

**A System Dynamics Model of the  
Growth and Diffusion of R&D Communities**

by

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Submitted to the Sloan School of Management  
in Partial Fulfillment of the Requirements of the Degree of

**Master of Science in Management**

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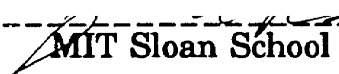
**Massachusetts Institute of Technology**

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**Abstract**

**Rappa and Debackere's 1989 study of the neural networks research community found two phenomena related to the growth and diffusion of R&D communities. They reported the 'bandwagon' effect, which is characterized by exponential growth in a field, and 'cycles of enthusiasm and despair', which begins with a bandwagon effect only to collapse almost as fast. This thesis is aimed at building a system dynamics model of researcher flow in and out of a field, in order to facilitate study the underlying causes of these phenomena.**

**The model is documented in detail and its behaviour discussed. For a fixed set of problems that appear suddenly, the simulation results show two sequential peaks in researcher population. The first is due primarily to the attractiveness of a new problem set, while the second is due primarily to the attractiveness of a field in which problem solving progress is being made. This double peak pattern can be seen in Rappa and Debackere's data on the neural networks community between 1970 and 1982. Further study is required to assess how closely the model's assumptions about the problem set match the neural networks reality, and to test the theory against data for other scientific fields.**

**Thesis Supervisor: Michael A. Rappa  
Title: Assistant Professor, Management**

## TABLE OF CONTENTS

<b>Acknowledgements</b> .....	4
<b>Chapter 1: Introduction</b> .....	5
<b>Chapter 2: Defining the Problem</b> .....	6
<b>Chapter 3: Structure of the Model</b> .....	9
Boundaries.....	10
Concepts Excluded .....	10
Sector Linkages .....	12
Researcher Population Sector.....	13
Stocks:.....	13
Flows:.....	17
Decision Processes:.....	18
Assumptions:.....	26
Problem Solving Sector .....	26
Stocks:.....	29
Flows:.....	30
Decision Processes:.....	32
Assumptions:.....	40
Field Attractiveness Sector.....	40
Stocks:.....	41
Flows:.....	43
Decision Processes:.....	43
Assumptions:.....	47
<b>Chapter 4: Behaviour of the Model</b> .....	49
Base Case - No Problem Set Expansion .....	49
Frontier Phase.....	52
Harsh Reality Phase.....	52
Productivity Phase .....	54
Technical Limits Phase.....	55
Comparison With Neural-Network Community .....	56
Sensitivity Analysis.....	58
First Peak .....	58
Second Peak .....	61
Join Rates .....	64
Problem Set Expansion.....	67
<b>Chapter 5: Conclusions</b> .....	69
<b>Chapter 6: Suggestions for Extension</b> .....	71
<b>References</b> .....	72
<b>Appendix</b> .....	74

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## **Chapter 1: Introduction**

Emerging technologies are developed by researchers who cooperate, compete, and in other ways interact within what has been described as an 'R&D community'. To better understand the role of a community in this context, Rappa and Debackere (1989) have described "some basic elements that may contribute to a general theory of how the emergence of a new technology occurs". Their study focussed on the neural networks<sup>1</sup> research community. This paper seeks to build a model of the growth and diffusion of R&D communities in order to illustrate the causal relationships underlying some of the phenomena described by Rappa and Debackere. Specifically, this study focuses on the 'bandwagon' effect and 'cycles of enthusiasm and despair'.

The model is built using the systems dynamic methodology. System dynamics is particularly appropriate to this task because the methodology demands that the model be built up out of small, easily understood causal links. Furthermore, it is relatively easy for non-technical reviewers to understand and modify. For an excellent introduction to the modelling tool used here, and system dynamics in general, see An Academic User's Guide to STELLA™ by Richmond, Peterson, and Vescuso (1987). A number of related system dynamics publications are listed in the References.

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<sup>1/</sup> For a detailed history of neural networks research see the DARPA study of 1988.

## **Chapter 2: Defining the Problem**

In their study of the neural networks community, Rappa and Debackere (1989) identified two phenomena (among others) associated with the growth and diffusion of R&D communities: the 'bandwagon' effect and 'cycles of enthusiasm and despair'. To understand the causal relationships underlying these phenomena, the author proposes to build a systems dynamics model of the flow of researchers in and out of an R&D community.

Rappa and Debackere describe the bandwagon effect as:

"the rush to join in on a trend, which has less to do with the underlying fundamentals than with the propensity for people to act on the basis of the actual or perceived actions of others. The bandwagon effect contributes to an atmosphere of a race to the emergence of a new technology, a race for the rewards that accrue to those who are first to stake claims to new knowledge in the form of patents or papers."

They speculate that the bandwagon effect is fueled by "an excessive degree of optimism" resulting in "unrealistic expectations about the technology's potential". However, they recognize the positive effect of this optimism in building up the 'critical mass' of researchers required to meet the challenges of the field in the near future.

The data from the neural networks study (see figure 2-1) shows that the number of researchers can not only grow quickly, but also drop quickly. From this, Rappa and Debackere postulate 'cycles of enthusiasm and despair' that start with the bandwagon effect and excessive optimism, followed by a sharp decline if expectations are not met.

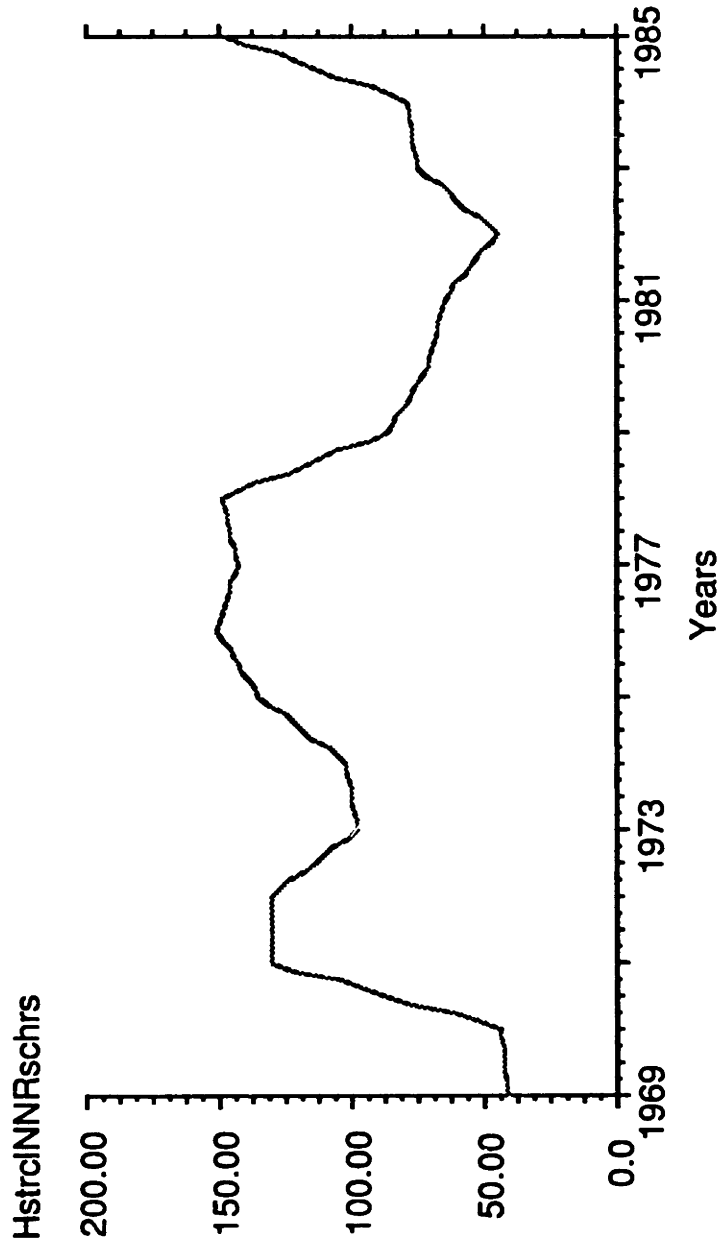


Figure 2-1: Historical Size of Neural Networks Research Community  
 (Source: Rappa & Debackere 1989, linear interpolation)

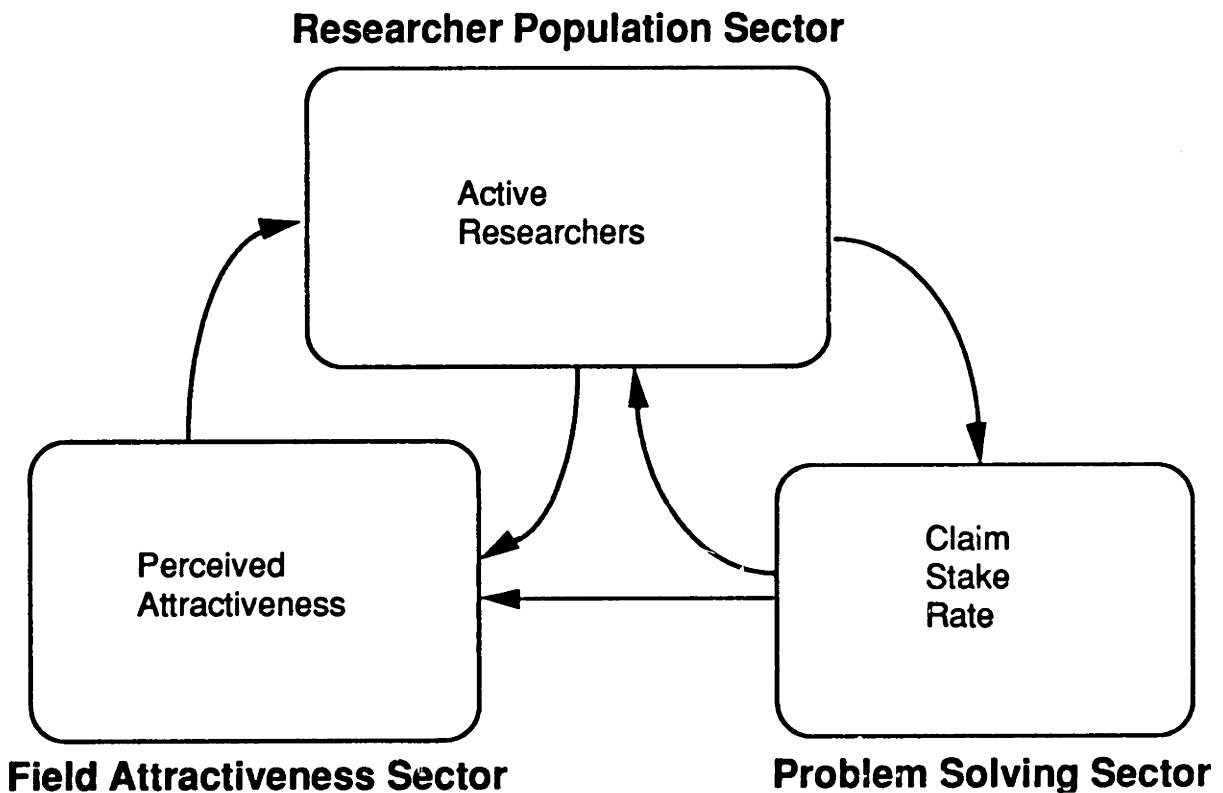
This model focuses on those factors that influence joining and quitting behaviour of researchers. The model should be of use to probe hypotheses about the primary causes of the bandwagon effect, and cycles of enthusiasm and despair, and to draw conclusions about the ways in which R&D communities function.



### **Chapter 3: Structure of the Model**

This chapter provides an overview of each sector of the model in order to give the reader a sense of the definitions, assumptions, connectivity, and limitations of the model. The reader is encouraged to skim this chapter as it is organized to be a reference with sub-topics providing ever greater detail. Descriptions of specific constants and relationships can be found in the listing of equations given in the Appendix.

The model (as shown in figure 3-1) is composed of three sectors:



**Figure 3-1: Overview of Model Sectors**

- **Researcher Population Sector:** This sector models the flow of researchers in and out of the community that is working on problems in the field of interest.
- **Problem Solving Sector:** This sector models the productive output of the research community, the output being information and problem solutions.
- **Field Attractiveness Sector:** Researchers decide whether or not to pursue this field of study based on their perceptions of its attractiveness. This sector models the process by which those perceptions are formed.

Before a detailed look at each sector (as presented later in this chapter), the boundaries of this model, and the major variables that tie the sectors together should be examined.

### Boundaries

Table 3-1 lists the primary endogenous variables, constant parameters, and excluded concepts. There are no exogenous variables in the sense of time series inputs to the model. The excluded concepts are discussed below.

### *Concepts Excluded*

**The Ph.D. population** (population of students entering doctoral programs) is aggregated with other working researchers because once graduating students have chosen their initial field of study, their switching behaviour is assumed to be identical to that of other researchers. Nonetheless, analysis of the model behaviour described later will show that student join rates and supervision capacity constraints have a significant effect on the community size. Therefore, the model should be extended to track Ph.D. students separately. However, given time constraints, this must fall outside the scope of the study.

**Table 3-1: Boundaries of the Model**

<b><u>Endogenous Variables</u></b>	<b><u>Constant Parameters</u></b>	<b><u>Excluded Concepts</u></b>
Student joining	Training rate	Ph.D. student population
Researchers with experience in the field but currently working in other fields (latent capacity)	Fractional retire rate	Technical obsolescence
Direct and indirect recruiting		
Data gathering and dissemination		
Researcher problem-solving productivity	Team sizes & concentration of researcher population	Entry barriers
Set of open research problems	Technological breakthroughs	
Claims staking		Public versus private research
Field attractiveness	Media effect	Funding

**Technical obsolescence** (lost potential of participation in research due to failure to maintain relevant technical skills and knowledge) is not explicitly modeled. Instead the author has assumed that the retire rate can be parameterized to reflect the total decay in research capacity, whether due to researchers' career choices or a decline in technical skills.

**Entry barriers** (factors restricting joining behaviour or attractiveness) are not explicitly modeled. Instead the author has assumed that attractiveness is somehow 'net' attractiveness given all the costs of switching into or out of a field given that these costs should be constant.

**Public versus private** research is not explicitly modeled. Given that private sector researchers may be more constrained in their choice of research agenda than academics, the model may most accurately reflect the public sector, which was our focus. The neural networks study by Rappa and Debackere (1989) shows that public sector researchers dominated the field in all years. Thus a focus on the public sector is probably a good approximation.

**Funding** was not explicitly included in the model. However, it could be an important extension because funding affects join rates, and funding is a key link in a feedback processes between the R&D community and government. If one assumes that the same processes that determine join rates also determine funding levels, then funding is implicit in the model structure. (E.g., NSF funding decisions are made by active researchers in the field.) Thus, funding is endogenous, but is entrained by and reinforces the feedback portrayed in the model.

### Sector Linkages

The following variables provide the major linkages between the three sectors of the model.

**ActiveResearchers** is the number of researchers currently pursuing problems in the field of interest and thus constitutes the R&D community being modelled. More researchers will raise the rate of progress in problem solving, but will reduce the relative attractiveness of this field as the rewards get divided more ways.

**PrcvdAttractiveness** is the perceived attractiveness (PA) of the field of interest relative to alternative fields. Higher PA will raise the field's join rates and reduce its quit rates, and thus will raise the number of active researchers. The attractiveness of a field reflects the level of expected rewards for the average researcher. The value of PA is calibrated as follows:

- 0: No attraction at all, no rewards expected
- 1: Equally attractive as the average alternative field, with same level of rewards expected
- 2: Twice the expected rewards of the average alternative field

**ClaimStakeRate** is the rate at which researchers lay claim to problem solutions. A higher claim-staking rate will raise the expected rewards from this field, but will also raise awareness among potential recruits of the progress being made in this field. The net result is to raise the number of active researchers. For definitional purposes, in an average field, the average researcher should lay claim to one problem solution per year. Claims are staked through mechanisms such as publications and patents.

With these primary linkages understood, the structure of the individual sectors can be examined.

### Researcher Population Sector

The researcher population sector models the flow of researchers in and out of the field of interest. (See figures 3-2, 3, & 4.) To describe its structure, the major stocks, flows, decision processes, and assumptions are discussed in detail.

#### *Stocks:*

A researcher can be included in any one of the following stocks:

**ActiveResearchers:** Active researchers are those currently working in the field of interest. They provide the productive capacity of the field and form the community whose growth and diffusion is being modelled.

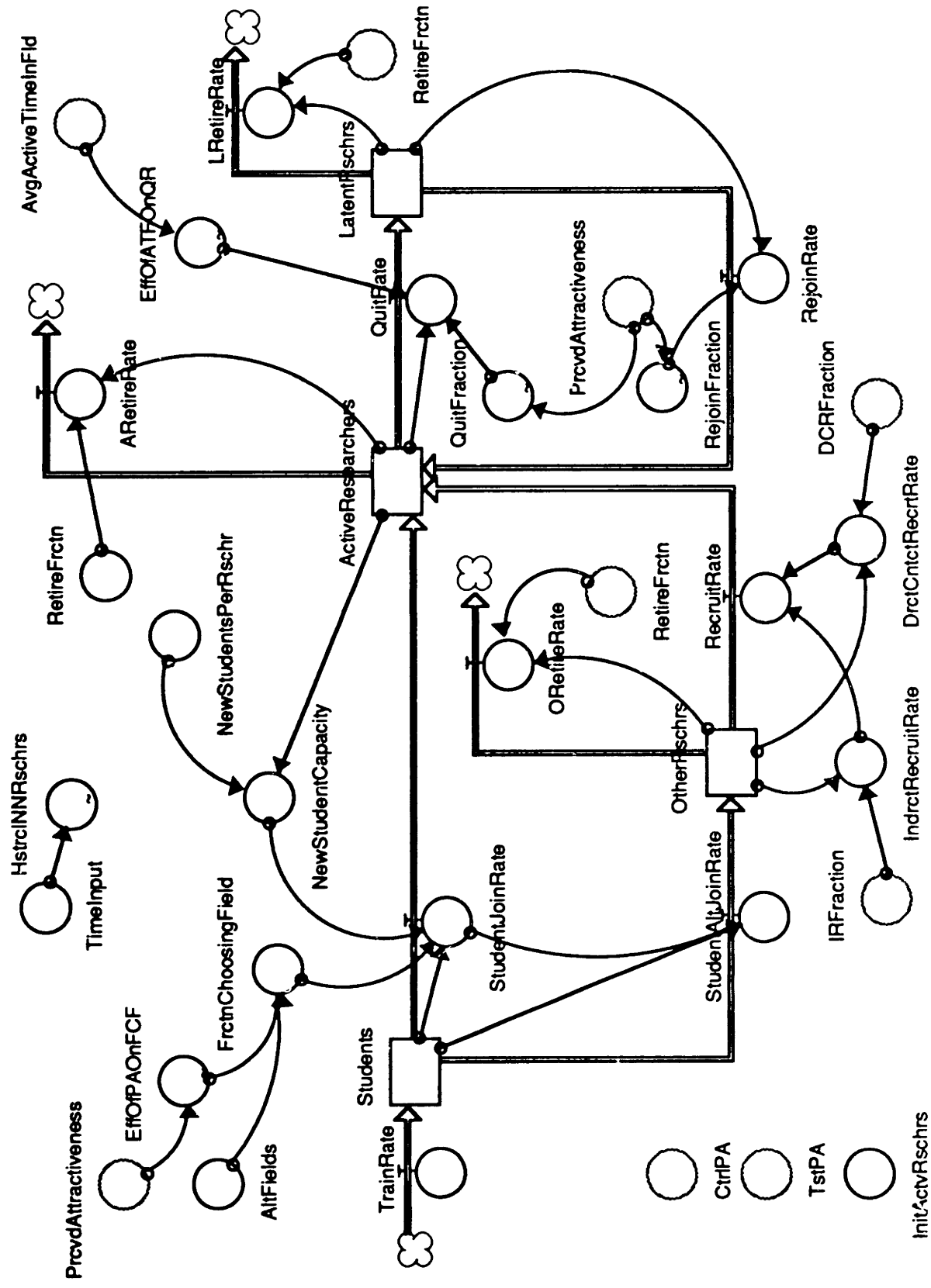


Figure 3-2: Researcher Population Sector

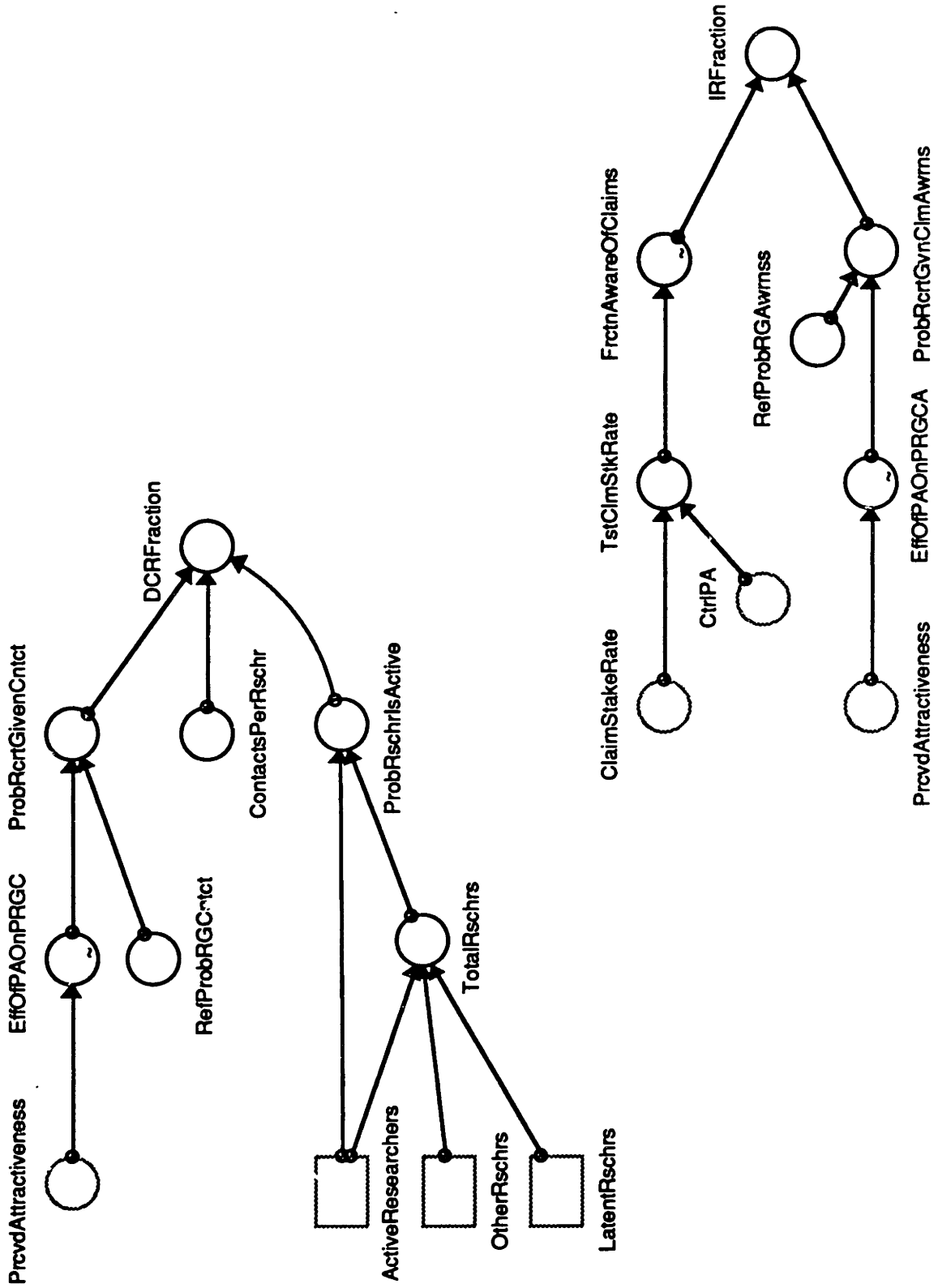


Figure 3-3: Researcher Population Sector (Continued)

