Tutorial 2: Systems Perspectives and Dynamics

Learning goals:

- Be able to define what a system is.
- Appreciate why systems dynamics are critical to understanding systems.
- Be able to use a stock and flow diagram to describe the dynamics of a system.
- Understand how systems dynamics can be described by mathematical equations and models.
- Understand the concepts of reinforcing and stabilizing feedbacks in systems.

In order to understand a socio-environmental problem- and to find solutions for them- we need to understand the problem from a systems perspective. We need to understand the socio-environmental system in which the S-E problem is embedded. In the previous lecture, we looked at the problem of the decline of coral-reefs. This problem is embedded in the context of the coral reef system, including the coral reef ecosystem, and the human influences and impacts on this ecosystem. In other words, to understand the problem of coral reef decline, we have to understand the coral reef system.

To understand this more fully, it would be helpful to first think about systems in general, starting with a definition.

What is a system? And perhaps a more challenging question: what is NOT a system?

Definitions of a system include:

- "is an assemblage or combination of things or parts forming a complex or unitary whole." (dictionary.com)
- "must consist of three kinds of things: elements, interconnections, and a function or purpose." (Meadows 2008)
- "an interconnected set of elements that is coherently organized around some purpose." (deVries 2013)
- "A cohesive entity consisting of key elements, interactions, and a local environment; must show spatiotemporal continuity" (Cummings and Collier 2005)

Given these definitions, which of these do you think are systems?

- An aquarium
- A school
- A bowl of popcorn
- Facebook

Systems have elements, interconnections, and function or purpose; how might we define these for each example?

- An aquarium:

    - Elements = fish, water, plants, nutrients… (but also human caretaker, aquarium supplies, aquarium supply store)
    - Interconnections= biological interactions between elements
    - Purpose= to maintain the health of the organisms within the aquarium. (Or to provide enjoyment to humans?)
- A school:
    - Elements = students, teachers, administrators, buildings, books, knowledge
    - Interconnections= teachers teach students, students gain knowledge by reading books, administrators set policies for students and teachers, etc.
    - Purpose= to educate students.
- A bowl of popcorn
    - Elements: pieces of popcorn, bowl
    - Interconnections: none (what about physical interaction between pieces of popcorn? No- random)
    - Purpose: none (or maybe it is to feed a human?)

    Not a system- interactions between elements are random, and the bowl of popcorn, while a physically defined unit, is not an "integrated whole"

- Facebook
    - Elements: account users, computers, internet connections
    - Interconnections: users interact with each other through FB interface and share information.
    - Purpose: social networking

In these examples, you can see that identifying and describing a system can be tricky, partly because the boundaries are for the system are often unclear. Some systems have physical boundaries that make it a bit easier to visualize- think about a lake or a school. But systems like Facebook or a national economy may not be recognized immediately as a system because they lack the physical boundaries that are easier to conceptualize.

Even if you recognize a system, it can be hard to describe it. For one, systems are often contained within other systems, so it might be challenging to decide where to draw the boundaries of a system. For many systems, the boundaries we draw are for our own understanding, but they do not represent a firm boundary in reality. For example, we might describe a public school as a system with the boundaries being the walls of the school. But we could also describe that school as a system within the broader system of the school district, and the school district is a system within the broader national public school system.

Systems can also have purposes within purposes. For example, in the school example, the purpose of the school is to educate, but within that, the purpose of students is to learn and the purpose of the teachers is to teach.

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To help us understand and describe systems, we often start with a diagram. In the last lecture, we talked about **concept maps**. While concept maps are very helpful for organizing and visualizing a system, there are other diagramming techniques for looking at a system, including spray maps, rich pictures, systems maps, influence diagrams, and multiple cause diagrams[1].

In the coral reef concept map, and many of these other maps, we are looking at a static picture of a system. But systems are more than elements, interconnections and purposes. If you want to understand how a system works, you have to understand its structure and how it behaves over time- you have to understand the *dynamics* of the system. One common way of looking at systems dynamics are with stock and flow diagrams.

