 1. Ratio of Wing Span to Length for U.S. Combat Aircraft.

TABLE II

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

Fahey, James C., U.S. Army Aircraft 1908-1946 (New York: Ships and Aircraft, 1946.
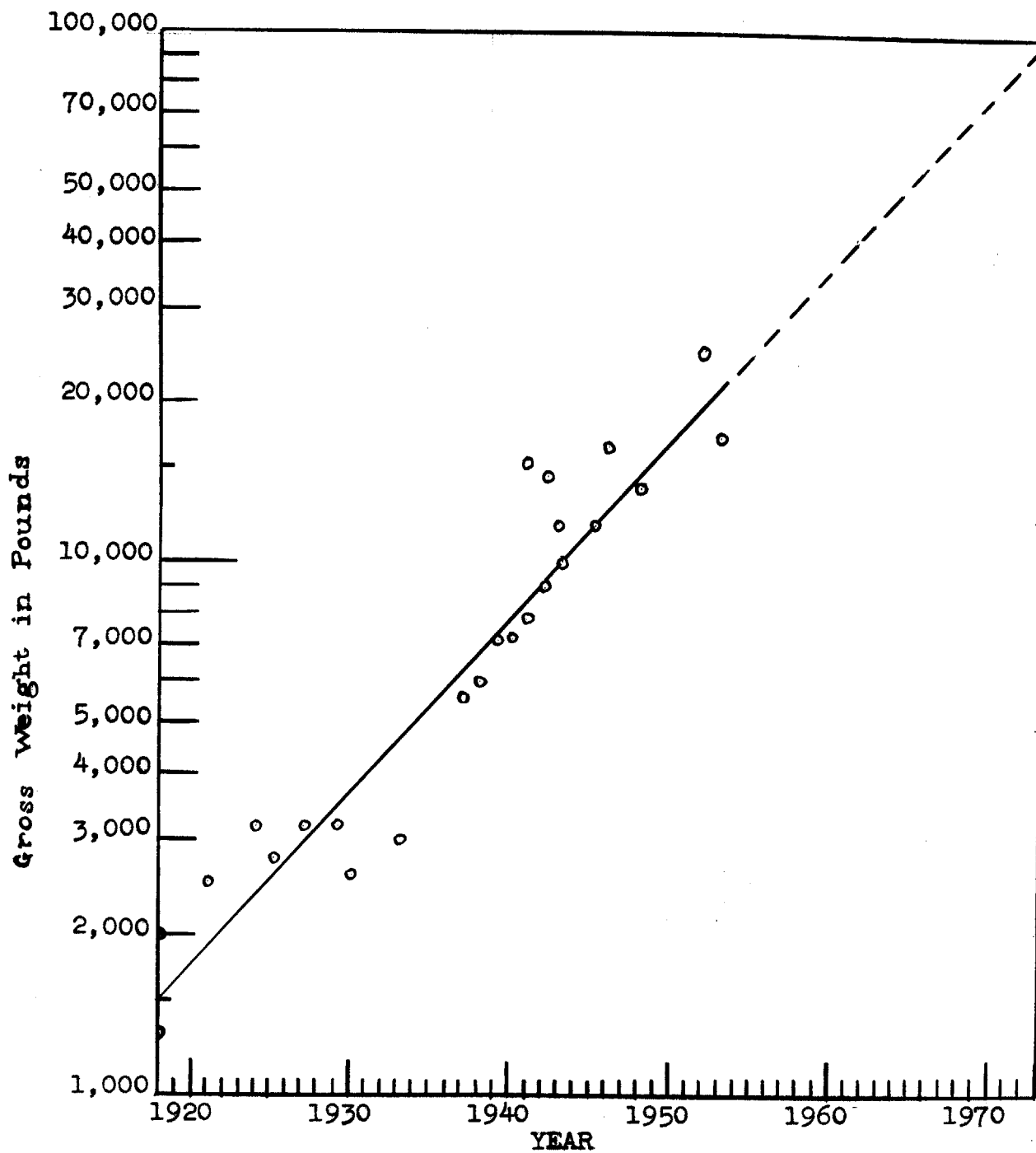
Figure 2.   Gross Weight of U.S. Single-Place Fighter Aircraft.

