System Dynamics: Introduction

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Complexity and Change

- Our world is complex and its elements are inter-related.

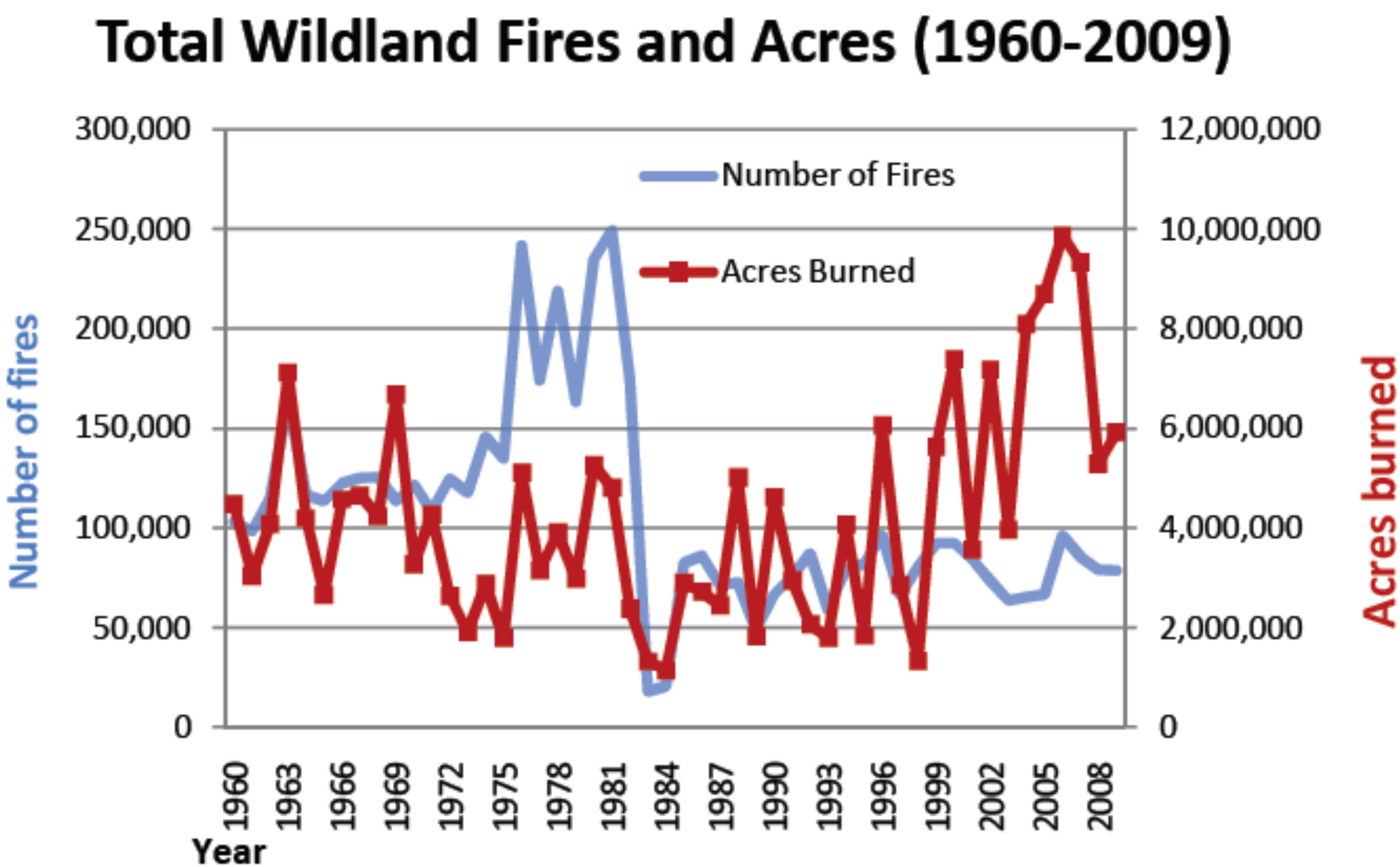
- Many times our policies and efforts aimed towards some objective fail to produce the desired outcomes, rather we often make matters worse
  - For instance:
  - Anti-biotic Resistance,
  - Pesticides Resistance
  - Impacts of Disasters (fires, floods etc.)

- Often our actions targeted to solve a problem are seemingly successful at first but later are found to have created new problems
  - For instance:

- “When you are confronted by any complex social system……, with things about it that you’re dissatisfied with and anxious to fix, you cannot just step in and set about fixing with much hope of helping……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

Examples of Policy Resistance

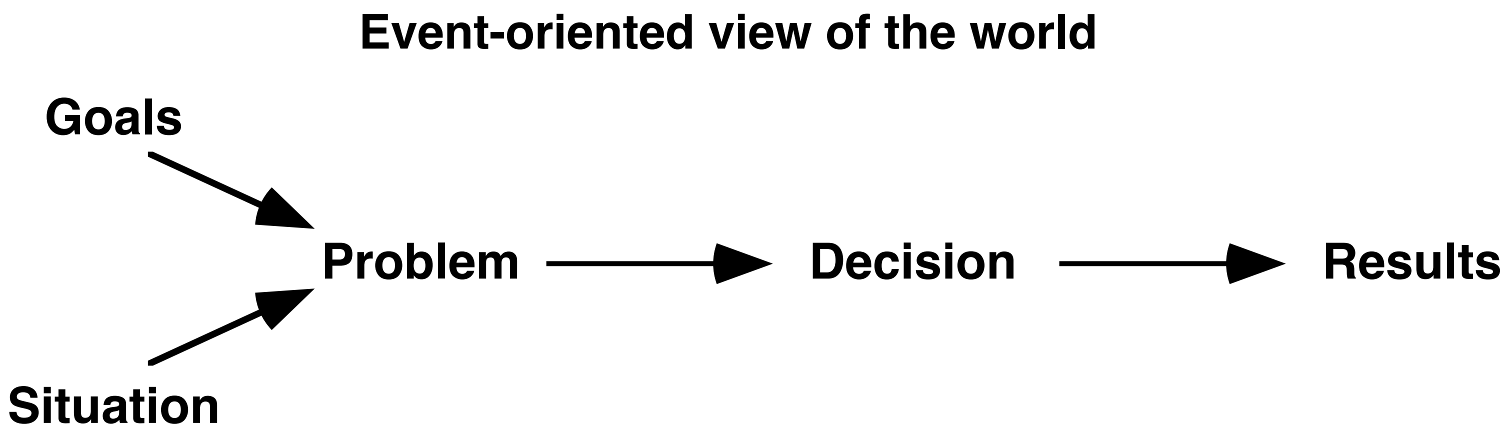


source: National Interagency Fire Center, http://www.nifc.gov/fire_info/fires_acres.htm

