System Dynamics Group
Sloan School of Management
Massachusetts Institute of Technology

Introduction to System Dynamics, 15.871
System Dynamics for Business Policy, 15.874
Professor John Sterman
Professor Brad Morrison

Assignment 2

Mapping the Stock and Flow Structure of Systems

Assigned: 16 September 2003; Due: 23 September 2003
This is an individual assignment.

This assignment will give you practice with the structure and dynamics of stocks and flows. Stocks and flows are the building blocks from which every more complex system is composed. 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.

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 flows. In human and social systems, often characterized by intangible, "soft" variables, identification is more difficult.

❑ A1. *2 points total.* 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

Prepared by John Sterman, Feb 87; last revision Sept. 2003

❑ denotes a question for which you must hand in an answer, a model, or a plot.
☛ denotes a tip to help you build the model or answer the question.

	Name	Type	Units
a.	Company Revenue		
b.	Customer service calls on hold at your firm's call center		
c.	GDP (Gross Domestic Product)		
d.	US federal budget deficit		
e.	Products under development		
f.	Corporate accounts payable		
g.	Cash flow		
h.	Book value of inventory		
i.	Promotion of Senior Associates to Partner at a consulting firm		
j.	Incidence of attacks on corporate web sites		
k.	Greenhouse gas emissions of the US		
l.	Yen/dollar exchange rate		
m.	Employee morale		
n.	Interest Rate on 30-year US Treasury Bond		
o.	Your firm's cost of goods sold (COGS)		
p.	Layers of management in a corporation		

B. Representing Stock and Flow Networks

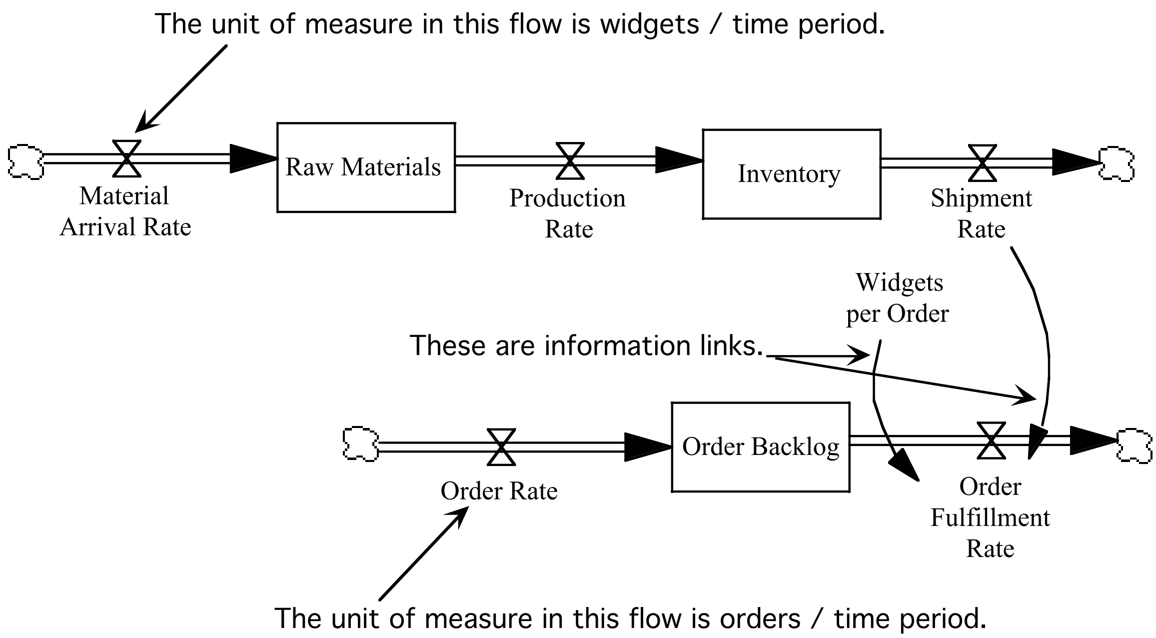
Systems are composed of interconnected networks of stocks and flows. Modelers must be able to represent the stock and flow networks of people, material, goods, money, energy, etc. from which systems are built.

For each of the following cases, construct a stock and flow diagram that properly connects the variables.