Stock and Flow Diagrams: Systems Dynamics

A **stock** is a part of the system that can be quantified: parts that can be counted or measured at a given time. A stock can be tangible- for example, money in a financial system or water in an agricultural system. Or it can be intangible, like knowledge in a school system or political capital in a government. Stocks are also referred to as "capital", as in "natural capital" or "human capital" or "economic capital"

Stocks change over time due to the actions of a **flow**.

For example, if money in your bank account is your stock, the flow might be payments to your credit card (outflow). Or a paycheck (inflow). In one case, the flow is reducing your stock (outflow), and in another, it is raising your stock (inflow).

Clouds represent the part of the system where the stocks come from and go to, but are not the focus of the diagram (hence they are often undefined)

Boxes represent parts of the system with measurable stocks

Thick arrows with spigots indicate the direction through which stock flows

Thin arrows indicate factors influencing the flow of stocks.

[1] http://www.open.edu/openlearn/money-management/management/guide-diagrams

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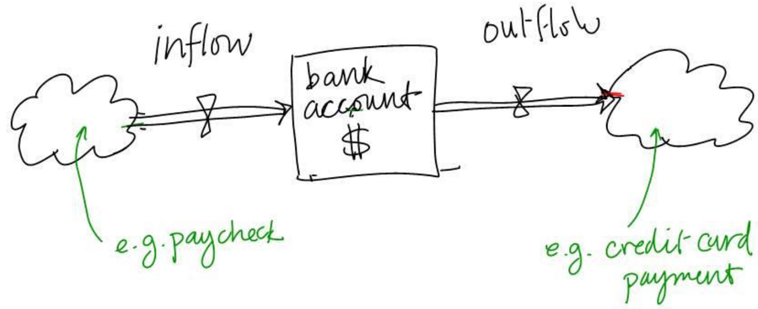

What are some stocks in natural systems? What about social systems?

Natural system stocks might be water, animals, forests, soil, minerals.

Social system stocks might include money, happiness, hunger, earning potential.

Sometimes stocks are referred to as “capital”, as in “natural capital” or “human capital” or “economic capital”

A stock may have multiple inflows and outflows:

- Bank account example: inflow= paycheck, interest, cash deposit; outflow = credit card payments, rent payments, finance charge

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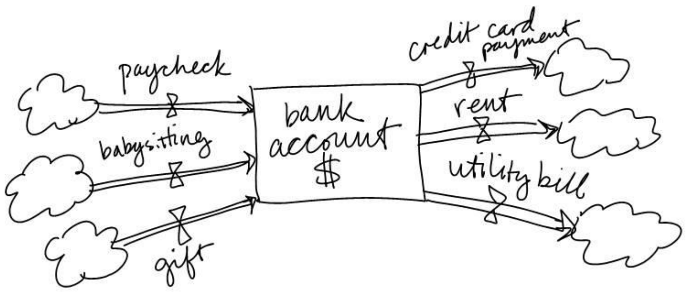

When inflow = outflow, we see a system that is in a **steady state** at that point in time.

So if the amount you spend = the amount you earn, your bank account is in a steady state

If you wanted the stock to rise, what would you do? What about making the stock fall?

If the outflow > inflow, stocks fall

If inflow > outflow, stocks rise

So you just manipulate the flows. This seems simple enough, but the picture becomes more complicated with multiple flows and differing flow *rates*: flows take TIME, and flow rates may change and may not be steady. As stocks change levels over time as the result of flows, we see the behavior of the system. We are looking at the system dynamics.

For example: For your bank account, you may have monthly paychecks and rent expenses, but you might have occasional bonuses or cash gifts or unexpected emergency bills. How do these affect the flow of your stock in and out of your bank account? What does your bank account look like *over time*?