Law of Unintended Consequences

- Our actions to solve some problem tend to make the problem worse or create new problems in its place
- “Counter Intuitive Behavior of Social Systems”
- Murphy’s Law
- 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’

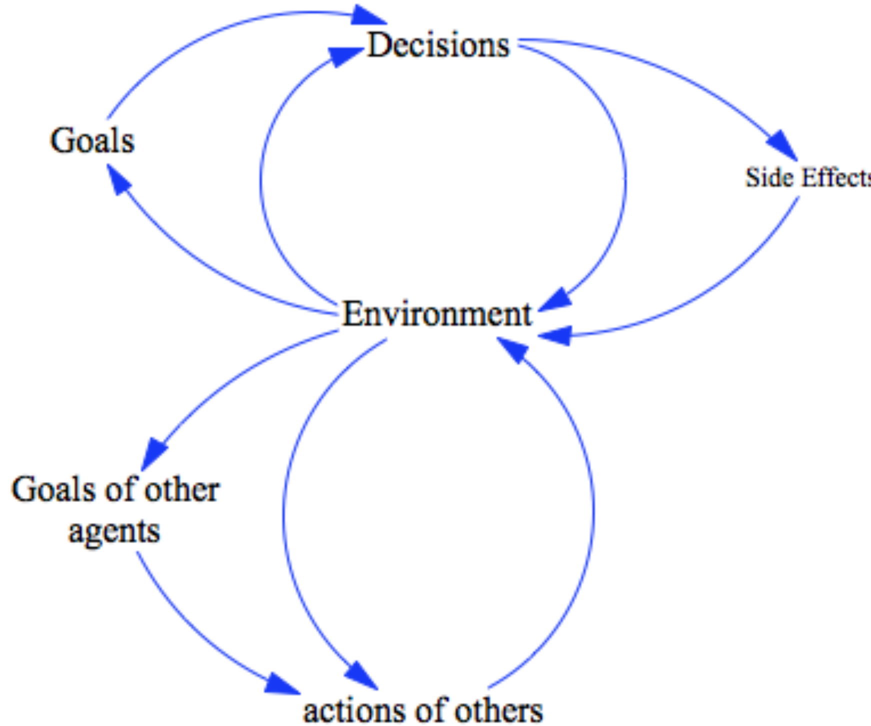
Causes of Policy Resistance: The Serial View



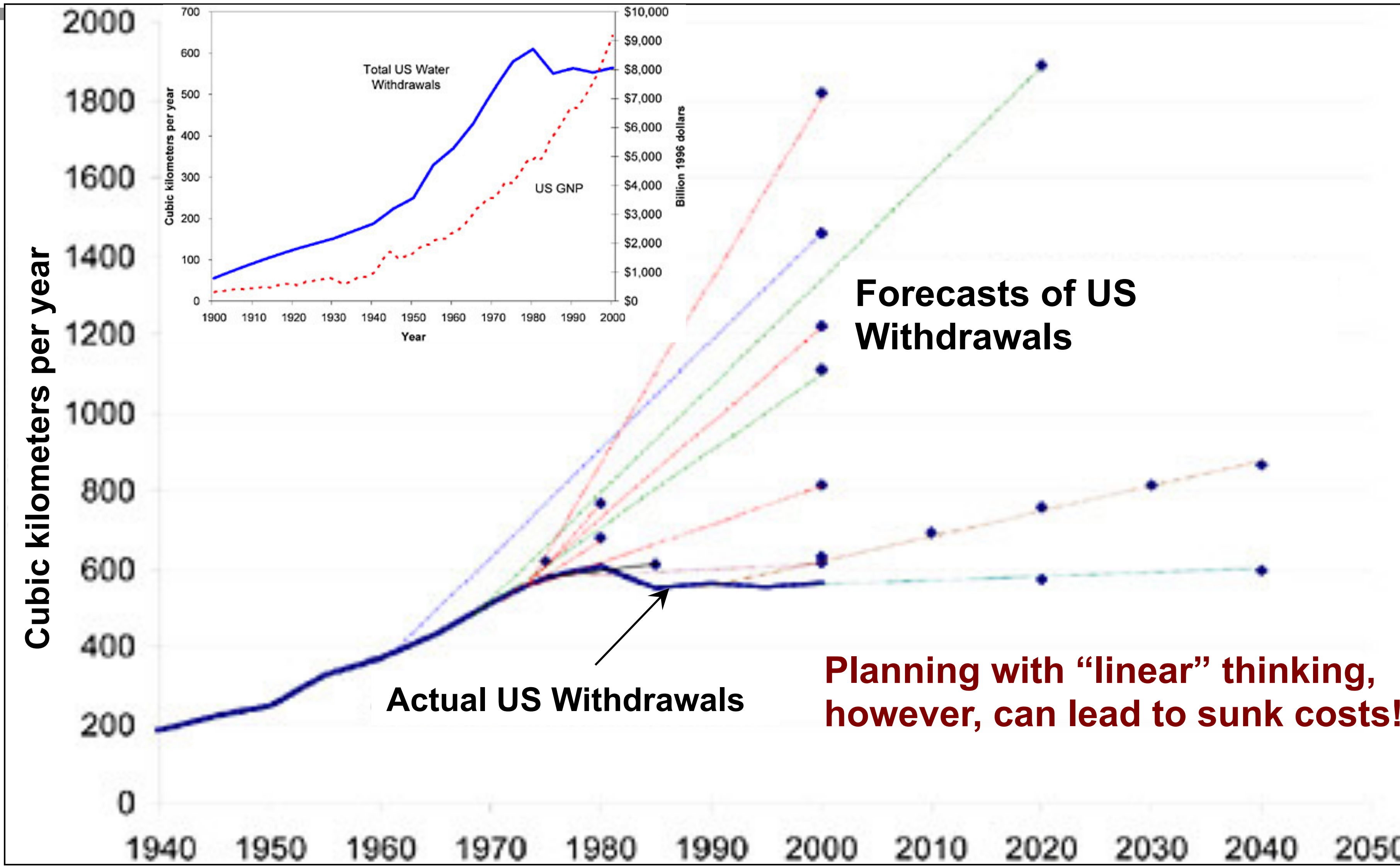
We typically tend to think of things as chains of cause and effect and often ignore the time delays between them

The Feedback View

- In reality, there is feedback.
- The results of our present actions define our future situation
- <u>Policy resistance is often due to incomplete understanding and accounting of full range of feedbacks</u>
- Consider the pesticide problem...
- Consider the mosquitoes eradication problem....



