



# System Theory

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**Systems Engineering**

1

# Overview

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- Describe how an enterprise fits the definition of a system
- Contrast reductionist thinking with systems thinking
- Apply systems thinking to understand and solve problems
- Create a causal loop diagram
- Create a stock & flow diagram

# What is a *System*?

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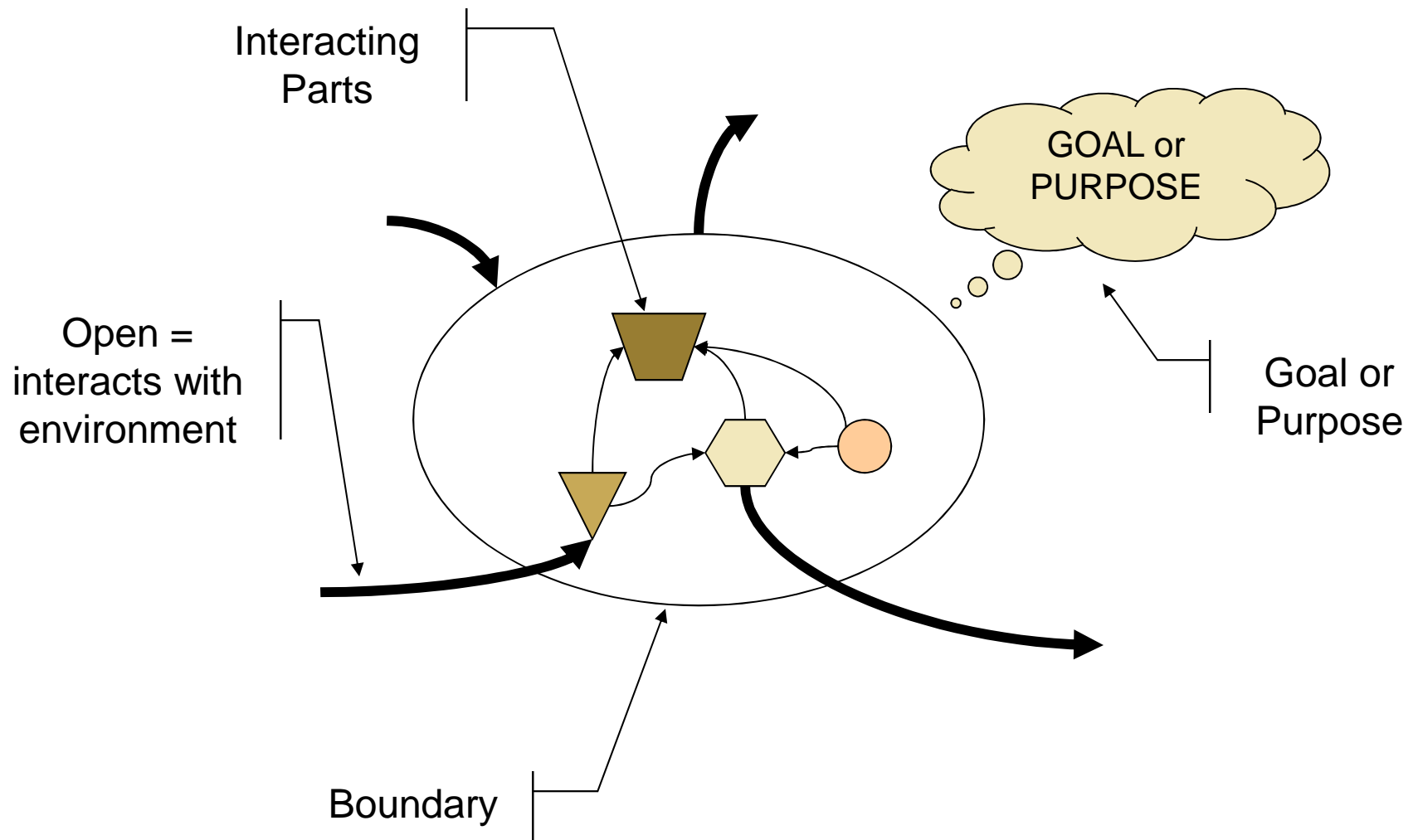


A system is an ***organized*** group of elements or ***components*** that work together for a specified ***purpose***. (Miller)

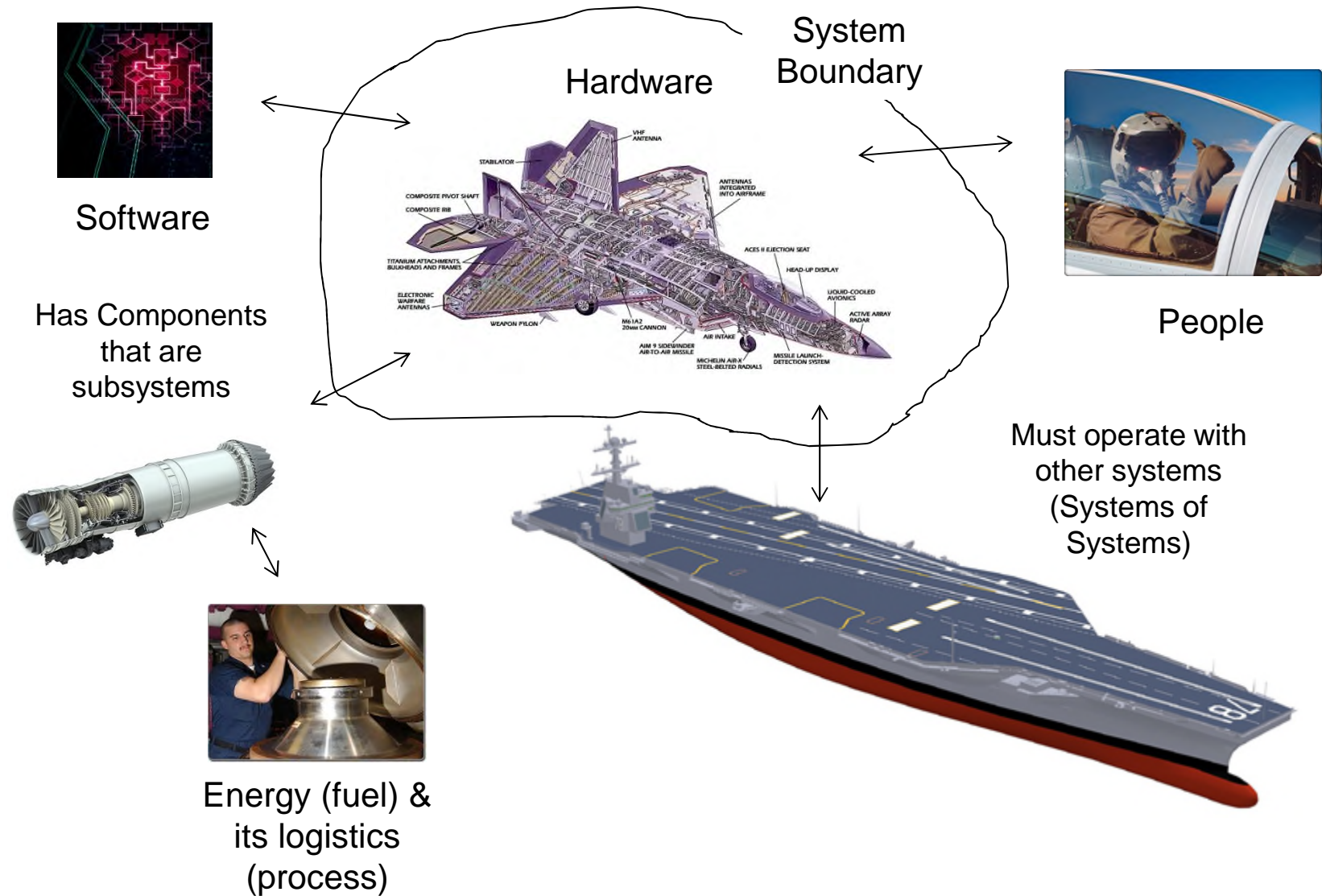
An ***interacting*** combination of ***elements*** to accomplish a defined ***objective***. These include hardware, software, firmware, people, information, techniques, facilities, services, and other support elements. (INCOSE)

A group of interacting, interrelated, or ***interdependent elements*** forming a ***complex whole***. (American Heritage Dictionary of the English Language)

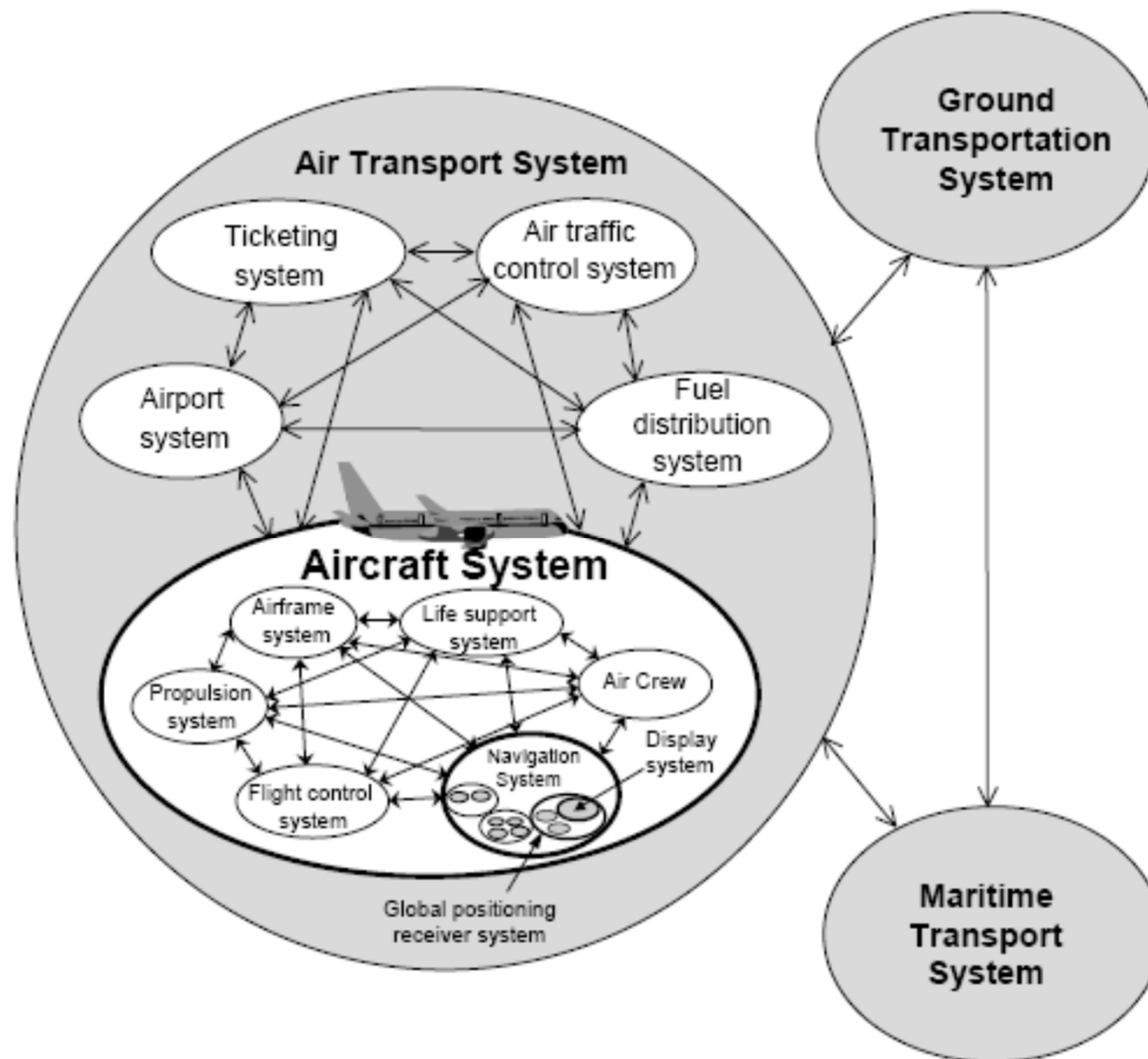
# System Definition



# Systems Definition: Components



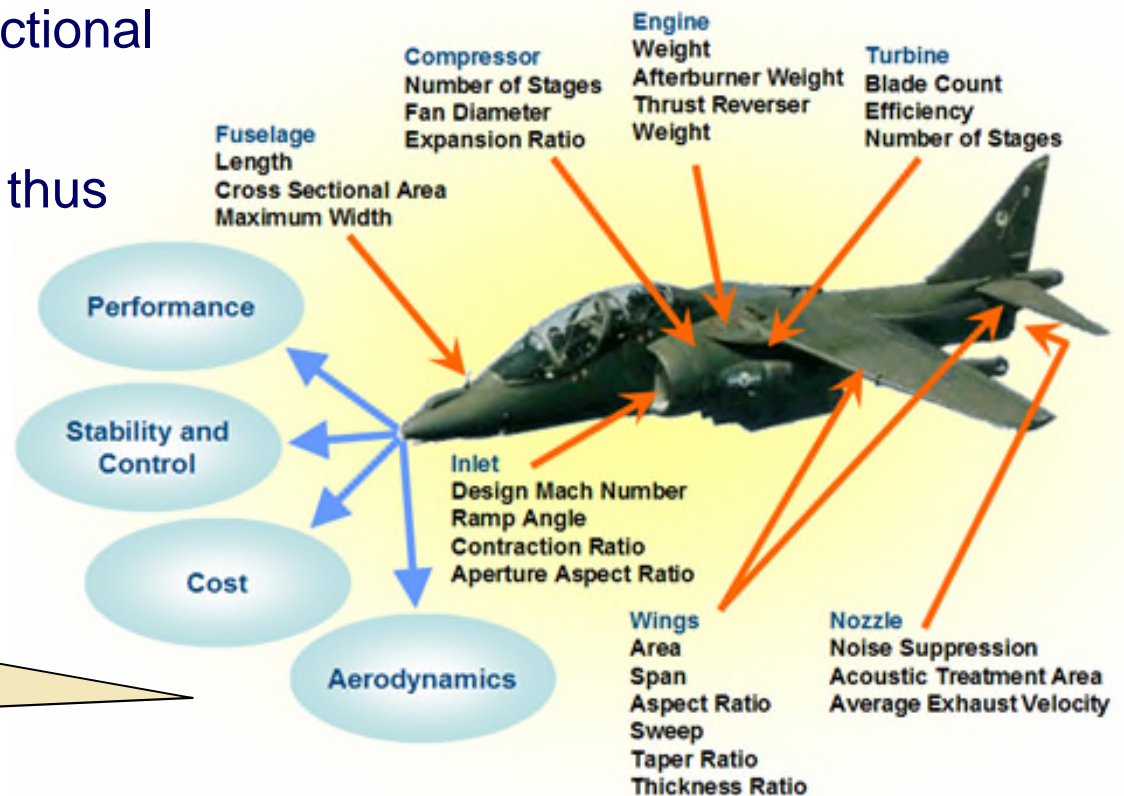
# Systems within Systems



# Emergent Properties



- Properties associated with the system as a whole that cannot be attributed to a single subsystem
- Are not identifiable in a functional decomposition
- Are often unexpected, and thus undesirable



A plane is designed to have certain aerodynamic properties, if they are emergent, then how is the plane designed?

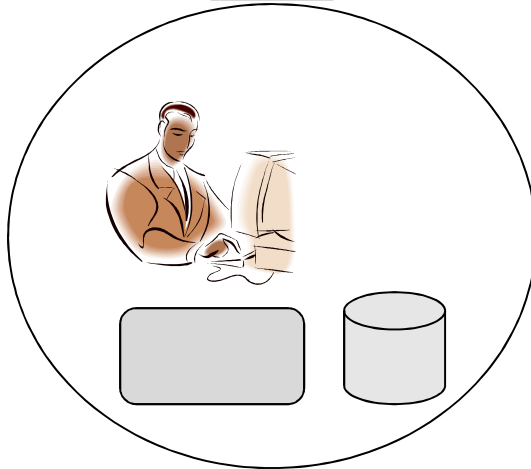


# Financial Network



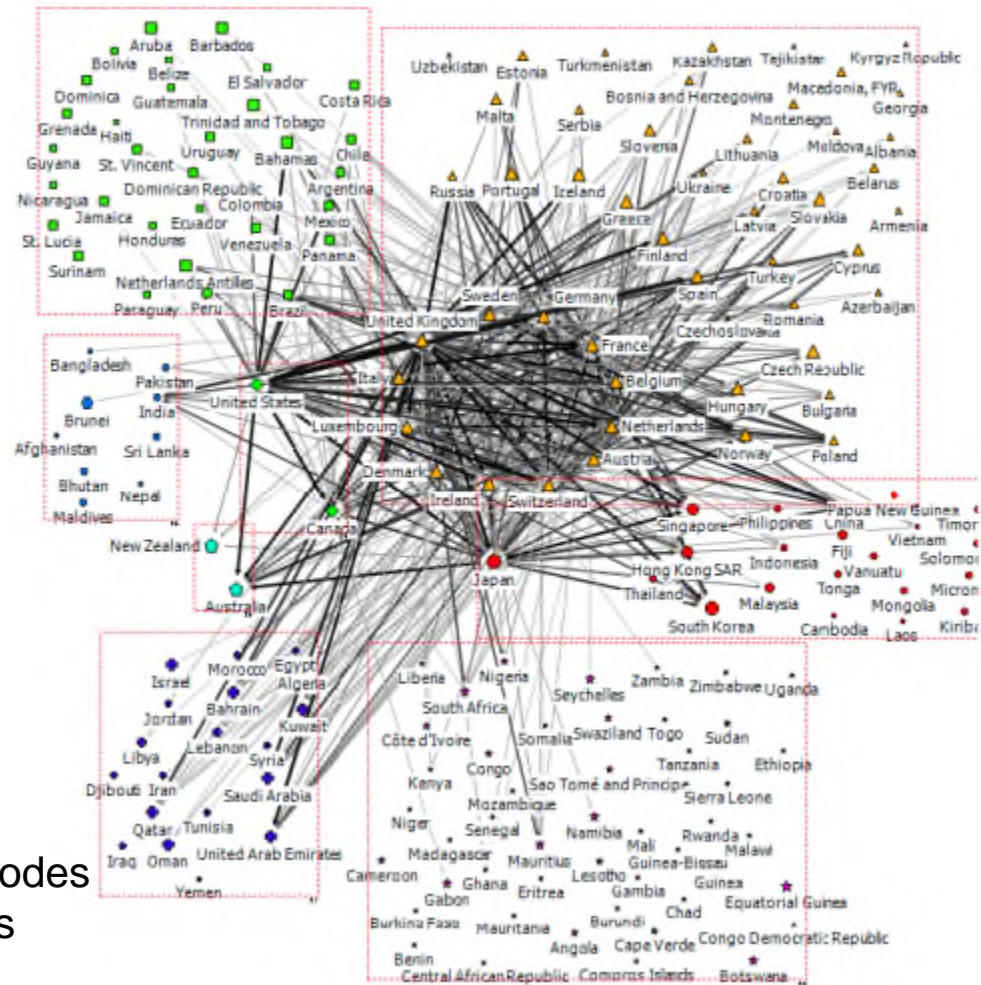
The Financial Market for trading securities is a Global **Virtual System of Systems**

