Unintended Effects of Changes in NIH Appropriations: Challenges for Biomedical Research Workforce Development

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ABSTRACT

The U.S. government doubled NIH appropriations between 1998 and 2003, aiming to significantly foster research activities in biomedicine. However, several indicators demonstrate not only that the impact of the budget increase fell short of expectations; in many cases it resulted in unintended negative effects. Compared to pre-doubling conditions, researchers now spend significantly more time writing grant proposals, impacting their ability to carry out research. Paradoxically, the probability with which a grant proposal is accepted for funding deteriorated sharply after the doubling and continues to fall. The average age of first-time NIH grant recipients has increased by almost a decade since the early 70's, while the percentage of biomedical doctorates securing tenured or tenure-track positions relentlessly drops. These trends represent a threat to the quality, stability, and availability of the U.S. biomedical research workforce.

This thesis takes a system dynamics approach to test the hypothesis that a sudden and temporary increase in research funds can result in unintended long-term effects hampering research discoveries and workforce development. A simulation model is therefore developed using the available literature and calibrated to replicate historical trends. The model is then used to perform experiments that test the effects of changes in certain parameters or policies. The outcomes of these experiments provide policy insights that can help improve the effectiveness of NIH funding and its impact on the workforce.

Thesis Supervisor: Richard C. Larson

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1. Introduction

1.1 NIH Background

The National Institutes of Health (NIH) is the largest funder of medical research in the world, the leading agency for non-classified research in the U.S. federal government, and largest single source of funds for academic research in the country (Collins, 2011; Brainard, 2004). It is one of eleven operating divisions that constitute the Department of Health and Human Services (HHS), the United States Government's principal health agency. NIH's mission is to seek and apply knowledge about living systems to enhance health, lengthen life, and reduce the burdens of illness and disability (NIH, 2011).

Underlining NIH's role as a government priority, President Barak Obama has referred to biomedical research as essential to the health of individuals and the economy as a whole (Glenn, 2011). The strong political support that NIH has historically enjoyed is reflected in the size and growth of its budget; in 2010 the agency spent over 30 billion dollars in medical research, a threefold increase from its 1980 budget (NIH, 2012).[1] Figure (1) illustrates how federal support for HHS overshadows all other non-defense federal R&D expenses; NIH represents over 97% of HHS' budget (NSF, 2012).

The NIH supports more than 200,000 scientists and research personnel across the U.S. and abroad, conducting research and training extramurally and within its own facilities (Smith, 2006). NIH-funded medical research has played a fundamental role in the increase of life expectancy in the United States, from 47 years in 1900 to 78 years in 2009 (NIH, 2011). Underscoring NIH's role in the nation's economy, Mack (2000) notes that if only 10 percent of the value of longevity increases resulted from NIH-funded research, it would indicate a payoff of about 15 times the annual investment. The agency is a prominent player in the advancement of cutting-edge, and sometimes controversial, science such as human embryonic stem cell research and nanotechnology. This leadership is reflected in the more than 80 Nobel Prizes that have been awarded for NIH-supported research (NIH, 2011).

Given NIH's sizeable budget and impact, its rapid growth in the past few decades, and the ambitious outcomes it targets, it is critical for relevant policy-makers to understand the dynamics of the underlining research workforce and its response to changes in funding levels. Poorly designed policies could negatively impact the quality, availability, and stability of this workforce, affecting the effective fulfillment

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[1] In constant 2010 dollars

of NIH's mission. To this end, it is first necessary to identify the population that this workforce is composed of and their typical professional development.

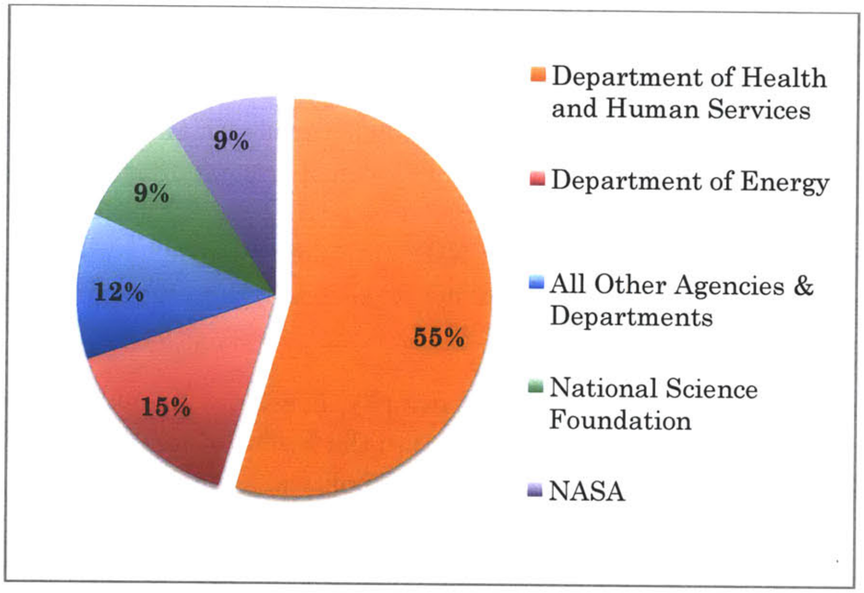

Figure 1. Estimated Federal Obligations for R&D by Agency Fiscal Year 2009 (NSF, 2012)

1.2 Workforce Characteristics and Career Progression

The scientific workforce qualified to carry out the research that NIH targets is primarily composed of PhD holders in biological and medical science fields such as biochemistry, epidemiology, and genetics, to name a few. Recent years have witnessed a tremendous increase in the production of these doctorates. Figure (2) shows how the number of degrees awarded has more than doubled in the past 20 years, a remarkable trend when compared to other fields in science and engineering (Sturtevant, 2008).

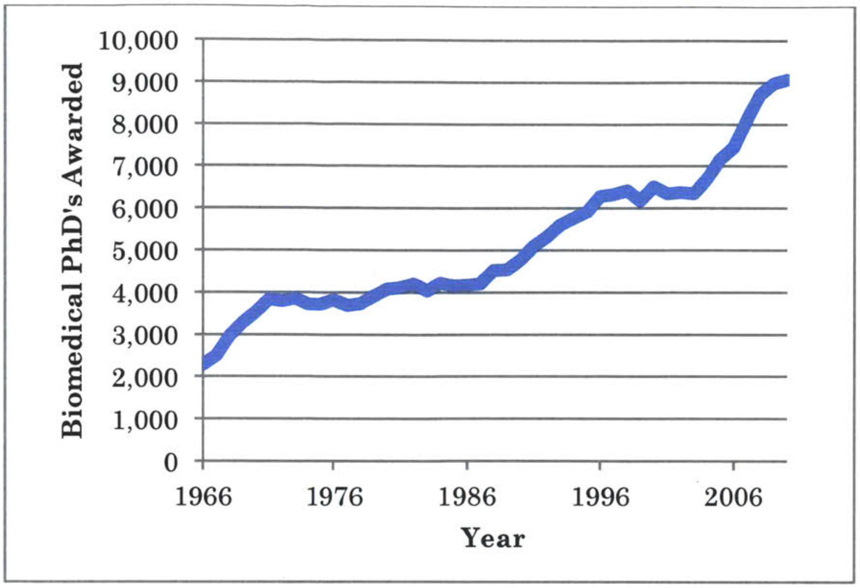

Figure 2. Doctorate Degrees Awarded in the Biological and Medical Sciences (Garrison & Ngo, 2011)

Upon graduation, doctorate degree holders typically have the choice between one of two broad sectors: academia or industry. Figure (3) shows how the number of biomedical PhDs employed in academia has remained relatively stable for the last two decades, while the number employed in industry doubled between 1995 and 2008. To make matters worse, the elimination of mandatory faculty retirement in 1994 further hindered the prospects of young investigators seeking tenured or tenure-track positions, particularly at research institutions. Using MIT as a case study, Larson and Gomez Diaz (2012) concluded that if tenured professors were to remain employed an additional 10 years on average, the hiring of new faculty would drop by approximately 20%.

This situation is at odds with the hopes and career aspirations of doctorates: "...an academic career has traditionally been the goal of most entering Ph.D. students in the biomedical sciences, and this ultimate objective is assumed in the design of graduate programs" (Garrison, Gerbi, & Kincade, 2003). In addition, the NIH awards 80% of its grant money to researchers affiliated with domestic higher education institutions; the remaining 20% is split between researchers at independent hospitals, research institutes, and non-profits (NIH RePORT, 2011). These proportions indicate, therefore, that NIH's main researcher population consists of PhD holders in biomedical fields who remain affiliated with domestic higher education institutions throughout their careers.

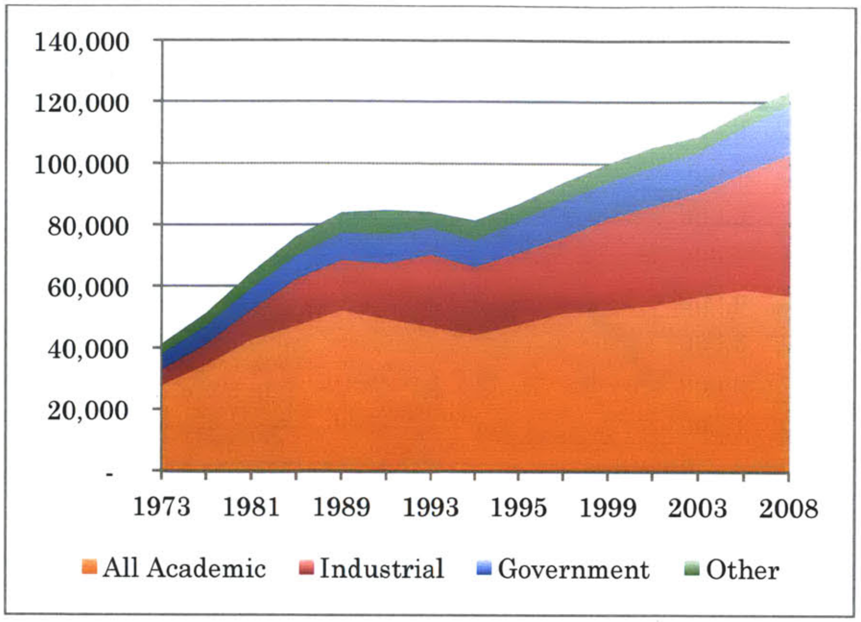

Figure 3. Employment of Biomedical Science PhDs
by Sector of Employment (Garrison & Ngo, 2011)

PhD holders who follow the academic path, and are able to successfully navigate the professional hurdles of reappointment and promotion, eventually achieve tenure. Before landing tenure-track appointments at research institutions, however, it is becoming increasingly common for biomedical doctorates to engage in postdoctoral training. The NIH defines a postdoctoral scholar as "An individual who has received a doctoral degree (or equivalent) and is engaged in a temporary and defined period of mentored advanced training to enhance the professional skills and research independence needed to pursue his or her chosen career path" (NIH OER, 2007).

According to Cathee Johnson Phillips, Executive Director of the National Postdoctoral Association, "...in biomedical fields, a postdoc has become required if a person has any hope of becoming a faculty member on the tenure track [...] because of the recent increases in graduate enrollment in the biological sciences, I would say that the biomedical industry will remain the leader of the pack in the creation of more postdocs" (Hibel, 2011). As seen in Figure (4), the number of biomedical postdocs in the U.S. more than trebled between 1979 and 2009 from 11,000 to over 37,000. This trend highlights the growing importance of the postdoctoral stage in biomedical doctorates' development towards full-time positions in higher education institutions.

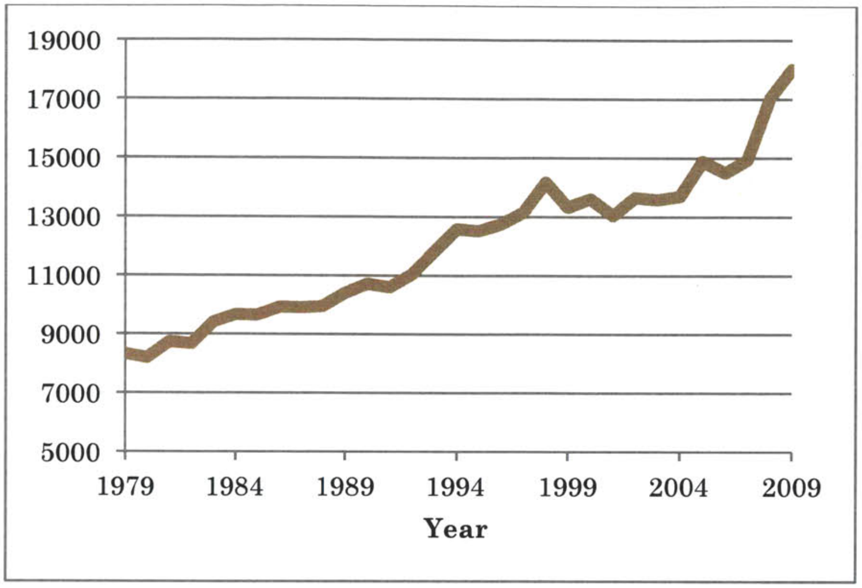

Figure 4. Biological and Medical Sciences Postdocs,
U.S. Citizens and Permanent Residents (Garrison & Ngo, 2011)

Since NIH funding targets researchers at all stages in academia described above—from graduate students, to postdocs, to tenured faculty—this is the main career pipeline that this analysis will focus on. The impact of NIH funding in the development of the workforce, however, is not straightforward and entails major complexities examined in the following section.

1.3 Challenges and Complexities

In order to shed light on the complex relationships that exist between different variables in the workforce ecosystem, a natural experiment is used to describe the noteworthy and unintended effects of abrupt changes in NIH funding levels.

In 1997, the U.S. Senate voted 98-0 to endorse the goal of doubling the NIH's budget in five years (Pear, 1998). The project was successful; between 1998 and 2003 Congress doubled NIH appropriations from $13.6 billion to $27.1 billion (Smith, 2006). Figure (5) plots this trend in constant 2010 dollars and highlights the relevant doubling period. Due to a general lack of understanding by decision-makers on how the biomedical workforce would respond to this increase, a seemingly positive development for the field ended up triggering a crisis once the growth halted (Monastersky, 2007). It is worth noting that as far back as 1998, a National Research Council committee had urged restraint in the rate of growth of PhD production in the life sciences. This conclusion drew strong criticism by some and was ignored by others, resulting in its final dismissal (Monastersky, 2007).

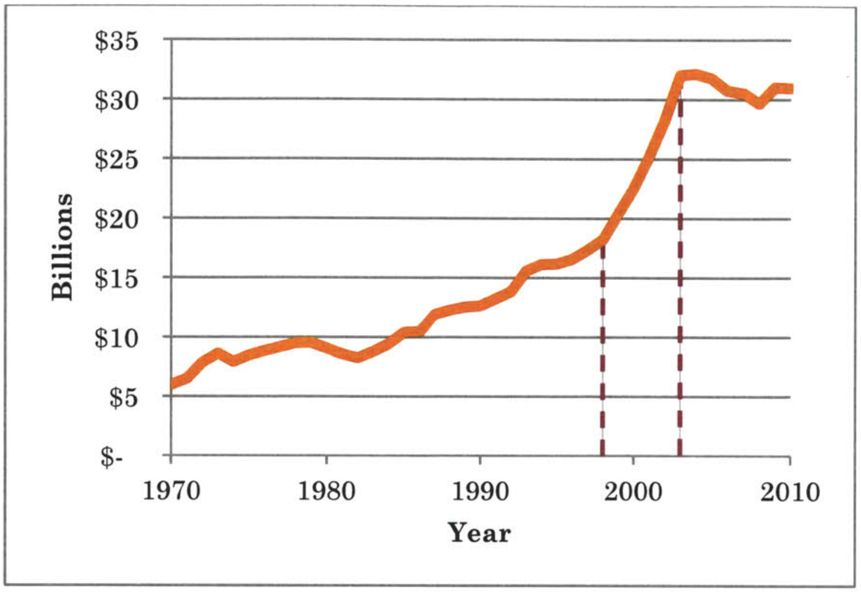

Figure 5. NIH Budget in Constant 2010 Dollars
(NIH, 2012)

The budget doubling flooded NIH with billions of dollars over a relatively short period of time, provoking the massive expansion of biomedical research that policy-makers had intended. Achieving the doubling of NIH's budget in five years required an annual growth rate of roughly 15% (Kaiser, 2003). Such steep budget growth created the conditions for a comparably steep increase in the number of researchers, particularly at the doctorate level. Consequently, expectations of federal support surged to levels that could not be sustained once the budget stopped growing (Couzin & Miller, 2007). The biggest strain on the budget ultimately came from this general increase in researchers (Timmer, 2008) and the relative declining availability of funds following 2003.