- ☛ Not all the variables need to be 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 challenge the assumption that 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.
- ☛ **Be sure to read Chapter 6 for more detail and examples**

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. The units of all flows in the materials chain are widgets/time period, and the units of the materials and inventory stocks are widgets. The units of the order flows are orders/time period. The order fulfillment rate is then given by the number of widgets shipped per period divided by the number of widgets per order, to yield orders/time period for the order fulfillment rate. Note also that 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 assignment, however, is to map the stocks and flows, so these feedbacks can be omitted for now. Later you will integrate stock and flow maps with causal-loop diagrams to close the feedback loops in a system. 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. Note also that the solution omits some structure that might be added if the purpose of the model required it—for example, an inventory shrinkage rate or order cancellation rate, or the installed base of product (the stock filled up by shipments). We could also have disaggregated the model further, for example, representing the fabrication process in more detail, or 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. *1.5 points*. A topic frequently in the news is the health (or lack thereof) of the US Social Security system. As in many nations, the US Social Security system is 'pay as you go': revenue received today from taxes paid by workers and their employers is used to pay benefits to those over the age of sixty-five. For the purpose of this question, assume that people start working at age twenty and begin receiving social security benefits at age sixty-five. Map the stock and flow structure of the US population as it relates to the social security system. Also map the stock and flow structure of money as it goes through the system. You should have two separate stock flow chains in this answer, one for people, one for money. Make sure they are appropriately linked with information arrows.
  - ☛ Not every dollar received today is paid out today. In fact, at various points in time, the system has had a substantial surplus. Make sure this is captured in your diagram.
  - ☛ Every model is built towards a specific purpose. If the goal of this effort is to understand the basic dynamics of social security, how complicated does your stock and flow structure representing the US population need to be? Do not make your diagram any more complicated than necessary.

