System Dynamics Group
Sloan School of Management
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Introduction to System Dynamics, 15.871
System Dynamics for Business Policy, 15.874
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Assignment 3
Formulating Models of Simple Systems

Assigned: 23 September 2003; Due: 2 October 2003
Please work on this assignment in a group totaling three people.

In the last assignment you explored the relationship between stocks and flows, focusing on how a stock changes as its rates of flow change. In this assignment you explore *feedback*—how levels can influence (or "feed back" to) the rates. This assignment gives you practice with the structure and behavior of fundamental feedback systems. These systems are building blocks from which more complex systems are composed. The assignment also sharpens your understanding of how system dynamics simulations actually work.

Some gentle advice: It is tempting to divide the assignment up among team members so each does only one part, then cut and paste to assemble your team answer. Resist the temptation. Do the work together, so each of you participates fully in the learning process. The divide-and-conquer strategy may appear to save time, but since you won't be learning what you need for future assignments (including the rest of the assignments in 15.871), it will actually cost you time.

A. Getting the Software

There are several excellent software packages available for system dynamics modeling. Three are included in the CD-rom that comes with *Business Dynamics*: ithink, Powersim, and Vensim. All are excellent and I encourage you to check each of them out. For our work this semester we will be using the VensimPLE software. VensimPLE is an academic version of the professional Vensim software. The professional version also supports features such as arrays, automated calibration, optimization, sensitivity analysis, data linking, and so on. VensimPLE has all the functionality we need for the course. Best of all, VensimPLE is free for academic use.

Download and install VensimPLE from the Vensim website, <www.vensim.com>. The Vensim download page is <www.vensim.com/download.html>. The current version is 5.2. Note that this is more recent than the version of VensimPLE that comes on the *Business Dynamics* CD-rom. Be sure to use the new version.

Prepared by John Sterman, Fall 1996. Most recent revision: September 2003.

❑ denotes a question for which you must hand in an answer, a model, or a plot.
• denotes a fact that you will want to include in the model under discussion.
☛ denotes a tip to help you build the model or answer the question.

B. Getting Familiar with the Software and Building Your First Model

The 15.871/874 section of the class server includes a VensimPLE tutorial . This tutorial will help you learn the Vensim software as you build a simple model.

❑ B1. *1 point*. Do the tutorial and build the model it describes.

- ☛ *Be sure to document your model*. Documenting your model means adding enough commentary and explanation so that the meaning of each variable, the reasoning behind each formulation, and the data sources for each parameter value are clear to your audience.
- ☛ *Always provide the units of measure for every variable, and check that every equation is dimensionally consistent*. Vensim can test your model for dimensional consistency (see the tutorial). Be sure to do this on all models you build. Models that fail the dimensional consistency test are meaningless. Often dimensional errors are symptoms of more serious conceptual difficulties.

B2. *1 point total*. Answer the following questions.

❑ a. What kind of feedback loop is created in your model?

❑ b. What is the initial deficit (given the base case parameters)?

❑ c. How long does it take for the deficit to double?

❑ d. How long does it take the deficit to reach $1 trillion/year?

❑ e. What is the relationship between the doubling time and the interest rate? (To discover a relationship, you may want to simulate with extreme interest rates—say, 3% per year and 15% per year).

❑ f. How does the time horizon (the length of the simulation) change the apparent shape of the curves? Why?

- ☛ To answer the question on time horizon, you need to look at your simulation over different periods of time. You can run the model once with a long time horizon (e.g., 100 years) and then change the time range viewed in graphs and tables. Select **Time Axis** from the **Control Panel** dialog box to change the time frame displayed in graphs and tables (see “The Control Panel” in the tutorial or User’s Guide).
- ☛ Vensim allows you to load multiple runs (or “datasets”) and then view the output of different runs in the same graphs and tables. For example, each run can make use of a separate interest rate. See “The Control Panel” in the User’s Guide for details on selecting datasets.