The swelling budget drove research institutions to spend their own money building more research laboratories in anticipation of winning NIH grants to operate them (Brainard, 2004). Universities added graduate students and postdocs in biomedical departments, increasing the pool of researchers competing for NIH grants (Monastersky, 2007). The dramatic surge in demand for researchers was met with a growth in supply, creating a scenario in which stability depended on continuous annual budget increases of 15%. Sustaining this growth was not only practically unfeasible; policy-makers never intended it.

Once the double-digit growth ended, biomedicine found itself in a situation where the supply of qualified researchers far outstripped demand. NIH's budget underwent an abrupt reversal after 2003, going from annual increases of 15% to boosts of around 3% in the years to follow; a decline in real terms when accounting for inflation.

"After a completed five-year doubling campaign [...] biomedical researchers hoped for a gradual easing into slower growth rates. But growth in the NIH budget slowed sharply to 3.2 percent in 2004, slowed even further to 2.0 percent in 2005, and [reversed] in 2006 with a declining budget for the first time since 1970. After adjusting for inflation, FY 2006 [was] the first time in 24 years that the NIH R&D portfolio [fell] behind inflation in the economy as a whole [...] the 2006 budget cut [was] steep enough to bring NIH R&D below the 2003 funding level in real terms, erasing the increases of the last two years." (AAAS, 2005)

Stagnant funding levels, combined with inflation, resulted in a 13% decline in NIH's purchasing power between 2003 and 2007 (Agres, 2007). Not unexpectedly, such a severe shock resulted in a wide array of negative effects for the biomedical research community. In 2007 Science magazine concluded that conditions worsened after NIH's budget doubled, as the infusion of money was far too rapid and not tied to structural reforms that could have enabled NIH to best use its growing resources (Benderly, 2007).

1.4 Troubling Indicators

This case study illustrates how the rapid growth of NIH's budget, a seemingly positive development, set the stage for a series of unintended negative effects due to the complex interactions between different components in the system. Among these effects, it is evident that the current stagnation in available grant awards, coupled with the increase in applications, has resulted in declining success rates. Figure (6) shows how this decline began shortly after the doubling efforts came into effect in 1998.

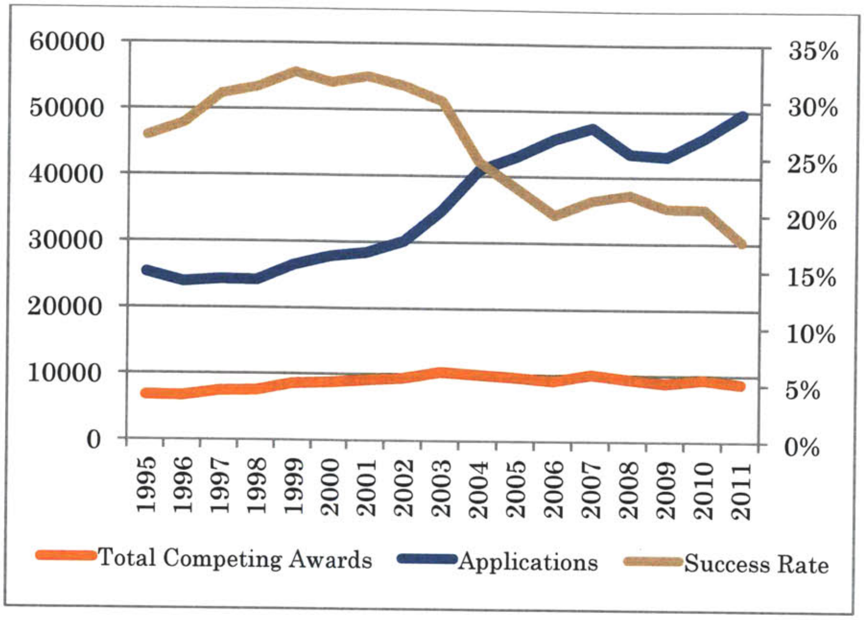

Figure 6. Competing Awards, Applications, and Success Rate
(Garrison & Ngo, 2012)

A second troubling indicator closely related to the decline in grant success rates is the rising age at which investigators secure their first R01 or equivalent grants. These types of grants are a critical milestone in a researcher's career, and are essential for their establishment in the scientific community. Figure (7) illustrates this rising trend, where a steep increase can be appreciated shortly after 1998.

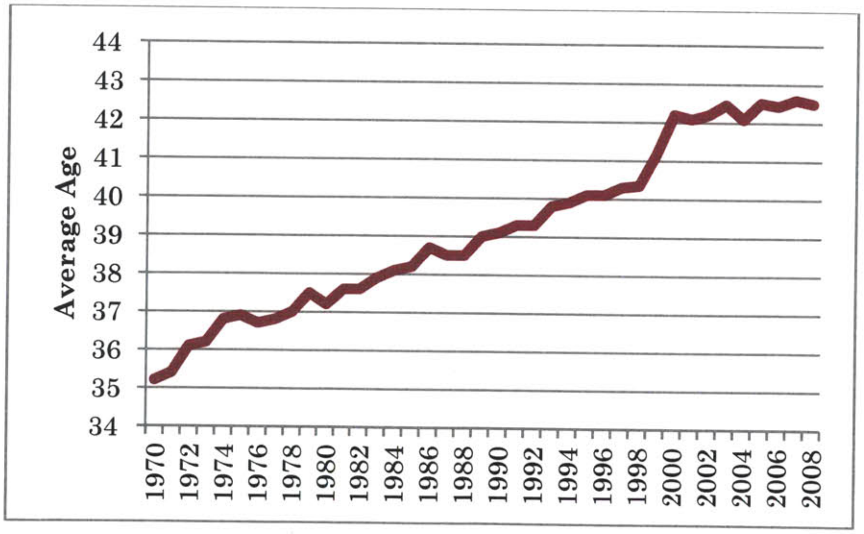

Figure 7. Average Age of First Time R01 Equivalent Investigators
(Garrison & Ngo, 2011)

As mentioned in Section 1.1, tenured positions are typically the long-term professional goal for biomedical doctorates, which contrasts with the relatively stagnant number of PhDs employed in the academic sector illustrated in Figure (3). The growth in PhD production has therefore translated into a declining percentage of doctorates landing tenured or tenure-track positions for the past three decades, virtually unaffected by the doubling of the budget. Figure (8) illustrates this trend. Furthermore, assume that in equilibrium the top X % of candidates enter the biomedical system as PhD candidates. If the number of available PhD slots were to double, then the top 2X % of candidates would enter the system, therefore impacting the quality of the overall talent pool.

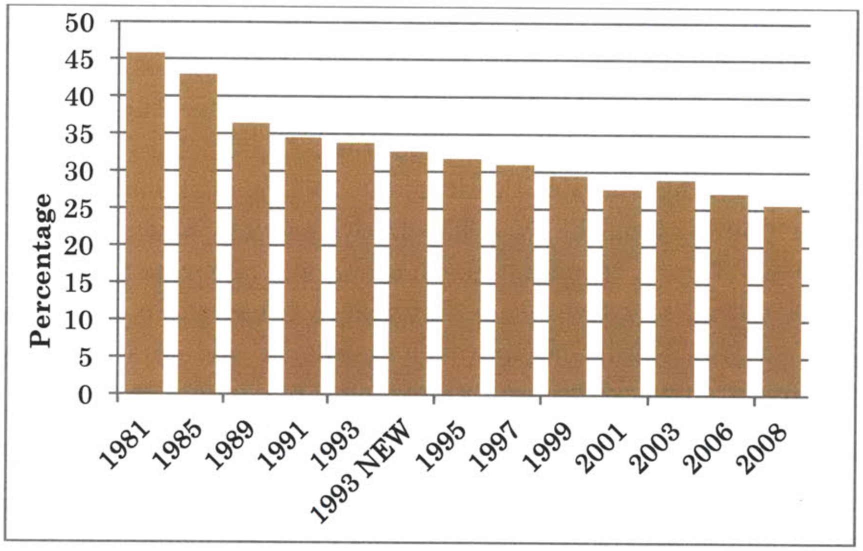

Figure 8: Percent of U.S. Biomedical Science PhDs Holding Tenure or Tenure-Track Positions (Garrison & Ngo, 2011)

Given the NIH's commitment to a stable and sustainable scientific workforce, the agency is growing increasingly concerned about the troubling indicators illustrated above (Ruiz Bravo, 2007). Despite the outcomes of the budget doubling, equivalent funding initiatives remain a popular proposition in the political realm (Hinck, 2010). Flat funding is typically seen as the culprit, and many sectors of the research workforce are clamoring for large budget increases once again. "What is often left unsaid is that the fundamental problems are structural in nature—biomedical research funding is both erratic and subject to positive-feedback loops that together drive the system ineluctably toward damaging instability" (Teitelbaum, 2008).

At this stage, one can only speculate about what the outcomes of different strategies for budget growth would have been. Similarly, the long-term side effects of current policies will be understood only until they become obvious. "Public policies often fail to achieve their intended result because of the complexity of both the environment and the policy-making process" (Ghaffarzadegan, Lyneis, & Richardson, 2011). Without formal and verified models that broadly describe such systems, identifying effective policies and foreseeing unintended side effects remain elusive tasks.

1.5 Problem Definition

> "In this era of scarce resources and a stagnant job market, careful planning for the direction of biomedical research is critical" (University of California - Davis Health System, 2011)

In light of the unintuitive consequences that abrupt budget increases can bring, the goal of this study is to examine how the NIH and its funding policies affect the development of the U.S. biomedical research workforce. This study is mainly interested in the pipeline that researchers go through, from enrollment in biomedical doctorate programs until retirement, looking at the intermediate steps and key decision points along the way. The analysis will focus on understanding how different variables interact, respond to each other, and generate feedback mechanisms that ultimately give rise to unforeseen behavior. In other words, this study will take a systems thinking approach in order to understand the dynamics of the biomedical research workforce and its response to changes in funding policies.

The size of the biomedical workforce, the unparalleled support it receives from federal funding, the consequential discoveries it makes, and the impact that such discoveries have on the nation's economy and its scientific leadership, are all reasons that warrant improved knowledge of this ecosystem. By providing an understanding of the dynamic characteristics and complexities that define the behavior of the biomedical workforce, the hope is to assist decision-makers in foreseeing unexpected effects of changes in policy. This improved understanding is instrumental in answering questions about the strategies that can enhance the effectiveness of public spending for biomedical research going forward.

Lastly, the dynamics of a particular research workforce and its relationship with public funding could bear similarities across various areas of knowledge. Other public agencies and organizations, such as the NSF, whose funding plays a critical role in the advancement of different scientific fields, could benefit from these transferrable insights.

1.6 Research Method: System Dynamics

> "In dealing with the dynamics of information feedback systems, the human is not a subtle and powerful problem solver" (Forrester, 1961, p. 99).

The case study outlined previously illustrates how the biomedical workforce is a system that involves a considerable degree of dynamic complexity. Understanding its behavior requires the simultaneous consideration of numerous variables and processes, such as funding levels and the number of doctorate candidates that exist in the 'production' pipeline. The structure of the system, which is described by the interactions between these variables and processes, is what dictates its overall behavior. In order to model such a complex system, it is therefore necessary to implement a method that allows the construction of computer simulations in which all the relationships can be described and the variables can respond dynamically to each other.

System dynamics is a modeling technique through which the structure and dynamics of complex systems can be understood. Using this technique, modelers can build formal computer simulations of real systems in order to uncover long-term side effects of decisions, and design effective policy strategies to achieve improved behavior (Sterman, 2000). System dynamics models are useful in identifying processes that involve feedback that can either be self-reinforcing or self-correcting. These types of processes, known as reinforcing or balancing feedback loops, give rise to the non-linear behavior that characterizes a wide range of complex systems in the real world. Mathematically, system dynamics is grounded in control theory and the modern theory of nonlinear dynamics (Sterman, 2000).

"System dynamics is the use of informal maps and formal models with computer simulation to uncover and understand endogenous sources of system behavior." (Richardson, 2011, p. 241)

The stock and flow structure that serves as the basic construct in system dynamics provides an appropriate platform to model the multi-stage development of the biomedical workforce, accounting for the delays involved between each of these stages. In system dynamics, stocks are accumulations within the system; they can represent populations, balances, or inventories, for example, and can only be affected by the flows connected to them. Flows represent the rate of movement of elements between stocks in the system. If the system were to be brought to a rest, stocks would continue to exist while flows would be unobservable. In mathematical terms, a stock is equal to the time-integral of its inflow minus the time-integral of its outflow.

Sterman (2000, pp. , 194) provides a helpful metaphor for understanding this basic stock and flow structure and its mathematical equivalents. Figure (8) illustrates his analogy, in which bathtubs represent stocks, pipes represent flows, and faucets (or drains) controlling the amount of water in the bathtub represent rates of inflow (or outflow). In this study, stocks will generally consist of biomedical researchers at different career stages, although they are also used to represent pools of financial resources and commitments.

Stock and flow structures are governed by Little's Law: the stock in transit is equal to the inflow rate multiplied by the average delay time ($L = \lambda W$), regardless of the probability distribution of the outflow (Sterman, 2000, p. 423). For example, if the enrollment rate in biomedical graduate programs (λ) is 20,000 students per year, and the average length of a doctoral program (W) is 6 years, there will be 20,000 * 6 = 120,000 students pursuing doctorate degrees (L) at any given time in steady state.

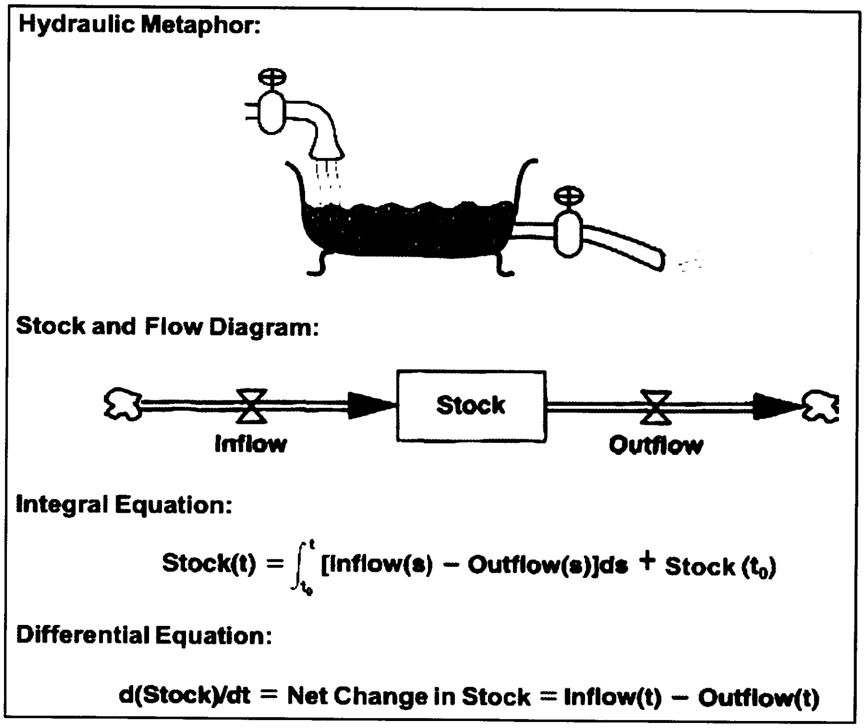

Figure 9. Sterman's Hydraulic Metaphor for System Dynamics' Stock and Flow Structure (Sterman, 2000, p. 194)

System dynamics models are framed graphically using stock and flow diagrams as shown in Figure (9), and produce visual output in the form of graphs showing the behavior of variables over time. These features aid intuition and make them appropriate for transmitting useful insights about complex, differential equation-based, models to policy-makers and audiences without strong mathematical backgrounds.

