Feedback Causality

"W*e'll never be able to go back again to the way we used to think." – anonymous holist*

So far in this course we have seen evidence that our conventional way of thinking often delivers poor results. Many times our solutions to problems do not last. Things change over time in ways that are unanticipated and problems do not stay fixed – the problem is our solutions themselves, because they are based on flawed mental models of how things work. I said a key to better mental models is understanding and incorporating feedback effects, because they help to explain the unexpected ways in which things in our world change over time. Therefore this part of the course will look more closely at feedback. I will introduce a way to visualize feedback in a new kind of mindmapping, how to read and create these diagrams, and how to use them in problem solving.

Let's review as we introduce the feedback perspective.

A Revolution in the Making

The insight that the world functions in complex, interdependent wholes drives a growing revolution in the way people are examining, understanding, and trying to manage our affairs in the world. We can find evidence far back in human history of attempts to comprehend how these wholes function.

Early glimmers of awareness of the ever-present feedback that ultimately drives what happens in the world come down to us from biblical maxims like "As ye sow, so shall ye reap", and reveal themselves in common sayings like "What goes around, comes around," "chickens coming home to roost," and in the lessons of folktales. But as the scientific revolution gathered steam in the last two centuries, its goal of accurate prediction reduced its focus to pieces of wholes, and reduced its products to explanation of events and short-term causes.

Only lately have scientists, seeing the inadequacy of methods bounded by these disciplinary traditions, seriously sought more holistic ways of doing science. These efforts, described variously as 'systems thinking' or 'complex systems science,' are still small and have encountered plenty of resistance in the scientific community. In the words of one holistic scientist, "You can always tell the pioneers – they're the ones with all the arrows sticking in their backs!" But they are creating powerful analytical tools that amount to a breakthrough in how science is done.

In the early seventies scientists used one of these tools - known as system dynamics simulation - to build a global model of what is causing the main threats to human civilization: unsustainable resource use, pollution, exponential population growth, and inequitable distribution of goods and services. Simulating various scenarios (superficial change, fundamental change, no change), they found none but the most difficult to carry out would prevent global overshoot of planetary carrying capacity, leading to at least some degree of collapse of present human populations and quality of life during the 21st century. Published under the title *Limits to Growth,* it became an international best seller and put the science of system dynamics modeling on the map. Quickly the model came under heavy fire from those in the scientific community who have a vested interest in older ways of doing science. Even louder criticism came from groups who have a financial interest in maintaining an economic system structured for endless growth. Nevertheless - republished several times with only minor revisions - the model has vindicated itself as the disturbing outcomes it pointed to over thirty years ago have so far come to pass. Today a consensus has emerged among top scientists of many nations that we need to take seriously the possibility of a global future that resembles one of the scenarios in *Limits to Growth.*

A New Tool

Thus far in this course we have presented systems thinking as an antidote to a way of thinking that reduces the focus of inquiry to small parts. In a world where everything is connected, that narrow focus sharply limits our understanding of why things work as they do. We pointed to the need for an approach that focuses on as many of the connections as necessary to explain a situation. To address the 'why' question we need a method that that reveals those connections as a web of causal relations. We called that web **the system of interest.** Here we will explore a way to accurately model our mental pictures of that web as a visible diagram.

One of the most difficult skills in holistic decision-making is learning to visualize and plan for both short and long term consequences. We are foiled first by our seemingly built-in desire for immediate gratification, and second by the increasing difficulty of visualizing consequences that arrive later in time and more distant in space from our problem focus.