## NODE



**A node is a financial firm**

- seeks profit maximization
- adversarial relation with other nodes
- may not make rational decisions
- enter/leave network
- not following scripted/defined behavior



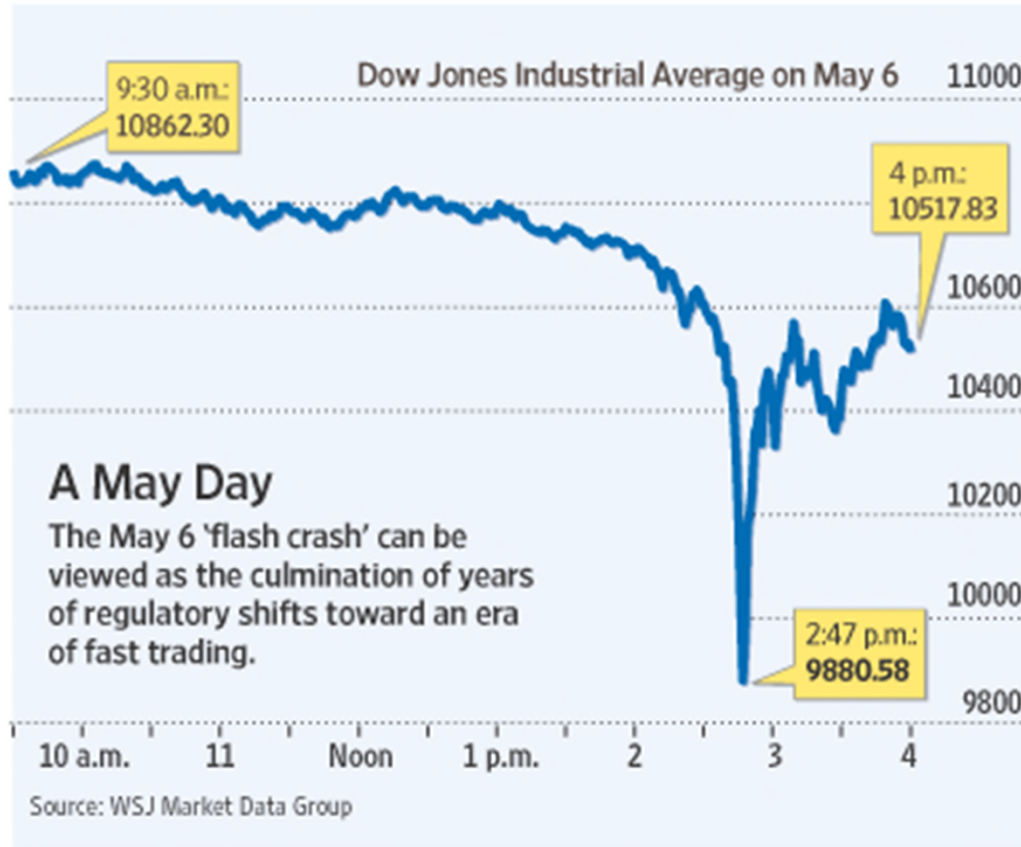


# Emergent Example



“Flash Crash” of May 6, 2010 during which Dow Jones Industrial Average dropped 600 points in 10 minutes (\$800B Market value).

Trigger event was identified as a single block sale of \$4.1B of futures contracts by a fund-management company – not named but easily identified as Waddell & Reed.



NOT a software bug

NOT some nefarious attack

NOT an identifiable missing policy

## EMERGENT BEHAVIOR

Interactions between  
independently managed systems

A complex pattern of interactions  
between high frequency algorithmic  
trading systems that buy/sell financial  
instruments.

# Emergence in CAS



Emergent behavior is often observed in **complex adaptive systems** – a system composed of independent **agents**, each with individual goals, motivation, and purpose that interact and exhibit emergent behavior



Why do geese fly in formation? (and why not to follow Wikipedia blindly)

Wikipedia says, “V formation boosts efficiency and flying range of birds due to upwash from the wingtip vortices of the bird ahead.”

OK, but do the Geese coordinate this? Do they have a goose policy and procedures (GP 1.01 2010) governing flight?

# Understanding Geese

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Each goose is an individual **agent**

The geese observe that flying is easier when they benefit from the upwash, so they naturally will fly in this more favorable position.

Each goose optimizes for themselves,

The geese interact



The interaction gives rise to the observed emergent behavior of a V formation

Geese on field in Long Island, NY

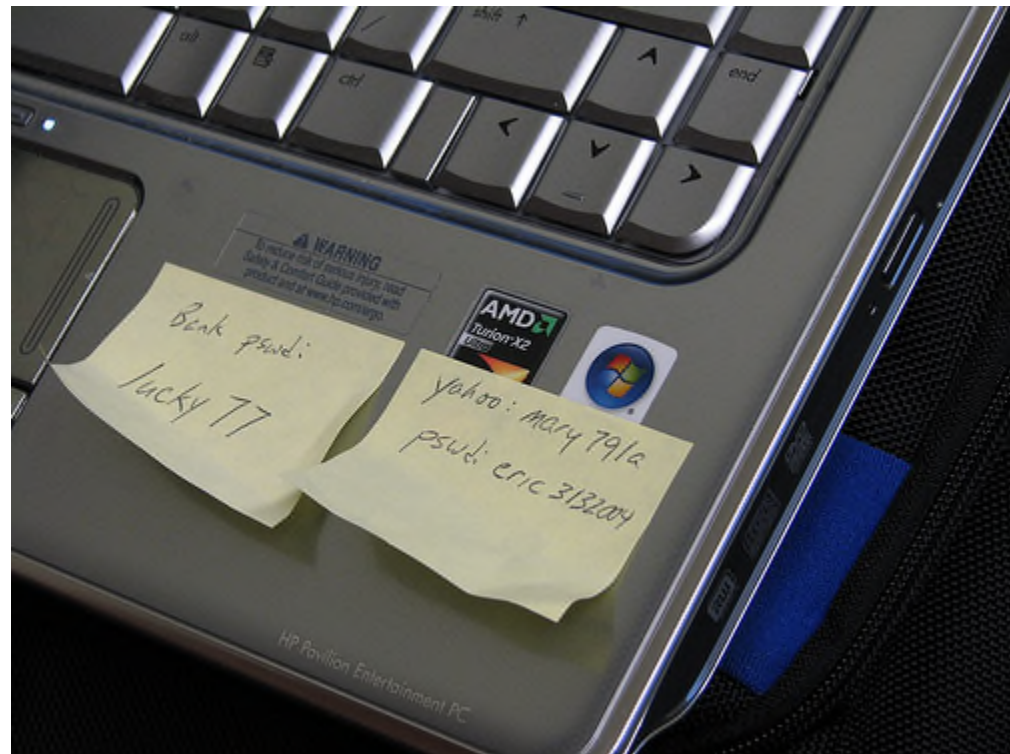
# Unintended Consequences



Not quite emergence,  
but related ...

## Example

Forcing users to have strong passwords for access to computer systems has the **unintended consequence** of causing many users to write their passwords on paper because they are difficult to remember - negating the security advantage of a strong password



# Emergent behaviors



Which properties / behaviors are typically emergent in a system?

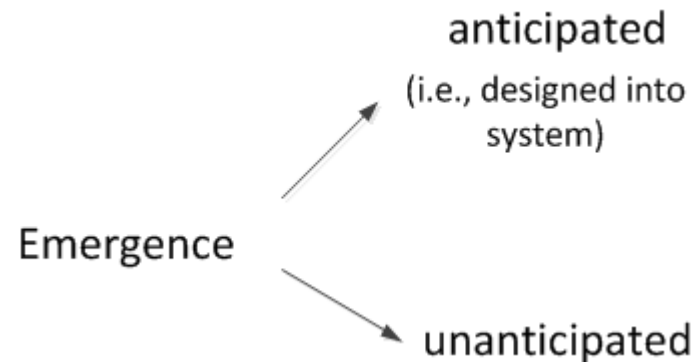
Property/behavior	Can be anticipated?	Allocated to a system component?
Weight of system		
<i>System reliability</i>		
System performance		
System usability		
System safety		
System cost		
Center of gravity for plane		

# Emergence

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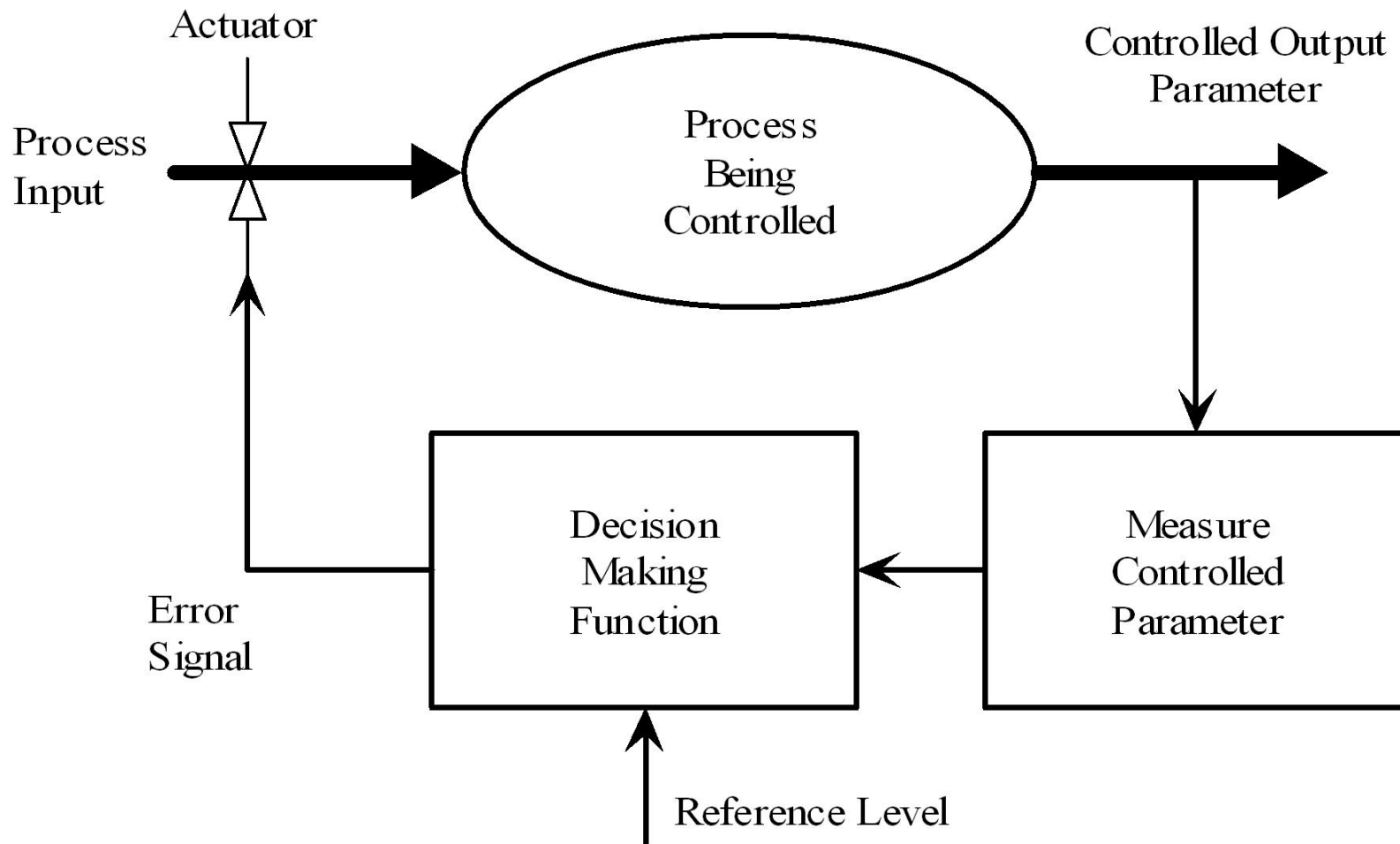
Emergence is due to interactions and relationships between system components as well as with their environment



May not be discoverable by M&S because we leave out of the models what we believe is unimportant



# Feedback & Control



# Examples of “non-complex” systems

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Almost any object designed by engineers is a system by definition. For example:

- ◆ Television
  - ◆ Refrigerator
  - ◆ Radio
  - ◆ Telephone
- 
- However, these products are usually designed based on a well-established technology and involve only a few disciplines

# Complex Systems

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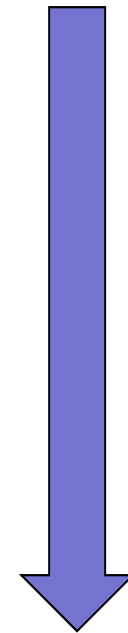


- SE is required when the design artifact is more complex:
  - ◆ Some of its key elements use advanced technologies
  - ◆ Many diverse components requiring expertise in diverse disciplines
  - ◆ Involves development risk
  - ◆ Tightly coupled subsystems – aircraft components are tightly coupled, change engine or landing and weight changes, center of gravity, flight characteristics ...

# Number of Levels in Engineering Drawings



Product	Number of parts	Number of levels
Screwdriver (Black & Decker)	3	1
Roller Blades (Bauer)	30	2
Inkjet Printer (HP)	300	3
Copy Machine (Xerox)	2000	4
Automobile (GM)	10000	5
Airliner (Boeing)	100,000	6

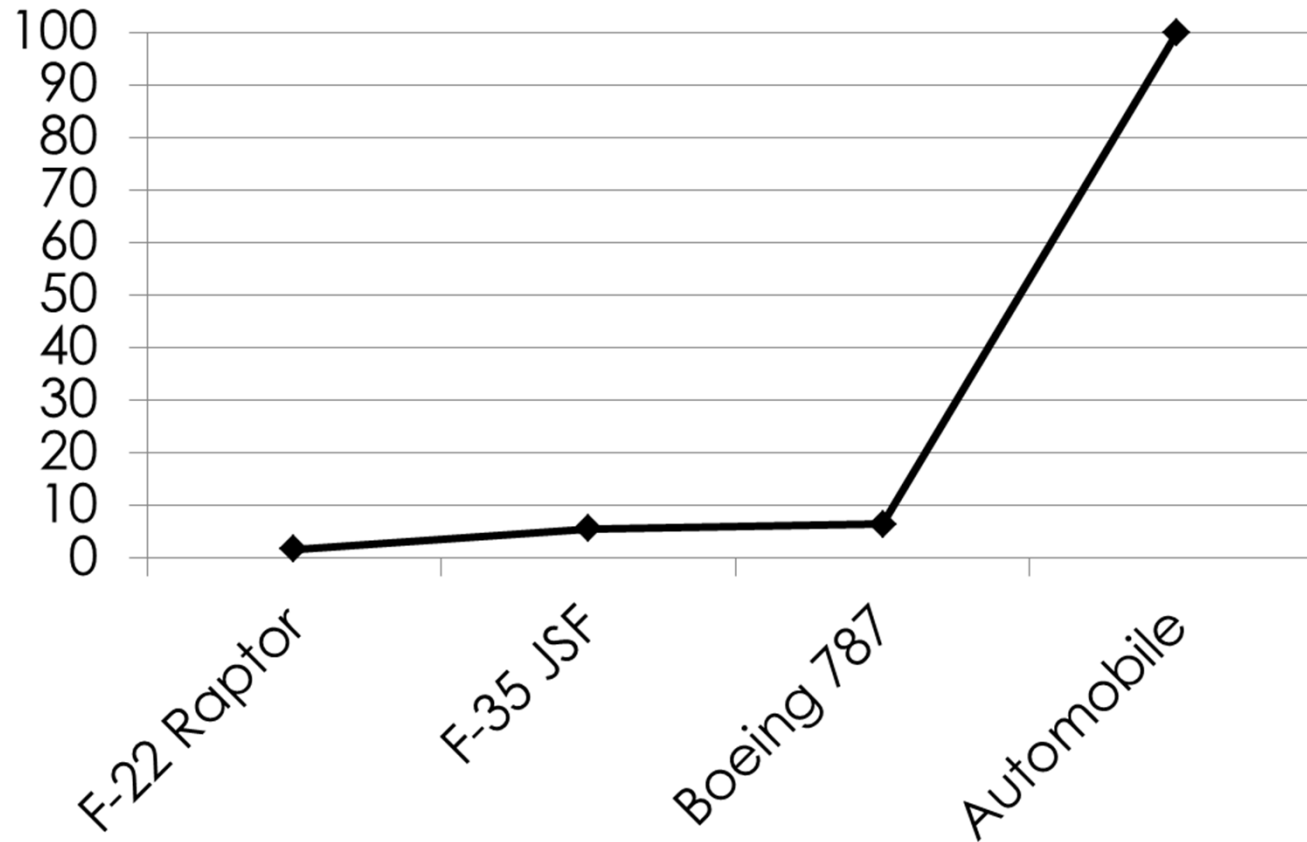


Source: K.T. Ulrich and S.D. Eppinger, Product Design and Development, 2<sup>nd</sup> Edition, McGraw Hill, 2000

# Software in Systems



## Million Lines of Code



2010 S-Class  
Mercedes has 20  
MLOC for radio &  
navigation system.

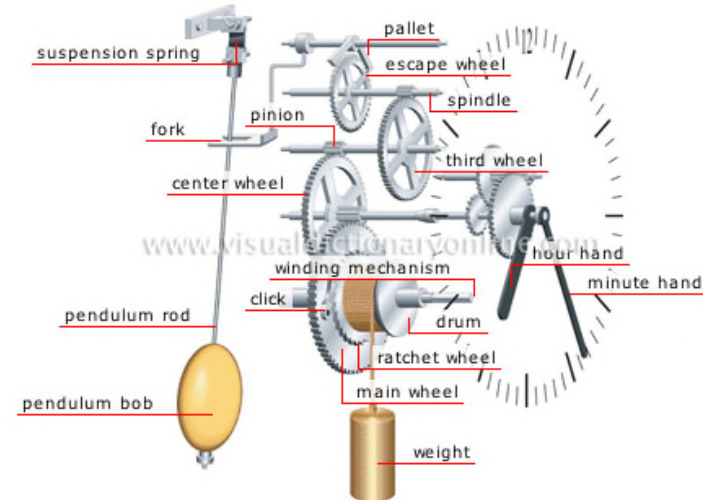
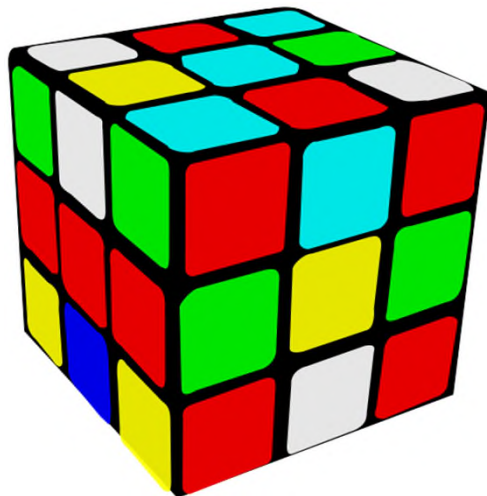
As many Electronic  
Control Units (ECU)  
as Airbus A380

R.N. Charette, This car runs on code,  
IEEE Spectrum, February 2009.

# Complexity



- Is complexity simply the large number of pieces a system has?