Lastly, the modeling effort proposed in this study is not intended to provide quantitative predictions of specific states of the real-world system in the future. Attempting to build a mathematical model with such forecasting capabilities is unrealistic for a system as complex as the one in question. Fortunately, the usefulness of a model does not depend on its ability to predict the future. Instead, the goal is to create a model that is able to represent the complex interdependencies in the real system. A model "...should show how changes in policies or structure will produce better or worse behavior. It should show the kinds of external disturbance to which the system is vulnerable. It is a guide to improving management effectiveness..." (Forrester, 1961, p. 56).

1.7 Data Sources

The data used to guide the development and calibration of the model are mainly sourced from the National Science Foundation's Survey of Earned Doctorates, Survey of Graduate Students and Postdoctorates in Science and Engineering, Survey of Doctorate Recipients, and the National Institutes of Health. Garrison and Ngo (2011; 2012), from the Federation of American Society for Experimental Biology (FASEB), have synthesized much of the relevant data contained in the aforementioned surveys in a series of consolidated reports.

2. Dynamic Complexities and Model Conceptualization

> "All systems, no matter how complex, consist of networks of positive and negative feedbacks, and all dynamics arise from the interaction of these loops with one another." (Sterman, 2000, p. 13)

2.1 Feedback Loops

The first step in this analysis is to identify endogenous feedback loops in the system that give rise to complex, and sometimes undesired, behavior. As such loops are identified, a causal diagram that describes the interaction between these feedback processes will be developed. Causal loop diagrams are a simplified version of the stock and flow diagram; they are "...an integral part of system dynamics modeling, helping to foster group knowledge and understanding and providing a concise view of an enormous amount of complexity and a starting point for simulation" (National Cancer Institute, 2007). The resulting diagram will serve as the precursor of the formal system dynamics model, while providing a visual description the overall structure of the system.

Figure (10) illustrates the starting point for the causal loop diagram: the intuitive process that an increase in budget aims to trigger. The polarity signs next to each arrowhead describe the relationship between the two variables connected by the arrow. Positive polarities describe relationships in which the two variables connected move in the same direction, while negative polarities describe movement in opposite directions.

Fostering research and boosting scientific discoveries are the main motivations for federal research spending. Government therefore responds to society's need for scientific progress by investing in research. Increasing NIH's budget allows the agency to fund a larger project pool, expanding the overall amount of research activity carried out by the workforce. Growing research activity enhances the achievement of successful scientific discoveries. The resulting increase in discoveries reduces the discrepancy between the level of discoveries targeted by policy-makers and the country's perceived scientific output. As this discrepancy falls, the desire to further increase NIH's budget decreases and the process eventually achieves a stable goal. Simple bivariate relationships, such as the ones described above, rest on a *ceteris paribus* assumption in which no other factors affect the goal-seeking processes they create. This is clearly not the case in the real-life system, underlining the need for a simulation technique that is able to calculate changes in variables throughout the entire model and dynamically reflect their effects on other variables. It is nonetheless helpful to understand how individual feedback loops would behave in isolation as a step towards conceptualizing the model.

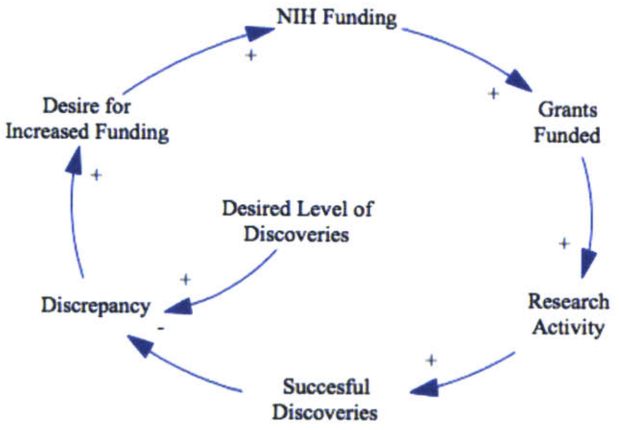

Figure 10. Basic Goal-Seeking Loop

Note that the desired level of discoveries is not an explicit quantifiable figure that policy-makers have agreed to through debate or analysis. Instead, it represents the levels of scientific progress that government aims to foster. For instance, suppose lawmakers feel that the country is progressively lagging behind other nations in terms of science. This would translate to a growing discrepancy between the actual and desired levels of discoveries, likely triggering increased spending. Additional variables need to be considered when modeling this variable, making it a dynamically evolving goal.

Changes in NIH funding trigger a crucial reinforcing feedback loop in which, as NIH funding increases (or decreases), the expectations for future funding will also increase (or decrease). This relationship became most evident during the doubling years: "The steep growth in spending [...] *built expectations* (emphasis added) and momentum that set the agency up for disappointment when the doubling was done" (Levin, 2007).

Expectations for increased funding lead to expansion, both of infrastructure and personnel. This effect was also observed during the aforementioned period: "Research institutions everywhere were breaking ground on new facilities and expanding their faculty [...] to fill the buildings, expecting to recoup their investments from the NIH grants investigators would haul in" (Couzin & Miller, 2007). Student bodies and research staff at institutions naturally grow as new facilities and faculty become available, enlarging the size of the overall academic biomedical workforce. A larger biomedical research workforce requires increased financial resources for the continued support of students, faculty, staff, and other fixed costs. The need for increased funding adds pressure to the NIH for further budget increases, therefore closing a process known as a reinforcing feedback loop. The addition of these reinforcing mechanisms is depicted in Figure (11).

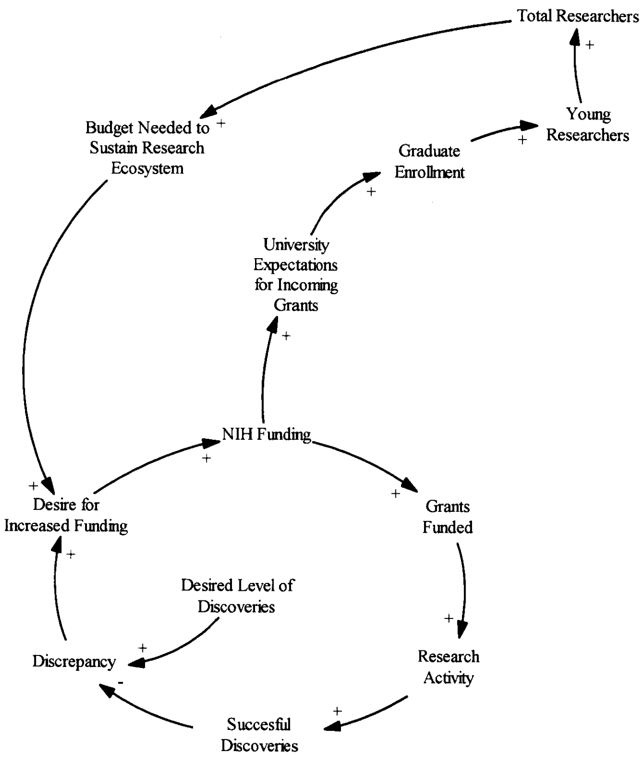

Figure 11. Addition of Reinforcing Feedback Loops Triggered by Growing Expectations

Graduate enrollment is not the sole determinant for the size of the biomedical workforce. By itself, the reinforcing feedback process described above would result in unfettered growth, or decline, in all of its constituent variables. Instead, this feedback process is countered by balancing mechanisms such as the initial goal-seeking loop illustrated in Figure (10) and the market forces of supply and demand.

Basic economic theory suggests that as the supply of researchers increases, their wages will eventually decrease, *ceteris paribus*. A drop in salaries for young researchers due to excess supply was documented after the doubling period: "*Oversupply of PhDs* [...] help established researchers in the short term due to *lower costs* [...]" (Monastersky, 2007). Lower salaries diminish the perceived attractiveness of a research career in academia, which drives researchers to other professional paths and eventually discourages prospective candidates from entering the field.

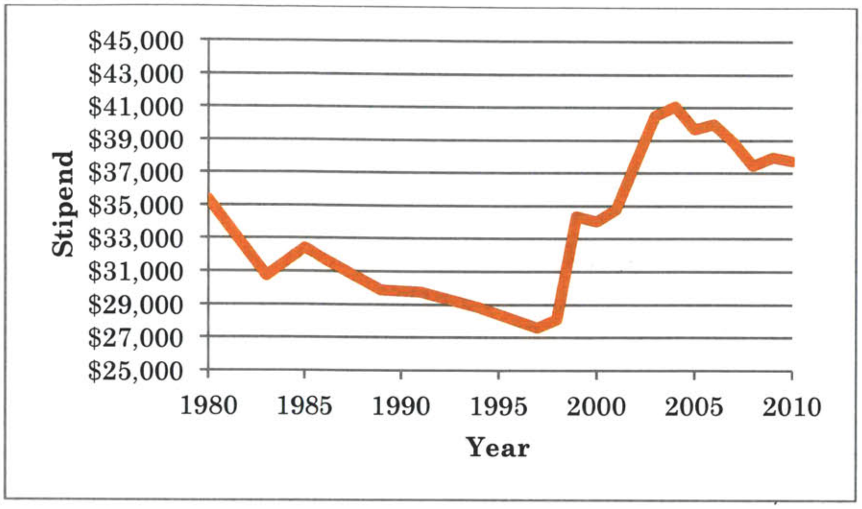

Figure 12. Stipend Levels, Kirschstein-NRSA Awards for New Postdoctoral Fellows (NIH OER, 2012)

Figure (12) shows the trend in NIH stipend levels for new postdoctoral fellows in constant 2010 dollars.[2] The steep increase in stipend levels seen during the budget doubling years can be attributed to the sudden rise in demand for researchers, while its subsequent drop could be a consequence of market forces accounting for the large number of researchers trained during the previous years. These changes could also be the result of efforts by policy-makers in the NIH to limit the number of postdoctorates supported through its grants, foreseeing the potential consequences of a future oversupply. In either case, such levels of volatility in salaries are arguably detrimental to the workforce.

A 1975 economic analysis by Richard Freeman, one of the foremost labor economists in the U.S., demonstrates how market forces affect the research workforce in the field of physics. Freeman concludes that changes in salaries for physicists can be attributed to R&D policies of the federal government, and that changes in the numbers of physics students result from economic responses to salary or job opportunity incentives (Freeman, 1975). In theory, this balancing feedback loop should therefore counter increases in the number of biomedical researchers. The biomedical workforce system, however, is not closed. "Given increased research funding, additional graduate students and postdocs can be readily recruited from large potential pools in countries with fewer such opportunities— precisely what

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[2] The NIH defines a stipend as a "payment made to an individual under a fellowship or training grant in accordance with pre-established levels to provide for the individual's living expenses during the period of training" (NIH RePORT 2012)

took place as the NIH budget was rapidly doubled" (Teitelbaum, 2008). The expected effect of market forces is therefore attenuated in this system given its open nature; a drop in salaries does not necessarily result in a reduced supply of researchers.

The process discussed above introduces an important concept when thinking about workforce development: the perceived attractiveness of a research career. Several variables have important effects on this perceived attractiveness. Figure (8) outlined the overall decline in the percentage of PhDs securing tenured or tenure-track positions. In 2007, the Chronicle of Higher Education reported: "The number of tenured and tenure-track scientists in biomedicine has not increased in the past two decades even as the number of doctorates granted has nearly doubled" (Monastersky, 2007). The new academic posts created due to the growth in NIH funding between 1998 and 2003 were "supported mainly by soft money and off the tenure track, dependent on grant renewals" (Benderly, 2007). The signals created by poor career prospects decrease the attractiveness of a research career, discouraging current young researchers. Again, given the readily available pool of potential graduate students, departing young researchers can be quickly replaced with new graduate students. Exit rates by young researchers are nonetheless a telling indicator of the overall health of the system. Figure (13) illustrates the processes described above.

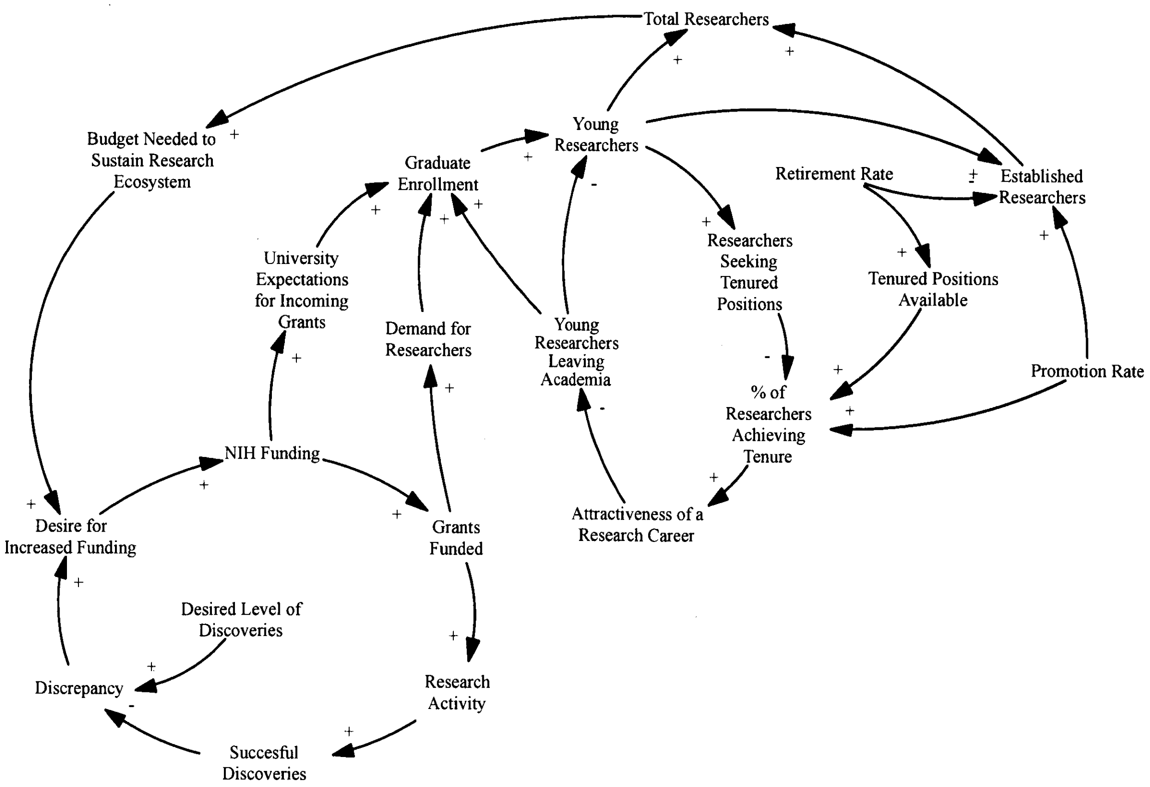

Figure 13. Lower Success in Landing Tenured Positions Discourages Current Young Researchers

Funding opportunities are another highly relevant determinant of the attractiveness of a research career. The period of budget doubling allowed for a significant increase in the number of grants made available by the NIH, which was met with an equally significant increase in the number of grant applications. This presents a situation analogous to adding lanes to a congested highway—traffic will almost always expand to fill the available space. These types of scenarios are known as instances of Parkinson's Law. In Parkinson's original formulation, "work expands to fill the time available for its completion" (Sterman, 2000, pp. 166, 184).

Once the budget doubling ended, the unrelenting growth in applications faced instead a stagnant, and even slightly declining, number of available grants. Drawing another parallel with the highway metaphor, it is as though the traffic attracted during the expansion phase kept growing even after the project was completed. And even worse, it is as if some of the additional lanes built were subsequently closed due to unavailable maintenance funds. This would make congestion even worse than it was before the expansion project.

Science magazine reported that increased funding helped drive more applicants to the NIH, and the chances of being funded by the agency on a first attempt plummeted from 21% in 1998 to 8% in 2006 (Couzin & Miller, 2007). A growing biomedical research workforce increases the number of applicants for NIH grants, which results in a larger applicant pool. This drives success rates down, which in turn decrease the perceived attractiveness of a research career. In 2007, Edward Miller, dean of Johns Hopkins Medicine, told a Capitol Hill news conference: "We are seeing young researchers quitting academic research in frustration, having concluded that their chances of having innovative research funded by NIH are slim to none" (Agres, 2007). The addition of these effects to the causal loop is illustrated in Figure (14).