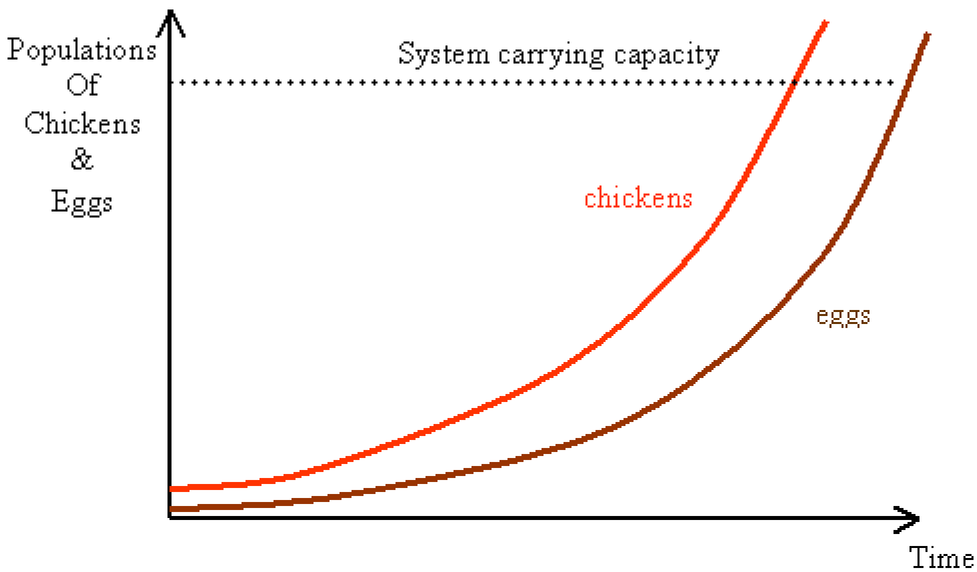
A second major obstacle in holistic decision-making derives from the limitations of looking for a root cause. Certainly it is good to search beyond proximate causes to find underlying ones. But burrowing beyond symptoms of problems, we often find not a root cause but a bewildering set of causes. Could the idea of one root cause be misleading us as to how wholes really work?

Systems science has created conceptual tools that can give us the understanding of causality that we need to get beyond 'root cause' and even come to grips with long-term effects. These tools of systems thinking include a very simple, but powerful **diagrammatic language** of systemic structure that:

- Improves our mental models of how the parts of a system interact through cause and effect to generate problem patterns over time, and
- Conveys our mental models easily to ourselves and to other stakeholders/decision makers, thus subjecting them to critical examination.

Understanding Patterns

The first step is to define any problem dynamically by creating a picture of how a problem behavior arose over time. For example, if we are a chicken farmer and our populations of chickens and eggs are growing out of control, we could describe that

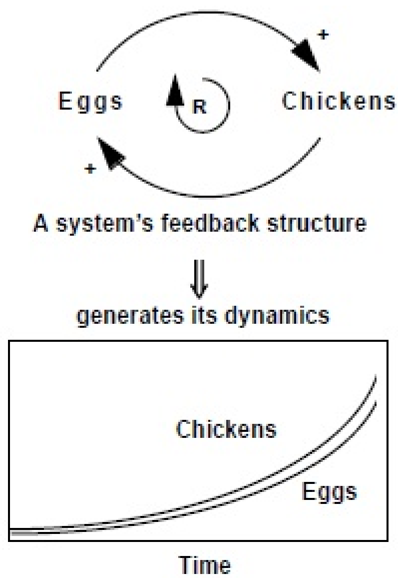


problem dynamically this way:

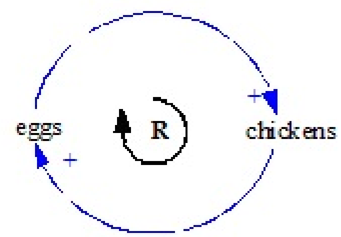
The second step is a simple way of drawing pictures that show in a glance the structures in our wholes that we think **explain** such problem behaviors. Known as causal loop diagrams (CLDs) in systems science, this tool is one product of the systems thinking movement that most anyone can learn. Used regularly, it can broaden holistic perspective.

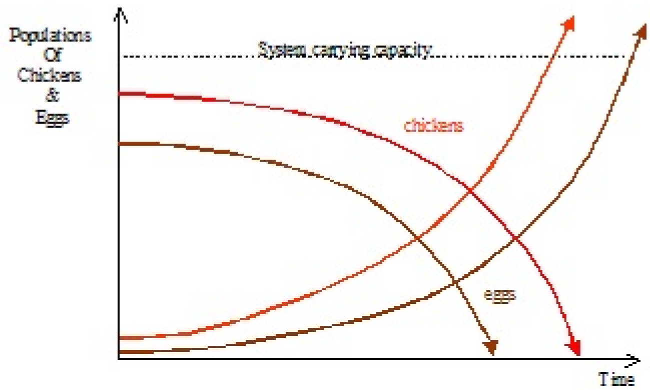
When seeking causes of problems we see in the world, why do we often find not a root cause but an interlocking range of causes? System science reveals that we are not in error. In complex wholes, cause does not come from one place; it comes from variables linked in circles. Because a change anywhere in the circle feeds back to impact the point of origin, these circles are called **feedback loops**.

