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*Linking systems thinking to powerful dynamic models*

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# Introduction to System Dynamics using Vensim

**Tom Fiddaman**

**2013**

**Foundation by Bob Eberlein**

# Big Picture

- **Predicting the consequences of proposed actions is useful**
- **We are terrible at predicting the behavior of systems, but pretty good at building models**
- **Computers are great at predicting the behavior of models**
- **Many actions require group coordination, so predictions have to be socialized**

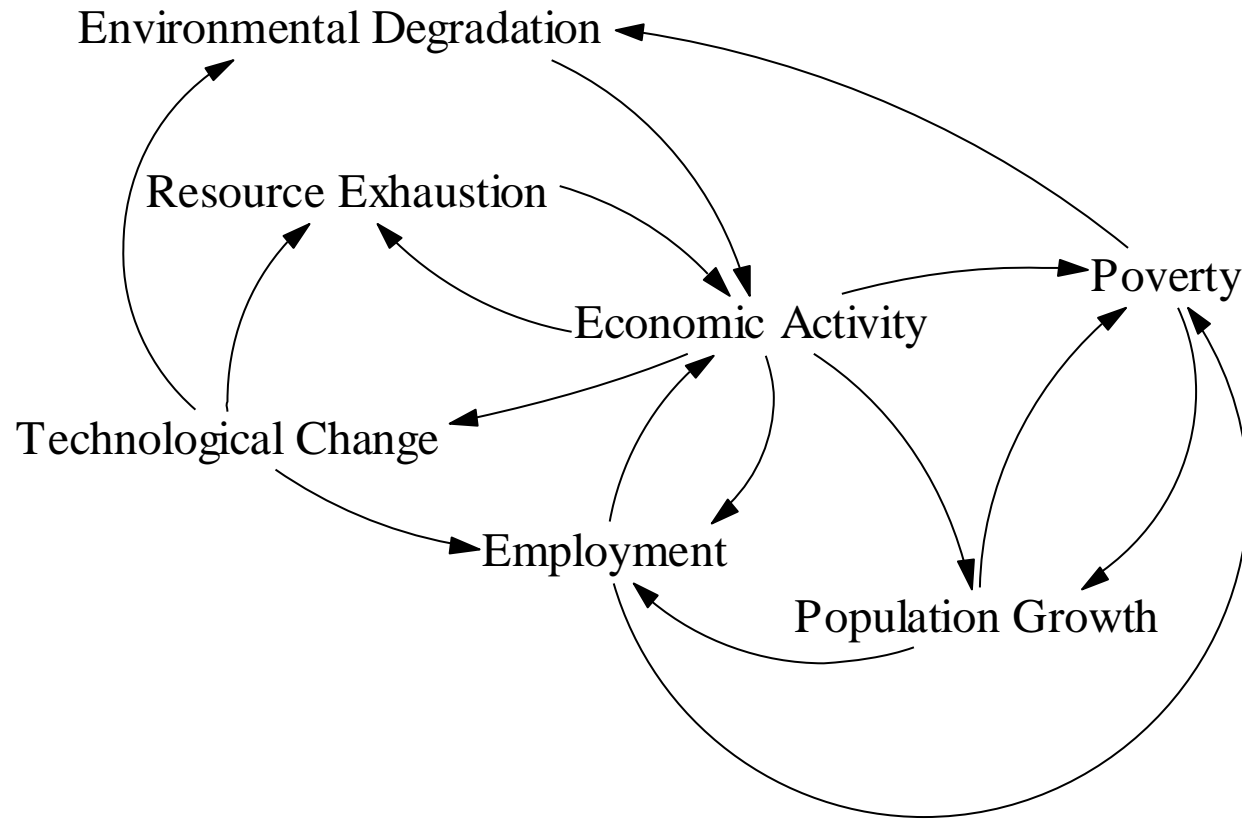
# Road Map

Vensim Mechanics	System Dynamics	Modeling Process
Diagramming	Stocks & flows	Choosing a method
Equations	Feedback loops	Conceptualization
Units	Behavior modes	Debugging
Runs	Nonlinearity	Model testing
Managing constants	Representing behavior	Validation
Data I/O	Equilibrium	Learning from surprise
Interfaces	Archetypes	Presenting
Synthesim®	Molecules	Change management
Lookups	Policy resistance	
Causal tracing	Events-Behavior-Structure	

# Motivation - Life is Complicated

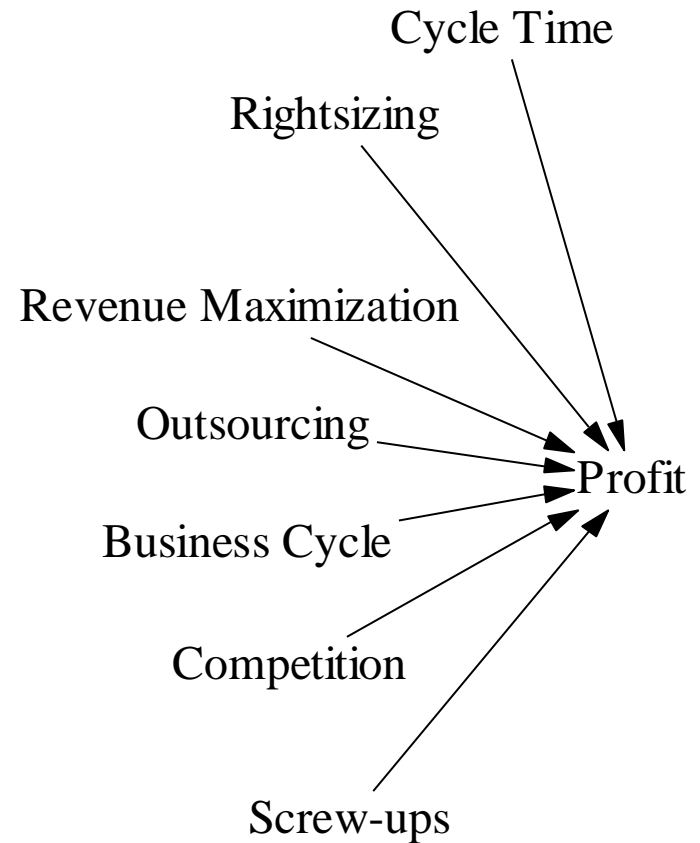
- **Global**
  - Climate change
  - Terrorism
  - Nuclear proliferation
- **National**
  - Campaign finance
  - Social security
  - Education
- **Business**
  - Economic crisis
  - IT revolutions
- **Personal**
  - Retirement savings
  - Addiction
  - Love

# Problems are coupled



# Coping Tools - Laundry List Thinking

- **External focus**
- **Linear causality**
- **Static importance weights**
- **Independent factors**
- **Non-operational specification**
- **Non-testable**



# Consequences

- **Forecasting, reactive decisions**
- **Event orientation**
- **Static, equilibrium focus**
- **Hard to answer "how, why" questions**
- **Hard to communicate or critique assumptions**
- **Limited learning or refinement of mental models**

# Systemic Thinking

- **Internal focus**
- **Circular causality**
- **Dynamic importance weights**
- **Interactions among factors**
- **Operational specification**
- **Testable**



# Events – Behavior - Structure

Leverage ⇕

Level of Description	Slinkies	Markets
Structure	It's a spring, $F=k*X$	Positive feedback from extrapolative expectations and relaxation of credit standards carries asset prices above fundamental value
Behavior	It's oscillating	Financial systems seem to have episodic crises
Events	First it stretched out, then it contracted, ...	The housing bubble burst