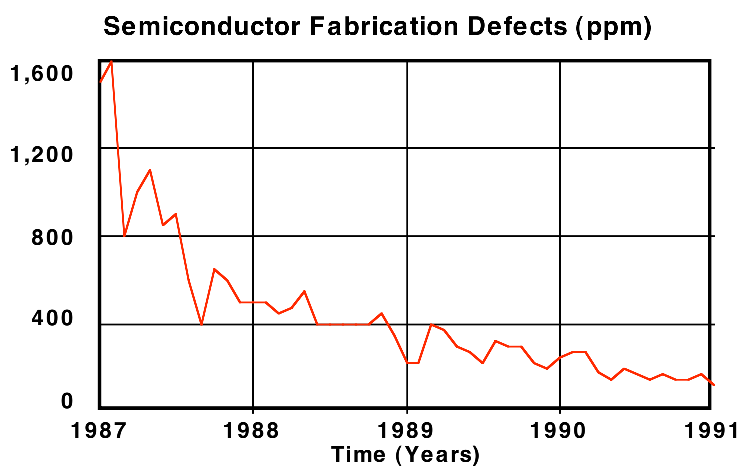
❑ g. Hand in your model (diagram and equation listing) and answers to the above questions. You need not hand in plots, but you should describe how you arrived at your answers.

C. Modeling Goal-Seeking Processes

All goal-seeking processes consist of negative feedback loops. In a negative loop, the system state is compared to a goal, and the gap or discrepancy is assessed. Corrective actions respond to the sign and magnitude of the gap, bringing the state of the system in line with the goal.

For example, consider programs designed to improve the quality of a process in a company. The process could be in manufacturing, administration, product development—any activity within the organization. Improvement activity is iterative. Members of an improvement team identify sources of defects in a process, often ranking benefits of correcting them using a Pareto chart. They then design ways to eliminate the source of the defect, and try experiments until a solution is found. They then move on to the next most critical source of defects. Advocates of Total Quality Management refer to this iterative cycle as the “Plan—Do—Check—Act” or “PDCA” cycle (also known as the Deming cycle, for quality guru W. Edwards Deming). In the PDCA process, the improvement team: (1) plans an experiment to test an improvement idea, (2) does the experiment, (3) checks to see if it works, then (4) acts—either planning a new experiment if the first one failed or implementing the solution and then planning new experiments to eliminate other sources of defects. The team continues to cycle around the PDCA loop, successively addressing and correcting root causes of defects in the process. This learning loop is not unique to TQM: All learning and improvement programs follow some sort of iterative process similar to the PDCA cycle.

The figure below shows data on defects from the wafer fabrication process of a mid-size semiconductor firm (from Figure 4-5 in *Business Dynamics*). The firm began its TQM program in 1987, when defects were running at a rate of roughly 1500 parts per million (ppm). After the implementation of TQM, the defect rate fell dramatically, until by 1991 defects seem to reach a new equilibrium close to 150 ppm—a spectacular factor-of-ten improvement. Note that the decline is rapid at first, then slows as the number of defects falls.



❑ C1. *1 point*. Create a model of the improvement process described above and compare its behavior to the data for the semiconductor firm. Once you have formulated your model, make sure the units of each equation are consistent. Hand in the diagram for your model and a documented model listing.

- Follow the instructions below precisely. Do not add structure beyond that specified.
- Select Initial Time = 1987, Final Time = 1991, and Time Step = 0.125 years. Check the box to save the results every Time Step. Finally, set the unit of measure for time to Years. These parameters are found in Settings... under the Model menu.

- The state of the system is the defect rate, measured in ppm. The defect rate in 1987 was 1500 ppm.
  - ☛ The defect rate is not a rate of flow, but a stock characterizing the state of the system—in this case, the ratio of the number of defective dies to the number produced.
- The defect rate decreases when the improvement team identifies and eliminates a root cause of defects. Denote this outflow the "Defect Elimination Rate."
- The rate of defect elimination depends on the number of defects that can be eliminated by application of the improvement process and the average time required to eliminate defects.
- The number of defects that can be eliminated is the difference between the current defect rate and the theoretical minimum defect rate. The theoretical minimum rate of defect generation varies with the process you are modeling and how you define "defect." For many processes, the theoretical minimum is zero (for example, the theoretical minimum rate of late deliveries is zero). For other processes, the theoretical minimum is greater than zero (for example, even under the best imaginable circumstances, the time required to build a house or the cycle time for semiconductor fabrication will be greater than zero). In this case, assume the theoretical minimum defect level is zero.
- The average time required to eliminate defects for this process in this company is estimated to be about 0.75 years (9 months). The average improvement time is a function of how much improvement can be achieved on average on each iteration of the PDCA cycle, and by the PDCA cycle time. The more improvement achieved each cycle, and the more cycles carried out each year, the shorter the average time required to eliminate defects will be. These parameters are determined by the complexity of the process and the time required to design and carry out experiments. In a semiconductor fab, the processes are moderately complex and the time required to run experiments is determined by the time needed to run a wafer through the fabrication process. Data collected by the firm prior to the start of the TQM program suggested the 9 month time was reasonable.
- Equipment wear, changes in equipment, turnover of employees, and changes in the product mix can introduce new sources of defects. The defect introduction rate is estimated to be constant at 250 ppm per year.