Thus, in a simple system consisting of chickens and fertile eggs, it is neither component, but rather the feedback loop, chickens-and-eggs, that is causing the system behavior—that stocks of both components grow exponentially over time. The one loop in our system example is called a **reinforcing loop** (**R** in the diagrams), because more chickens makes more eggs makes more chickens in escalating fashion. The feedback loops of the system (in this case only one) are its 'structure' and are what generates its 'dynamics:' what it does to the chicken and egg populations over time.
[chickens-eggs positive feedback]

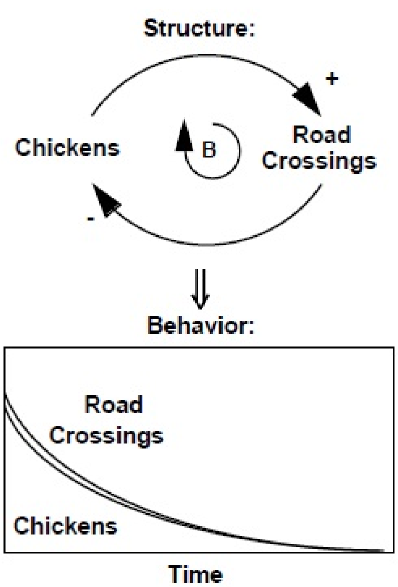


Reinforcing feedback can also accelerate change downwards. An example might be: increasing fox predation throws the chicken population into decline, but increases the fox population, which in turn increases predation and accelerates the decline of the chicken population (and eggs). In everyday language we often label these trends vicious circles or virtuous circles according to how they affect our goals for the system.

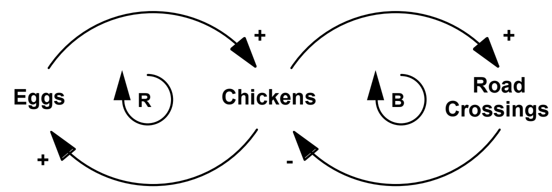


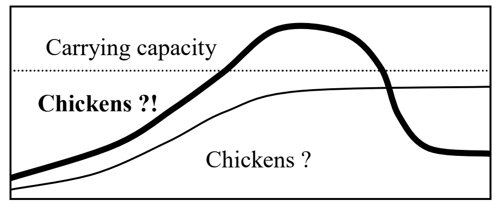


As any farmer knows, this simple system, structured as it is for exponential growth, would eventually overshoot the carrying capacity of its resource base and collapse. But systems science recognizes that there is typically another kind of feedback loop in most wholes, one that works to limit growth and stabilize the system.

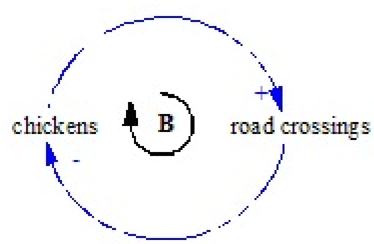


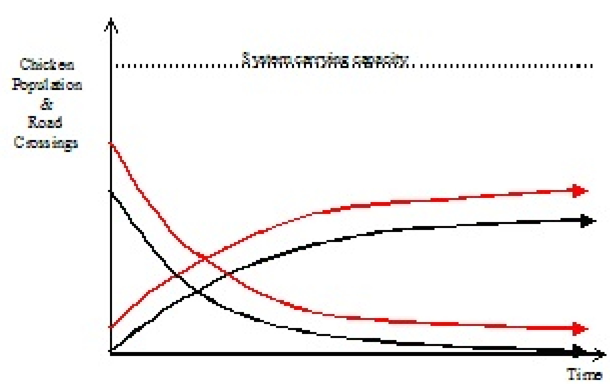
Chickens-and-roadcrossings is an example that might work in our simple demonstration system. The **balancing loop** (**B** in the diagrams) in this case is: more chickens tends to cause more road crossings, which in turn causes fewer chickens. By itself, this loop eventually leads to the end of the chicken population. But joined to the reinforcing loop, the system could generate the behavior the manager desires, depending on how the two loops are managed: which loop is allowed to become dominant.





Hence, as with reinforcing feedback, balancing feedback can work in both directions, to counteract either a rise or a decline in a key variable. An example of the former might be: the farmer increases chicken and egg sales to counteract (balance) the rising chicken population and keep it within the carrying capacity of the farm. An example of the latter might be: as the chicken population declines from road crossing losses, the number of chickens crossing the road declines, which decreases road crossing losses, thus slowing the decline in the chicken population.