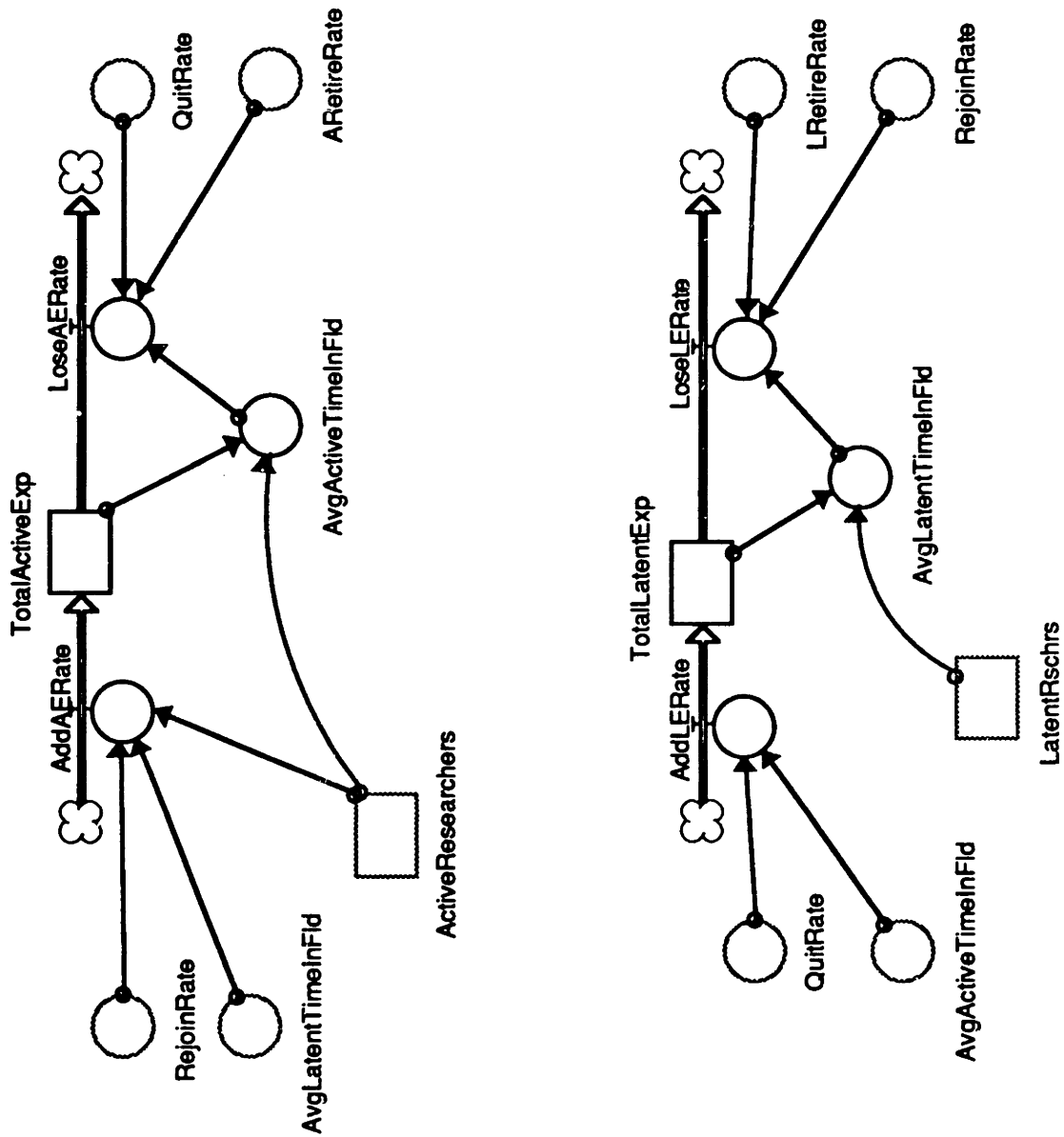


Figure 3-4: Researcher Population Sector (Continued)



**Students:** These are recent graduates who are choosing to enter a doctoral program in a field of research and thus are becoming researchers. This stock is cleared every year as all students are assumed to have joined either the field of interest (becoming active researchers) or some alternative field (becoming other researchers). Researchers do not accumulate in the student category.

**OtherRschr:** Other researchers are those who have never worked in the field of interest but who could potentially be attracted into it.

**LatentRschr:** Latent researchers are those who have some experience in the field of interest but who are now working in an alternative field. They could potentially be attracted back.

*Flows:*

The flows of researchers between the stocks described above are governed by the following rates:

**StudentJoinRate:** New researchers choose a field of research based on the perceived attractiveness of that field. The fraction choosing the field of interest (*FrctnChoosingField*) rises with perceived attractiveness around a base fraction determined by the number of alternative fields. However, this demand can be limited by the capacity of active researchers to supervise new graduate students.

**RecruitRate:** The recruit rate represents the annual number of researchers in other fields who are recruited into the field of interest, but have no prior experience in this field. They are recruited either directly through contact with an active researcher (*DrctCntctRecrtRate*, direct contact recruit rate) or indirectly through exposure to claims staking activity (*IndrctRecruitRate*, indirect contact recruit rate). See the descriptions of the decision processes *DCRFraction* (direct contact recruit fraction) and *IRFraction* (indirect recruit fraction) for more details.

**RejoinRate:** The number of latent researchers rejoining the field per year is a fraction ( $\text{RejoinFraction}$ ) of the total number of latent researchers. The fraction is determined by the perceived attractiveness (PA) of the field. This assumes that latent researchers are well acquainted with the status of research in this field and thus their rejoining decision is only based on PA.

**QuitRate:** The number of active researchers leaving the field is determined by perceived attractiveness modified by a reluctance to abandon the field if much effort has been invested in it. Reluctance is determined by the effect of average time in the field ( $\text{EffOfATFOnQR}$ ). Rappa postulated that the more time the average researcher has invested in a field, the less likely he/she is to leave it. For example, over time a researcher builds up valuable status and recognition in a field that may be lost by switching fields, and accumulates field-specific skills and knowledge that create a productivity advantage for the current field.

**RetireRate:** The rate at which researchers retire is assumed to be a fixed fraction of the total ( $\text{RetireFrctn}$ ). The same fractional rate is applied equally to all researchers whether they be active or otherwise.

**TrainRate** is the annual number of graduating students who will pursue research in either the field of interest or an alternative field.

### *Decision Processes:*

The decision processes that govern the flow of researchers are presented here (in alphabetical order).

**AltFields:** The number of alternative fields that the average new researcher can choose between is set at 100. This model implies that with a perceived attractiveness of 1, each of the 100 alternatives is an equally likely choice and thus 1% of the students will join the field of interest. For example, any student qualified to join the neural networks community should be able to join at least 10 other fields, but probably not

more than a few hundred. Thus 100 seemed to have the right order of magnitude.

**AvgActiveTimeInFld:** The 'average active time in field' is the average years of experience working in the field of interest per active researcher. (See figure 3-4.)

**AvgLatentTimeInFld:** The 'average latent time in field' is the average years of experience working in the field of interest per latent researcher. (See figure 3-4.)

**ContactsPerRschr:** The number of contacts per year that the average researcher has with researchers outside his/her field is set at 100. A typical contact might be a discussion of progress with someone in the same lab or at a conference. Ten such contacts seem too few for the average researcher, yet hundreds seems too high, thus 100 was the chosen estimate.

**DCRFraction:** The 'direct contact recruit fraction' is the fraction of other researchers recruited in a year through direct contact with active researchers. (See figure 3-3.) The fraction depends on the annual number of contacts an average researcher experiences (**ContactsPerRschr**), the probability that these contacts are with active researchers (**ProbRschrIsActive**), and the probability of recruitment given a contact with an active researcher (**ProbRcrtGivenCntct**).

**EffOfATFOnQR:** The effect of average time in the field (ATF) on the fraction of active researchers leaving the field is shown in figure 3-5. There is no effect when ATF is less than 1.5 years because researchers have very little invested in the field. When ATF is greater than 3.5 years, the average active researcher has a considerable investment in his/her work and the importance of this investment cannot increase much. It is assumed that this type of consideration can convince at most half of those contemplating quitting to stay. These values are only qualitative estimates and thus should be verified using data such as that in Rappa and Debackere's recent survey of the neural networks community.

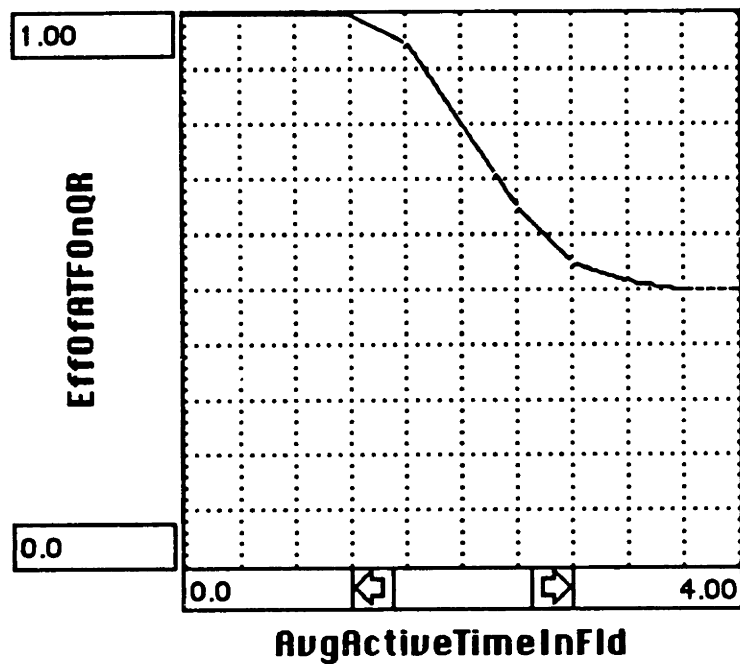


Figure 3-5: Effect of Avg. Time in Field on Quit Rate

**EffOfPAOnFCF** is effect of perceived attractiveness (PA) on the fraction of students choosing the field. As shown in figure 3-6, zero PA will attract zero students. As PA rises towards the average level of 1, more and more students will be willing to join as the disparity relative to alternatives diminishes. Above-average attractiveness attracts more than the average number of students. However the marginal gains are decreasing as fewer students remain who are able to join and will only be swayed by high PA. The author assumes that a very attractive field will be able to attract a maximum of 5 times the normal number of students.

**EffOfPAOnPRGC** is the effect of perceived attractiveness (PA) on the probability of other researchers choosing this field given contact with an active researcher. The reference probability is set to 0.001 and with the effect of PA can be multiplied by a factor as high as 5 to give a maximum probability of 0.005. As shown in figure 3-7, zero PA will attract zero recruits. As PA rises towards the average level of 1, more and more of the potential recruits will be willing to join as the disparity relative to alternatives diminishes. Above average attractiveness attracts more

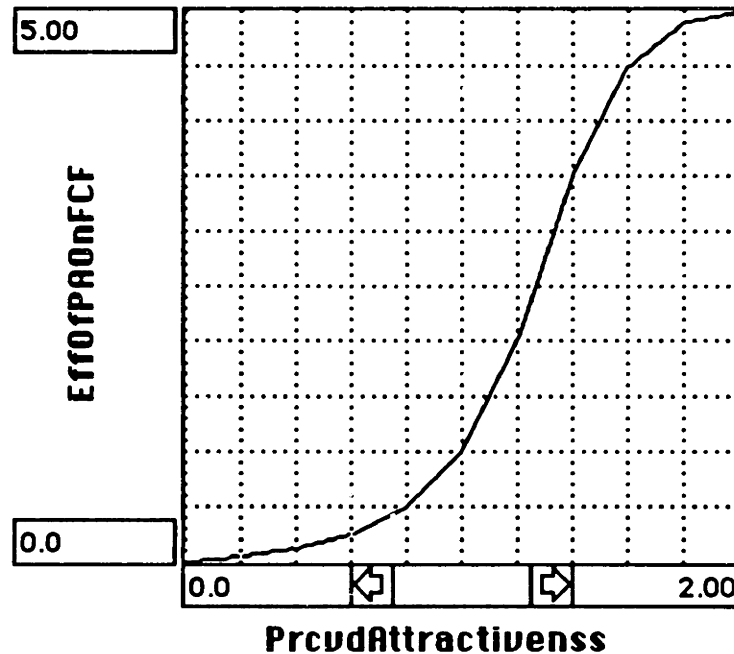


Figure 3-6: Effect of Perceived Attractiveness on Fraction of Graduating Students Choosing This Field

than the average number of recruits. However the marginal gains are decreasing as fewer potential recruits remain who are able to join and will only be swayed by high PA. The author assumes that a very attractive field will be able to attract a maximum of 5 times the normal number of potential recruits (before considering capacity constraints).

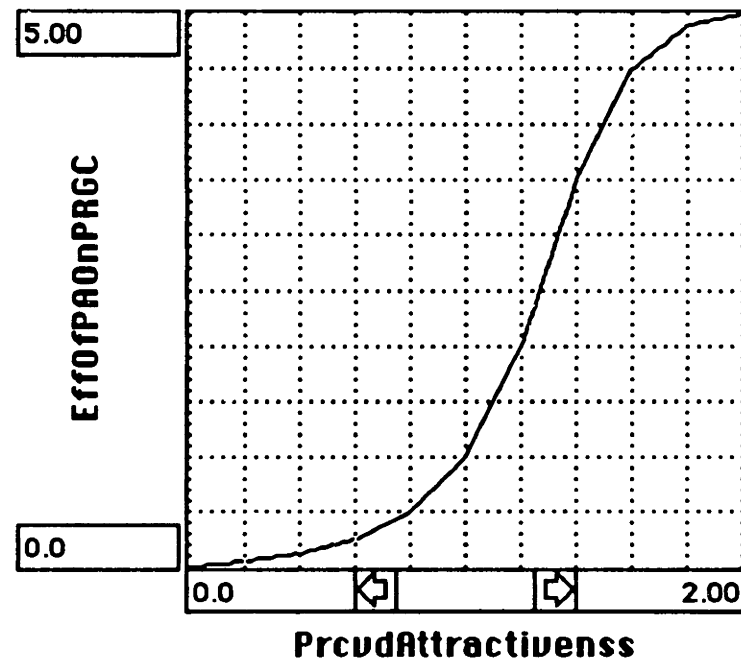


Figure 3-7: Effect of Perceived Attractiveness on the Probability of Recruitment Given Contact with an Active Researcher

**EffOfPAOnPRGCA** is the effect of perceived attractiveness (PA) on the probability of other researchers choosing this field given awareness of the claims staked in this field. The reference probability is set to 0.0014 and with the effect of PA can be multiplied by a factor as high as 5 to give a maximum probability of 0.007. As shown in figure 3-8, zero PA will attract zero recruits. As PA rises towards the average level of 1, more and more of the potential recruits will be willing to join as the disparity relative to alternatives diminishes. Above average attractiveness attracts more than the average number of recruits. However the marginal gains are decreasing as fewer potential recruits remain who are able to join and will only be swayed by high PA. The author assumes that a very attractive field will be able to attract a maximum of 5 times the normal number of potential recruits.

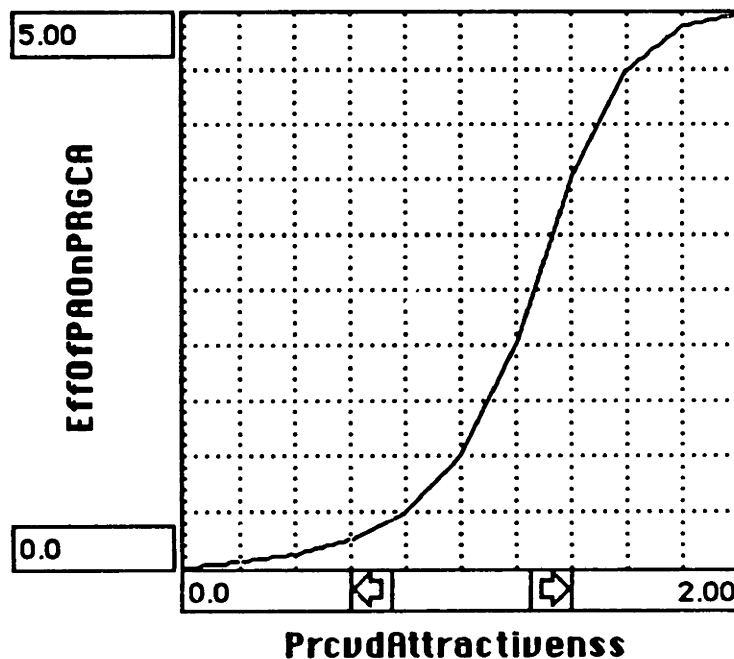


Figure 3-8: Effect of Perceived Attractiveness on Probability of Recruitment Given Claims Awareness

**FrctnAwareOfClaims** is the fraction of researchers in other fields that are aware of the claims staked in the field of interest. The concept is analogous to advertising in that the higher the claims stake rate (advertisements placed), the higher the fraction aware of the status of the field (product). As shown in figure 3-9, zero claims stake rate (CSR) will result in zero awareness. Raising CSR (more papers and patents)

will always result in higher awareness, but with decreasing marginal gains due to decreasing probability of exposing new potential recruits with additional claims staking. The author assumes that at most 90% of the other researchers will be aware of the claims staked in this field, and that this limit is reached at CSR = 200. This corresponds to 100 researchers being doubly productive, or 200 researchers being normally productive.