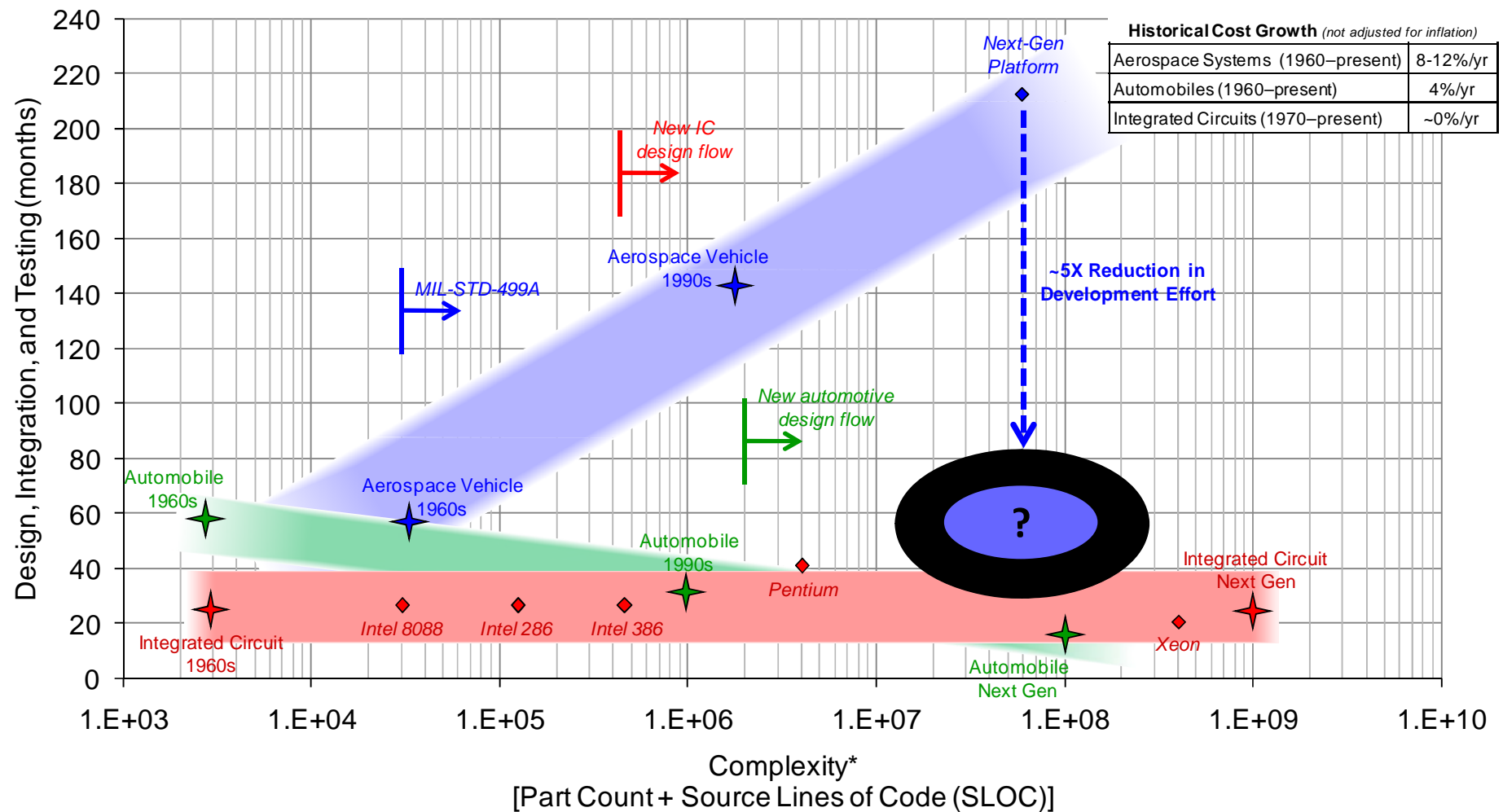


- What about emergent behavior that cannot be predicted from system components?
- Ability to understand?





# Historical schedule trends with complexity



# Complexity Growth



F-35 is Complex, but this complexity helps it achieve operational performance several times better than F-16

F-35 Supply Chain is Complex, but this helps maintain industrial base and gather sales/input from allies

F-16	F-35
15 subsystems	130 subsystems
1000 interfaces	100,000 interfaces
40% functions by software	90% functions

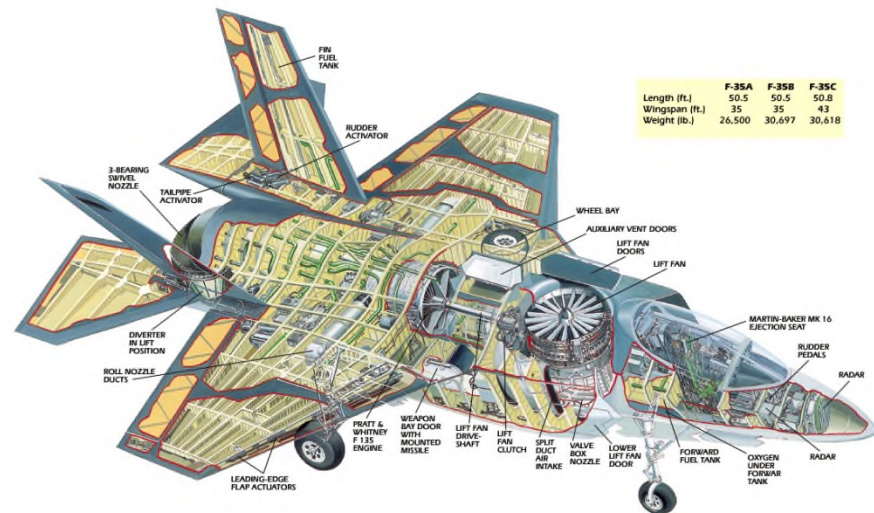


Image Source: [www.windsofchange.net](http://www.windsofchange.net)

Data Source: Arena et al. Why has the cost of fixed-wing aircraft risen? RAND technical report, 2008.

Slide 22

# Complexity

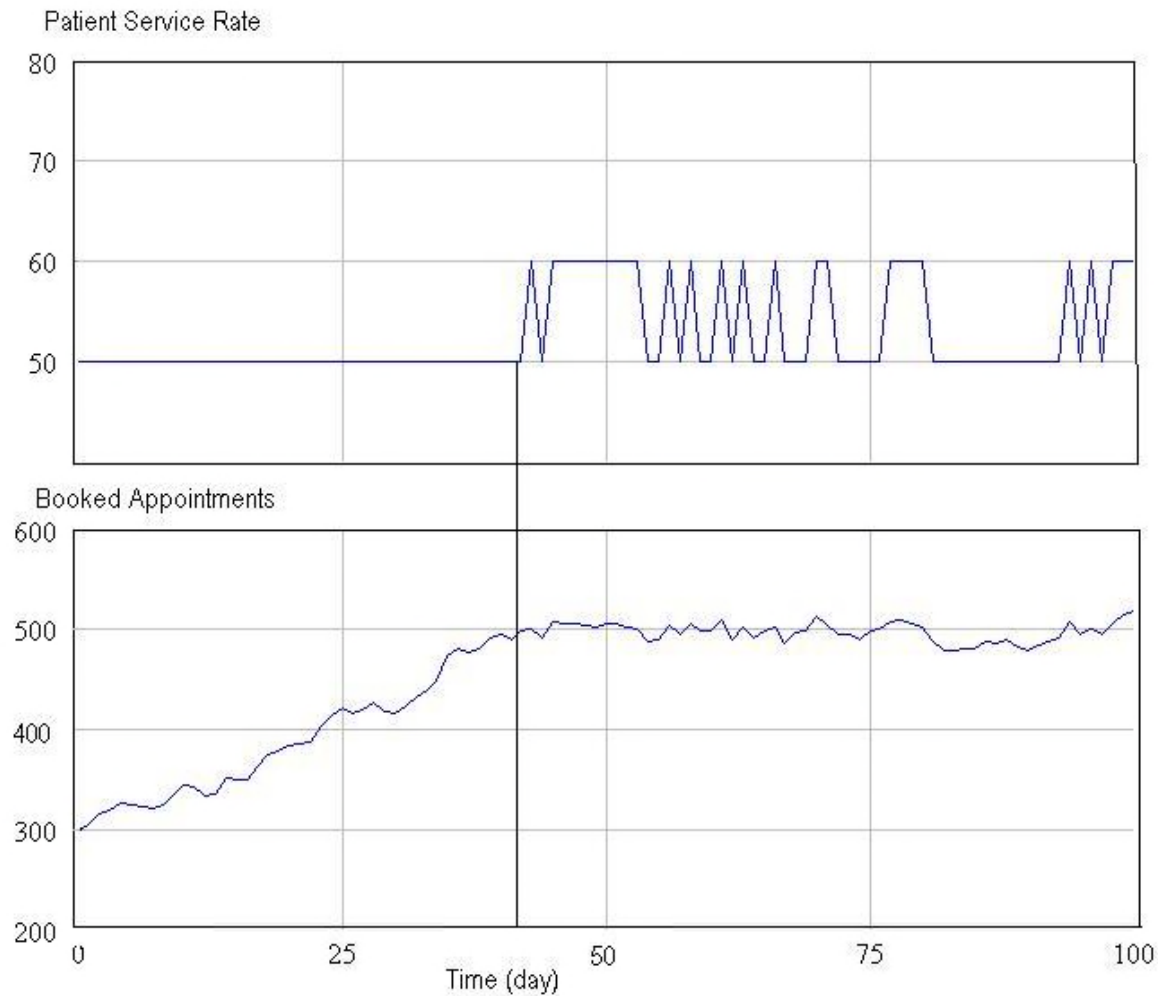
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- ***Complex Adaptive Systems*** – a system composed of independent agents, each with separate goals, that interact and exhibit emergent group behavior



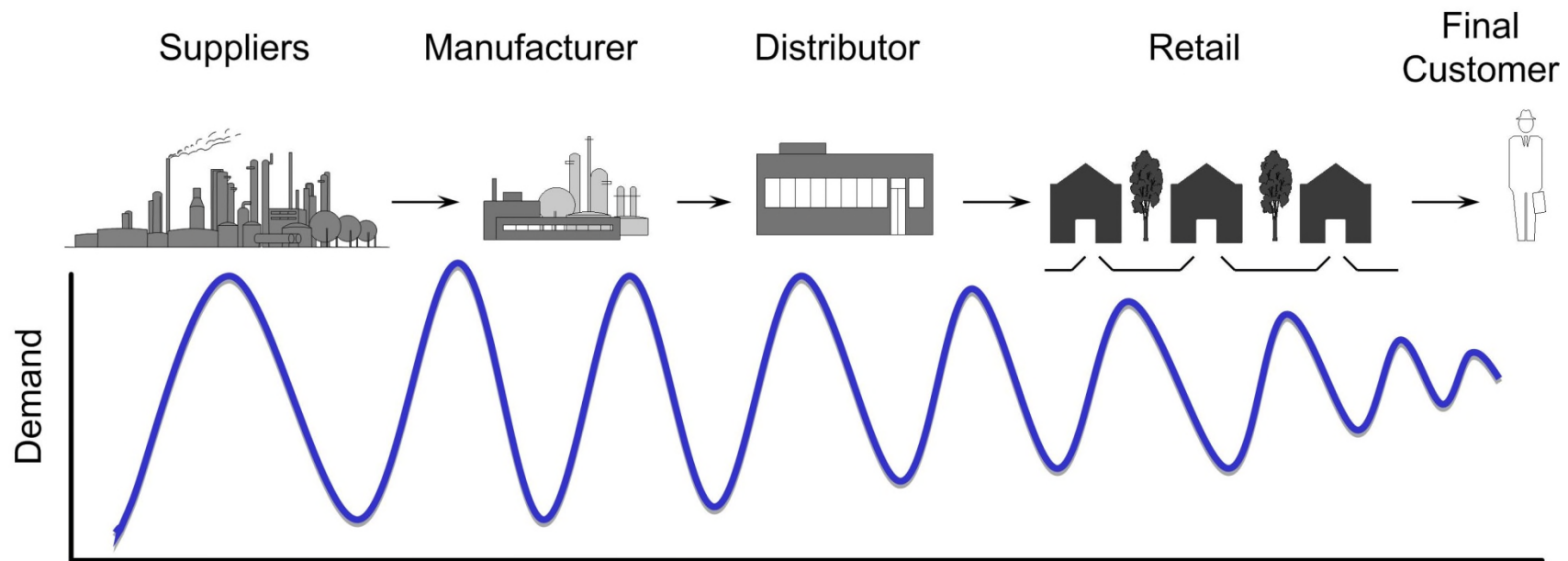
# Dynamic



# Dynamic



- System changes over time
- Open systems are self-regulating, they adjust to changes in their environment (human body maintains constant internal temperature regardless of outside temperature).



# Equifinality



Equifinality simply means there are many means to an end

Nowadays, a consumer can find multiple variants of almost any product



Folk wisdom – “there’s more than one way to skin a cat”





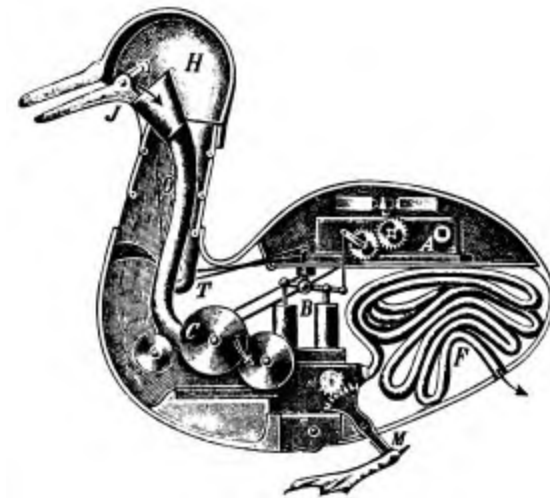
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# Systems Thinking

# Reductionist Thinking



- The idea that by decomposing a system we can understand how it works
- Dominate form of thinking in engineering
- A Newtonian or mechanistic view of systems



Duck of Vaucanson

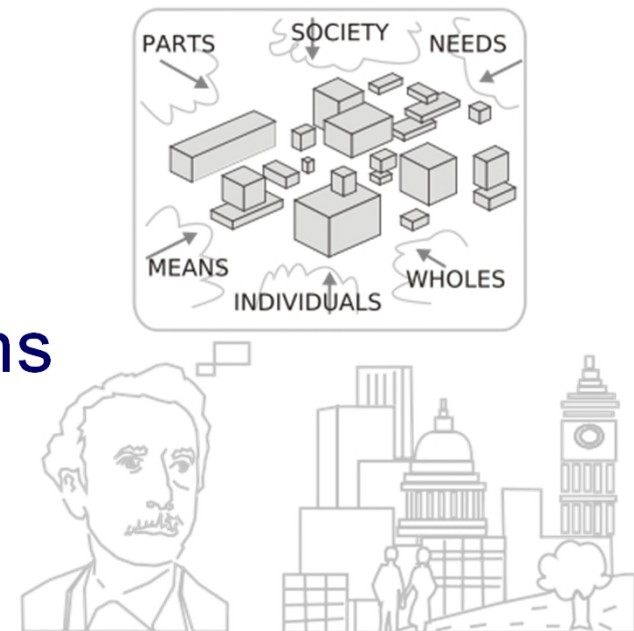
Can we replicate biological systems through engineering design? Such as self-healing air frames?

a mechanical duck which could move in the typical, wagging way of a duck, eat and digest fish, and excrete the remains in a "natural" way. The mechanism was driven by a weight and had more than a thousand moving parts, which were concealed, some inside the duck, and some in the base on which the bird stood.

# Systems Thinking

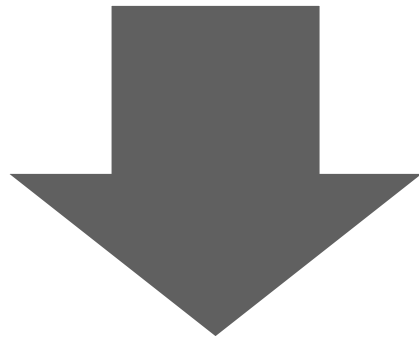


- A way of thinking about enterprises that stresses the importance of relationships
- A paradigm for thinking about the world
- A language and set of definitions
- A set of tools to understand systems

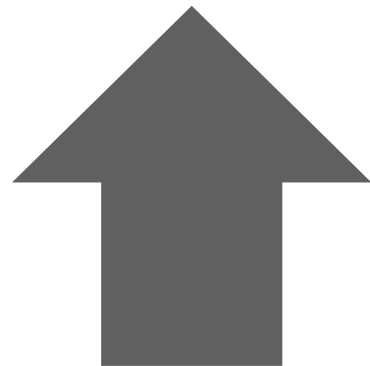


# Systems/Reductionist Thinking

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**System Thinking** derive the properties of the parts based on the properties you want of the whole.  
Start with concept of the whole – draw the house first without any rooms, details, etc.  
Might reduce performance of part to satisfy performance goals of whole.



**Reductionist Thinking** derives the properties of the whole based on the parts.  
Engineering curriculums are designed to promote this via the analytical training in math, calculus, physics, ...  
Explanation of the whole comes from the cumulative properties of the parts.  
Jump too early into design of parts without sufficient architectural concept for how the system will perform.