TABLE III

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
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.
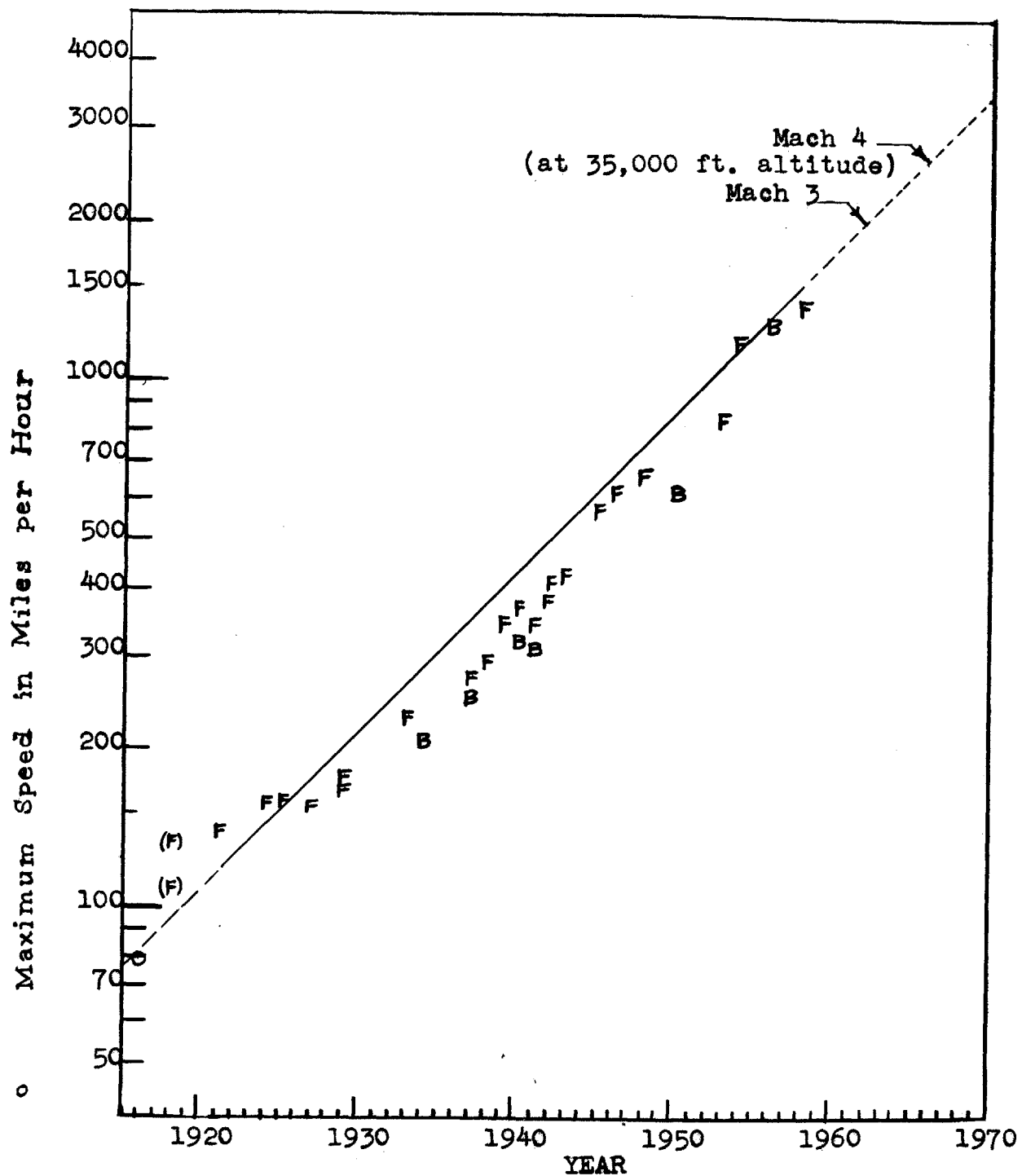
*World Record Performance.