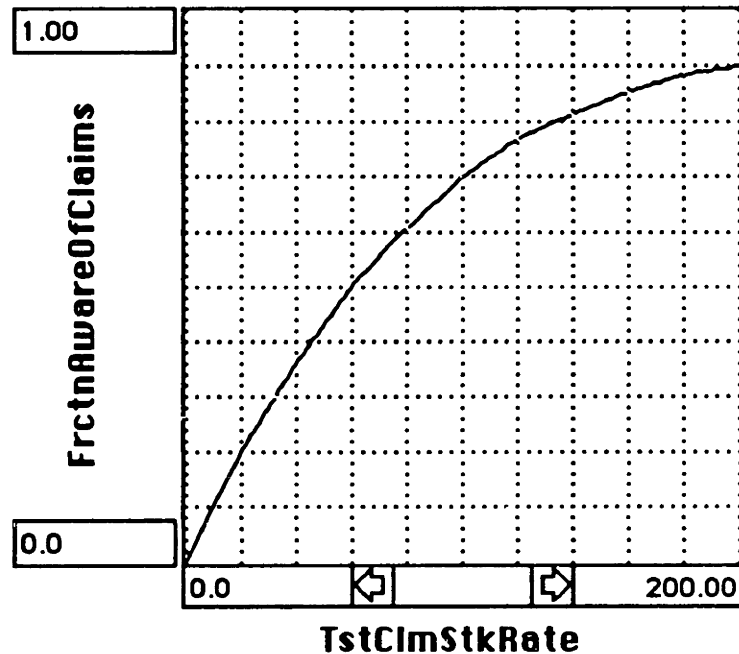


Figure 3-9: Fraction of Other Researchers Aware of Claims Staked in this Field

**IRFraction** (indirect recruit fraction) is the fraction of other researchers recruited in a year indirectly through exposure to claims staking activity by active researchers. (See figure 3-3.) The fraction depends on both the level of awareness of the field among potential recruits (**FrctnAwareOfClaims**), and the probability of recruitment given awareness (**ProbRcrtGivenClmAwrns**).

**NewStudentsPerRschr**, the number of new students that can be added per year for supervision by an active researcher, is set at 0.75. Six Ph.D. students seems to be a reasonable limit for an individual researcher, thus a maximum of 1.5 new students per year (assuming a 4-year program). But not all active researchers supervise students (e.g. Ph.D. students are considered to be active researchers) thus

NewStudentsPerRschr is less than 1.5. Thus 0.75 seems a reasonable number. That the number will vary as the population mix changes is not considered.

**ProbRschrIsActive** is the probability that a researcher is active given a contact with him/her. The probability is estimated by dividing the number of active researchers by the total of all researchers.

**QuitFraction:** The fraction of active researchers leaving the field of interest for another field is derived from perceived attractiveness (PA). As shown in figure 3-10, zero PA will result in a very high defection rate. (The author assumed 90% in a year.) With normal PA (1) the annual turnover would be whatever is the average over all fields. (The author assumed 20% in a year.) When PA is very high (2), turnover will be some small non-zero number because there are always some individuals who have better opportunities or commitments elsewhere. (The author assumed 1.5%.) Note that QuitFraction does not include retirees, only those pursuing research in another field.

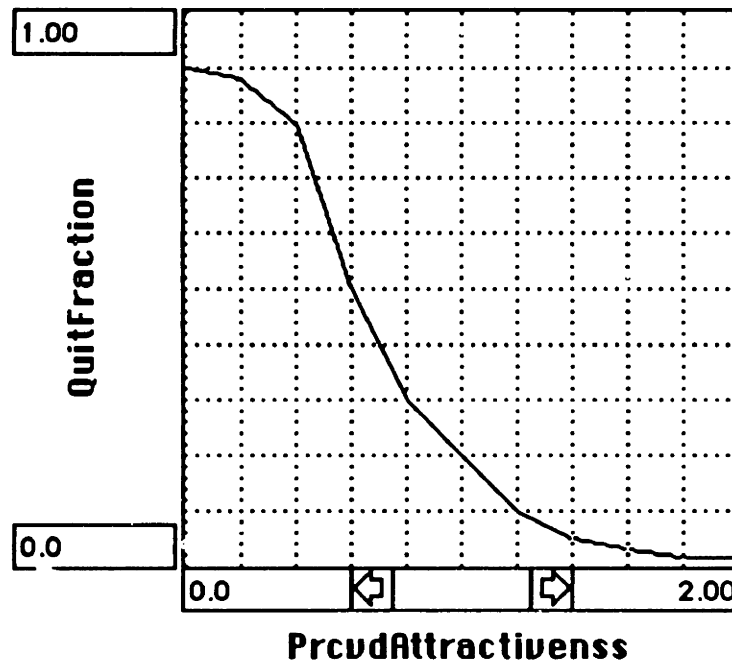


Figure 3-10: Fraction of Active Researchers that will Quit Per Year



**RefProbRGAwrnss:** The reference probability of recruitment given awareness of the claims staked in the field of interest is set at 0.0014. In other words, with normal perceived attractiveness ( $PA = 1$ ), 14 in ten thousand other researchers will be recruited through reading of journals, patents, etc. From FrctnAwareOfClaims, 70% of the approximately 10,000 other researchers will be aware of the claims staking in this field, or about 7000 researchers. Assume 20% of the total other researchers switch fields in a year, or about 2000 researchers. Thus out of the 100 alternatives, 20 researchers will come to the field of interest. If half are recruited through indirect channels, then 7000 aware researchers will yield 10 recruits, or a probability of 0.0014.

**RefProbRGCntct:** Reference probability of recruitment given a contact with an active researcher is 0.001. This means that with normal perceived attractiveness ( $PA = 1$ ), one in a thousand contacts between an active researcher and other researchers will result in recruitment. In approximation, there are 100 active researchers making 100 contacts each per year, or 10,000 contacts. Assume 20% of the other researchers switch fields in a year, or about 2000 researchers. Thus out of the 100 alternatives, 20 researchers will come to the field of interest. If half are recruited through direct contact, then 10,000 contacts will yield 10 recruits, or a probability of 0.001.

**RejoinFraction:** The fraction of latent researchers rejoining the field of interest is determined by the perceived attractiveness ( $PA$ ) of the field. As shown in figure 3-11, zero  $PA$  will result in zero rejoins. As  $PA$  rises towards average attractiveness (1), more and more latent researchers will rejoin as the disparity between the field of interest and the alternatives becomes less significant. If all fields were equally likely then the fraction would be 20%/100 fields or 0.2%. But moving into a field with which one has some experience is more likely than other fields. Thus, the author chose a higher number of 1.5% rejoining in a year. High  $PA$  (2) will result in a large number of latent researchers rejoining in a year. The author assumed 50%.

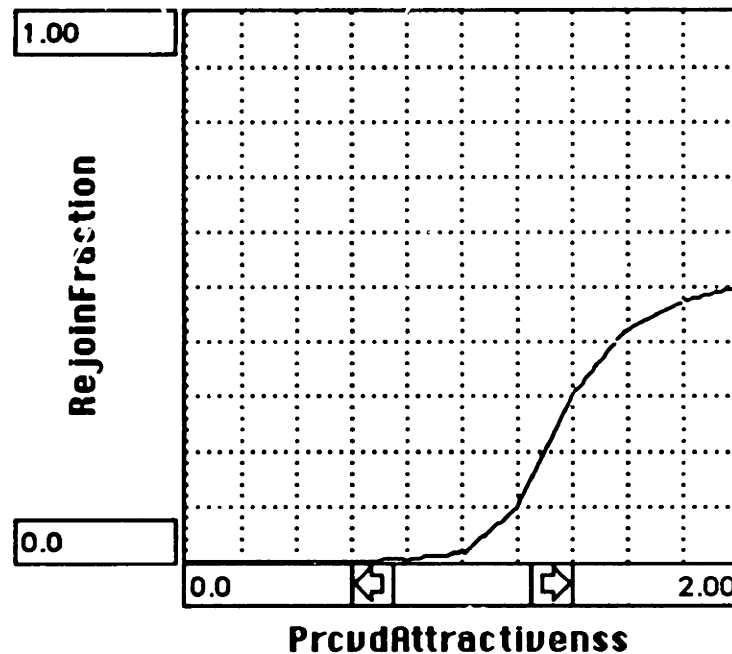


Figure 3-11: Fraction of Latent Researchers that will Rejoin Per Year

*Assumptions:*

The total number of researchers (active or otherwise) is constant at 10,000 because the total retirement rate (RetireFrctn) and the training rate of new researchers (TrainRate) are constant. This assumption is made so that the dynamics can be studied independent of changes due to general growth in the researcher population.

Problem Solving Sector

The problem solving sector models the productive output of the R&D community, specifically, information produced and problems solved. (See figures 3-12, & 13.) To describes its structure, the major stocks, flows, decision processes, and assumptions will be discussed.

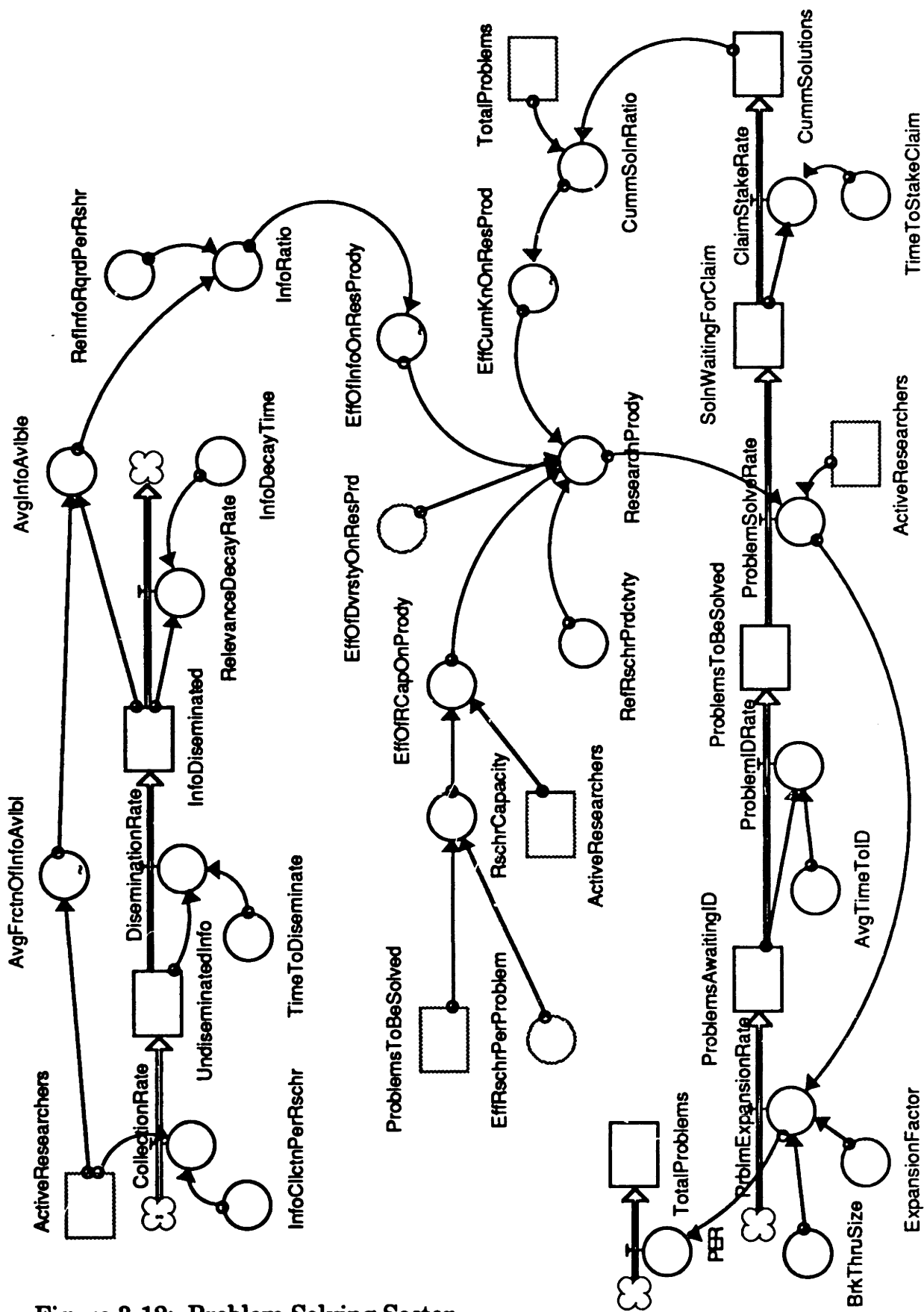


Figure 3-12: Problem Solving Sector

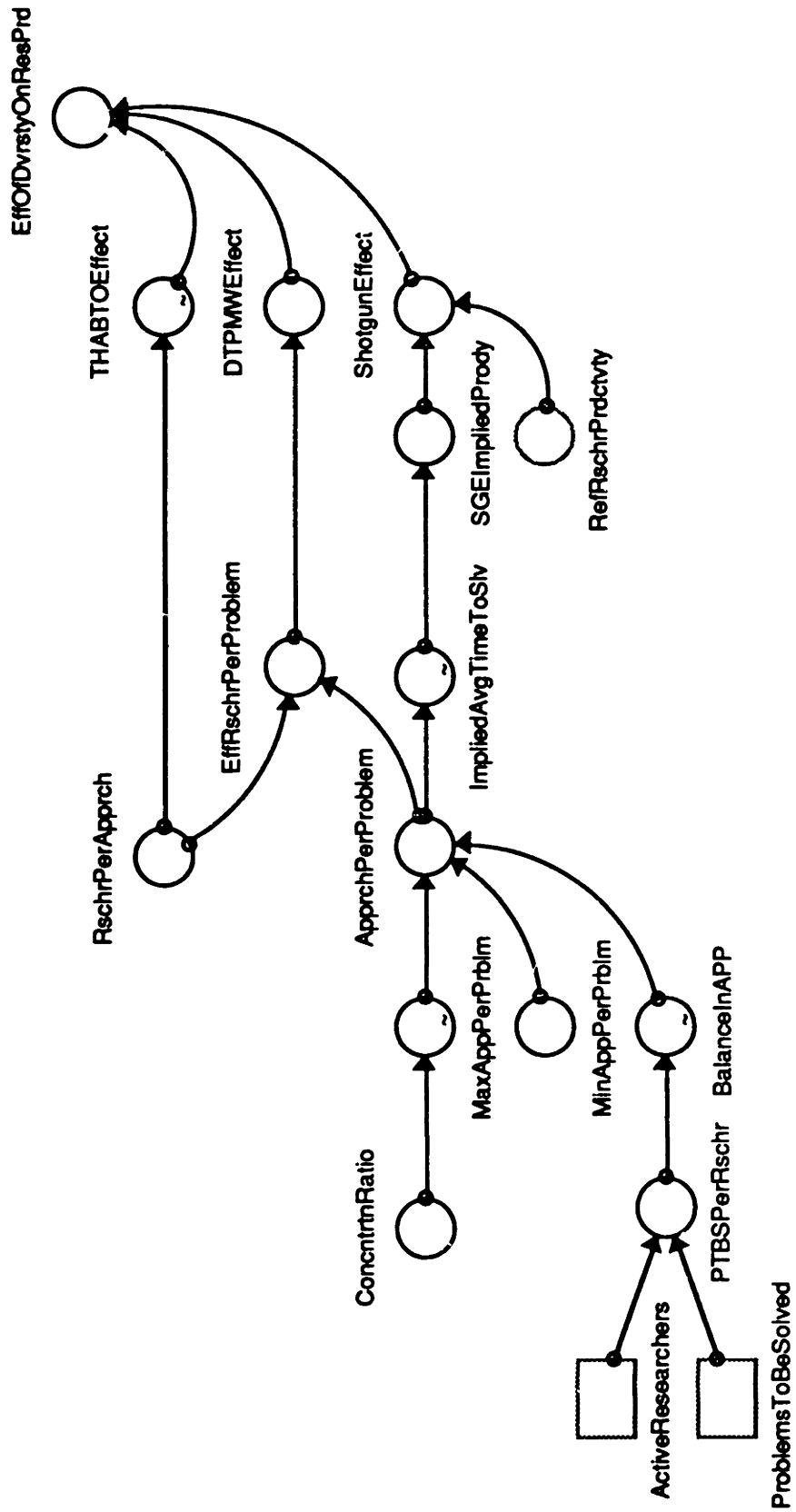


Figure 3-13: Problem Solving Sector (Continued)

*Stocks:*

**Information** is an intermediate product of active researchers that is used in problem solving. Unlike the knowledge behind a patent, information is of little or no direct commercial value. It includes raw data from experiments and even results from failed experiments. The value of information is as an input to the problem solving process.

More information in general leads to higher problem solving productivity, albeit with decreasing marginal returns. In advance of problem solving there is no way to judge the value of a specific piece of information, so it is shared among researchers. In contrast problem solutions are valuable and thus a claim must be staked before the originator is willing to share the new knowledge. In the model, a piece of information can be in one of the following stocks:

**UndiseminatedInfo** is newly collected data that is not yet analyzed and is not yet available to the community at large, and thus does not affect problem solving.

**InfoDiseminated** is the information that is available to the R&D community for problem solving. Its relevance to current and future problem solving activity decays over time.

**Problems** are hurdles in the way of the R&D community as it pursues its goal of realizing a technological achievement. A field is defined by the goal and associated problem set. For example, the goal of the neural networks community is to create a useful information-processing machine using structures modelled after brain cells. One set of problems being addressed

relates to signature recognition, and one problem is dealing with partially obscured characters.

Researchers are motivated by the rewards associated with solving these problems. The solutions help solve more problems later, although researchers are reluctant to share their solutions until their claim is secure. In the model, problems can be in one of the following stocks:

**ProblemsAwaitingID** is the set of problems that must be overcome in order to achieve the R&D community's technological goal, but which have not been recognized yet by researchers as problems that need to be solved.

**ProblemsToBeSolved** is the set of recognized problems to be solved by the R&D community.

**SolnWaitingForClaim** is the set of solved problems for which claims must be staked before they are shared with the rest of the community.

**CummSolutions** is the set of solved and shared problem solutions.

*Flows:*

The flows of information and problems between the stocks described above are governed by the following rates:

**CollectionRate** is the rate at which information is produced by the R&D community. On average, the rate at which a researcher can do surveys, run experiments, etc. is constant (1 info unit per researcher per year) and thus the collection rate is linearly proportional the size of the community.

**DiseminationRate** is the rate at which new data is shared with the community at large. The rate is determined by the average time for a piece of information to diffuse throughout the community

(TimeToDiseminate) which was assumed to be 6 months. The dissemination rate for a community will depend on the concentration of researchers and the communications technology available. (E.g., E-mail has reduced the time taken for news to spread amongst researchers.) Although, the dissemination rate is probably not constant, in the model a constant value is used for simplicity.

**RelevanceDecayRate** is the rate at which information loses its relevance to current and future problem solving. The rate is determined by the average time for a piece of information to lose its relevance (InfoDecayTime) which was assumed to be 2 years. Although assumed to be constant in the model, the decay rate is probably inversely proportional to the rate of progress in the field.

**PrblmExpansionRate** is the rate at which the set of problems to be overcome expands. The size of the problem set is determined by the technological goal of the community. A sudden breakthrough which makes a technology seem feasible (e.g., high-temperature superconductivity) is modelled by a pulse of expansion in the problem set. A gradual growth in the goals of the research community is modelled by a multiple of the problem solving rate (ProblemSolveRate).

**ProblemIDRate** is the rate at which problems are identified by the community as hurdles to be overcome in order to achieve the technological goal.

**ProblemSolveRate** is the rate at which problems are solved by the community of active researchers. The rate depends on the number of active researchers and their productivity (ResearchPrody), both of which will vary over time.

**ClaimStakeRate** is the rate at which problems have claims staked against their solutions depends on the average time for a researcher to publish a paper or file a patent which is relatively constant.

### *Decision Processes:*

The following are the decision processes significant to the parameterization and structure of the problem solving sector (in alphabetical order).

**ApprchPerProblem** is the average number of different solution approaches to a problem undertaken by the community. Many approaches may be attempted by different researchers but only one will solve the problem first. The author postulates that the average number of approaches per problem varies within a range. When there are many open problems per researcher, diversity per problem is low because researchers prefer to take on a different problem rather than pursue a different approach to a problem already under attack by another researcher. However, when the open problem set is small relative to the number of active researchers, diversity on individual problems is high because other problems are not readily identified by prospective researchers. Thus **ApprchPerPrblm** is the weighted average in the range between **MinAppPerPrblm** (the minimum average approaches per problem) and **MaxAppPerPrblm** (the maximum) as determined by **BalanceInApp** (the balance in min and max approaches).

**AvgFrctnOfInfoAvlbl** is the average fraction of disseminated information that is available to the average active researcher. As shown in figure 3-14, as the number of active researchers approaches zero, all of the community has access to all of the information available. At the other extreme, the average member of a very large community will have access to only a small fraction of all the information generated by the community. The author chose 20% for this fraction.



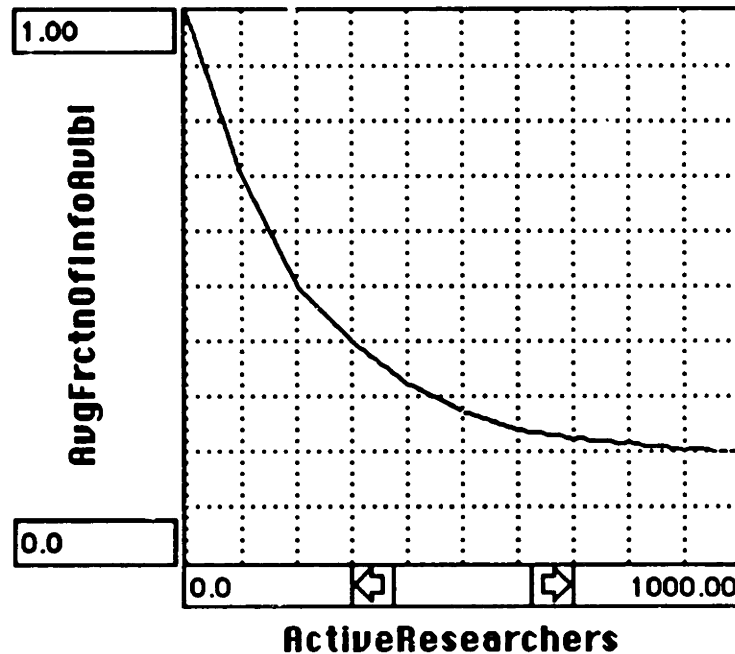


Figure 3-14: Fraction of Disseminated Information Available to the Average Researcher

**BalanceInAPP** is the balance in approaches per problem that depends on the size of the open problem set relative to the number of active researchers. As shown in figure 3-15, when problems to be solved per researcher (PTBSPerRschr) is low, the balance is shifted to the upper limit of the range in approaches per problem (see *ApprchPerProblem*), and vice versa.