Systems science adopts the positive and negative symbols to use in these diagrams because they are in universal use around the world, in mathematics, for example. We often use these symbols to label loops as well as arrows. We call reinforcing loops positive feedback and often symbolize them with a (+). And we call balancing loops negative feedback and often symbolize them with a (-). However, as in mathematics, they do not imply an ethical judgement as they might in another context. For example the positive feedback loop chickens-and-eggs that causes accelerating growth or decline may be desirable or undesirable depending on the situation and the farmer's goals. If a rising chicken population is overshooting the capacity of the farm to feed the chickens, the farmer might judge the positive feedback loop undesirable, and change the system structure, perhaps by adding negative feedback in the form of chicken sales.

Looking for Feedback

How do these revelations help us better understand the causes of problem behavior patterns we see in the wholes we must manage? From the systems thinking perspective, the structure of all complex systems of every type and scale – the rumen food web of a cow, the soil ecosystem, the social network of a community or an enterprise, a local economy or a system of international relations - consists of sets of just these two types of feedback loops that operate together in many combinations.

Furthermore, **it is this feedback structure that generates the long-term behavior trends** in our wholes that we need to understand – that we earlier called Pogo's Law - and that humans have the most trouble grasping. So if we can begin to recognize and identify these two types of feedback in our wholes under management, some pulling, some pushing, we can do a better job of deciding where and when in this structure to apply leverage that will move the system in the direction we desire.

Understanding Cause & Effect

Causal Loop Diagrams are ways to visualize linkages between important variables in your system where a change in one variable causes either a decrease or increase in another. Here are a few simple rules for reading CLDs:

- The arrows show the direction of causality. So in the above reinforcing loop one arrow indicates that a change in the chicken population causes a change in the egg population. The other arrow indicates that a change in the number of eggs causes a change in the number of chickens, as the eggs hatch.

- The signs (+, -) on the arrows have a special meaning, different from the usual one. A plus (+) means that a change in one variable has an effect **in the same direction** on the other, at least relative to what it would have been. Thus an increase in the chicken population causes an increase in the egg population. And a plus (+) **also** means that a decrease in the chicken population causes a decrease in the egg population.

- A minus (-) means that a change in one causes a change **in the opposite direction** in the other, at least relative to what it would have been. So in the above balancing loop more road crossings tends to reduce the chicken population. And fewer road crossings implies a higher chicken population than there would have been had the number of road crossings stayed the same. All causal links effect change in either the same or opposite direction from the causal action.

- As with causal links, feedback loops also occur in only two types, as mentioned earlier. To identify the kind of loop we must trace its causality around the entire circle. Starting with any variable, imagine either an increase or decrease, and trace the effect through all the elements of the loop. If a change in the original variable in the end causes an additional change of that same variable **in the same direction**, we call it a reinforcing loop (**R**) because it reinforces the original dynamic. More chickens means more eggs, which increases the chicken population even more. A reinforcing loop will cause exponential growth (or decline) that accelerates change in all variables in the loop.

- If a change in the variable we start with leads around the loop to a change **in the opposite direction,** we call it a balancing loop (**B**) because it tends to counteract the original change, decelerating change. More chickens means more road crossings, which tends to reduce the chicken population (as chickens get hit by cars!).

Learning to see feedback structure and its consequences is not as complicated as it sounds. Like learning a musical instrument, it gets better with practice. An expanding branch of the SD network has taught elementary school children to diagram the feedback they experience in the wholes in their lives, and even to create simulation models on the computer where they can model the feedback structures in their lives and learn what consequences changes would have in the long term.

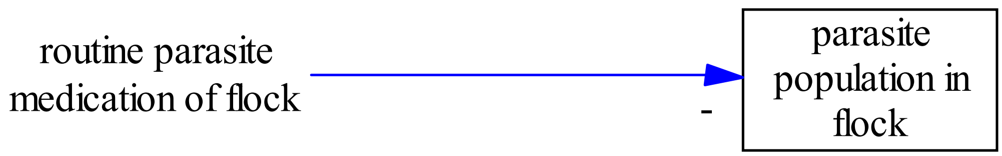
Once we see that cause and effect often runs in circles, we can appreciate what a hash verbal communication makes of our understanding of system behavior, because it runs in straight lines (subject-verb-predicate), and rather too short ones at that. Then we can grasp the advantages of a diagrammatic language of circles and arrows that can communicate the dynamic, causal interconnections of all system components at a glance. This language is information dense, packing pages of prose into a single picture, and unlike prose, the language is unambiguous.