Stock and Flow diagrams can help us visualize the parts of the system and identify the pathways through which stock flows. But it's hard to see the systems dynamics…

To get a better sense of a systems dynamics, a systems model is very useful. Let's take a look at our banking example now with a model. First, we'll need to translate the example into mathematical language.

For simplicity, let's look at the first diagram (for simplicity, we are looking at one inflow = paycheck and one outflow = living expenses)

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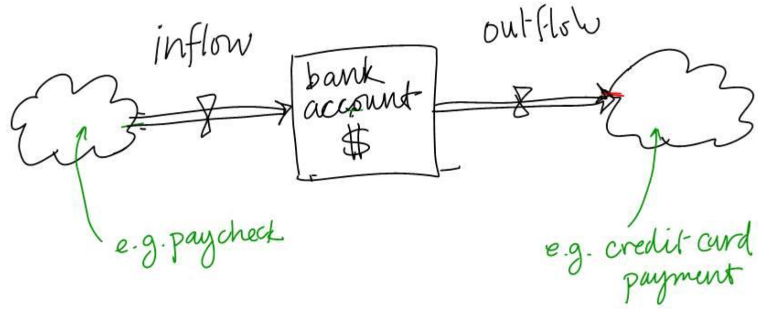

The first step to seeing how the system behaves and changes over time, let's first identify the parts of the system we want to consider:

"S" = stock/$ in bank

"s" = savings rate

"E" = expenses

"I" = income

"t" = time

To see how the level of the stock changes over time, we need to calculate the levels of the stocks at multiple points in time. If you've had Calculus, you might remember that a **derivative** measures the instantaneous rate of change of a function. In the case of a linear function, the derivative is the slope of the line (y = mx + b, where m = change in y/change in x…. draw this) The notation used for the rate of change is dy/dx (change in the independent variable over the change in the dependent variable), where dx = the change in the x variable, and dy = the change in the y variable.

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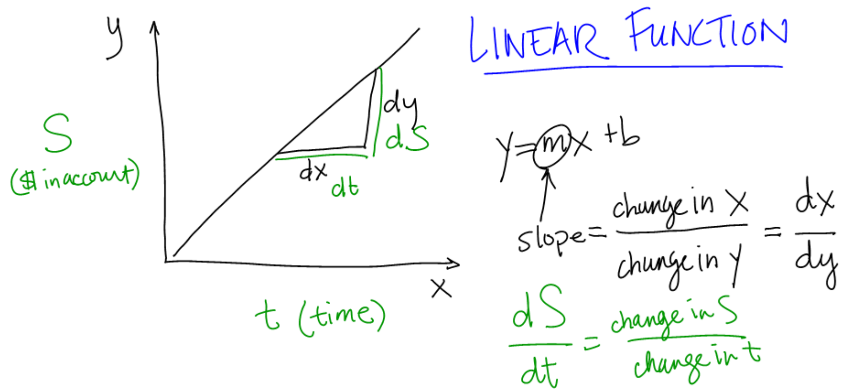

We are interested in how stock levels ($ in our account) changes over time. Expressed mathematically, we are interested in dS/dt. If you haven't had Calculus, just remember that dS/dt represents how stock levels change over time ($ in account). How the stock changes over time in our simplified system depends on how much money you put into your account minus how much you spend. Here, we are assuming that we spend a steady, fixed amount (i.e. your rent, groceries, etc. all stay the same).

dS/dt = I*s – E

if all of your inflow (i.e. paycheck) goes directly in bank, s = 1. If nothing makes it to the bank, your savings rate "s" = 0.