**ConcntrtnRatio** is a measure of how concentrated the community is within the supporting institutions. All active researchers in one lab implies a concentration ratio of 1. The concentration ratio will approach 0 as the community is evenly distributed among more and more labs. This ratio influences the diversity of approaches to problem solving. (See *MaxAppPerPrblm*.)

**DTPMWEffct:** The Dividing-The-Pie-More-Ways Effect accounts for decreases in productivity when more than one researcher is working on a problem. The output of the group is divided by the number of researchers working on that output in order to determine productivity per researcher (i.e., a factor of  $1/\text{Researchers per Problem}$ ). The gains of co-operation and competition are accounted for in the *THABTOEffect* and the *ShotgunEffect*.

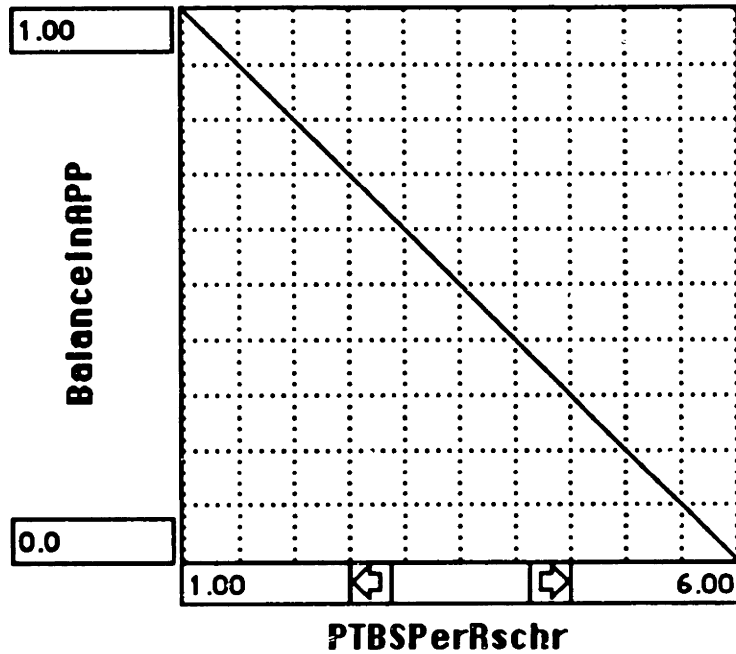
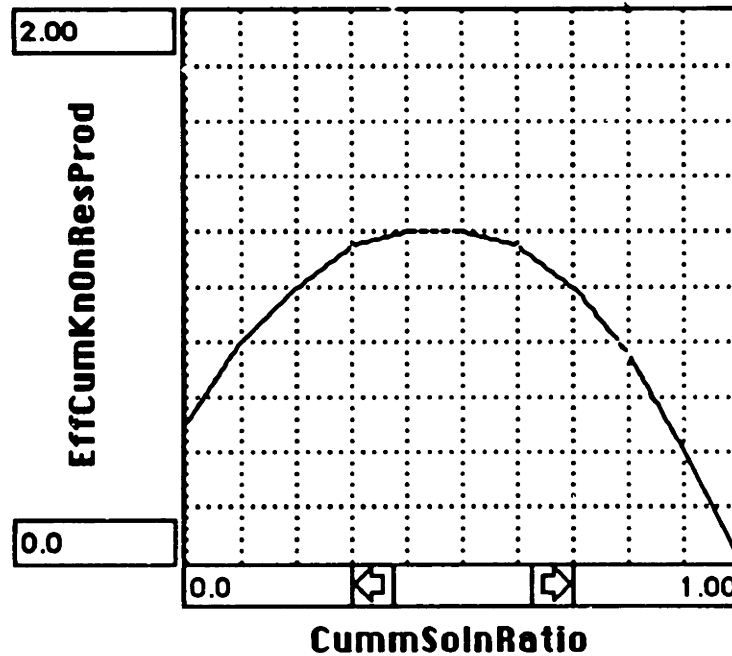


Figure 3-15: Balance Between Max. and Min. Number of Approaches to Problem Solving

**EffOfCumKnOnResPrody** is the effect of cumulative knowledge or problem solutions on researcher productivity. As shown in figure 3-16, early on productivity is reduced due to a lack of knowledge to build on. However, each problem solved makes the next easier to solve. At the same time the problems are getting harder to solve because the easy ones were done first or the final problems are pushing the limits of the technologies upon which the field depends. Thus at some point the two effects balance and produce a maximum productivity increase which the author have assumed to be 20% at about half way through the total problem set. The last problem is impossible to solve and thus productivity at this point is reduced to zero. This is consistent with the technology never achieving all the goals initially envisioned by the community.

**EffOfDvrstyOnResPrd** is the effect of diversity of solution approaches on researcher productivity. This effect can be thought of as three sub-effects:



**Figure 3-16: Effect of Cumulative Knowledge on Researcher Productivity**

- **The Two-Heads-Are-Better-Than-One Effect (THABTOEffect)** accounts for increases in productivity when more than one researcher cooperate on a solution approach. For example, if a researcher can get feedback and ideas on my work from another researcher, then he/she should be able to solve problems faster. The productivity gain is captured here. The fact that the other researcher spent some time working with me is in isolation a reduction to productivity and is captured in the next sub-effect.
- **The Dividing-The-Pie-More-Ways Effect (DTPMWEffect)** accounts for decreases in productivity when more than one researcher is working on a problem. For example, when two researchers are working together, the output must now be divided by two to determine productivity per researcher. Any gain in productivity because together they could work faster than apart, is captured in the previous sub-effect. DTPMWEffect also captures the reduction in productivity due to separate teams pursuing different solution approaches to a problem. Only one team will solve it first and stake a claim against it. The output is one problem solved, but must be divided by the total number of researchers in both teams

to derive average productivity. Any gains in productivity because there were two teams are captured in the next sub-effect.

- The Shotgun Effect accounts for productivity gains that arise when separate teams of researchers pursue different solution approaches to the same problem. These gains can arise because a race mentality develops or simply because more approaches implies a higher likelihood of hitting a profitable one that yields a solution quickly.

**EffOfInfoOnResPrody** is the effect of information availability on researcher productivity. As shown in figure 3-17, zero information results in zero productivity. A little bit of information does not allow for much productivity either. There is a threshold at which enough information is available to start making significant progress. However, soon there are decreasing marginal returns from adding more information because of limited ability to sift through it all, let alone make sense of it. The author assumes that the limit on productivity gains is about 40% and is reached with twice the reference level of information available.

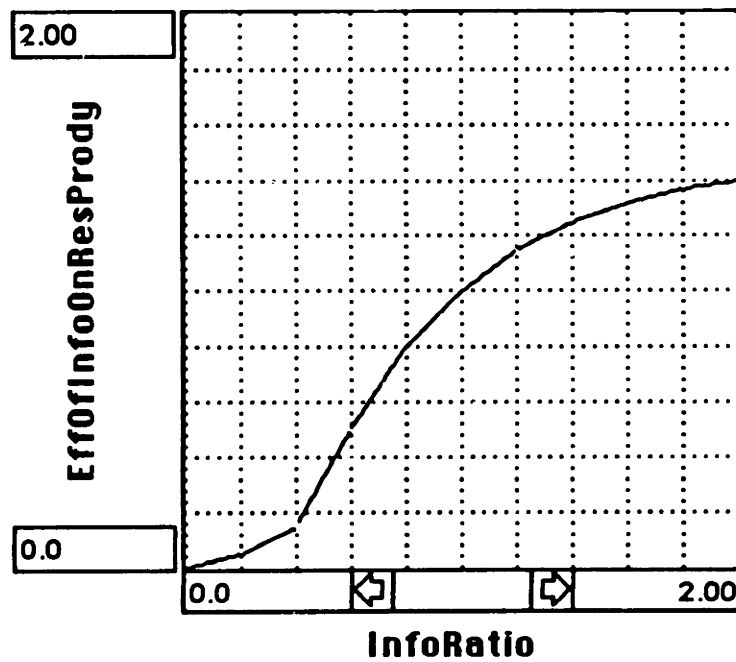


Figure 3-17: Effect of Information Availability on Researcher Productivity

**EffOfRCapOnPrody** is the effect of effective researcher capacity on researcher productivity. The field of interest has an effective researcher capacity because of the limits the community will implicitly impose on solution approaches per problem (**ApprchPerProblem**) and researchers per solution approach (**RschrPerApprch**). These factors combine to limit the number of researchers addressing a particular problem. Given a limited problem set, this then limits the number of researchers that can be productively employed. The rest are spending their time looking for a problem to work on. **EffOfRCapOnPrody** measures the reduction in productivity due to these underemployed researchers.

**ImpliedAvgTimeToSlv** is the implied average time to solve a problem given the number of different approaches being taken to solving it. As shown in figure 3-18, adding additional approaches will always reduce the average time solve, but with decreasing marginal returns. Two approaches to a problem is assumed to give an average solution time of 1 year. One approach will take 40% longer, and three will take 20% shorter.

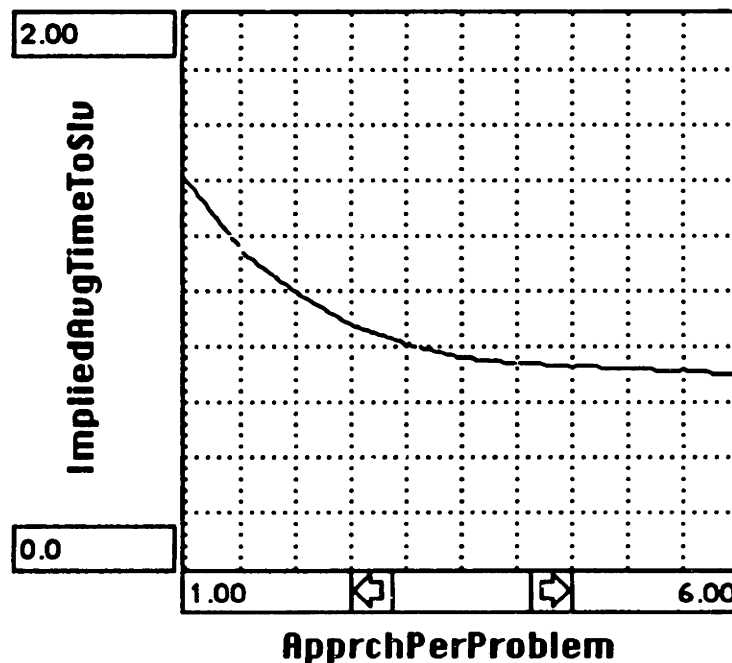


Figure 3-18: The Avg. Time to Solve a Problem Implied by the Number of Approaches Attempted

**MaxAppPerPrblm** is the upper limit on the average number of different approaches to a problem that the community will undertake, and is determined by the community's concentration ratio (**ConcstrtnRatio**). As shown in figure 3-19, a very low concentration ratio will support the most diversity of approaches. With a low concentration ratio, the limiting mechanism works as follows. A researcher contemplating working on a problem will hear on the grapevine who else is working on it, and will be discouraged if he/she hears of many teams already pursuing it. The author assumed that the average will be at most 4 approaches per problem. With a high concentration ratio, (e.g., all the active researchers work for one institution, say IBM), the institution itself will mandate a limit on the number of different approaches to problems in order to optimize the utilization of their resources. The author assumed that the average within one institution will be at most 1.5 approaches per problem.

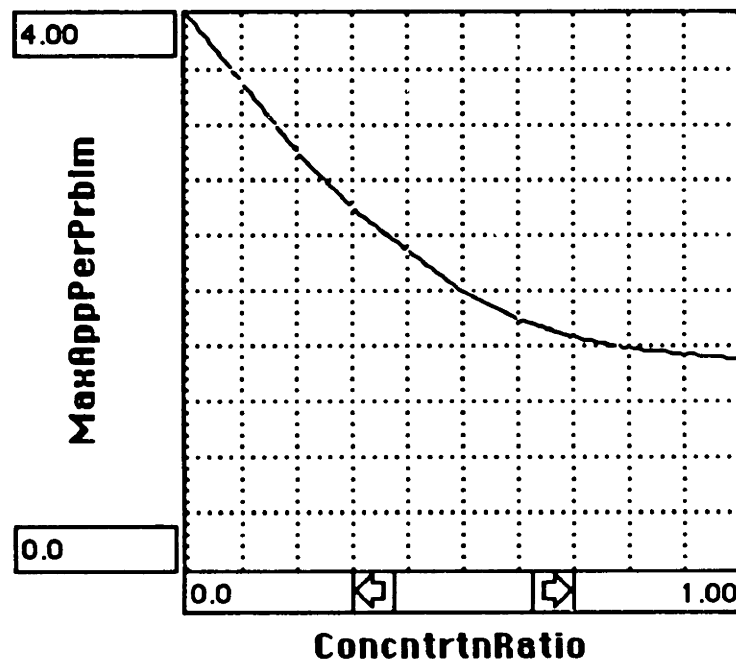


Figure 3-19: Maximum Avg. Number of Different Approaches Attempted to Solve a Problem

**RefInfoRqrdPerRshr** is the reference level of information required by the average researcher in order to have normal productivity. The reference level is set to 100 units per researcher which is equivalent to having

access to the information gathered by half of the reference community of 100 researchers over 2 years.

**RschrPerApprch** is the average number of researchers co-operating together on an approach to solving a problem. The average number depends on the preferences of the individuals (e.g., a researcher may like working in a large group, or like working with particular individuals), and on the policies of the organizations involved (e.g., projects will be staffed with at most two scientists). These policies and preferences are not likely to change, so **RschrPerApprch** is assumed to be a constant at 3 researchers per approach.

**ShotgunEffect:** The Shotgun Effect accounts for productivity gains that arise when separate teams of researchers pursue different solution approaches to the same problem. More solution approaches attempted per problem imply a shorter average time to develop a solution. With more approaches there is a higher probability of at least one of the approaches providing quick results, and as well, a competitive atmosphere can develop. When time to solve is combined with the effective number of researchers per problem (**EffRschrPerProblem**), an implied productivity can be calculated (**SGEImpliedPrody**). The ratio of the implied productivity to the reference productivity is the shotgun effect.

**THABTOEffect:** The Two-Heads-Are-Better-Than-One Effect (**THABTOEffect**) accounts for increases in team productivity due to increases in team size. As shown in figure 3-20, access to more collaborators will always add to a team's productivity. (Output per researcher at some point falls because growth in team output eventually falls behind growth in team size, but that effect is captured in **DTPMWEffect**.) The author assumed that beyond 7 researchers per approach, additional heads add little to the process, with the maximum productivity gain for a team being 900% relative to what an individual could accomplish on his/her own. To derive productivity per researcher one needs to divide by team size (which is the purpose of the **DTPMWEffect**).

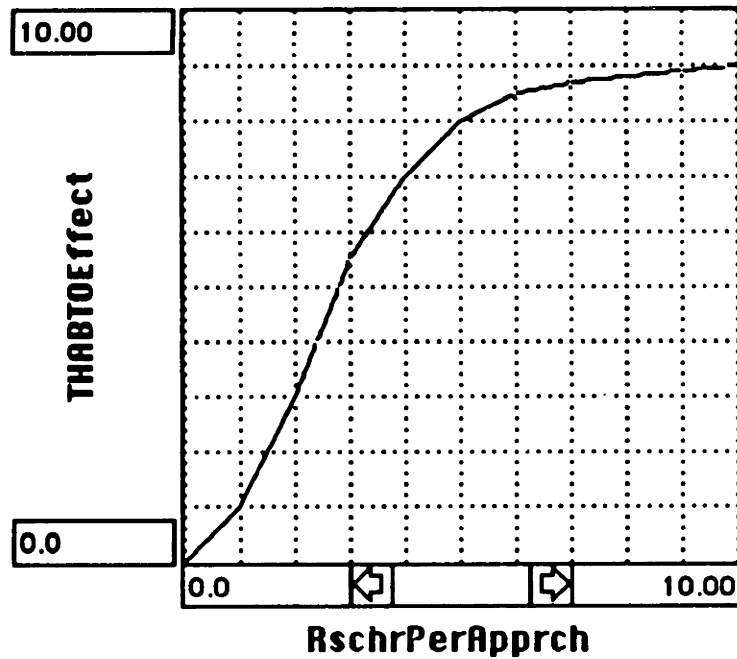


Figure 3-20: The Two-Heads-Are-Better-Than-One Effect

**Assumptions:**

**Researcher problem-solving productivity is assumed to depend only on:**

- the availability of relevant information
- the number of diverse solutions attempted
- the number of researchers cooperating on a problem approach
- the fraction of the problem set solved to date
- the availability of problems to work on

**Researcher information-generation productivity is assumed to be constant.**

**Field Attractiveness Sector**

The field attractiveness sector models the process by which the perceived attractiveness of the field of interest develops. (See figure 3-21.) The movement



of researchers into a field is like a gold rush in that researchers are motivated by the potential rewards of working in the field. There are three dimensions to the attraction of a gold rush, and by analogy to the attraction of a field of research.

- 1) As soon as the first nugget is stumbled upon, people suddenly realize that there is a large territory out there that might offer similar nuggets. In research terms, this is **new problem attractiveness** (**NewPrblmAttrctvnss**), i.e., the mere articulation of a new research agenda with large potential rewards creates attraction.
- 2) Soon, information about geology, routes, and camping techniques are diffusing through the interested community of prospectors creating even more attraction to the gold rush. In research terms, this is **new information attractiveness** (**NewInfoAttrctvnss**), i.e., the excitement finding and discussing interesting experiments, new ways of looking at nature, etc. creates attraction.
- 3) Finally, new entrants actually start finding nuggets of their own, creating even more attraction. In research terms, this is **new claims attractiveness** (**NewClaimsAttrctvnss**), i.e., the garnering of rewards from research attracts other researchers into the field.

Perceived attractiveness is the combination of all three of these effects. To describe the structure of this sector, the major stocks, flows, decision processes, and assumptions are discussed in detail below.

*Stocks:*

This sector contains the following stocks:

**NewProblems** is the set of open problems that are still newly identified and thus are generating new problem attractiveness.

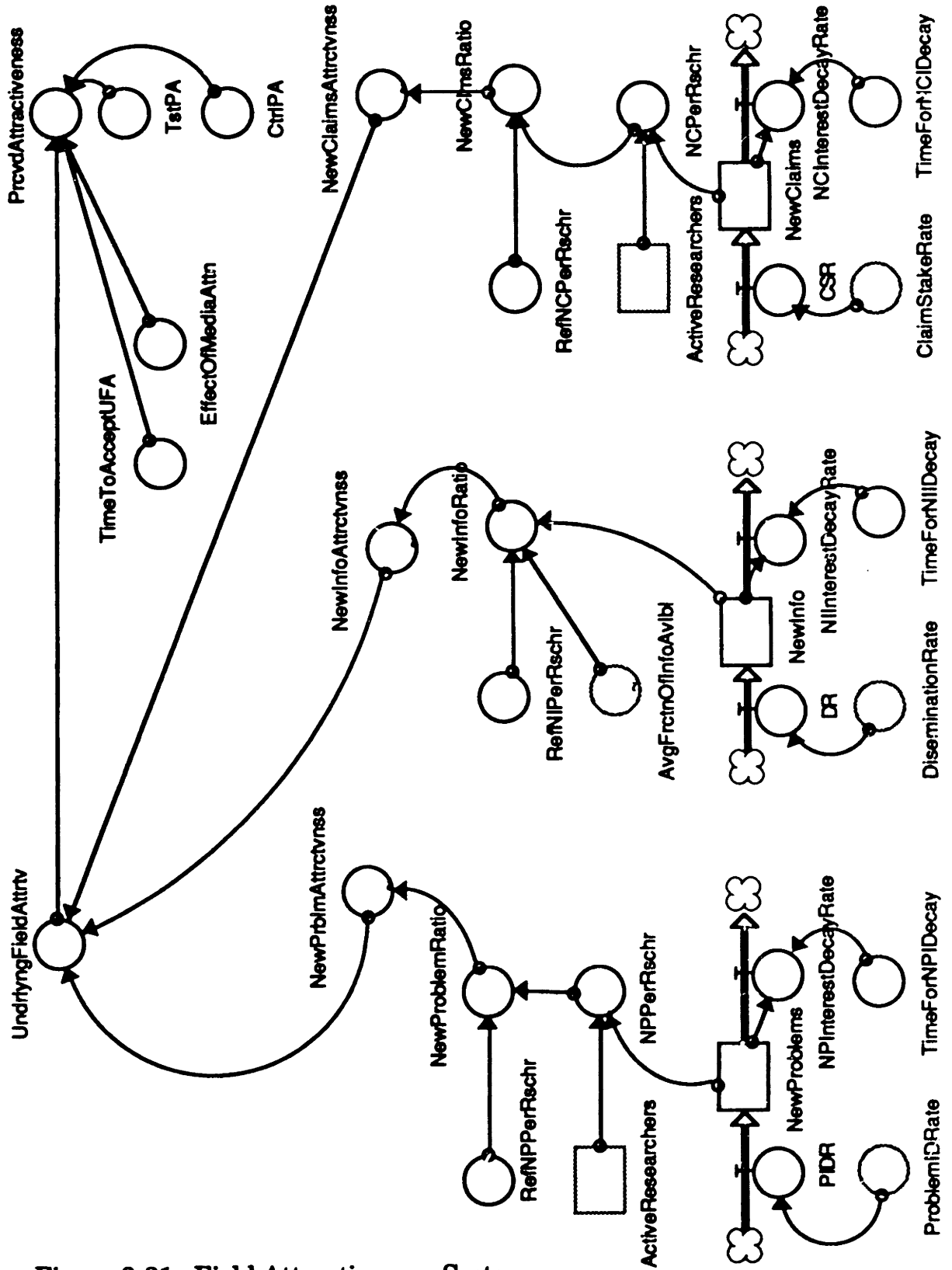


Figure 3-21: Field Attractiveness Sector

**NewInfo** is the set of new pieces of information that are still new and thus are generating new information attractiveness.