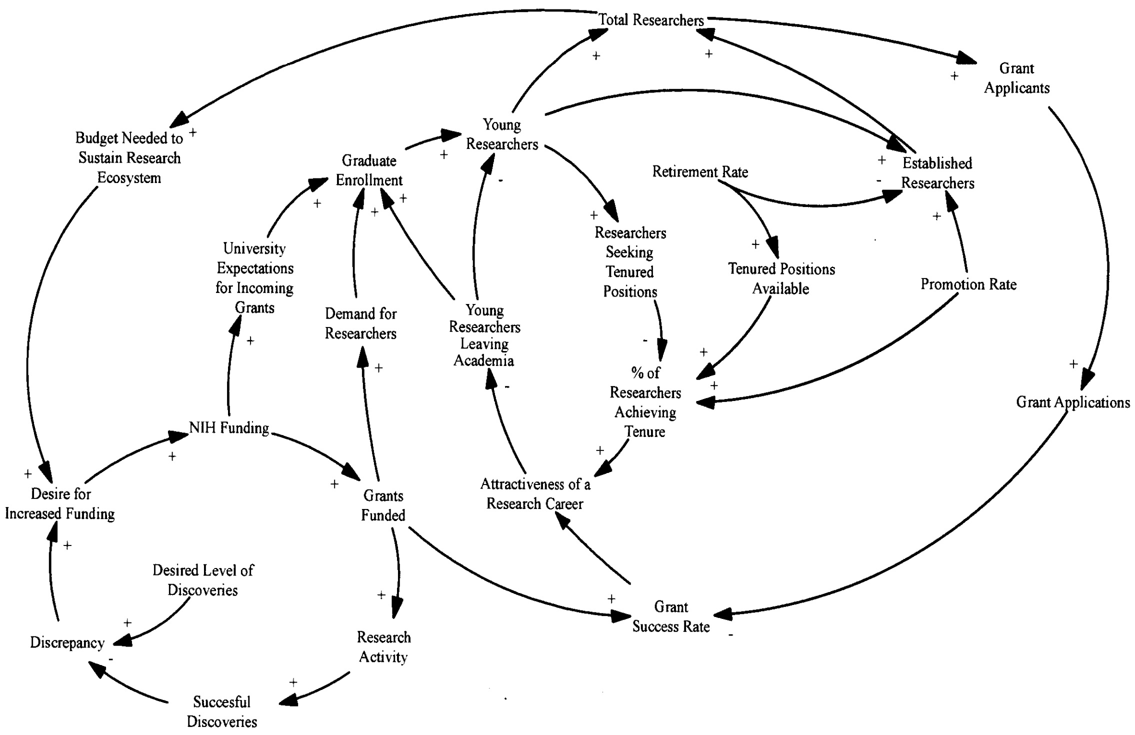

Figure 14. Impact of Lower Grant Success Rates

Being able to secure NIH grants is an essential professional step for young biomedical researchers seeking tenured positions at U.S. colleges and universities. It is common for young faculty members to win two to three R01 awards to support a lab before they can gain tenure (Monastersky, 2007). As success rates drop, the amount of time taken for researchers to secure sufficient grants rises, lengthening the average training period typically at the increasingly common postdoctoral stage. Longer postdoctoral appointments further impact the attractiveness of a research career: “Graduate students see long periods of training, [...] they get a sense that this is a really frustrating career path..." (Monastersky, 2007). Once again, the declining attractiveness of a research fuels the number of researchers leaving academia. Figure (15) illustrates this effect.

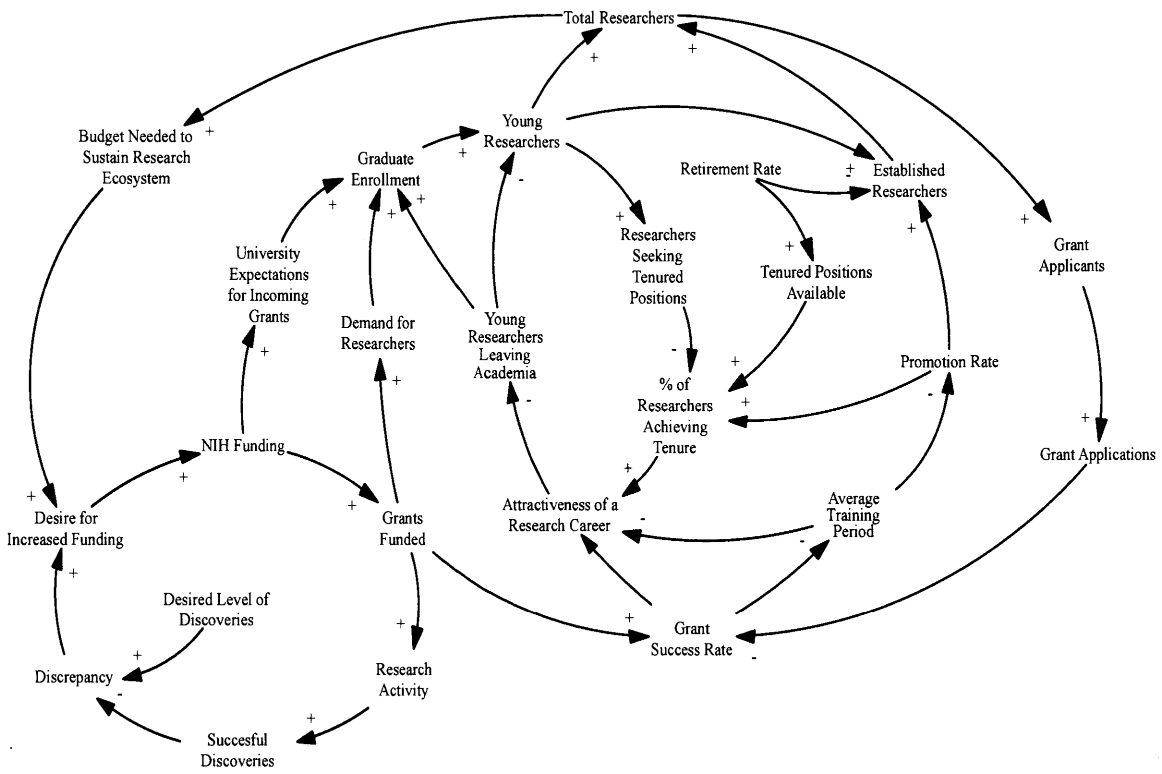

Figure 15. Impact of Longer Training Periods

There exists another important loop, in this case reinforcing, arising from the effects of a larger applicant pool. During the budget doubling, the number of applications grew at an even faster clip than the number of potential applicants, as scientists, concerned about their chances of getting funded, began submitting proposals more frequently (Couzin & Miller, 2007). This behavior underscores a natural response of individuals to decreasing success rates. As the percentage of researchers funded drops, the perceived competition for funding increases. Higher competition drives applicants to submit even more applications in order to enhance their chances of receiving a grant. As the numbers of grant applications per applicant increase, the total applications submitted will also increase and further drive success rates lower. This creates a dangerous reinforcing feedback loop in the system that is illustrated in Figure (16).

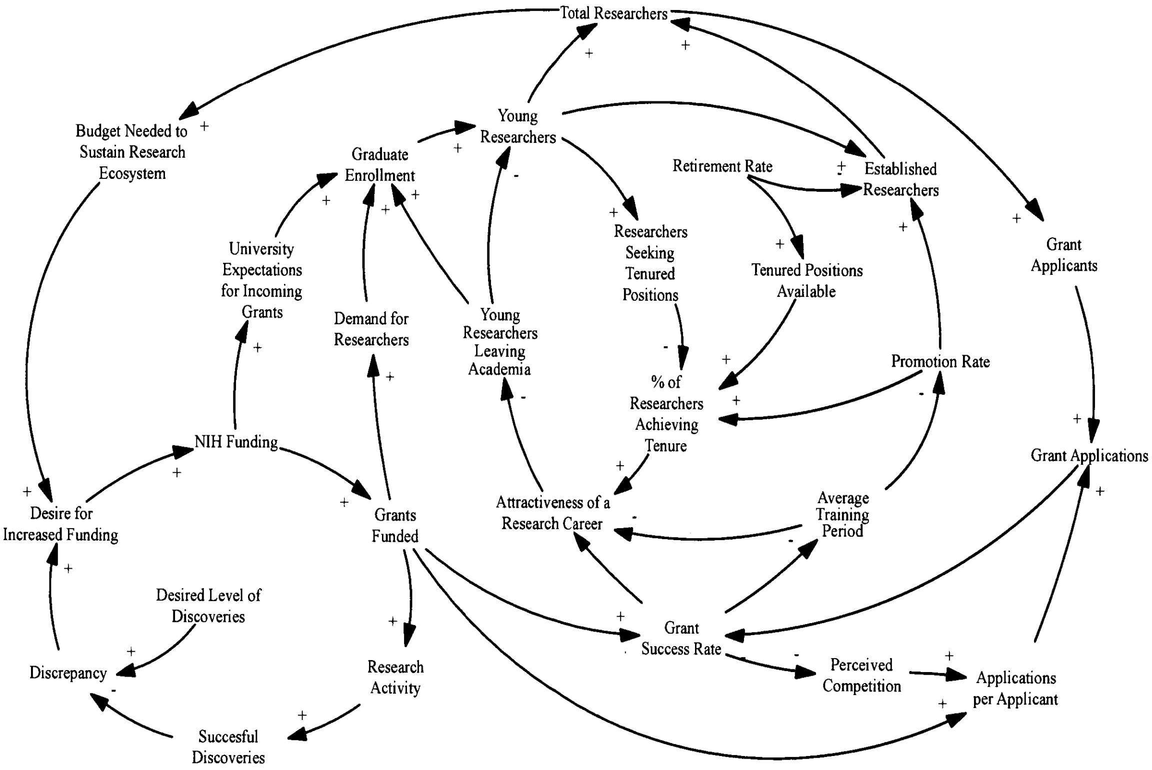

Figure 16. More Applications per Applicant Drive Success Rates Lower

A higher rate of applications per applicant, which can also be fueled by funding expectations, has broader implications other than lower grant success rates. Given that competition increases with a larger application pool, the quality of the grant applications needs to be kept intact, if not increasingly higher. More applications per applicant, of constant—or increasing—quality, unequivocally result in more time spent by researchers writing grant applications. In 2007, "Robert Siliciano, an infectious disease expert at Johns Hopkins University School of Medicine, told the Senate panel the reduction in NIH grants has forced him to scale back on promising research into optimizing antiretroviral therapies. 'Typically, in the past, I would spend about 30 percent of my time applying for grants; now about 60 percent of my time is spent preparing applications,' he said" (Agres, 2007).

The need for submitting more applications affects not only the amount of time available for scientists to perform research, but their attitudes towards research itself. Also in 2007, Stephen M. Strittmatter, a professor of neurology and neurobiology at Yale University's School of Medicine, told legislators that due to increased competition, "researchers shy away from real discoveries. They've become worriers, not explorers" (Agres, 2007). It is straightforward to infer that the consequences of spending more time writing grant applications negatively impact the rate of successful discoveries made by the biomedical academic workforce. This, by itself, is clearly an undesirable outcome. Figure (17) illustrates the addition of this balancing feedback loop to the causal diagram.

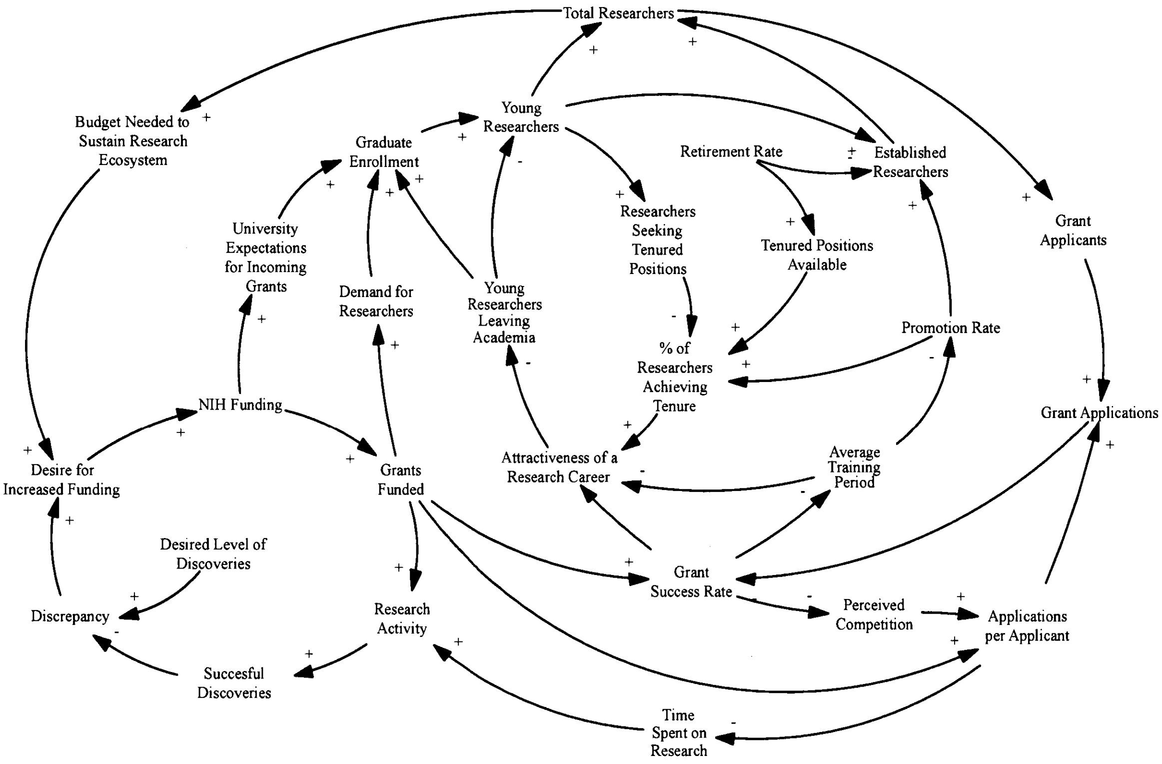

Figure 17. Lower Available Time for Research Decreases Research Activity

A large and rapid inflow of federal dollars to the agency creates parallel expectations in policy-makers of large and rapid biomedical discoveries. “Currently, it often takes decades for an important discovery in the laboratory to actually benefit people” (University of California - Davis Health System, 2011). Expectations of significant results in a short timeframe are not only unrealistic; they set the stage for even greater disappointments given the process described above, in which large and rapid inflows can eventually result in *lower* discovery rates. Government expectations for important and visible results became evident in the post-doubling period: "People are in a sort of 'show-me' mode up here," says Daniel R. Pearson, an aide to Democratic members of the House Science Committee. "They're thinking, 'we gave you all this money. What are we getting for it?'" (Brainard, 2004).

Political pressure to support increases in NIH’s budget build as the desired level of discoveries exceeds the attained level of discoveries with available resources. As the workforce is unable to find adequate support for its continued research activities, lobbying efforts intensify. With enough political pressure, the desire to increase funding finally moves to bridge this gap. As a result, political pressure builds up during periods of stagnant funding, and depletes after significant steps to increase the budget. Once the doubling came to an end in 2003, political support for further increases in NIH's budget had been depleted after 5 consecutive years of unprecedented budget growth. Enough political pressure would need to build up before further increases are approved. This balancing mechanism is added to the causal loop in Figure (18).

