Introduction to Engineering Systems, ESD.00

System Dynamics - I

Lecture 2

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- “You cannot meddle with one part of a complex system from the outside without the almost certain risk of setting off disastrous events that you hadn’t counted on in other, remote parts. If you want to fix something you are first obliged to understand… the whole system… Intervening is a way of causing trouble.”*

*Lewis Thomas (biologist and essayist), quoted in Business Dynamics, J. Sterman, 2000

Systems Thinking

- Our world is complex and its elements are inter-related.
- We need to understand that "we can't do just one thing" – things are interconnected and our actions have numerous effects that we often do not anticipate or realize.
- Many times our policies and efforts aimed towards some objective fail to produce the desired outcomes, rather we often make matters worse
  - For instance:
- *Systems Thinking* involves holistic consideration of our actions – it is needed to deal with the complexity of our world

What is System Dynamics?

- System Dynamics is a method that helps us learn and understand complex systems
- It is fundamentally interdisciplinary and brings together tools and theories from a wide variety of traditional disciplines.
- At its core, its foundations are on nonlinear dynamics and mathematical feedback control theory, and it draws from economics, social psychology and other sciences.
- We use system dynamics to construct models of socio-technical systems, and use computer simulation to determine how these systems may behave in the real-world

Law of Unintended Consequences

- Murphy's Law

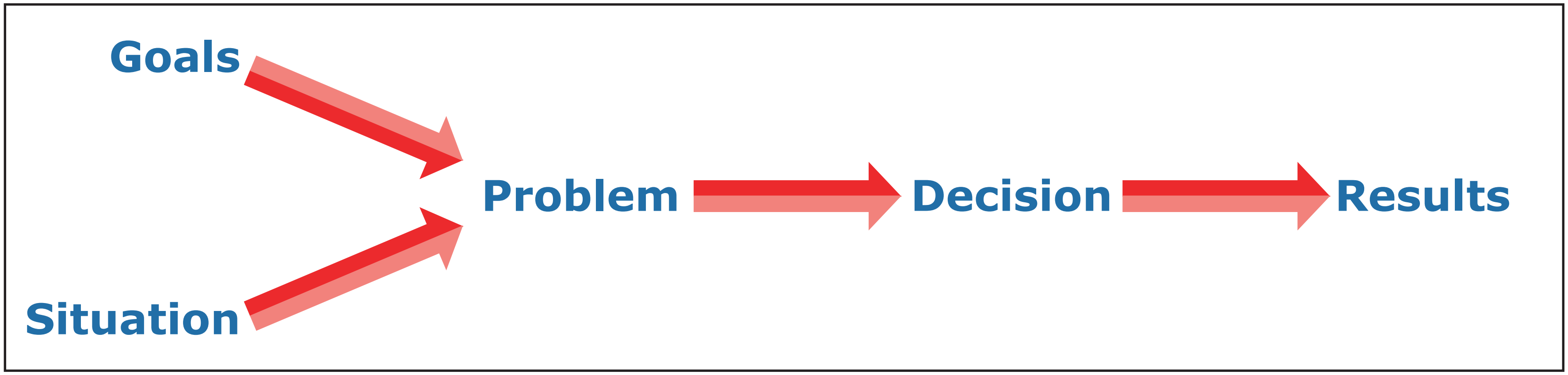
- "Counter Intuitive Behavior of Social Systems"

- Unexpected dynamics often lead to 'policy resistance, i.e. the tendency for interventions to be delayed, diluted, or defeated by the response of the system to the intervention itself'

- Our actions to solve some problem tend to make the problem worse or create new problems in its place (can you think of examples?)

Causes of Policy Resistance: The Serial View

Event-oriented view of the world



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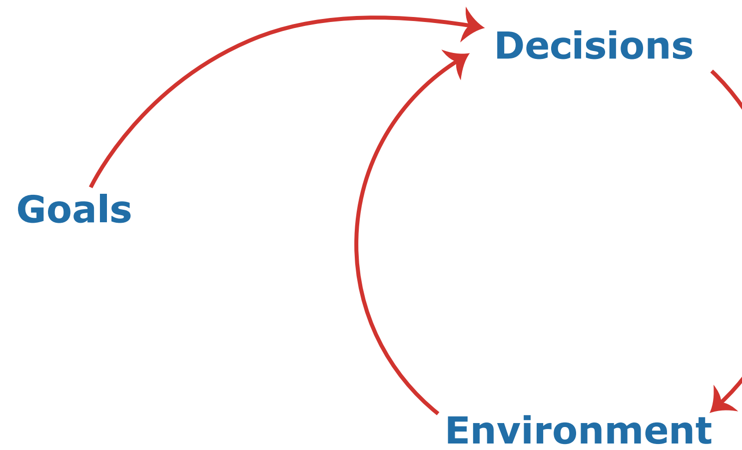
Ref: Figure 1-3, J. Sterman, Business Dynamics: Systems Thinking and Modeling for a complex world, McGraw Hill, 2000