# System Dynamics

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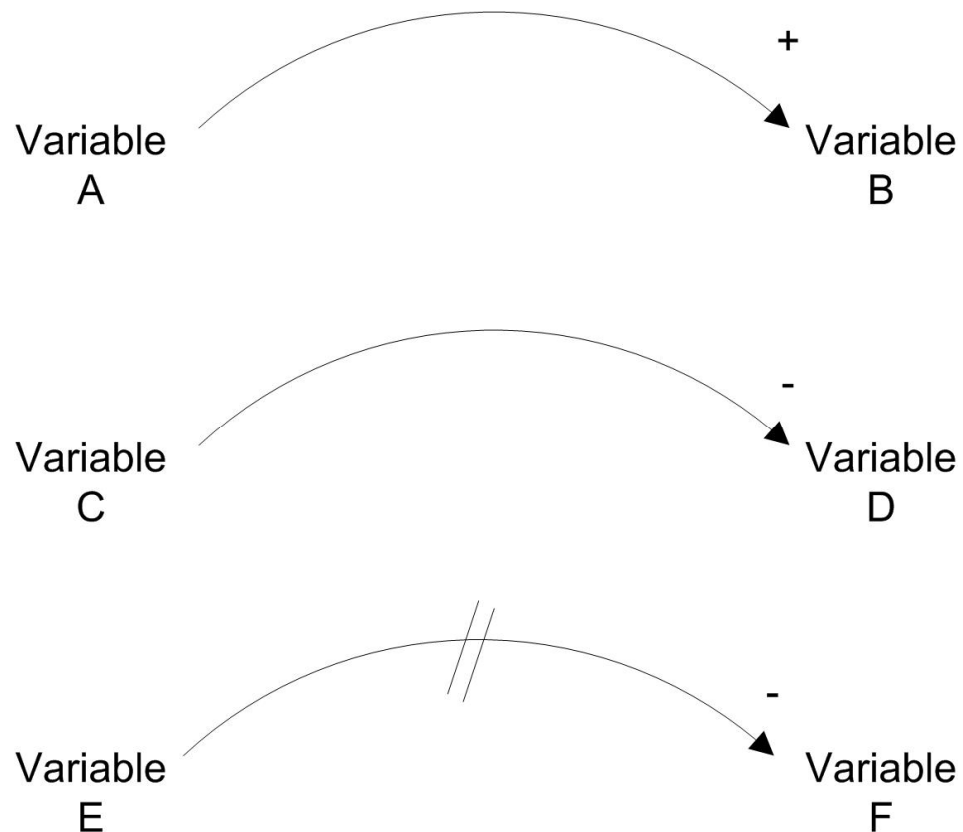


- A theory and a set of tools to study systems
- Developed at MIT by Forrester
- Combines computer simulation, control theory, and decision-making with systems theory
- Two tools to support thinking:
  - ◆ Causal Loop Diagrams
  - ◆ Stock & Flow Diagrams with simulation

# Causal Loop Diagrams



- Depicts system as interrelated system of variables

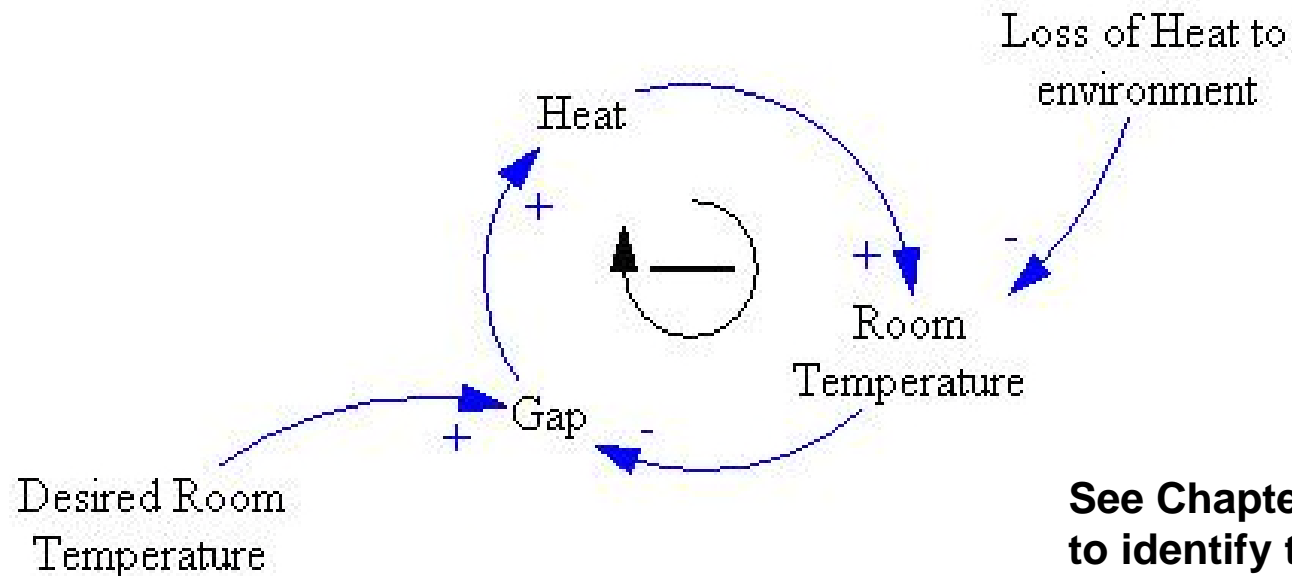




# Feedback Loops



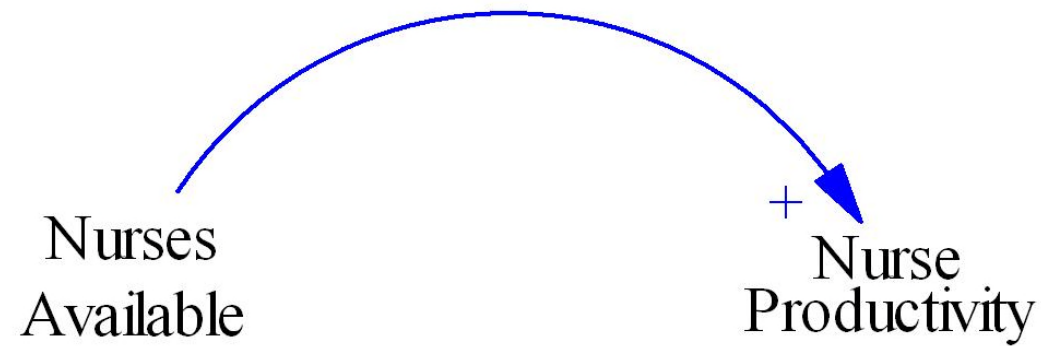
*Heat loss is through  
windows, doors, etc.*

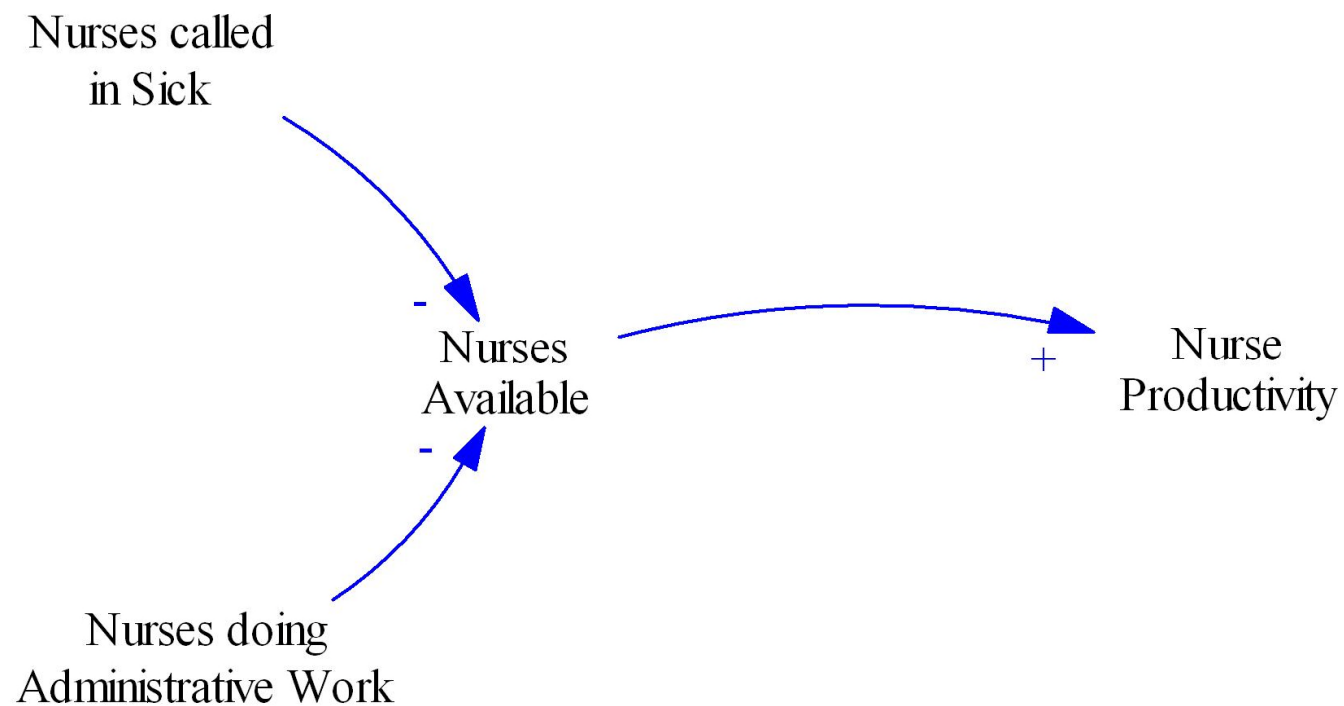


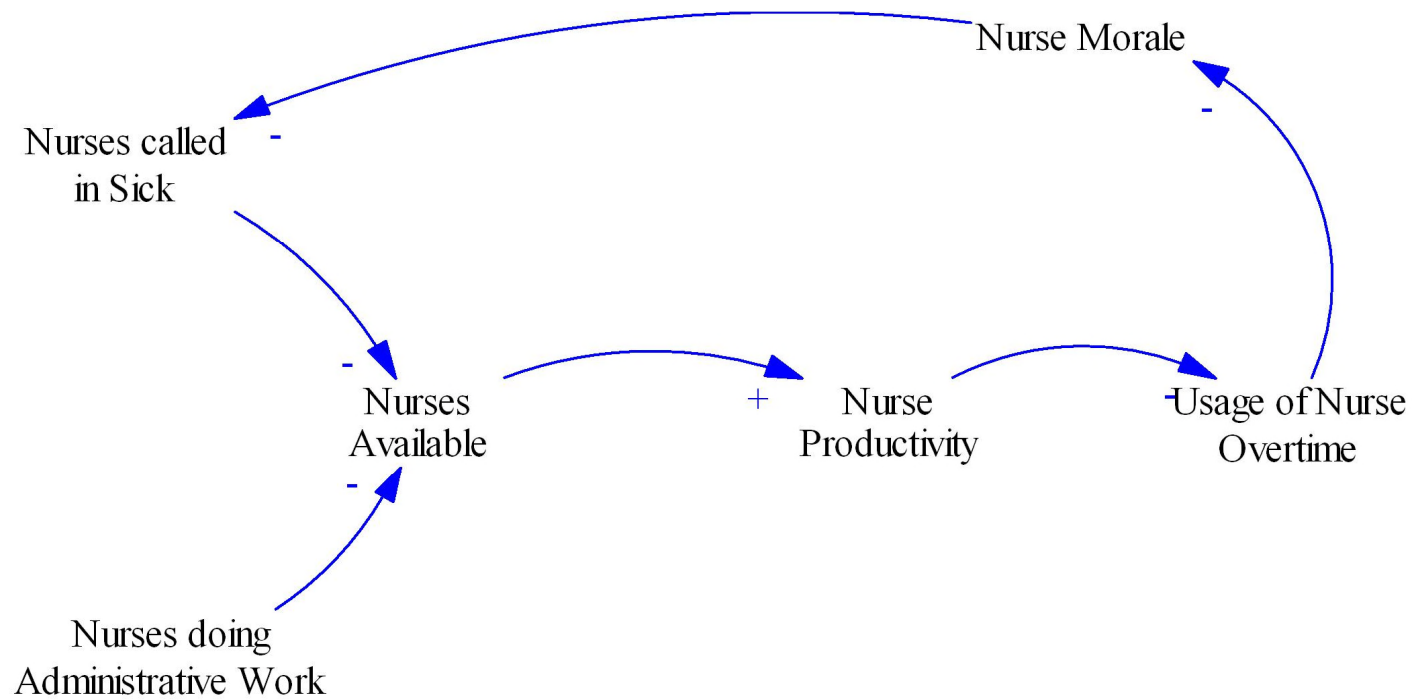
**See Chapter 2 for how  
to identify the polarity  
of the loop**

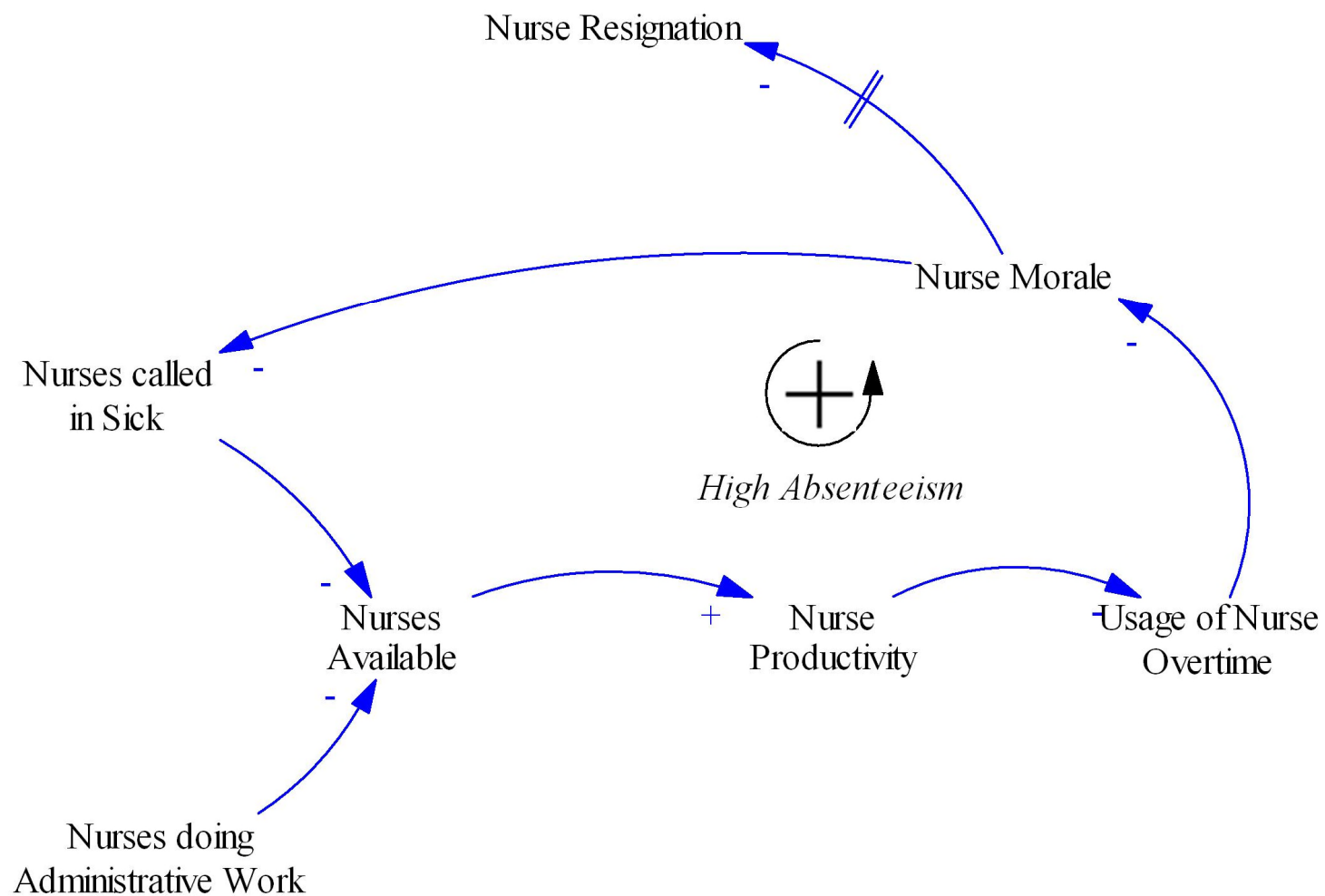
# Example Causal Loop

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# Causal Loop Adv/Dis

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- In a group, facilitates brainstorming and system understanding
- Uncover all possible relationships
- Uncover complexity
- No analytical capabilities (qualitative)
- Diagrams may not be valid – difficult to check



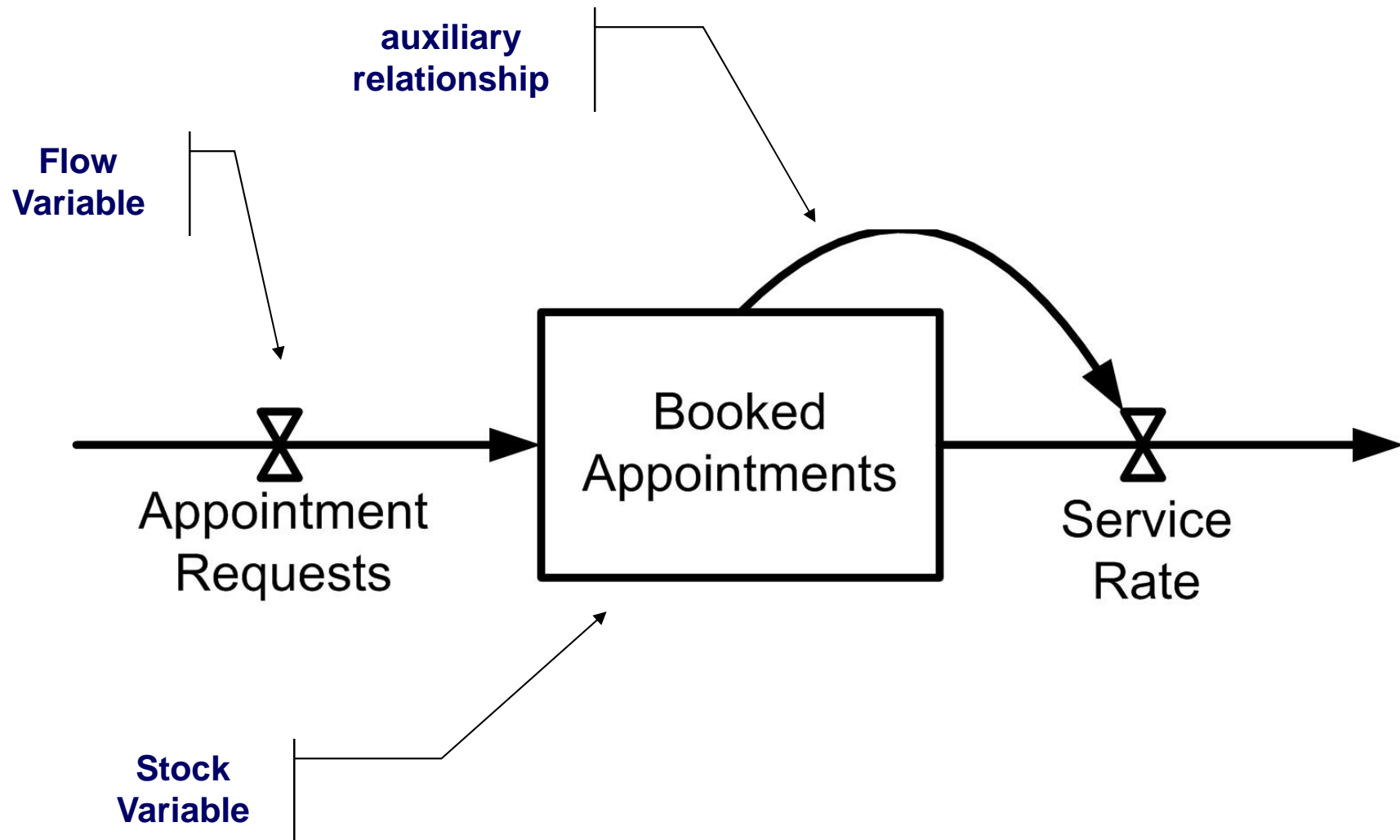
# Stock & Flow Diagrams

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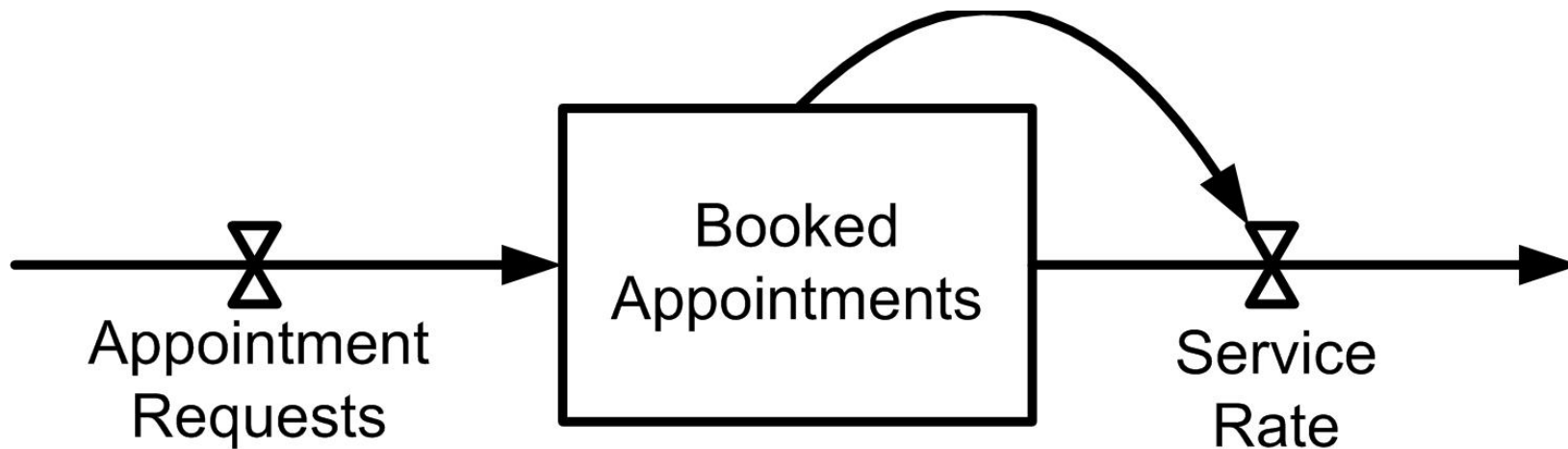