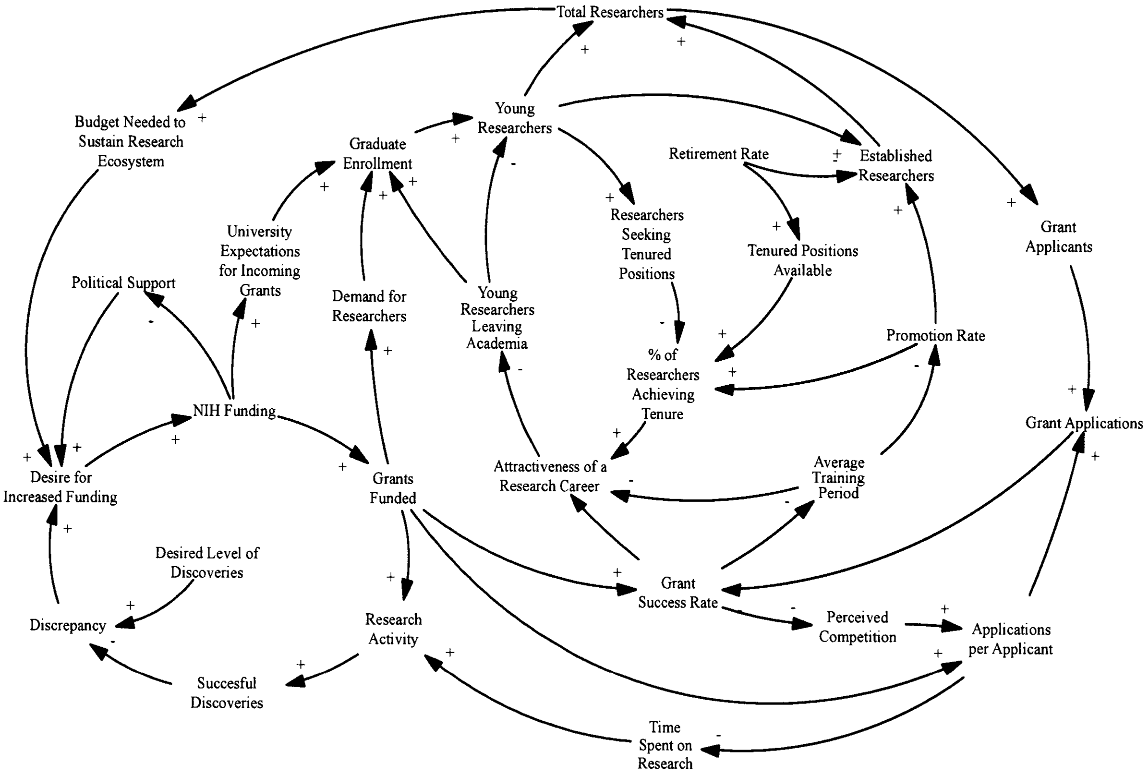

Figure 18. Political Support Depletes After 5 Years of Funding Increases

A salient aspect of the initial years of budget doubling was the shift in allocation of grants between young and established researchers: "The increase in the total number of R01 grants [...] went disproportionately to established researchers" (Brainard, 2004). "In 1995, 25 percent of the R01 and similar grants went to scientists age 40 and younger. By 2005, the fraction going to that group dropped to 15 percent, while researchers older than 51 were gobbling up almost half of the big grants" (Monastersky, 2007). As the competition for research grants increased, the criteria for awarding grants became increasingly stringent. Experienced researchers were therefore increasingly likely to submit proposals that met these criteria, and absorbed a larger percentage of the grant pool. This creates a potential reinforcing feedback loop in which as the percentage of grants given to young researchers decreases, their professional development is severely impacted and their future chances are further diminished. Figure (19) shows the addition of this loop to the causal diagram.

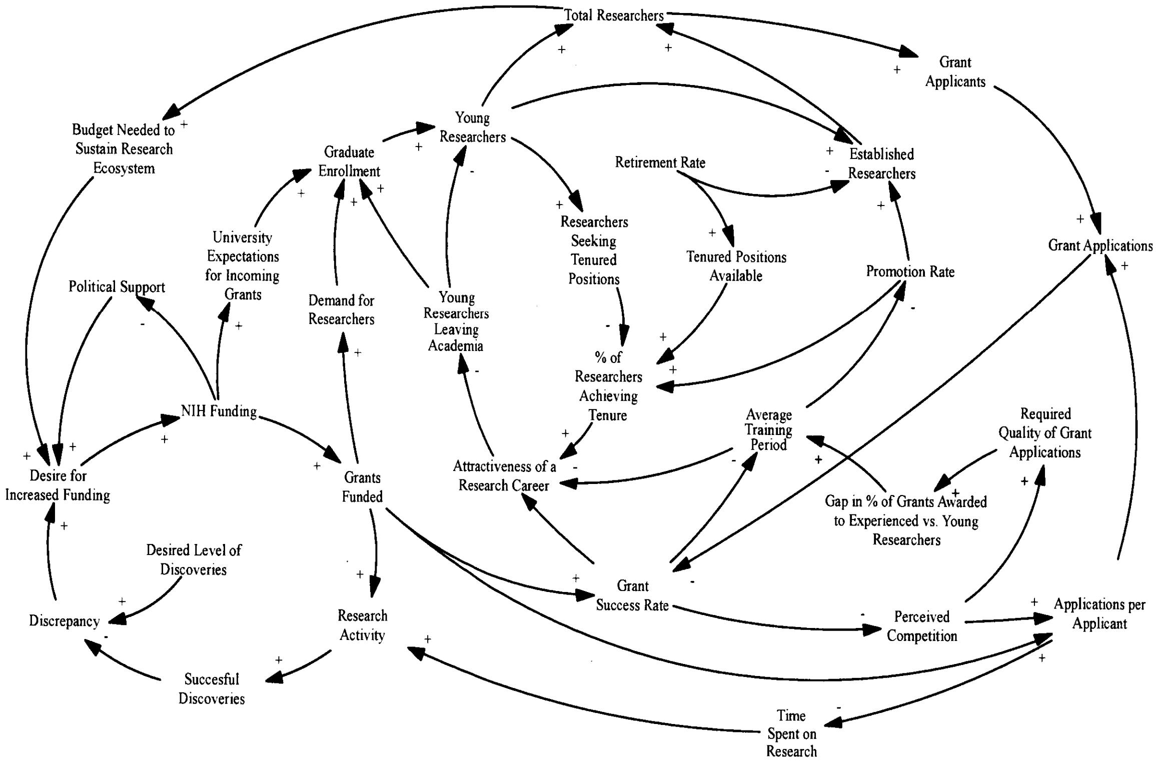

Figure 19. Impacts of Lower Success Rate for Young Researchers

Given the damaging effect that the previous reinforcing loop can have on the future biomedical workforce, NIH countered its effects through explicit policies that seek to close the funding gap between experienced and young researchers. These policies, such as the New Investigators Program (Ruiz Bravo, 2007), act as a countering goal-seeking loop that comes into play when the professional advancement of young researchers is threatened. Figure (20) shows the widening and subsequent narrowing gap between success rates for first-time and established researchers during and after the doubling years. Figure (21) adds this policy response to the final version of the causal diagram that is used for developing the system dynamics model.

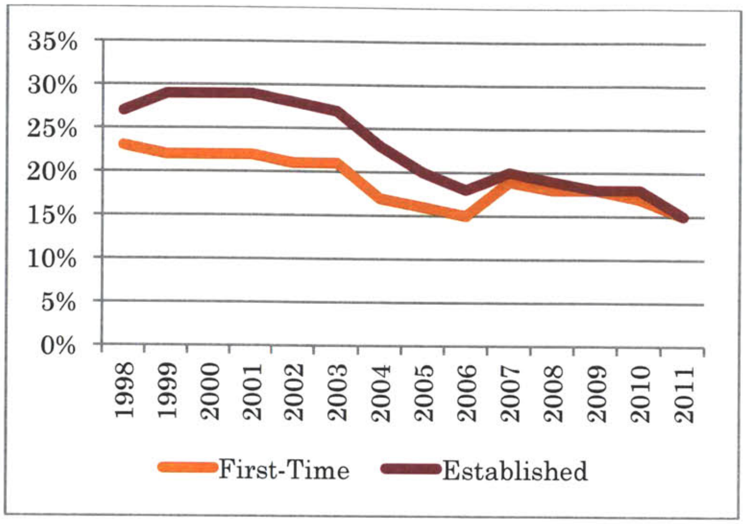

Figure 20: Grant Success Rates for Researchers by Career Stage (NIH, 2011)

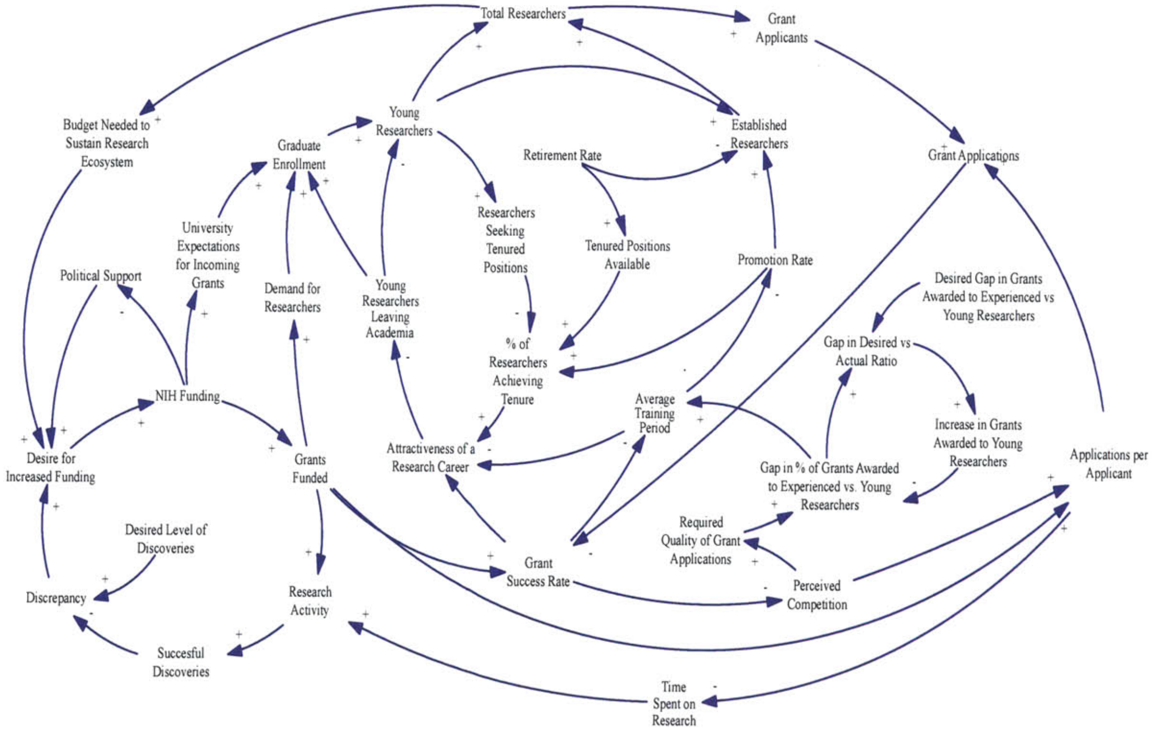

Figure 21. Response to Widening Gap Between Young and Established Researchers

2.2 Stocks and Delays

Delays have a defining influence in the system described above. "Delays are a critical source of dynamics in nearly all systems" (Sterman, 2000). Given that this study deals with a system that involves the professional development of individuals, the time it takes for variables to have an effect on each other is certainly non-trivial. For example, the time elapsed between enrollment in a doctorate program and graduation is close to 6 years. Similarly, it takes time for common perceptions on career paths to evolve, and for researchers to adapt to changes in the system. As a result, the time it takes for the effects of balancing or reinforcing loops to manifest themselves is substantial, and such delays often lead to undesired oscillatory behavior in the system.

When output lags behind a given input, an accumulation takes place between the two flows, which makes stocks an integral component of delays. The central stock and flow structure in the workforce system is the progression of researchers from the moment they enroll in biomedical graduate programs until they retire from academia. For the purposes of this analysis, two main stocks will be considered: young researchers and established researchers. This is a simplification of the actual pipeline, in which researchers go through several more stages: PhD candidates, postdoctoral scholars, assistant professors, associate professors, tenured professors, etc. The dynamic complexities caused by the delays involved in career progression, and their impact on the overall system, are nonetheless captured by reducing these stages to the two stocks mentioned above. This approach follows Einstein's oft-cited philosophy of making things as simple as possible, but not too simple; the model should be complex enough to capture the overall behavior of the real system.

The stock of young researchers includes those professionals who are yet to receive enough grants to support a lab or achieve tenure. While it is rare for established researchers to leave academia, young researchers dropping out of academia is a critical outflow and is therefore included in the model. Figure (22) illustrates the stock and flow structure of the workforce pipeline used in this analysis. The cloud-like shapes in this figure represent stocks that are beyond the model's boundaries. For example, this analysis is not concerned with researchers who leave academia in their early careers; the underlining assumption is that it is uncommon for them to return to the relevant pipeline. Despite the undeniable importance of the stages preceding enrollment in biomedical doctorate programs, this analysis assumes unconstrained availability of applicants. For a study that uses system dynamics to model the relevant pipeline preceding graduate school and discusses the challenges that this system is currently facing please refer to Sturtevant (2008).

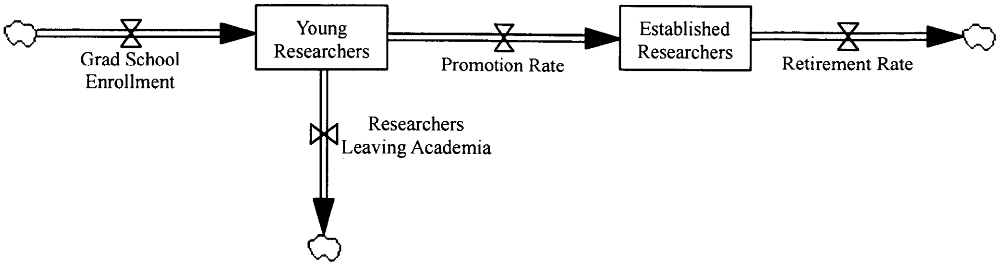

Figure 22. Simplified Workforce Pipeline Model

The main workforce pipeline depicted in Figure (22) is embedded in the causal loop diagram developed in section 2.1. Critical variables—such as funding levels and success rates—affect, and are affected by, this pipeline's stocks and flows.

The stock and flow structure is also used to model the financial commitments that a new grant entails. In this case we have one stock, NIH commitments, that has one inflow—new commitments—and one outflow—fulfilled commitments. Figure (23) illustrates this structure. When a researcher is awarded an R01 or equivalent grant, he or she will not receive the entire grant's worth on the first year. Since these grants typically span periods of four years, projects will receive approximately one-fourth of the entire grant each year. The amount of financial resources available for new grants therefore depends both on that year's budget and on previous financial commitments. This is important because the commitments made by NIH during years of unusual budget growth can extend to subsequent periods of financial stagnation. When this happens, the availability of funds for new grant awards is severely diminished so that previous commitments can be met.

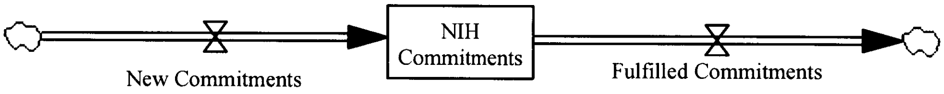

Figure 23. Stock and Flow Structure Used to Model Financial Commitments

To illustrate this point numerically consider the following simplified scenario, which is summarized in Table (1). Suppose that in 2012 the NIH has $10B available to fund both new and existing grants. Total grant funding in all years preceding 2012 has remained constant, and the duration of grants is fixed at 4 years. The agency would then need to disburse \$2.5B for grants awarded in each of the previous 3 years, totaling \$7.5B, and leaving \$2.5B available to sponsor new grants. Assume further that NIH grant funding undergoes a 15% increase in 2013, growing to \$11.5B. Follow-on obligations for the previous 3 years still amount to \$7.5B, leaving \$4.0B to fund new grants—a staggering 60% increase compared to 2012. In 2014 the NIH again receives a 15% increase in available grant funds. In this case, follow-on obligations for the previous 3 years would now total \$2.5B + 2.5B + \$4.0B = \$9.0B, leaving \$4.2B to fund new grants. In 2015 the 15% increase is maintained, yielding the cash flows illustrated in Table (1). In 2016, however, grant funding remains stagnant. NIH spending on new grants would then drop by 44% from \$4.5B in 2015 to \$2.5B in 2016, severely impacting success rates and the stability of the system.