We typically tend to think of things as chains of cause and effect and often ignore the time delays between them

The Feedback View

- In reality, there is feedback – the results of our present actions define our future situation



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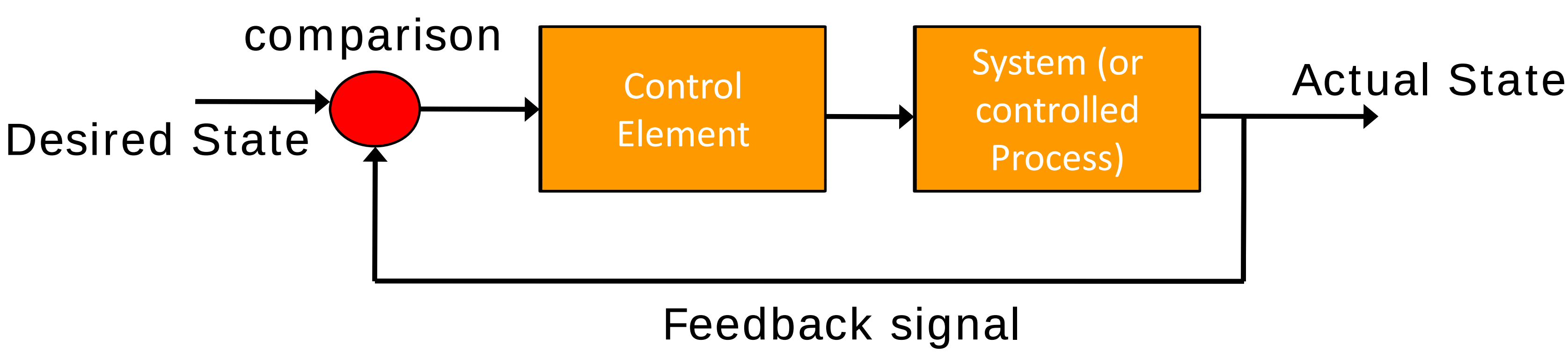
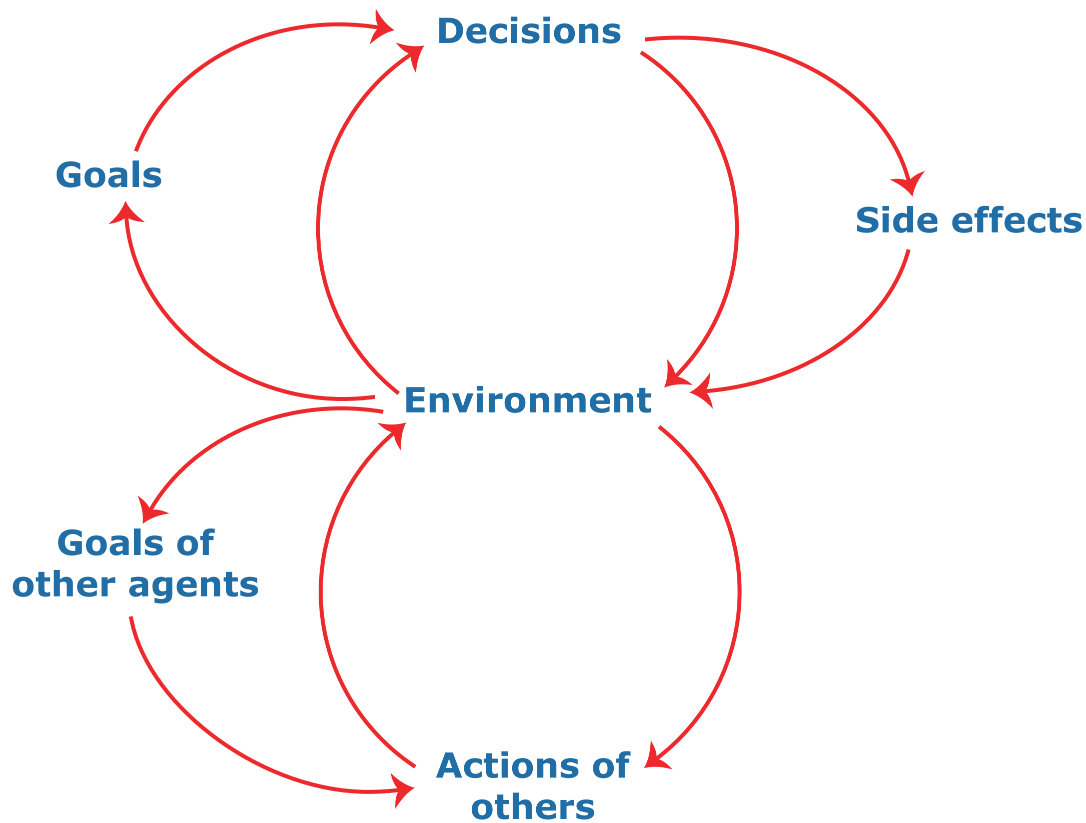
- Examples of feedback