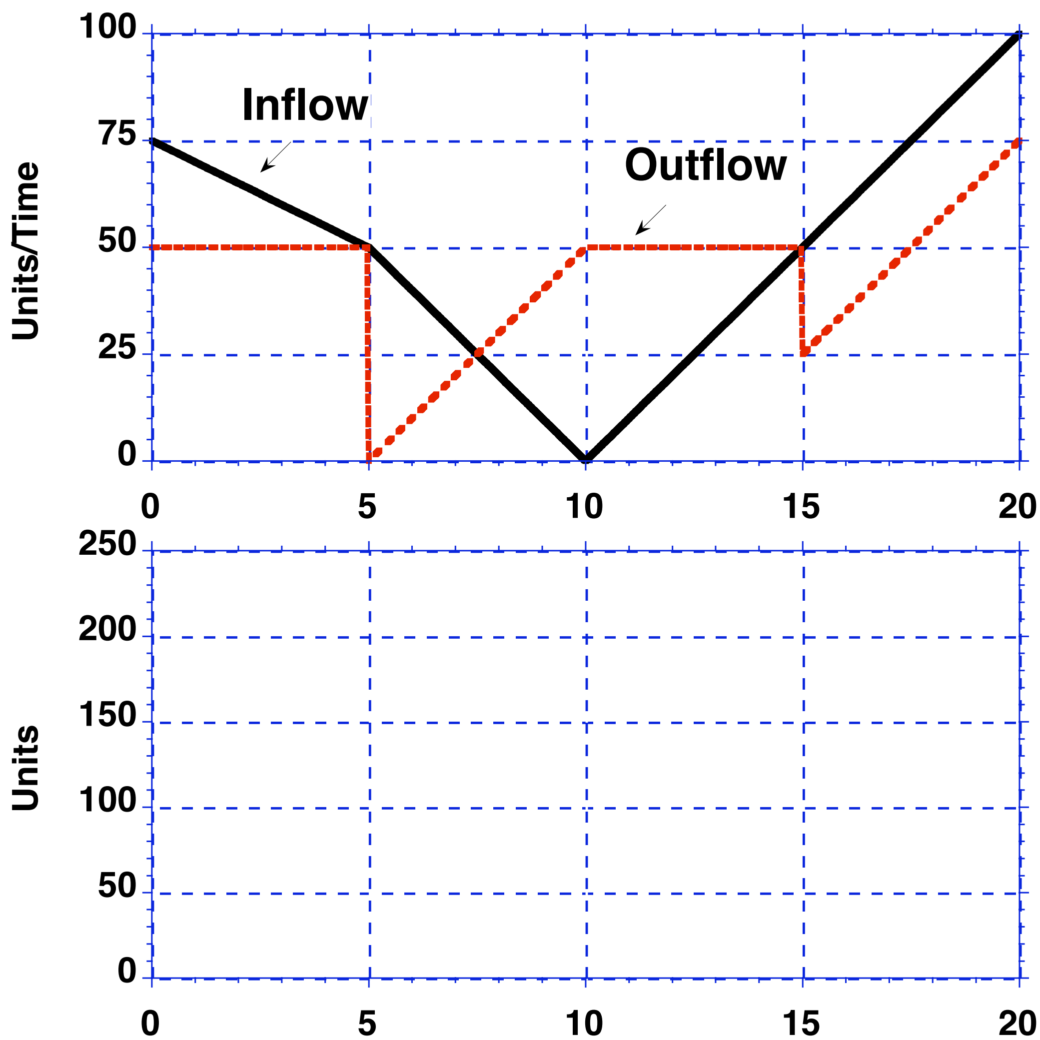
- ❑ B2. *1.5 points*. E-commerce firms must now compete aggressively for customers, both against on-line rivals and brick & mortar competitors. Map the stocks and flows of on-line customers for an e-commerce firm. To make it concrete, consider Amazon.com. Market research shows that awareness and adoption follow several stages: First, people must acquire a computer and internet service (yes, there are still people who are not yet on-line). Once online, people usually do not immediately dive into e-commerce. Instead, they become "browsers" who may visit e-commerce websites such as Amazon, but typically don't make any purchases. After a while, some of these browsers begin to make purchases from on-line sources. People can become loyal shoppers (make all their purchases in a given category such as books from Amazon, or from one of its competitors), or independent shoppers (who purchase from multiple sites based on prices and other conditions at the moment). Loyal shoppers can defect (if, e.g., prices are high or service is poor). Those defecting become independent shoppers as they try other providers. If these independent shoppers remain unsatisfied, they may abandon e-commerce altogether, becoming former e-shoppers who return to brick and mortar sources, using online vendors only to browse for information (e.g., using Amazon.com for reviews or to find books). Over time, some independent shoppers may become loyal to a particular vendor, either one of Amazon's competitors or Amazon itself.
  - ☛ Be sure to consider outflows from as well as inflows to each category of shopper.
  - ☛ It is not necessary to represent all the different e-commerce players separately. Instead, consider Amazon's loyal customers and aggregate all customers loyal to other online booksellers into a single category.
  - ☛ Over the relevant time horizon for this issue (the adoption and diffusion of e-commerce) you can ignore population growth and deaths.

C. Accumulation and Graphical Integration and Differentiation

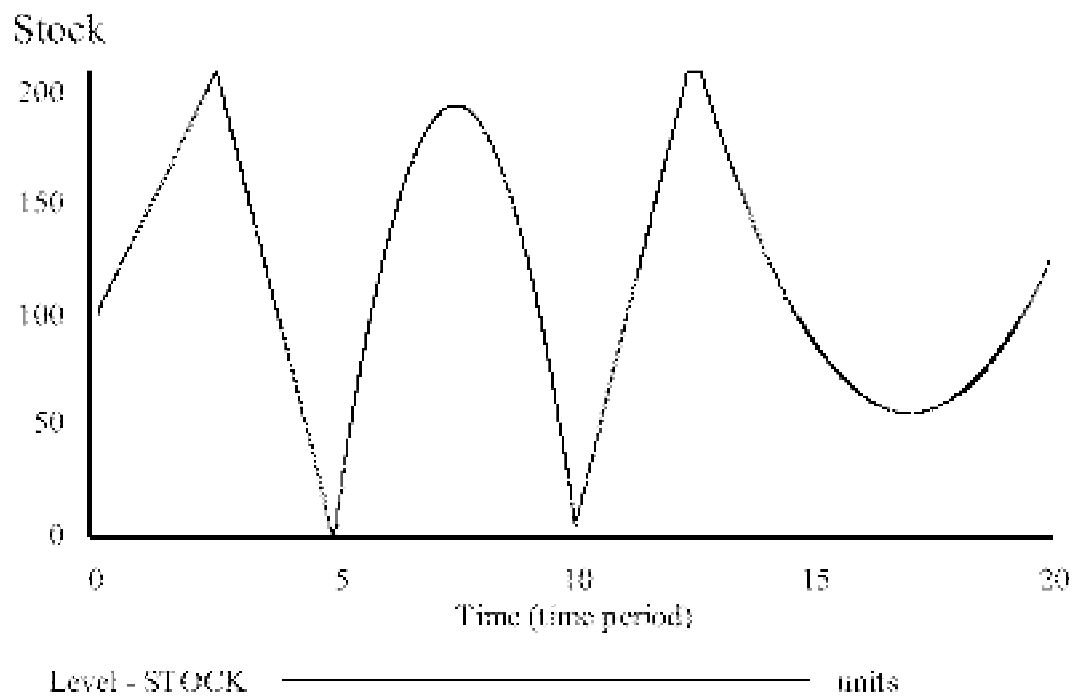
Stocks are accumulations. The difference between the inflows and outflows of a stock accumulates, altering the level of the stock variable. The process of accumulation gives stocks inertia and memory and creates delays. Since realistic models are far too complex to solve with formal analysis, it is important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