Year	Grant Funds	Follow-on Obligations	Funding for New Grants
2012	\$10.0 B	\$7.5 B	\$2.5 B
2013	\$11.5 B	\$7.5 B	\$4.0 B
2014	\$13.2 B	\$9.0 B	\$4.2 B
2015	\$15.2 B	\$10.7 B	\$4.5 B
2016	\$15.2 B	\$12.7 B	\$2.5 B

Table 1. Impact of Stagnant Funding on New Grants

Stocks of researchers at different career stages and financial commitments in dollar amounts are easy to conceptualize given the tangible nature of their units. Other more abstract concepts, however, also need to be modeled if they are deemed to play a critical role in the real system. Political pressure, as described in section 2.1, is one such concept. Figure (24) illustrates the stock and flow structure used to model political pressure. Even though the feasibility of quantifying historical levels of buildup and depletion of political pressure is debatable, the intuition behind this structure is straightforward. Stagnant budgets increase the inflow of pressure into the stock, resulting in its accumulation, while pressure is released after increases in budget. The rates of pressure inflow or outflow depend on the magnitude and duration of funding stagnation or increase. While the units in which political pressure is measured will not have any tangible meaning, the behavior of this structure is of critical importance to the system.

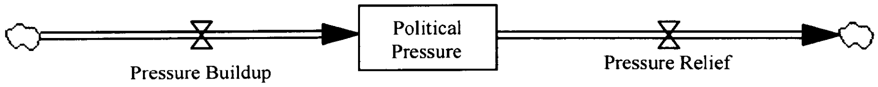

Figure 24. Stock and Flow Structure Used to Model Political Pressure

The system described in this section, in which pervasive feedbacks and delays give rise to high levels of complexity, likely typifies the kind of problem that Nobel Laureate Herbert Simon had in mind when setting forth concept of bounded rationality:

> "The capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problem whose solution is required for objectively rational behavior in the real world or even for a reasonable approximation to such objective rationality." (Simon, 1957, p. 198)

In order to understand and avoid troublesome side effects, leverage its feedback mechanisms, and make a positive impact in this complex workforce system, it is essential to make use of computer modeling and simulation methodologies. The notion of designed experimenting in the real-life system is clearly impractical and unfeasible, while computer-aided simulation renders experimentation possible (Sterman, 2000). "By using a model of a complex system, more can be learned about internal interactions than would ever be possible through manipulation of the real system; [...] mathematical models make controlled experiments possible and allow us to see the effect of the separate parts of the system." (Forrester, 1961, pp. 55, 130). Figure (25) shows the resulting system dynamics model implemented to simulate the causal diagram, stocks, and flows discussed in this section.

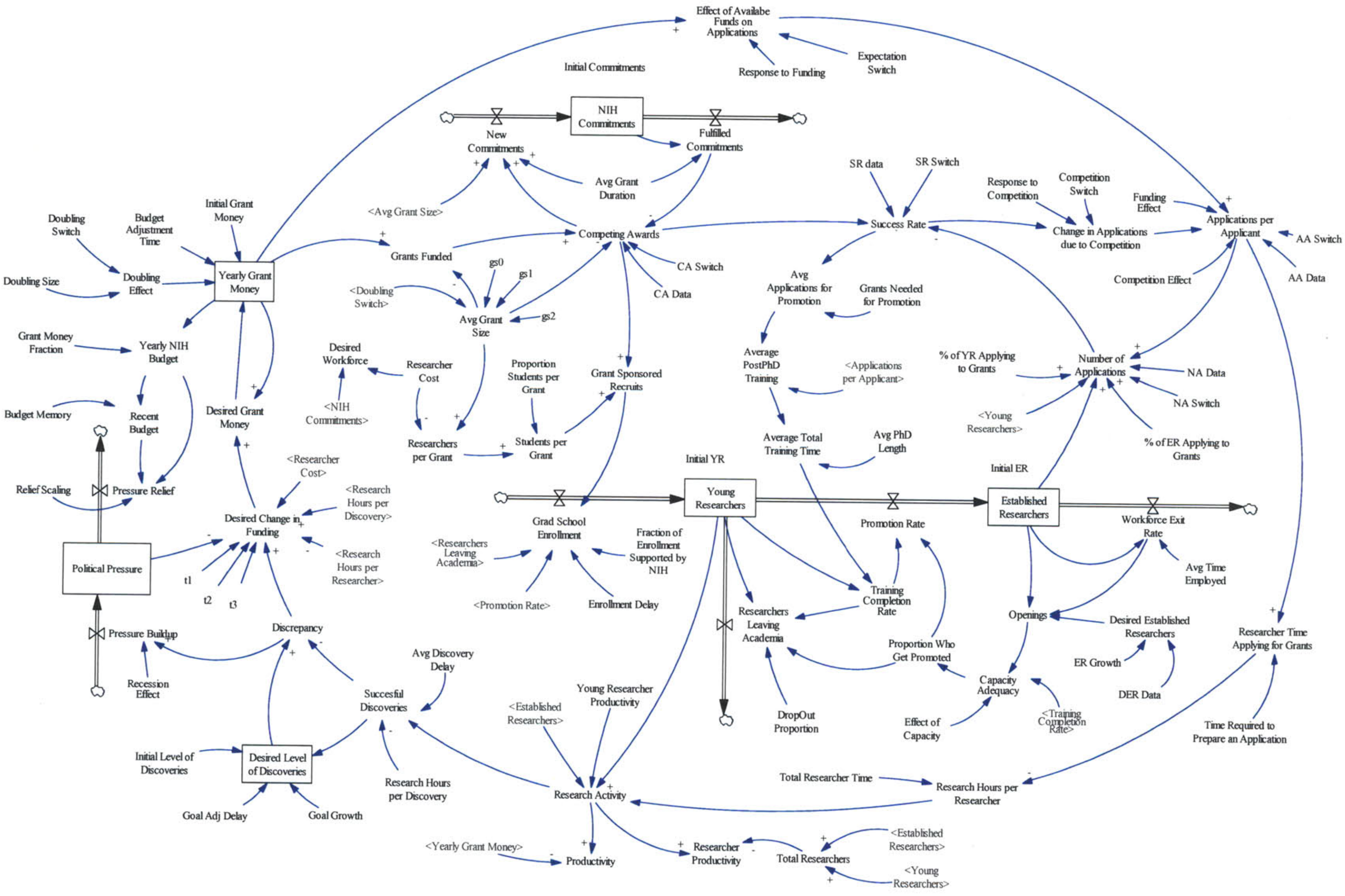

Figure 25. System Dynamics Model Implementation

3. Simulation Results

3.1 Model Validation

In order to validate the behavior of the model, its output is compared to U.S. historical data between 1970 and 2012. Figure (26) shows how NIH's budget in the simulation closely follows the trend in the average historical rate between 1970 and 1998. The decision to double NIH's budget in 5 years is considered exogenous to the model and therefore the yearly increases during that period are added exogenously. The decline in NIH budget after 2003, however, is the model's endogenous response to such an unprecedented period of growth. This decline is largely a result of the depletion of political support during the doubling years, leaving little political will to push for subsequent increases. The budget starts to recover a few years later, after enough political support accumulates once again, but experiences renewed stagnation given the economic woes suffered after 2008. The overall health of the economy is not endogenous to the model and therefore its decline is also an exogenous input.

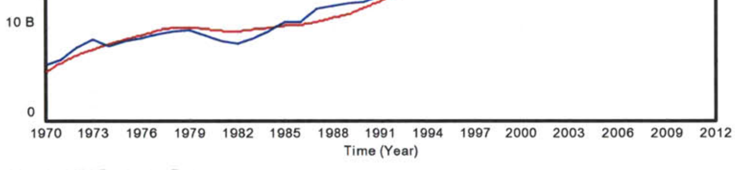

Figure 26. NIH's Yearly Budget,
Actual and Simulated

In terms of the number of grant applications received by NIH during this period, Figure (27) shows that the simulation replicates the growth experienced shortly after 1998. The simulation does not exactly follow the same growth pattern, in which there was an initial moderate increase followed by a steeper rise. Furthermore, the data also shows a brief drop in the number of applications in 2007 that the model does not replicate. This could have been caused by factors not considered in the model, which is expected given the unfeasibility of accounting for all variables that affect the real system. Nonetheless, the model shows how the number of applications decelerates after the doubling is completed but continues to grow, outpacing the stagnating budget after 2003. The data suggests a similar behavior after the brief decline in 2007. The available data for applications per applicant and success rates give further context to the troubling situation that the workforce experienced during the post-doubling years.

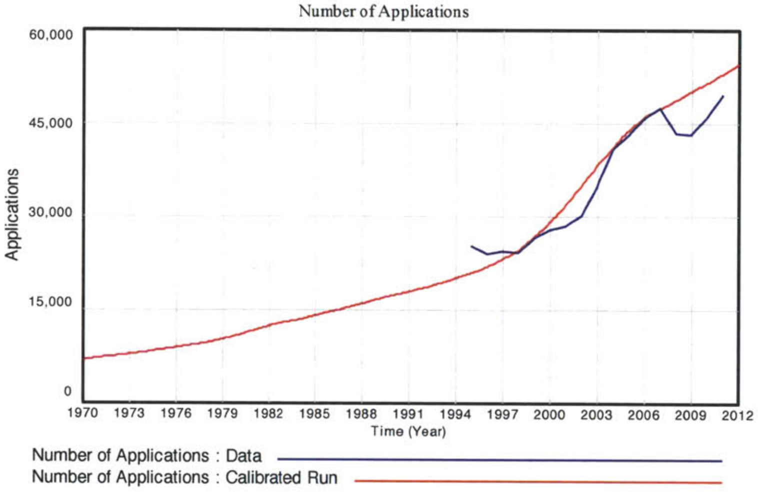

Figure 27. Number of Grant Applications Received by the NIH Each Year, Actual and Simulated

Section 2.1 described how an increase in grant applications is not only the result of a growing research workforce, but also the consequence of a considerable rise in the average number of applications submitted by each grant applicant. Figure (28) shows how the simulation output compares to the available, albeit sparse, data. In the simulation, a jump in this number coincides with the beginning of the budget doubling period; the corresponding jump in the data happens slightly later. Again, the number of applications per applicant undergoes an initial moderate increase followed by steeper growth that is not replicated by the model. The overall behavior, however, is captured in the simulation.

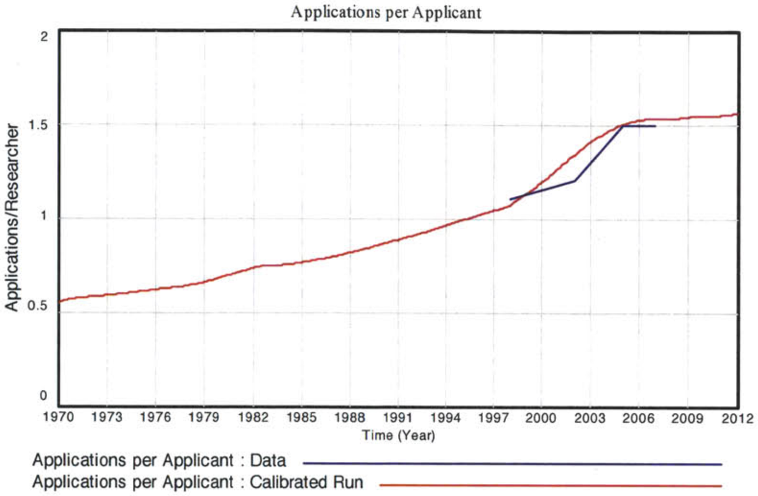

Figure 28. Average Number of Applications Submitted per Applicant, Actual and Simulated Data

As for the number of competing awards available, Figure (29) shows how the simulation replicates the growing trend in the historical data followed by stagnation. Even though the short-term oscillations in the historical data are not entirely captured by the simulation, the overall match is satisfactory. It is worth noting that the NIH raised the average grant size during the doubling years to avoid creating an unsustainable number of awards (Kaiser, 2005). This is considered in the model and helps explain why the increase in competing awards is not as steep as the increases in budget. It also reveals NIH's awareness of some of the potential destabilizing effects associated with changes in funding, supporting the hypothesis presented in section 2.1 regarding the jump in postdoctoral salaries. The magnitude of these destabilizing effects, however, proved to be much larger than expected in light the outcomes discussed throughout this study.

The stagnation in budget and competing grants, coupled with a continuously growing number of applications, foreshadows the behavior of the success rate curve. Figure (30) shows how the simulation captures oscillation in success rates, a small short-lived increase during the doubling years, and a dramatic drop that matches the historical data. Even though the simulation does not exactly replicate the timing and steepness of actual changes in success rates, it does reflect the overall oscillating and declining behavior.

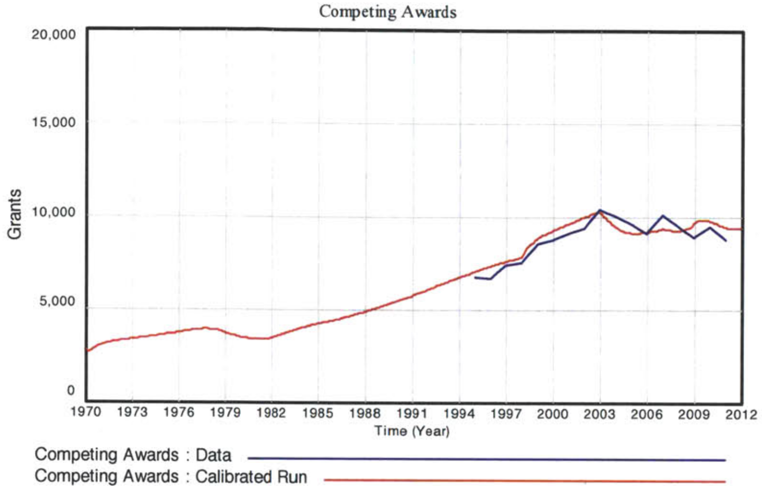

Figure 29. Number of Competing Awards, Actual and Simulated

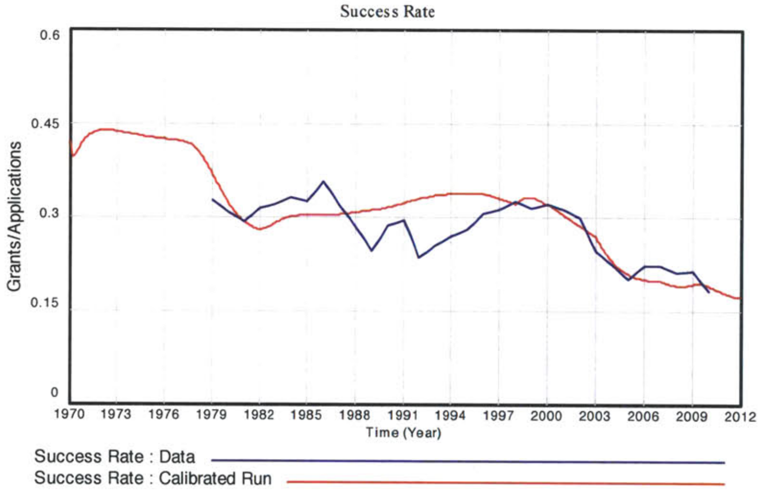

Figure 30. Grant Awards Success Rate, Actual and Simulated Data

3.2 Policy Experiments

The development of mathematical models such as the one presented in this paper is, on its own merit, a process that greatly improves the understanding of the underlining system. A major benefit of the modeling effort, however, is the possibility of simulating a series of policy scenarios and examining the model's overall response to such changes. This section therefore explores a series of counterfactual scenarios that answer "what if" questions regarding the absence or implementation of different policies, particularly related to funding. Since the model consists of a large number of parameters that can be modified, this analysis is limited to changes in variables concerning policies that decision-makers within government, and within the NIH, can implement.

3.2.1 Absence of a 5-Year Doubling Policy

Given that this paper focuses largely on the effects of doubling NIH's budget and its aftermath, the first scenario explored is one in which this steep increase doesn't take place. To operationalize such scenario, experiment #1 consists of turning off the exogenous input used to replicate the unprecedented inflow of funds between 1998 and 2003. The resulting budget outcome is shown in Figure (31). This experiment shows that without the doubling, funding levels would have surpassed those in the calibrated run shortly after 2009. In current dollars, this translates to an annual growth rate of approximately 8%. FASEB officials reached a similar conclusion in 2006, when they calculated that NIH's budget would "soon stand at the same point it would have reached if it had simply continued its historic rate of growth" (Mervis, 2006). The simulation also shows how the exogenous impact of an economic downturn would have been comparably smaller given that political support would not have been depleted after 2003.