The Feedback View

- Policy resistance is often due to incomplete understanding and accounting of full range of feedbacks
- Consider the pesticide problem…
- We will spend a lot of time thinking, identifying and modeling these feedbacks in our system dynamics work



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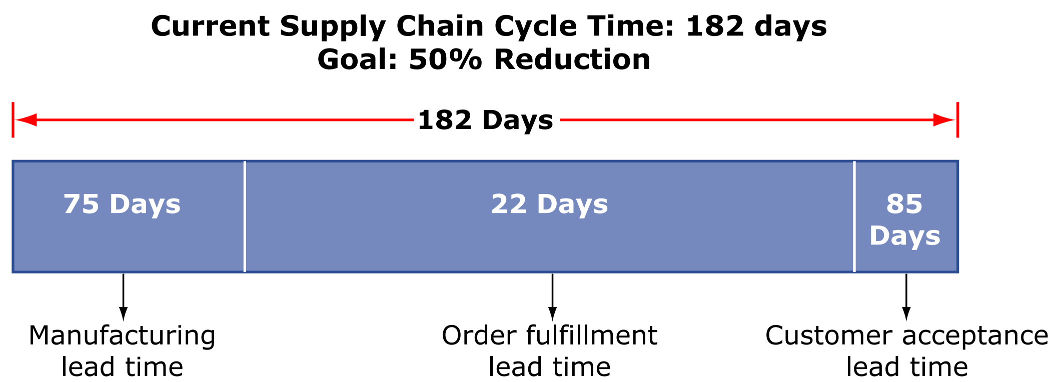
Ref: Figure 1-4, J. Sterman, Business Dynamics: Systems Thinking and Modeling for a complex world, McGraw Hill, 2000

Mental Models

- Mental models are widely discussed in psychology and philosophy
- Concept of mental models is central in System Dynamics
- Forrester stresses **that all decisions are based on models, usually mental models**.
- In System Dynamics, 'mental models' are our beliefs of networks of causes and effects that describe how a system operates – it is our framing or articulation of the problem



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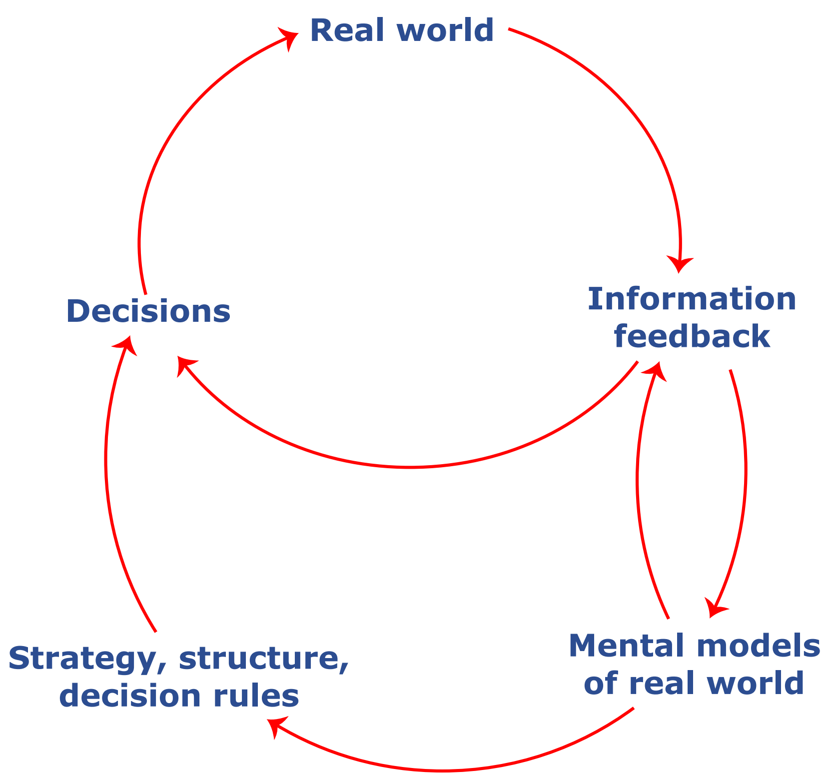
Ref: Figure 1-10, J. Sterman, Business Dynamics: Systems Thinking and Modeling for a complex world, McGraw Hill, 2000