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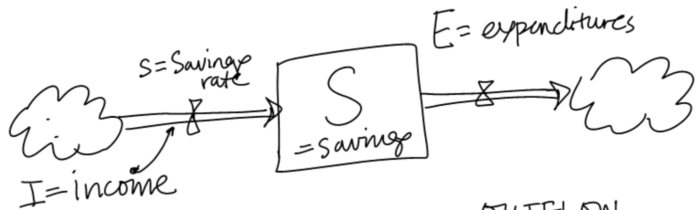

$$\text{rate of change } \frac{dS}{dt} = \overbrace{I \times s}^{\text{INFLOW}} - \overbrace{E}^{\text{OUTFLOW}}$$

if s = 1,
all income into bank

Using this equation, we can build a model to show what happens over time. Dr. Andres Baeza-Castro has built a simple model of this scenario in R; the model calculates the stock levels across time and plots the results on a graph. The code for this model can be found in the file “Savings_Example_BaezaCastro.R”, which can be downloaded from the Tutorials section of the SESYNC website. R Studio is required to open the file and follow along in the following section:

Scenario 1 (model 1): Let’s say that you have \$1000 in the bank. Your savings rate is 1. You spend half of your \$2000 monthly paycheck on your monthly living expenses (rent, utilities, food, etc.) E = \$2000. What happens to your account over time? (stays the same)

What happens if your monthly income goes up? Let’s say \$2010 per month?

What happens if your monthly income goes down? Let’s say \$1990 per month?

(concepts include equilibrium or steady state, linear relationship)

Scenario 2 (model 1):

Now let’s consider another scenario. Instead of putting all of your paycheck into your savings account, you decide to donate 10% of your monthly paycheck to a charity, deduction taken straight out of your paycheck (s = 0.9). Now what happens?

Question: with this scenario, what would you need to adjust to get the system into equilibrium or steady state?

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Feedback Loops (model 2):

Scenario 3: Now let's add the fact that your account is interest bearing. Let's say your account earns 3 % APY. This is calculated on a monthly basis based on how much is in your account; i.e. the interest is compounding.

How do we add this mathematically? Let's call the interest rate "i". Now the input into your savings account includes interest.

$dS/dt = (I*s + i* S_{(t)}) – E$

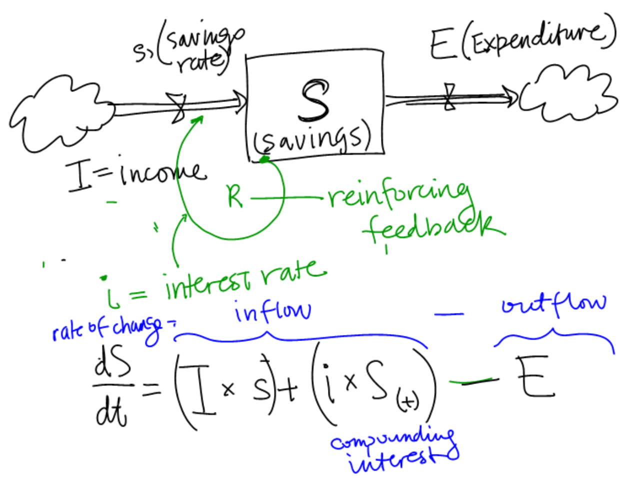
If the interest rate is 0.03 (3 %), what happens over time?

This is an example of a ***reinforcing feedback loop***. Reinforcing loops are also known as **positive feedback loops**. Positive here does not mean "good". Rather, it means "additive" or self-perpetuating. It can be a vicious cycle or a self-fulfilling prophecy.

This is also an example of a nonlinear function.

Scenario 4: What if you found a bank with an incredible savings rate of 15% APY? What happens to your account over time? Make a prediction.

Now see what happens with the model.



Stabilizing or balancing feedback loop (or negative feedback loop):

Let's go back to our stock and flow diagram. What happens when you see that the stock (money) in your bank account is decreasing? A good guess is that you do some adjustments: you spend a little less or maybe you work more hours or find an odd job to get more money. You are regulating the behavior of the system. You are regulating the money in your account by adjusting the inflows and outflows. What if you notice that the money in your bank account seems to be rising? Maybe you decide to do a little shopping or donate some money. In both scenarios, the overall level of money in your account changes- the stock levels change- as a result of decisions you made based on what you observed about how much money (stock) you have in your bank account. You have just illustrated the concept of **feedback** in a system! Specifically, a stabilizing- or balancing- feedback loop- this is when the level of a stock is maintained.

