Massachusetts Institute of Technology
Sloan School of Management

15.871 Introduction to System Dynamics
Fall 2013

Assignment 3
Mapping the Stock and Flow Structure of Systems

Assigned: Monday September 23, 2013; Due: Monday September 30, 2013
Please do this assignment in a team totaling three people.

This assignment gives you practice with the structure and dynamics of stocks and flows. Stocks and flows are the building blocks from which every dynamic system is constructed. The ability to identify, map, and understand the dynamics of the networks of stocks and flows in a system is essential to understanding the processes of interest in any modeling effort.

☞ Be sure you have carefully read Ch. 6 and 7 of *Business Dynamics* before doing this assignment.

☞ **Submitting your work:** One member of your team should submit your team's write up and model on the course website, as a single zip file containing a word document and a Vensim mdl file. Make sure the write up lists the full names of all members of your team.

A.   Identifying Stock and Flow Variables

The distinction between stocks and flows is crucial for understanding the source of dynamics. In physical systems it is usually obvious which variables are stocks and which are flows. In human and social systems, often characterized by intangible, "soft" variables, identification may be more difficult.

❑ A1. For each of the following variables, state whether it is a stock or a flow, and give units of measure for each.

Name	Type	Units
Example: Inventory of beer	Stock	Cases
Example: Beer order rate	Flow	Cases/week

	Name	Type	Units
1.	Daily Sales of the iPhone 5S		
2.	US National Debt		
3.	China's trade surplus		
4.	Employee experience		
5.	Accounts Payable		
6.	College athletes declaring their intention to turn professional		
7.	Book value of inventory		
8.	Promotion of Senior Associates to Partner at a consulting firm		
9.	Fans of Lance Armstrong		
10.	Euro/dollar exchange rate		
11.	Employee morale		
12.	Greenhouse gas emissions of the US		
13.	Interest rate on 30-year US Treasury Bond		
14.	Runners passing the finish line		
15.	Firm's cost of goods sold (COGS)		

B.   Mapping Stock and Flow Networks

Systems are composed of interconnected networks of stocks and flows. Modelers must be able to represent the stock and flow networks of people, material, goods, money, energy, etc. from which systems are built.

For each of the following cases, construct a stock and flow diagram that properly maps the stock and flow networks described.

☞   Not all the variables are connected by physical flows; they may be linked by information flows, as in the example below.

☞   You may need to add additional stocks or flows beyond those specified to complete your diagram (but keep it simple). Be sure to consider the boundary of your stock and flow map. That is, what are the sources and sinks for the stock and flow networks? Are you tracking sources and sinks far enough upstream and downstream? This process of deciding how far to extend the stock and flow network is called "challenging the clouds" because you question whether the clouds are in fact unlimited sources or sinks.

☞   Consider the units of measure for your variables and make sure they are consistent within each stock and flow chain.

Example: A manufacturing firm maintains an inventory of finished goods from which it ships to customers. Customer orders are filled after a delay caused by order processing, credit checks, etc. Map the stock and flow structure, drawing on the following variables: Inventory, Raw Materials, Production, Order Backlog, Order Rate.