# Structures & Their Possible Behaviors (continuous time)

System Order (# of independent Levels)

	1	2	3+
Linear	Growth, Decay, Equilibrium	◀ Same, plus Oscillation	◀ Same
Nonlinear (typical examples)	▲ Same, plus S-shaped (logistic) growth	◀ ▲ Same, plus Overshoot & Collapse, Limit Cycles	◀ ▲ Same, plus Chaos

# Origins of Counterintuitive Behavior

- **Surprise**
  - Exponential growth & delays; the French farmer's lily pond
- **Nonlinearity**
  - Eat 1 pickle – yum. Eat 100 pickles – not so much.
- **Shifting loop dominance**
  - Policies work better under some conditions than others.
- **Compensating feedback**
  - Push on the system and the system pushes back.
- **Tipping points arise from nonlinearity that enables shifting loop dominance**



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# Conceptualization

# Get Clear About the Project

- **State the Purpose**
  - Problem description
  - Theory of change
- **Capture Reference modes**
  - Data
  - Thought experiments
  - Extreme conditions
  - Hoped-for and feared behavior
- **Establish the Scope of the Problem**
  - Boundary
  - Time horizon
- **Dynamic hypothesis**

## Other Aids

- **High-level Views**
  - Sector Boundary Diagram
  - Policy Structure Diagram
  - “Onion” layers
- **Idea Generation**
  - Hexagons/Post-its
  - Fishbone diagrams
  - Mind mapping
  - Flight simulators

# Two Ways Forward

## Loop by loop

- **Pick an “interesting” loop**
- **Identify the stocks around the loop**
- **Write equations**
- **Add another related loop**

## Start with stocks

- **Identify Stocks**
  - Accumulations
  - Sources & sinks
  - Delays
  - “Main Chains”
- **Link with flows**
  - Changes
  - Inflows
  - Outflows
- **Describe decisions that govern flows**

# Closing loops

- **Goals**
- **Decisions**
- **Constraints**
  - Resources
  - Feedstocks
  - Capital stocks
  - Physics
  - Material outflows



# Simulating

- **Always be done**
  - Work in small pieces
  - Stay close to a working model
  - Run frequently
- **Follow the scientific method**
  - Initialize in equilibrium
  - Change one thing at a time
- **Maximize learning**
  - Write down expectations before each simulation
  - Every defect is a treasure
  - Surprise = learning
  - Keep track of what you discover

# Testing

- **Test inputs**
  - STEP
  - PULSE
- **Extreme conditions**
- **Reality Checks**
- **Parameter sensitivity**
- **Fit to data**

# Outcomes

- **Reality Checks**
  - Do physical stocks remain non-negative?
  - Do variables approach infinity or zero?
  - Does the behavior look like the reference mode?
- **Equilibrium**
  - Does the system return to equilibrium?
  - Does it return to its initial equilibrium?
- **Steady State**
  - Does the system exhibit steady growth or decay?
  - Do actual conditions meet goals?
- **Oscillation**
  - Do oscillations damp out, grow, or sustain?

# Improve the Model

- **Explain gaps between reference modes and model behavior**
- **Challenge clouds**
- **Look for missing loops**

# Communicating Results

- **Buy-in**
  - Information gathering
  - Reality Check
  - Operational explanations
- **Diagrams**
- **KISS**



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# Causal Loop Diagramming

# Variable Naming

- **Nouns (not events)**
  - *aspirin consumption*, not *take aspirin*
- **Positive sense**
  - *happiness* or *misery* instead of *unhappiness*
- **Clear direction**
  - *adjusting* is ambiguous
  - A link that can be positive or negative probably represents two superimposed processes
- **Quantity that can vary**
  - (quantifiable, but not necessarily measurable)

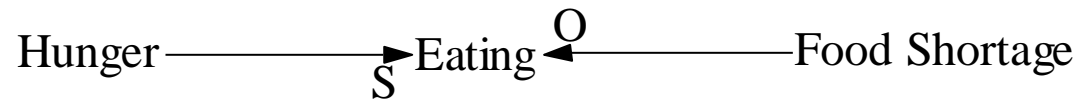
# Link Interpretation

- **Cause, not correlation**
- **Polarity:**
  - "All other things being equal, ..."
  - Flow  $\Rightarrow$  Stock
    - "X adds to Y"
    - "If X increases, Y will increase from what would have occurred without the change in X"
  - Other relationships:
    - "A change in X causes a change in Y in the same direction"

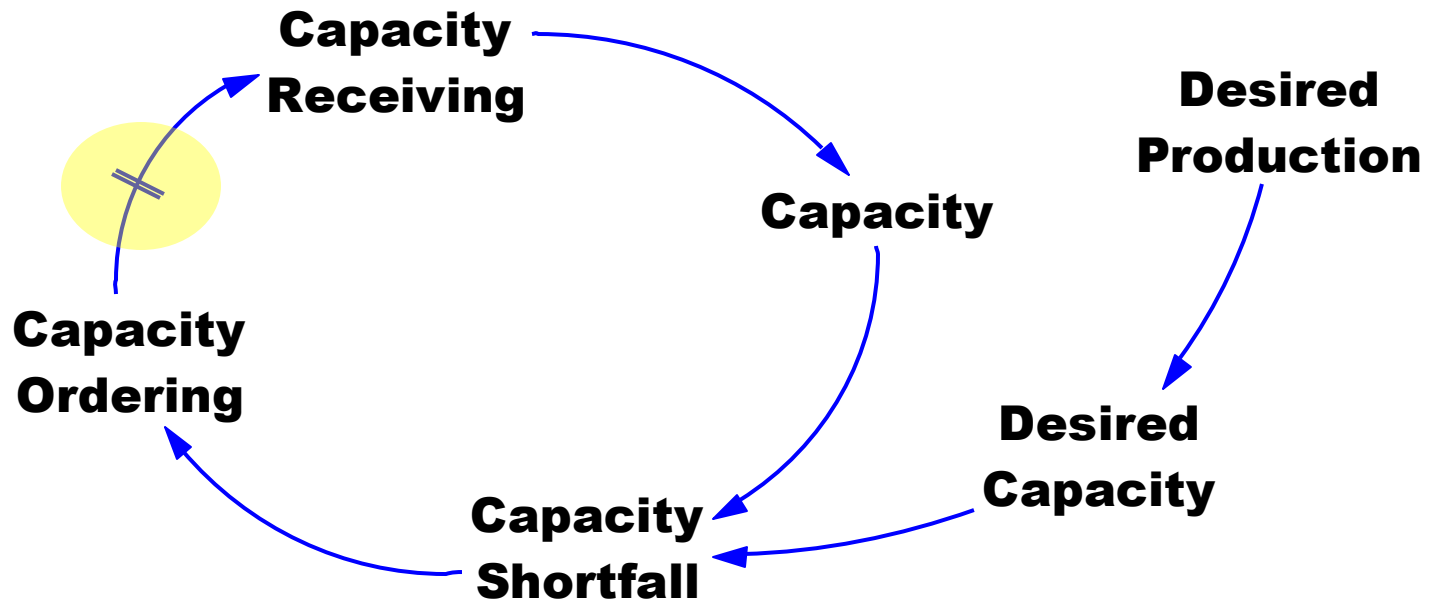


# Link Polarity Conventions

Preferred:



# Delays



# Loop Polarity

- **Identifying**

- Count “–” links (error prone)
  - Odd number implies that an initial disturbance is reversed, so loop is negative or balancing
- Walk through the loop, telling the story (better)

- **Conventions**



Positive



Negative



Reinforcing

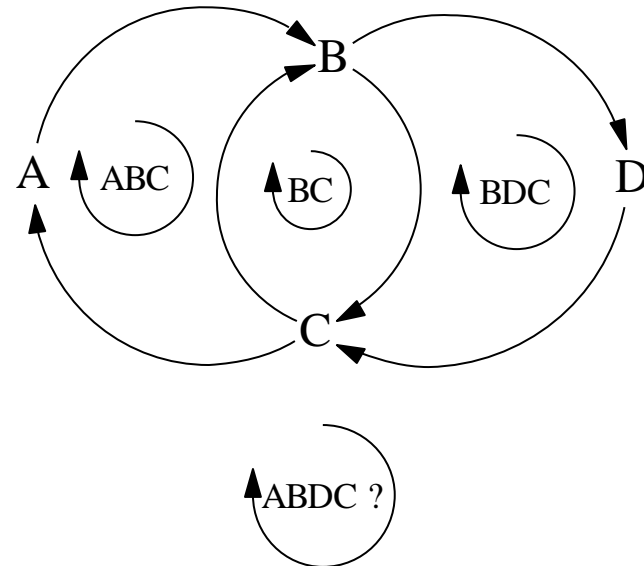
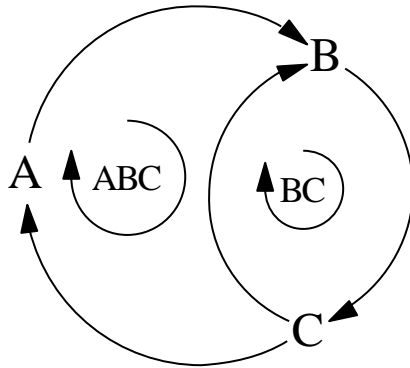


Balancing



# Limitations

- **Stock/flow relationships aren't well represented**
- **Behavior**
  - ~~Weick's rule (count + and - loops)~~ **no!**
  - Need to simulate!
- **Topology – things don't always work out:**





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# Putting Stocks & Flows Together

# Stocks (levels, states, integrals)

- **Functions**

- Accumulation
- Memory
- Delay

- **Examples**

- Pressure to act
- Resources
- Constraints

- **Types**

- (Non)material
- (Non)conserved

- **Naming**

- Nouns

# Flows (derivatives, rates)

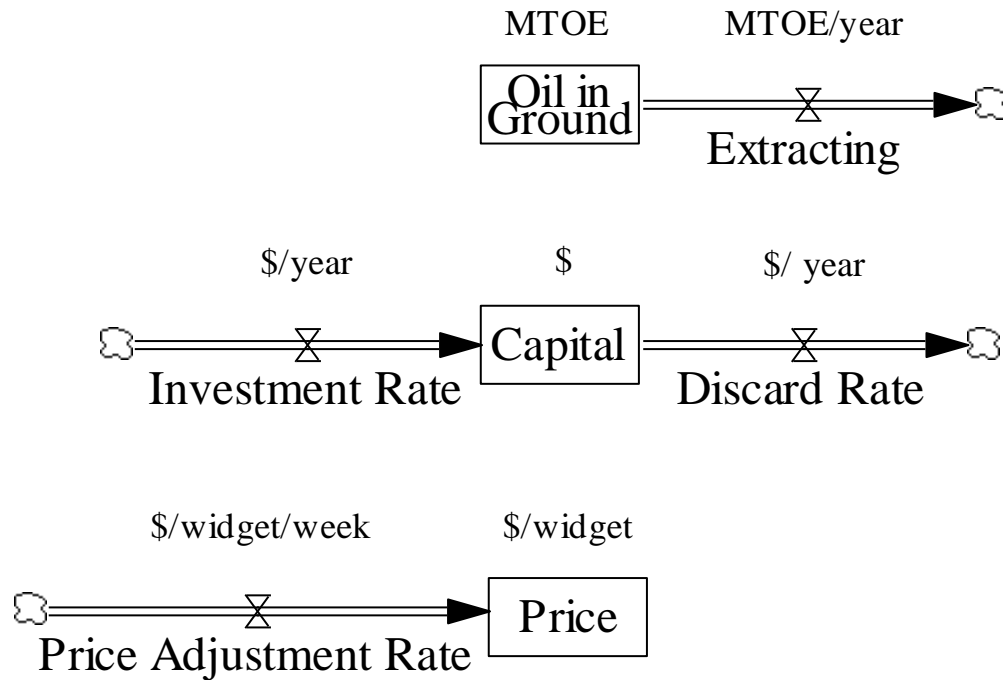
- **Functions**
  - Change stocks
  - Feeding
  - Draining
- **Naming**
  - ... rate
  - ...ing
  - Not events
- **Determined by stocks, not flows**

# Distinguishing Stocks & Flows

- **Units**
  - Stocks: stuff
  - Flows: stuff/time
- **"Stop the world" thought experiment**
  - Stocks persist
  - Flows disappear



# Examples



# Distinguishing Stocks & Flows

Variable	Stock or flow?	Possible units
Revenue		
Liabilities		
Physical plant		
Engineering staff		
GDP (gross domestic product)		
CO2 emissions		
Morale		
Technology		
Depreciation		
Construction starts		
Hiring		

