LIMITS TO GROWTH OF PHYSICS

by

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ABSTRACT

Recent developments in the job market for newly graduating PhD's in Physics and in the funding for research are compatible with a claim that we are reaching the limit to growth of physics. A system dynamics model of physics professional manpower explains the historical growth if all constraints are removed, and conforms to recent behavior if one absolute constraint on size is added. The interim period of transition from unconstrained growth to an equilibrium size is when the social and personal problems arise. A complex model of the many interactions which might be significant is proposed. The clarity of a system dynamics model should allow this proposal to be a focus for discussion about system behavior, and a catalyst for considering both additions to our understanding, and additions to the system itself.

Conclusions reached from exercise of the model include both a greatly changed role for the graduate student in the University, and the necessary advent of a competitive system for allocating research resources.

Thesis Supervisors: Edward Roberts
Title: Professor of Management

Lee Grodzins
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ACKNOWLEDGEMENTS

This thesis is a synthesis by me of the expertise of my committee. Professor Ed Roberts captivated me in the classroom with system dynamics, and has guided me through the problems of modeling a social system. Professor Lee Grodzins of the Physics Department had been an ideal source of support with both data and model suggestions about physics manpower. As a consequence, I have had to spend minimal effort either on the substantive content of system dynamics, or on the acquisition of data, but instead have concentrated on trying to increase my understanding of the system.

Professor Philip Morse, President of the American Physical Society, buoyed my hopes that this was a worthwhile field of research, and most important, introduced me to Professor Grodzins.

Somehow I must also thank those who over the years developed the methodology and computer programs of system dynamics, for I have been overwhelmed by the ease with which the novice can use these tools.
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I. INTRODUCTION

How big are you, baby? 
Why, don't you know, 
You're only so big 
And there's still room to grow.¹

Physics is a world in crisis! What is the crisis? It is in the eye of the beholder. The tenured professor may perceive no job crisis -- the unemployed graduate does. The established researcher may not worry about funding -- the young researcher thinks he is the victim of crisis. New and growing facilities, such as the Batavia accelerator, do not feel the anguish of older facilities which are closing, such as the Cambridge accelerator. Is the focus of the crisis funding, jobs, manpower, disenchantment with science, or shifting national goals? I contend that the causal factor behind all these perceptions is that we are reaching the limits to growth of physics.

The Problem

The number of scientists has been growing exponentially at a 7% annual rate since 1920, and probably since 1700 A.D.² This pattern is reflected by the production of scientific papers,³ shown in fig. (1)
The American Institute of Physics (AIP) membership, the national register of scientists, and production of new PhD's have all risen at about 7.5%. (Some of these data are presented in Chapter II.)

As late as 1964 the AIP, aided by the Bureau of Labor, predicted continuing growth through 1970, with demand for physicists to exceed supply by 21,000 jobs (55%) in 1970.

However, some saturation value for physics in particular and science in general was inevitable. With the historical exponential growth rate more rapid than the rest of the economy, R & D expenditures would have equaled the GNP in about 2100 A.D. In fact, the realistic issue should have been, is 3% of GNP (1963) a reasonable amount, or can we continue to grow to 6% in 1973, or even 12% in 1983?
As we now know, in the late 1960's the historical pattern of growth broke down. Graduating PhD's had difficulty in finding jobs. Universities had no capacity to hire additional faculty. Research funds were no longer unconstrained. In fact, we embarked on a predicted pattern of limited growth.

The Pattern

Most natural phenomenon do not follow an exponential curve forever, but in fact follow the logistic curve of smooth approach to a saturation value.\(^5\)

If some of the feedback loops which inform the system of its coming saturation are missing, the system may crash into its limit.
Depending on the details, the system might overshoot or oscillate.

The Models

This project started as an attempt to model the physics job market, to see if we could smooth out the temporary fluctuations taking place. The complex model which evolved would approximate the historical behavior of the system of physics
only if all constraints were removed! This led me to the conclusion that I was not observing a temporary job crisis, but rather seeing the limit to growth of physics.

It is easier after the fact to recognize such an event. Credit must be given to those who predicted its occurrence before the event. With the time scales involved, it may be another thirty years before we can say with certainty if the current behavior was indeed the limit, or just a bump on the curve of growth. One thing is sure -- if we haven't reached the limit, we will soon -- there just isn't much room left.

With this insight, I reduced my model to a version that confines itself to considering just the behavior resulting when a specific limit to size is placed on the unconstrained system. The two extreme cases of pure growth and pure saturation can be solved analytically. These solutions are presented in Chapter III. The more complex general case is solved by computer simulation, using the methodology of systems dynamics, in Chapter IV.

In Chapter V, I propose a complex model which adds many causal subsystems and feedback loops to the simple model. My goal is to provide a model which can be exercised to study the consequences of possible alternative policy decisions. In present form the complex model does not completely achieve this goal because I am not sure how complete the system is or how important each component is. But the model does form a convenient focus for discussion of just these two points.
Even the simple version of the model has implications about the future nature of the system of physics. These implications had already been recognized by men deeply involved in these problems. Nevertheless, I think it is a testimony to the designers of System Dynamics that its methodology has so rapidly led me to the same concerns.

Even the basic premise that there is a limit to growth is alien to our social culture. Forrester's work on World Dynamics and Meadow's refinement of that work into The Limits to Growth are frequently denounced. Yet most detractors never make explicit objections to the model -- only to the conclusion. They fall into the trap that the methodology of system dynamics tries to avoid -- they are working with non-explicit mental models based on a presumption that growth and death are the only alternatives.

Models of the sort used here differ from forecasting techniques in an important way. These models are based on cause and effect, with an emphasis on the information feedback loops active in the system. In contrast the AIP prediction of needed manpower was based solely on extrapolation.

**Implications**

The consequences of an equilibrium system of physics are staggering. The present tenor of university research will change -- in fact the entire attitude toward graduate education must be reconsidered. Our current methods of funding research will have to be overhauled.
Let me make these implications explicit. If we move from the growth phase to the static phase by changing only one variable (extreme cases), then:

i. Each physics professor will have two PhD students in his lifetime, or

ii. 90% of those entering physics graduate school will work outside academia, or

iii. only 20% of those entering physics graduate school may earn the PhD, or

iv. the average stay in physics graduate school must be increased to 12 years, or

v. activity on the graduate physics faculty must be limited to 13 years.

The extremes of the simple model probably could never be achieved in real life, because other constraints on the system would come into play. For example, most of the alternatives would probably reduce the graduate school enrollment, and so the conclusion would not be so extreme. The complex model of chapter V tries to include some of these forces, and so affords some opportunity for exploring various policies for picking an operating point within the confines of these extremes.

Although at this point the reader has not seen the evidence for these conclusions, it seems appropriate to explore these implications a little further. For a professor to have only two PhD students in his lifetime (and two non-PhD winners) would upset the current approaches to university research.
Either the professor will have to accept a lower effort with little technical assistance, or he will have to move closer to the industrial approach to research, with professional support. Another alternative would be to vest the graduate students in the few outstanding men, leaving most professors with no graduate student support.

The number of physics graduates staying in academic professions will decrease. In the extreme only 20% of the PhD's (10% of those entering graduate school) will join faculties. Physics departments and their faculty will have to develop attitudes and curricula that groom the majority of students for non-academic jobs. Otherwise unemployment will drive down the graduate school enrollment. Even in recent years with 25% of entering students (50% of PhD's) staying in universities, there has been concern about the training and attitudes of those looking for jobs.\textsuperscript{13}

It is possible to paint a compromise picture -- one of universities where the graduate students go only to outstanding professors. Qualifications for graduate school will be high, and fewer applicants will finish the PhD. The intermediate degrees will become more meaningful. The atmosphere will approximate more closely that of industrial and government laboratories, with professional technical support. The end product will be better prepared to go into industrial research upon graduation.

I suspect that MIT will be thankful for its laboratories such as the National Magnet Lab, and regretful of the dives-
titure of the Draper Labs, because of the necessary trend toward industrial type research. On the other hand, superior schools such as MIT will be able to avoid the consequences of the limits to growth longer if they do not choose to take a role of leadership in the problems of the profession.