Double-Loop Learning

- Systems Thinking comes with replacing a narrow, static, short-run view with a broad, dynamic and long-term view of our systems and policies



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Ref: Figure 1-11, J. Sterman, Business Dynamics: Systems Thinking and Modeling for a complex world, McGraw Hill, 2000

Bounded Rationality

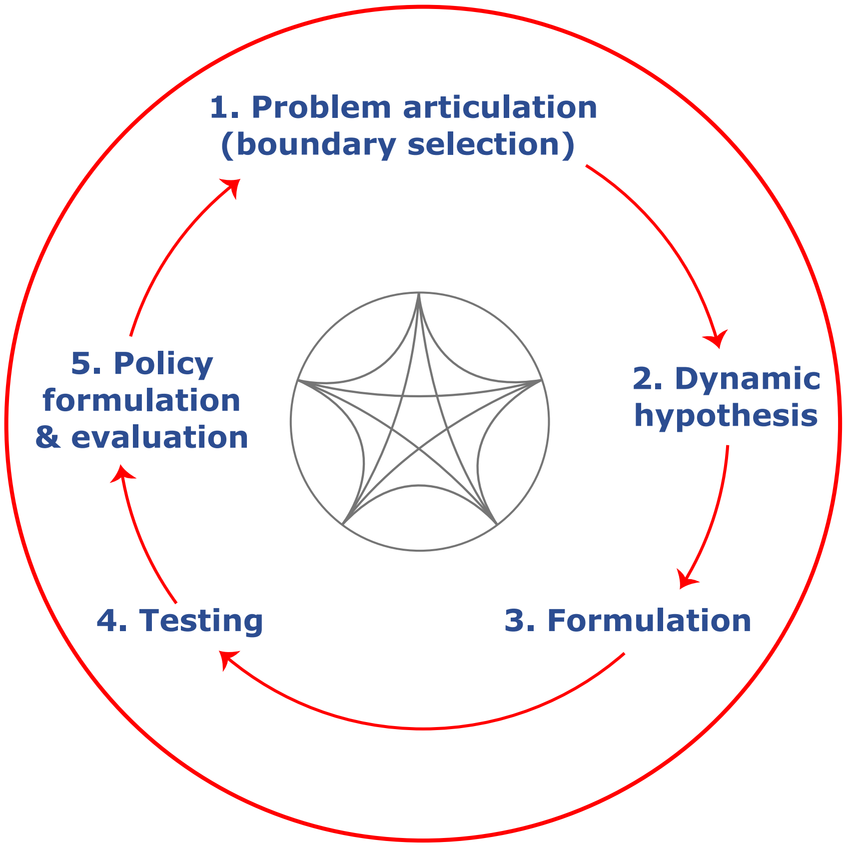
"The capacity of the human mind for formulating and solving complex problems is very small compared to the size of the problem whose solution is required for objectively rational behavior in the real world or even for a reasonable approximation to such objective reality". (Herbert Simon, 1957)

Simulation

- Creating and simulating a model lets you make your mental model explicit, and then helps you see how your defined system structure will behave in time.
- Formalizing qualitative models and testing via simulation often leads to radical changes in the way we understand reality.
- Discrepancies between formal and mental models stimulate improvements in both, including changes in basic assumptions, time horizon and dynamic hypothesis.