# Auxiliaries (converters)

- **Indicators**
- **Functions**
- **External inputs**
- **Decisions**

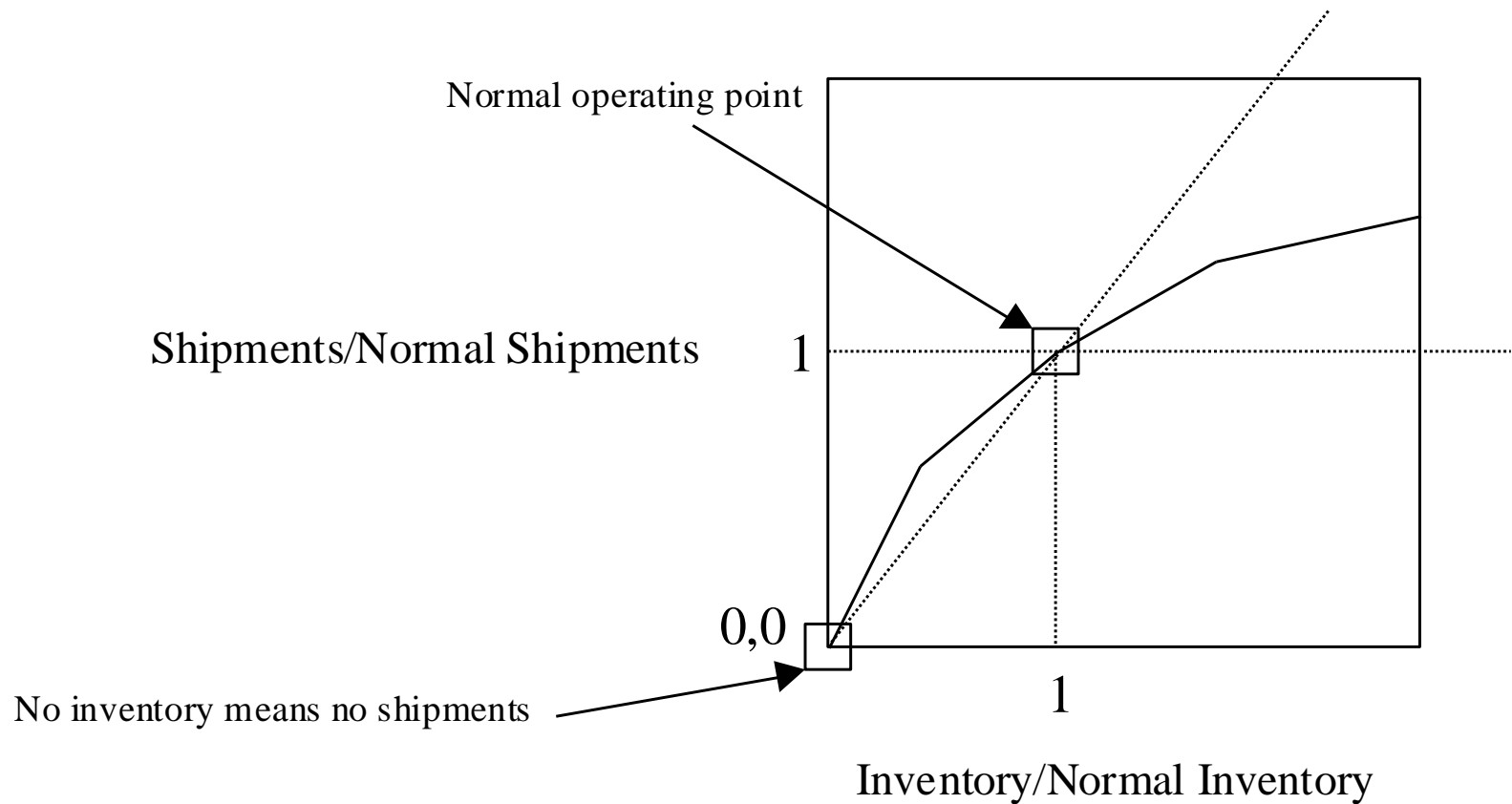
# Information Channels

- **Delay**
- **Distortion**
- **Bias**
- **Error**
- **Crosstalk**
- **Persuasiveness**

# Lookups & Functional Forms

- **Normalization**
- **Domain**
- **Range**
- **Direction**
- **Anchor points**
- **Reference lines**
- **Kinks**
- **Monotonicity**

# Lookup Elements



# Style

- **Descriptive names**
- **One concept  $\leftrightarrow$  one equation**
- **Loopy loops**
- **No spaghetti**



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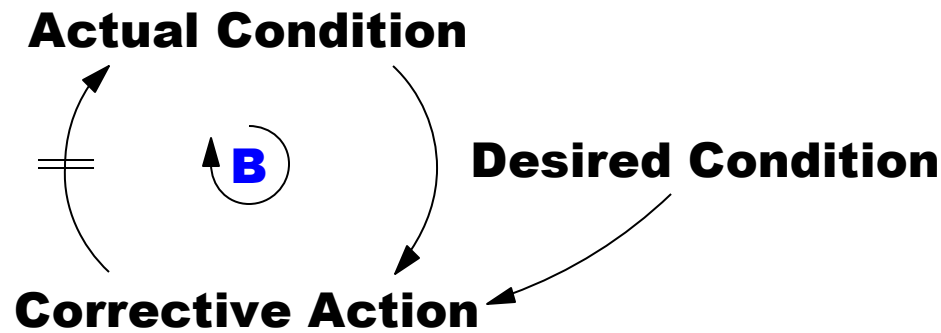
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# Systems Archetypes