Another impact of a limit to growth of physics is that both the manpower and the funding for new projects will be at the expense of old projects. Most of the current methods for granting funds do not have a mechanism for this comparison. It is important that the scientific community face up to the problem of developing funding procedures effective in a competitive environment. A poor resolution of this issue could squelch the future of scientific inventiveness.

Questions Raised

A change from the historical growth pattern is beyond our control. But we still have some control over our own fate, over the final operating point of the system. System dynamics modeling of the policy alternatives can help us to achieve our goals, because in a complex system with multiple feedback loops the consequences of an action are not always expected. Exploration of this type requires some questions to be answered about our goals, because in the constrained system individuals no longer have complete freedom to do what they want and be supported for doing it.

i. Do we want graduate school support for faculty at the expense of no jobs for graduates? Or do we want jobs for
all graduates at the expense of support for faculty?

ii. What mechanisms are viable for control of the number of graduate students? Can we expect national cooperation, or will a limit on enrollment by top rate schools be offset by increased enrollment by low rate schools, leading to a reduction in the average quality of education?

iii. Should institutions such as the AIP get involved at a decision making level?

iv. Where do we worry about the quality of the graduate enrollment? At what point, for the good of society, should we encourage bright students to enter other fields?

v. How do we establish new patterns of funding? How do we protect the quest for new knowledge? Who will be given the power to stop support? Will peer review enter here?

vi. Is the physics community willing to look at itself and its attitudes in the light of the possibilities? How do we change academic attitudes toward industrial research?

Reader's Guide

The next chapter summarizes some of the information about the job crisis in physics. The drastic shift in employment patterns is indicated. The chapter also discusses the rationale of system dynamics modeling.

Chapter III covers the limiting cases of the simple model, where analytical solution is possible. This chapter is designed to be read with no knowledge of system dynamics.
Chapter IV discusses the complete solution of the simple model, using the notation, terminology, and computer programs of system dynamics. The methodology makes explicit all my assumptions.

Chapter V outlines a proposal for a more complex model which attempts to include a wide range of causal relations. At this stage in history we do not know enough of what is happening to compare the results to data and deduce model validity therefrom. But we do have a tool for trying to observe the effects of various changes in the system.

The chapter on conclusions repeats the conclusions stated in this introduction. It also includes my conclusions about this research effort.

An annotated bibliography is included for information retrieval by future researchers.
II. PROBLEM AND METHODOLOGY:

Setting the Stage

The audience for this thesis should consist of two groups -- physicists who are familiar with the problem but not with the methodology of system dynamics, and system dynamicists who are not familiar with the problem. Each section below stands alone, and isn't needed for the continuity of the thesis.

Problem

In the introduction I ask the question: "Is there a crisis in Physics?" Much of the evidence is anecdotal; since 1968 the letters column of Physics Today has been filled with letters about the job crisis. But there is some hard data available. Fig. 2 plots the number of job seekers and the number of specific openings listed at the APS annual meeting.\textsuperscript{14}

Also very informative is a chart, Fig. 3, of the number of domestic job advertisements in Physics Today.\textsuperscript{15}

A number of other studies comment on the questions of job availability and funding in physics.\textsuperscript{14, 16, 17}
Fig. 2  
Job Registry
The numbers of job seekers and job openings at the annual APS meetings.
Fig. 3
Job Advertisements in the January issues of Physics Today
Methodology

Why model at all, and why use system dynamics? Forrester\textsuperscript{18} sums up the argument for modeling:

There is nothing new in the use of models to represent social systems. Everyone uses models all the time. Every person in his private life and in his community life uses models for decision making. The mental image of the world around one, carried in each individual's head, is a model. One does not have a family, a business, a city, a government, or a country in his head. He has only selected concepts and relationships which he uses to represent the real system. A mental image is a model. All of our decisions are taken on the basis of models. All of our laws are passed on the basis of models. All executive actions are taken on the basis of models. The question is not whether to use or ignore models. The question is only a choice between alternative models.

The mental model is fuzzy. It is incomplete. It is imprecisely stated. Furthermore, even within one individual, the mental model changes with time and with the flow of conversation. The human mind assembles a few relationships to fit the context of a discussion. As the subject shifts, so does the model. Even as a single topic is being discussed, each participant in a conversation is using a different mental model through which to interpret the subject. Fundamental assumptions differ but are never brought into the open. Goals are different and are left unstated. It is little wonder that compromise takes so long. And it is not surprising that consensus leads to actions which produce unintended results.

The human mind selects a few perceptions, which may be right or wrong, and uses these as a description of the world around us. On the basis of these assumptions a person estimates the system behavior that he believes is implied. If he desires an improved behavior, he judges what action might be taken to alter the system. But this process is often faulty.

System Dynamics is an outgrowth of Forrester's work on Industrial Dynamics.\textsuperscript{19, 20} It is the methodology used in Urban Dynamics,\textsuperscript{18} World Dynamics,\textsuperscript{10} and The Limits to Growth.\textsuperscript{11} It has been used to study R & D dynamics,\textsuperscript{21} legal systems,\textsuperscript{22}
and drug abuse. Systems Dynamics is an important tool for those problems and the current one for many reasons:

i. It is a cause and effect approach, rather than extrapolation of historical data.

ii. It considers the dynamical behavior of the system. For example, the five year lag between PhD students entering and graduating sets the time scale of the system behavior.

iii. There is an emphasis on the feedback loop structure. In most physical systems the feedback is the prime determinant of system behavior, and the same appears to be true for social systems.

iv. There is an explicit convention for flow diagraming a system.

v. There is a focus on the equations which represent the policy decisions important to system behavior.

vi. A compiler for a digital computer (DYNAMO) implements the system dynamics models. With this high level language the user need only enter the equations describing the model -- he does not have to develop the algorithm for solving those equations.
III. THE SIMPLE MODEL

There is a trichotomy between the historical, logical, and complete approaches to describing a research effort. In this case the historical approach would be confusing, because the simple model was an outgrowth of a complex one. A careful description of the complete model would overwhelm the reader with detail, and make it hard to visualize the basic nature of the model. Therefore I have chosen the logical approach.

The simple model discussed in this chapter is treated as two separate models. One deals with the historical growth phase of physics. The other deals with a hypothesized future static phase. These two phases are, in reality, limiting cases of the two loop model treated in the next chapter. These limiting cases can be treated analytically, so this chapter avoids the formalisms of system dynamics. As a consequence it also fails to make the explicit committment of mental models to paper required by the discipline of system dynamics.

The next chapter deals with a model of the same total level of complexity, and guided by the same basic assumptions. However, it is cast into the formalism of system dynamics. The serious reader is urged to concentrate on that chapter because of the explicit description it affords of the way the
system of physics manpower operates. Also, since the system is easily simulated on a computer with the DYNAMO\textsuperscript{24} compiler, we are no longer restricted to limiting cases, but can observe the transition period as well. Since we are currently in the transition, this period is of great interest.

It should be emphasized that the model discussed in this chapter is simplistic -- it ignores many details of the true system. It is included to show the manner in which a simple unconstrained system can undergo exponential growth.

The model also is very macroscopic. For example, it uses a student faculty ratio deduced from total graduate enrollment and from total physics faculty size. However, only a portion of the total faculty has graduate students, and they have a much higher ratio than used here. Using those figures instead should lead to much the same answer. I have chosen to use the most macroscopic figures, instead of the more structured ones.

A. The Growth Phase

Exponential growth is the outcome of a single positive feedback loop. The assumptions necessary to make a single loop dominant in the behavior of the physics manpower system are:

\underline{Assumption 1:} The rate of entrance to graduate school is controlled only by the university faculty.

\underline{Assumption 2:} Demand for new faculty members has exceeded supply.
Assumption 3: Funding has not been a constraint.

None of these assumptions is true today! But I suspect that they are close approximations to the real situation in existence until the mid 1960's.

Each of these assumptions sums up a number of others. For example, the first one implies that there is always an ample source of prospective students. These more finely structured details are left for the complex version of the model discussed in Chapter V.