Figure 3. Speed Trend of U.S. Military Aircraft.

TABLE IV

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 III and Figure 3.

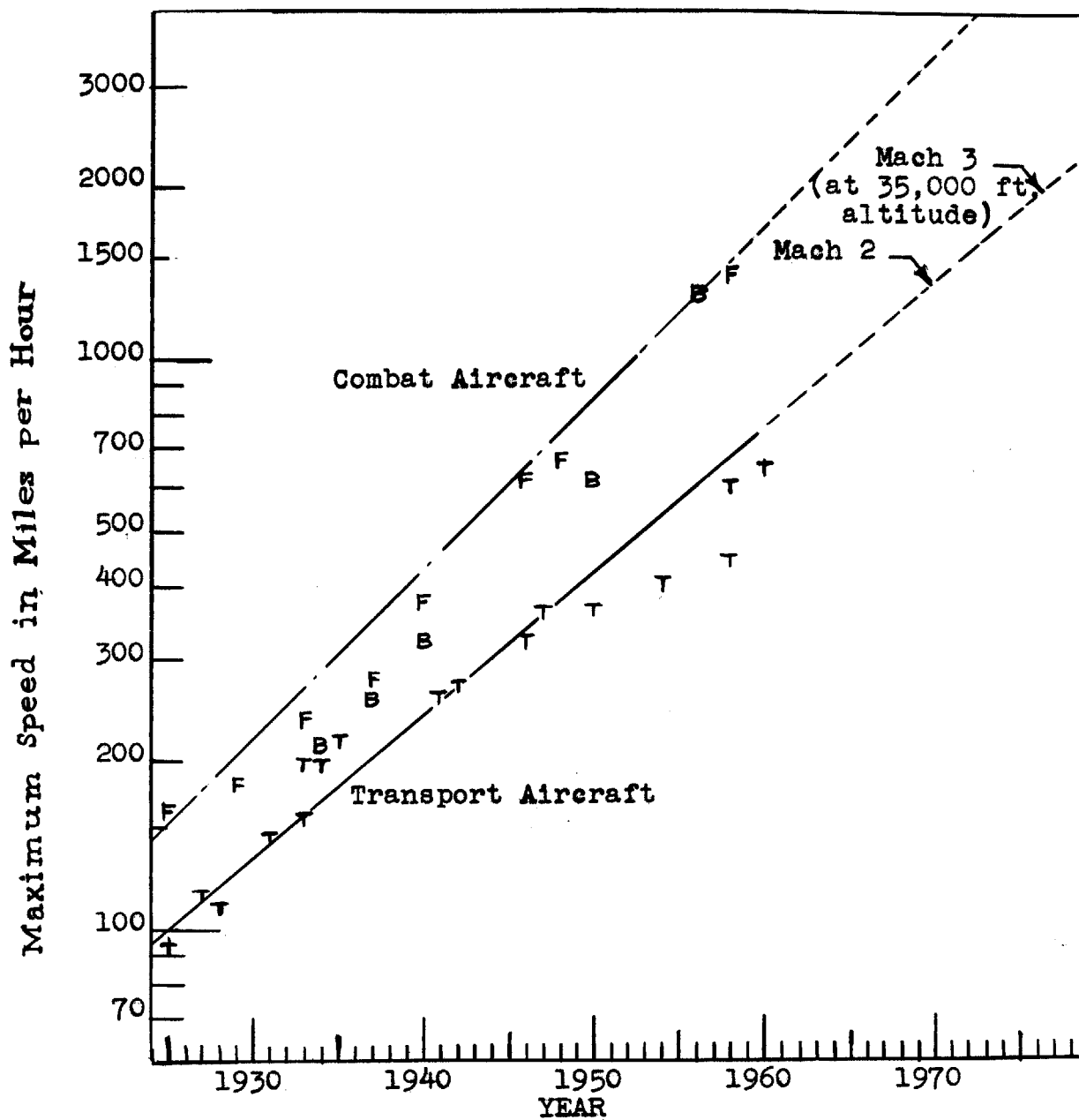Fahey, James C., U.S. Army Aircraft 1908-1946 (New York: Ships and Aircraft, 1946.