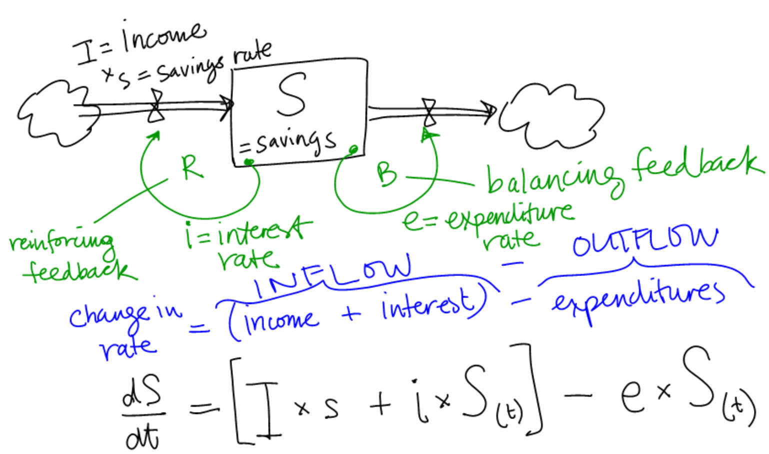
Let's go back to our model (model 3):

In the previous model, we assumed that our expenses were a fixed amount every month. Very unrealistic! What if, instead, how much we spend depends on how much money we have in our bank account? How would we express that mathematically?

If "e" = our rate of spending, then $\mathbf{E = e*S_{(t)}}$. How much we spend each month depends on our rate of spending times how much we have in the account. So if you make your spending decisions based on how much money you have in your account, this is the equation that represents how you calculate your monthly spending amounts.

To see how this affects your bank account over time, let's return to the equation in the previous scenario, but this time E is no longer a fixed amount. Rather, the amount you spend is a function of how much you have. So now we replace "E" with $\mathbf{e*S_{(t)}}$.

$\mathbf{dS/dt = (I*s + i* S_{(t)}) - e*S_{(t)}}$



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Let's see what happens over time through the model:

Scenario 5: Let's say we spend 50% of what is in our bank account each month. e = 0.5. Your Income is $2000/month, all of which you put into your account. The interest rate is 0.03 (or 3 %). What happens to your account (S) over time?

A Socio-Environmental Example: Agricultural Fields and Rabbits

Let's now look at another example.

Rabbits, as you know, can wreak havoc in a garden and on agricultural crops with their impressive capacity to eat and dig through vegetation. Combined with the fact that they are prolific breeders, rabbits are a major pest species in many areas. As Australians can tell you, rabbits can have dramatic impacts on crops and ecosystems, and can be a huge and costly problem.

Let's consider the following scenario:

Imagine that you are a farmer. You grow cereal grains (wheat, barley, oat), which rabbits love to eat, and you consistently lose crops to these voracious pests. Eradication of the robust rabbit population is nearly impossible, so you must constantly take action to control and manage the population to reduce your crop losses.

Some of the options for controlling the rabbit populations include gassing (most effective), fencing, trapping, shooting, and repellents. Each of these control methods require repeated application to control the population. While fencing is the most cost effective method, it still requires continual maintenance. Thus, rabbit control is a constant but necessary expense for you. But how much should you spend each year on rabbit control?

To help answer this question, let's consider how this socio-environmental system works. What are the parts and how do they interact?

First, what are the parts of the system? [crops, rabbits, income from crop harvest, savings in bank]

What are the stocks? (helps to identify these as quantifiable elements.) [crop biomass, money, number of rabbits]

The amount of crops in the system can be measured in biomass, and the amount depends on the growth rate of the crops (inflow) and how much is harvested or consumed (outflow).