A few words about these assumptions are in order, since they form the backbone of the model. I see the graduate student is fulfilling a need of the university as much as the other way around. Therefore I assert that, until recently, the size of the total graduate class has not been controlled by the number of undergraduates that want to go to graduate school, but by the number of graduate students the faculty wants to have to serve as teaching assistants and research assistants (especially thesis research).

The increasing population and increasing portion going to college have served to keep the need for physics faculty ahead of the demand. The percentage of graduates choosing to join faculties has been fairly constant. 25

The funding of science has grown at a rate exceeding the growth of the scientific manpower. 7 Until recently, the notion has prevailed that a scientific proposal of merit would be funded.
Each one of the above statements could be expanded and debated at length. However, the expansion and discussion are much more explicit when in the system dynamics framework, so I postpone further discussion until then. If necessary, the reader is encouraged to approach the rest of this chapter with the attitude "if these assumptions are true, then . . . ."

Model

A scheme of the model is shown below in Fig. 4.

The size of the faculty controls the size of the graduate class because of the need to maintain a certain graduate student/faculty ratio. Some portion of the students elect to join faculties, increasing the number of professors, and around and around in a positive feedback loop. To keep the model at the one loop level we must disregard the attrition of pro-
fessors. This is a fair approximation during the growth phase, as only about 1% of the total would leave each year.

Solution

The one loop system can be solved analytically. If

\[ a = \text{the graduate student/faculty ratio} \]
\[ b = \text{the fraction of graduates that join faculties} \]
\[ c = \text{the fraction of students that graduate with the PhD} \]
\[ d = \text{the average time in graduate school} \]
\[ P = \text{the number of professors} \]

then \( S \), the number of students, is given by:

\[ S = a \times P \]

and the number that become professors, i.e., the change in the number of professors in a period of time is

\[ \frac{P}{t} = \frac{S \times b \times c}{d} \]

or:

\[ \frac{dP}{dt} = \frac{a \times b \times c}{d} P \]

which has the solution:

\[ P = \text{const } e^{\frac{abc}{d} t} \]

(1)

Values

I emphasize again that I have chosen a macro approach, and am using values which allow the solution to be in terms of total faculty size with no additional computation.

\( a = 1.5 \), the student/faculty ratio as deduced from the total school enrollment and total physics faculty size.
b = 0.5 the portion of the graduates that enter faculties is quite constant\textsuperscript{27, 28} 
c = 5 years the median time in graduate school.\textsuperscript{29} This has been pretty constant since 1920\textsuperscript{30} 
d = 0.5 about half of the students entering graduate school do not finish the PhD.\textsuperscript{31} 

Result

\[ P = \text{const} \, e^{\frac{1.5 \times .5 \times .5}{5} t} \]
\[ P = \text{const} \, e^{0.075t} \]  \hspace{1cm} (2)

Validity of Results

The form of equation 2 indicates a growth rate of 7.5\% per year, which leads to a doubling time of ten years. We can compare this to a number of measures of the size of physics.

The American Institute of Physics (AIP) has an unduplicated membership growth rate of 7.5\% per year from 1923 to 1963.\textsuperscript{32}

The national register of physicists grew faster than 7.5\% until 1957, then grew at 7.5\% until 1966.\textsuperscript{32, 33} The initial higher growth rate is explained by an increasing coverage of the register, which has been virtually complete at 80\% of the AIP figure since 1957.

The number of PhD's granted in physics grew at a 7.5\% per year rate from 1920 to 1962.\textsuperscript{34}

The total scientific population grew at 6.5\% from 1900 to 1963. A figure of approximately this size has applied
since 1700.\textsuperscript{2}

Fig. 5 gives the data listed above, with the solid line showing the predictions of this theory. The constant in Eqn 2 was based on the number of physicists in 1933. The number of PhD's granted was deduced using the constant noted above, and the fact that 50\% of those in the national register were employed in educational institutes.

Does the good fit of Eqn. 2 to the data indicate that the assumptions afford a reasonable approximation to the system? The reader must judge for himself. Even if the results are fortuitous, the lesson of the basic formulation is that, in social as in physical systems, a single positive feedback loop leads to exponential solutions.
Fig. 5
Numbers of Physicists

- □ PhD's granted
- ○ AIP membership
- X National register

predicted by simple model, using 1933 as a base year

10^3

10^4

10^2

1920 1930 1940 1950 1960

PhD's GRANTED

MEMBERSHIP
B. The Static Phase

The behavior of this portion of the model is based on one assumption:

**Assumption 4:** There is some temporal limit to growth of physics.

This is a controversial assumption! But most of the system behavior, most of the varied crises which have occurred since 1965, can be explained by this assumption (recall that I backed into this simple assumption by study of a more complex model).

It is difficult to verify this assumption -- it started to affect the system only a few years ago. The arguments for this assumption were discussed in Chapter I. To reiterate the main ones, at the growth rates of the early 1960's, the national R & D budget would have equaled the Gross National Product in about 2015, and everyone in the country would have been a scientist or engineer soon thereafter.

**Subassumption:** For the purposes in this chapter of obtaining a simple solution, I assume that there is zero population growth.

**Model**

In the model shown in Figure 6 the university now controls the number of graduates that can join the faculty. This rate is the same as the attrition rate, but is formulated to allow
the need for professors, which could be controlled by student body size, to control the rate.

**Fig. 6 The Static Model**

Graduate Students

\[ \downarrow \]

Professors \[ \rightarrow \] need for new Professors

Former Professors \[ \Rightarrow \] equilibrium number of professors

---

**Solution**

Assumption 4 states that

\[ \frac{dp}{dt} = 0 \]

Since the change in faculty now considers both the number entering and the number leaving,

\[ \frac{dp}{dt} = \frac{a b c p}{d} - \text{attrition rate} \times P \]

---

**Result**

Since the attrition rate is the inverse of the faculty lifetime, we require that:
\[
\frac{a b c}{d} = \frac{l}{\text{faculty lifetime}}
\]

We can look in the consequences in a period of a faculty lifetime, without ever deciding exactly how long that is. In the extreme cases:

i. If only the student/faculty ratio varies, then each professor will have only four graduate students in his lifetime, or about one every ten years. Of this, only two would be allowed the PhD.

ii. If only the fraction of graduates that joins faculties varies, then only about 20% may do so. This means only 10% of those that enter graduate school join faculties.

iii. If only the dropout rate is varied, then only 20% of those that enter graduate school may earn a PhD. This would still require the same average stay in graduate school in spite of whether the degree is awarded or not.

iv. If only the average stay in graduate school is varied, then it must become 10 to 15 years. And keep in mind that this average stay includes the no degree and masters degree students as well as the PhD students.

v. If the faculty lifetime is varied (how?) then it needs to be reduced to 13 years. Note that if this reduction takes place by limiting the number of years the individual may be a graduate professor, then the total throughput through the system remains low. If the individual completely leaves the faculty, then throughput rates of about the current are possible.
The real future of course will lie somewhere between these extremes. The complex model of the later chapters should form a basis for starting to explore the implications of policies that try to pick an operating point in this five dimensional space. One thing is clear. The historical and the present positions are not on the five dimensional surface of the future solution. The implications of just moving to that surface are large. They were discussed in the introduction, and so are not repeated here. But we still have some control over where our operating point is on that surface, and it is time to start facing the decisions involved in picking that point.
IV. THE NOT-SO-SIMPLE MODEL
or Limits to Growth

The attempt to keep Chapter III devoid of references to System Dynamics was to avoid a communications block. It is now time to undertake a more sophisticated approach. As soon as we couple the two phases of the simple model in the last chapter, we start to move to a level of complexity beyond easy intuitive comprehension. Even within the framework of the four assumptions, the simple model is naive. We must look carefully for the causal relationships involved. We must stop to consider the time delays which so strongly affect the dynamics of the system. To observe the behavior of the model, we are forced toward a numerical computer solution.