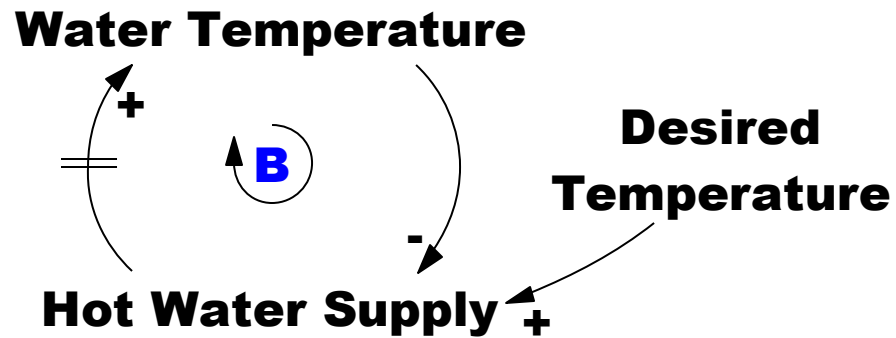


# Delayed Balancing Loop

- **Aggressive correction leads to overshoot and instability**
- **Be patient**

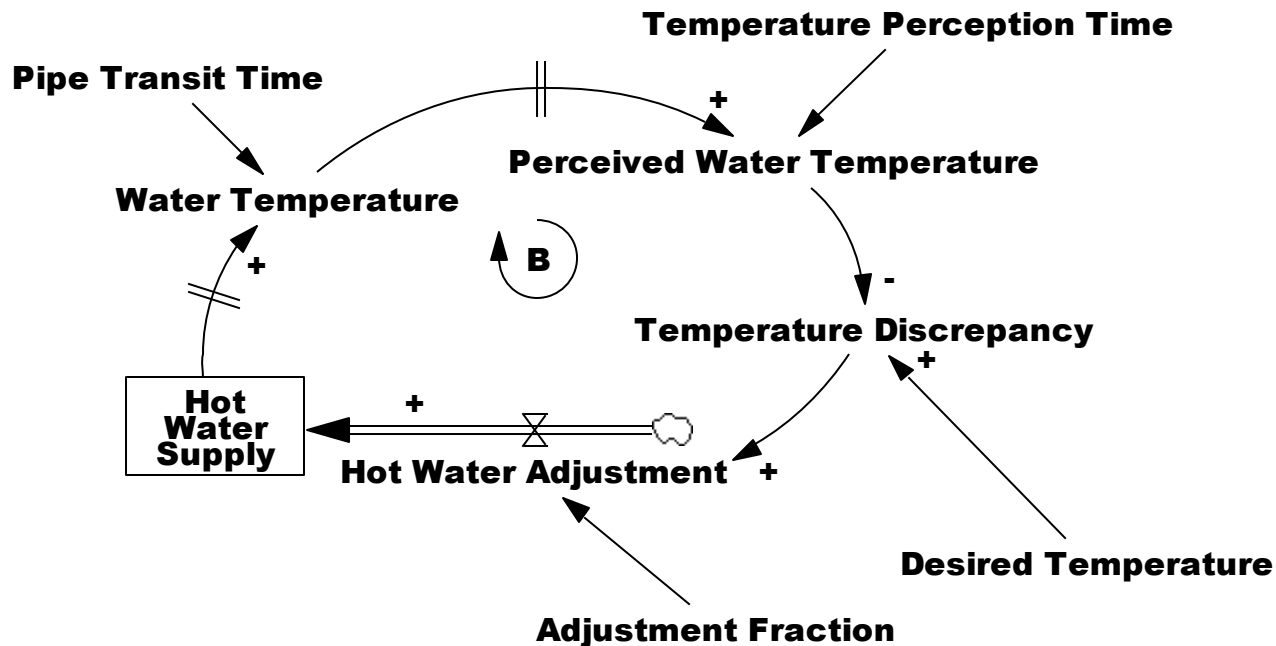


# Filling in the Template

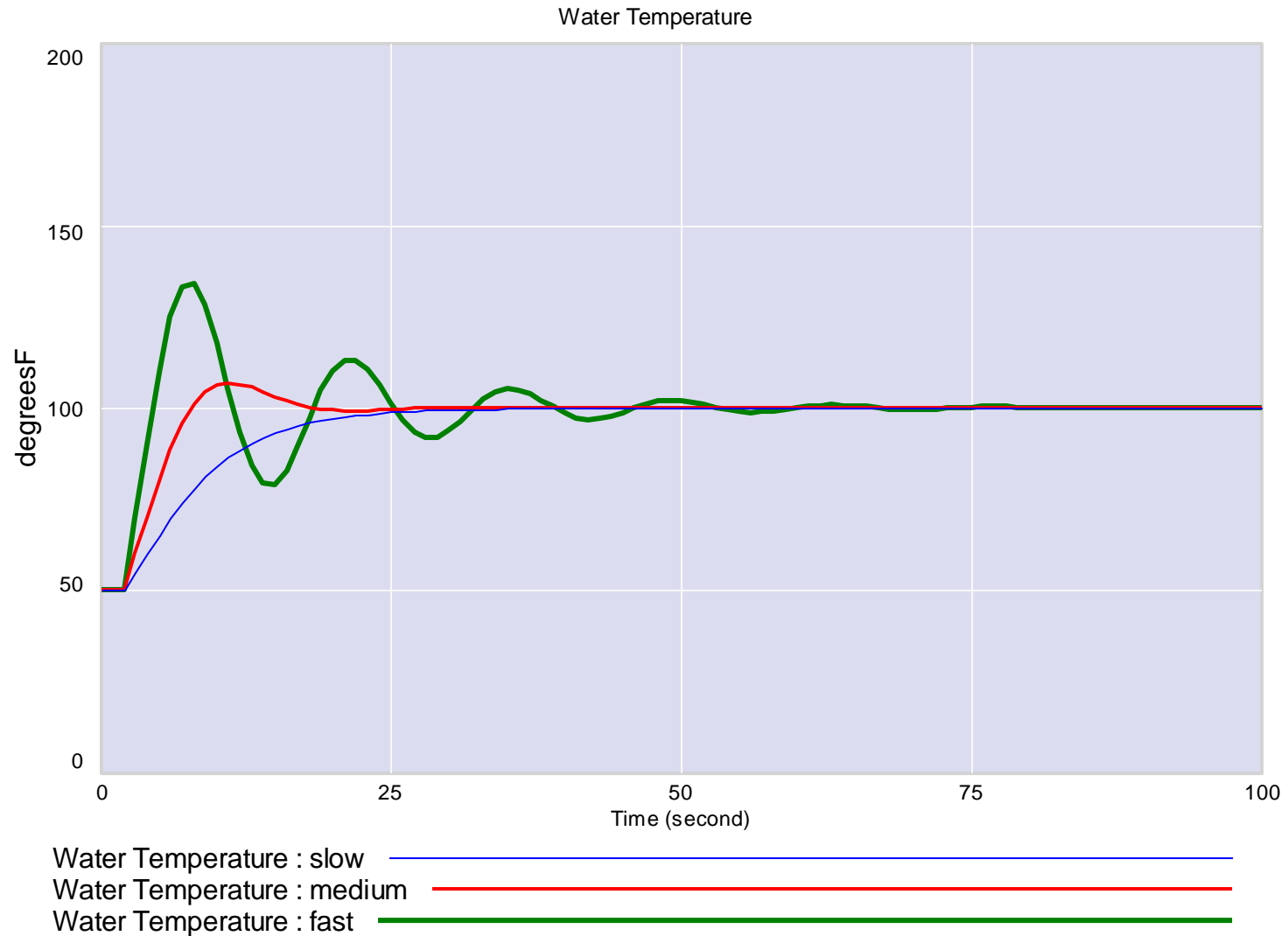


# Modeling

- Causal loop diagrams are typically underspecified – modeling requires more information
- Modeling also reveals much more about the system, including dynamics that can not be distinguished from a diagram alone