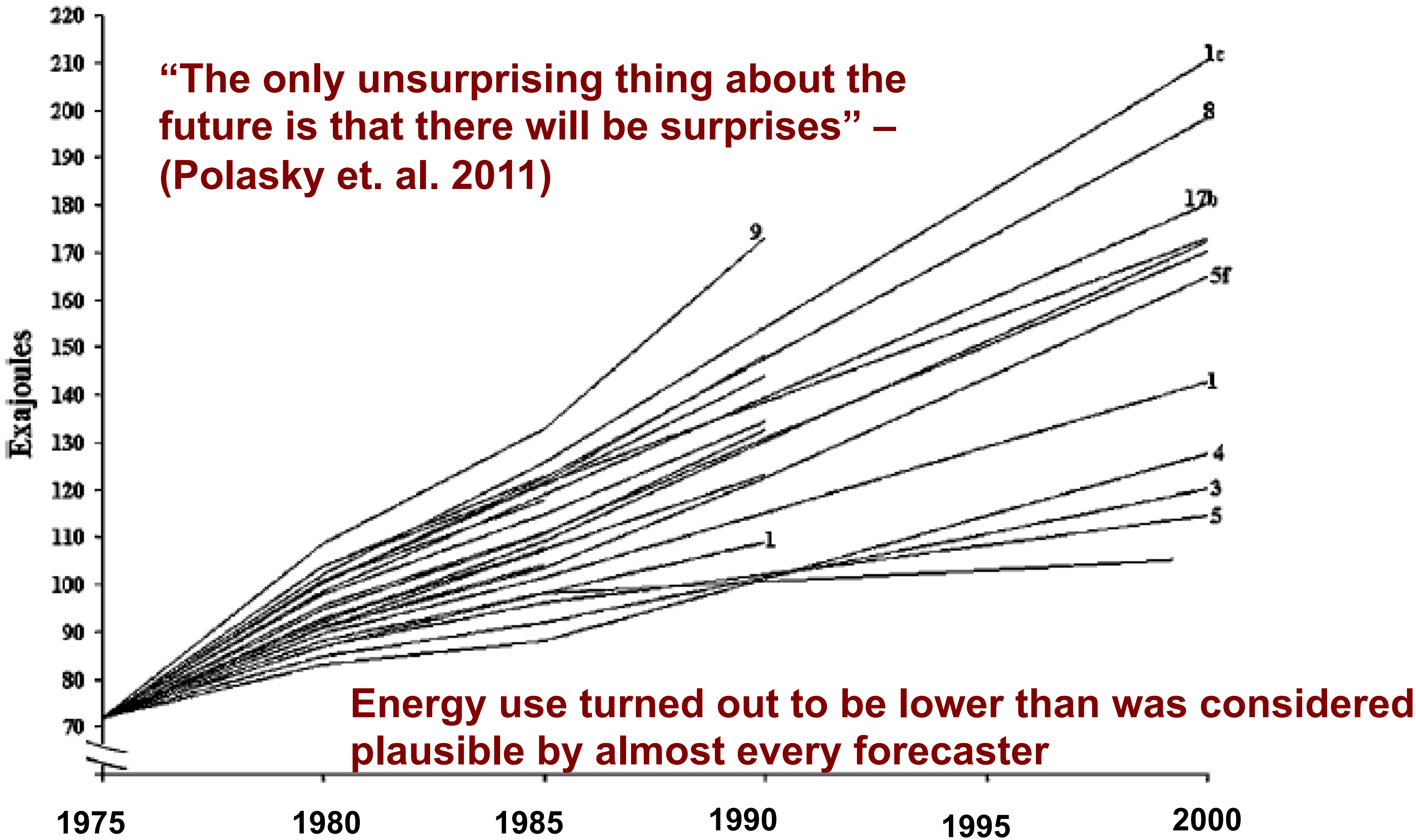
Some actions can lead to positive side effects..



Source: *Desalination: A National Perspective*, WSTB, NAE, 2008

Some more examples of projections…

Projection of total US primary energy use from the 1970s



Paul P. Craig, Ashok Gadgil, and Jonathan Koomey, (2002), What can history teach us? A retrospective examination of long-term energy forecasts for the United States. *Annual Review of Energy and the Environ*ment, 27:83–118

Systems Thinking

- 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.

- *Systems Thinking* involves holistic consideration of our actions – it is needed to deal with the complexity of our world.

- Systems Thinking is about
  - taking a long-term view
  - thinking about change in systems
  - *considering direct as well as in-direct impacts* of our actions and their side-effects
  - identifying high leverage points to avoid *policy resistance*

Characteristics of Complex Systems

- **Adaptive** (the capabilities and decision rules of agents in complex systems change over time)
- **Counterintuitive** (cause and effect are distant in time and space)
- **Characterized by trade-offs** (the long run is often different from the short-run response, due to time delays. High leverage policies often cause worse-before-better behavior while low leverage policies often generate transitory improvement before the problem grows worse.
- **Governed by feedback** (actions feedback on themselves)
- **Nonlinear** (effect is rarely proportional to cause, and what happens locally often doesn't apply in distant regions)
- **History-dependent** (taking one road often precludes taking others and determines your destination, you can't unscramble an egg)
- **Dynamic** complexity arises due to interactions among different agents over time. Systems with even a few elements can exhibit dynamic complexity.

Systems Thinking is Critical for Our Survival in the Anthropocence

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.

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

What is Systems 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

Jay W. Forrester
(1918- 2016)

MIT Sloan School of Management

Founder of the field of Systems Dynamics

- Systems dynamics modeling consists of qualitative/ conceptual and quantitative/numerical modelling methods.

- Qualitative modelling, e.g. using causal loop diagrams, improves our conceptual system understanding.