System Dynamics,20, 35 and the DYNAMO24 compiler which supports it, furnishes the ideal framework to take these steps. Not only does it lead the practitioner toward a perspective on the problem which is general yet detailed, but it also forms an effective medium for communication. In the following models, all my positive assumptions are out in the open. If the reader notices a missing causal relationship, it is not there! I may have assumed it away, I may have data to contradict it, or I may never have thought of it. But he may rest assured that there are no hidden relationships, no hidden assumptions, no gut feelings which are not explicit, even to the author.
Conventions of System Dynamics

The basic concepts of system dynamics modeling were discussed in Chapter II. For a thorough background, the reader must be referred to the texts on the subject. I include here some comments on the conventions of flow charts and equation writing to make the following chapters more intelligible.

The simple loop models of Figures 4 and 6 are converted to a flow diagram by considering which elements of the system are levels and which are rates. The levels are integrations of the rates, and usually are the observables of the system, such as the number of students. The rates are the policy statements of the system, such as "How many graduate students shall we let enter per year?"

Along with these two basic variables, we have time delays which set the temporal scale of the system, and auxiliaries which are variables of convenience. The symbols used are shown in Fig. 7.
A source or sink

A rate

A level

A delay
delay time constant
output
type of delay

A delay which keeps track of material in the delay

An auxiliary

A constant

material flow
money flow
information flow

Fig. 7 Symbols of Systems Dynamics
In writing equations, we merely say that the value of a level now is equal to its old value plus all the rates changing it multiplied by the time from then to now.

New Level = Old Level + dt * rates of change

The Dynamo compiler uses the following notation to achieve this:

\[ \text{LEVEL}.K = \text{LEVEL}.J + \text{DT} \times \text{RATE}.JK \]

We see that K is the new time, J is the old time, and JK is the period from old to new.

The rate equations sum up the real meat of the model -- they state explicitly what factors I think affect each policy decision. For example:

\[ \text{LGS}.KL = \text{DELAY}(\text{EGS}.JK, \text{TGS}) \]

states that the rate of Leaving Graduate School is only the rate of Entering Graduate School in the previous period, delayed by the average Time in Graduate School. This simple equation emphasizes the assumption that no other factors affect the rate!

The DYNAMO compiler starts with initial values for all the levels, calculates the current rates from them, calculates a new set of levels, and iterates the whole process. The reader will recognize that this is just a linear approximation to integration. But this algorithm is solving a multi-loop feedback equation problem without simultaneous solution of differential equations! The result is such rapid computation that we can afford to reduce the integration interval to a fine enough mesh to make the linear approximation quite valid.
The user of DYNAMO need only furnish the equations which describe the system, along with appropriate constants and initial values. The solution algorithm is built into the compiler. To identify the various types of equations, a label is introduced into the first column:

L Level
R Rate
N Initial condition
C Constant
A Auxiliary
T Table

Non analytical relations between variables are afforded by use of the table function. Also included are Delay macros (subroutines) and macros which pick maximum or minimum values.

The Growth Phase Revisited

When we try to make explicit the causal relationships and the important information links, even within the confines of the three first assumptions in the last chapter, the model expands to that of Fig. 8. This model treats the manpower system as continuous, instead of discrete with large seasonality. The four constants of the last chapter are again treated as constants.

1. Entering graduate school. This rate is determined solely by the number of new students the university needs.

\[ ENGS \times L = ENGS \times FRTM \]
\[ FRTM = 1 \]
\[ ENGS = \text{ENTERING GRADUATE SCHOOL} \]
\[ ENGS = \text{NEED FOR GRADUATE STUDENTS} \]
Fig. 8 The Growth Model. This non-structured version does not separate graduate from non-graduate faculty. It thus also does not account for years a new professor does not have graduate students. Use of the correct unstructured data minimizes the affect of these simplifications.
2. Leaving graduate school. This is based on the rate of those that previously entered graduate school, smoothed in such a way as to approximate the actual distribution of lengths of time in graduate school. The form of the DELAY function is described in the appendix.

\[
\text{LGS} \cdot \text{KL}=\text{DELAY} (\text{ENG} \cdot \text{JK} \cdot \text{TN} \cdot \text{ING} \cdot \text{K} \cdot \text{OLD} \cdot \text{GS})
\]

- \text{ENG} = \text{ENTERING GRADUATE SCHOOL}
- \text{TN} = \text{TIME IN GRADUATE SCHOOL}
- \text{ING} = \text{IN GRADUATE SCHOOL}
- \text{OLD} = \text{OLD LEVEL OF GRADUATE STUDENTS}

3. Unemployment. Given this name for want of a better one, this level describes the number of students that have finished graduate school and are not yet disposed of.

\[
\text{JNP} \cdot \text{K} = (\text{JNP} \cdot \text{J} + \text{I} \cdot \text{J} \cdot \text{T})(\text{LGS} \cdot \text{JK} \cdot \text{NEW} \cdot \text{JK} \cdot \text{JGRP} \cdot \text{JK})
\]

- \text{JNP} = \text{UNEMPLOYMENT (NEW GRADUATES)}
- \text{LGS} = \text{LEAVING GRADUATE SCHOOL}
- \text{NEW} = \text{NEW EMPLOYMENT OF PROFESSIONALS}
- \text{JGRP} = \text{DROP OUTS}

4. New employment of professors. This is the fraction of those leaving school who are eligible (complement of the dropout rate) who choose to take a university job. The lack of any other inputs is a restatement of the assumption about demand for faculty.
NEWP.KL=UNP.K*DR*PGTF/FBTM
DR=.5
PGTF=.5

NEWP = NEW EMPLOYMENT OF PROFESSORS
UNP = UNEMPLOYMENT (NEW GRADUATES)
DR = DROP OUT RATIO
PGTF = PORTION GRADUATES TO ENTER FACULTY

5. Drop out rate. The rest of those leaving school go somewhere else. Note that placing this rate "valve" at this location in the model treats the dropouts (non PhD winners) as if they stayed in school for the same period of time as the PhD winners. This is compensated for in the choice of the delay time in the LGS equation. A more correctly structured model would explicitly incorporate the differences, but I judge the improvement not to be worth the complexity. Note that even if I had not discussed this point, it is explicit in the figure and the equations!

\[ \text{nout}, KL = \text{UNP}, K \times (1 - \text{DR} \times \text{PGTF}) \]

nout = DROP OUTS
UNP = UNEMPLOYMENT (NEW GRADUATES)
DR = DROP OUT RATIO
PGTF = PORTION GRADUATES TO FACULTY

6. Number of professors. This is a permanent collection of all those who chose to enter faculties. The absence of an attrition valve leaking professors out of the accumulation keeps this model within the constraints of the last chapter.
Again we can notice the assumptions about no other source of professors.

\[ \text{PROF} \cdot \text{K} = \text{PROF} \cdot J + \text{DT} \cdot \text{NEWP} \cdot JK \]

**PROF** - NUMBER OF PROFESSORS

**NEWP** - NEW EMPLOYMENT OF PROFESSORS

7. Need for graduate students. This is the number of faculty times the graduate student ratio. While a more structured model might separate the faculty into graduate and non graduate faculty, the different graduate student/faculty ratio tends to cancel this out. Thus in reality about one half of the professors are graduate faculty, but each as twice as many students as the overall ratio would indicate. An early version of this model let this be the difference between the needed graduate students, and those in graduate school. This led to too slow a growth rate, presumably because of the delay times involved. If we include in this decision link information about the number of recent graduates, the growth rate is in agreement with historic data.

\[ \text{NGS} \cdot K = \max (\text{PROF} \cdot K \cdot \text{GSP} - \text{INGS} \cdot K + \text{UNP} \cdot K + 1) \]

**NGS** - NEED FOR GRADUATE STUDENTS

**PROF** - PROFESSORS

**GSP** - GRADUATE STUDENTS PER PROFESSOR

**INGS** - IN GRADUATE SCHOOL

**UNP** - UNEMPLOYMENT (RECENT GRADUATES)
8. Results. Figures 9 and 10 give the results of growth phase of the mode, while Figure 11 is a numerical printout of these results.

\[
\begin{align*}
L_{PHOT} & = \log_{10}(\text{PHOT}) \times 4243 \\
L_{ING} & = \log_{10}(\text{ING}) \times 4343 \\
\text{TIME} & = 1920
\end{align*}
\]