Figure 4. Comparative Speed Trends of Combat and Transport Aircraft.

TABLE V

DOMESTIC TRUNK AIRLINE OPERATIONS

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
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

$$\text{Seating Capacity} = \frac{\text{Passenger Miles}}{\text{Plane Miles X Load Factor}}$$
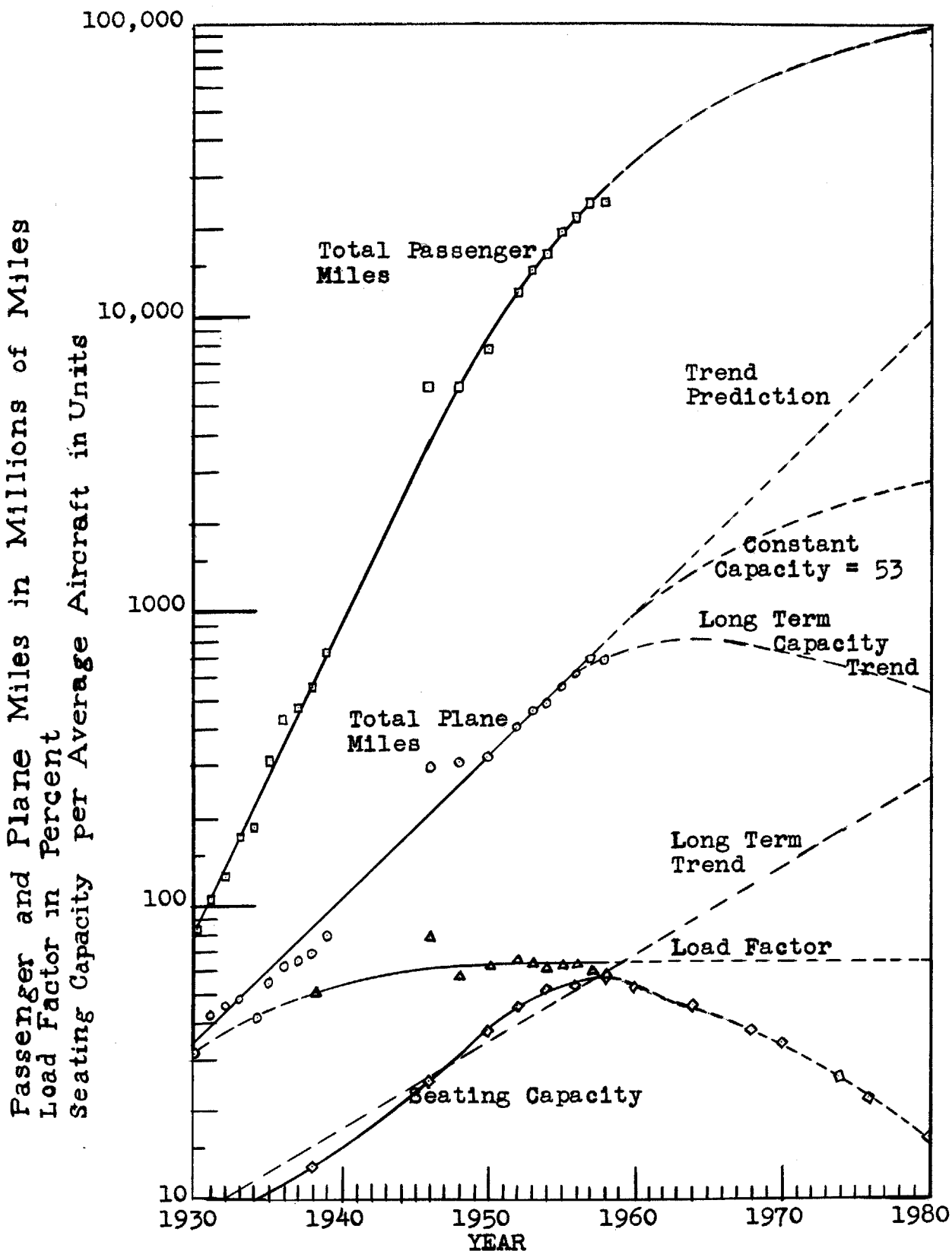
Figure 5. Domestic Trunk Airline Operations.
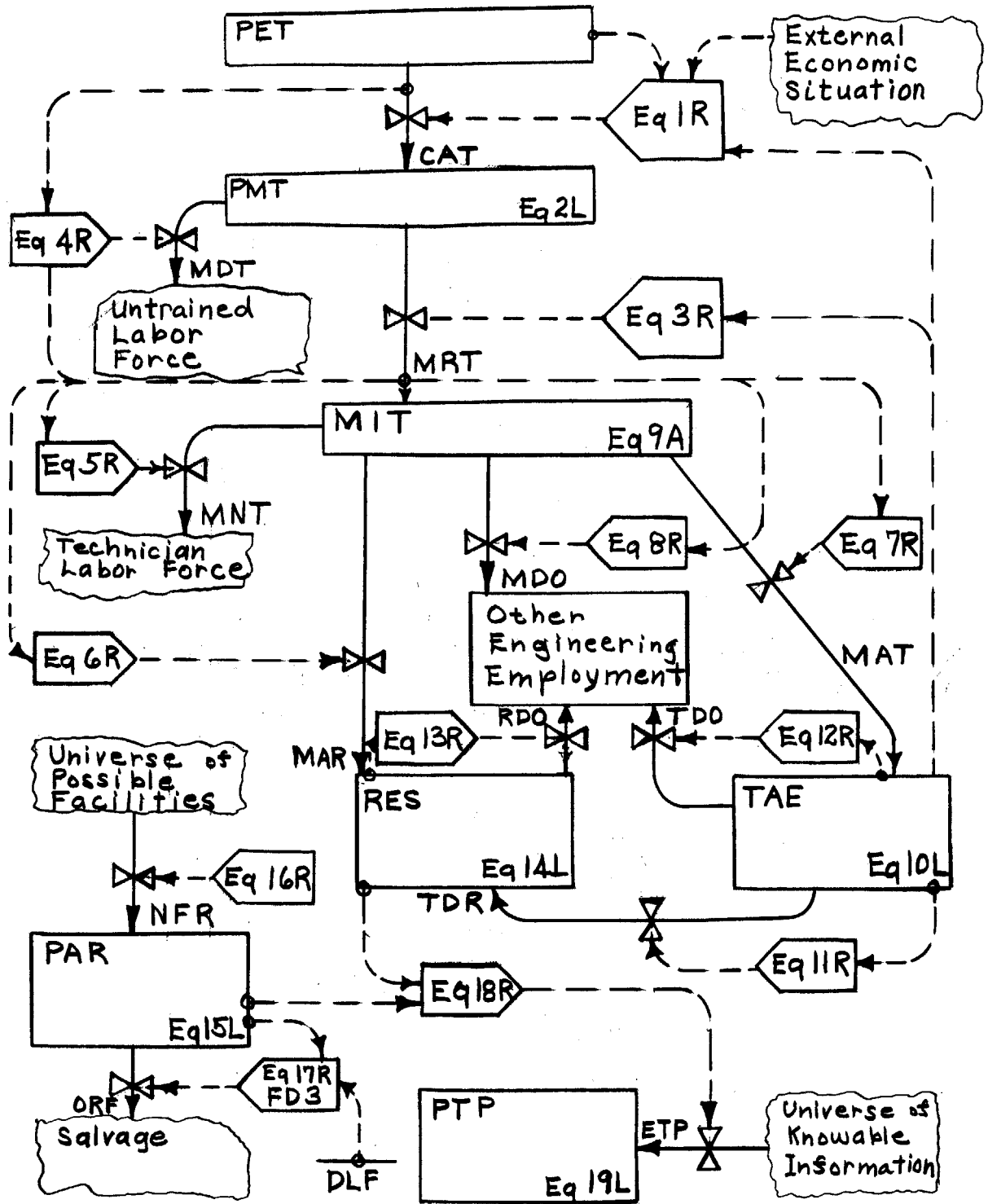
APPENDIX B