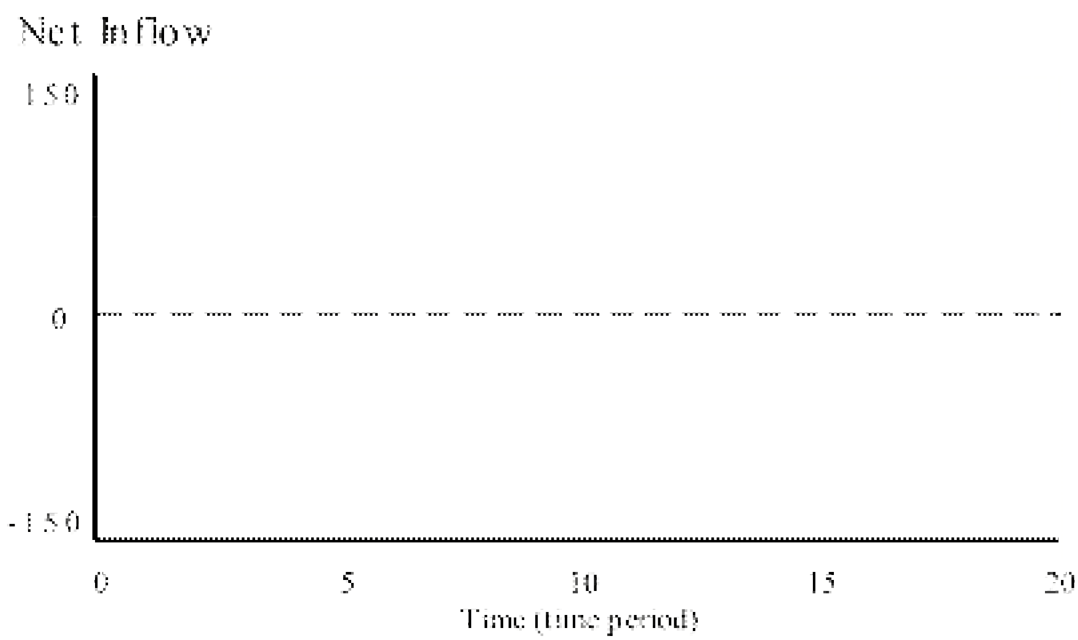
☛ **Do not use the computer. The goal is to develop your intuition about stocks and flows. Be sure to read Chapter 7 first.**

❑ C1. *1/2 point*. On the graph provided, 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.



❑ C2. *1/2 point*. This exercise asks you to graphically *differentiate* a stock to understand the behavior of the net rate of flow to the stock. By estimating the slope of the stock at each point, create a graph of the net rate of change in the stock. That is, in the graph below you are given the behavior of the stock over time and must infer the behavior of its net inflow. (This is the inverse operation of graphical integration, the previous exercise.) Graphically differentiate the stock and provide numerical values for key points in the net flow graph (maxima and minima).