**NewClaims** is the set of problems against which claims have been recently staked and thus are generating new claims attractiveness.

*Flows:*

The flows into the above stocks are identical to flows in the Problem Solving Sector. The flows out of the stocks described above are governed by the following rates:

**NCInterestDecayRate** is the rate at which claims lose their appeal of newness and thus are no longer considered representative of the potential rewards from the field.

**NIInterestDecayRate** is the rate at which information loses its appeal of newness and thus no longer generates excitement in the field.

**NPInterestDecayRate** is the rate at which problems lose their appeal of newness and thus are no longer considered to be part of a new frontier.

*Decision Processes:*

This section describes (in alphabetical order) those decision processes that are significant to the parameterization and decision structure of this sector.

**EffectOfMediaAttn** is the effect of media attention of the perceived attractiveness of the field of interest. Media attention can distort researchers' assessments of new problem scope, the significance of new information, and the claims staked, both positively and negatively. For the purposes of this model, the effect of media attention is assumed to be neutral. Later experiments may consider the effect of media attention.

**NewClaimsAttrctvnss** is the level of underlying field attractiveness generated by new claims staked. As shown in figure 3-22, zero new

claims generate no attractiveness. However, more new claims always make the field more attractive. There are increasing marginal gains until a threshold is reached where the rewards are so promising that potential researchers are as excited as they could imagine. The author has assumed that attractiveness will increase until a limit is reached at about 3 times the reference level of new claims which will generate 4 times the average attractiveness of all field.

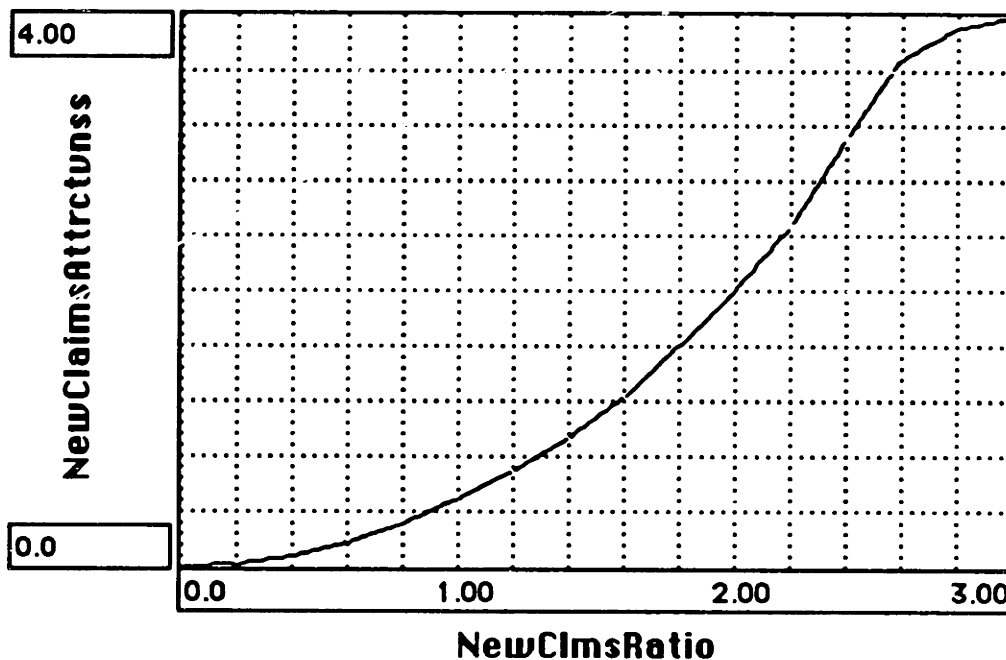


Figure 3-22: New Problem Attractiveness Function

**NewInfoAttrctvnss** is the level of underlying field attractiveness generated by new information diffusing through the R&D community. As shown in figure 3-23, zero new information generates no attractiveness. However, more information always makes the field more attractive, but with decreasing marginal gains. Furthermore, interesting research findings make the field enjoyable to work in but do not directly provide the rewards that motivate researchers. Thus information will not generate nearly as high attractiveness as the other factors. Therefore the author has assumed that at the extreme, 5 times the reference level of new information will generate only 70% of the average attractiveness of all fields.

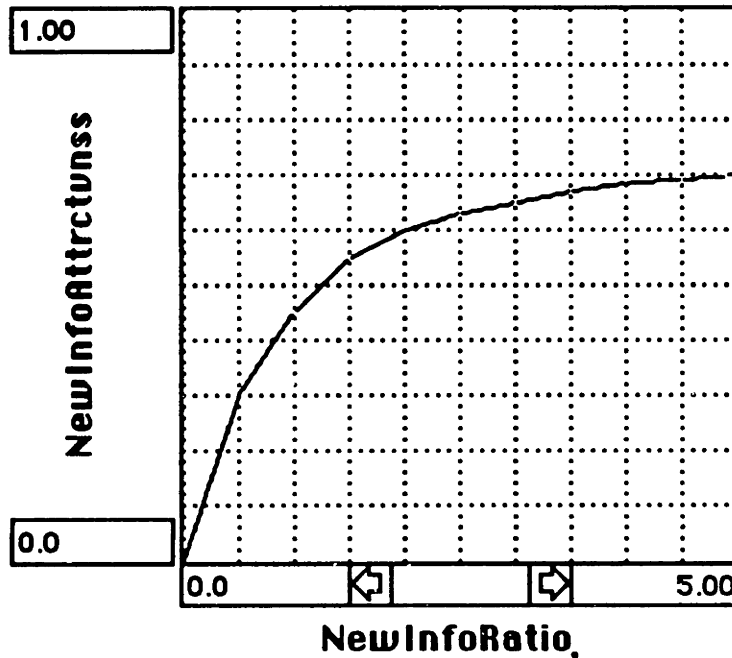


Figure 3-23: New Information Attractiveness Function

**NewPrblmAttrctvnss** is the level of underlying field attractiveness generated by new problems opening up promising frontiers. As shown in figure 3-24, zero new problems generates no attractiveness. A broader frontier is always more attractive, but with decreasing marginal gains. The author has assumed that at the extreme, 5 times the reference level of new problems will generate 2 times the average attractiveness of all fields.

**PrvdAttractiveness** is the attractiveness to the field of interest perceived by the average researcher (active or otherwise). There is an underlying attractiveness to the field of interest (**UndrlyngFieldAttrtv**) but perceptions in the community do not adjust instantaneously. This adjustment time is characterized by **TimeToAcceptUFA**.

**RefNCPerRschr** is the reference level of new claims staked per active researcher required to generate half the normal attractiveness of this field. The author expects that claims staking has the strongest influence on field attractiveness. Thus, in the steady state for the average field, about half the attractiveness should be generated by claims and so this parameter should be set to normal productivity (1 claim per researcher per year).

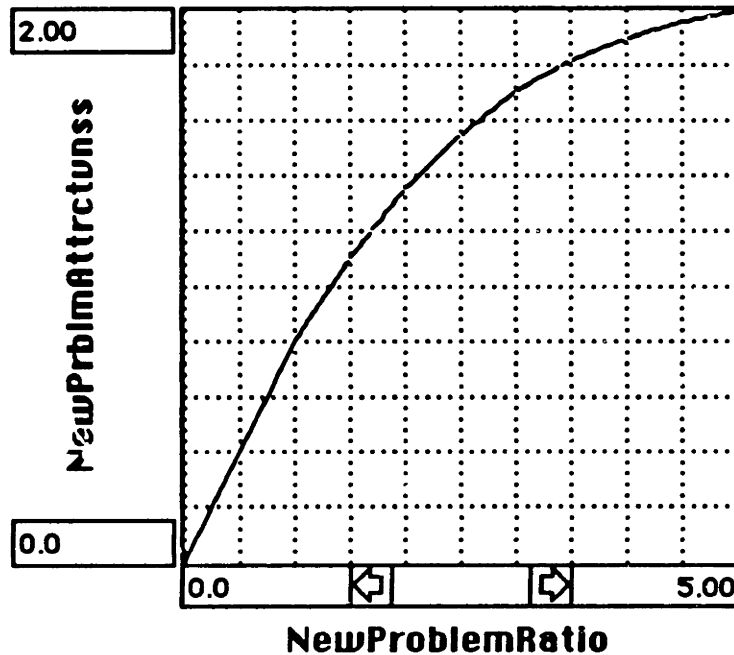


Figure 3-24: New Problem Attractiveness Function

**RefNIPerRschr** is the reference level of new information available to the average active researcher required to generate half the normal attractiveness of this field. If half of the normal attractiveness can be generated by new information alone then there are exciting findings and discussions underway in this field. If an active researcher had a steady supply of new information equivalent to the output of 50 researchers (or half of the information required for normal productivity) then there would be lots of interesting findings to discuss. However, the setting of this parameter is rather arbitrary and needs to be investigated further.

**RefNPPerRschr** is the reference level of new problems per researcher required to generate half the normal attractiveness of the field. If half of the normal attractiveness can be generated by new problems alone then there are exciting opportunities in the field, and easy to find too. A level of 3 new problems per currently active researcher would make it easy for new recruit to find interesting and exciting projects.

**TimeForNCIDecay** is the average time that a claim staked against a problem is considered to be new, and thus offers a recent indication of the rewards that can be won in this field. At the end of this time, a

claim becomes old news and thus does not generate attraction based on its newness. A claim that is 2 or more years old seems quite remote from the potential of the field today, thus the author chose 1 year as the value for this parameter.

**TimeForNIIDecay** is the average time that a piece of information is considered to be new, and thus offers a freshly intriguing topic for the community to discuss and probe. Eventually information becomes old news and thus does not generate attraction based on its newness. In some ways information is like a humorous story. It is fun to hear the first time, and to think about it. It is fun to repeat it for your colleagues, but eventually everyone's heard it. The author estimated that this process would exhaust itself in 1 year.

**TimeForNPIDecay** is the average time that a problem is considered to be new, and thus offers a new frontier of exploration. At the end of this time, a problem becomes old news and thus does not generate attraction based on its newness. It may take months to settle into a new research agenda, thus the newness of a problem will take longer than this to fade. However, after a couple of years researchers will have published papers on the topic and gained a lead addressing the problem. Thus this parameter is probably less than 2 years, and so 1 year was chosen as the estimate.

**TimeToAcceptUFA** is the time taken by an average researcher to adjust his/her perceptions of the underlying field attractiveness to a new level. Although perceptions do not adjust instantaneously, it does not take years for researchers to recognize opportunities. Thus an intermediate value of 6 months was chosen.

#### *Assumptions:*

**Underlying field attractiveness** is comprised only of attractiveness generated by new problems, new information, and new claims. Furthermore, new problem and new claims attractiveness are determined by the level of new problems and claims per active researcher to reflect the fact that overcrowding reduces attractiveness

**and that these perceptions are formed by what potential recruits hear directly or indirectly from active researchers.**



## **Chapter 4: Behaviour of the Model**

Four aspects of model behaviour are considered here:

- Base case of the R&D community's response to a problem set of fixed size with no expansion.
- Sensitivity analysis of the effect of parameter variation on the base case results.
- Join rates and the role of latent researchers.
- Implications on behaviour of problem set expansion.

### **Base Case - No Problem Set Expansion**

In the base case, some breakthrough makes feasible a set of research agendas. These research agendas together form a set of problems to be addressed by the R&D community. With no problem set expansion, the set is of fixed size throughout the life-cycle of the community. The base case illustrates the community's response to a sudden appearance of a fixed problem set. Figure 4-1 illustrates the flow of problems from their initial appearance (waiting to be identified), to open problems (waiting to be solved), to solved problems and staked claims. The time horizon of the simulation is 16 years.

The base case response is the double peak plot of the active researcher population shown in figure 4-2. The first peak is due primarily to attractiveness generated by new problems, while the second peak is due primarily to attractiveness generated by claims staked against problems solved. There are four phases to this dynamic which the author labels the 'frontier', 'harsh reality', 'productivity', and 'technical limits' phases.

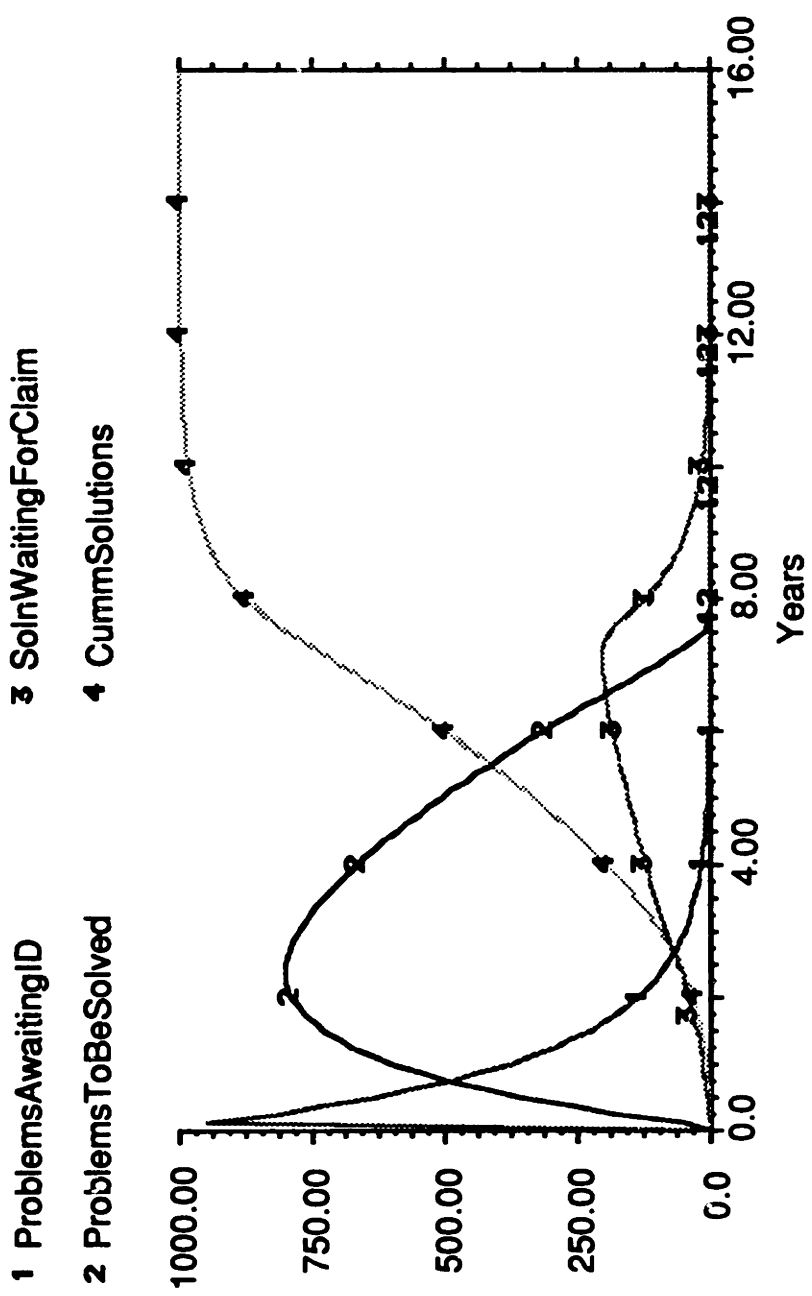


Figure 4-1: Problem Flow from Identification to Solution

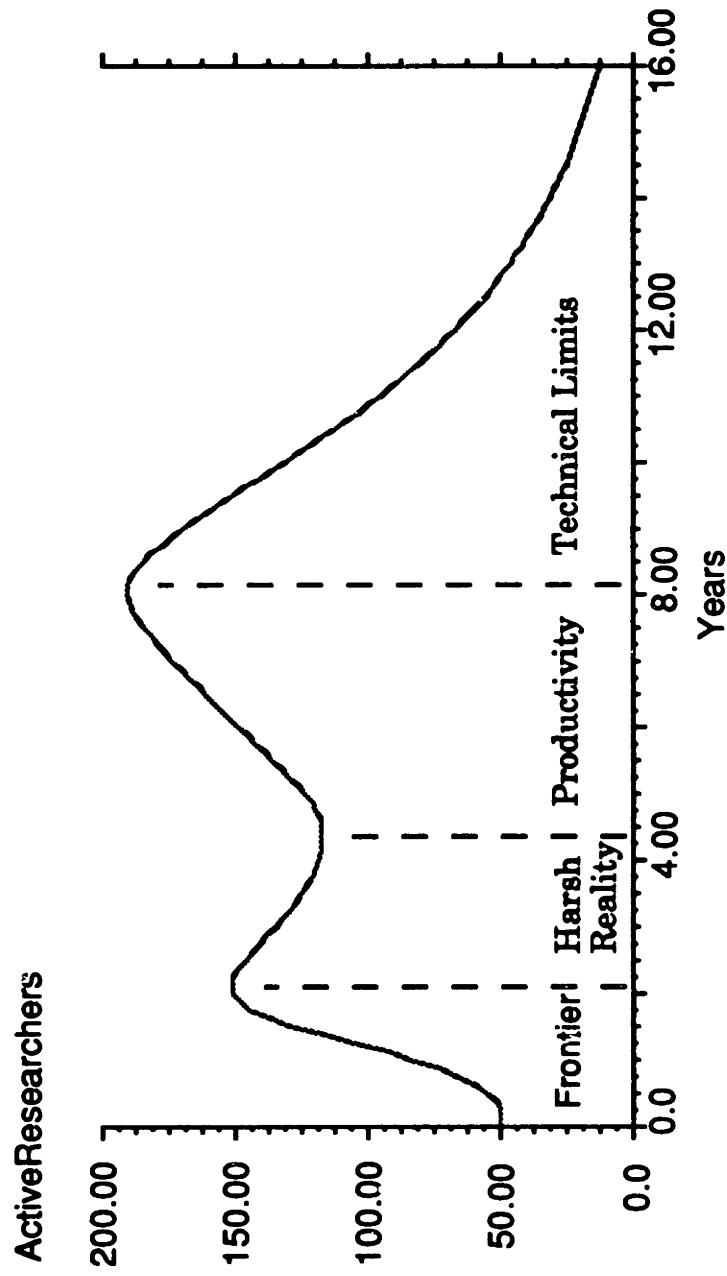


Figure 4-2: Phases of R&D Community Growth

*Frontier Phase*

This is the initial rush into the field that best illustrates the bandwagon effect. Figure 4-3 shows the causal loops that dominate the behaviour in this phase. Immediately after the breakthrough, the number of new problems rises, which in turn raises perceived attractiveness (PA). The number of recruits will rise quickly in response to a rise in PA because of the positive feedback loop shown between recruits and active researchers, which dominates the behaviour early on. (Increasing the number of active researchers increases both the number of new graduate students that can be brought into the field, and the number of contacts between active researchers and other researchers.) The positive feedback loop creates the exponential growth that characterizes the bandwagon effect.