- The short-comings of causal loop diagrams is the inability to analyze the diagram
- Stock & Flow are continuous simulation (think water flow through pipes)

# Stock & Flow illustrated



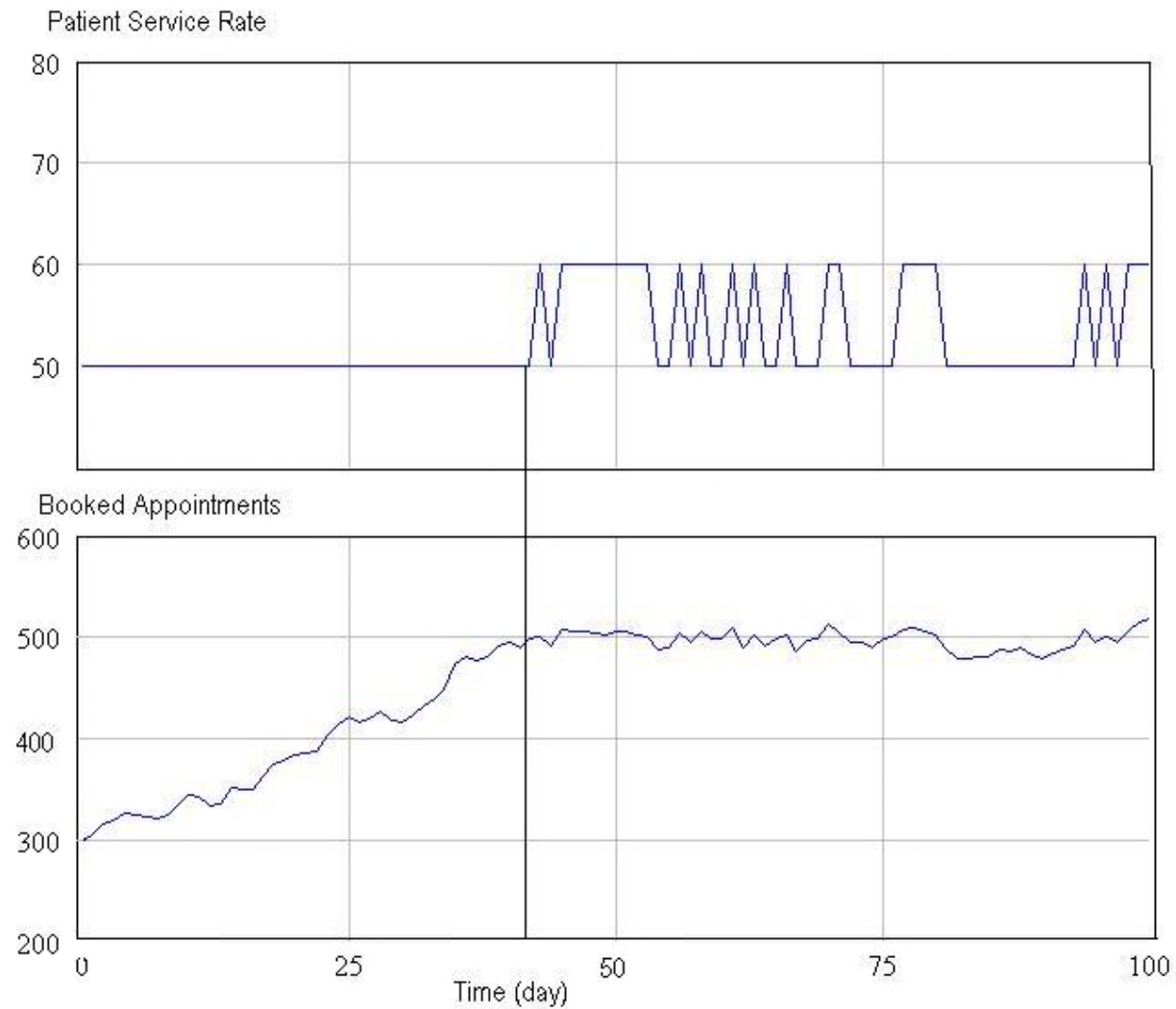
# Stock & Flow Illustrated



$$\textit{Booked Appointments} = 300 + \int_0^t \textit{Appointment Request}(t) dt - \int_0^t \textit{Service Rate}(t) dt$$

**See Chapter 2 for equations for flow rates**

# Simulation Results





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# **Example application of model for Miami's public hospital dermatology clinic**

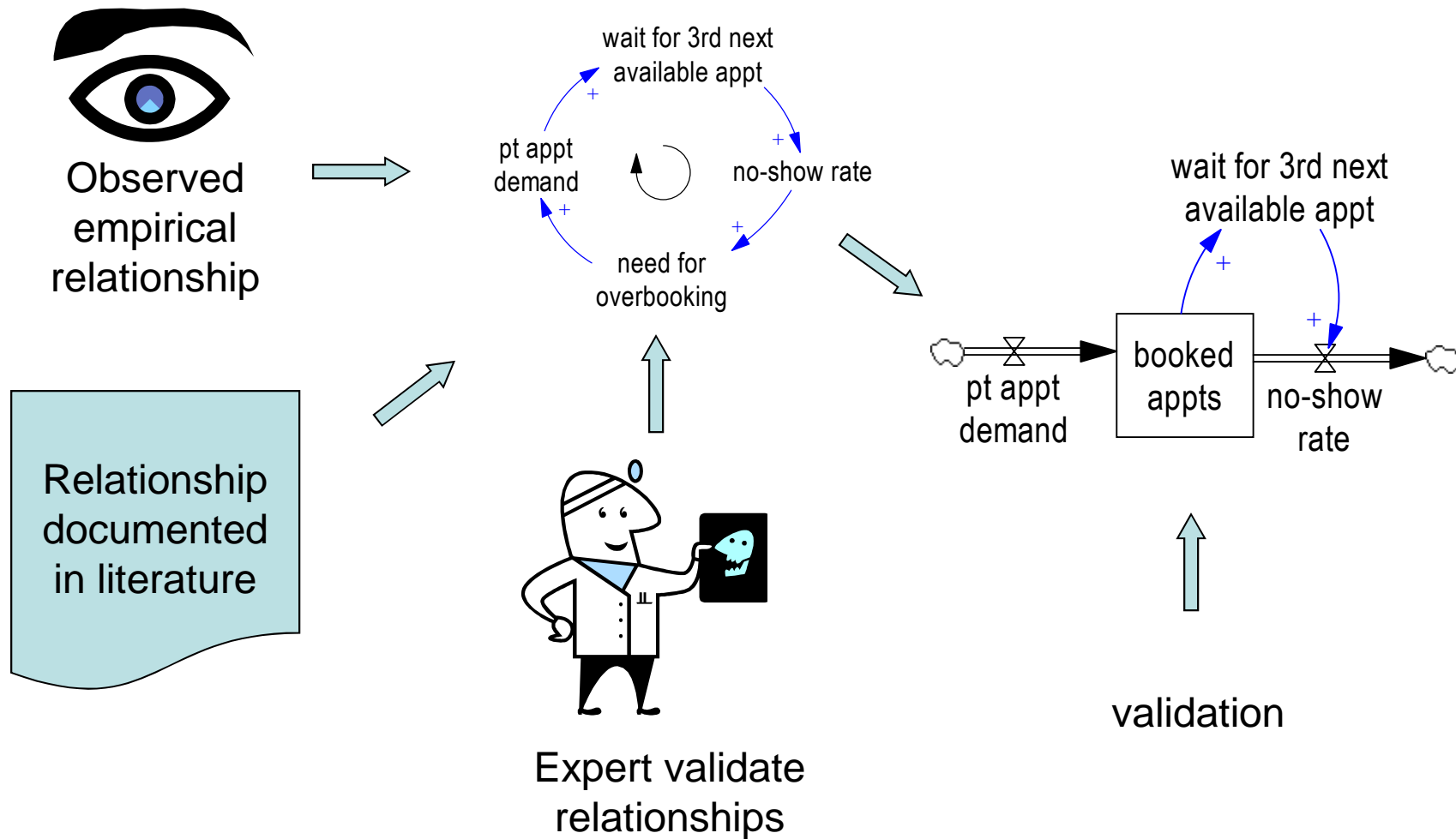
# Patient Behavior

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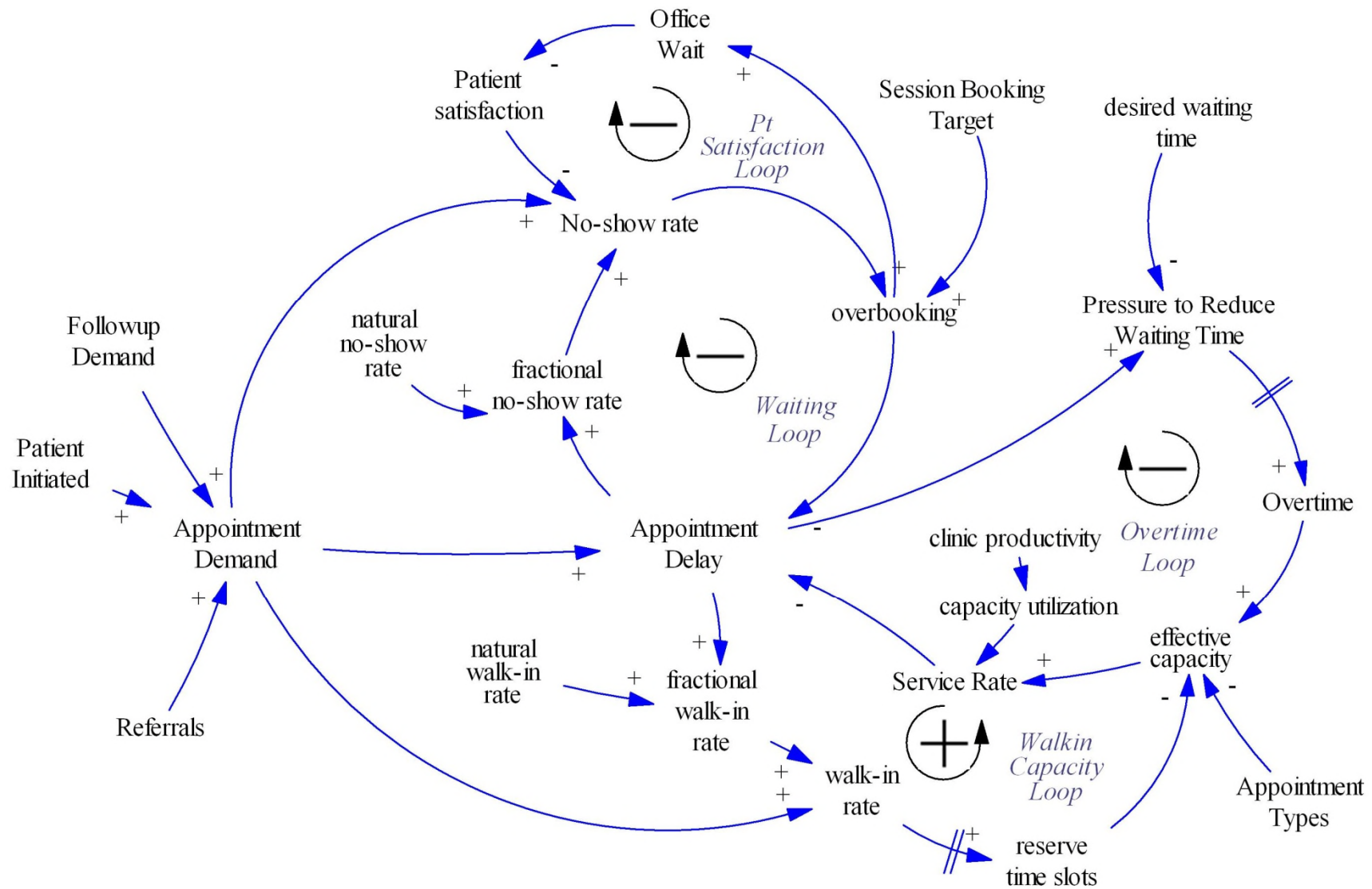
- Patient behavior affects system performance
  - ◆ Show rates
  - ◆ Interaction with doctor
  - ◆ When they seek medical attention
  - ◆ Preventive medicine
  - ◆ Walk-in behavior
- Changes in policy will affect patient behavior
  - we cannot assume patient behavior remains unchanged before/after intervention!

# Developing System Dynamics Model





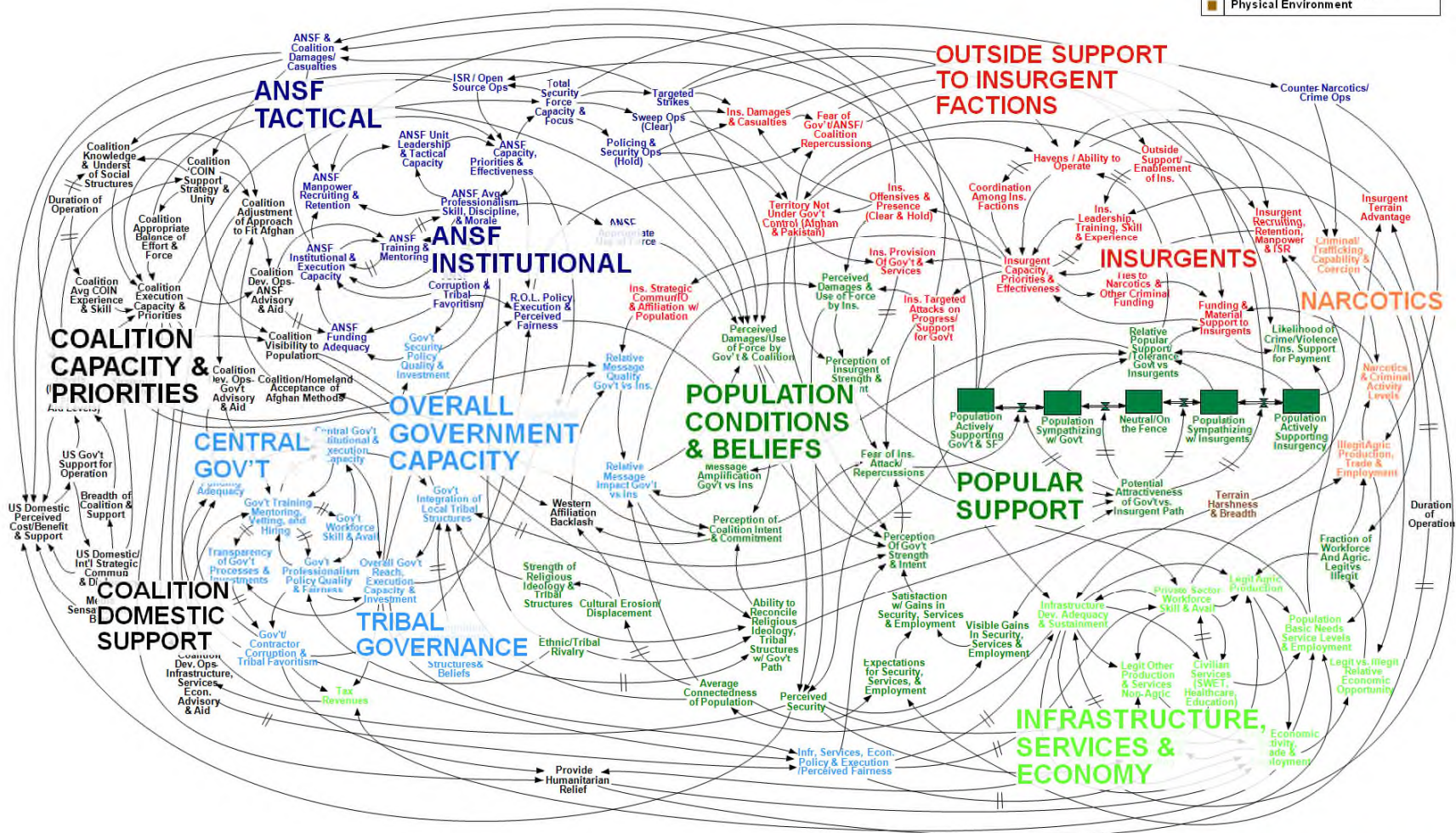
# Causal Loop Diagram



# Afghanistan Stability / COIN Dynamics

/// = Significant Delay

- Population/Popular Support
- Infrastructure, Economy, & Services
- Government
- Afghanistan Security Forces
- Insurgents
- Crime and Narcotics
- Coalition Forces & Actions
- Physical Environment