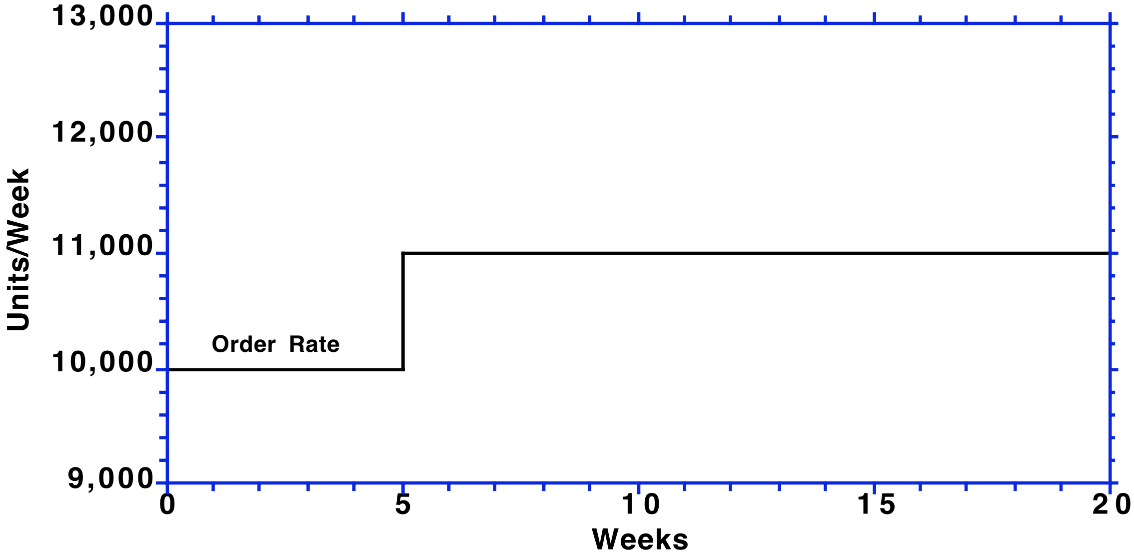


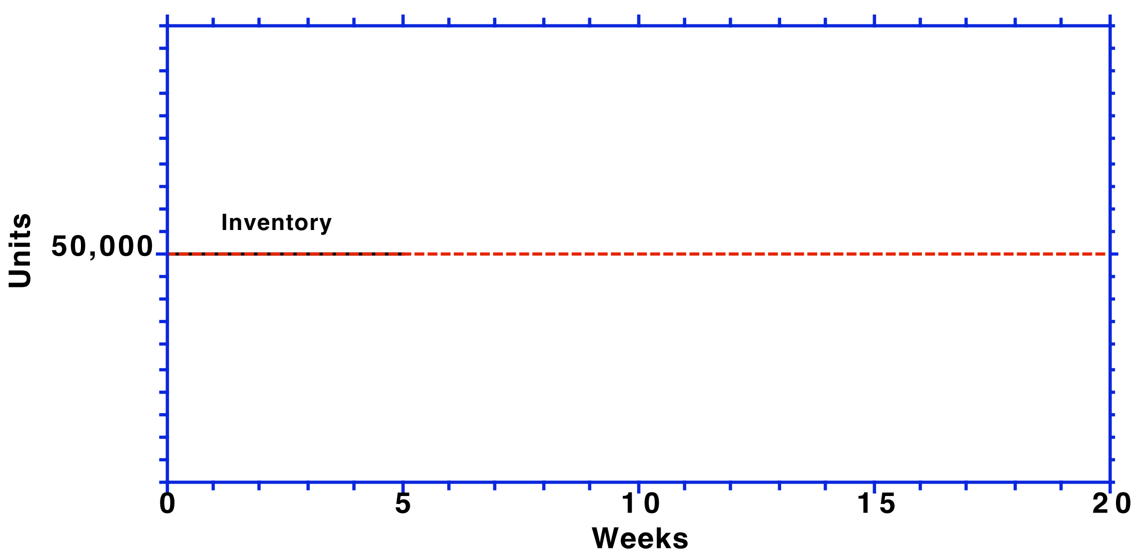


❑ C3. *1 point*. Consider a manufacturing firm. The firm maintains an inventory of finished product. The firm uses this inventory to fill customer orders as they come in. Historically, orders have averaged 10,000 units per week. The firm strives to maintain an inventory of 50,000 units to provide excellent customer service (that is, to be able to fill essentially 100% of every order). Although the firm has ample capacity to handle variations in demand, it takes time to adjust the production schedule, and to make the product—a total lag of four weeks.