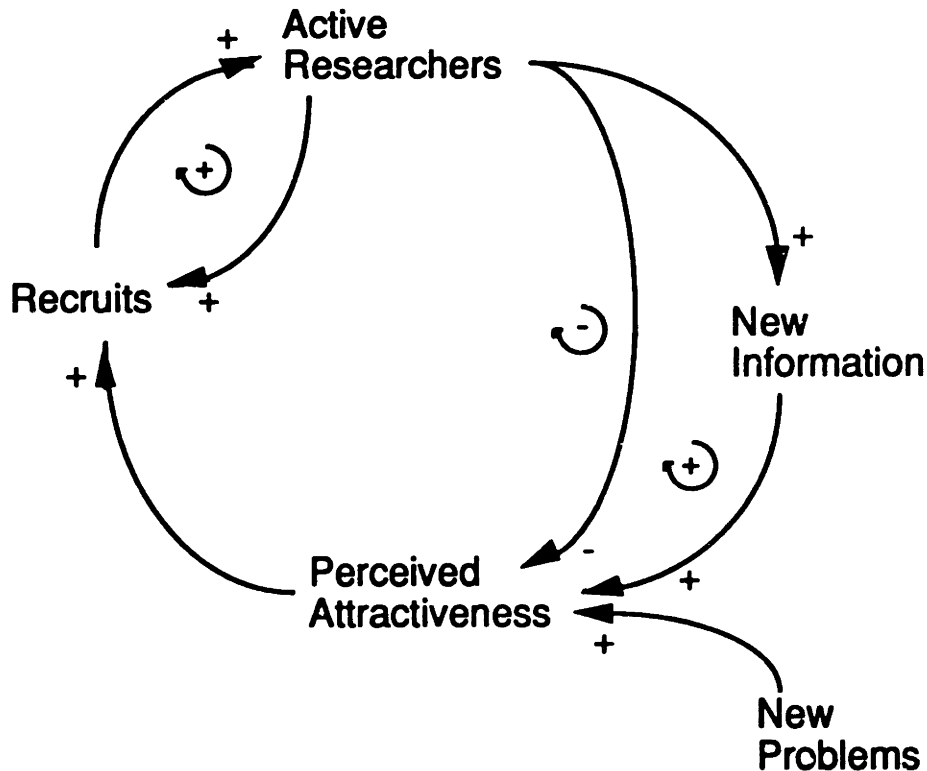


Figure 4-3: Frontier Phase Feedback Loops

This growth is limited by the eventual overcrowding in the field (raising the number of active researchers lowers PA) and by the novelty of the problem set wearing off. The crowding-out effect is produced by the negative feedback loop between active researchers and perceived attractiveness, and dominates model behaviour later in the frontier phase.

*Harsh Reality Phase*

Once the novelty of the problem set begins to wear off, the attractiveness of the field must be maintained by attraction generated by the flow of new information, at least until problem solving can begin to generate attractiveness. The harsh reality of the problem set's difficulty sets in to remedy any initial over-optimism. As perceived attractiveness falls to reflect the current reality, the fraction quitting the field rises. Figure 4-4 illustrates the primary feedback loops of the harsh reality phase.

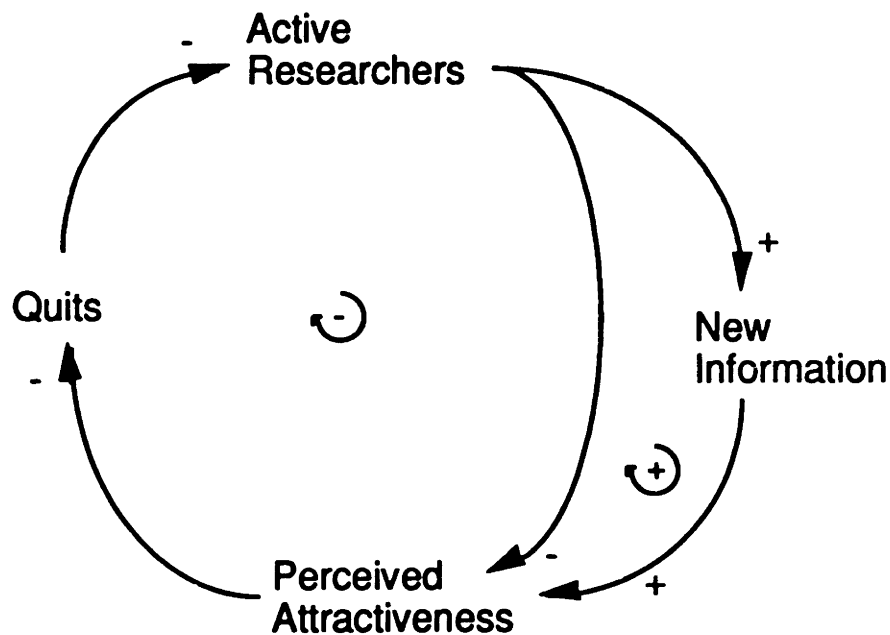


Figure 4-4: Harsh Reality Phase Feedback Loops

The negative feedback loop between active researchers and perceived attractiveness (PA) dominates model behaviour during the harsh reality phase, quickly adjusting the population in response to lower PA. The positive feedback loop through new information continues to provide impetus for growth, however, its strength diminishes with rising PA and it acts with considerable delay.

### *Productivity Phase*

Eventually the level of problem solving rises enough to generate attractiveness that reverses the decline in the field. Figure 4-5 illustrates the dominant feedback loops of the productivity phase. Along with the positive feedback loops found in the frontier phase, there is a new one involving claims staking. Additional active researchers will raise problem solving and thus claim staking. More claims staked results in higher perceived attractiveness of the field as potential researchers see the rewards accruing to the participants. Thus recruit rates rise, further raising the number of active researchers in positive feedback loop.

The second growth phase is limited primarily by the number and difficulty of the problem to be solved. Eventually progress slows to the point where the attractiveness generated by new claims staked is no longer growing.

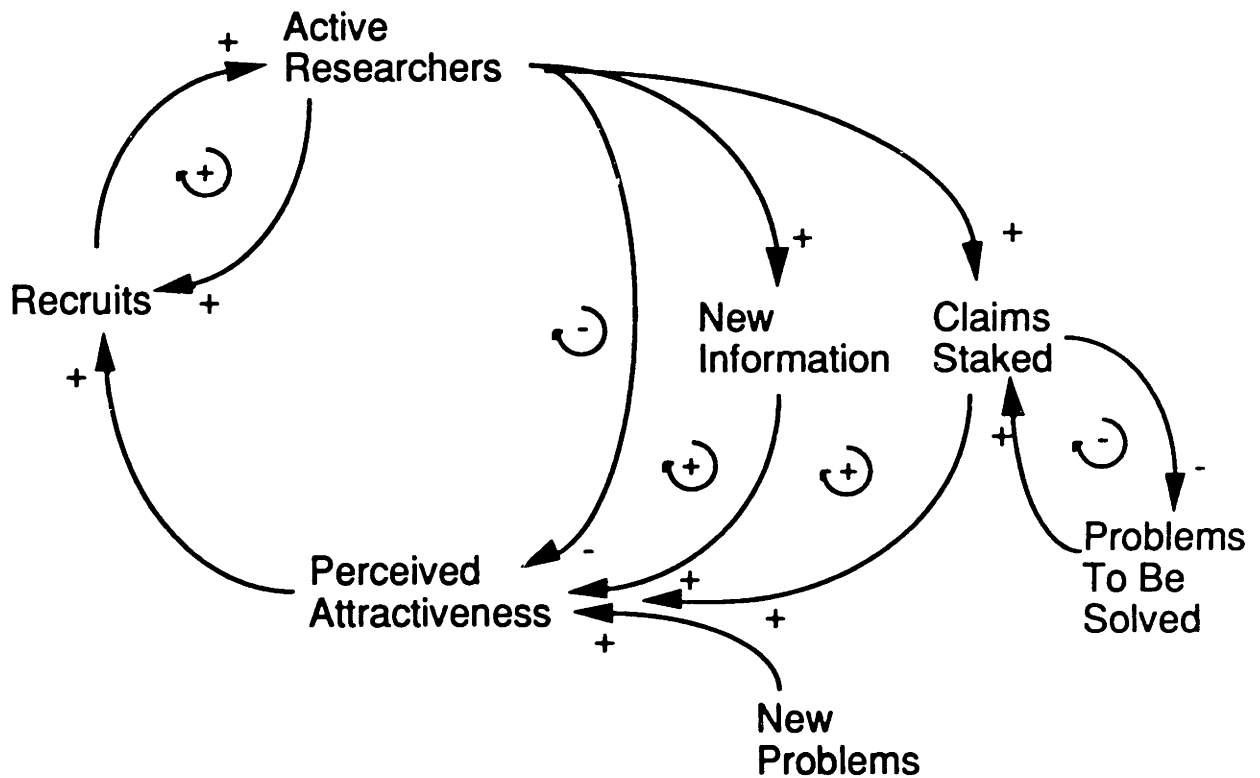


Figure 4-5: Productivity Phase Feedback Loops

### *Technical Limits Phase*

The attractiveness generated by new claims will start to fall as researchers approach the limits of current technology in their problem solving activity. Eventually only the most difficult problems remain, ones that current technology is only marginally able to support. Productivity falls off and

attractiveness due to new claims staked falls in response. As a result the same feedback loops that dominated in the harsh reality phase, now dominate in the technical limits phase. The number of active researchers decays as they realize that few rewards will be won by remaining.

### *Comparison With Neural-Network Community*

Figure 4-6 reproduces data from the study by Rappa and Debackere of the neural network community (NNC)<sup>2</sup>. In terms of the base case behaviour, the NNC data can be interpreted as showing a breakthrough in 1969-71 followed by the familiar double peak dynamic, followed by a third peak caused by another breakthrough around 1983-85.

The first breakthrough (somewhere in 1969-71) may have been a combination of advances in biological models of brain function, along with the Minsky and Papert controversy. The stimulus from biology was probably Marr's 1969 paper, 'A Theory of Cerebellar Cortex', which is often cited by neural networks researchers.

The other stimulus was probably Minsky and Papert's 1969 book, Perceptrons: An Introduction to Computational Geometry, which highlighted the limitations of the neural networks of the time and argued that the field was diverting resources from the more promising field of artificial intelligence. The fallout was a drop in funding for neural networks, but also considerable publicity. Perhaps, the controversy raised significant new problem interest by articulating the problems faced by the neural networks community, and the

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<sup>2/</sup> Rappa and Debackere define an active researcher as anyone who publishes a paper in the field in the current year.



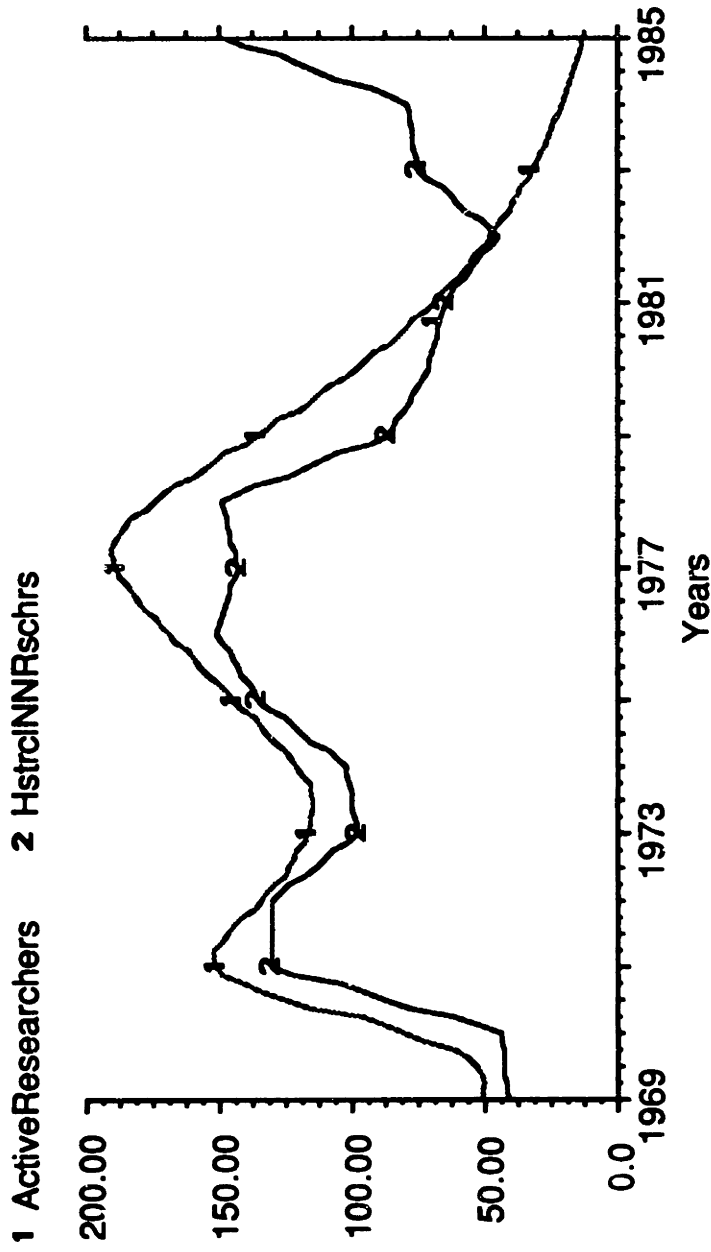


Figure 4-6: Comparison of Historical and Simulated Neural Network Community Size (Source: Rappa & Debackere 1989, linear interpolation)

new recruits were simply undeterred by Minsky and Papert's gloomy assessment of the field's potential.

The second breakthrough (somewhere in 1983-85) was probably a combination of works by Hopfield, Mead, and Hillis, combined with advances in integrated circuit technology which made new implementations feasible. Hopfield (1982) demonstrated the ability of relatively simple networks to perform human-like tasks. Mead (1985) demonstrated that parallel analog neural networks can be implemented in VLSI at high densities. Hillis (1985) further articulated the open problem set and the potential of the field by describing the Connection Machine, a massively parallel processor.

### Sensitivity Analysis

The sensitivity of the model can be examined by considering the effect of parameter variation on the two main features of the dynamic, i.e., each of the two peaks in active researcher population.

#### *First Peak*

The first peak in active researcher population is driven primarily by three factors: new problem attractiveness, new information attractiveness, and student join rate. Although other factors influence this peak, these three have the strongest influence.

New problem attractiveness (NPA) has the strongest influence over the first peak primarily because perceived attractiveness (PA) is almost entirely determined in the early years by the size of the new opportunities. The following parameters control NPA:

**TimeForNPIDecay:** time for new problem interest decay.

**RefNPPerRschr:** reference new problems per researcher.

**NewPrblmAttrctvnss:** the attractiveness generated by the level of new problems open to the community.

Figure 4-7 illustrates the effect of halving TimeForNPIDecay (i.e., problems are only considered new for half as long). Because problems lose their novelty faster, less NPA is generated and fewer researchers join the field during the first frontier phase. The reduction in the first peak has a spill over effect into the second peak because it takes longer for problem solving momentum to build up from the smaller base. The net result is that the life-cycle is extended by several years. Changes in the other two parameters have similar effects.

If a critical mass of researchers can not be assembled, then subsequent problem solving does not raise PA high enough to keep the community from dwindling out of existence. Figure 4-7 illustrates the failure to develop a critical mass when the parameter TimeForNPIDecay is divided by three. Similar behaviour is observed when the initial community size is set to a value less than 11, because a critical mass for problem solving never develops.

New information attractiveness (NIA) influences the first peak primarily because the level of new information builds (with a time lag) as the size of the community grows. The following parameters control NIA:

**TimeForNIIDecay:** time for new information interest decay.

**RefNIPerRschr:** reference new information per researcher.

**NewInfoAttrctvnss:** the attractiveness generated by the level of new information available to the community.

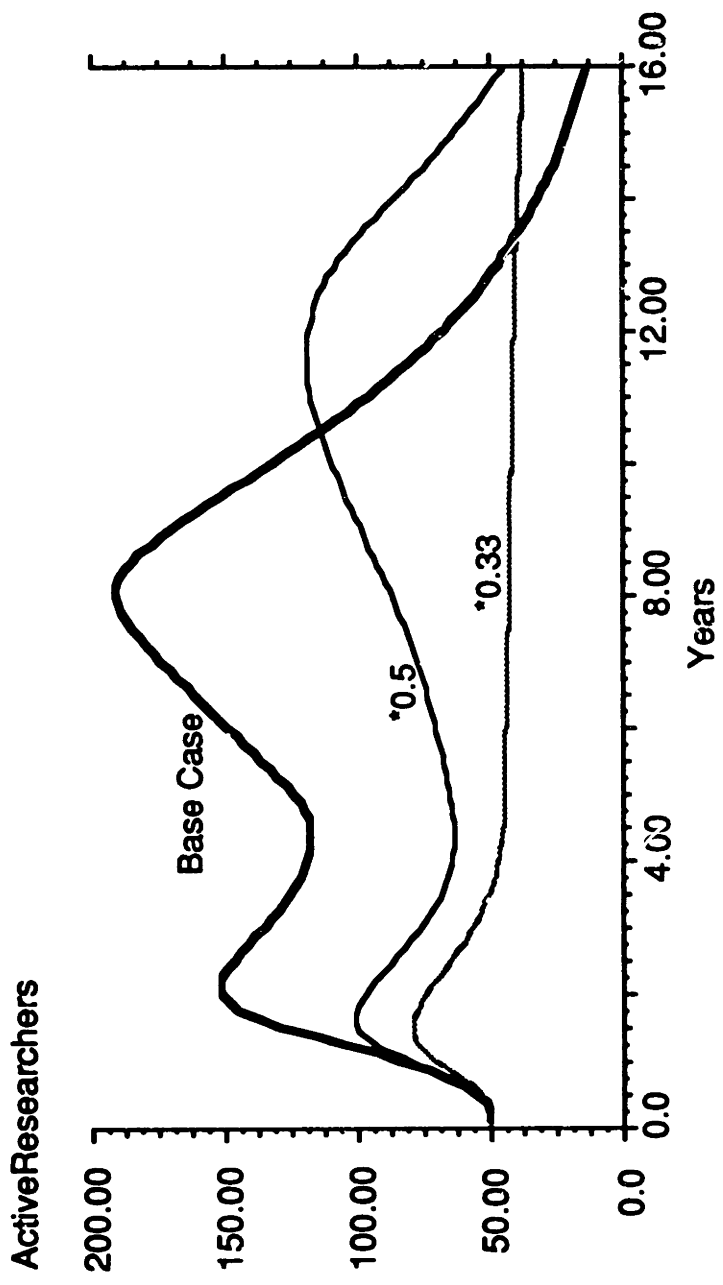


Figure 4-7: Effect of Varying TimeForNPIDecay on Model Behaviour

New graduate student recruit rates influence the first peak because the community grows primarily through students. Furthermore the recruiting through most of the frontier phase capacity constrained by the number of potential supervisors among the active community. The capacity limit is determined by  $NewStudentsPerRsch$  (the annual number of new students that the average active researcher can take under supervision). The first peak is particularly sensitive to changes in this parameter.

### *Second Peak*

The second peak in active researcher population is driven by the following five factors in rough order of importance: researcher productivity, new claims attractiveness, new information attractiveness, new problem attractiveness, and quit/join rates.

Researcher productivity (RP) has the strongest influence over the second peak primarily because perceived attractiveness (PA) is almost entirely determined in the later years by the rate of problem solving. The following parameters have the strongest influence on RP:

**AvgFrctnInfoAvbl:** the fraction of disseminated information available to the average researcher.

**EffOfCumKnOnResPrody:** the effect of cumulative knowledge on researcher productivity.

**EffOfInfoOnResPrody:** the effect of available information on researcher productivity.

**InfoDecayTime:** the length of time that an average piece of information retains its relevance to the current research agenda.

**RefInfoReqdPerRschr:** the reference amount of information required by the average researcher to make normal progress.

**THABTOEffect:** the Two-Heads-Are-Better-Than-One effect that captures the productivity gains of cooperation among researchers.

Figure 4-8 illustrates the effect of reducing **AvgFrctnInfoAvbl** (e.g., only 70% as much information is disseminated through the community to the average researcher). With less information, researchers are less productive and claims staking rates are lower. The result is lower PA and thus fewer recruits. The net result is that life-cycle is extended by several years. Changes in the other parameters have similar effects.

If the reduction in productivity is strong enough, then PA does not rise high enough to keep the community from dwindling out of existence. Figure 4-8 illustrates the failure to develop a critical mass when the parameter **AvgFrctnInfoAvbl** is cut in half. Lower productivity implies a higher critical mass hurdle.

Parameters that control new claims attractiveness and quit/join rates have effects similar to those that control productivity. They control the strength of the intermediate relationships that link PA to the number of active researchers. Some example parameters are:

**ContactsPerRschr:** the average annual number of contacts between a researcher and other researchers outside his/her field.