- L_{PHOT} = \log_{10}(\text{PHOT}) \times \text{constant}
- L_{ING} = \log_{10}(\text{ING}) \times \text{constant}
- TIME = 1920

Prof. = PROFESSORS

Prof. = PROFESSIONAL

Ingr. = INGRADUATE SCHOOL

Ingr. = INGRADUATE SCHOOL
Fig. 10 Log Plot of Results of Growth Model
<table>
<thead>
<tr>
<th>TIME</th>
<th>ENG5</th>
<th>ENG5</th>
<th>L65</th>
<th>UNP</th>
<th>MFNP</th>
<th>PRFNP</th>
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<td>2015</td>
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<tr>
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</tr>
</tbody>
</table>

Fig. 11 Numerical Printout of Results
The combination model
The Static Phase Revisited

In the analytic version of the model of the static phase, discussed in chapter III, I assumed that faculty size was limited, and thus in the limit, constant. This meant that the rate of faculty hiring was equal to the attrition rate. In the model of Figure 12 I have framed this notion as a negative feedback loop trying to control the faculty to an externally given equilibrium level. The value of doing this is that the model can be exercised by allowing the equilibrium value to change, whatever the reason.

1. New employment of professors. This is now determined solely by the need for new faculty. This assumes an adequate supply of candidates.

\[ \text{NEWP.KL} = \frac{\text{WNP.K}}{FBTM} \]

- NEWEMPLOYMENT OF PROFESSORS
- NEED FOR NEW FACULTY

2. Number of professors. This is now increased by new employment and decreased by attrition.

\[ \text{PROF.K} = \text{PROF.J} + \text{DT} \cdot (\text{NEWP.JK} - \text{ATRP.JK}) \]

- NUMBER OF PROFESSORS
- NEWEMPLOYMENT OF PROFESSORS
- ATRITION OF PROFESSORS
Fig. 12 The Static Model
3. Attrition. We could just say that this is the number available divided by the average lifetime (as a faculty member). But that isn't true in a dynamic mode, as witness the validity of the treatment which ignores attrition altogether in the growth mode. Therefore we take this to be a delay function of the new employment of a faculty lifetime ago.

\[
ATRP \times K = DELAY \times \text{NEW} \times K \times \text{NEW}\text{EMPLOY} \times \text{PROF} \times K \times \text{OLD LEVEL}
\]

\[
\text{NEW} \times K \times \text{NEW EMPLOY} \times \text{PROF} \times K \times \text{OLD LEVEL}
\]

A more complete model would detail attrition among death, retirement, and job change. 17

4. Need for new faculty. This is just the difference between the equilibrium size and the actual size.

\[
\text{NEW} \times K \times \text{NEW EMPLOY} \times \text{PROF} \times K
\]

\[
\text{NEW EMPLOY} \times \text{PROF} \times K
\]

Put them together and what have you got?

The two phases are combined in Figure 13. The nice additivity of the models stems from the fact that they were really created by the separation of this more complex model. The only change is to make the hiring policy responsive to both types of inputs.
Fig. 13 The combination model. The complete program listing is located in the Appendix.
1. New employment of professors. This is allowed to be the student determined value of part A until the equilibrium faculty size is reached. Then it switches to the university determined value of part B.

\[ \text{NEWP} = \min(\text{NNF} \cdot \text{K} \cdot \text{UNP} \cdot \text{K} \cdot \text{R} \cdot \text{PGTF}) / \text{FBT} \]

\[ \text{DR} = 5 \]

\[ \text{PGTF} = 0.5 \]

- NEWP = NEW EMPLOYMENT OF PROFESSORS
- NNF = NEED FOR NEW FACULTY
- UNP = UNEMPLOYMENT (NEW GRADUATES)
- DR = DROP OUT RATIO
- PGTF = PORTION GRADUATES TO FACULTY

I have not included any smoothed transition process.

Results

The results of the computer simulation of this Not-So-Simple model are shown in Figs. 14, 15, and 16. The pre 1965 portion agrees nicely with data, which are superimposed. There is little accumulated data on the intervening period.

A few predictions of the behavior are possible. When the equilibrium is (was) reached, the hiring of new professors takes a drastic plunge. For about five years, each year is worse than the last for candidates for faculty positions. Then the picture starts to brighten, but slowly. It takes about thirty years for the system to reach equilibrium. But this new equilibrium is only about two thirds the size of the peak.

The model moves to the limit surface in an interesting way. I expected the change to occur by moving along the portion
Fig. 14 Results of the Combination Model
Fig. 15 Log Plot of Results of Combination Model
| TIME   | ENG1 | ENG2 | LAS  | UNP  | EWP  | EWP  | PROF  | PROF  | ASTM | NTRF | NTF  |
|--------|------|------|------|------|------|------|-------|-------|------|------|------|------|
| 0.00   | E+00 | E+00 | E+00 | E+00 | E+00 | E+00 | E+00  | E+00  | E+00 | E+00 | E+00 | E+00 |
| 10:40  | 2.30 .1 | 1.23  .1 | 1.46  .1 | 2.41  .1 | 1.48  .1 | 1.48  .1 | 2.41  .1 | 1.48  .1 | 1.48  .1 | 1.48  .1 | 1.48  .1 | 1.48  .1 |
| 10:45  | 3.79  .4 | 1.54  .5 | 2.46  .5 | 2.76  .2 | 1.46  .4 | 1.46  .4 | 2.76  .2 | 1.46  .4 | 1.46  .4 | 1.46  .4 | 1.46  .4 | 1.46  .4 |
| 10:50  | 3.77  .1 | 2.95  .2 | 3.10  .3 | 3.15  .1 | 3.15  .1 | 3.15  .1 | 3.15  .1 | 3.15  .1 | 3.15  .1 | 3.15  .1 | 3.15  .1 | 3.15  .1 |
| 10:55  | 5.21  .3 | 2.55  .2 | 4.88  .3 | 4.88  .3 | 4.88  .3 | 4.88  .3 | 4.88  .3 | 4.88  .3 | 4.88  .3 | 4.88  .3 | 4.88  .3 | 4.88  .3 |
| 11:00  | 7.49  .4 | 3.38  .6 | 9.25  .8 | 9.25  .8 | 9.25  .8 | 9.25  .8 | 9.25  .8 | 9.25  .8 | 9.25  .8 | 9.25  .8 | 9.25  .8 | 9.25  .8 |
| 11:05  | 1.30  .6 | 4.33  .3 | 7.03  .3 | 7.03  .3 | 7.03  .3 | 7.03  .3 | 7.03  .3 | 7.03  .3 | 7.03  .3 | 7.03  .3 | 7.03  .3 | 7.03  .3 |
| 11:10  | 1.37  .1 | 4.45  .4 | 1.26  .9 | 4.16  .6 | 1.26  .9 | 1.26  .9 | 4.16  .6 | 1.26  .9 | 1.26  .9 | 1.26  .9 | 1.26  .9 | 1.26  .9 |
| 11:20  | 2.94  .9 | 8.75  .0 | 1.26  .9 | 1.26  .9 | 1.26  .9 | 1.26  .9 | 1.26  .9 | 1.26  .9 | 1.26  .9 | 1.26  .9 | 1.26  .9 | 1.26  .9 |
| 11:25  | 2.98  .9 | 11.11  | 2.56  .8 | 1.45  .6 | 1.45  .6 | 1.45  .6 | 1.45  .6 | 1.45  .6 | 1.45  .6 | 1.45  .6 | 1.45  .6 | 1.45  .6 |
| 11:30  | 2.97  .1 | 1.40  .8 | 2.16  .5 | 2.16  .5 | 2.16  .5 | 2.16  .5 | 2.16  .5 | 2.16  .5 | 2.16  .5 | 2.16  .5 | 2.16  .5 | 2.16  .5 |
| 11:35  | 2.96  .9 | 1.36  .0 | 2.79  .9 | 3.57  .6 | 3.57  .6 | 3.57  .6 | 3.57  .6 | 3.57  .6 | 3.57  .6 | 3.57  .6 | 3.57  .6 | 3.57  .6 |
| 11:40  | 2.96  .9 | 1.36  .0 | 2.64  .6 | 3.43  .8 | 3.43  .8 | 3.43  .8 | 3.43  .8 | 3.43  .8 | 3.43  .8 | 3.43  .8 | 3.43  .8 | 3.43  .8 |
| 11:45  | 2.95  .5 | 1.27  .1 | 2.45  .7 | 3.46  .0 | 3.46  .0 | 3.46  .0 | 3.46  .0 | 3.46  .0 | 3.46  .0 | 3.46  .0 | 3.46  .0 | 3.46  .0 |
| 11:50  | 2.85  .0 | 1.25  .3 | 2.45  .3 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 |
| 11:55  | 2.95  .0 | 1.25  .3 | 2.45  .3 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 | 3.43  .2 |
| 12:00  | 2.60  .1 | 2.12  .0 | 2.67  .6 | 2.67  .6 | 2.67  .6 | 2.67  .6 | 2.67  .6 | 2.67  .6 | 2.67  .6 | 2.67  .6 | 2.67  .6 | 2.67  .6 |