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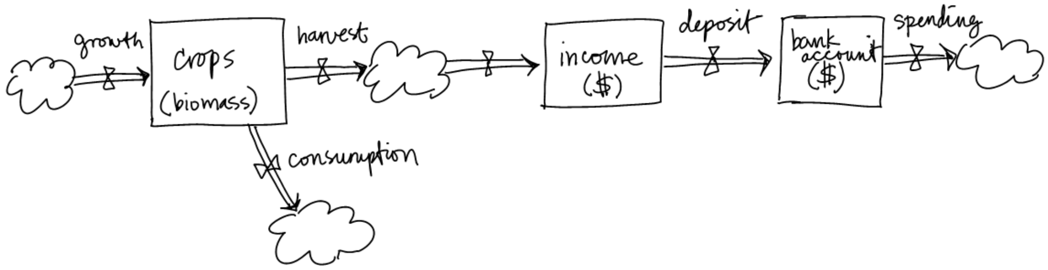
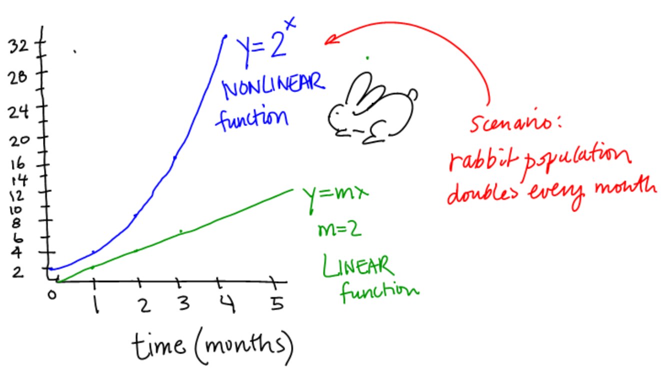
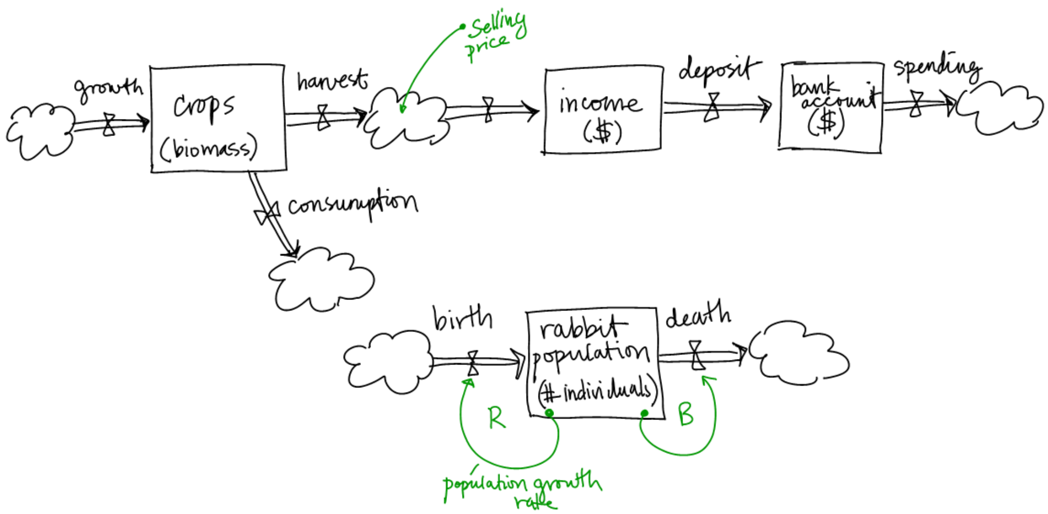


The harvested crop is then sold at market price, and the profits are your income. As a farmer, this is your sole source of income, and a large portion of it goes into your bank account for your basic living expenses.

Now let's look at the rabbit population. As we've seen, the rabbit population has an impact on the crops, and harvest yields determine how much money is available for rabbit population control. Another factor to consider in this system is that rabbits reproduce rapidly, and there is a **reinforcing feedback loop** in this system. The more rabbits there are, the faster the population grows.