Parasite Problems

I said before that looking for the root cause gets us only part way to an understanding of the downstream consequences of decisions because we have been taught to perceive change in the world as unidirectional, where problems lead to actions that lead to permanent solutions. Building visual models that show all the important causal relationships that contribute to a problem behavior can get us much further. Let’s take the example of what decision would best control parasites in sheep.

Although we may have heard of disadvantages of medication, we are probably already doing it, so we use the "Five Whys" and decide that the root cause is that we are failing to medicate routinely. So we apply routine parasiticide treatments to the sheep and sure enough, it works. We can model the causal relationship this way:

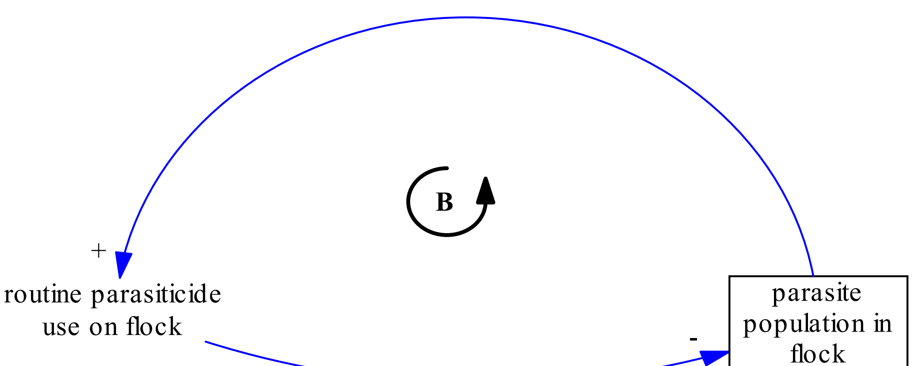
The arrow shows the direction of cause and effect, and the sign (-) tells us that a change in the first variable causes a change **in the opposite direction** in the second variable. So

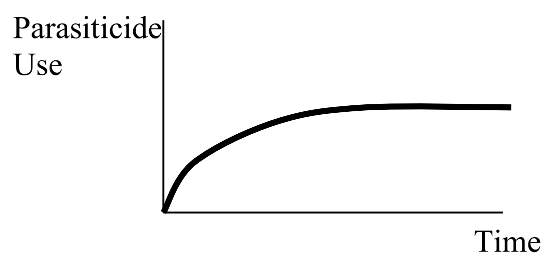


if we decrease routine parasite medication of the flock, the parasite population in the flock will increase, all other conditions remaining unchanged. It also means that if we increase routine parasite use, the flock parasite population will decrease.

Since stepping up routine medication is expensive in materials and labor, the favorable effect of a decrease in the parasite population may lead some shepherds to eventually cut back again on the number of medications. We can model this response this way:

This shows that the original ramp up of treatment led to a response (reduced parasite population) that in turn prompted another response (reduced medication) **in the same direction**, thus reducing parasiticide use. This is the meaning of the plus sign (+). The final effect was to **feed back** and counteract the original action. For clarity we identify