❑ C2. *0.5 point total.* Run your model with the base case parameters, and *hand in the plot.*

❑ a. *Briefly* describe the model's behavior.

❑ b. How well does your simulation match the historical data? Are the differences likely to be important if your goal is to understand the dynamics of process improvement and to design effective improvement programs?

❑ c. Does the stock of defects reach equilibrium after 9 months (the average defect elimination time)? Referring to the structures in your model, explain why or why not.

❑ C3. *0.5 point.* Experiment with different values for the average defect elimination time. What role does the defect elimination time play in influencing the behavior of other variables?

- ❑ C4. *0.5 point total.* The stock reaches equilibrium when its inflows equal its outflows. Set up that equation and solve for the equilibrium defect rate in terms of the other parameters.

- ❑ a. What determines the equilibrium (final) level of defects? Why?

- ❑ b. Does the equilibrium defect rate depend on the average time required to eliminate defects? Why/Why not?

- ❑ C5. *0.5 point total.* Explore the sensitivity of your model's results to the choice of the time step or "dt."

  ☛ Before doing this question, read Appendix A in *Business Dynamics*.

- ❑ a. Change the time step for your model from 0.125 years to 0.0625 years. Do you see a substantial difference in the behavior?

- ❑ b. What happens when dt equals 0.5 years? Why does it behave as it does?

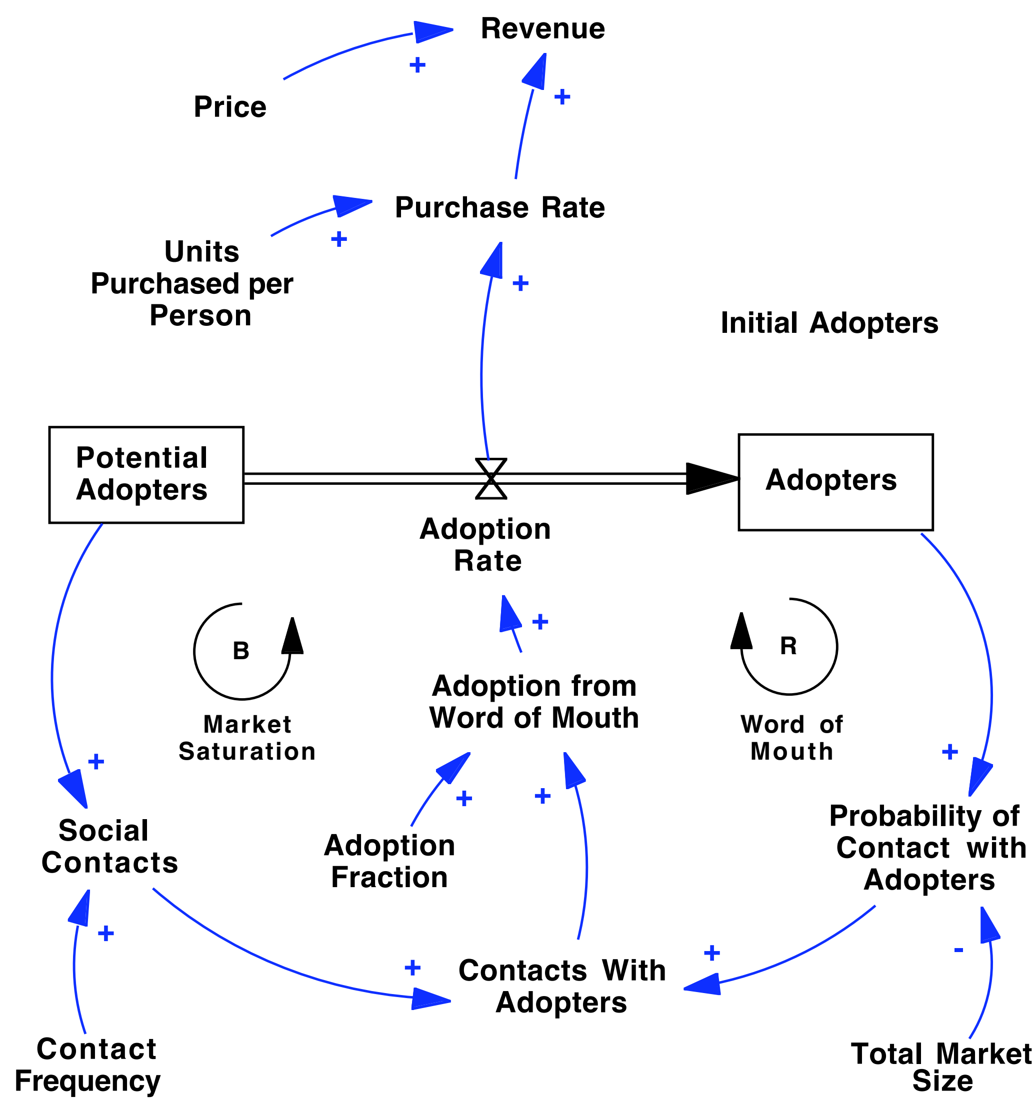
- ❑ c. What happens when dt equals 1 year? Why does the simulation behave this way?