**NewClaimsAttrctvnss:** the attractiveness generated by recent claims staked against problem solutions.

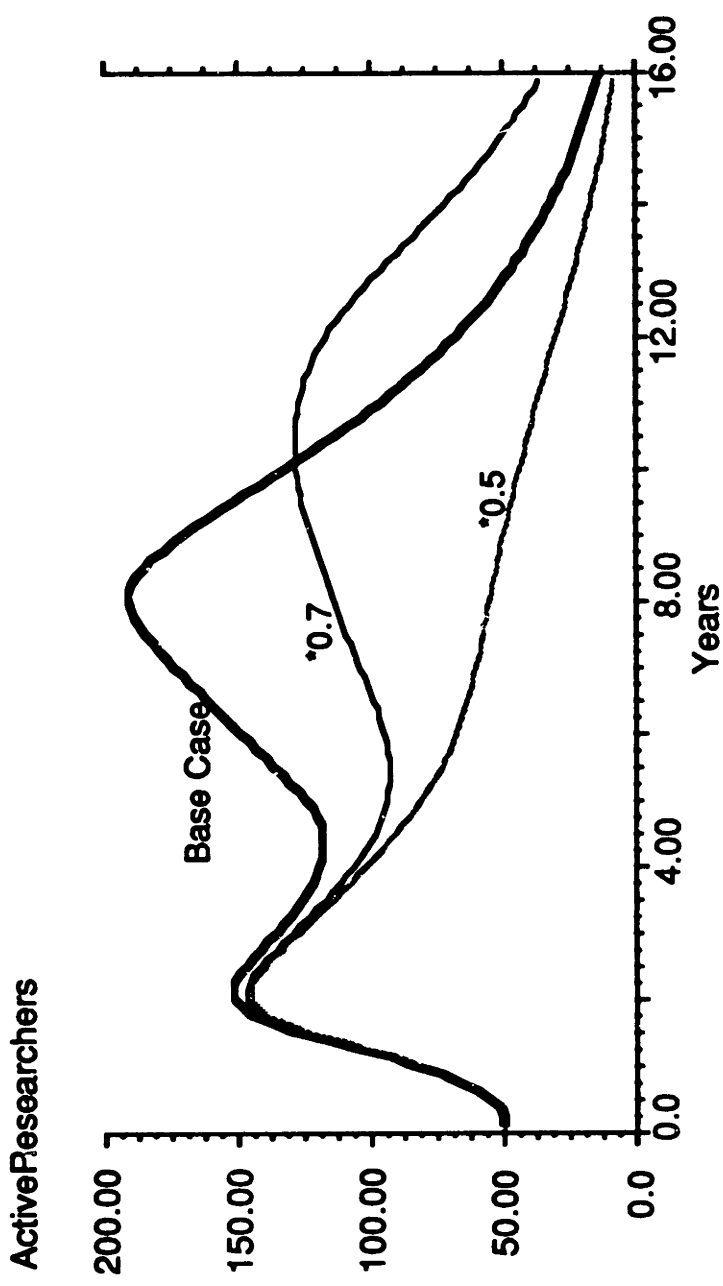


Figure 4-8: Effect of Varying AvgFrctmOfInfoAvbl on Model Behaviour

**QuitFraction:** the fraction of active researchers leaving the field in a year.

**TimeForNCIDecay:** the length of time that the average claim is considered new and thus is representative of the sort of rewards that a researcher can gain by working in a field.

New information attractiveness influences the second peak in much the same way as the first peak. The level of new information builds (with a time lag) as the size of the community grows. More new information means higher PA.

New problem attractiveness (NPA), as described with respect to the first peak, has a spill over effect on the second peak. Although there is very little NPA in latter years, NPA builds the membership in the early years that provides the critical early momentum to problem solving.

### Join Rates

Figure 4-9 illustrates the rates at which researchers join the field in the base case. There are two points of interest here. First, the majority of new recruits come from graduating students. Second, latent researchers do not provide a significant net inflow to the field.

The discussion of latent researchers only applies to the growth of the second peak because at the start of the first peak, latent researchers is initialized to zero. However, over the life-cycle, the number of latent researchers (as shown in figure 4-10) never grows large enough to be able to contribute a significant number of recruits, even if all rejoined. The author was unable to find a reasonable set of parameters that produced a significantly different result.



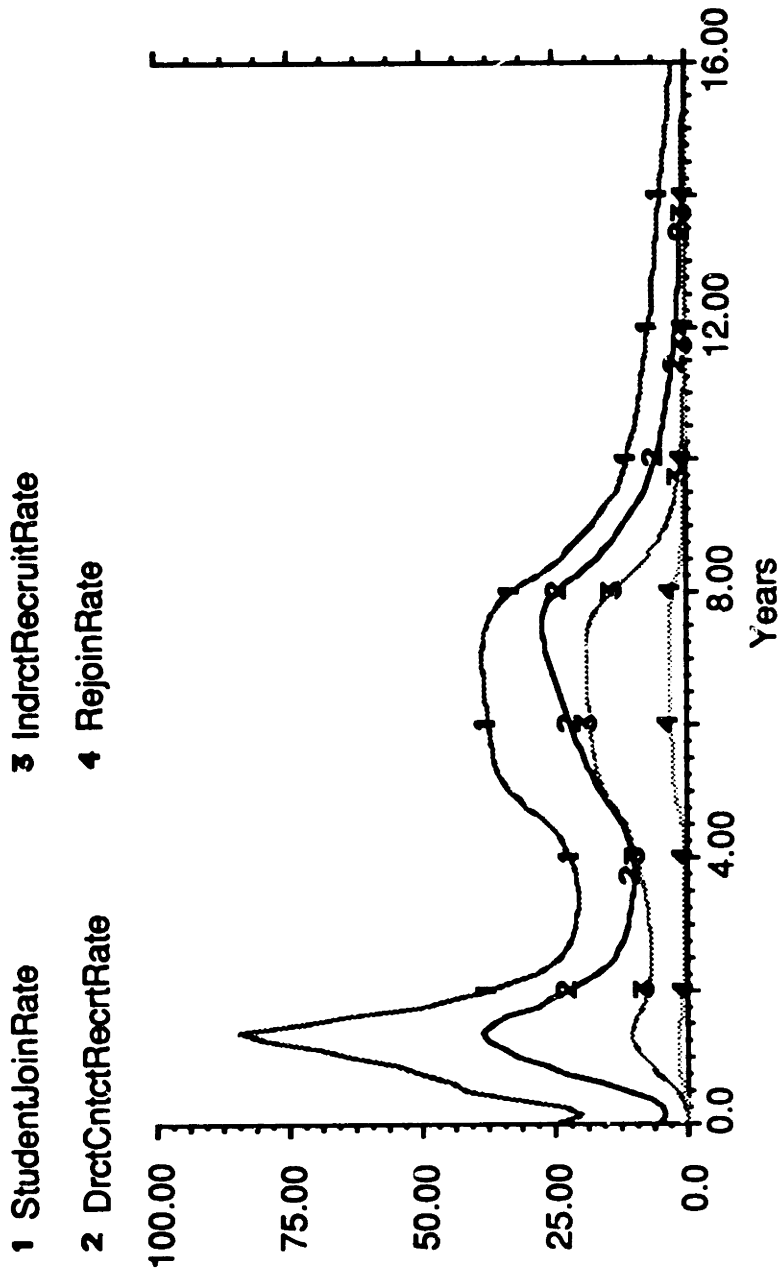


Figure 4-9: Comparison of Join Rates

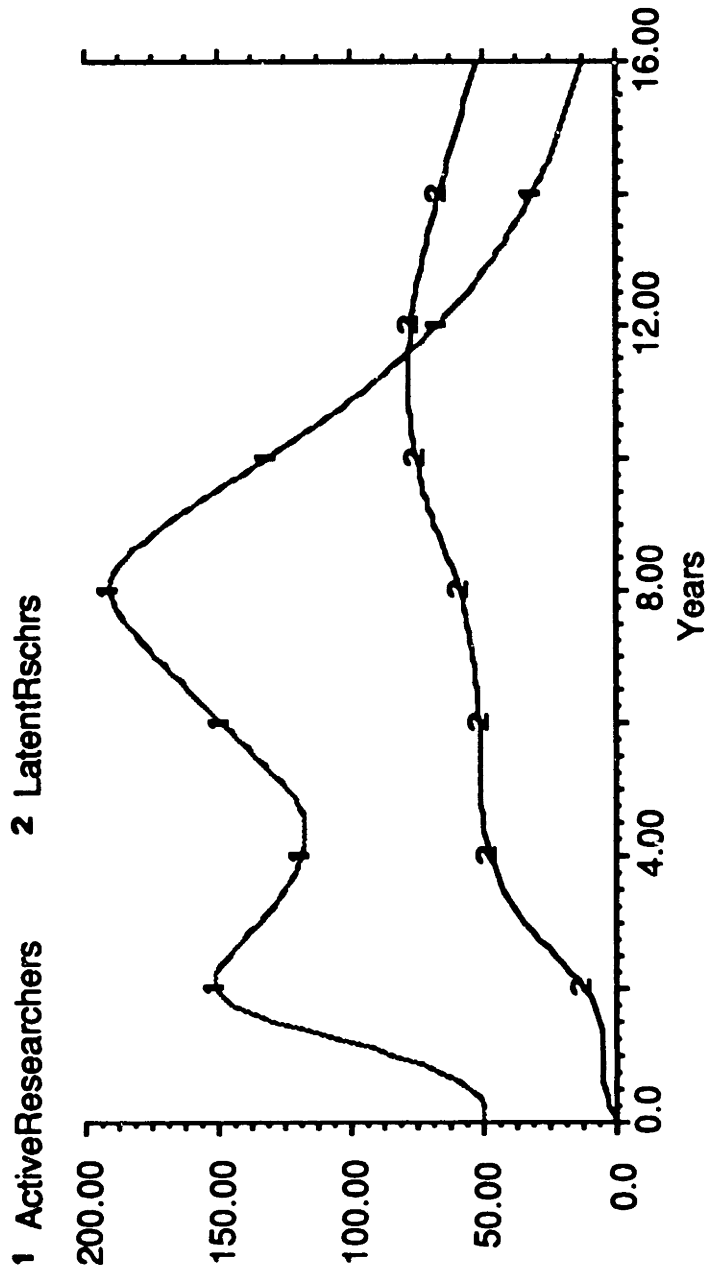


Figure 4-10: Comparison of Active and Latent Researchers

**The limited effect of latent researchers on growth is due to two factors:**

- **The pool of latent researchers does not accumulate to large numbers because the retire rate is comparable to the in-flow from active researchers.**
- **The flow of latent researchers back into the field is limited by the number alternative fields that a latent researchers could choose from. Many latent researchers will switch into other fields rather than return simply because there are so many other fields to choose from.**

### **Problem Set Expansion**

**When the problem set expands gradually over time rather than instantaneously as in the base case, the dynamics of the two peaks blur into each other. Instead of the double peak pattern, the result is closer to a single higher peak (if expansion stops at some point) or sustained growth (if expansion continues). Figure 4-11 illustrates the pattern of active researcher population that results from a short expansion in the problem set as shown (with an initial problem set size of 250 rather than 1000 as in the base case).**

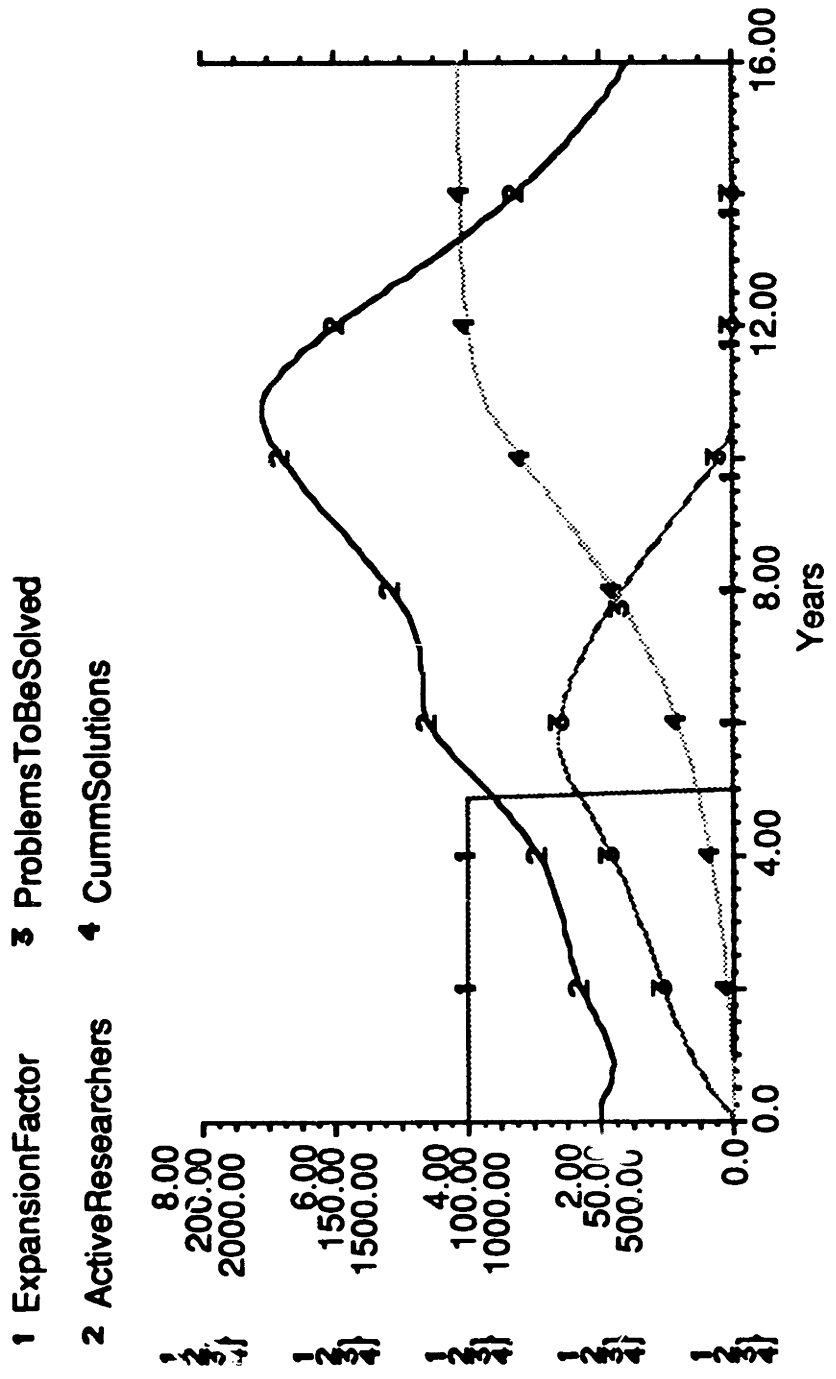


Figure 4-11: Effect of Problem Set Expansion on Model Behaviour

## **Chapter 5: Conclusions**

The objective of this model building exercise was to examine some of the concepts described by Rappa and Debackere (1989), specifically, the bandwagon effect and cycles of enthusiasm and despair. Together with Prof. Rappa, the author has mapped out what they believe to be the important causal relationships involved and has created a simulation of the growth and diffusion of an R&D community. The model uses parameters that have been judged qualitatively to be reasonable. Rappa and Debackere at this writing are analyzing survey data that may be used to quantitatively parameterize the model.

With the assumption of a problem set of fixed size, the simulation reproduces roughly the behaviour of the neural network community between 1970 and 1982, as reported by Rappa and Debackere (1989). After 1982, another surge in neural network research takes place. In the context of the model, the more recent growth in membership is interpreted as the result of another breakthrough that opened another larger problem set.

An R&D community's growth is seen as occurring in two phases. The 'frontier' phase is characterized by growth stimulated by the attractiveness of a new set of research problems. The 'productivity' phase comes later and is characterized by growth stimulated by the attractiveness of researchers staking claims to problem solutions. If the problem set expands over time, then the two phases may overlap and blur into each other.

In both growth phases, the number of active researchers rises exponentially because of positive feedback loops. For example, additional active researchers

can provide increased capacity to recruit and absorb graduating students which creates more active researchers. Similarly, additional active researchers will come in contact with more potential recruits in other fields, resulting in more recruits and thus more active researchers.

With this positive feedback, a 'bandwagon' effect is observed followed by sharp reductions in membership. This results in a 'cycles of enthusiasm and despair' pattern as observed in the neural networks study. Furthermore, the model demonstrates the 'critical mass' effect whereby the field fails to accomplish significant problem solving if membership is low early on in the life-cycle.

In the model, growth comes primarily from graduating students, and little from latent researchers rejoining the field. Both of these results could be verified through analysis of Rappa and Debackere's recent survey data.

## **Chapter 6: Suggestions for Extension**

The following extensions could be considered to carry this project further:

- The model could be parameterized using the survey data currently under analysis by Rappa and Debackere.
- The Ph.D. student population could be modelled separately to better define the effect of student recruiting. Currently the capacity constraint on student recruiting is constant per active researcher, including those who are new student recruits. Clearly, the model would be more accurate if the constraint depended on non-Ph.D. researchers only.
- A good validation for the model results would be to look for the double peak pattern in the histories of other fields such as high-temperature superconductivity.
- Another validation of the model would be to use the survey data to verify that most recruits are students and that few are latent researchers.
- The effect of media attention could be incorporated endogenously into the model.
- The model assumes an identifiable set of open problems being addressed by the R&D community. An extension of this work could attempt to verify that this is a reasonable approximation, and to investigate researchers' perception of the problem set.
- The historical data, used for comparison with the simulated population size, are based on papers published. A more appropriate comparison might be with simulated claims staking rates rather than population size.

## **References**

**DARPA Neural Networks Study (1988)**

**AFCEA International Press, Fairfax, VA**

**Hillis, D. (1985)**

**The Connection Machine**

**MIT Press, Cambridge, MA**

**Homer, J.B. (1982)**

**'Theories of the Industrial Revolution: A Feedback Perspective'**

**DYNAMICA, vol. 8, pp. 30-35**

**Homer, J.B. (1987)**

**'A Diffusion Model with Application to Evolving Medical Technologies'**

**Technological Forecasting and Social Change, vol. 31, pp. 197-218**

**Hopfield, J.J. (April 1982)**

**'Neural Networks and Physical Systems with Emergent Collective Computational Abilities'**

**Proceedings of the National Academy of Sciences, USA, vol. 79**

**Marr, D. (1969)**

**'A Theory of Cerebellar Cortex'**

**Journal of Physiology, London, vol. 202, pp. 437-470**

**Mead, C. (1985)**

**'A Sensitive Electronic Photoreceptor'**

**Chapel Hill Conference on Very Large Scale Integration**

**pp. 463-471**

**Minsky, M.A. and Papert, S.A. (1969)**

**Perceptrons: An Introduction to Computational Geometry**

**MIT Press, Cambridge, MA**



**Rappa, Michael A. and Debackere, Koenraad. (June 1989)**

**"The Emergence of a New Technology: The Case of Neural Networks"**

**Working Paper #3031-89-BPS**

**MIT Sloan School of Management, Cambridge MA**

**Richmond, B., Peterson, S., Vescuso, P. (1987)**

**An Academic User's Guide to STELLA™**

**High Performance Systems, Lyme, NH 03768**

**Roberts, E.B. editor (1978)**

**Managerial Applications of System Dynamics**

**MIT Press, Cambridge, MA**

**Sterman, J.D. (1985)**

**'The Growth of Knowledge: Testing a Theory of Scientific Revolutions  
with a Formal Model'**

**Technological Forecasting and Social Change, vol. 28, pp. 93-122**

## **Appendix**

### **STELLA™ Model Equation Listing**

**ActiveResearchers = ActiveResearchers + dt \* ( RecruitRate - QuitRate + RejoinRate + StudentJoinRate - ARetireRate )**  
**INIT(ActiveResearchers) = InitActvRschr**  
**{Researchers active in this field of research}**

**CummSolutions = CummSolutions + dt \* ( ClaimStakeRate )**  
**INIT(CummSolutions) = 0 {Problems}**  
**{Solved Problems Who's Solutions Are Generally Available to the Research Community}**

**InfoDiseminated = InfoDiseminated + dt \* ( DiseminationRate - RelevanceDecayRate )**  
**INIT(InfoDiseminated) = InitActvRschr\*InfoDecayTime**  
**{Information units}**  
**{Information diseminated throughout the research community that is still relevant to the research agendas}**

**LatentRschr = LatentRschr + dt\*(QuitRate - RejoinRate - LRetireRate)**  
**INIT(LatentRschr) = 0**  
**{Researchers who had worked in this field but who have been attracted into other fields. The assumption is that they can be attracted back into this field.}**

**NewClaims = NewClaims + dt \* ( CSR - NCInterestDecayRate )**  
**INIT(NewClaims) = 0 {Problems}**  
**{The number of problems with recent claims staked against them}**

**NewInfo = NewInfo + dt \* ( DR - NIInterestDecayRate )**  
**INIT(NewInfo) =**  
**ActiveResearchers\*TimeForNIIDecay {info units}**  
**{The number of units of new info that are attracting researchers to this field}**

**NewProblems = NewProblems + dt \* ( PIDR - NPInterestDecayRate )**  
**INIT(NewProblems) = 0 {Problems}**  
**{The number of new problems that are attracting researchers to this field}**

**OtherRschr** = **OtherRschr** + **dt** \* ( **-RecruitRate** + **StudentAltJoinRate** - **ORetireRate** )

**INIT(OtherRschr)** = 10000-**InitActvRschr**

{Researchers working in other fields that have never worked in this field}

**ProblemsAwaitingID** = **ProblemsAwaitingID** + **dt** \* ( **-ProblemIDRate** + **PrblmExpansionRate** )

**INIT(ProblemsAwaitingID)** = 0 {Problems}

{Problems that are now accesible to identification by the research community}

**ProblemsToBeSolved** = **ProblemsToBeSolved** + **dt** \* ( **-ProblemSolveRate** + **ProblemIDRate** )

**INIT(ProblemsToBeSolved)** = 0 {Problems}

{Problems identified by the research community as open for reasonably likely profitable research attention}

**SolnWaitingForClaim** = **SolnWaitingForClaim** + **dt** \* ( **ProblemSolveRate** - **ClaimStakeRate** )

**INIT(SolnWaitingForClaim)** = 0 {Problems}

{The number of Problems solved that are waiting for claims on the value of the solution to be staked through publication, patents, etc.}