Fig. 16  Numerical Printout of results 
of combination model
that enter faculties axis. Indeed there was a major change here. But the actual student faculty ratio changed. This implies a sensitivity to the delay times in graduate school and for making decisions. That is, we never were at the truly desired ratio because of delays in the system.
V. THE NOT-SIMPLE-AT-ALL MODEL or Future Shock

The model discussed in the previous chapters ignores a number of forces which could operate in the system, and perhaps are operating during this transition period. It also leaves out a large number of bookkeeping operations of great interest. The desire to emphasise the feedback loop which controls the graduate school population caused me to leave out an accounting of those who did not enter faculties. Yet here is where much of the job problems arises.

The model described here was developed before the versions of the previous chapters. It was during attempts to force this model to conform to the historical behavior of physics manpower that I focused in on the simple concept of unconstrained growth.

It would help both the exposition and the exercise of the model to realign this version so that the "basic loop" is the same as the simple model. Then all the causal subsystems could be hung on that as a backbone. However, the additional effort will have to wait.

The basic concept of the model was explained in the introduction of this paper. Moving to the exact computer program requires a number of details. It is especially important to consider the formulation of the rate equations in the system, as these form the policy setting assumptions used.
The Basic Loop

Figure 17 shows the basic loop of the model. In this loop, the manpower flows from an external universe. It is controlled by a rate of entry into graduate school. At some time later, the students leave graduate school, and enter the job market, which I call the unemployment pool. From here they can go to work in industry or government, or in a university. They leave employment at an attrition rate, and leave the model. The pool of unemployeds does not grow indefinitely, but also has an attrition rate into a pool of "never employed in physics."

The reason for separating the flow into two channels is that the professors are in a position of regeneration. They generate more physicists.

This could be further broken down between universities and colleges, tenured and untenured faculty, and teachers or researchers.

The assumptions in the flow are:

a. There is a sufficient pool of BS holders to satisfy the entering graduate school rate. This is probably true because there can be a flow into physics from other disciplines. A more complex model would delve into the undergraduate and high school manpower pools and decisions.

b. That there is no cross over from industry to university and back. This certainly is not true, but if it is a balanced flow then it is inconsequential.

c. The manpower which leaves by attrition does not enter
Fig. 17 Basic Loop of the Complex Model. This details the flow of manpower. One strong assumption is that the flow between academic and other employment cancels out and can be ignored.
the picture again. In the case of industry, where I have allowed layoffs, this says that the laid off worker never re-enters the field. In fact, in limited cases, only about 10% do so. 16

BASIC LOOP
ENTERING GRAD SCHOOL MODEL 21 JAN

If we just open the valves of the two hiring equations (industry and university), and set percent attrition rates, the behavior of the loop depends on the entering graduate school rate. If it is constant, then everything remains constant. When we apply an information feedback to control this rate, we have a complete feedback system. If the number entering graduate school depends on the available jobs, the system is an oscillator. If the number depends on the unemploy-
ment, the rate declines toward zero every time someone doesn't get a job, and never rises. If the rate depends on the professors' need for graduate students, we have a positive feedback loop, with an exponential blowup, as described in the simple model. The negative feedback loop in this situation is the information about unemployment. Strong emphasis on this leads to a calmer system.

Of particular interest is the time constant of the system. With just a pipeline five year time delay in graduate school the oscillations have a period of ten years. Later, when we consider informational delays, this period moves to about fifteen years. The problem is of much longer duration than I had expected.

Entering Graduate School

Why does a student enter graduate school in physics? We really don't know. Surveys of attitudes of students\textsuperscript{36} include such reasons as "inspired by college physics," "challenging," "encouraged by family," etc. The job opportunities were not included. I do not know if this reflects the attitudes of the students, or whether the pollsters failed to include these questions.

On the other hand, a study has shown a fairly close correlation between the general support of physics and the enrollment.\textsuperscript{37} How do we model the result?

Because of the uncertainty in the reasons students enter graduate school, the model employs a number of variable mul-
tipliers so that the consequences of various policies on the part of the students can be studied. Thus one input to the number is derived from knowledge of the present job market. Another input is derived from knowledge of the number of graduates who aren't finding jobs. A third is derived from the professors' need for graduate students, as opposed to a need for graduates. Finally, I propose that some constant proportion of the physics undergraduates will go to graduate school without much regard for the job market.

There is no input in the model for information about the number of students who are competing for the jobs available, or about forecast of the jobs to be available when the student graduates, because I find no evidence that the students are aware of this information. It would be interesting to include these effects, and see what happens.
The use of a three year time delay for information about jobs is an educated guess. I presume a year knowledge about graduates not finding jobs, because most contacts will disappear within that time.

**Leaving Graduate School**

Figure 18 shows the model for the rate at which students complete graduate school and enter the job market.

This rate depends on the rate at which students entered graduate school approximately five years ago. The rate is also affected by the attrition from graduate school. In this version of the model I have considered the attrition to be a constant percentage. Thus the rate for leaving graduate school with a completed degree is the completion ratio (complement attrition ratio) times a delay of the rate for entering graduate school.
A 6th order delay is generated by a delay of a delay, with each delay time one half the desired value. Figure 19 plots a number of delay functions against actual date\textsuperscript{29} for students graduating in 1963. The 6th order delay is somewhat deficient in conforming to the long lingerers. The 3rd order squared function is shaped better, but has the disadvantage of requiring a normalization, which is simple for a step function input, but not obvious for a variable input. By combining functions, a better conforming delay could be generated, but it is hard to argue that the shape of this function is important enough to merit the attention. This function should be modified to use the exponentially loaded DELAYE macro discussed in the appendix.

Average time in graduate school has been used as a constant. Data over a forty year time period\textsuperscript{30} shows a $\pm 1/2$ year variation in the mean time in graduate school. About one half of this (1/2 year total) is a long term (40) year trend. The largest excursion from the mean occurred during World War II, when the time dropped by about 3/4 a year from the long term average. After the war there was a period when the time was about 1 year over the long term average. The
Fig. 19 Delay In Graduate School
1 = DELAY1
3 = DELAY3
6 = DELAY3(DELAY3 )
* = DELAY3²

Data from ref. 29
number of degrees granted during the war fell to a sharp bottom, so even these excursions can be explained. But the significant point is that even such a strong perturbation as WW II did not change this variable much, so I am justified in calling it a constant.

Attrition from graduate school is also taken to be a constant. This attrition includes those students who settle for masters degrees, since the scope of this study is limited to PhD's. Again, while we may argue that there are cause and effect mechanisms which could vary this number, the data show it to be pretty constant. The ratio of students getting PhD to those entering (the same students) was .39 in 1964, and .41 in 1969.31

The Need for Professors

The model for the need for professors (inclusive term for all university instructors) is shown in Figure 20.
It is based on a proposition by Cartter\textsuperscript{8} that "teachers required varies directly with the absolute size of the . . . enrollment."