D. Combining Positive and Negative Feedback

Having explored the behavior of simple positive and negative feedback systems, let's turn to a more complex setting where multiple loops interact nonlinearly. The growth of new products often follows S-shaped growth patterns. As discussed in chapter 4, S-shaped growth results from a system in which positive feedbacks dominate early on, but, as the state of the system grows relative to its limits, negative loops begin to dominate. Consider the growth of a new product or product category, such as mobile phones, DVD, or the world wide web. If successful, the installed base (number of cell phones, DVD units, or web sites) usually grows exponentially for a while. Eventually, however, as the market begins to saturate, growth slows and the installed base reaches a maximum determined by the size of the potential market for the product category. Chapter 4 of the text provides examples of such S-shaped growth.

What are the positive feedbacks that generate the initial exponential growth in the diffusion of a successful innovation, and what are the negative feedbacks that limit its growth? The spread of rumors and new ideas, the adoption of new technologies, and the growth of new products can all be viewed as epidemics in which the innovation spreads by positive feedback as those who have adopted it 'infect' those who have not. The concept of positive feedback as a driver of adoption and diffusion is very general, and can be applied to many domains of 'social contagion.' As early adopters of a new product expose their friends, families, acquaintances and colleagues to it, some are persuaded to try it or buy it themselves. In all these cases, those who have already adopted the product come into contact with those who have not, exposing them to it, infecting some of them with the desire to buy the new product, and further increasing the population of adopters. Any situation in which people imitate the behavior, beliefs, or purchases of others, any situation in which people 'jump on the bandwagon,' describes a situation of positive feedback by social contagion. Of course, once the population of potential adopters has been depleted, the adoption (infection) rate falls to zero.

The figure below shows a contagion model of innovation diffusion.



Structure of a simple new product model

Potential adopters come into contact with adopters through social interactions. A fraction of these contacts result in adoption of the new idea or purchase of the new product as the result of favorable word of mouth. Revenue is given by the price and purchase rate; purchases equal the adoption rate times the number of units bought by each adopter. No aftermarket revenues are considered.

The total potential market for the product is divided into two stocks: those who have already purchased the product (the Adopters) and those who have not yet adopted it (the Potential Adopters). As people adopt the product, the Adoption Rate rises, moving people from the Potential Adopter pool to the Adopter pool.

The Vensim equations for the stock and flow structure are therefore:

Adopters = INTEG(Adoption Rate, Initial Adopters) (1)

Potential Adopters = INTEG(–Adoption Rate, Total Market Size – Adopters) (2)

The number of Initial Adopters is modeled as a parameter so you can easily change it for sensitivity tests without editing the model equations.

Note that there are no inflows to or outflows from either stock from outside the system boundary (the adoption rate moves people from one category to the other). Therefore the Total Market Size is constant since Potential Adopters + Adopters = Total Market Size. The Total Market Size will be set as a parameter (constant) in your simulation.

What determines the Adoption Rate? In this model, adoption occurs only through word of mouth:

Adoption Rate = Adoption from Word of Mouth (3)

What then determines Adoption from Word of Mouth? Potential adopters come into contact with adopters through social interactions. However, not every encounter with an adopter results in 'infection' (that is, adoption and purchase of the product). The persuasiveness of the word of mouth and the attractiveness of the product affect the fraction of word of mouth encounters that result in adoption of the product. The fraction of contacts that are sufficiently persuasive to induce the potential adopter to buy the new product, called the Adoption Fraction, is the probability that a given encounter between an adopter and potential adopter results in purchase by the potential adopter. Hence,

Adoption from Word of Mouth = Adoption Fraction * Contacts with Adopters (4)

The rate at which potential adopters come in contact with adopters depends on the total rate at which social interaction occurs and the probability of encountering an adopter.