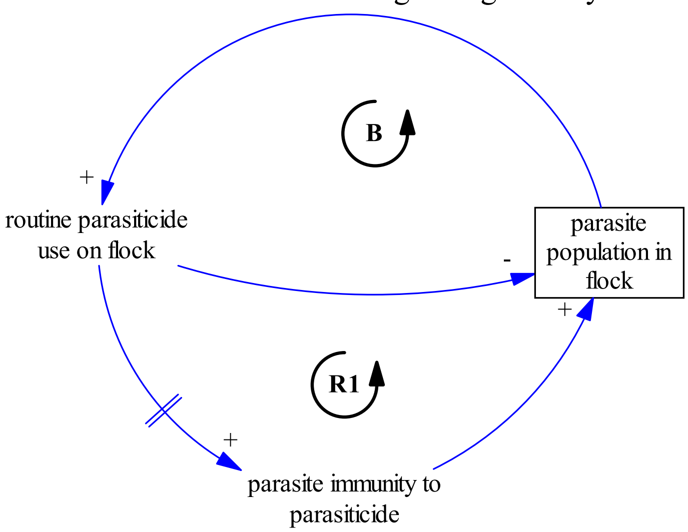


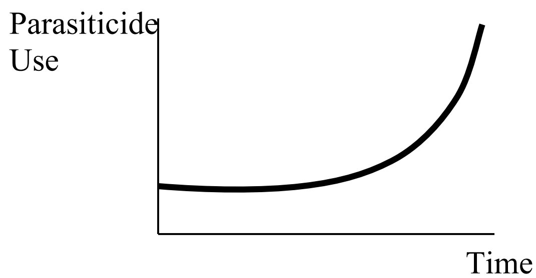


this feedback as a balancing loop (**B**), because it tends to set limits on any tendency to continually increase (or decrease) the level of treatment, as shown in the time graph.

Regardless of whether the balancing feedback behavior occurs, in every case other things are happening over time, which are important to understand. Increases in routine medication cause the parasite population to adapt with improved genetic immunity to the medication, leading to mounting flock parasite populations, and further increases in medication, creating a reinforcing feedback loop **R1** (dotted lines) with its typical accelerating behavior over time in all variables:

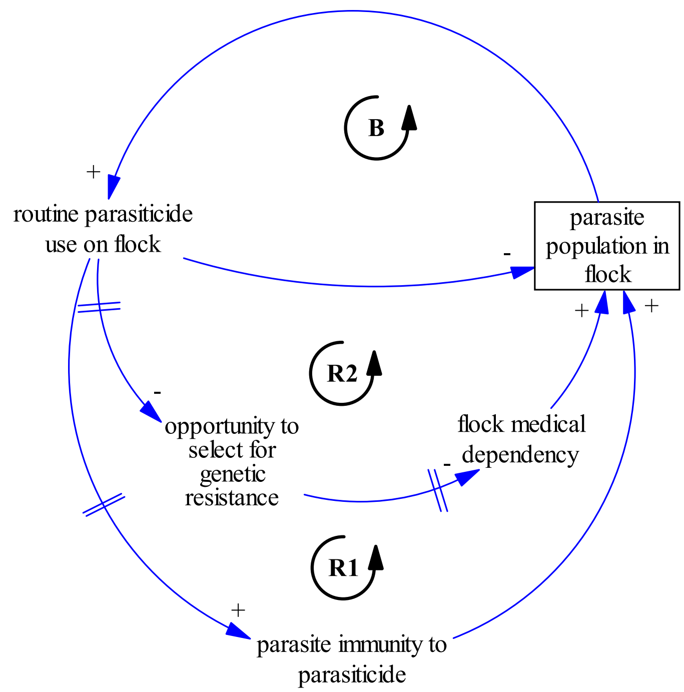
We show that the genetic immunity occurs slowly by drawing a delay marker on the arrow (//). One might conclude that this is easy to understand without building a model, but the fact that shepherds, veterinary specialists, and the scientists who created the medication have managed to gradually destroy the efficacy of most sheep parasiticides by





advocating or practicing routine use suggests otherwise.

Ramping up routine parasiticide use on the flock has another downstream effect. Because the flock is constantly medicated, the shepherd cannot tell which sheep are genetically most vulnerable to parasite infestation. Opportunities to select for genetic resistance decrease. So although the effect takes place gradually because of the delays, the flock becomes increasingly genetically addicted to the medication. Dependency on medication eventually causes higher parasite populations in the sheep flock than would be the case without the addiction, all other things being equal. The end result is endless increases of medication levels, modeled in reinforcing loop **R2** (dotted lines)**,** also a loop with delays.



Furthermore, the model makes clear that feedback loops **R1** and **R2** have a multiplier effect on each other as they relate to management of the problem. All these effects are **counterintuitive** responses to the more routine use of the medication, **responses that are not even mentioned in textbooks that teach livestock parasitism in graduate courses in major agricultural schools!** The tragic end results for the sheep industry are gradually diminished genetic parasite resistance in most common commercial sheep breeds, compounded by an increasingly useless set of common parasite medications.

"We may look alike, but because I'm a clone I'm actually someone's intellectual property."