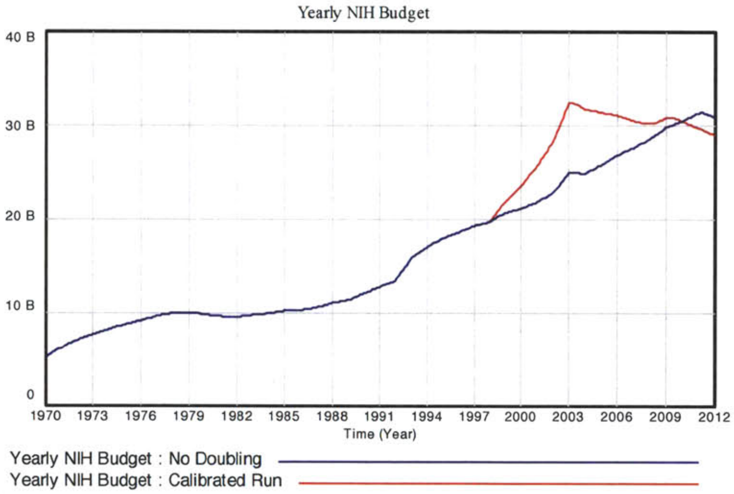

Figure 31. Experiment #1: NIH Budget

To understand the wider effects of not doubling the budget, a series of outcomes related to grants are first examined in Figure (32), focusing on the 1997-2012 period. The number of competing grants in this counterfactual experiment is initially lower but steadily grows beyond the number in the calibrated run. The exogenous economic shock causes a delayed but steeper drop in competing grants given that the average grant size is held constant in the experiment. As for the number of applications per applicant, the experiment shows a much smoother increase. Although an increase in this variable is still troubling, it is certainly preferable to have its growth be more moderate. This results in a decreased number of total grant applications, which also grows at a lower rate. Finally, success rates remain considerably higher throughout most of the examined period. The sudden drop near the end is a response to the drop in competing awards, which can be ameliorated by modifying the average grant size as was done by the NIH during the doubling.

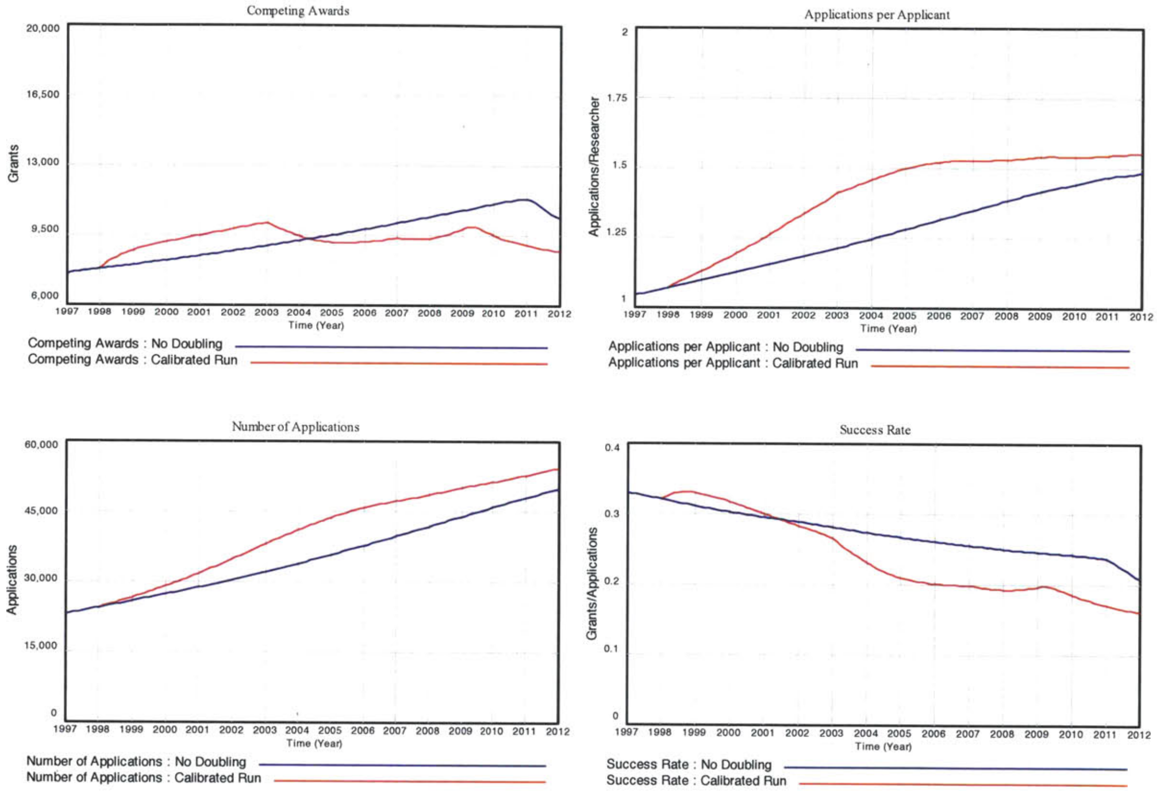

Figure 32. Experiment #1: Competing Awards, Applications per Applicant, Number of Applications, and Success Rate

Outcomes related to research output and productivity are examined in Figure (33). Despite the consistently lower budget in the experiment, it shows a relatively unchanged level of research activity, measured in total hours per year, compared to the base case. The total number of researchers and the time spent by them writing grants are factors that influence this aggregate research activity. In the counterfactual run, researchers spend less time writing grant applications, which explains why even though funding is lower and the number of researchers is smaller, research activity remains relatively unchanged. These outcomes also help explain why productivity, measured as research activity per dollar spent, remains significantly higher throughout most of the examined period. The jump in productivity in the calibrated run shortly before 2010 is caused by the drop in funding due to the exogenous economic shock. This shock affects the experimental run with a delay, which is why productivity starts to rise almost 2 years later in this case.

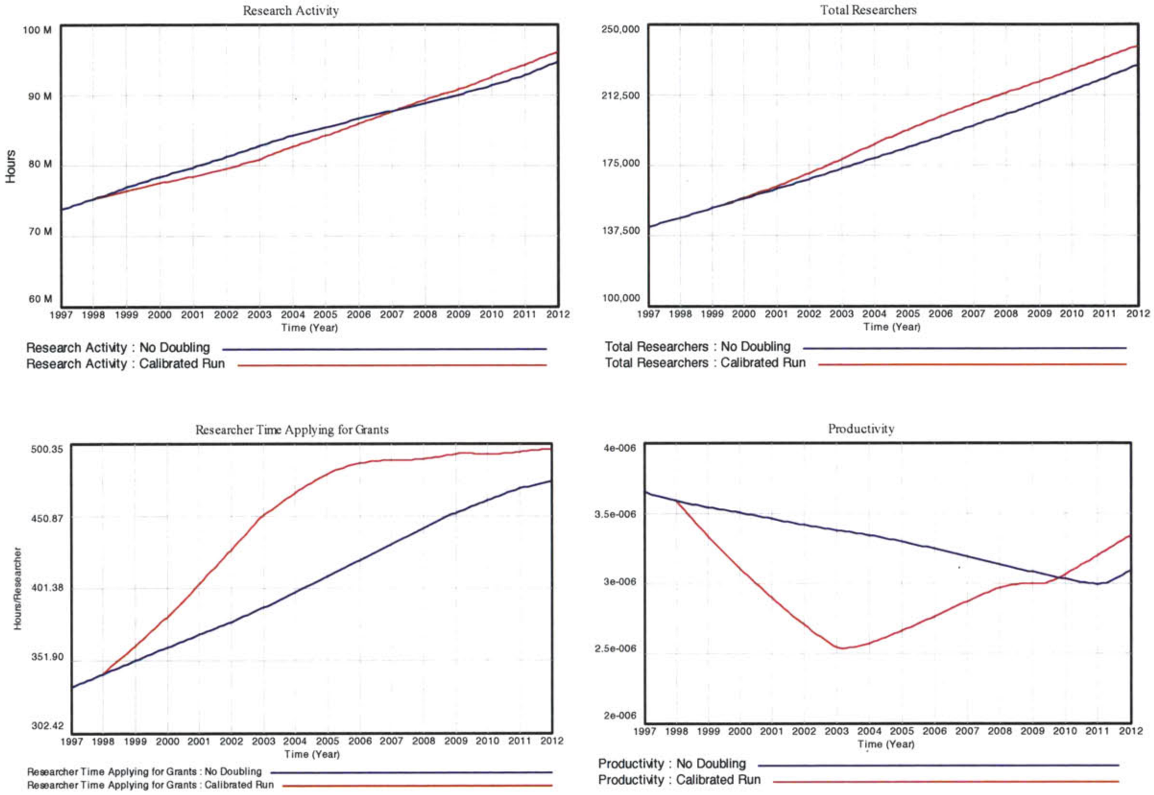

Figure 33. Experiment #1: Research Activity, Total Researchers, Researcher Time Applying for Grants, Productivity

3.2.2. Additional Funding Policy Experiments

The U.S. Congress holds the final decision regarding yearly NIH appropriations, which renders the scenario tested in 3.2.1 one that the NIH can influence indirectly through budget requests but not determine directly. A series of additional experimental policies are therefore proposed, including one that the NIH has greater control over. The outcomes of these experimental policies are then presented side-by-side with the calibrated run and the historical data for ease of comparison.

The second experiment tackles the issue of training more scientists than the workforce can support in the long term. Doing so leads to an imbalance between supply and demand of professional academic researchers, among other negative consequences (Ripple Effects Communications Inc., 2012). An increased number of graduate students were supported with the large influx of funds that the NIH started to receive in 1998. As argued earlier, this new wave of students will eventually become grant and job applicants, impacting competition and success rates.

Experiment #2 therefore tests a policy in which a cap is imposed on the number of graduate students that can be supported through NIH grants. This policy is designed to accompany large budget increases such as the one experienced between 1998 and 2003, and is relaxed during periods of budget stagnation. To operationalize this experiment, the average fraction of students supported by a typical NIH grant is reduced by 50% between 1998 and 2003.

The third experiment addresses the problem that arises when the number of new grants awarded by the NIH each year undergoes volatility. Increases in the number of grants awarded during periods of financial prosperity represent commitments that can spill over to periods of stagnation. This reduces the availability of new grants, inducing volatility and destabilizing the system. As mentioned above, the NIH attempted to ameliorate this issue during the doubling years by increasing the average grant size. An alternative approach is tested in this experiment.

In order to dampen the undesired effects arising from variance in the number of grants awarded by the NIH, experiment #3 tests a policy that fosters smooth and sustained growth in their number each year. Under this policy, financial resources exceeding the level required to support this sustained growth are not spent on additional grants. Instead, such additional funds are used to create a financial buffer aimed at maintaining grant stability during periods of budget cuts. This policy is implemented by creating a new stock of financial resources, thereby modifying the structure of the system. Inflows to this stock occur when the available funds exceed what is needed to maintain a given level of yearly growth, while outflows take place when additional funds are needed to maintain this level.

The outcomes to experiments #1, #2, and #3 are plotted together in Figure (34) along with the calibrated run. Bear in mind that the only changes in each of these experimental runs are the ones discussed in the paragraphs above, i.e. in #2 and #3 the exogenous efforts to double the budget between 1998 and 2003 still take place.

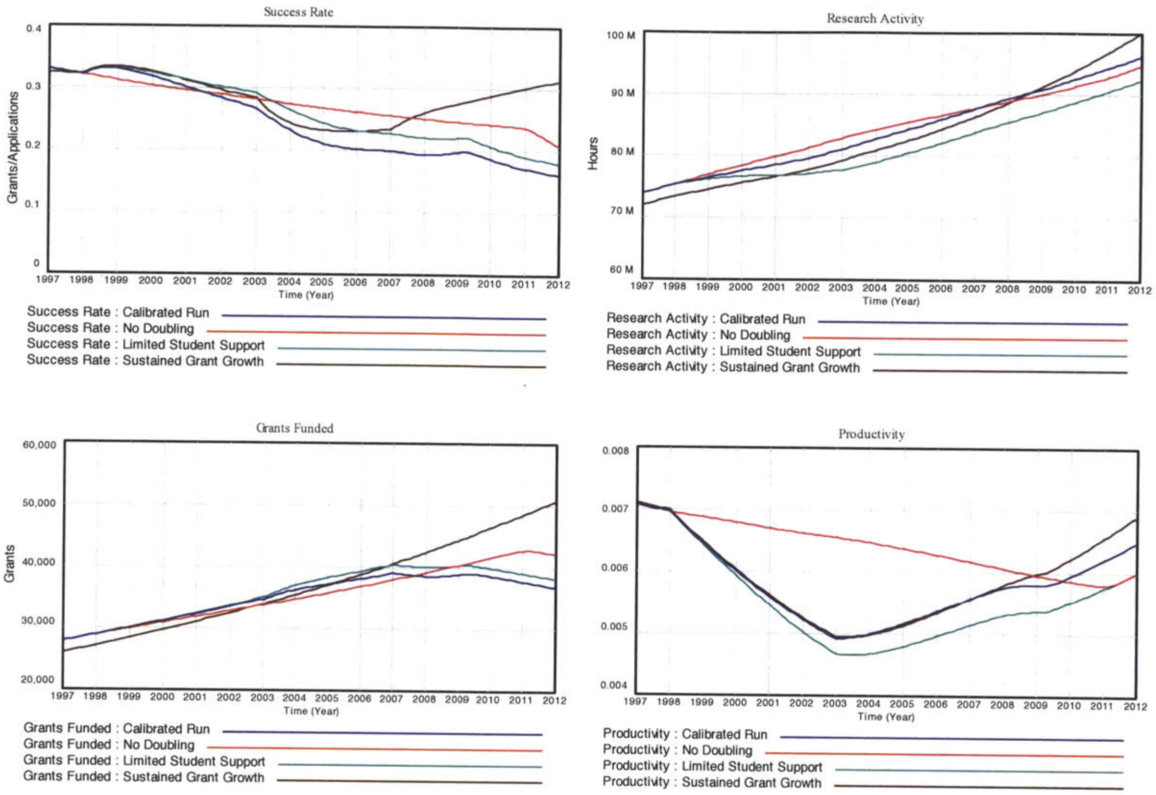

Figure 34. Major Outcomes of Experiments #1, #2, #3, and Calibrated Run

Limiting student support when the budget experiences steep growth results in a moderate gain in success rates, compared to the base case, due to the reduced number of grant applicants. The tradeoff, however, is that with a smaller pool of researchers, the aggregate level of research activity also decreases even though the number of grants funded is slightly higher. As a corollary, experiment #2 also has the lowest levels of productivity throughout the examined period. This policy's relatively straightforward implementation makes it an attractive option, but it is critical to carefully evaluate whether its benefits for success rates outweigh its costs in research output.

In contrast, the implementation of the policy tested in experiment #3 is significantly more complicated; it requires a change in the system's structure, with all the political obstacles that such a change entails. Its benefits, however, are consistent throughout the examined outcomes. Success rates maintain relative stability during the years following the budget doubling due to the sustained growth in the number of grants available. This results in higher productivity after 2009, not only due to the drop in spending, but also due to the continuously growing level of research activity. This is a change that could transform the overall behavior of the system in the right direction, inducing greater stability and enhancing the development of the research workforce.

4. Discussion

Through the implementation of a system dynamics model, this study has shown how a sharp and temporary rise in NIH funding can result in unintended negative consequences. An increase in funding, and the corresponding growth in the number of grant awards available, results in a larger pool of graduate students and researchers entering the system. With additional researchers in the system, the number of applicants for NIH grants eventually increases. If the growth in funding stagnates, or even decelerates, the previous growth in applicants will result in lower grant success rates and therefore in increased competition. Higher competition levels translate to additional time spent writing grant applications, which eats into valuable research time. All these effects have a negative impact on the attractiveness of a research career, hurt productivity, and imperil the stability and availability of the future workforce.