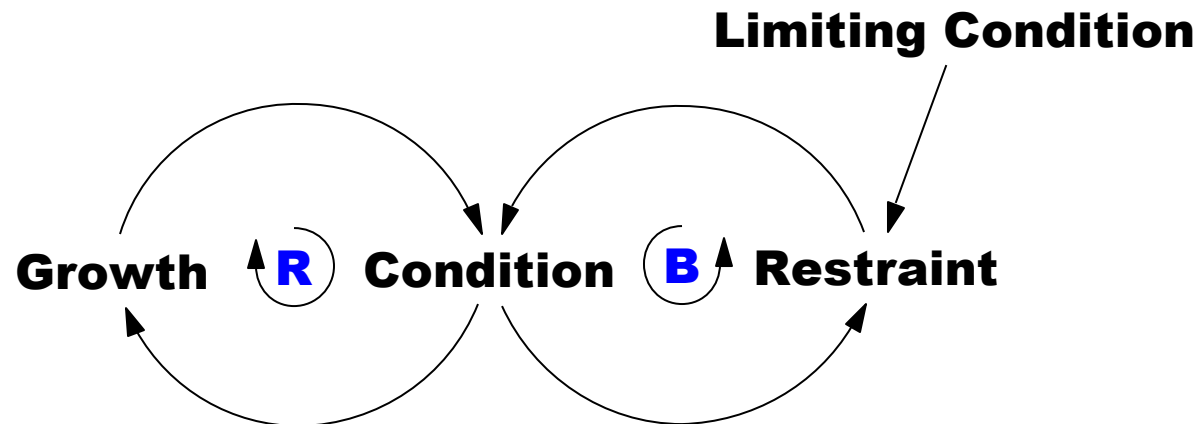


# Aggressive vs. Conservative Adjustment



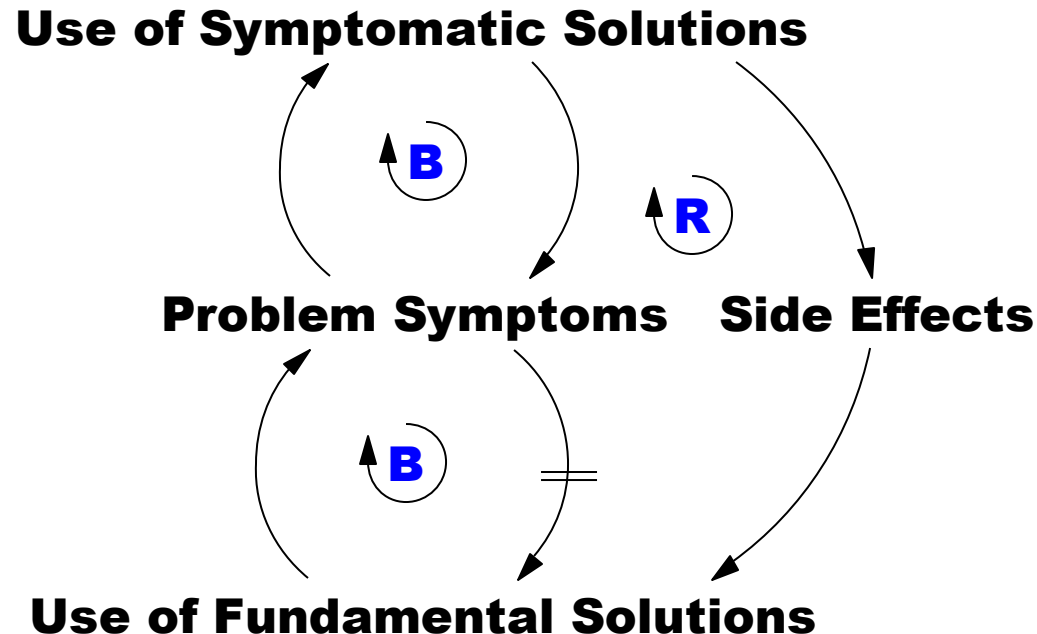
# Limits to Growth

- Remove limit instead of pushing growth



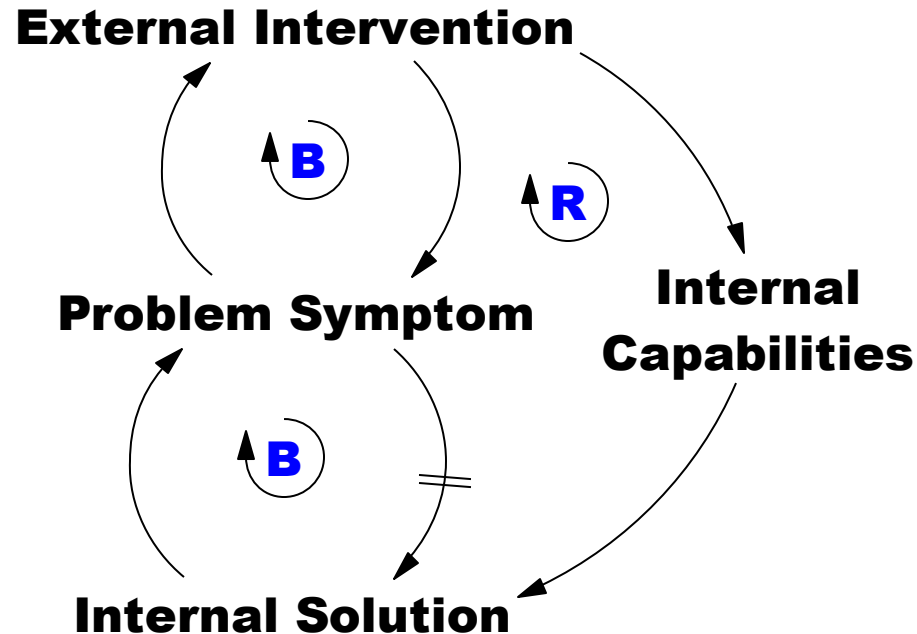
# Shifting the Burden

- Focus on fundamental solutions



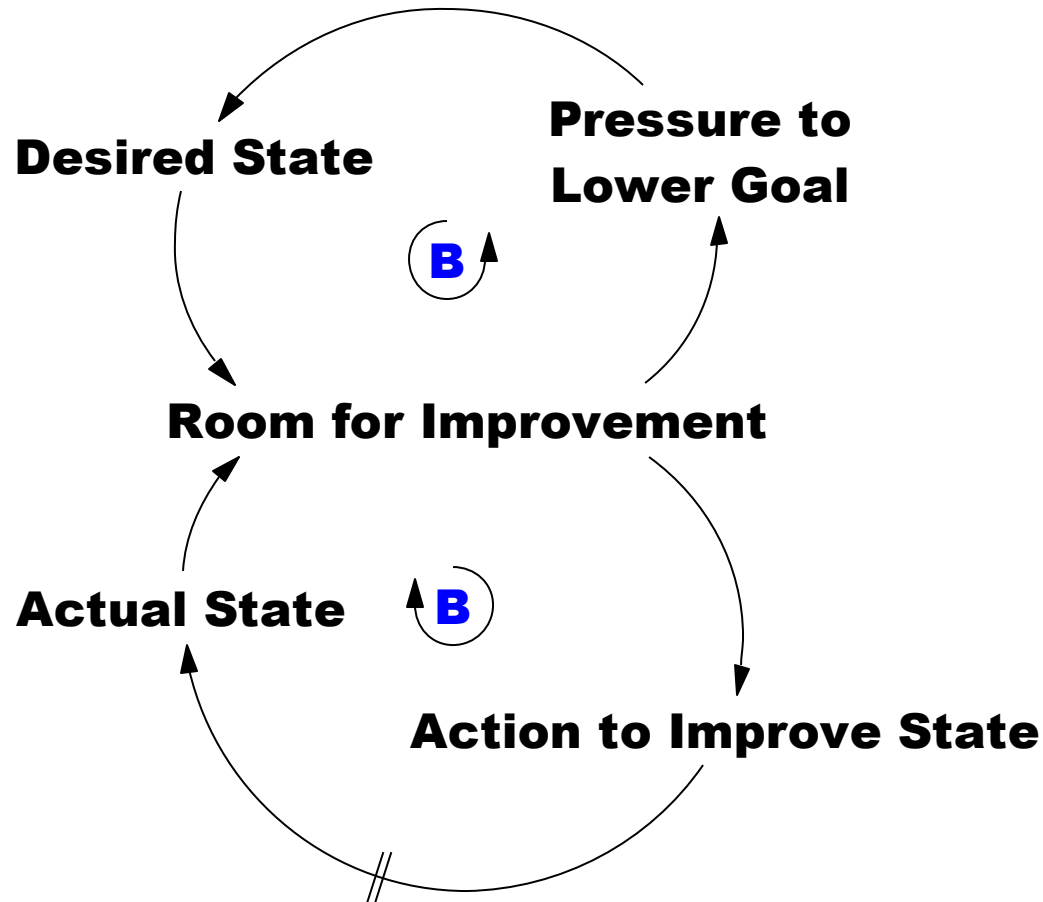
# Shifting the Burden to the Intervener

- Teach people to fish



# Eroding Goals

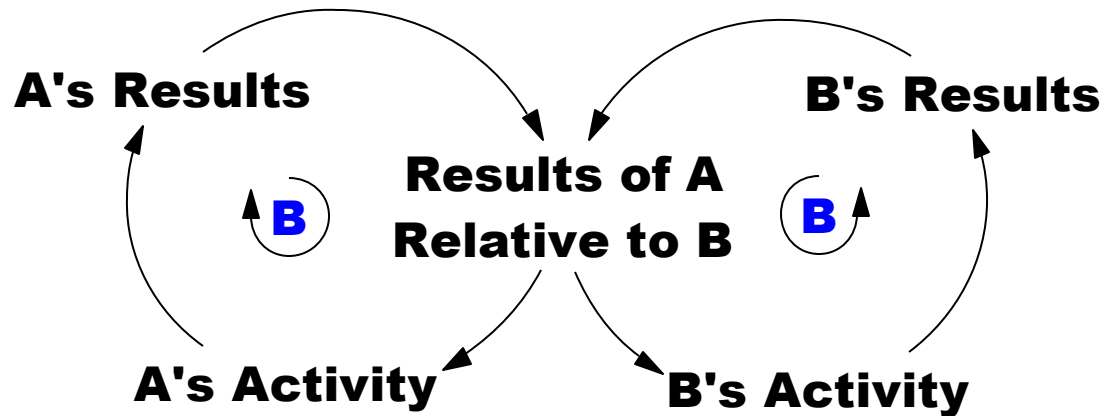
- Hold the vision





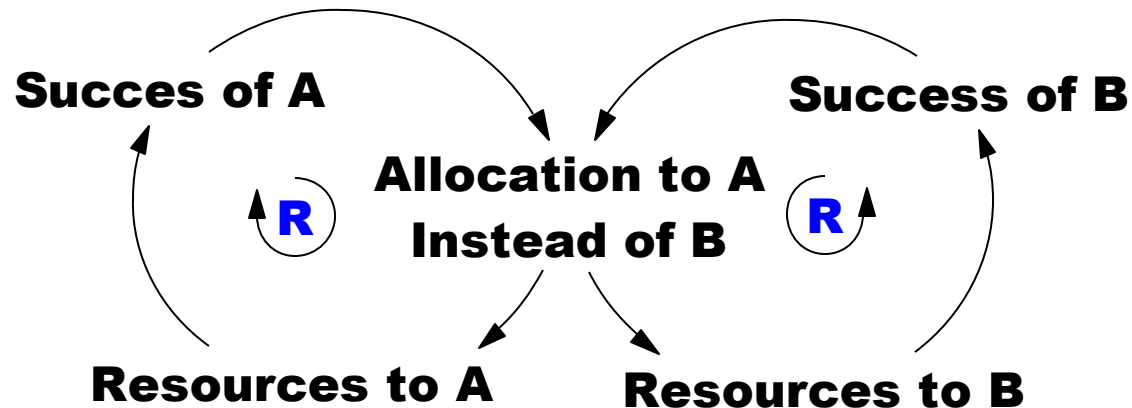
# Escalation

- Look for mutual win
- Try to reverse the cycle



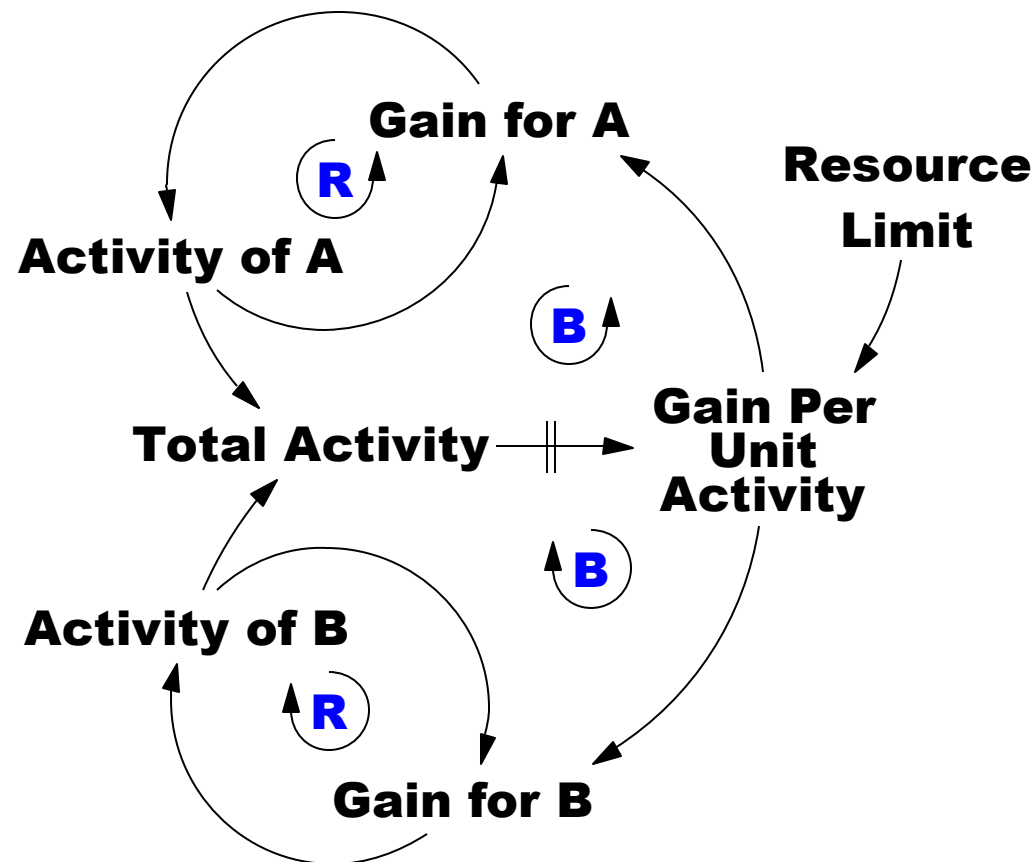
## Success to the Successful

- Restructure rewards to weaken coupling



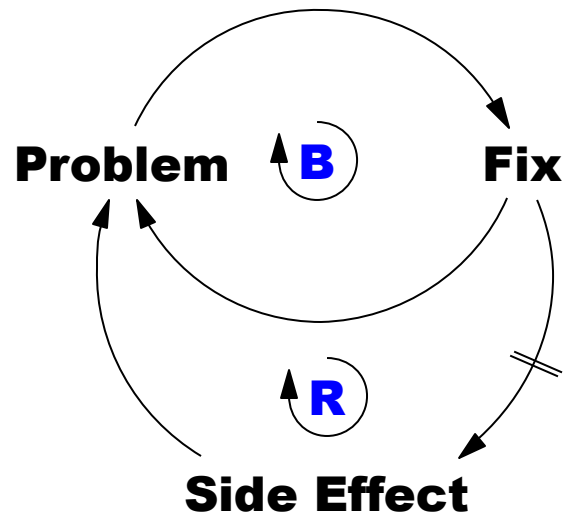
# Tragedy of the Commons

- Manage the common resource for mutual benefit



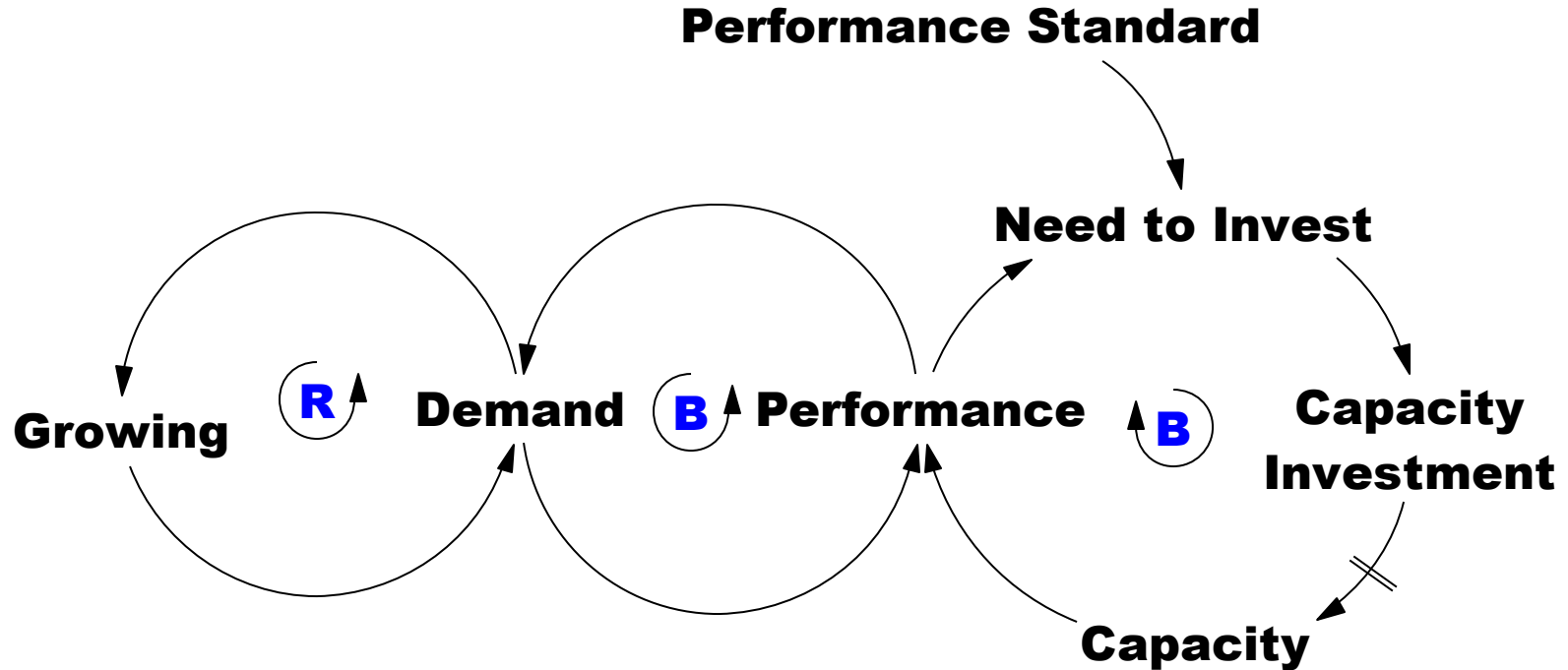
# Fixes that Fail

- Focus on long term



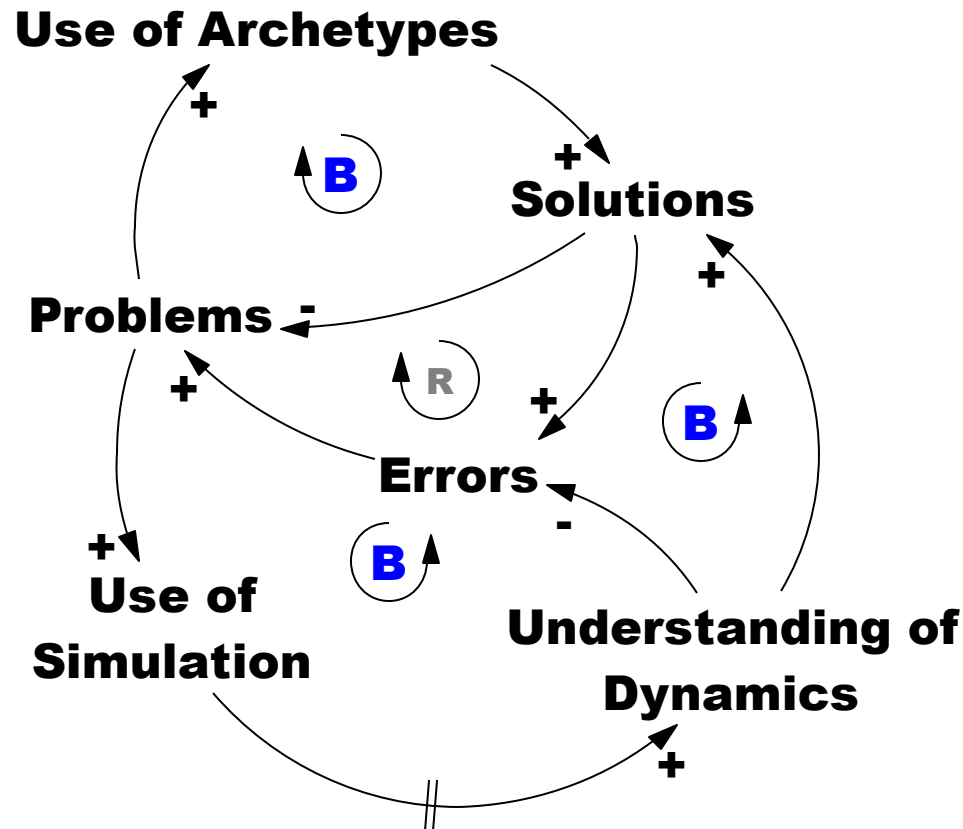
# Growth and Underinvestment

- Build capacity in advance of demand



# Shoehorning the Problem into the Archetype

- **Simulation experience adds leverage to systems thinking tools like archetypes**





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# Policy Resistance

# Addressing Symptoms

- **Urgency**
- **Proximity**
- **Experience with simple systems**
- **Institutional boundaries**
- **Salience**