Thus the model starts with a table for the population of college age youths. We already know what this number will be for the next twenty years. It is not unreasonable to assume steady state population thereafter. At this level, I have used the fraction of the population which goes to college as a constant. The student/physics faculty ratio has historically been rather constant.\textsuperscript{26} The model is programmed to use a table function for this ratio so that we can investigate the consequences of a change. Such a change would occur, for example, if physics were to lose its status as a required science course at many colleges, and failed to make the offerings attractive enough to be elected.\textsuperscript{38}

\begin{verbatim}
POPP=TABLE(PTAB*TIME*.40.5)
PTAB=3.7/7/3.7/7/3.7/7/3.7/7/3.7/7/3.7
NUS=PUP*K*NUN
NUN=3.3
NPU=NUS*K*CPP
CPP=2.0

POP - POPULATION
PTAB - TABLE OF POPULATION
NUS - NUMBER OF UNIVERSITY STUDENTS
NUN - PERCENTAGE OF UNIVERSITY STUDENTS
NPU - NUMBER OF PHYSICS UNDERGRADUATES
CPP - PERCENT THAT ELECT PHYSICS
\end{verbatim}

The table shown above (PTAB) defines a constant population for the purpose of looking at the dynamics. The actual population used for real world simulation is given by Figure 21:\textsuperscript{39}
Employment of Professors

This is a simple control loop, shown in Figure 22.

The loop tries to control the hiring rate so that the number of professors is equal to the need for faculty. Thus the error
signal (difference between actual and needed faculty), defined as need for new faculty, drives the rate for new employment of professors. The shape and delay time of the information delay in this loop appears to affect the output perhaps more than I would like. A third order delay caused a drastic overreaction of the rate, so I have chosen a first order delay (= SMOOTH in this version of Dynamo). The delay time I have used is three years.37

NEW EMPLOYMENT OF PROFS 21 JAN

PROF.K=PROF.J*UT5(NEWP.JK-ATHP.JK)
PROF=4000
NEWP.KL=MIN(TNEW.K*UNP.K/2)
INE.A=SMOOTH(NEWP.K*UNP.K)
TIME=3
NF.K=NF.K*CFK
CFK=A=(TIM.M/1.0+14.5)
FRTAB=3333/3333/3333/3333
NNF.K=NF.K-PROF.K

PROF = EMPLOYMENT OF PROFESSORS
NEW = NEW EMPLOYMENT OF PROFESSORS
ATHP = ATTENTION OF PROFESSORS
INE = TO NEW EMPLOYEES PERCEIVED NEED FOR NEW FACULTY
UNP = UNEMPLOYMENT
NF = NEED FOR NEW FACULTY
TIME = DELAY TO NEW PROFS FROM NEED FOR NEW FACULTY
NNF = NUMBER OF UNIVERSITY STUDENTS
CFK = STUDENT FACULTY RATIO
FRTAB = TABLE OF NEEDED FACULTY STUDENT RATIO

Attrition of Professors

Just what controls the attrition of professors? I have developed my own model for this. First, for those professors under tenure, attrition is governed by retirement, death,
changing field, or moving into administration. While the availability of jobs elsewhere may affect some aspects of this, it seems reasonable to use constant \% figures in these cases. The model is provided both with a constant attrition rate for investigation of the dynamics, and with a table for the projected rate due to the age distribution already built into the system,\(^{17}\) see Figure 23.

The attrition of untenured faculty is another story. I again claim that the job market does not affect this attrition rate. The way the university does respond to lower its faculty size is to cease hiring new untenured faculty and reduce tenure grants. Since the ratio that gain tenure is low, the effect can be strong.
Graduates who cannot find jobs in the physics profession become discouraged and look elsewhere. If they find a job outside the profession, they rarely reenter physics. This is shown by the model of Figure 24.

I have used a first order loop. Although a third order delay might seem more appropriate because everyone will look for a while, most of the students will have been looking for a job before leaving school, and may accept non professional jobs very soon after leaving. I have assumed the time constant of this loop to be one year. The anecdotal evidence is that few graduates are in the job market one year after graduating.
Funding

The model of the effects of funding level is perhaps the most arbitrary component of the general model. As shown in Figure 26, below, I use funding levels only to determine the number of industrial and government jobs. Funding surely must affect university employment, the number of fellowships affect the number of graduate students, etc. But in fact, these effects all seem to involve second or higher order effects. At this level of sophistication, I am claiming that funding of universities only affects the amount of research, not the amount of teaching, and thus not the number of professorial jobs. Likewise, the presence of fellowships makes
it easier to go to graduate school, and makes the life of the student more comfortable, but does it affect the number that go?

One important point considered by the model of Figure 25 is that funding levels are volatile. If a program is funded, but insufficient manpower are available to carry it out, the jobs are not available for long. Either the program is killed, other specialties take the jobs, or "upgrading" takes place.

Because of this, the model is formulated in terms of a funding level per year.
Employment in Industry and Government

The funding level is converted into a number of jobs by a constant multiplier, shown in Figure 26.
I have not complicated the model with inflation factors at this stage. The number of jobs is then compared to the employment, to see what changes should be made. This controls the hiring rate, in a first order loop with a one year time constant.

HIRE IN INDUSTRY AND GOVERNMENT

\[ \text{HIRE} = \min \left( \frac{\text{NEMP} \cdot k \cdot \text{UNEMP} \cdot k}{2} \right) / \text{CDH} \]

\[ \text{CDH} = 1 \]

- \( \text{NEMP} \): New Employment
- \( \text{UNEMP} \): Unemployment
- \( \text{CDH} \): Time Constant for Hiring in Industry

**Attrition of Employment**

The employed work force undergoes attrition due to death and retirement just like the professorial employment. There is also attrition due to a lack of jobs. This works in a
faster delay loop, with an assumed one year time constant, as in Figure 27.

Again, the more detailed structure has not been included, of the time and age dependence of the body of employees.

**Attrition of Industry and Government Employment**

\[ \text{ATR} = \frac{\text{EMP}}{30} \]

- **ATR** = Attrition from Inds and Govt
- **EMP** = Employment in Industry and Government

**Post Docs**

If there is a lack of jobs (negative excess jobs), some of the excess can go into the pool of post docs. This pool is given both maximum and minimum sizes, in Figure 28.
The persons are in this loop for a third order delay centered about one year.

POST JOBS, EXTRAORDINARY 21 JAN

\[ IPD_{NL} = \text{max} (\text{min} (E_{AK}, K \cdot P_{UMA}) \cdot \Pi_{DMN}) \]

- \[ P_{UMA} = 500 \]
- \[ \Pi_{DMN} = 100 \]

I have left out the complicating effects of fund availability on the maximum number of positions available.

**Results**

One production run with a moderate bit of exercising led to thirty five pages of computer output. In a moderate attempt at completeness, I include 24 of those pages, reduced to small size, as Figures 29 through 35. I can make no claim to a complete understanding of the results. I believe that I will need to spend some interactive time with the program, turning on and off portions of importance, in order to develop
my understanding and refine my intuition. Therefore I merely present the result, and leave it to the interested reader to make comparisons.
Fig. 29 A & B  Results: Basic Run
Fig. 29 C & D Results: Basic Run
Fig. 30 A & B Results: With Real Time Variance of Population
Fig. 30 C & D Results: With Real Time Variance of Population
Fig. 31 A & B Results: With Funding Growth
Fig. 31 C & D Results: With Funding Growth
Fig. 32 Results: With Funding Decrease
Fig 32  C & D  Results: With Funding Decrease
Fig. 33 A & B : Results: With Real Population Variance, and sharp decrease in rate of funding increase
Fig. 33 C & D Results: With Real Population Variance and sharp decrease in rate of funding increase
Fig. 34 A & B Decreased Requirement for Physics Service Courses
Fig 34 C & D  Results: Decreased requirement for Physics Service Courses

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Fig. 35 - A
The complete Complex Model

Continued
VI. CONCLUSIONS

About System Dynamics

System dynamics was very useful for this problem, and I think that should extend to many social issues. I was able to learn both the implementation of system dynamics and a lot about the specific problem of manpower within this short research effort. The result is to get to about the frontier of understanding in this area so that future work could be a real contribution to knowledge. I had picked a problem for which I knew very good data were available, and was extremely fortunate to have the most highly expert advice both on the methodology and on the substantive problem.