Contacts with Adopters = Social Contacts * Probability of Contact with Adopters (5)

People in the relevant community are assumed to interact with one another at some rate. The Contact Frequency is the number of other people each person in the community comes in contact with, on average, per time period. Therefore, the total number of contacts experienced by all potential adopters per time period is

Social Contacts = Contact Frequency * Potential Adopters (6)

What fraction of these contacts is with a person who already has the product and can generate word of mouth? That is, what is the probability of contact with adopters? The most common assumption is that people in the community interact randomly, so that the probability of contact with an adopter is simply equal to the fraction of adopters in the total community:

Probability of Contact with Adopters = Adopters/Total Market Size (7)

Finally, the revenue generated by the product is given by the price and purchase rate; the purchase rate, in turn, is the product of the adoption rate and the number of units bought by each adopter:

Revenue = Purchase Rate * Price (8)

Purchase Rate = Adoption Rate * Units Purchased per Person (9)

❑ D1. *1 points total*. Create a Vensim model corresponding exactly to the innovation diffusion model given in the diagram above and equations 1-9. Document your model and hand it in.

☛ Select Initial Time = 0, Final Time = 10 (years), and Time Step = 0.0625 years. Check the box to save the results every Time Step, and finally, set the unit of measure for time to Years. These parameters are found in **Settings…** under the **Model** menu.

☛ The initial condition for Potential Adopters is Total Market Size – Adopters. This ensures that the potential and actual adopter stocks always sum to the total market size.

☛ Check to make sure your model is dimensionally consistent. NOTE: you may need to specify some “Units Synonyms”. For example, you might have the units ‘people’ and ‘person’ in the units fields for different variables. You need to tell Vensim to treat these as synonyms. To do so, select the **Units Equiv.** tab from **Settings…** under the **Model** menu. Enter the equivalent units and enter the equivalent units, separated by commas, for example: Household, Households; or Unit, Units.

☛ ***DO NOT*** add any additional structure or parameters. Implement the model exactly as specified above.

❑ a. Selecting parameters:

Before you can run your model, you need to select parameters. Suppose the product in question is a consumer electronic item similar to DVD players. To keep the model simple, assume the price of the product is constant (though we know the prices for such products typically fall over time). Market research reveals the following:

- The product sells for $200/unit
- At that price, each adopting household will purchase one unit, on average.
- There are about 100 million households in the United States. Select households as the unit of measure for the potential adopter and adopter populations. The marketing department argues strongly that the product is so great every household will eventually get one. Therefore Total Market Size is 100 million households.
- The contact frequency is estimated to be 100/year (that is, one member of each household contacts a member of a different household at the rate of about two per week).

  You need to estimate the adoption fraction—the fraction of households who adopt the product after a word of mouth encounter. Select a value you believe is plausible for this type of product. *Briefly* justify your choice.

☛ Of course, prior to the introduction of a new product, there are no adopters and the installed base is zero. Set Initial Adopters to 0.

❑ D2. *3 points total*. Simulating the model.

☛ Before simulating, create a set of ‘Custom Graphs’ to show the behavior of your model by clicking on the control panel icon in the VensimPLE toolbar (the dial on the right end of the toolbar). Then select the **Graphs** tab, and select **New** to create each new graph. Create one graph with Adopters and Potential Adopters on the same scale, a second graph showing the Adoption Rate, and a third graph showing Revenue. The online user’s guide to Vensim has more details on custom graphs.

- ❑ a. Run your model. Explain the resulting behavior. What happens, and why? How could you solve the problem revealed by the simulation?
- ❑ b. Implement and test your proposed solution.
- ❑ c. Present graphs showing the stocks of potential and actual adopters, the adoption rate, and revenue.
- ❑ d. Explain the behavior in terms of the feedback structure of the system. What fraction of the total market has adopted the product when revenues peak? Why?
- ❑ e. Explore the sensitivity of your model to the different parameters and initial conditions until you understand its behavior. You do not need to present graphs of your sensitivity tests. Do you think the lifecycle generated by your model is reasonable? Based on your simulations, would you change your estimate of the adoption fraction? How could you attempt to estimate the parameters in reality?

❑ D3. *1 point*. Finally, critique the model by making a list of the restrictive or unrealistic assumptions of the model. For example, the model does not include any feedback from the price of the product to the size of the market or adoption rate. Do not propose solutions for these problems.

> ☛ Brevity helps. Example:
>
> “1. The total size of the market is fixed, ruling out both population growth and changes in market size as product attractiveness (price, features, etc.) change.”