- **Compensating feedback**
  - Relaxation of inherent control mechanisms
  - Side effects



# Addressing Causes

- **Compensating feedback**
  - Threat to existing positions
  - Lack of natural incentives
  - Relaxation of inherent control mechanisms
  - Side effects

# Examples

- **Shifting the burden**
  - Intervener
- **Worse-before-better**
  - Overshoot
- **Eroding goals**
  - Encore
- **Success to the successful**
  - Hot or not
  - Proactive vs. reactive

# Setting Policy

- **Tap natural forces**
- **Use leverage, amplification**
- **Avoid dependency**
- **Paradoxical intervention**



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## Rules of Thumb

# Negative feedback (goal seeking, exponential decay)

- **Decay**
  - $\text{Stock} = \text{INTEG}(-\text{Outflow})$
  - $\text{Outflow} = \text{Stock} * \text{Decay Rate}$
- **Smoothing**
  - $\text{Stock} = \text{INTEG}(\text{Change})$
  - $\text{Change} = (\text{Goal} - \text{Stock}) / \text{Time Constant}$
- **Time constant = 1/decay rate**
- **Half life = 0.7 \* time constant (because  $\text{Log}(2) \sim 0.7$ )**
- **$\sim 2/3$  of adjustment at 1 time constant**
- **$\sim 95\%$  at 3 time constants**
  
- **Example: my perception of the price of gasoline adjusts 20% of the way toward reality per day. After a step change in prices, my expectations have adjusted 95% of the way to reality after  $3 * (1/.2) = 15$  days or about two weeks.**