The Modeling Process

1. What is the problem, what are the key variables, what is the time horizon?
2. What are the current theories of the problematic behavior? Create causal maps.
3. Create a simulation model by specifying structure and decision rules.
4. Check if model reproduces the problematic behavior, check extreme conditions.
5. What future conditions may arise? What will be the effect of a policy or strategy?



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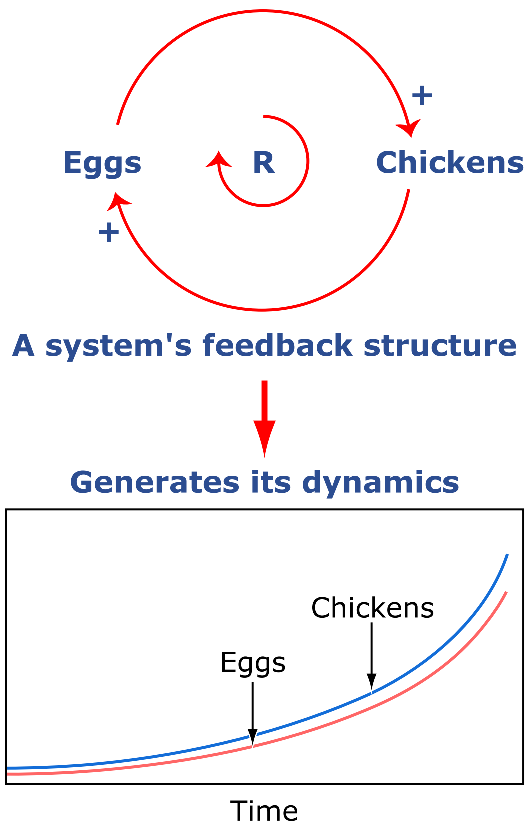
Ref: Figure 3-1, J. Sterman, Business Dynamics: Systems Thinking and Modeling for a complex world, McGraw Hill, 2000

Formulating a Hypothesis

- “A dynamic hypothesis is a working theory of how the problem arose”
- System dynamics seeks endogenous explanations for phenomena. An endogenous theory generates the dynamics of the system through the interaction of variables and agents represented in the model.
- Create a model boundary chart, a list of endogenous, exogenous, and excluded variables that define the scope of the model

Causal Loop Diagrams (CLD)

- CLDs are maps that show links between variables with arrows that signify cause and effect.
- They help in eliciting and capturing mental models
- CLDs describe the hypothesis about the causes of the dynamics



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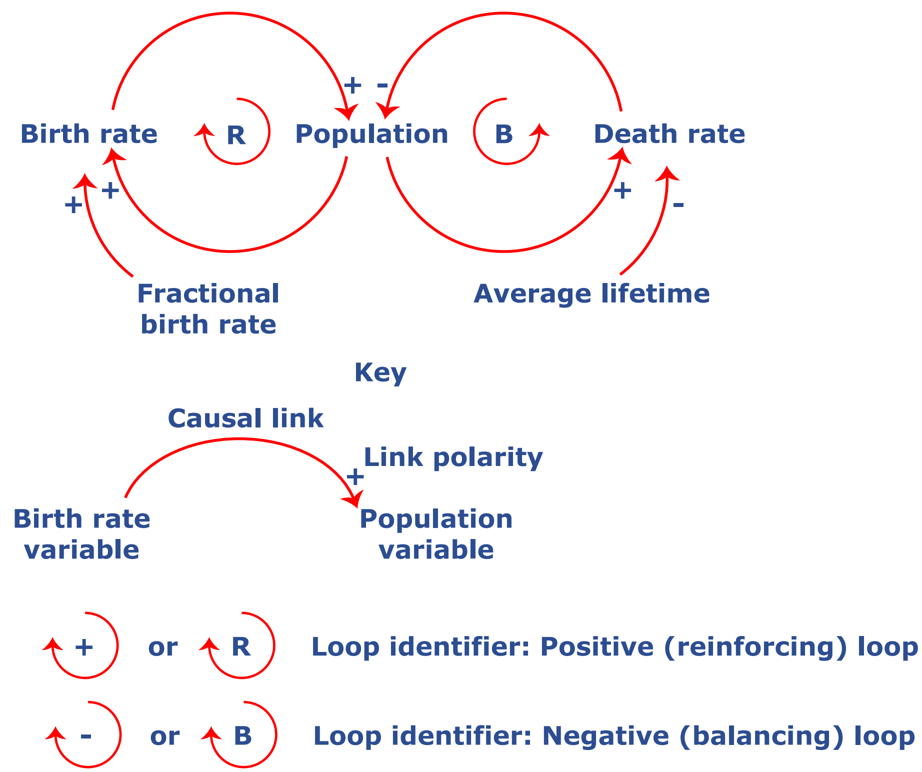
Ref: Figure 1-5a, J. Sterman, Business Dynamics: Systems Thinking and Modeling for a complex world, McGraw Hill, 2000