**Students** = **Students** + **dt** \* ( **TrainRate** - **StudentAltJoinRate** - **StudentJoinRate** )

**INIT(Students)** = **TrainRate** {Researcher}

{The number of students deciding on which field to choose}

**TotalActiveExp** = **TotalActiveExp** + **dt** \* ( **AddAERate** - **LoseAERate** )

**INIT(TotalActiveExp)** = 75 {Researcher-Years}

{The cummulative experience in this field amongst currently active researchers}

**TotalLatentExp** = **TotalLatentExp** + **dt** \* ( **AddLERate** - **LoseLERate** )

**INIT(TotalLatentExp)** = 0 {Researcher-Years}

{The cummulative experience in this field amongst researchers no longer active in this field}

**TotalProblems** = **TotalProblems** + **dt** \* ( **PER** )

**INIT(TotalProblems)** = 0.1

{Problems}{Total number of problems solved or to be solved by this community of researchers}

**UndiseminatedInfo = UndiseminatedInfo + dt \* ( CollectionRate - DiseminationRate )**

**INIT(UndiseminatedInfo) = InitActvRschr\*TimeToDiseminate**  
{Information units}{Information collected by researchers but not yet shared with their colleagues}

**AddAERate = ActiveResearchers+RejoinRate\*AvgLatentTimeInFld**  
{Researcher-Years per Year}

{Rate of adding to the total experience base of the active researchers per year is one year for each active rschr plus the experience of rejoining latent rschrs}

**AddLERate = QuitRate\*AvgActiveTimeInFld**  
{Researcher-Years per Year}

{Rate of adding to the total experience base of the latent researchers per year is the experience of quitting active rschrs}

**AltFields = 100** {Number of alternative fields of research}

{Used to reflect the probability of a researcher choosing this field when he is making a choice amongst all possible fields}

**ApprchPerProblem = MinAppPerPrblm\*(1-BalanceInAPP)+MaxAppPerPrblm\*BalanceInAPP**

{Approaches Per Problem}{The average number of different approaches attacking a problem concurrently}

**ARetireRate = ActiveResearchers\*RetireFrctn**  
{Researchers per year}

{The rate at which researchers active in this field will retire}

**AvgActiveTimeInFld = IF ActiveResearchers < 0.1 Then 0 Else TotalActiveExp/ActiveResearchers**

{Years}

{The average years of experience in this field of active rschrs}

**AvgInfoAvlble = InfoDiseminated\*AvgFrctnOfInfoAvlbl**  
{Info units}

{The info available to the average rschr out of all the info disseminated plus what info is self-produced}

**AvgLatentTimeInFld = If LatentRschr < 0.1 Then 0 Else TotalLatentExp/LatentRschr**

{Years}{The average years of experience in this field of latent rschrs}

**AvgTimeToID = 1 {Year}**

{Average time between a problem's being first accessible to identification and its identification as an open research problem}

**BrkThruSize = 1000 {problems}**

{The number of problems made accessible to identification as open problems by the research community as result of the breakthrough}

**ClaimStakeRate = (SolnWaitingForClaim/TimeToStakeClaim)**  
**{problems}**

{Rate at which problems have claims staked against them}

**CollectionRate = ActiveResearchers\*InfoClctnPerRschr**

**{Information units per quarter}**

{The rate at which the research community generates research information to feed the problem solving process}

**ConcntrtnRatio = 0.5**

{Dimensionless metric for the concentration of researchers in labs}

**ContactsPerRschr = 100**

{Contacts with other researchers in a year}

**CSR = ClaimStakeRate**

**CtrlPA = 0 {Control Switch = 0 or 1}**

{1 = Perceived attractiveness is set to test input}

**CummSolnRatio = CummSolutions/TotalProblems**

**{Dimensionless}**{the ration of cummulative solutions to the total size of the breakthrough problem set}

**DCRFraction =**

**ContactsPerRschr\*ProbRschrIsActive\*ProbRcrtGivenCntct**

**{1/year}**

{Fraction of rschrs that will be recruited for the first time from other fields in a year through direct personal contacts}

**DiseminationRate = UndiseminatedInfo/TimeToDiseminate**

**{Information units per year}**

{Rate of Info Disemination to Other Researchers}

**DR = DiseminationRate**

**DrctCntctRecrtRate = OtherRschr\*DCRFraction**

{Researchers per year}

{The number of researchers recruited from other fields in a year through direct personal contacts}

**DTPMWEffect = (1/EffRschrPerProblem) {Dimensionless}**

{The effect of Dividing The Pie More Ways, that is with more than one researcher working on a problem the value of the claim is divided more ways}

**EffectOfMediaAttn = 1**

{The effect of media attention positive and negative on the attractiveness of this field. 1 = neutral, 0 = kills all interest, 2 = Extremely heightened interest}

**EffOfDvrstyOnResPrd = THABTOEffect\*DTPMWEffect\*ShotgunEffect**

{Dimensionless}

{The combined effect of diversity on rschr productivity}

**EffOfRCapOnPrody = If ActiveResearchers < RschrCapacity Then 1 Else RschrCapacity/ActiveResearchers**

{Dimensionless}

If undercapacity then productivity of avg rschr falls to reflect underutilized rchrs searching for further problems}

**EffRschrPerProblem = RschrPerApprch\*ApprchPerProblem**

{Researchers per problem}

{The effective number of researchers working concurrently on the same problem as determined by team sizes and the limit on the number of approaches that the community will try}

**ExpansionFactor = 0 {Dimensionless}**

{The number of new problems opened up for each problem solved}

**FrctnChoosingField = (1/AltFields)\*EffOfPAOnFCF**

{1/Years}{Fraction of students per year joining this field is the normal join fraction (1/the no. of alternatives) times the effect of perceived attractiveness}

**IndrctRecruitRate = OtherRschr\*IRFraction**

{Researchers per year}

{The number of researchers recruited from other fields in a year indirectly through claims staking with publications, patents, etc.}

**InfoClctnPerRschr = 1**

{Information units per Researcher per Year}

{By definition the average researcher will collect 1 unit of research information in a year}

**InfoDecayTime = 2 {Years}**

{Average time for information to lose relevance to current research agendas}

**InfoRatio = AvgInfoAvlble/RefInfoRqrdPerRshr**

{Dimensionless}{The ratio of the average amount of information available to a researcher over the reference amount of information required to make normal progress}

**InitActvRschr = 50 {Researchers}**

{The initial size of this field's active research community}

**IRFraction = FrctnAwareOfClaims\*ProbRcrtGvnClmAwrn**

{1/year}

{Fraction of researchers in other fields who are recruited for the first time to this field through claims staked}

**LoseAERate = (QuitRate+ARetireRate)\*AvgActiveTimeInFld**

{Researcher-Years per Year}

{The rate at which the experience base of active rschrs is depleted due to quits to other fields and retirements}

**LoseLERate = (LRetireRate+RejoinRate)\*AvgLatentTimeInFld**

{Researcher-Years per Year}

{The rate at which the experience base of latent rschrs is depleted due to rejoins to this field and retirements}

**LRetireRate = LatentRschr\*RetireFrctn**

{Researchers per year}{The rate at which latent researchers will retire}

**MinAppPerPrblm = 1.5 {Approaches per problem}**

{The average number of different approaches attacking a problem when there are many more problems than rschrs}

**NCInterestDecayRate = NewClaims/TimeForNCIDecay**

{Problems per year}

{The rate at which claimed problems lose their ability to attract researchers to this field because they are no longer new}

**NCPeRschr = NewCiaims/(ActiveResearchers+0.001)**  
{Claimed problems/Researcher}  
{The number of new claims staked against problems per researcher active in the field}

**NewClmsRatio =NCPeRschr/RefNCPeRschr**  
{Dimensionless}  
{The ratio of new claims per rschr to the reference level}

**NewInfoRatio = (NewInfo\*AvgFrctnOfInfoAvlbl)/RefNIPerRschr**  
{Dimensionless}  
{The ratio of new info available to the reference level}

**NewProblemRatio =NPPeRschr/RefNPPeRschr**  
{Dimensionless}  
{the ratio of new problems per rschr to the reference level}

**NewStudentCapacity =**  
**ActiveResearchers\*NewStudentsPerRschr {Rschr}**  
{Maximum number of new students that can be recruited into the field due to supervision constraints}

**NewStudentsPerRschr = 0.75 {Researcher per Researcher}**  
{Number of new students that the average active researcher can take on for supervision}

**NIInterestDecayRate = NewInfo/TimeForNIIDecay**  
{Info units per year}  
{The rate at which units of new info lose their ability to attract researchers to this field because they are no longer new}

**NPInterestDecayRate = NewProblems/TimeForNPIDecay**  
{Problem per year}  
{The rate at which problems lose their ability to attract researchers to this field because they are no longer new}

**NPPeRschr = If ActiveResearchers < 0.1 Then 0 Else**  
**NewProblems/ActiveResearchers {Problems/Researcher}**  
{The number of new problems per rschr active in this field}

**ORetireRate = OtherRschr\*RetireFrctn**  
{Researchers per year}  
{The rate at which other researchers retire}



**PER = PrblmExpansionRate**

**PIDR = ProblemIDRate**

**PrblmExpansionRate = PULSE(BrkThruSize, 0,100) +**

**ProblemSolveRate\*ExpansionFactor**

**{problems per year}**

**{The rate at which problems become accessible to identification by the rsch community}**

**PrvcdAttractiveness =**

**SMTH1(UndrlyngFieldAttrtv\*EffectOfMediaAttn,TimeToAcceptUFA,1)**

**\*(1-CtrlPA)+TstPA\*CtrlPA**

**{Attractiveness units}**

**{The attractiveness of this field as pereived by the research community}**

**ProblemIDRate = ProblemsAwaitingID/AvgTimeToID**

**{Problems / Year}**

**{The rate at which problems are identified as open to profitable research attention}**

**ProblemSolveRate = ActiveResearchers\*ResearchPrody**

**{Problems solved per year, derived from rschrs times productivity}**

**ProbRcrtGivenCntct = RefProbRGCntct\*EffOfPAOnPRGC**

**{Dimensionless}**

**{The probability of recruitment given a personal contact with a researcher in this field}**

**ProbRcrtGvnCImAwrns = RefProbRGAWrnss\*EffOfPAOnPRGCA**

**{Probability of recruiting a researcher from another field given awareness of claims staked in this field}**

**ProbRschrIsActive = ActiveResearchers/TotalRschrs**

**{Dimensionless; The probability that a researcher is active in this field}**

**PTBSPerRschr = ProblemsToBeSolved/ActiveResearchers**

**{Problems per Researcher}**

**{The number of open problems per researcher active in the field}**

**QuitRate = ActiveResearchers\*QuitFraction\*EffOfATFOnQR**

**{Researchers/Year}**

**{The number of active researchers that leave to work in another field in a year}**

**RecruitRate = DrcntctRecrtRate+IndrcntRecruitRate**  
{researchers per year}  
{the total number of newly recruited researchers}

**RefInfoRqrdPerRshr = 100** {Info units}  
{The reference amount of information required by a researcher to make normal progress}

**RefNCPerRschr = 1** {Claimed problems per researcher}  
{The reference number of claimed problem solutions per researcher required to generate half the normal attractiveness of this field}

**RefNIPerRschr = 50** {Info units per researcher}  
{The reference amount of new information available to the average active researcher required to generate half the normal attractiveness of this field}

**RefNPPerRschr = 3** {Problems per researcher}  
{The reference number of new problems open to active researchers required to generate half the normal attractiveness of this field}

**RefProbRGAwrnss = 0.0014**  
{The reference probability of recruiting a researcher from another field of research given his/her awareness of the claims staked in this field}

**RefProbRGCntct = 0.001**  
{Dimensionless}  
{The normal probability of recruitment given a personal contact with a researcher in this field}

**RefRschrPrdctvty = 1** {Puzzles per Researcher per Year}  
{The reference productivity of an average researcher in normal times, normal as defined by the comments for other variables}

**RejoinRate = LatentRschr\*RejoinFraction**  
{Researchers per year}  
{The number of latent researchers rejoining this field in a year}

**RelevanceDecayRate = InfoDiseminated/InfoDecayTime**  
{Information units per year}  
{The amount of information in a year that has lost its relevance to current research agendas}

**ResearchPrody =**  
**RefRschrPrdctvty\*EffOfInfoOnResPrody\*EffCumKnOnResProd\*EffOfDvrst**  
**yOnResPrd\*EffOfRCapOnPrody**  
{Problems per researcher per year}  
{Productivity of the avg rschr is the ref prod'ty times effects of info,  
cumm knowledge, diversity, capacity}

**RetireFrctn = 0.25 {1/Years}**  
{The fraction of researchers that retire in a year.}

**RschrCapacity = ProblemsToBeSolved\*EffRschrPerProblem**  
{Researchers}  
{The number of researchers that can be supported by the current  
problem set}

**RschrPerApprch = 3**  
{Researchers per approach to a problem,  
feeds the Two Are Heads Better Than One Effect}

**SGEImpliedPrody = 1/(ImpliedAvgTimeToSlv\*1)**  
{Problems per Researcher Year, the productivity level implied by the  
Shotgun Effect of multiple approaches to a problem assuming one rschr  
per prblm, the # of rschrs will be accounted for in DTPMWEff}

**ShotgunEffect = SGEImpliedPrody/RefRschrPrdctvty**  
**StudentAltJoinRate = Students-StudentJoinRate**  
{Researchers per year}  
{The number of students choosing alternative fields in a year}

**StudentJoinRate =**  
**Min(Students\*FrctnChoosingField, NewStudentCapacity)**  
{Researchers per year}  
{The number of students choosing to join this field in a year}

**TimeForNCIDecay = 1 {Year}**  
{The average time that a claim stake against a problem is considered  
new by researchers}

**TimeForNIIDecay = 1 {Years}**  
{The average time for a researcher to lose interest in a unit of new info  
because it is no longer recently identified}

**TimeForNPIDecay = 1 {Years}**  
{The average time for a researcher to lose interest in a problem because it is no longer recently identified}

**TimeToAcceptUFA = 0.5 {Years}**  
{Average time taken by researchers to accept a new level of field attractiveness}

**TimeToDiseminate =0.5 {Years}**  
{Average Time to Diseminate to the Research Community the Data Collected}

**TimeToStakeClaim = 1 {Years}**  
{Average Time to stake a claim against a problem's solution through publication, patent, etc.}

**TotalRschr = OtherRschr+ActiveResearchers+LatentRschr**  
{Researchers}  
{The total number of researchers in the population both in and out of the field of interest}

**TrainRate = 2500 {Researchers}**  
{The number of students entering research careers per year that have the potential to enter this field}

**TstCImStkRate = ClaimStakeRate**  
**\*(1-CtrlPA)+CtrlPA\*100**  
{For test purposes only}

**TstPA = 0.55**  
{Test input for perceived attractiveness}

**UndrlyngFieldAttrtv =**  
**(NewPrblmAttrctvnss+NewInfoAttrctvnss+NewClaimsAttrctvnss)**  
{Attractiveness units, the underlying level of attraction of this field to which the average researcher's perception will migrate}

**AvgFrctnOfInfoAvlbl = graph(ActiveResearchers)**  
(  
0.0,1.00),(100.00,0.700),(200.00,0.500),(300.00,0.400),(400.00,0.325),(500.00,0.275),(600.00,0.240),(700.00,0.225),(800.00,0.215),(900.00,0.205),(1000.00,0.200)

**BalanceInAPP = graph(PTBSPerRschr)**  
(1.00,1.00),(1.50,0.900),(2.00,0.800),(2.50,0.700),(3.00,0.600),(3.50,0.500),(4.00,0.400),(4.50,0.300),(5.00,0.200),(5.50,0.100),(6.00, 0.0)

**EffCumKnOnResProd = graph(CummSolnRatio)**  
(0.0,0.500),(0.100,0.800),(0.200,1.00),(0.300,1.15),(0.400,1.20),  
(0.500,1.20),(0.600,1.15),(0.700,1.00),(0.800,0.750),(0.900,0.400),  
(1.00, 0.0)

**EffOfATFOnQR = graph(AvgActiveTimeInFld)**  
(0.0,1.00),(0.400,1.00),(0.800,1.00),(1.20,1.00),(1.60,0.950),(2.00,0.800),  
(2.40,0.650),(2.80,0.550),(3.20,0.515),(3.60,0.500),(4.00,0.500)

**EffOfInfoOnResPrody = graph(InfoRatio)**  
(0.0,0.0),(0.200,0.0500),(0.400,0.150),(0.600,0.500),(0.800,0.800),  
(1.00,1.00),(1.20,1.15),(1.40,1.25),(1.60,1.32),(1.80,1.37),(2.00,1.40)

**EffOfPAOnFCF = graph(PrcvdAttractiveness)**  
(0.0,0.0),(0.200,0.0500),(0.400,0.125),(0.600,0.250),(0.800,0.500),  
(1.00,1.00),(1.20,2.00),(1.40,3.50),(1.60,4.50),(1.80,4.90),(2.00,5.00)

**EffOfPAOnPRGC = graph(PrcvdAttractiveness)**  
(0.0,0.0),(0.200,0.0500),(0.400,0.125),(0.600,0.250),(0.800,0.500),  
(1.00,1.00),(1.20,2.00),(1.40,3.50),(1.60,4.50),(1.80,4.90),(2.00,5.00)

**EffOfPAOnPRGCA = graph(PrcvdAttractiveness)**  
(0.0,0.0),(0.200,0.0500),(0.400,0.125),(0.600,0.250),(0.800,0.500),  
(1.00,1.00),(1.20,2.00),(1.40,3.50),(1.60,4.50),(1.80,4.90),(2.00,5.00)

**FrctnAwareOfClaims = graph(TstCimStkRate)**  
(0.0,0.0),(20.00,0.200),(40.00,0.360),(60.00,0.500),(80.00,0.610),  
(100.00,0.700),(120.00,0.770),(140.00,0.815),(160.00,0.855),  
(180.00,0.885),(200.00,0.900)

**Hstrc!NNRschr = graph(TimeInput)**  
(1969.00,41.00),(1970.00,44.00),(1971.00,130.00),(1972.00,130.00),(1973.00,98.00),  
(1974.00,102.00),(1975.00,135.00),(1976.00,151.00),(1977.00,143.00),  
(1978.00,149.00),(1979.00,86.00),(1980.00,71.00),(1981.00,65.00),  
(1982.00,45.00),(1983.00,75.00),(1984.00,79.00),(1985.00,148.00),  
(1986.00,264.00),(1987.00,493.00)

ImpliedAvgTimeToSlv = graph(ApprchPerProblem)  
(1.00,1.40),(1.50,1.15),(2.00,1.00),(2.50,0.880),(3.00,0.810),(3.50,0.760),  
(4.00,0.740),(4.50,0.730),(5.00,0.720),(5.50,0.710),(6.00,0.700)

MaxAppPerPrblm = graph(ConcstrtnRatio)  
(0.0,4.00),(0.100,3.50),(0.200,3.00),(0.300,2.60),(0.400,2.30),  
(0.500,2.00),(0.600,1.80),(0.700,1.66),(0.800,1.58),(0.900,1.54),  
(1.00,1.50)

NewClaimsAttrctvns = graph(NewClmsRatio)  
(0.0,0.0),(0.200,0.0200),(0.400,0.0800),(0.600,0.180),(0.800,0.320),  
(1.00,0.500),(1.20,0.700),(1.40,0.940),(1.60,1.24),(1.80,1.62),(2.00,2.00),  
(2.20,2.46),(2.40,3.10),(2.60,3.70),(2.80,3.92),(3.00,4.00)

NewInfoAttrctvns = graph(NewInfoRatio)  
(0.0,0.0),(0.500,0.300),(1.00,0.450),(1.50,0.550),(2.00,0.600),  
(2.50,0.630),(3.00,0.650),(3.50,0.670),(4.00,0.685),(4.50,0.690),  
(5.00,0.700)

NewPrblmAttrctvns = graph(NewProblemRatio)  
(0.0,0.0),(0.500,0.400),(1.00,0.800),(1.50,1.10),(2.00,1.35),(2.50,1.55),  
(3.00,1.71),(3.50,1.82),(4.00,1.90),(4.50,1.96),(5.00,2.00)

QuitFraction = graph(PrcvdAttractiveness)  
(0.0,0.900),(0.200,0.880),(0.400,0.800),(0.600,0.500),(0.800,0.300),  
(1.00,0.200),(1.20,0.100),(1.40,0.0500),(1.60,0.0300),(1.80,0.0150),  
(2.00,0.0150)

RejoinFraction = graph(PrcvdAttractiveness)  
(2.00,0.500),(1.80,0.475),(1.60,0.425),(1.40,0.300),(1.20,0.100),  
(1.00,0.0150),(0.800,0.00500),(0.600, 0.0),(0.400, 0.0),(0.200, 0.0),  
( 0.0, 0.0)

THABTOEffect = graph(RschrPerApprch)  
(0.0,0.0),(1.00,1.00),(2.00,3.00),(3.00,5.50),(4.00,7.00),(5.00,8.00),  
(6.00,8.50),(7.00,8.70),(8.00,8.80),(9.00,8.90),(10.00,9.00)