- Quantitative modelling, e.g. using stock-and-flow models, allows us to investigate and visualise the effects of different intervention strategies through simulation
  - Quantitative modelling also requires us to make explicit statements about assumptions underlying the model, identify uncertainties with regards to system structure, and identify gaps in data availability. This promotes model transparency

The Modeling Process

1. What is the problem, what are the key variables, what is the time horizon?

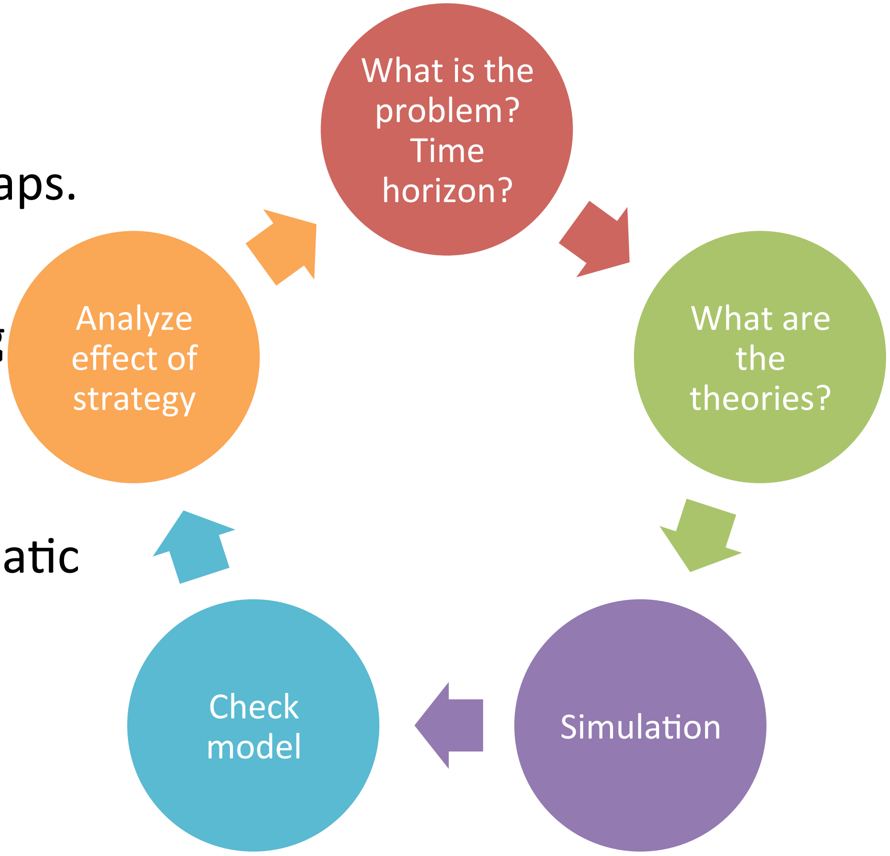
2. What are the current theories of the problematic behavior? Create causal maps.

3. Create a simulation model by specifying structure and decision rules

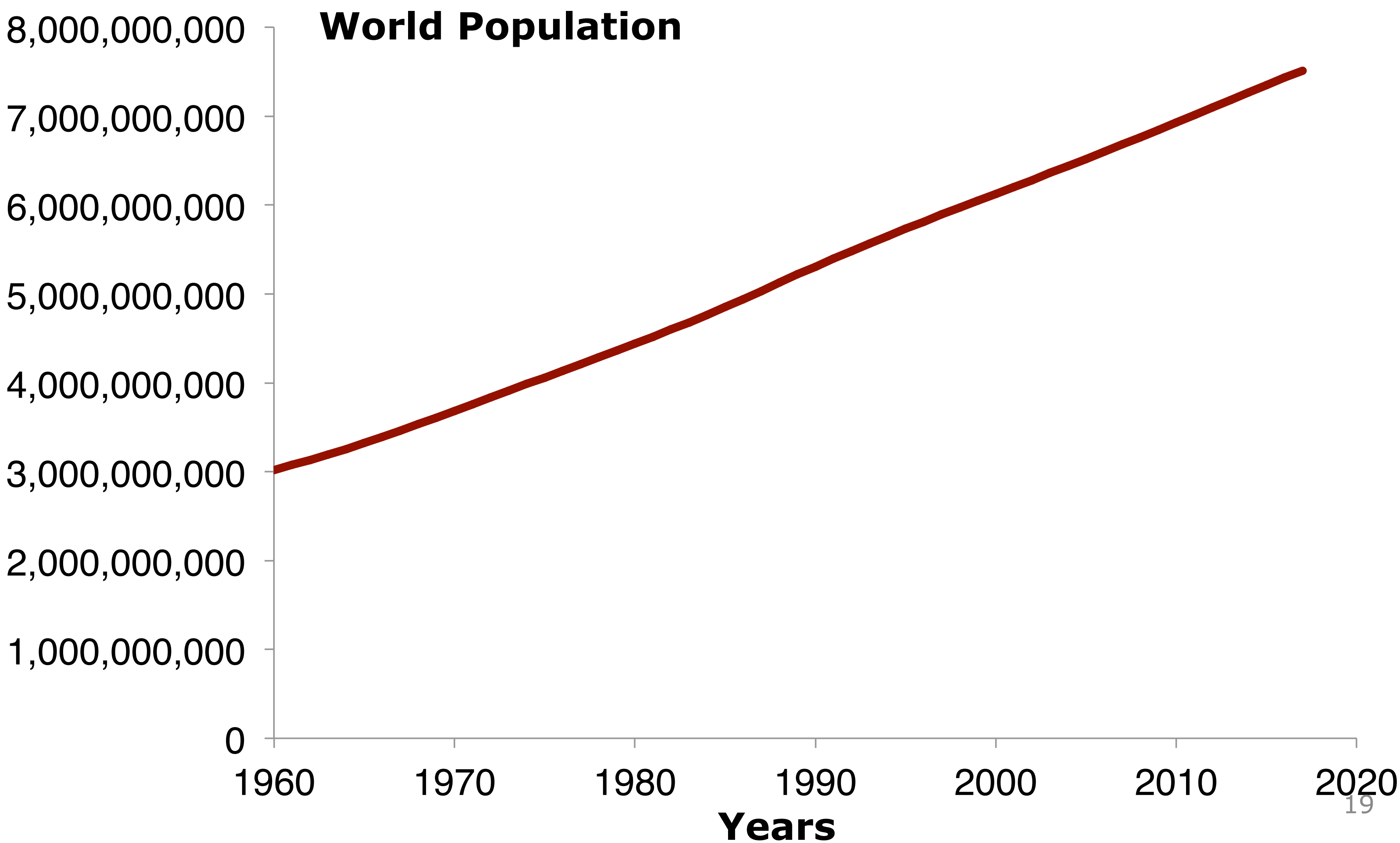
4. Check if model reproduces the problematic behavior, check extreme conditions.