The manner in which systems dynamics forces assumptions into the open forces a lot of careful thinking about the system. It also furnishes an excellent communications vehicle.

The DYNAMO compiler eliminates concern over computer programming. I was familiar with solutions of rate equations, and find this the nicest approach I have used. I think it cannot be emphasised too heavily that a strong computer programming background is not necessary to operate system dynamics models with the DYNAMO compiler.

About Physics

The conclusions about physics were discussed in the introduction. The historical exponential growth of physics is
explainable as a positive feedback loop with no constraints. The present behavior is consistent with the proposition that physics is reaching the end of its growth. Even if this is not true, the limit is in the near future.

The static system of the future will require changes in the universities' attitudes, research and curricula. We still have some hope of controlling the final operating point, but we need to start considering the goals of the profession. The transient repercussions of reaching the limit will last for about thirty years, but the worst is over in about five.

**About This Thesis**

I achieved both a working knowledge of system dynamics and of the system of physics manpower. I developed a number of insights which others may have had, but this is a respectable accomplishment in a masters thesis.

The model as presented in Chapter IV is at once sufficiently general yet complete enough to present to physicists without shame. The model of Chapter V needs further refinement before it is used in a serious way, but it does have the potential for expanding our knowledge about system behavior beyond the current frontiers.
References

2. *ibid.*, p. 8 and p. 14
3. *ibid.*, p. 18
15. Data collected by surveying the January issue of *Physics Today* for each volume from 16 (1963) to 26 (1973)
23. Levin et. al. Narcotics and the Community
25. A.I.P. 1964, op. cit., p. iii
26. *ibid.*, p. 18 and p. 40
27. *ibid.*, p. 36
32. ibid., p. 34
33. A.I.P. 1969, op. cit., p. 97
34. A.I.P. 1964, op. cit., p. 31 and sources cited therein
35. Discussed and used in references 10, 11, 18, 19, 20, 21
36. L. Grodzins, unpublished; A.I.P. 1969 op. cit., p. 43
37. L. Grodzins, private communication; also E. Roberts, private communication
Annotated Bibliography

American Institute of Physics Reports, 1964 and 1969. These are a major source of data concerning all aspects of physics manpower, education, and financial support. They also serve as a good source or referrals to work in the field.

Brode, Wallace R. Science 173, 206 (1971) discusses the effect of saturation on manpower in science and engineering. He predicts surplus from 1968 to 1985, and then a deficit on out to 2030. None of his predictions are based on less than 1% per year population increase, whereas we have (at least temporarily) reached zero population growth. Nevertheless, this is a good paper to read for a different view of the same problem.

Cartter, Allan M. (reference 8). Only the first few pages of this book are of value for aspects of my model. However the rest of the book would be very useful for any study involving the quality of graduate education. Cartter (reference 38) has also been active in predicting over-supplies of PhD manpower.

Forrester, Jay W. (references 10, 18, 19, and 20). Of all his books, I found *Industrial Dynamics* to be the one to read to learn system dynamics.

Pugh, Alexander L. (reference 24). The DYNAMO manual is a must for anyone wanting to program a system dynamics problem. It does a clear job of explaining how to get
the program into the DYNAMO language. It does not serve as an adequate reference for having a valid set of equations. More exotic programs are also difficult -- I ran into problems trying to write a MACRO.

De Solla Price, Derek (reference 1). When I first read this book I found that he was saying in 1962 the things I independently concluded in this study in 1973. Since his conclusions were before the fact, this has to be considered an important book on this subject.
APPENDIX A

The DELAYE Macro

The Delay macros built into DYNAMO load up a set of internal initial conditions as if the variable in question had been a constant for all time before the program turns on. In the case of rapid growth, this is false, and leads to a distortion of the results for the first couple of delay times. To overcome this, I modified the DELAY macro to exponentially smooth initial conditions. The modification was done to a version of the DELAY routine which computes the material (in my case, men) in the delay pipeline.

If the function has been varying at an exponential rate,

\[
\begin{align*}
Y & \\
\log Y & \\
\end{align*}
\]

then its logarithm is linear. We can easily extrapolate a central point between the oldest data and the newest by:

\[
\log Y_2 = (\log Y_1 + \log Y_3)/2 \quad \text{which reduces to:} \quad Y_2 = \sqrt[2]{Y_1 \cdot Y_3}.
\]
Thus this Macro requires a function OLD which is the value of the variable one delay time before the time at which the normal initial conditions are taken.

MACRO DELAYE (INPUT, LY, PE, SL)


$SLV1=DEL*INPUT

$DEL.K=LY.K/3

$T1.K=SLV1.K/$DEL


$SLV2=SLT (SLV1&SLV3)

$T2.K=SLV2.K/$DEL


$SLV3=OL & DEL

DELAYE.K=SLV3.K/$DEL


VEND
APPENDIX 3

COMPLETE MODEL 1 MARCH 1973 3/22/73

MACK, DELAYE(I=INPUT, D=DELAY, P=PIPE, L=LOAD)
L $L1 = $L1 + $L1 * J * D1 $T = (I=INPUT, J=RT1, )
N $L1 = $DEL * INPUT
A $DEL = $DLY * 1 / 3
R $RT1 = $L1 < $DEL
N $L2 = $RT1 * J * D2 $T = ($RT1, JK = $RT2, JK)
L $L2 = $L2 + $L2 * J * D2 $T = ($RT2, JK = DELAYE, J)
N $L3 = $L3 < $DEL
A DELAYE = $L3 < $DEL
A PIPE = $L1 + $L2 + $L3

NOTE
NOTE ENTERING GRADUATE SCHOOL
N TIME = 1/29
N ENGS = ENG1 / 4PM
C FBT = 1
R LGS = DELAYE(ENGS, JK, TGS, INGS, KL, DLS)
C TGS = 5
N LGS = 11/29
C OLGS = 1/8
L UNP = INP + T (LGS, JK, NEWP, JK, PROF, JK)
N UNP = 22
R NEW = 1 / NEW(ENG, UNP, GPF) / FBT
C DUS = 3
C PUTF = 2
R DRT = INP B (1 - UNP / PUTF)
R ATDF = DELAYE(NEW, JK, ADEL, PROF, X, 1, DDF)
C OLDF = 2
N PROF = 79
C ADEL = 3
A NNK = PROF - PROF
C EOF = 92.19
L Gra = DTL / LGS
N Grin = DT / 1.8
A NGS = MAX(PROF, X, GSF + INGS, X, GRA, K, X)
C GSF = 1
A LPROF = LOG10(PROF) * 434.3
A LINGS = LOG10(INGS) * 434.3
PRINT ENGS, INGS, LGS, UNP, NEWP, DROF, PROF, ATDF, NNC, NGS
PLT ENGS, LGS = LUNP = 0 / NEWP = 0 / PROF = P / INGS = 1
PLT LPROF, LINGS
SPEC DT = 5, LENGTH = 20Z / PLT DF = 2 / PROF = 5
RUN READ DATA BASIC MODEL
<table>
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NOTE

NOTE INDUSTRY AND GOVERNMENT EMPLOYMENT 21 JAN

NOTE

NOTE MINUS .5A = .5A .4A .3A .2A .1A

NOTE

NOTE INDUSTRY AND GOVERNMENT EMPLOYMENT 21 JAN

NOTE

NOTE PRINT JUC = CATASTROPHIC 21 JAN

NOTE

NOTE PRINT JUC = CATASTROPHIC 21 JAN

NOTE

NOTE C1 = -.1167 1.1

NOTE

NOTE CONTROL SECTION

NOTE

NOTE

NOTE

NOTE SPEC IF = 1 / LENGTH = 26 / PLT PERS = 8 / PRI PERS = 2

NOTE BASIC RUN

UNGS NOT DEFINED
USED IN PRINT OR PLOT CALL

ERROR MESSAGES
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