Diagram Notations

Ref: Figure 5-1, J. Sterman, Business Dynamics: Systems Thinking and Modeling for a complex world, McGraw Hill, 2000

- Variables are: Birth rate, population, death rate, fractional birth rate, average lifetime
- Variables are connected by 'causal links' (arrows) with assigned polarities
- Polarities indicate how the independent variable affects the dependent variable
- Loop identifiers indicate direction of circulation and type (balancing or reinforcing)



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Link Polarity

Ref: Table 5-1, J. Sterman, Business Dynamics: Systems Thinking and Modeling for a complex world, McGraw Hill, 2000

Symbol	Interpretation	Mathematics	Examples
$X \xrightarrow{+} Y$	All else equal, if X increases (decreases), then Y increases (decreases) above what it would have been. In the case of accumulations, X adds to Y.	$\partial Y/\partial X > 0$ In the case of accumulations, $Y = \int_{t_0}^{t} (X + \ldots.)ds + Y_{t_0}$	Product quality $\xrightarrow{+}$ Sales Effort $\xrightarrow{+}$ Results Births $\xrightarrow{+}$ Population
$X \xrightarrow{-} Y$	All else equal, if X increases (decreases), then Y decreases (increases) below what it would have been. In the case of accumulations, X subtracts from Y.	$\partial Y/\partial X < 0$ In the case of accumulations, $Y = \int_{t_0}^{t} (-X + \ldots.)ds + Y_{t_0}$	Product price $\xrightarrow{-}$ Sales Frustration $\xrightarrow{-}$ Results Deaths $\xrightarrow{-}$ Population

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Causation and Correlation

- Causal diagrams must include only genuine causal relationships
- Correlations represent past behavior, not underlying system structure
- Serious policy errors/judgments can result from erroneous assumptions of causality

Loop Polarity

- Trace the effect of a change around the loop.
- If feedback effect reinforces the original change, it is a positive (reinforcing) loop.
- If feedback effect opposes the original change, it is a negative (balancing) loop

Clarity in Polarity

- Links must have unambiguous polarity

- If it is unclear which polarity to assign, it is likely there are multiple pathways between the two variables under consideration. Elaborate those pathways until no ambiguity is left.

Clarity in Logic

- Models become complex with too much detail
- Too little detail can make model confusing
- Add enough structure so that it is easy to grasp the logic

Goals of Negative Loops

- Negative feedback loops have goals (desired states)
- These loops function by comparing actual state with desired state and making adjustments in response to discrepancy
- Make the goals explicit
- Knowing the goals helps in thinking how the goals are formed, how they may change over time.

Actual & Perceived Conditions and Delays

Image by MIT OpenCourseWare.

Ref: Figure 5-17, J. Sterman, Business Dynamics: Systems Thinking and Modeling for a complex world, McGraw Hill, 2000

Case Study:
Managing Your Workload

- Issue/case
  - need to balance course load/work and personal life
  - Two possible strategies

- Key variables
  - Assignment rate [tasks/wk]
  - Work completion rate [tasks/wk]
  - Assignment backlog [tasks]
  - Grades [0-100]
  - Workweek [hours/wk]
  - Energy level [0-100, 100: fully rested, 0: comatose]

Creating a Reference Mode

- State Time Horizon
- Use several graphs for clarity
- Plot variables with same units on same axis for easy comparison
- Quantitative data not necessary, make estimates of the behavior – don't omit variables simply because no numerical information is available
- There should be a basis in the data for each reference mode
- Details matter!
- Graphs should be consistent with any stock and flow relationships

CLDs

- Assignment backlog decreases with work completion rate and increases with the assignment rate.

- Work pressure increases workweek, but if pressure is too high, you'll devote less effort to the assignments to get work done quickly by cutting corners