Now imagine that the order rate for the firm's products suddenly and unexpectedly rises by 10%, and remains at the new, higher rate, as shown in the graph below. Before the change in demand, production was equal to orders at 10,000 units/week, and inventory was equal to the desired level of 50,000 units.

Sketch the likely path of production and inventory on the graphs below. Provide an appropriate scale for the graph of inventory. Explain *briefly*.





D. Linking stock and flow structure with feedback

Often it is important to include the stock and flow structure of a system in your causal diagrams, thus coupling stock and flow maps with the feedback structure. As an example, consider the student workload model in section 5.4 (pp. 159-169).

❑ D1. *1 point* Redraw Figure 5-24 on p. 167 to show the stock and flow structure of the situation explicitly. You will need to decide which variables in the diagram are stocks and identify the relevant flows affecting them. That is, your diagram will include the same feedback loops as the original but show the important stocks and the flows affecting them explicitly.

☛ What kind of variable is Energy Level? Due Date?

☛ Assume that the effort devoted to assignments is affected by the average of the grades earned to date, not the grade on the most recent assignment (that is, if you are averaging a C up to now, but desire an A, you would put in greater effort, even if you received an A on your most recent assignment).

❑ D2. *1 point* Suppose a student had run his/her energy level down by getting much less sleep than normal (too many late night parties and road trips, for example). Specifically, suppose the student normally requires 8 hours of sleep per night to be well rested, but during the first half of the semester averaged only 5 hours per night, with consequent reduction in energy level. In addition, the student has been completing fewer tasks than are assigned. The graphs on the following page show the situation.

On the graph provided, sketch the trajectory of the assignment backlog during the first half of the term.

The graphs also show the student's aspirations to recover during the second half. Specifically, the graphs show energy level rising back to normal during the second half of the term.

On the graph, draw the pattern for hours of sleep per night required to achieve the student's plan for the recovery of the energy level.

Next, what do you think the implications of the trajectory for sleep would be for the work completion rate? Sketch, on the appropriate graph, the path you believe the work completion rate would take in this situation. Explain briefly.

☛ There is no single correct answer, but your trajectory should be consistent with the feedback loop and stock/flow structure described in your causal diagram.

☛ Assume that work is assigned continuously throughout and semester and that there are no vacation periods or other breaks in the semester.

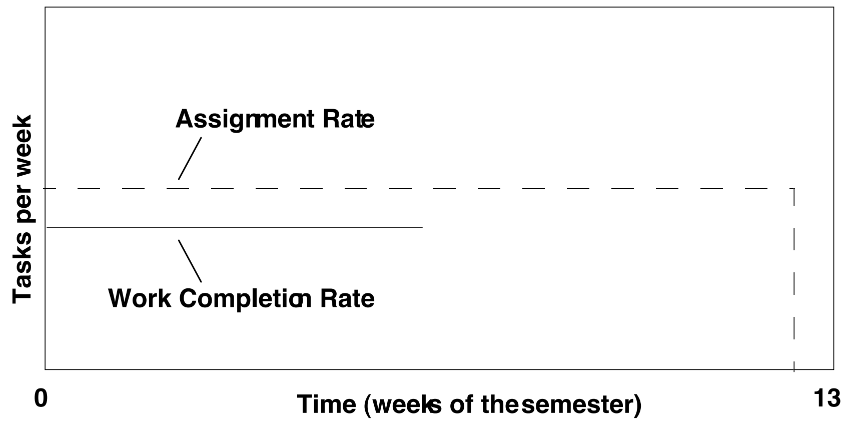
Now, given the path you sketched for the work completion rate during the second half of the term, draw the behavior of the assignment backlog.