Figure 1. Flow Diagram for Knowledge-Progress System

TABLE I

KNOWLEDGE-PROGRESS SYSTEM EQUATIONS

DT = 1 Year   Eq. No.

$$CAT.KL = APT \times \frac{PET.K}{3} \times \left[\frac{ESE.K}{ESA.K}\right]^3 \times TAE.K$$ (1R)

$$PMT.K = PMT.J + DT(CAT.JK - MRT.JK - MDT.JK)$$ (2L)

$$MRT.KL = MRT.JK + (AST)(TAE.K - TAE.J)$$ (3R)

(Note: DT(MRT.KL) cannot exceed PMT.K + DT(CAT.KL)

$$MDT.KL = 1/3 \left[(CAT.IJ + CAT.JK + CAT.KL) - (MRT.IJ + MRT.JK + MRT.KL)\right]$$ (4R)

$$MNT.KL = (AFL)(MRT.HI) + (AFT)(MRT.IJ) + (AFS)(MRT.JK) + (AFF)(MRT.KL)$$ (5R)

$$MAR.KL = (AGR)(AGE)(MRT.GH)$$ (6R)

$$MAT.KL = (AGT)(AGE)(MRT.GH)$$ (7R)

$$MDO.KL = (AGO)(AGE)(MRT.GH)$$ (8R)

$$MIT.K = MIT.J + DT(MRT.JK - MNT.JK - MAR.JK - MAT.JK - MDO.JK)$$ (9A)

$$TAE.K = TAE.J + DT(MAT.JK - TDR.JK - TDO.JK)$$ (10L)

$$TDR.KL = \frac{ACR-ACT}{ACR+ACT} \times TAE.K$$ (11R)

$$TDO.KL = \frac{ACO-ACT}{ACO+ACT} \times TAE.K$$ (12R)

$$RDO.KL = \frac{ACO-ACR}{ACO+ACR} \times RES.K$$ (13R)

$$RES.K = RES.J + DT(MAR.JK + TDR.JK - RDO.JK)$$ (14L)

$$PAR.K = PAR.J + DT(NFR.JK - ORF.JK)$$ (15L)

NFR.KL = Rate of facility construction, determined
outside of the system   (16R)

$$ORF.KL = FD3(PAR.K, \ DLF) \tag{17R}$$

$$ETP.KL = f(RES.K),(PAR.K)$$

$$Assume = \frac{RES.K \ x \ PAR.K}{RES.K \ \div \ PAR.K} \tag{18R}$$

$$PTP.K = PTP.J \ \div \ ARP(ETP.JK) \tag{19L}$$

TABLE II

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
    = $\frac{.026}{13000} = 2 \times 10^{-6}$

13. ARP = Proportionality constAnt relating performance improve-
    ment 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

TABLE II (continued)