As you can see, the population growth is not a linear function. It is a nonlinear function.



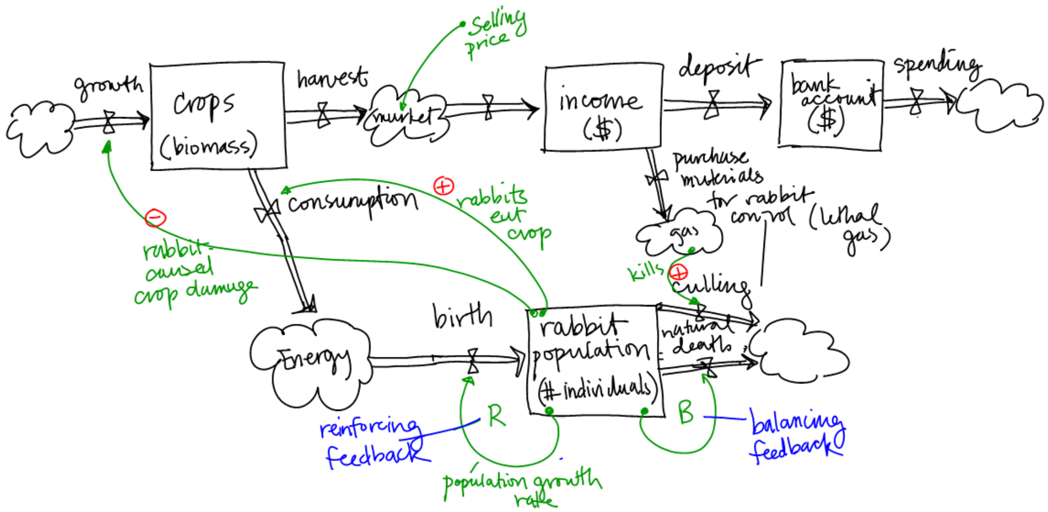
There is also a **balancing loop (negative feedback loop)**- the rate of death for the rabbits is a function of the total rabbit population (the greater the rabbit population, the higher the death rate) due to competition for food and other limiting factors.

Now let's take a look at how these systems interact:

First, part of your income from the sale of your crops needs to go towards managing the rabbit population. You decide to use lethal control methods to control the rabbits (gassing), and spend money each month to buy toxic gas for reducing the rabbit population.

Looking at the part of the system diagram for the rabbits, let's change the outflows for the rabbit population. Instead of one outflow of "death", we will further distinguish between the types of deaths that affect the rabbit population: natural deaths, and deaths as a result of the gassing ("culling"). Rabbits also link to the crop and income system by influencing the crops. Rabbits can both inhibit growth of crops by damaging the plants and digging around the plants, and they can also consume the biomass of the crops directly. When the rabbits consume the crops, the biomass of the plants is metabolized and eventually incorporated into the rabbit population (both in the rabbit that consumed the plant and its baby bunnies).

As you can see in the diagram, the connection between the rabbits, crops, and income links these subsystems together inextricably. This diagram gives you a sense of what the structure of the system looks like and how the parts influence each other. You can see that feedback loops are a part of the structure, and that the natural and social factors in the system are linked. But to see the dynamics and behavior of the system, a dynamic systems model is helpful.



Please note that this example has been further developed into a modeling exercise by Dr. Andres Baeza-Castro and Dr. Neil Carter. Their exercise, titled "A simple example of a socio-environmental system: coupled rabbit and farm dynamics" can be found in Teaching Resources section of SESYNC's Education subsite.

Another socio-environmental systems example: Pesticide resistance and cotton farming

If your stock is cotton crop, your stock decreases when the crop is attacked by moths. To keep moths from eating the cotton crops, farmers often spray pesticides. While this temporarily reduces moth populations, it also drives the evolution of pesticide resistant moths. Thus, over time, the resistant moth population grows, which causes farmers to spray more toxic pesticides, yet again moths evolve resistance. Over time, the moth population becomes more resistant to pesticides and the pesticides become less effective. The moth population grows and cotton crop stock drops. This is an example of how systems are full of surprises. Cotton farmers did not expect their actions to have unintended consequences. But understanding the feedbacks in the system helps us to understand this surprising result.