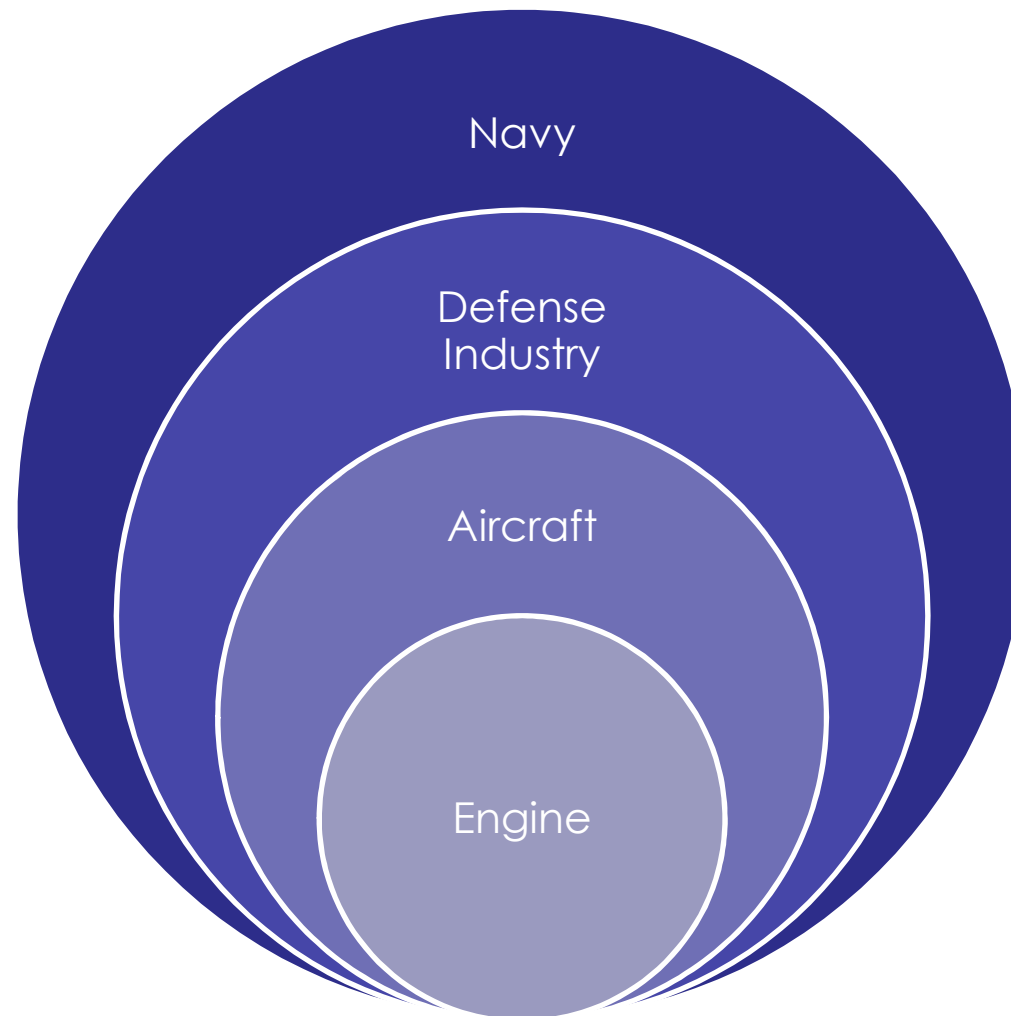


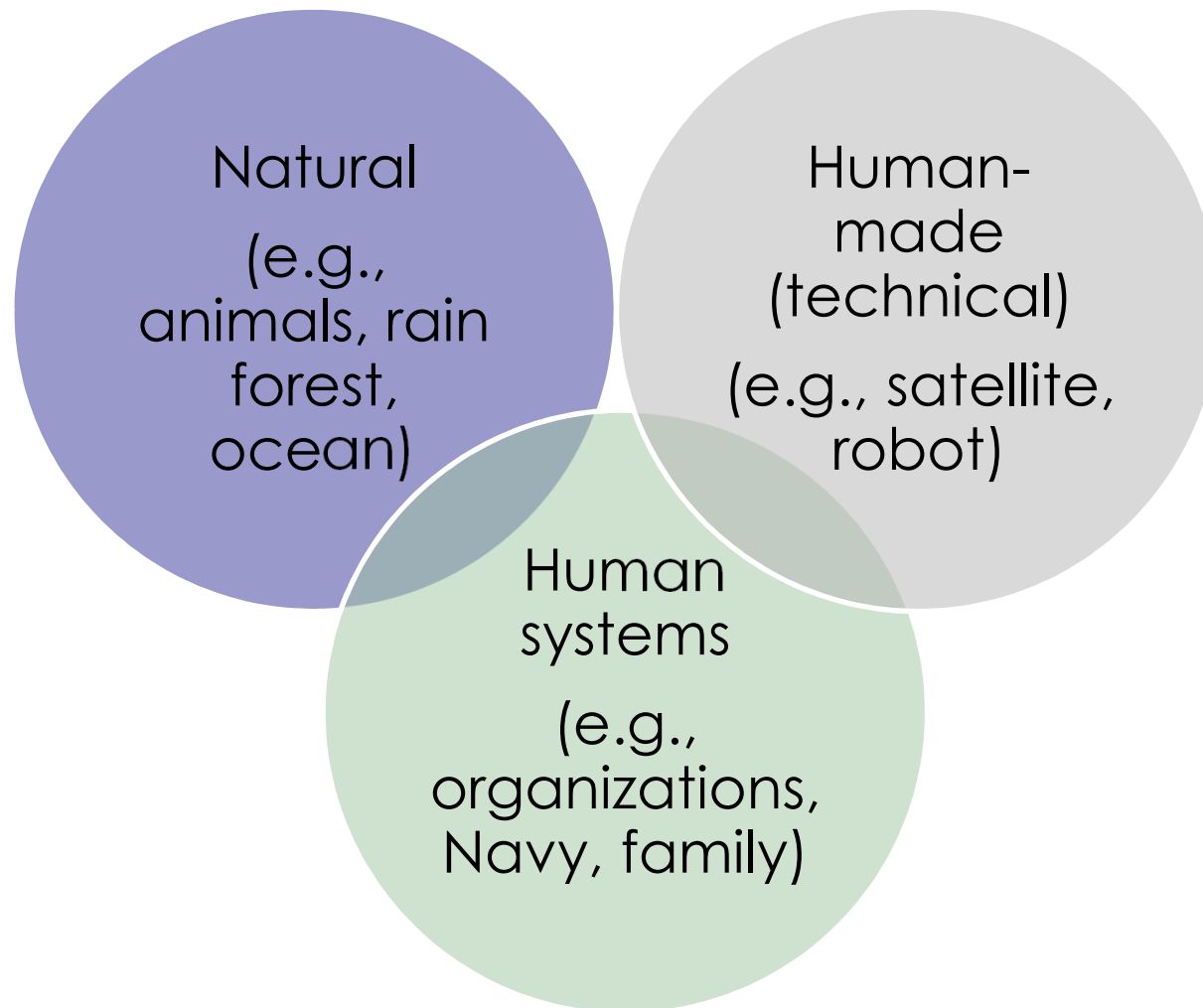
WORKING DRAFT - V3

This is a Causal Loop diagram that was published in the NY Times as used by General McChrystal to help understand Counter Insurgency Operations (COIN)

# Systems within Systems

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- Systems thinking is about interdependence and interrelationships. Systems are, in practice, patterns of relationships.



# Summary

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- Define the enterprise boundaries that help best solve the problem.
- Understand the system structure, identify its subsystems & parts.
- Determine the stakeholders, their perspectives and their goals.
- Remember there are many ways to achieve the goals (equifinality).
- Understand the interaction with the environment (enterprises are open systems).
- The enterprise has behavior that can be observed only at the enterprise level and cannot be deduced by analyzing subsystems of the enterprise in isolation.
- To maintain stability in a changing environment the enterprise must adapt, which requires feedback loops from the environment.
- Enterprises are purposeful systems because it can both choose its goals and its means to attain those goals. Additionally, the people in the enterprise are purposeful.
- The enterprise is hierarchical, it is composed of lower-level subsystems, and the enterprise is part of higher-level systems (e.g., supply chains).
- There are multiple ways to define the subsystems depending on the observers views (e.g., organizational subsystems, process subsystems, etc.).



# **Systems Thinking: Maritime Domain Protection System**

**SE3100  
Winter 2012**

**Ronald E. Giachetti, Ph.D.**

Professor  
Systems Engineering

April 9, 2018

**Systems Engineering**

53



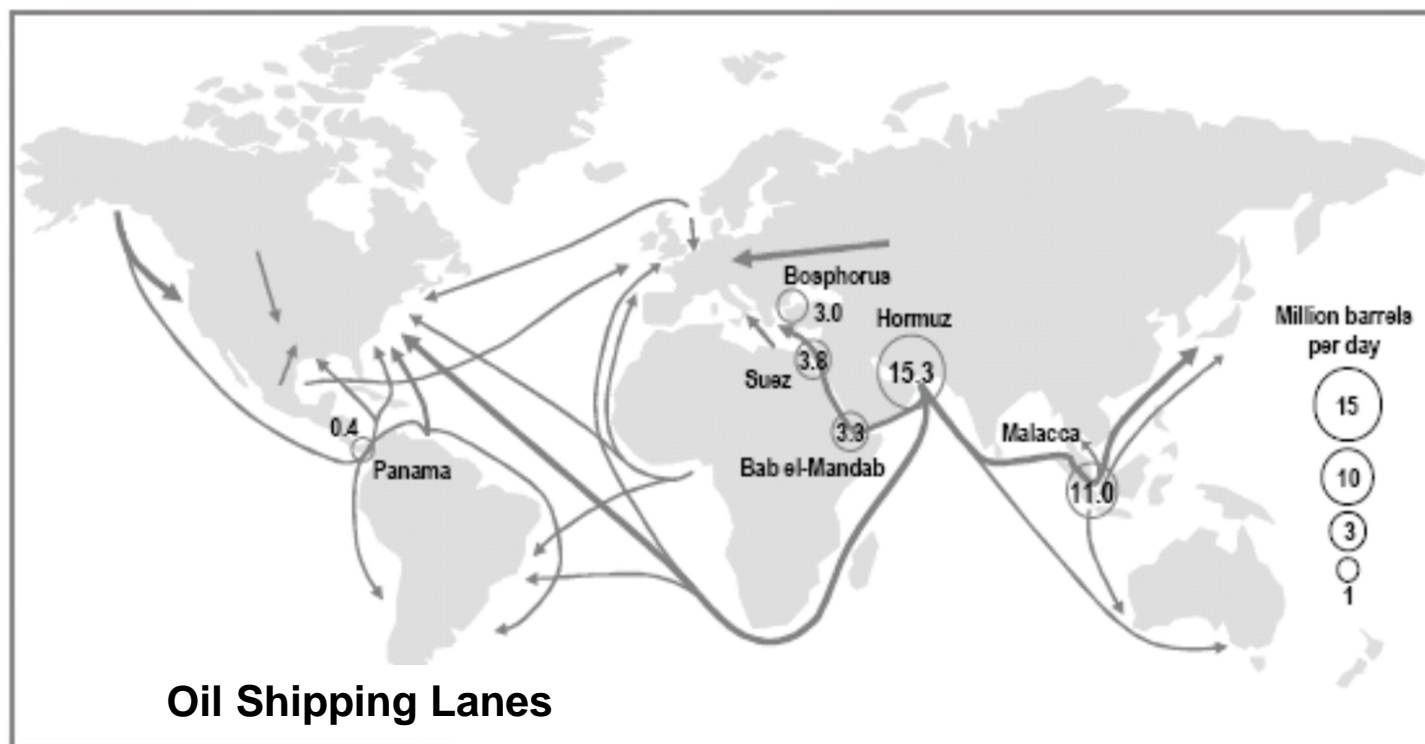
# Overview

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- The goal is a **maritime domain protection system** against piracy and terrorist threats. It should bring together a diverse set of technologies to enable persistent intelligence, surveillance, reconnaissance, and enable potential action. Protecting world-wide shipping is not the goal, we will focus on the bottlenecks.

# World Shipping



## Other Commercial Shipping Lanes



# Piracy in Somalia



- Motivation: Make \$\$\$
- In 2010, 1,181 people taken hostage, half were released after payment of a ransom.
- In early 2011, 760 remained in captivity, usually on their own high-jacked vessels.
- Some ships used as “Mother ships” which extend range.
- Mostly controlled by gangs
- Pirates spend about \$30k for each mission (12 armed men)
- Have supply chain and need a means to profit on ransoms (financial markets)

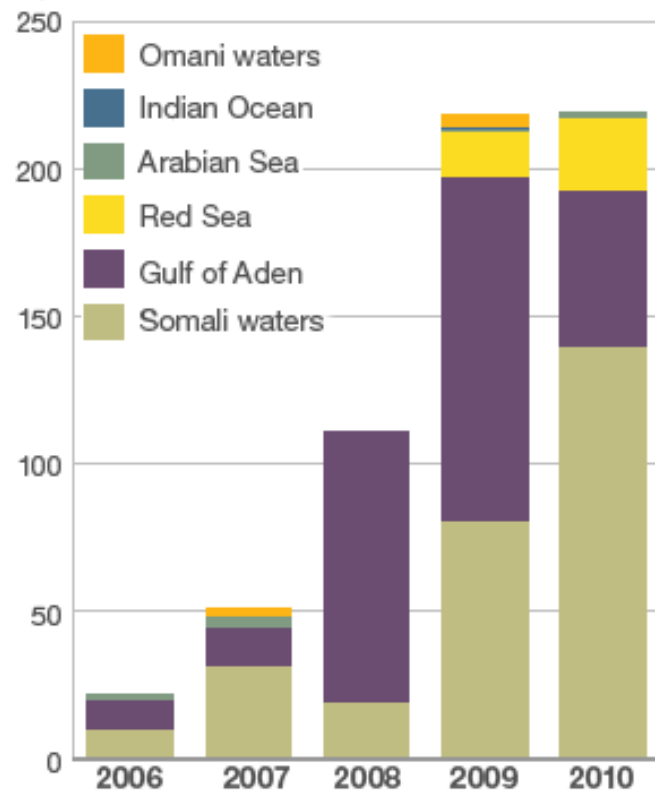


# Exponential growth



## Somali pirate attacks

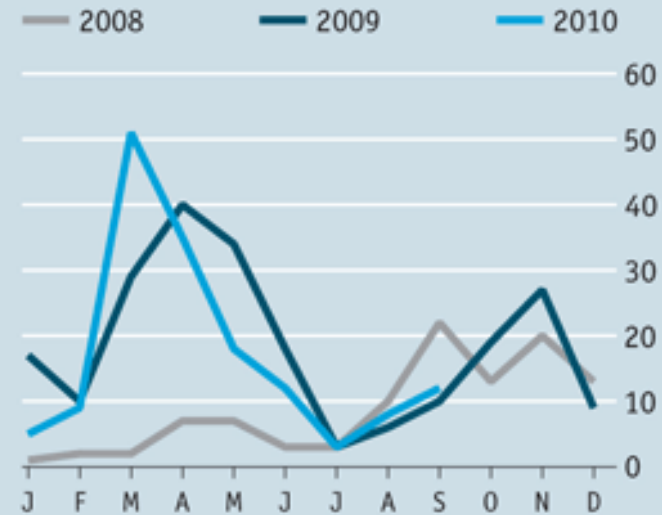
Number of attacks



Source: IMB

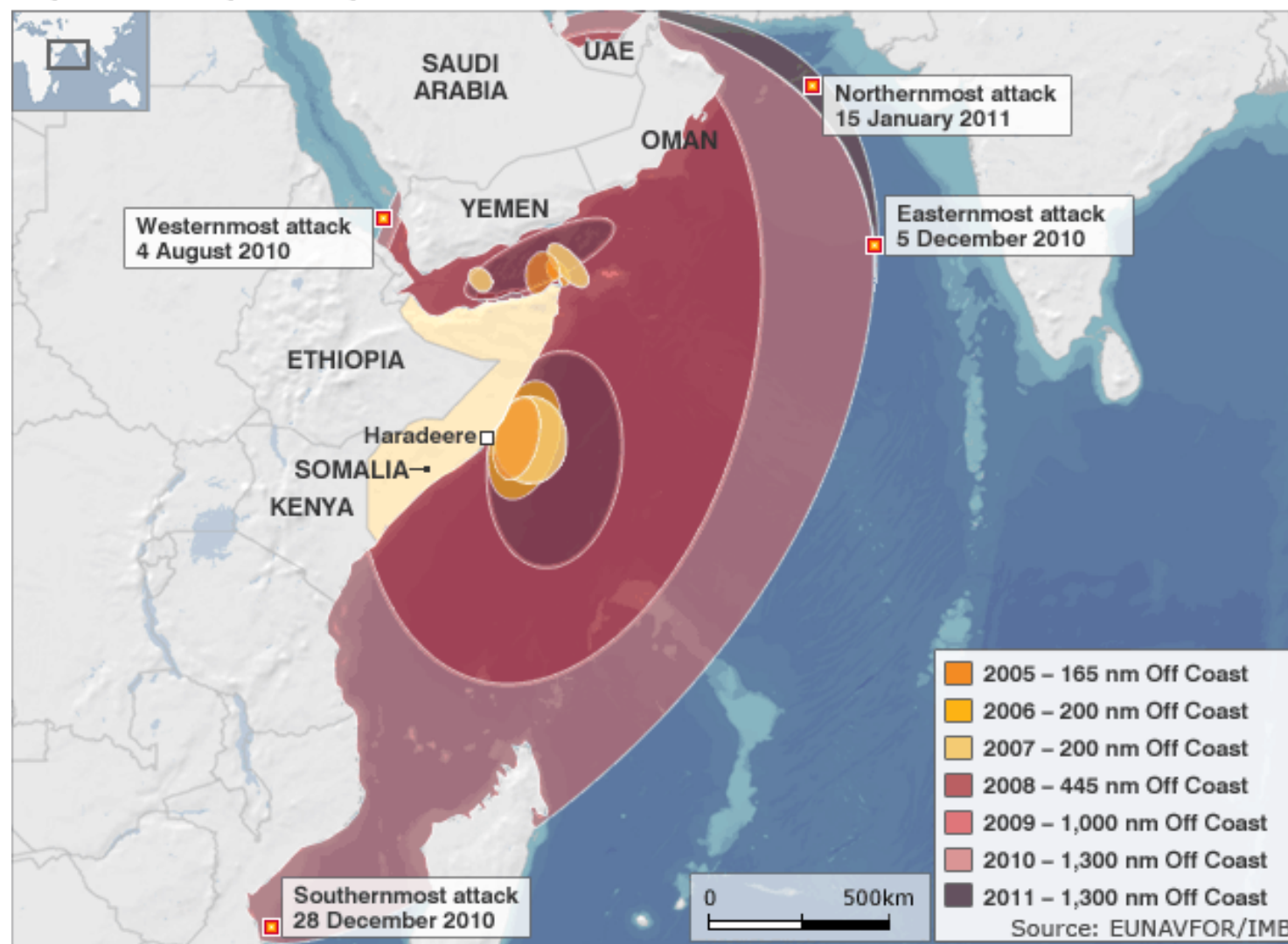
## Back in season

Monthly attacks by Somali pirates



Source: Control Risks

## Expansion of pirate operations





# Issues



- Political, Economic, Social, and Technical issues that enable piracy
  - Think of the “**supply chain**” for piracy
  - How do shipping companies respond?
  - How do navy’s respond?
- 
- Piracy is motivated by financial gain, what is financial cause/effect?
  - Rules of engagement, many countries are essentially following a “catch-and-release” policy, how do laws affect piracy?



USS Kidd responds to Iran fishing vessels aid (Jan 2012).



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## Number of Piracy Attacks





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What causes the “Number of Piracy Attacks”  
to increase or decrease?

1. Brainstorm and Make a list of causes:

the supply chain for piracy.

the motivation for piracy.

Conditions that enable piracy

PEST (political, economic, social, and technical).

2. Organize your list by classifying causes. Show as columns  
with column heading the “class name” and the individual  
causes underneath.



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# Example Solution to Problem follows

WHAT IS PROBLEM / GOAL?