5. What future conditions may arise?

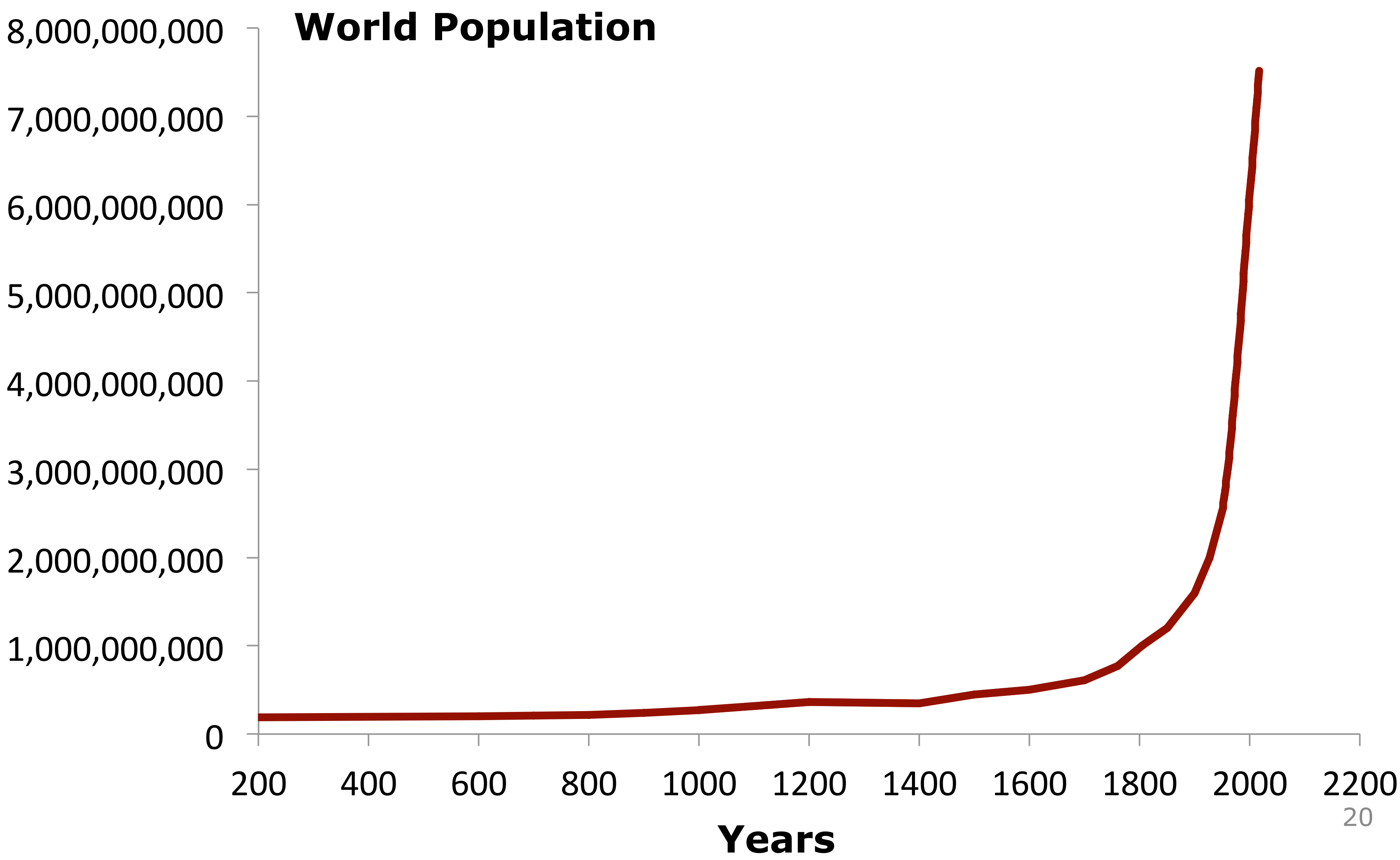
6. What will be the effect of a policy or strategy?



Influence of Time Horizon



Influence of Time Horizon



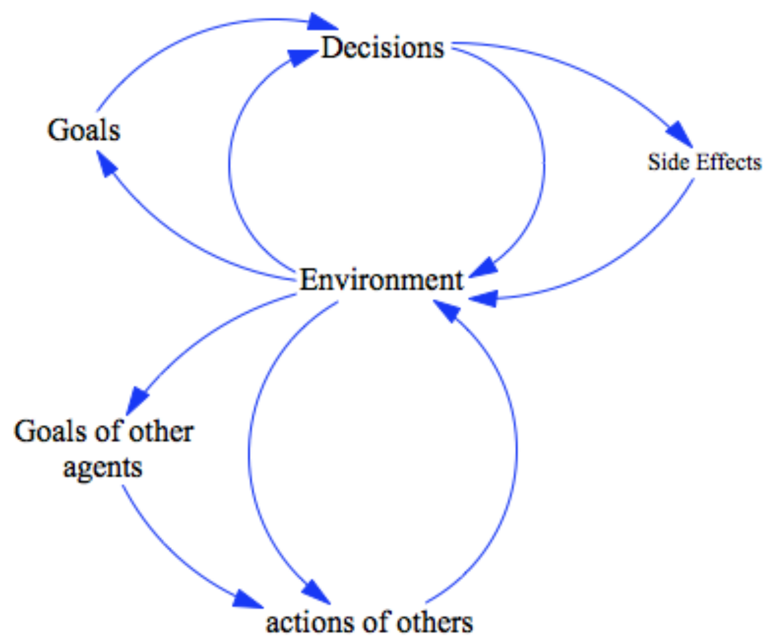
Formulating a Hypothesis

- "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.

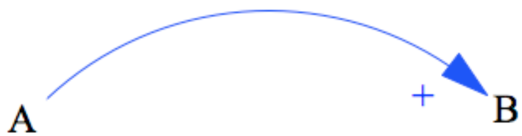
- Create a model boundary chart, a list of endogenous, exogenous, and excluded variables that define the scope of the model

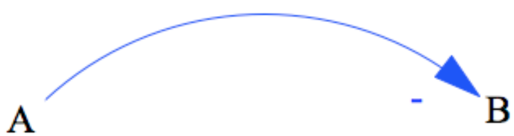


Causal Loop Diagrams (CLDs)

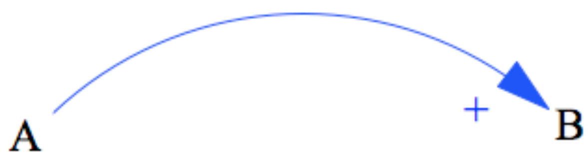
- CLDs are maps that show links between variables with arrows that signify cause and effect.
- CLDs describe the hypothesis about the causes of the dynamics
- In a CLD, variables are connected with arrows that represent a cause and effect relationship.
- An arrow pointing from a variable say ‘A’ to a variable ‘B’, indicates that A causes B
- Each causal link is labeled with a polarity – indicated with a plus or a minus sign.
- The polarities represent how the independent variable affects the dependent variable

Causal links with polarities





Positive Link Polarity



Mathematical Meaning:

$$\frac{\partial B}{\partial A} > 0$$

English Interpretation:

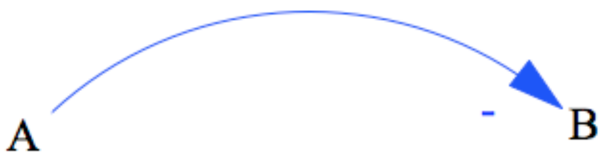
All else equal, if A (cause) increases, then B (effect) increases above what it would have been

All else equal, if A (cause) decreases, then B (effect) decreases below what it would have been

In the case of accumulation, A adds to B.