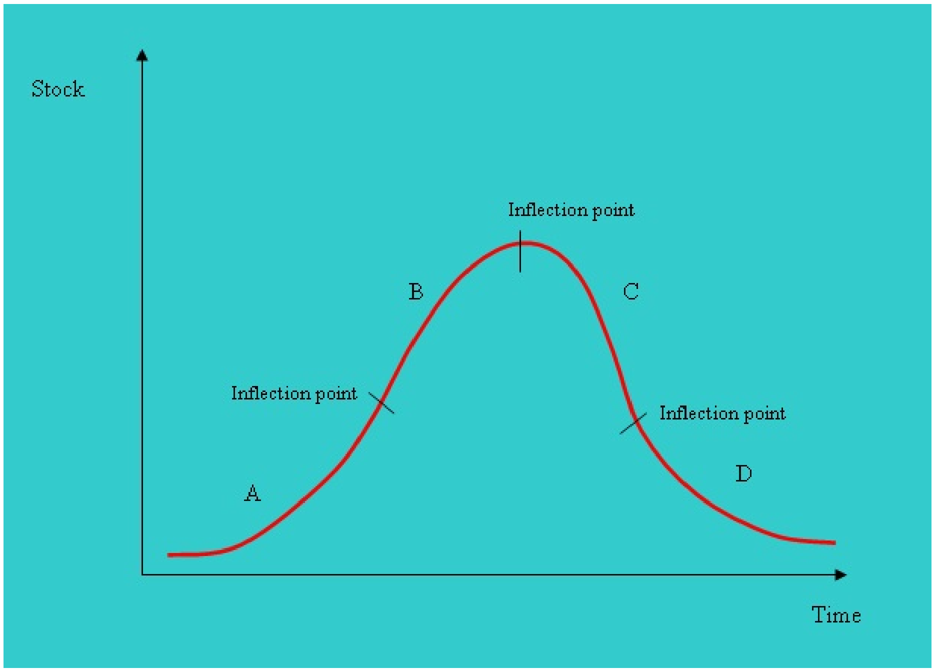
Now that we have a model of the dynamics (behavior over time) of the problem in response to medication, how can it guide our decision making to protect the flock from parasites? From our final model we can see that a decrease in routine parasiticide use will increase opportunities for genetic selection. This is true because it will reveal the unresistant sheep, which then we can cull, leaving the more resistant ones. Several years of this selection will yield a flock that has the maximum possible genetic resistance to parasites. Decreasing the medication will leave the flock still somewhat vulnerable to parasites. However, once a parasite resistant flock is achieved this partial solution can be combined with grazing management practices that provide a full solution. Thus a sustainable solution exists that does not require medication, although it is rarely mentioned by educators in sheep husbandry. The point is that by revealing a partial alternative to medication, the modeling process encourages a full exploration of that option, which turns out to have beneficial ripple effects. The non-medical solution saves the farmer the cost of constant medication and, if adopted by the sheep industry, would solve the problem the loss of potency of the medication due to over use and resultant parasite immunity. Then the medications would still be effective for emergency use.

In sum, this example demonstrates that the systems thinking approach of modeling a problem to discover the appropriate system of interest can reveal positive and negative feedback effects that radically change how we understand a situation.

Feedback Dominance

What is most important to understand in a situation is why things change over time as they do. The first step in understanding is to learn the historical behavior and describe it, typically in a time graph. Once we have a time graph of change, we build a model to discover the structure of positive/reinforcing and negative/counteracting feedbacks in the system of influence that explains the behavior in the time graph.

The shape of the time graph of historical behavior that concerns us in a situation gives us a rough indication of the feedback structure that we need to include in a model that intends to explain the behavior. One or more of the following curves will appear in a time graph of nonlinear behavior.



It is important to discover which type of feedback is dominant in the situation, because feedback dominance is often the key to understanding change in the situation. For example, as you saw in the chicken-egg-roadcrossing model described previously, it makes a difference to what happens to the chicken population whether the reinforcing loop or the balancing loop is the stronger one.

A - positive feedback dominates: growth accelerates
B - positive feedback exists but negative feedback dominates: growth decelerates
C – positive feedback dominates: decline accelerates
D – positive feedback exists but negative feedback dominates: decline decelerates

Although they may not all apply in a given situation, these four types of feedback dominance cover all possible nonlinear behaviors, including s-shaped growth and oscillation. The value of recognizing what each means in terms of feedback dominance is that when each is encountered in a time graph, they guide modeling to create feedback structures that could explain them. Such a model allows policy makers to identify points of leverage in the system that could shift feedback dominance in a way that maintains or generates desired behaviors over time.