Solution:
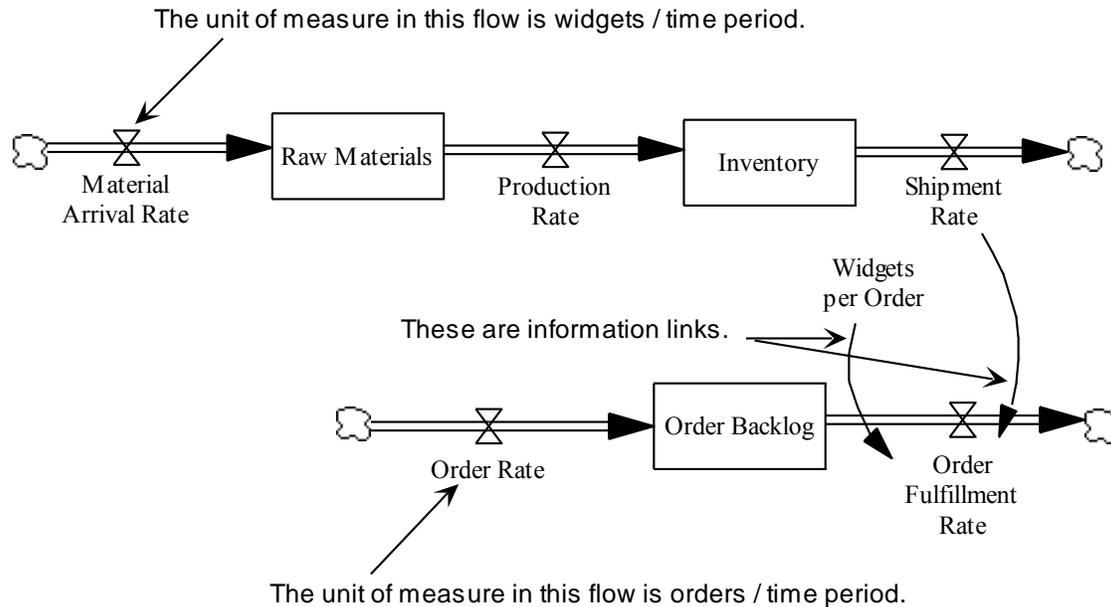
Comment: There are two linked stock and flow networks here: first, the physical flow of materials as they are fabricated into products and shipped to customers; second, the flow of orders. The two networks are linked because there is a direct relationship between physical shipments and order fulfillment (assuming no accounting glitches or inventory shrinkage!)—every time a product is physically shipped, the order is removed from the backlog and denoted as filled. The link between the Shipment Rate and Order Fulfillment Rate is an information link, not a material flow. Note that considering the units of measure helps identify the linkages between the two stock and flow chains. Units:
- All flows in the materials chain: widgets/time period
- Materials and inventory stocks: widgets
- Order flows: orders/time period
- Order fulfillment rate: order/time period (since it is the number of widgets shipped per period divided by the number of widgets per order).

Only the information links directly connecting the stock and flow networks are captured. Other information links that must exist are not represented. For example, the shipment rate must depend on the finished goods inventory (no inventory—no shipments). The purpose of this exercise, however, is to map the stocks and flows, so these feedbacks can be omitted for now. Note that the shipment rate, material arrival rate, and order fulfillment rate were not included in the group of variables listed in the description but must be introduced to complete the stock-and-flow network. Also, the solution omits some structure that might be added if the purpose of the model required it, such as inventory shrinkage and order cancellation flows and the installed base of product (the stock filled up by shipments). The model could be disaggregated further, e.g., splitting the order backlog into two stocks, "orders awaiting credit approval," and "orders approved." The choice of detail is always governed by the purpose of the model.

❑ B1. Firms often have great difficulty bringing new products to market on time and with the quality and functionality customers demand. Map the stocks and flows of the new product development process for a typical high-tech firm. Product development includes the following stages: concept generation, detailed design, prototyping, testing, and launch. At each stage, projects are evaluated, with some continuing on and the rest cancelled.

⊠ Don't forget to 'challenge the clouds' in this example. What happens after new products are launched? How long do new products remain on the market?

❑ B2. A computer manufacturer maintains a large call center operation to handle customer inquiries. Customers with questions or problems call a toll free number for help. In this firm, incoming calls are answered by a voice recognition system that routes calls to an automated system or, if the customer elects, to a live customer service representative (CSR). Calls default to the automated system but customers can, at any time, press "0" or say "representative" to speak to a CSR, or, of course, hang up. Callers electing to speak to a CSR may be placed on hold until an agent becomes available. If the call is answered before the customer gets frustrated and hangs up, the CSR may be able to resolve the issue. Often, however, the CSR is unable to solve the problem and forwards the call to a supervisor or specialized department such as technical support. The issue may or may not be resolved by these specialists. Map the stock and flow structure of calls as they flow through the system.

⊠ In reality, customer inquiries arrive by phone, by email, and by live chat from the firm's website. You don't need to consider these channels separately. Likewise, do not attempt to separate inbound calls into different categories such as billing problems or tech support questions. Assume there is a single flow of calls coming in to the system. These calls are then divided into those electing the automated system and those electing to speak to an agent.