The side effects described above are not inevitable and a series of strategies can be implemented to prevent them. Perhaps the most salient lesson arising from this study is that sudden and significant changes in funding levels have the potential to severely destabilize a system that is already vulnerable to oscillations due to multiple feedback loops and delays. The negative effects of a stagnant or decreasing budget can be intuitively foreseen, but for steep and short-lived growth these effects are not as intuitive. Sustained, smooth, and therefore predictable growth levels in funding, foster the conditions for the necessary stability in the system. Stability can play a crucial role in preventing high levels of competition and frustration, stimulating productivity while building a more favorable perception of a biomedical research career. The unpredictable reality of political decisions, however, poses a real obstacle to ensuring stable and uninterrupted budget growth.

Other alternatives can help stabilize the system without the need for an outright political assurance of sustained budget growth. Among these are the modifications of policies that exacerbate the impacts of volatile funding, such as the requirement imposed on NIH to fully utilize its annual appropriations every year. Whereas private corporations are able to manage financial windfalls and conserve some resources for the future, NIH must spend nearly all the money it receives the year it receives it by law (Couzin & Miller, 2007).

Under the current system, sudden growth in NIH's budget translates to a direct increase in the annual number of grants awarded. Each grant awarded represents, on average, a 4-year financial commitment by NIH to the underlining project.

Reduced availability of new grants, coupled with a growing workforce size, intensifies the effects of a sluggish budget. If the agency was given more freedom to manage its budget under a longer time horizon, much like a corporation, the volatility of year-on-year political decisions could be attenuated, enhancing the stability of the system.

The previous discussion also highlights the impact of NIH's budget on the overall size of the workforce and the real potential for generating an oversupply of researchers following sharp budget increases. Accounting for these systematic effects, instead of freely allowing the use of NIH grants to sponsor unusual waves of new graduate students, can further reduce instability in the system. Implementing isolated policies aimed only at reducing the number of students supported by the NIH, however, has limited benefits and can negatively impact the overall levels of scientific output.

In addition, political campaigns that target the doubling of budgets are still commonplace and are an example of policy resistance despite the undesirable outcomes that past initiatives have yielded. This study contributes to the growing body of system dynamics literature that studies how seemingly positive policies might not be as effective in practice, and can instead worsen the conditions of a particular system. These types of models can serve as persuasive tools to influence policy-makers, while allowing for simulation experiments before actual policies are implemented.

Lastly, the dynamics of a particular research workforce and its relationship with public funding, biomedicine and the NIH in this case, could bear similarities across various areas of knowledge. Other public agencies and organizations, such as the NSF, whose funding plays a critical role in the advancement of science, can benefit from these transferrable insights and policy strategies. Future work on the model presented in this paper, and on similar new models, can shed light into additional strategies that government and other players can implement to enhance the behavior of complex systems.

Appendix A: Model Equations

"% of ER Applying to Grants"=

0.29

Units: Dmnl

Percentage of established researchers applying to grants

"% of YR Applying to Grants"=

0.13

Units: Dmnl

Percentage of young researchers applying to grants"

AA Data:=

GET XLS DATA('Model_Data.xlsx' , 'Data' , 'A' , 'G2')

Units: Applications/Researcher

Applications per applicant data used for calibration. Sources:

http://www.hhs.gov/advcomcfs/meetings/minutes/cfsac071128min.html
http://cjasn.asnjournals.org/content/3/6/1878.full
http://www.hhs.gov/advcomcfs/meetings/minutes/cfsac071128min.html

AA Switch=

0

Units: Dmnl [0,1,1]

Switch to use endogenous vs. exogenous number of applications per applicant. Used for calibration.

Applications per Applicant=

(Funding Effect*Effect of Availabe Funds on Applications+Competition Effect *Change in Applications due to Competition)* (1-AA Switch) + AA Data*AA Switch

Units: Applications/Researcher

Average PostPhD Training=

Applications per Applicant * Avg Applications for Promotion

Units: Years

Average Total Training Time=

Average PostPhD Training + Avg PhD Length

Units: Years

Avg Applications for Promotion=

IF THEN ELSE(Success Rate = 0 , 5, Grants Needed for Promotion/Success Rate)
Units: Applications

Avg Discovery Delay=
0.5
Units: Years [0,5,0.5]

Avg Grant Duration=
4
Units: Years

Avg Grant Size=
gs0+Doubling Switch*(RAMP(gs1,1998,2003)-RAMP(gs2,2003,2007))
Units: Dollars/Grant

Avg PhD Length=
5.52
Units: Years [0,6]
Source:
http://www.ncbi.nlm.nih.gov/books/NBK56989/table/ch3.t5/?report=objectonly

Avg Time Employed=
30
Units: Years

Budget Adjustment Time=
8.5
Units: Years

Budget Memory=
7
Units: Years
Variable representing the delay involved in the release of political pressure

CA Data:=
GET XLS DATA('Model_Data.xlsx' , 'Data' , 'A' , 'F2')
Units: Grants
Grant data used for calibration.
Source:
http://report.nih.gov/NIHDatabook/charts/Default.aspx?sid=1&index=1&catId=2&chartId=20

CA Switch=
0
Units: Dmnl [0,1,1]
Switch to use endogenous vs. exogenous competing awards. Used for calibration

Capacity Adequacy=
Effect of Capacity(Openings/Training Completion Rate)
Units: Dmnl

Change in Applications due to Competition=
smoothI(IF THEN ELSE(Competition Switch , Response to Competition(Success Rate),1),1,1)
Units: Applications/Researcher
Calculates the response of applications per applicant to competition levels using the s-shaped function 'Response to Competition'

Competing Awards=
max(0,Grants Funded-(Fulfilled Commitments/Avg Grant Size))*(1-CA Switch) + CA Data*CA Switch
Units: Grants
New grants available

Competition Effect=
0.48
Units: Dmnl [0,1,0.02]
Magnitude of competition effect on applications per applicant

Competition Switch=
1
Units: Dmnl [0,1,1]
Switch to turn on and off the effect that competition has on applications per applicant

DER Data:=
GET XLS DATA('Model_Data.xlsx' , 'Data' , 'A' , 'H2')
Units: Researchers
Source: (Garrison, 2011)

Desired Change in Funding=
t1*((1/(1+EXP(-Political Pressure/t2)))-t3)*Discrepancy*Research Hours per Discovery/Research Hours per Researcher*Researcher Cost

Units: Dollars
Calculates the dollar amount needed to close the discrepancy between desired and actual levels of discoveries. Uses logistic function with calibrated transformations t1, t2, and t3, to simulate response to political pressure.

Desired Established Researchers=
DER Data+RAMP(ER Growth , 2010 , 2070)
Units: Researchers
Available tenured positions, uses external 'DER Data'

Desired Grant Money=
max(Yearly Grant Money + Desired Change in Funding,0)
Units: Dollars

Desired Level of Discoveries=
smoothI(Successful Discoveries*Goal Growth,Goal Adj Delay,Initial Level of Discoveries)
Units: Discoveries

Desired Workforce=
NIH Commitments / Researcher Cost
Units: Researchers

Discrepancy=
Desired Level of Discoveries - Successful Discoveries
Units: Discoveries
Difference between desired and actual level of discoveries

Doubling Effect=
Doubling Switch*Doubling Size*PULSE(1998,5)+1
Units: Dmnl
Exogenous variable used to simulate increase in budget between 1998 and 2003

Doubling Size=
0.38
Units: Dmnl [0,2]
Exogenous variable used to simulate increase in budget between 1998 and 2003

Doubling Switch=
1
Units: Dmnl [0,1,1]
Switch used to turn on and off the doubling effect between 1998 and 2003

DropOut Proportion=
    0.03
Units: Dmnl [0,1,0.01]

Effect of Available Funds on Applications=
    IF THEN ELSE(Expectation Switch , Response to Funding(Yearly Grant Money), 1)
Units: Applications/Researcher
Calculates the response of applications per applicant to funding levels using the s-shaped function 'Response to Funding'

Effect of Capacity(
    [(0,0)-(2,2)],(0,0),(1,1),(2,1))
Units: Dmnl

Enrollment Delay=
    1
Units: Year

ER Growth=
    150
Units: Researchers/Year
Estimated growth in the number of tenured positions based on available data

Established Researchers= INTEG (
    Promotion Rate-Workforce Exit Rate,Initial ER)
Units: Researchers
Stock of established researchers

Expectation Switch=
    1
Units: Dmnl [0,1,1]
Switch to turn on and off the effect that funding has on applications per applicant

Fraction of Enrollment Supported by NIH=
    0.3
Units: Dmnl
Source:
    https://webcaspar.nsf.gov/

Fulfilled Commitments=
(NIH Commitments/(Avg Grant Duration-1))
Units: Dollars/Year

Funding Effect=
0.49
Units: Dmnl [0,1,0.02]
Magnitude of effect of funding on applications per applicant

Goal Adj Delay=
2
Units: Year [0,20]
Delay in adjustment of discovery goal

Goal Growth=
1.16
Units: Dmnl
Target discovery growth

Grad School Enrollment=
Smooth(Grant Sponsored Recruits/Fraction of Enrollment Supported by NIH + Researchers Leaving Academia + Promotion Rate,Enrollment Delay)
Units: Researchers/Year
Total enrollment in biomedical graduate programs

Grant Money Fraction:=
GET XLS DATA('Model_Data.xlsx' , 'Data' , 'A' , 'J2')
Units: Dmnl
Fraction of total NIH budget for grants. Source:
http://officeofbudget.od.nih.gov/pdfs/FY09/Mechanism%20Detail%20by%20IC,%20FY%201983%20-%202008.pdf

Grant Sponsored Recruits=
Competing Awards*Students per Grant
Units: Researchers
Yearly biomedical graduate students supported by the NIH

Grants Funded=
Yearly Grant Money/Avg Grant Size
Units: Grants
Total grants funded in a given year, includes competing and noncompeting

Grants Needed for Promotion=
3
Units: Grants

gs0=
375000
Units: Dollars/Grant
Average grant size

gs1=
20000
Units: Dollars/Grant
Increase in average grant size during budget doubling. Source:
http://report.nih.gov/NIHDatabook/Charts/Default.aspx?showm=Y&chartId=158&catId=2

gs2=
18000
Units: Dollars/Grant
Decrease in average grant size after doubling. Source:
http://report.nih.gov/NIHDatabook/Charts/Default.aspx?showm=Y&chartId=158&catId=2

Initial Commitments=
5.5e+09
Units: Dollars

Initial ER=
20000
Units: Researchers

Initial Grant Money=
2.9e+09
Units: Dollars

Initial Level of Discoveries=
38000
Units: Discoveries

Initial YR=
50000
Units: Researchers

NA Data:=
GET XLS DATA('Model_Data.xlsx' , 'Data' , 'A' , 'E2')
Units: Applications
Data for number of applications used for calibration. Source:
http://report.nih.gov/NIHDatabook/charts/Default.aspx?sid=1&index=1&catId=2&chartId=20

NA Switch=
0
Units: Dmnl [0,1,1]
Switch to use endogenous vs. exogenous number of applications. Used for calibration

New Commitments=
Competing Awards*Avg Grant Size*(Avg Grant Duration-1)
Units: Dollars/Year

NIH Commitments= INTEG (
New Commitments-Fulfilled Commitments,Initial Commitments)
Units: Dollars

Number of Applications=
("% of ER Applying to Grants" * Established Researchers + "% of YR Applying to Grants" * Young Researchers) * Applications per Applicant * (1-NA Switch) + NA Data * NA Switch
Units: Applications
Total number of applications submitted to the NIH each year

Openings=
max(Desired Established Researchers-Established Researchers+Workforce Exit Rate,0)
Units: Researchers

Political Pressure= INTEG (
Pressure Buildup-Pressure Relief,0)
Units: Pressure

Pressure Buildup=
Discrepancy-PULSE(2009,3)*Recession Effect
Units: Pressure/Year
Political pressure inflow

Pressure Relief=
    ((Yearly NIH Budget - Recent Budget)/Recent Budget)*Relief Scaling
Units: Pressure/Year
Political pressure outflow

Productivity=
    Research Activity/Yearly Grant Money
Units: Hours/Dollars

Promotion Rate=
    Training Completion Rate * Proportion Who Get Promoted
Units: Researchers/Year
Rate of promotion from young to established researchers

Proportion Students per Grant=
    0.05
Units: Dmnl
Source:
    http://report.nih.gov/UploadDocs/Enumeration_DataReport_20081219.pdf

Proportion Who Get Promoted=
    Capacity Adequacy
Units: Dmnl

Recent Budget=
    Delay1(Yearly NIH Budget,Budget Memory)
Units: Dollars

Recession Effect=
    10000
Units: Dmnl
Exogenous effect of economic downturn

Relief Scaling=
    17500
Units: Dmnl

Research Activity=
    Research Hours per Researcher*(Established Researchers+Young Researchers*Young Researcher Productivity)
Units: Hours

Research Hours per Discovery=
1920
Units: Hours/Discovery

Research Hours per Researcher=
max(Total Researcher Time-Researcher Time Applying for Grants,0)
Units: Hours/Researcher

Researcher Cost=
100000
Units: Dollars/Researcher
An estimate of salaries + overhead per researcher

Researcher Productivity=
Research Activity/Total Researchers
Units: Hours/Researcher

Researcher Time Applying for Grants=
Applications per Applicant*Time Required to Prepare an Application
Units: Hours/Researcher

Researchers Leaving Academia=
Training Completion Rate * (1-Proportion Who Get Promoted) + DropOut Proportion*Young Researchers
Units: Researchers/Year

Researchers per Grant=
Avg Grant Size/Researcher Cost
Units: Researchers/Grant

Response to Competition(
[(0,0)-(1,3)], (0,2.1),(0.1,2),(0.2,1.61278),(0.29052,1.25188),(0.535168,0.845865),
(1,0.823308))
Units: Applications/Researcher
Calibrated s-shaped function

Response to Funding(
[(-2.14748e+09,0)-(2.21475e+10,2)],(-1.6274e+09,0.0902256),
(9.72976e+08,0.0902256), (3.35047e+09,0.150376), (5.43077e+09,0.285714),
(7.43678e+09,0.578947),(9.44279e+09,0.857143), (1.23404e+10,1.20301),
(1.49407e+10,1.48872),(1.76897e+10,1.71429),(2.02901e+10,1.81203))
Units: Applications/Researcher

Calibrated s-shaped function

SR data:=

GET XLS DATA('Model_Data.xlsx' , 'Data' , 'A' , 'D2')

Units: Dmnl

Success rate data used for calibration. Source:

http://www.faseb.org/Policy-and-Government-Affairs/Data-Compilations/NIH-Research-Funding-Trends.aspx

SR Switch=

0

Units: Dmnl [0,1,1]

Switch to use endogenous vs. exogenous success rates. Used for calibration

Students per Grant=

Researchers per Grant*Proportion Students per Grant

Units: Researchers/Grant

Succesful Discoveries=

Smooth(Research Activity/Research Hours per Discovery,Avg Discovery Delay)

Units: Discoveries

Success Rate=

Competing Awards/Number of Applications * (1-SR Switch) + SR data*SR Switch

Units: Grants/Applications [0,1]

t1=

9

Units: Dmnl [0,20,1]

Logistic function parameter, max y-value

t2=

1125

Units: Dmnl

Logistic function parameter, steepness

t3=

0.45

Units: Dmnl

Logistic function parameter, y-axis transformation

Time Required to Prepare an Application=
320
Units: Hours/Application
Estimate of hours required using NIH grant preparation guidelines. Source:
http://www.niaid.nih.gov/researchfunding/grant/pages/newpiguide.aspx

Total Researcher Time=
1920
Units: Hours/Researcher
Estimate of the total number of hours in a year that a researcher devotes to work

Total Researchers=
Established Researchers+Young Researchers
Units: Researchers

Training Completion Rate=
Young Researchers/Average Total Training Time
Units: Researchers/Year

Workforce Exit Rate=
Established Researchers/Avg Time Employed
Units: Researchers/Year

Yearly Grant Money=
smoothI(Desired Grant Money*Doubling Effect,Budget Adjustment Time,Initial Grant Money)
Units: Dollars

Yearly NIH Budget=
Yearly Grant Money/Grant Money Fraction
Units: Dollars

Young Researcher Productivity=
0.2
Units: Dmnl

Young Researchers= INTEG (
Grad School Enrollment-Promotion Rate-Researchers Leaving Academia,
Initial YR)
Units: Researchers
Stock of young researchers

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