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

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

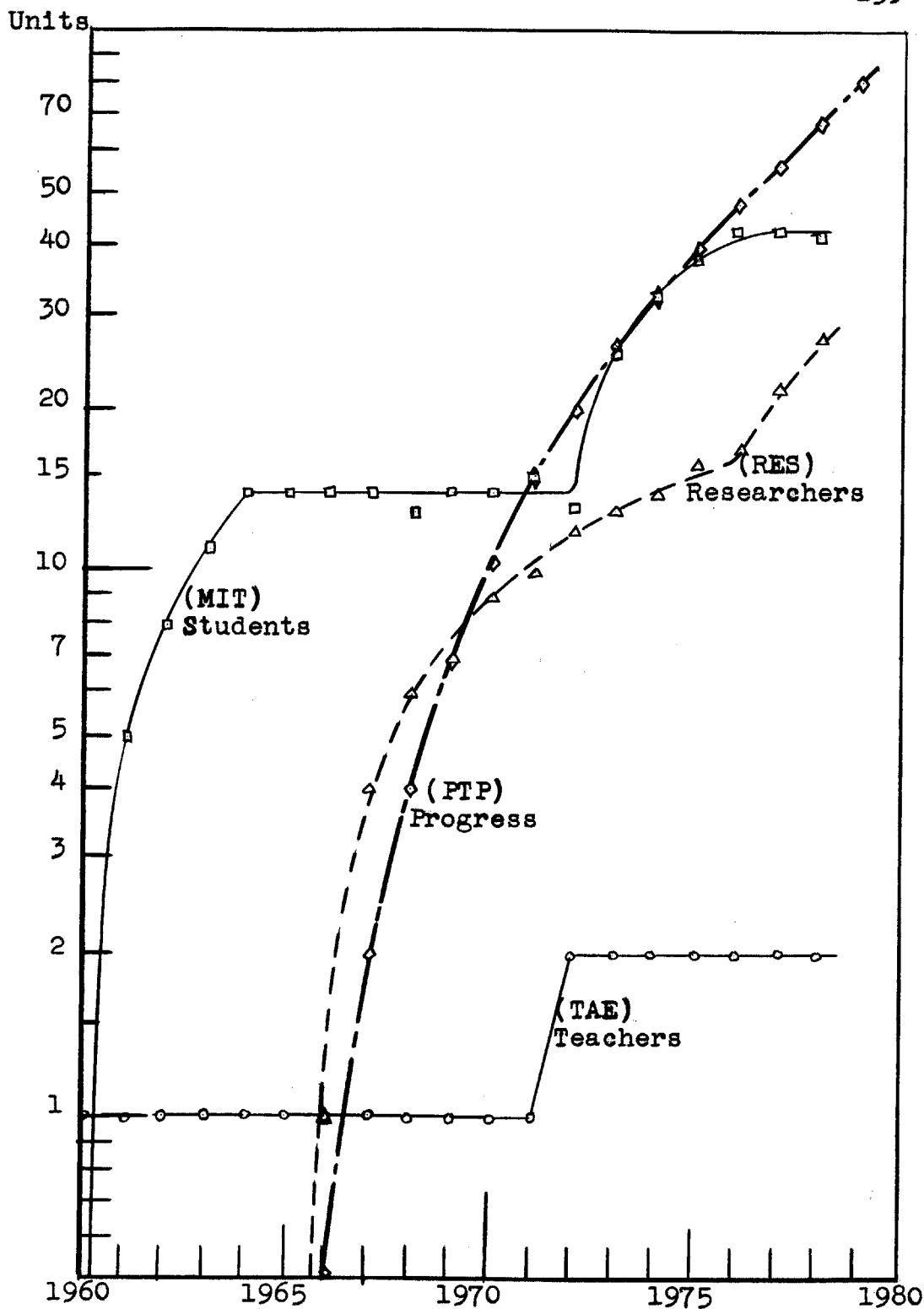37. TDR = Teachers Diverted to Research & development