C. Dynamics of Accumulation

Stocks are accumulations. The difference between the inflows and outflows of a stock accumulates, altering the level of the stock variable. The process of accumulation gives stocks inertia and memory and creates delays. Since realistic models are far too complex to solve with formal analysis, it is important to understand the relationship between flows and the behavior of stocks intuitively.

☞ The goal is to develop your intuition about stocks and flows. Be sure to read Chapter 7 first. Consider the following system:

❑ C1. The top graph below shows the behavior of the two flows, or rates: the inflow (the solid line) and outflow (dashed line) for the stock. On the graph provided below, *draw the trajectory of the stock* given the inflow and outflow rates shown. Indicate the *numerical*

values for any maxima or minima, and for the *maximum or minimum values of the slope* for the stock. Assume the initial quantity in the stock is 100 units.
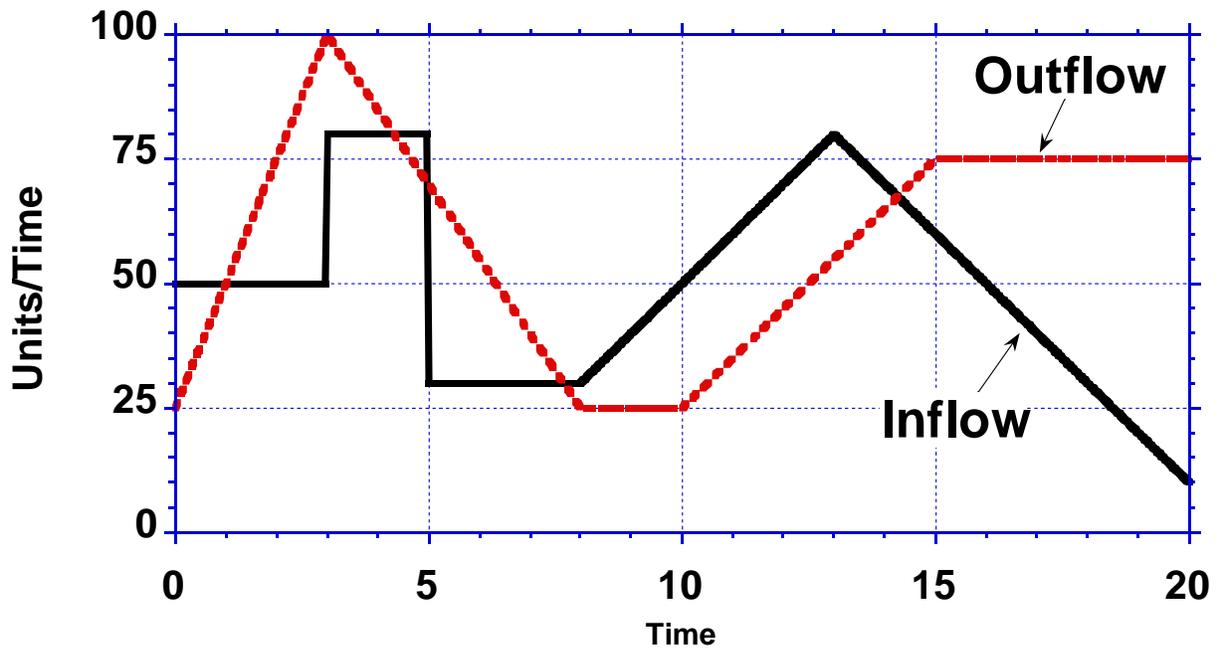
Stock
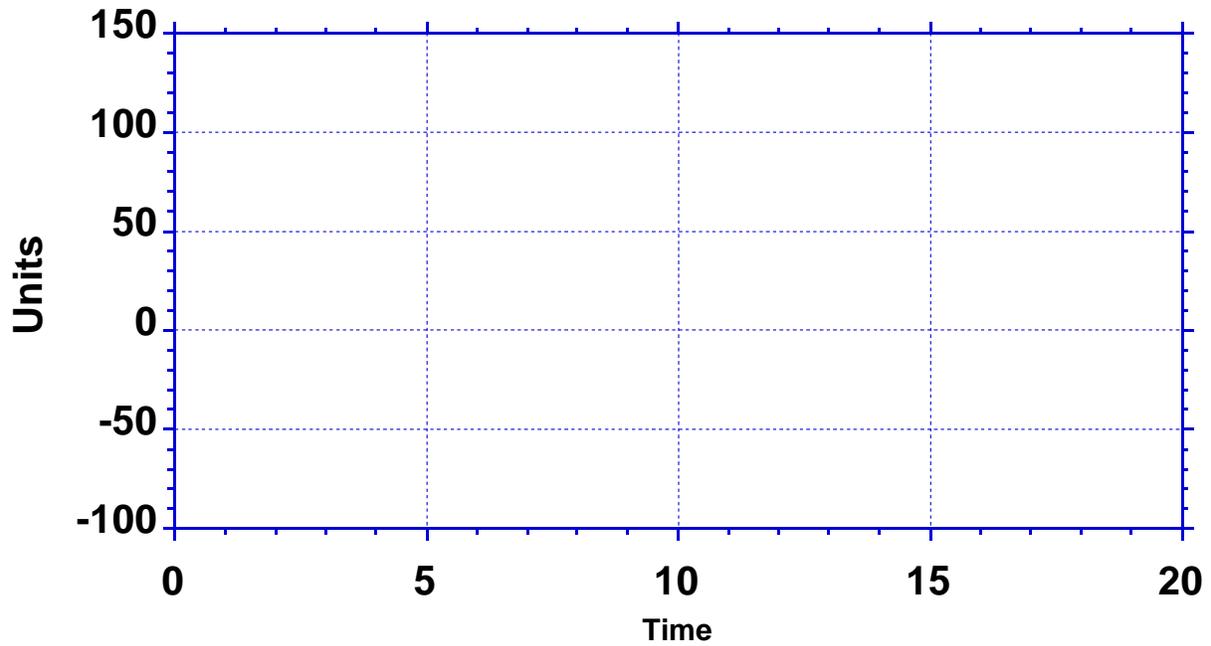
### D.	Modeling Goal-Seeking Processes