1. ELIMINATE PIRACY
  2. PROTECT SHIPPING
  3. PREVENT PIRACY
- } How we frame the problem is critical.

Let's say we want to find causes/enablers of piracy.

1. OUR MAIN VARIABLE OF INTEREST IS :

# of PIRATE ATTACKS

PUT IN MIDDLE. START HERE.

How does this variable behave over time?

2. LIST VARIABLES THAT CAUSE/ENABLE/INFLUENCE THIS VARIABLE.

"THE SUPPLY CHAIN"

Types of Variables

RATE  
NUMBER  
SOCIAL EMOTION.

3. GROUP THEM

PEST = Political, Economic, Social, Technology  
MISS ANY AREAS?

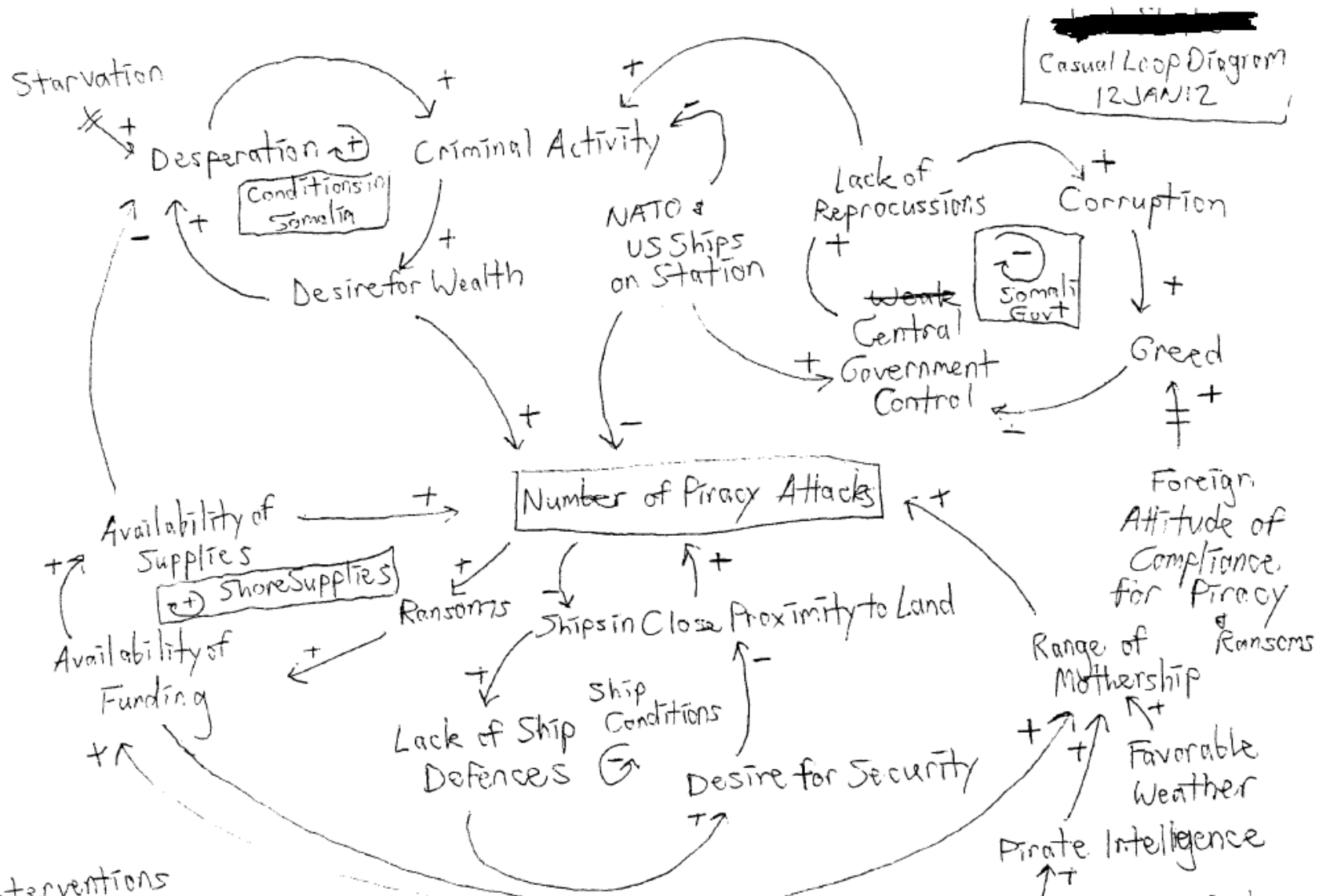
4. DID YOU CAPTURE MOTIVATION FOR PIRACY? \$\$\$!

5. FEEDBACK LOOPS.

AS PIRATES ARE SUCCESSFUL, WHAT HAPPENS?

6. HOW DO SHIPPING INDUSTRY RESPOND? NAVY?





### Interventions

1. NATO involvement in the region.

Their presence will decrease both the amount of criminal activity & piracy attacks. They will also increase what little government control is in place.

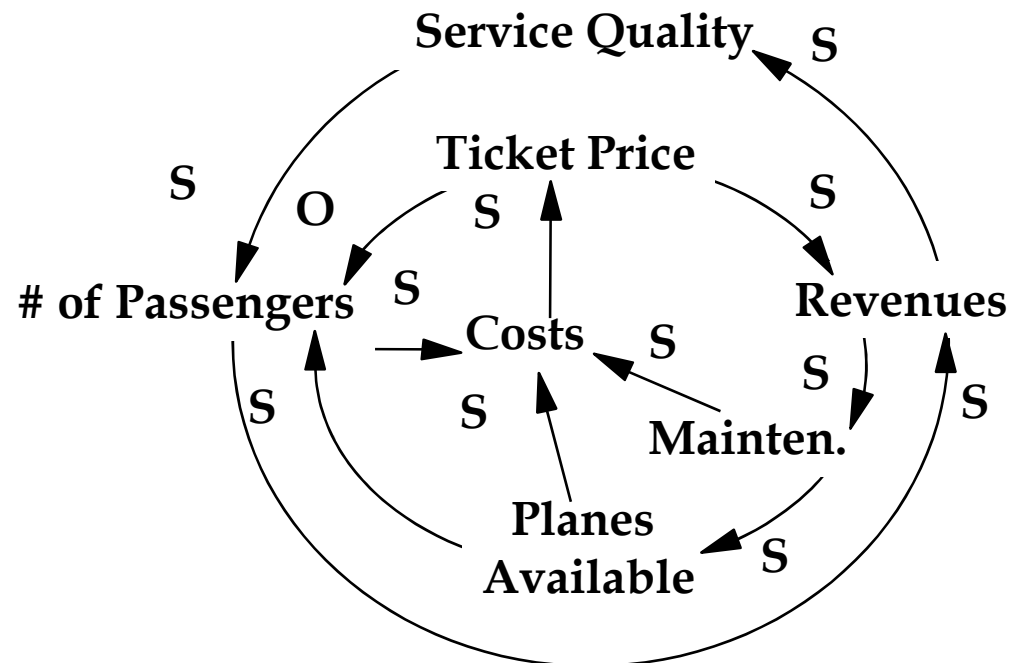
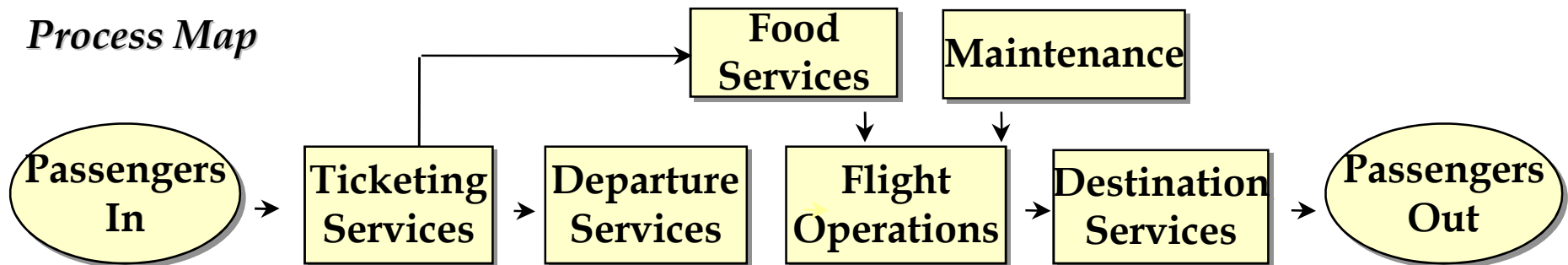
2. International attitudes towards piracy will encourage compliance to pirate demands thus increasing greed and attacks.



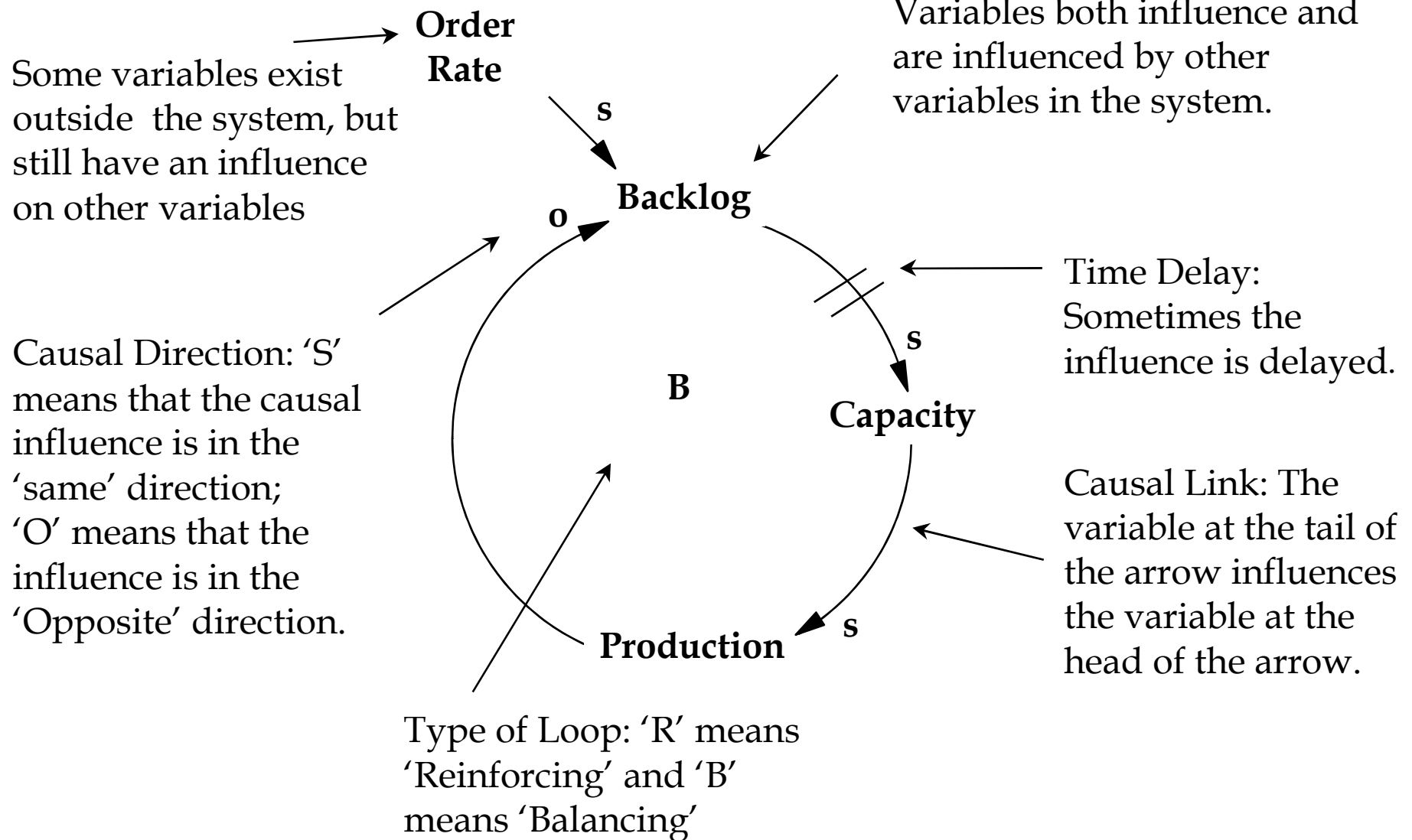
## Background on System Dynamics

# A "Process" versus a "System"

## Process Map



# Anatomy of a Causal Loop

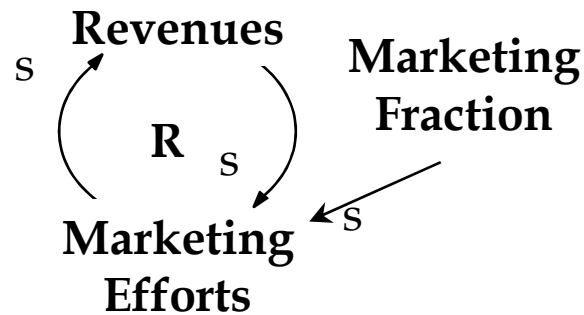




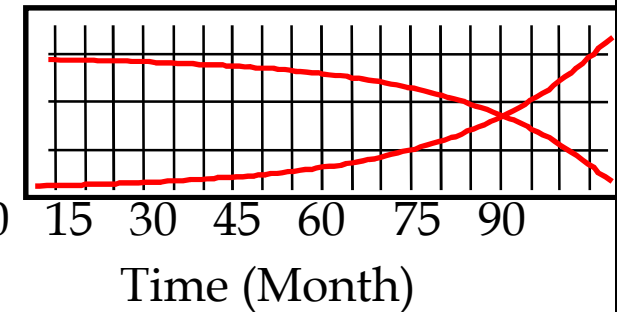
# Structures

# Patterns of Behavior

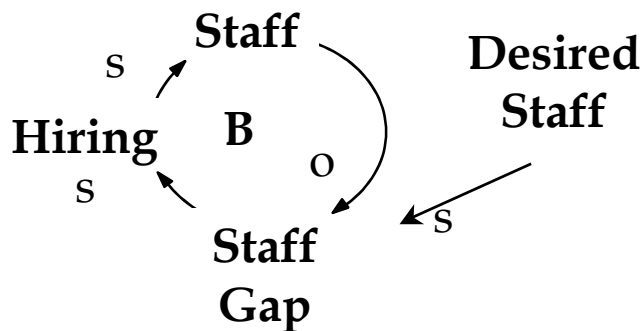
*Reinforcing Loop*



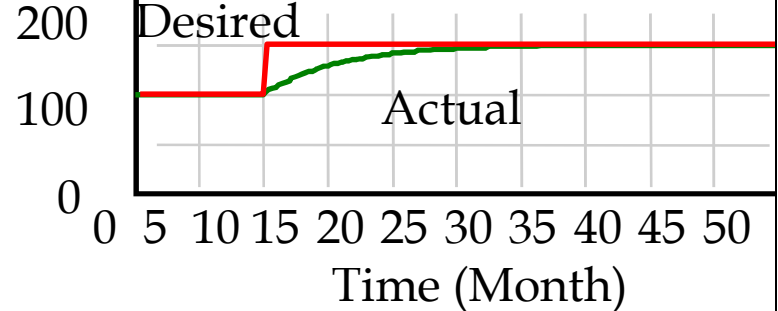
Sales  
60,000  
30,000  
0



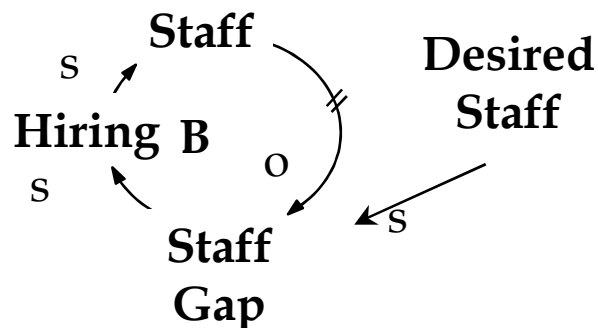
*Balancing Loop*



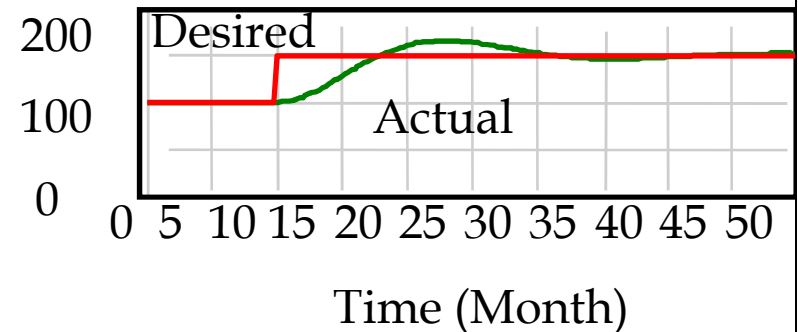
Staff Level  
Increasing



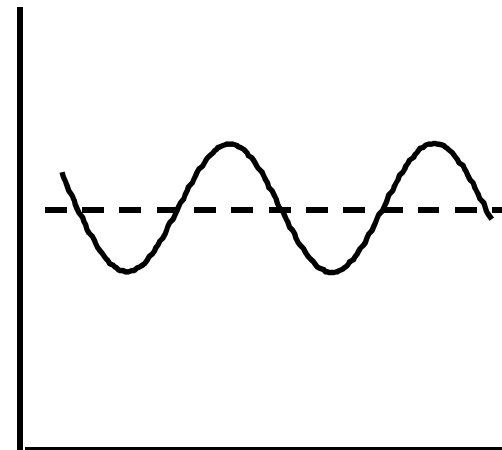
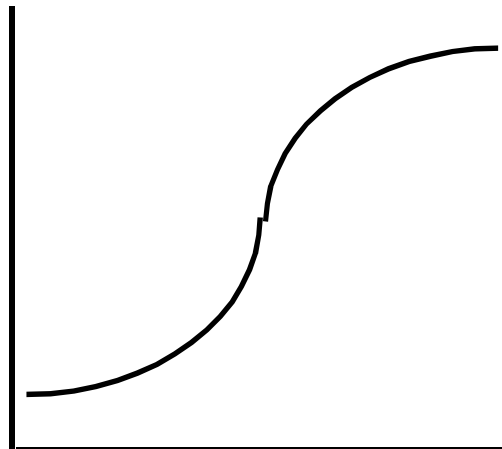
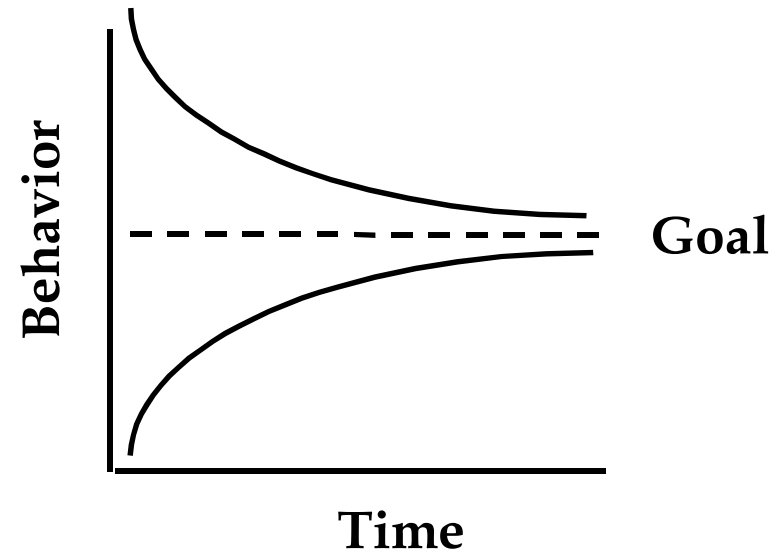
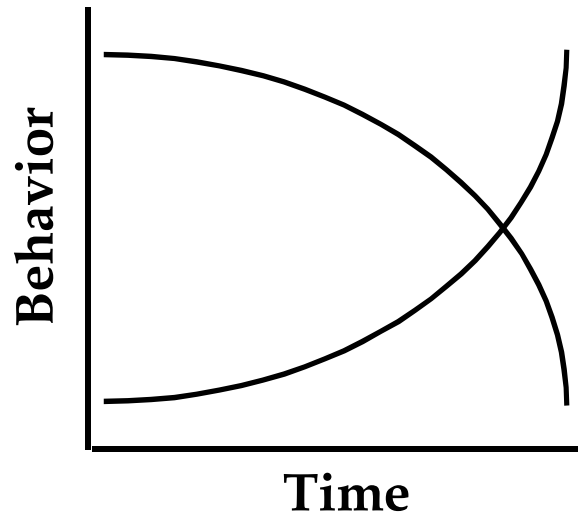
*Balancing Loop with a Delay*