## Positive feedback (exponential growth)

- **Stock = INTEG( Inflow ); Inflow = Stock\*Growth Rate**
- **Time constant =  $1/\text{growth rate}$**
- **Doubling time =  $(70\%)/(\% \text{ growth rate})$**
- **Example: a city's population grows at 5% per year. It will double in  $70/5 = 14$  years, and quadruple in 28 years.**

# Initializing in Equilibrium

- **Definition of equilibrium: stocks aren't changing;**  
 $\Sigma(\text{flows}) = 0$
- **Little's Law:**  
**(average value of a stock)**  
**= (average inflow) \* (average residence time)**
- **Typical strategy:**
  - Initial stock = Initial inflow \* residence time,
  - Where residence time = mean time constant of outflows,  
which is a harmonic mean, e.g.,  $\tau_{mean} = 1 / (\frac{1}{\tau_1} + \frac{1}{\tau_2})$



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## Resources



# Vensim Resources

- **The Vensim forum:**
  - <http://www.ventanasystems.co.uk/forum/viewforum.php?f=2>
- **The SD society & forum:**
  - <http://www.systemdynamics.org>
  - <http://www.systemdynamics.org/forum/>
- **My model library:**
  - <http://models.metasd.com>
- **Books**
  - Business Dynamics (Sterman)
  - Strategy Dynamics (Warren)
  - Modeling the Environment (Ford)
  - Industrial Dynamics (Forrester – the classic)