All goal-seeking processes consist of balancing (negative) feedback loops. In a balancing 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. Quality professionals refer to this iterative cycle as the "Plan—Do—Check—Act" or "PDCA" cycle (also known as the Deming cycle, for the late 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, including Six Sigma, follow an 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.

Semiconductor Fabrication Defects (ppm)
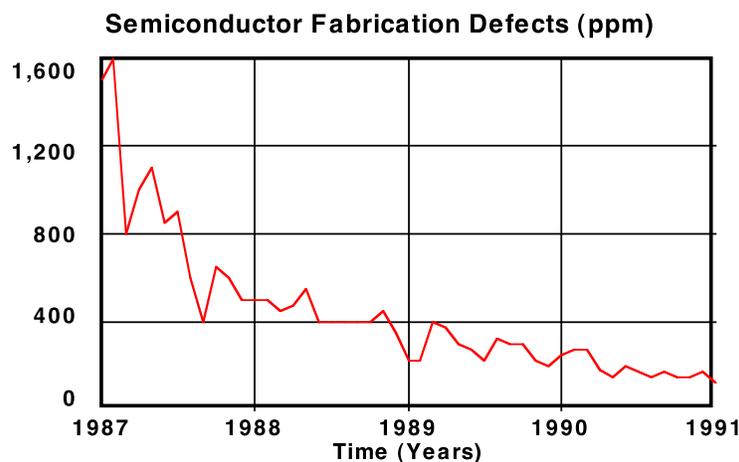
❑ D1.	Create a model of the improvement process described above and compare its behavior to the data for the semiconductor firm. Once you have formulated your model, make sure

the units of each equation are consistent. Hand in your final documented Vensim model file (.mdl file).

☞ Follow the instructions below precisely. Do not add structure beyond that specified.

- 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 and analyze the results. 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.

❑ D2. 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.

❑ D3. 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?

❑ D4. 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?

❑ D5. Explore the sensitivity of your model's results to the choice of the time step or "dt" (for "delta time").

     ☞   Before answering 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 the model behave as it does?

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

15.871 Introduction to System Dynamics
Fall 2013