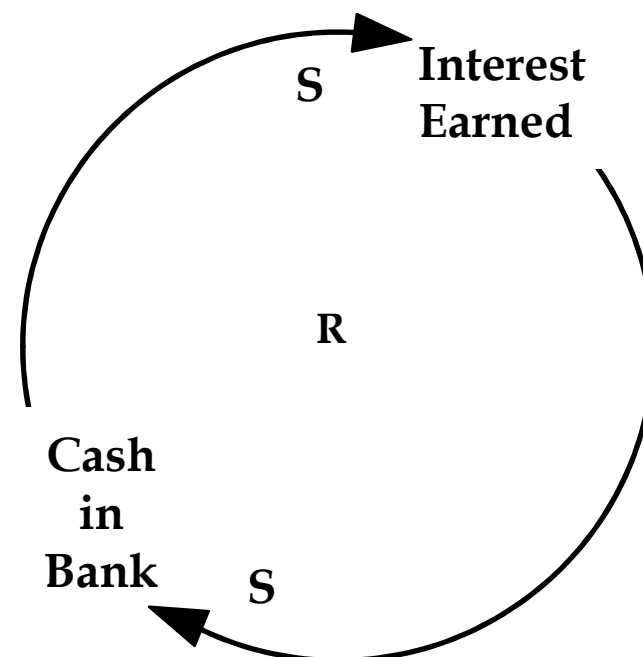
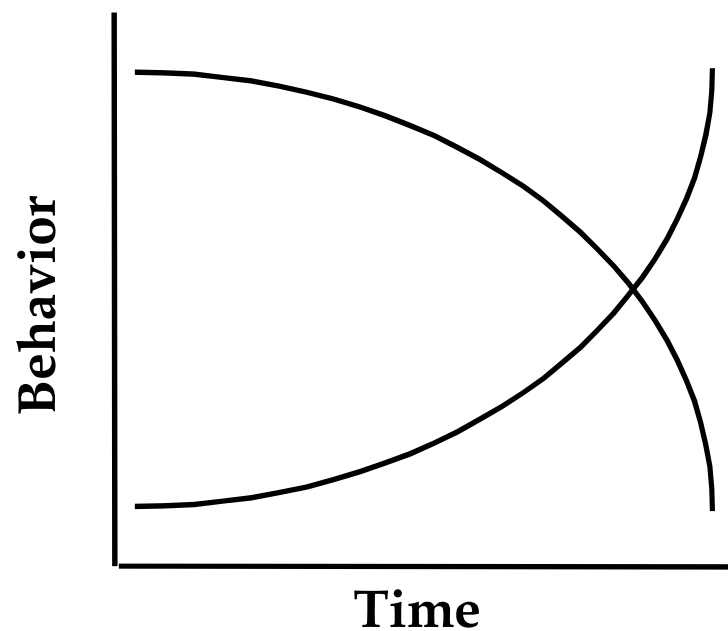
Staff Level  
Oscillating



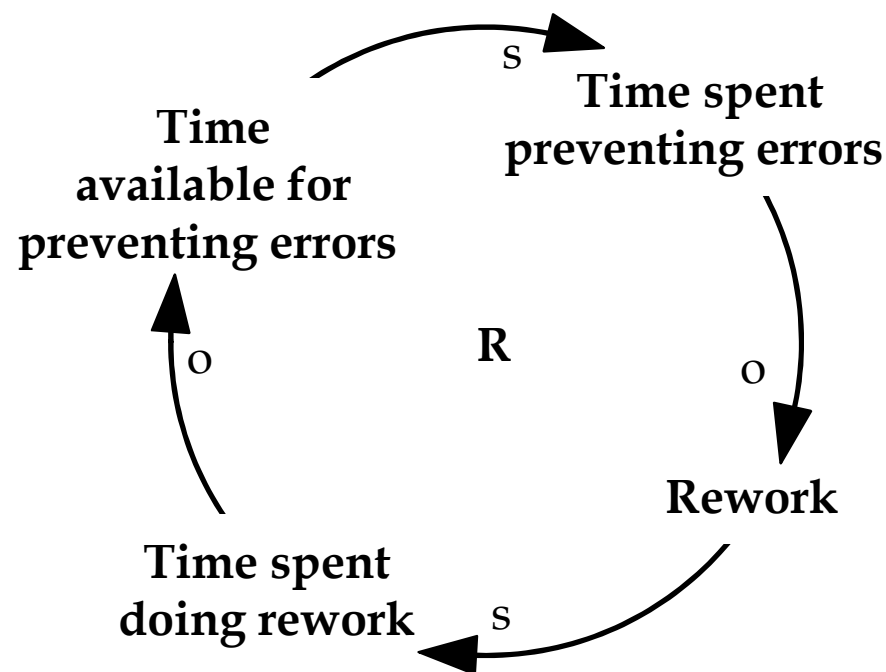
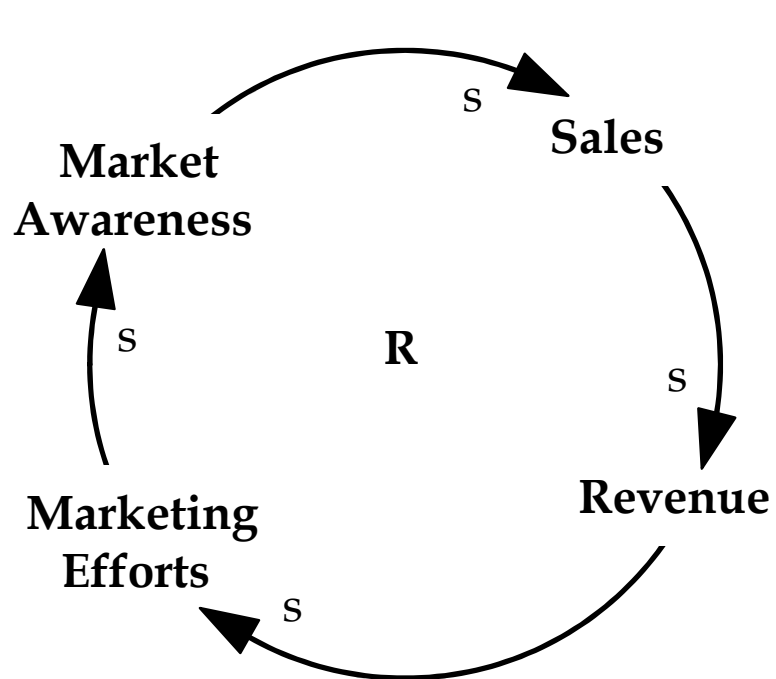
# Common Behavior Patterns in Business



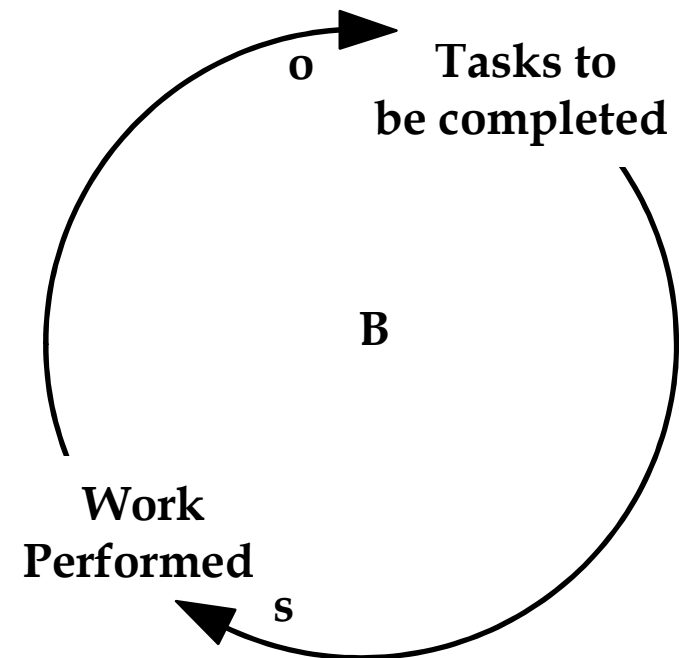
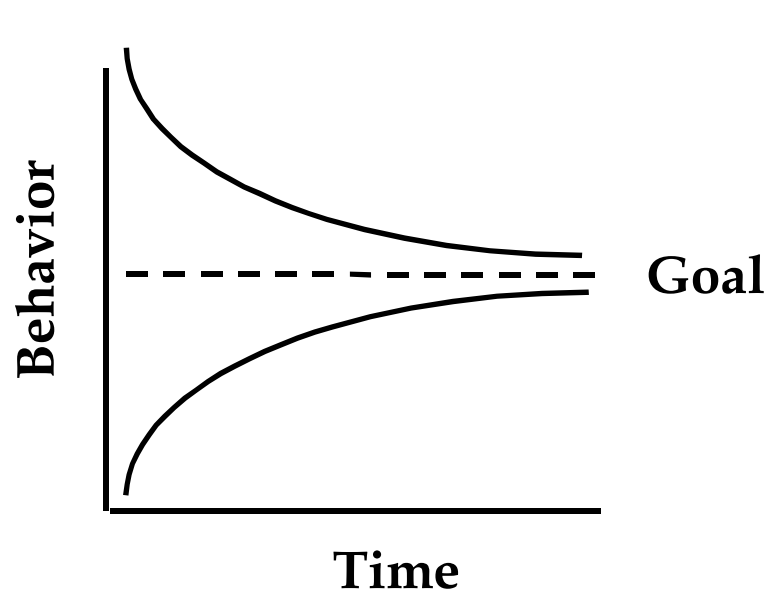
# Exponential Growth - Reinforcing Loop



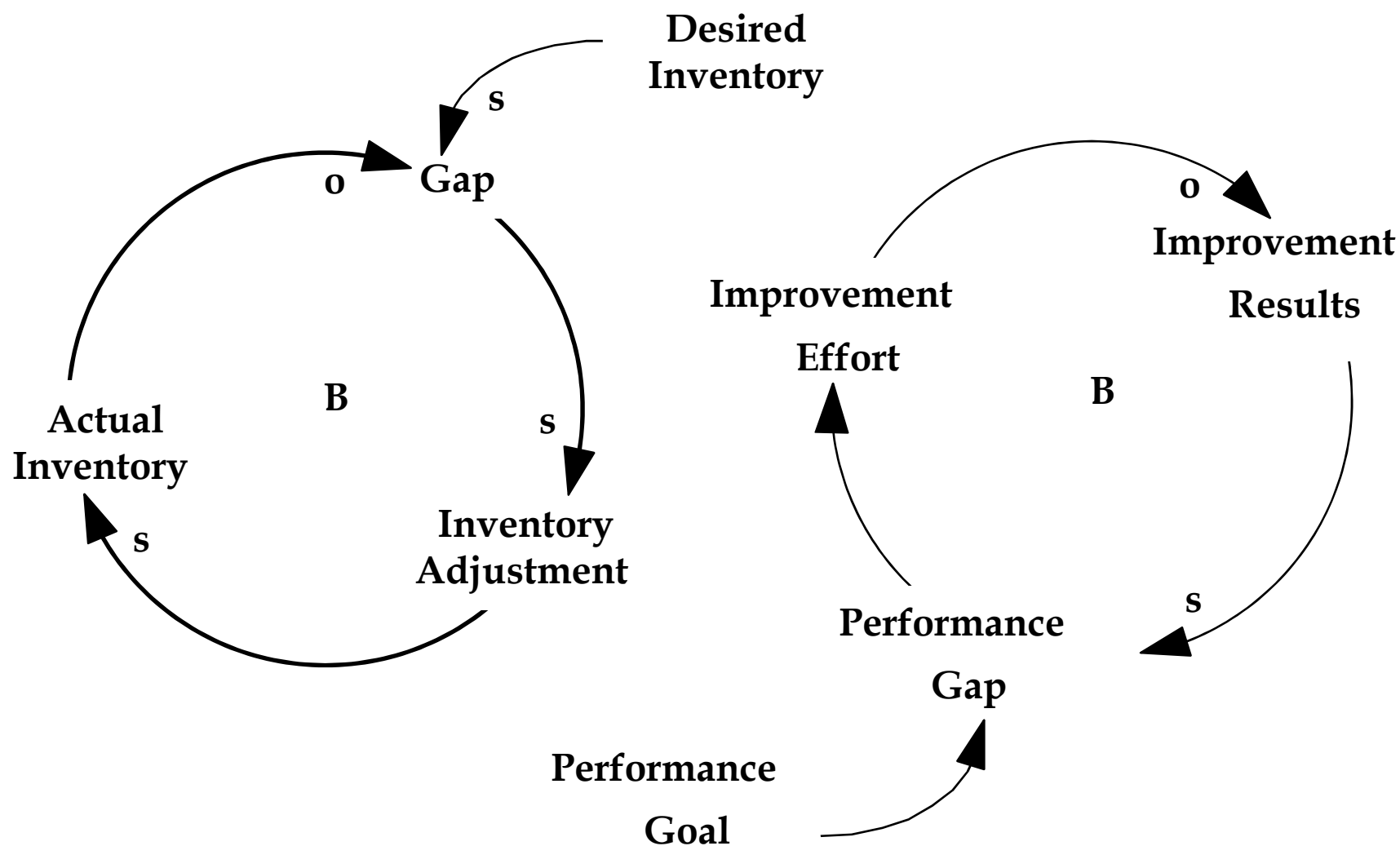
# Reinforcing Loops - Other Examples



# Goal-seeking Behavior - Balancing Loops



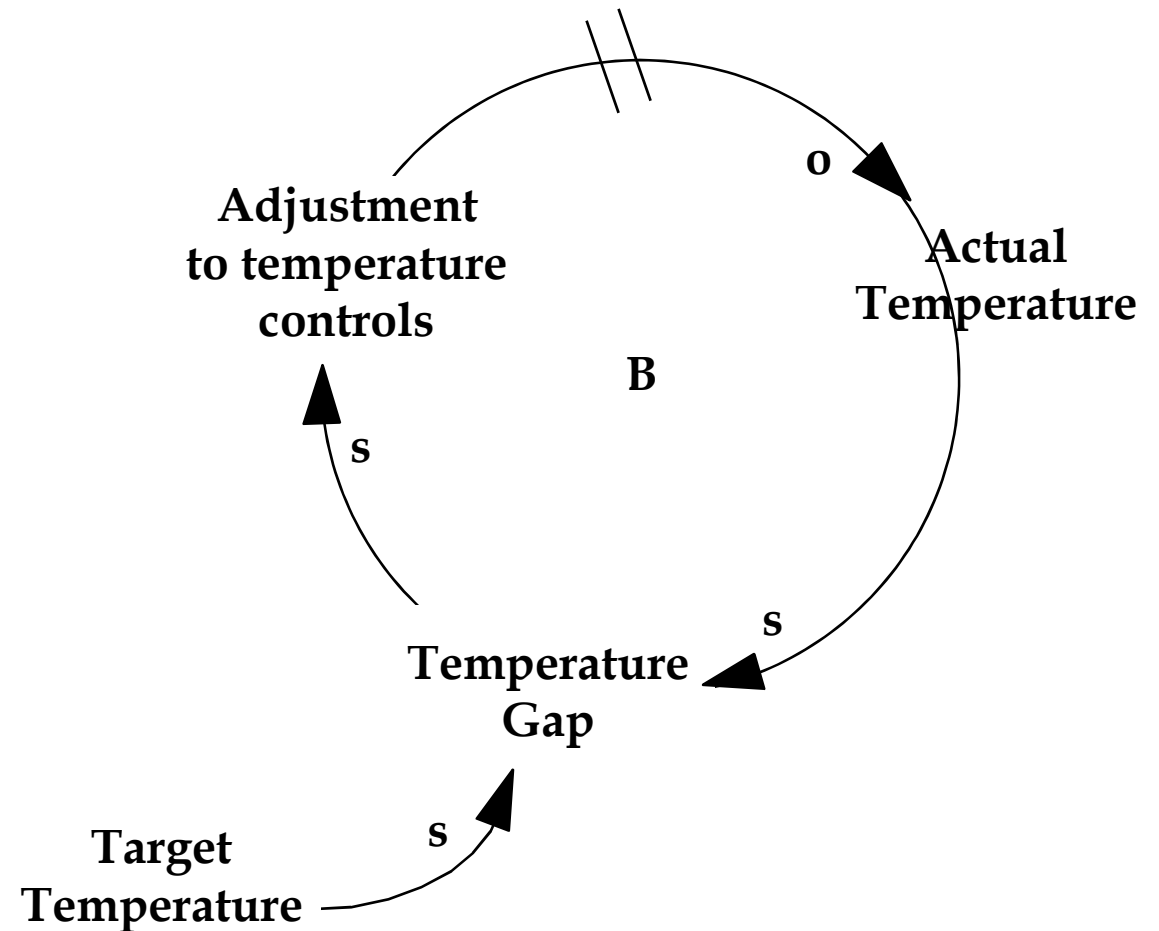
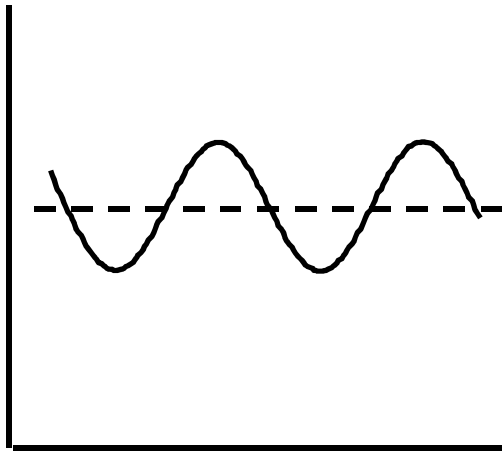
# Balancing Loops - Other Examples





# Balancing Loop

## Oscillating Behavior - with a Delay



# Balancing Loops w/Delays - Other Examples