Try drawing a stock and flow diagram of this example.

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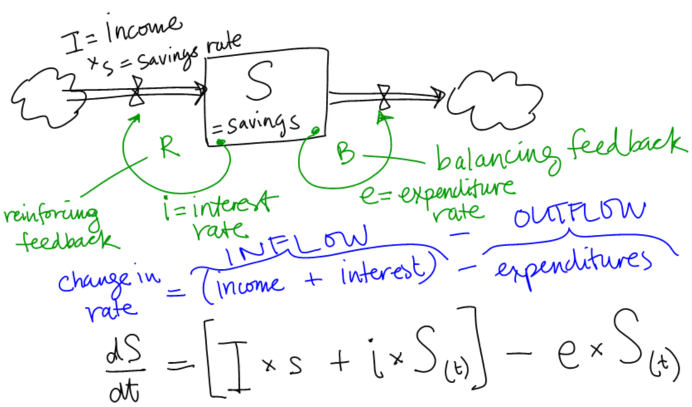
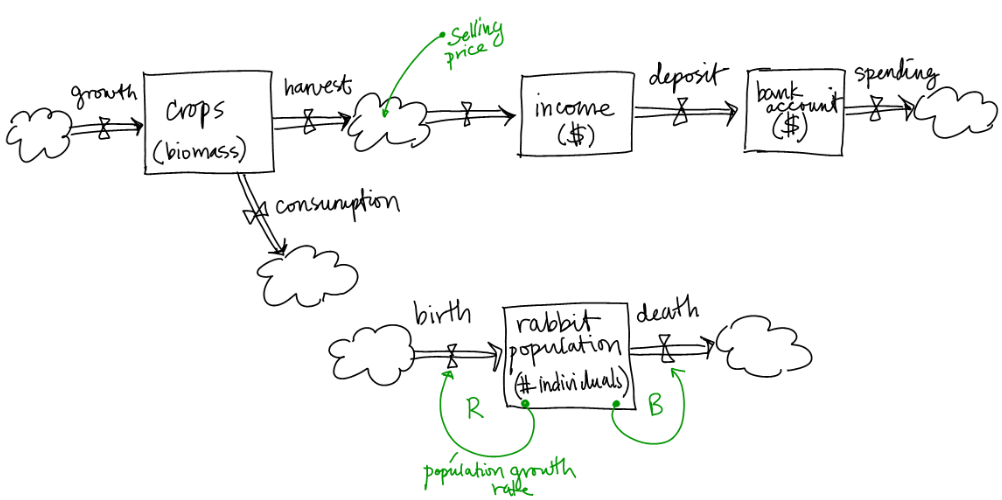
Feedback Loops

Feedback loops are an important characteristic of systems, particularly complex systems (not all systems have feedback loops). Understanding these feedback dynamics becomes very important to understand the behavior of a system. As you see more examples and diagrams of systems, you might start systems behaving in similar ways. You may also notice that similar structures in systems lead to similar behaviors. For example, let's return to the bank account example with the reinforcing and the balancing feedback structure:



Does this structure look familiar from other examples? Let's look at breeding rabbits:



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EXERCISE:

Another example might be immigration: When immigrants establish themselves in a country, the US for example, there is a reinforcing feedback on the rate of immigration as more immigrants come to the same country, potentially because they are inspired by others' success or to join their friends and relatives. As immigrant communities grow and establish, the attractiveness of immigrating to those communities grows, and so does the overall population. However, there are balancing feedbacks in this system as well, including government policies that restrict immigration numbers and competition for resources and jobs when immigrant populations grow too large. What might the structure for immigration populations look like? Use the above examples to try constructing a stock and flow diagram of this example.