Example

Negative Link Polarity



Mathematical Meaning:

$$\frac{\partial B}{\partial A} < 0$$

English Interpretation:

All else equal, if A (cause) increases, then B (effect) decreases below what it would have been

All else equal, if A (cause) decreases, then B (effect) increases above what it would have been

In the case of accumulation, A subtracts from B.

Example

Assigning Polarities

- The causal links show what would happen IF there were a change
- A CLD does not represent what will exactly occur

- Note the “what it would have been” clause in the definition

- It is important to note that *<u>what actually happens</u>* is due to a confluence of multiple variables – a variable maybe affected by several inputs

- An increase in cause may not necessarily increase the effect

- Simulation is needed to know what actually occurs

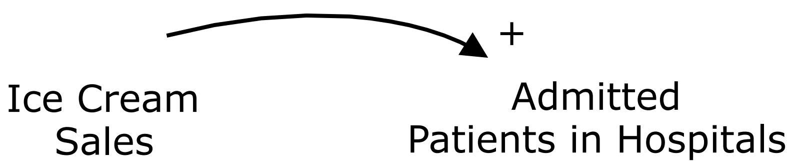
- CLDs describe the hypothesis about the causes of the dynamics – they show system structure ***NOT*** resulting behavior

- When determining polarity, assume all other variables (inputs etc.) are constant, and then determine relationship between cause and effect

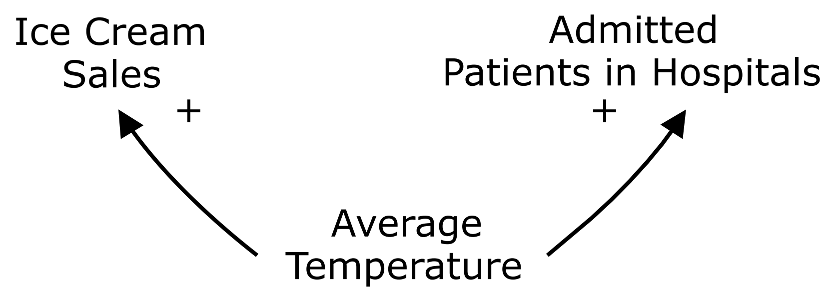
Causation and Correlation

- 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

Incorrect

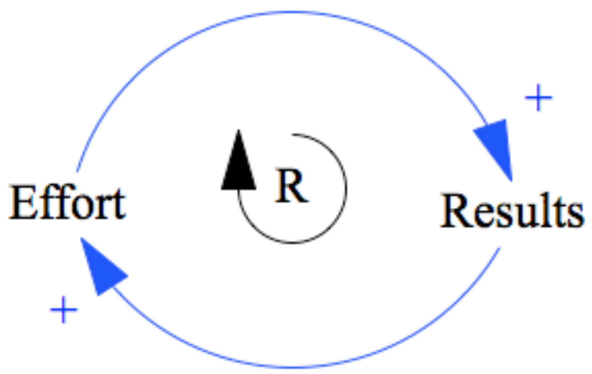


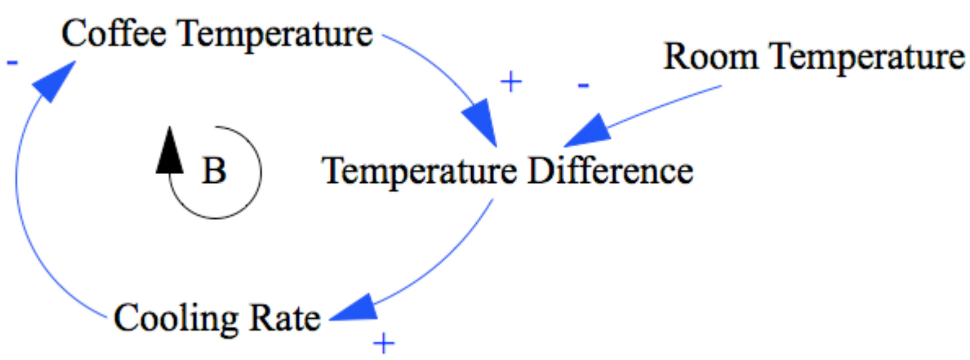
Correct



Loops

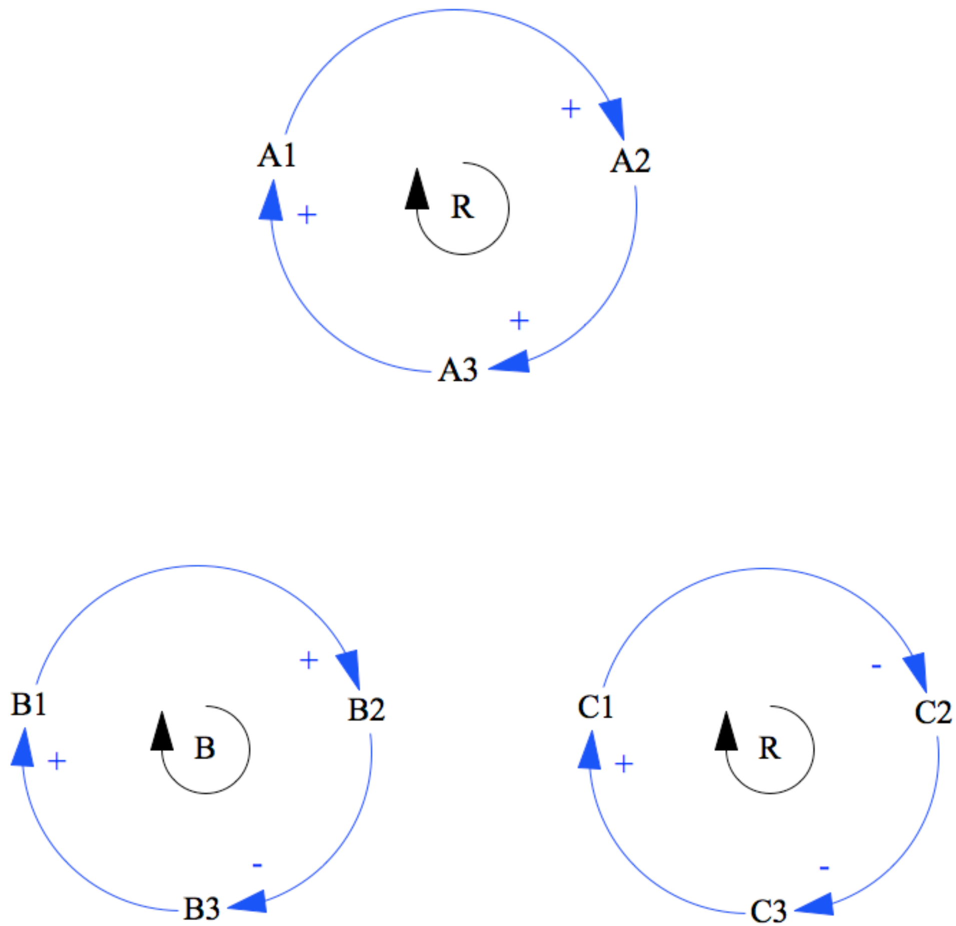
- In most CLDs, the causal links get organized in a way that produces loops in the diagram.
- These loops represent feedbacks in the system.
- There are two kinds of feedbacks:
  - self-reinforcing (positive)
  - self-correcting (negative or balancing).