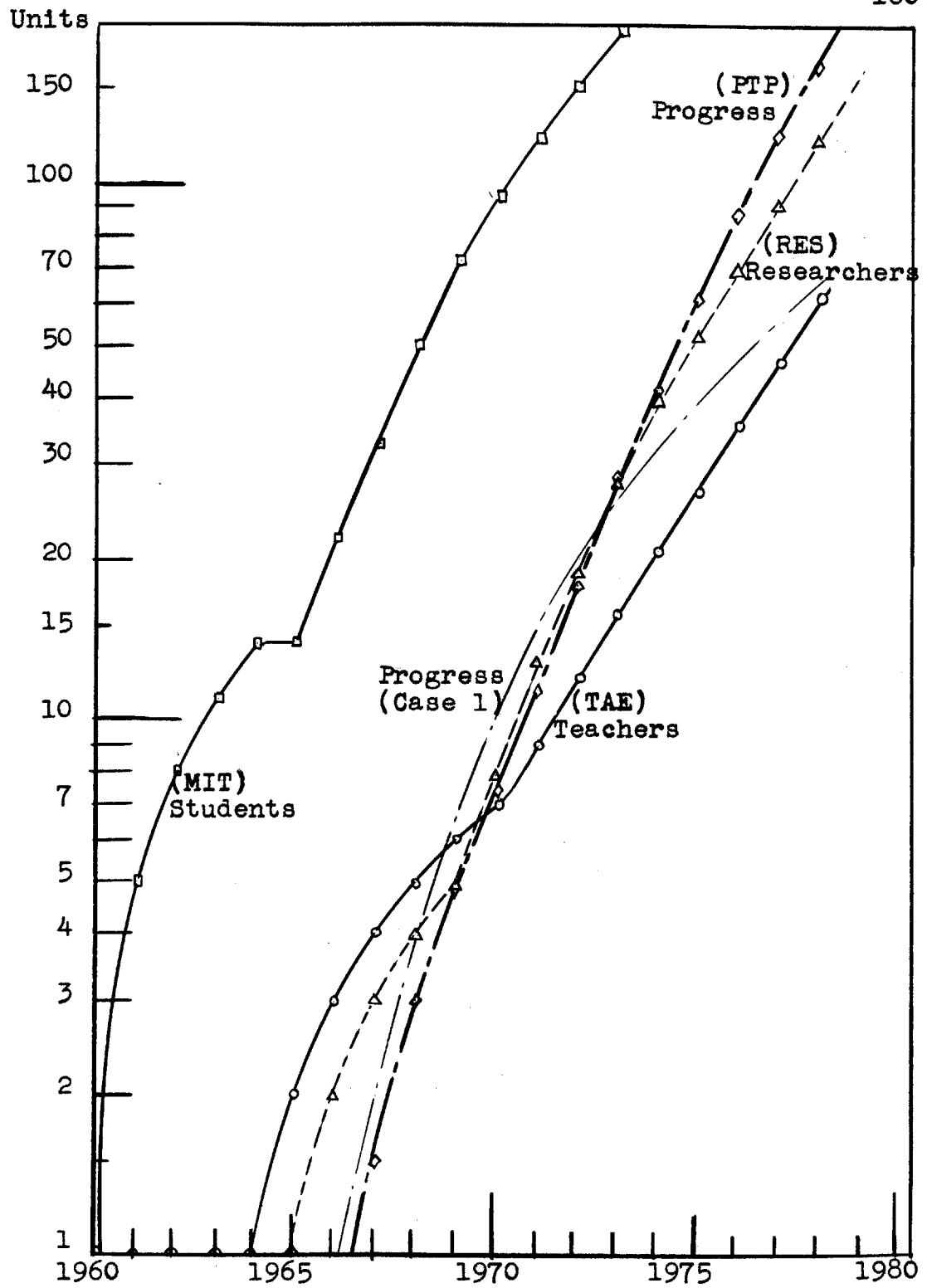Figure 2. Knowledge-Progress Model: Case 1--New Technical Field, Present Teaching vs. Research Ratio.

Figure 3. Knowledge-Progress Model: Case 2--New Technical Field, High Teaching vs. Research Ratio.