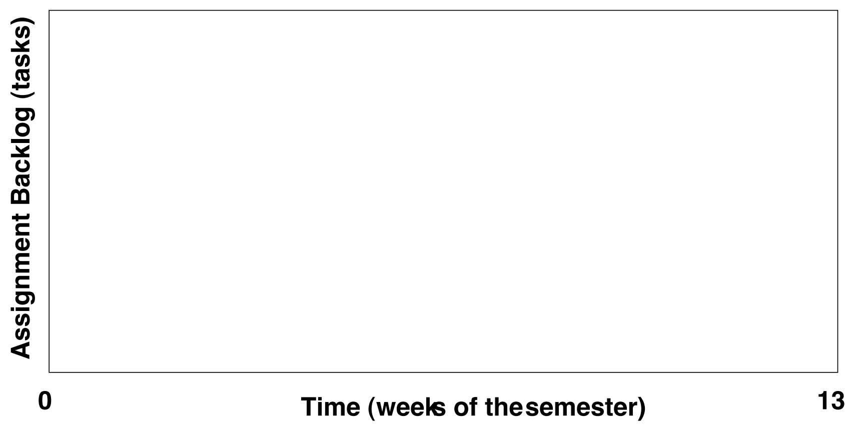
❑ D3. *1 point* Critique the following argument made by the student:

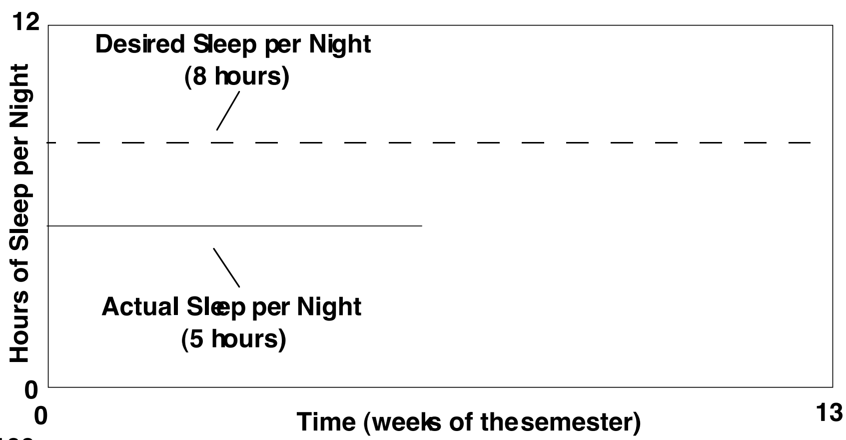
> "Given the total amount of work to be done over the course of the term, it doesn't matter whether I do it steadily or party a lot early on, then bear down and get it done at the end of the term. The cumulative number of tasks I have to do is the same, and so the total amount of time I have to put in over the course of the term is the same."

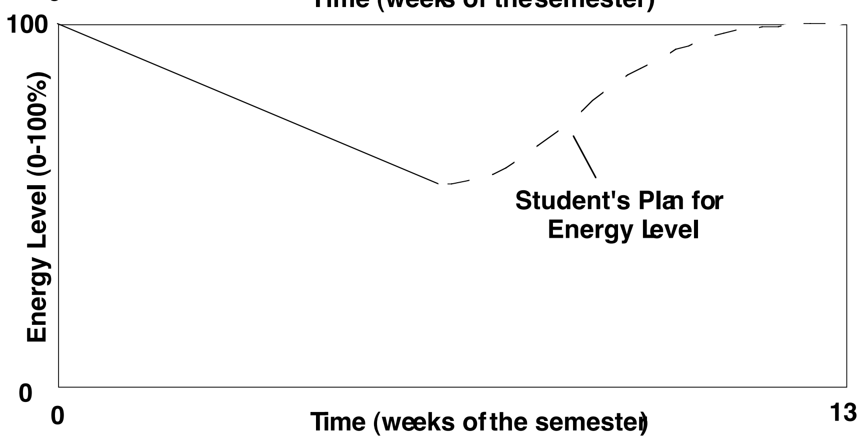
☛ A good answer will be grounded in your causal diagram and also draw on your own experience and knowledge of the process. A good answer will also be *brief*.

☛ Now, get some rest!


Assignment Rate
Work Completion Rate
Tasks per week
0
13
Time (weeks of the semester)


Assignment Backlog (tasks)
0
13
Time (weeks of the semester)


12
Desired Sleep per Night
(8 hours)
Actual Sleep per Night
(5 hours)
Hours of Sleep per Night
0
0
13
Time (weeks of the semester)


100
Student's Plan for
Energy Level
Energy Level (0-100%)
0
0
13
Time (weeks of the semester)