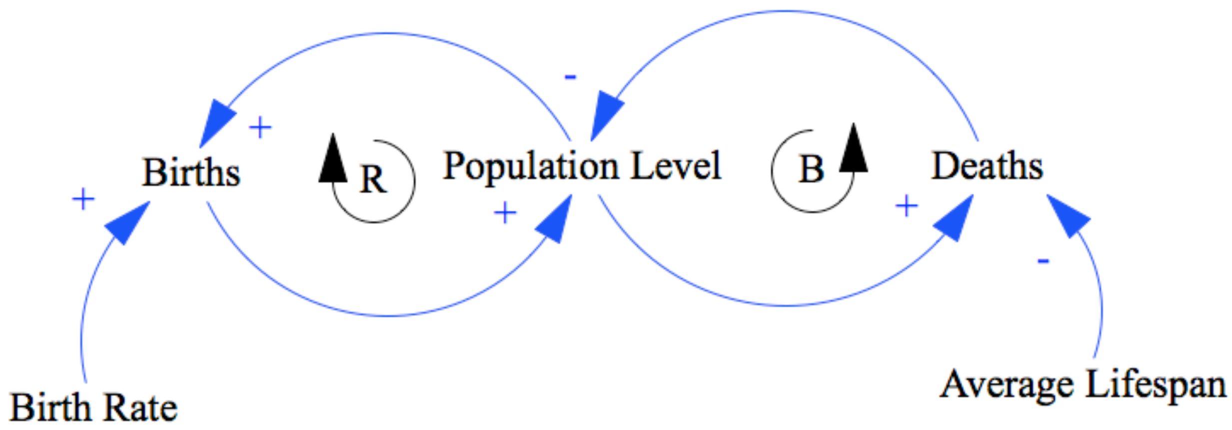




Loop Polarity

- The polarity or type of a loop, *i.e.* whether it is reinforcing or balancing, is determined by following the effect of a change in a variable through the loop.
- If the *change* is *amplified* then it is a reinforcing loop. If the *change is opposed* then it is a balancing loop.
- The R and B symbols indicate the type: R for reinforcing and B for balancing





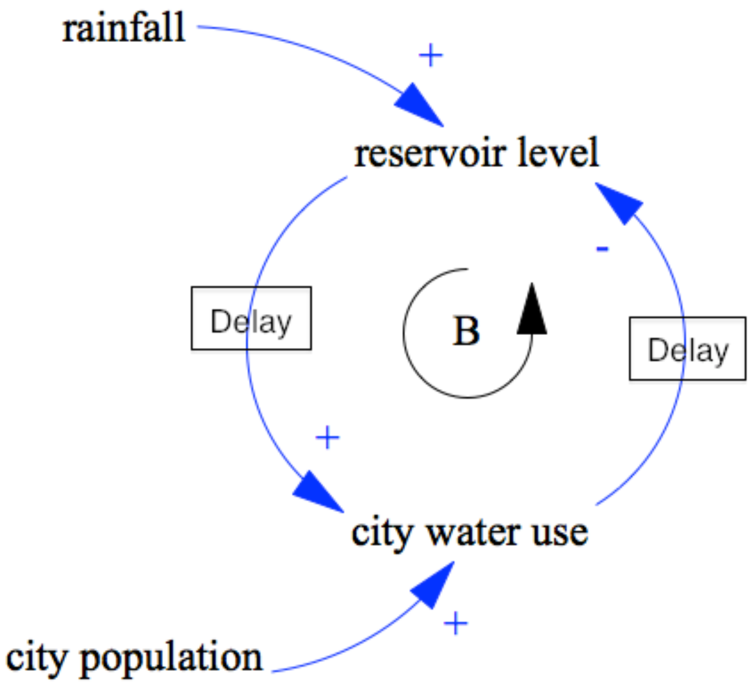
- Variables are: Birth rate, population, death rate, fractional birth rate, average lifetime

- Loop identifiers (shown as R and B) indicate direction of circulation and type (balancing or reinforcing)

Ref: Sterman, 2000

Time Delays

- Time delays often give rise to complex dynamics in systems.
- The effect of a cause may be distant in time (rather than immediate) and is often the reason why short term and long term impacts of an action may be different for a system.
- CLDs allow for explicitly indicating time delays. A time delay is represented with a box on the causal link

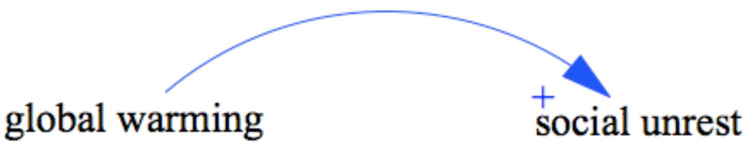


Clarity in Polarity

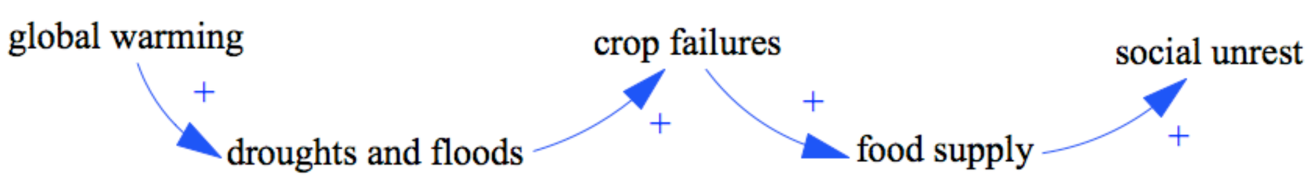
- Links must have unambiguous polarity
- If it is unclear which polarity to assign, it is likely there are multiple pathways between the two variables under consideration.
- Elaborate pathways until no ambiguity is left.

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
- A.

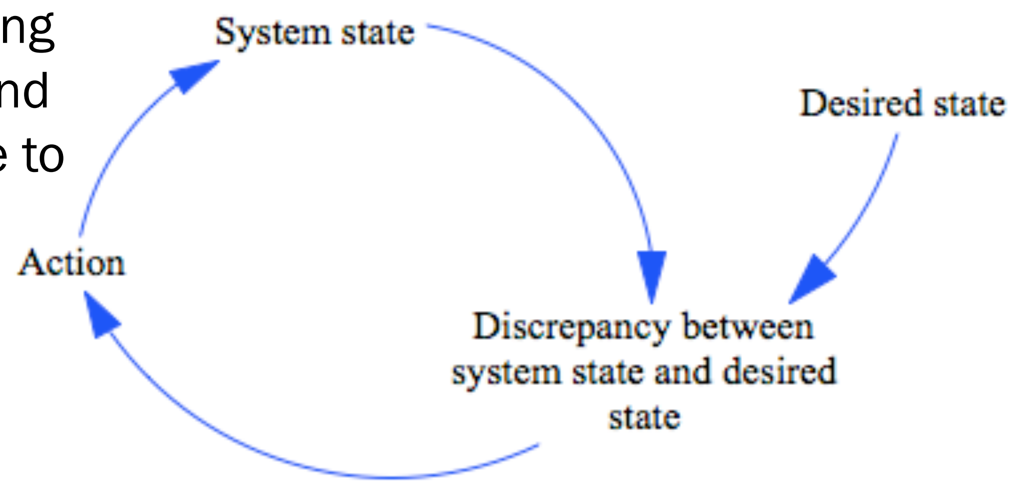


B.



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 and Perceived Conditions and Delays

Figure Source: Sterman, 2000

Software Tools for Drawing CLDs

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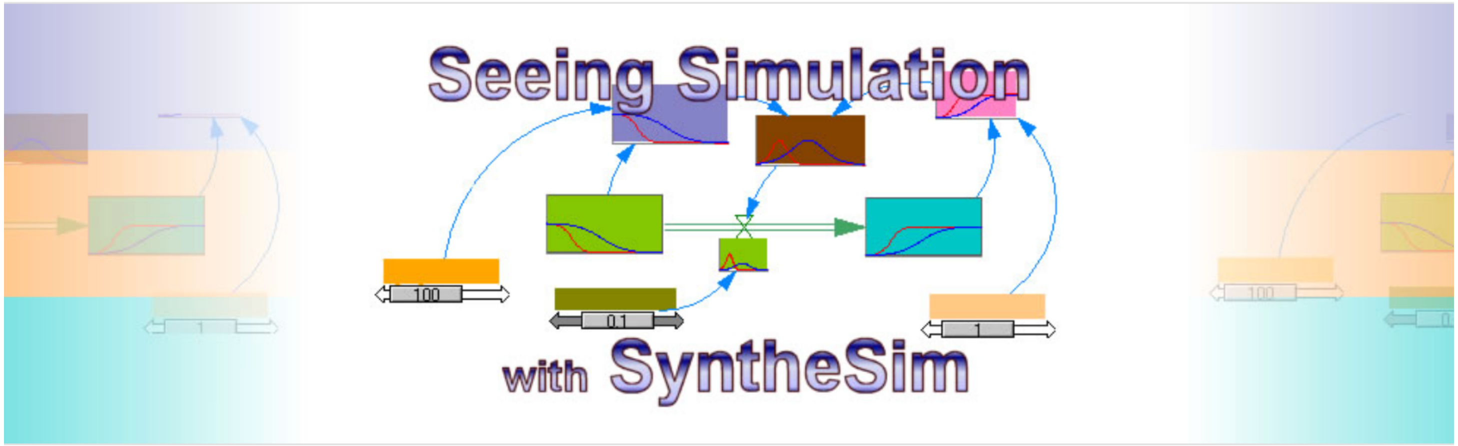

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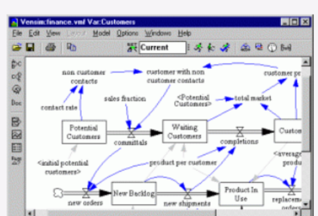
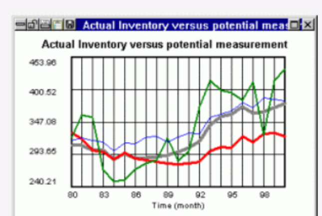


Applications



Ventity™ Bundle

Two

Vensim tool bar for creating CLDs

Use to set polarity

delete

Create a variable

Create a causal link

Add comment
(loop identifier)

Causal Loop Diagram

Model Validation

- The key factor influencing the acceptance and success of models is their practical usefulness.
- A model is useful when it serves the purpose for which it was developed: it addresses the right problem at the right scale and scope, and it represents system response correctly (is considered valid).
- Models are an abstraction of reality, and the greater the level of uncertainty and complexity of the problem, the more superficial objective comparisons between predicted results and observed data become.
- As a result, model validation becomes a social process where model structure and outcome are negotiated until judged valid and useful by all involved parties
- This concept of model usefulness requires transparency of the model development process and the model itself.

Some Rules to Model By:

- Develop a model for solving a problem
  - Model should have clear purpose, do not include extraneous factors
  - Start simple, add details as necessary over time

- Approach model with skepticism
  - Model is not reality (only a limited abstraction)

- Use other tools and data
  - Effective models use data and empirical analysis

- Model should be developed iteratively and jointly with stakeholders
  - Avoid black boxes, build understanding and trust

- Validate with continuous testing, iteration, and stakeholder input

Additional Information

Vensim can be downloaded from:

http://vensim.com

Systems Dynamics Society

http://www.systemdynamics.org

Systems Dynamics Conference

https://conference.systemdynamics.org

Systems Dynamics Review (journal)
http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1099-1727

References

- **Business Dynamics: Systems Thinking and Modeling for Complex World,** Sterman, McGraw Hill (2000).

- I. Winz, G. Brierley and S. Trowsdale, “The Use of System Dynamics Simulation in Water Resources Management”, *Water Resources Management* (2009) 23:1301–1323