Systems: A Primer

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Purpose

To provide a visual and text-based introduction to systems.

Contents

Introduction

These notes provide some basic information about systems and applications of systems in a non-mathematical way.

System Basics

Thoughts on Models

Models are representations of reality, not reality itself.

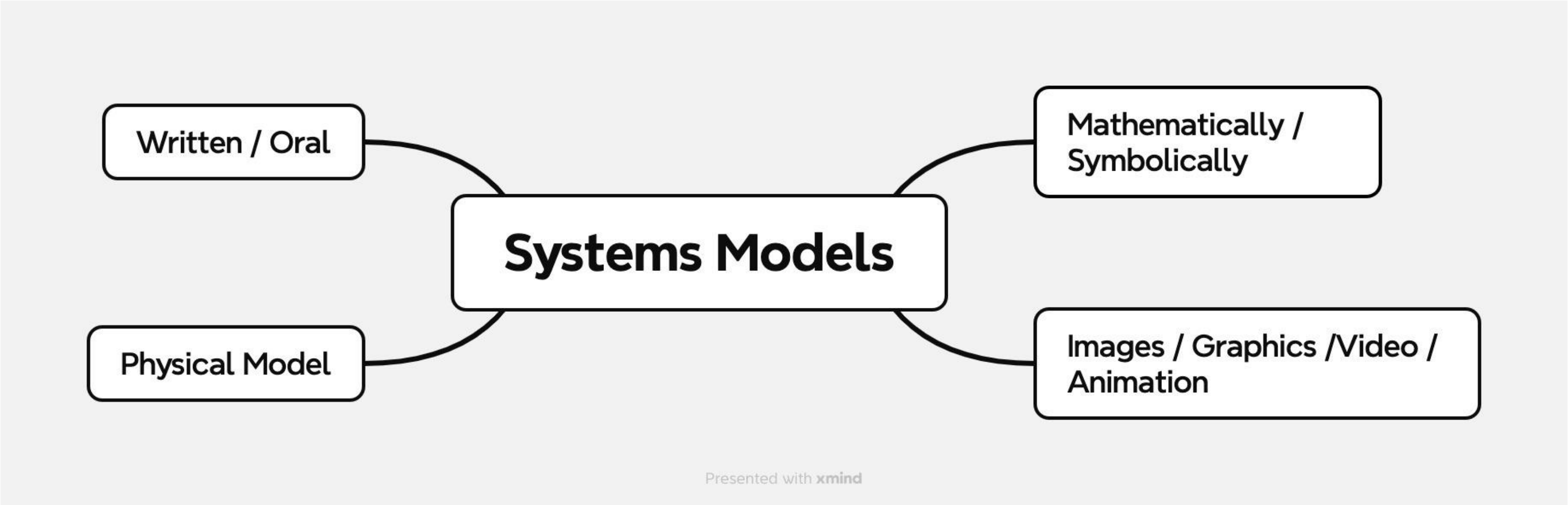
A map is not the territory.

"All models are wrong, but some are useful."

Attributed to George E. P. Box, a British statistician

Descriptions

Systems can be described or modeled in terms of:



A Written Description of a System

Early Definitions

- A **system** is a set of interrelated elements (agents) exhibiting behavior according to Meadows (2008).
  - Thus, three things are present: elements (agents), relationships between elements (agents), and some sort of behavior(s).
- According to Forrester (1971), a **system** is a set of components (or parts) that function together to achieve some purpose.

Definitions

Going Forward

- Component
  - A component is a contributing element of a system but is not a functional system such as a boundary or interface on a boundary.
- Structure
  - The arrangement, organization, or interrelationships of agents, components, and subsystems within a system.
  - It is essentially a blueprint of a system.
- Algorithm
  - A set of steps to do something such as performing a computation.
  - A recipe.

Definitions

Going Forward

- Subsystem
  - A subsystem is an interdependent system contained within a larger system.
- Agent
  - An interactive biotic or abiotic element that can make decisions and create or execute / follow an algorithm.
- Relation
  - A relation is a set of ordered pairs; for example:
    - Math: $a = b$, $a< b$, $a*b$
    - Language: Joan is a student, H_2O is a molecule

System

Written Definition

- System
  - A set of elements and their relations that exhibit behavior.
  - Elements may be agents, components, or subsystems.
  - Behavior of elements and relations is expressed in algorithms.
  - Relations include the interconnections, interactions, or dependencies among the elements
  - The arrangement or pattern of elements and their relations make up the structure of the system.

System

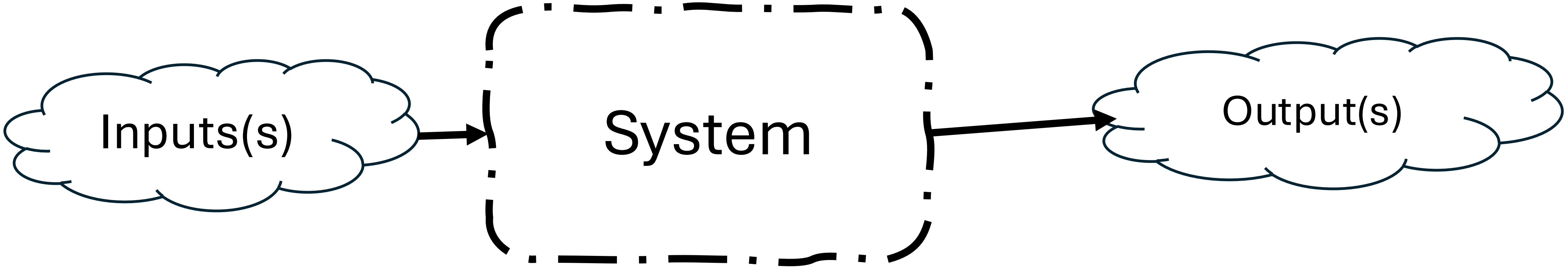
Mathematical Definition

- In set-theoretic terms,
  - A *system* **S** is a 3-tuple: S= {E, R, B}, where
    - E = {e_1, e_2, ... e_i}, a set of elements
    - R = {r_1, r_2, ...r_j}, a set of relations in S
    - B = {a_1, a_2,... a_k}, a set of algorithms that express behavior for E and R

Note: This set-theoretic definition is simplified from Mobus (2022) as it does not specifically include history, I/O, or a boundary, but these will be included later.

A Systems Model

Context Diagram (Image)

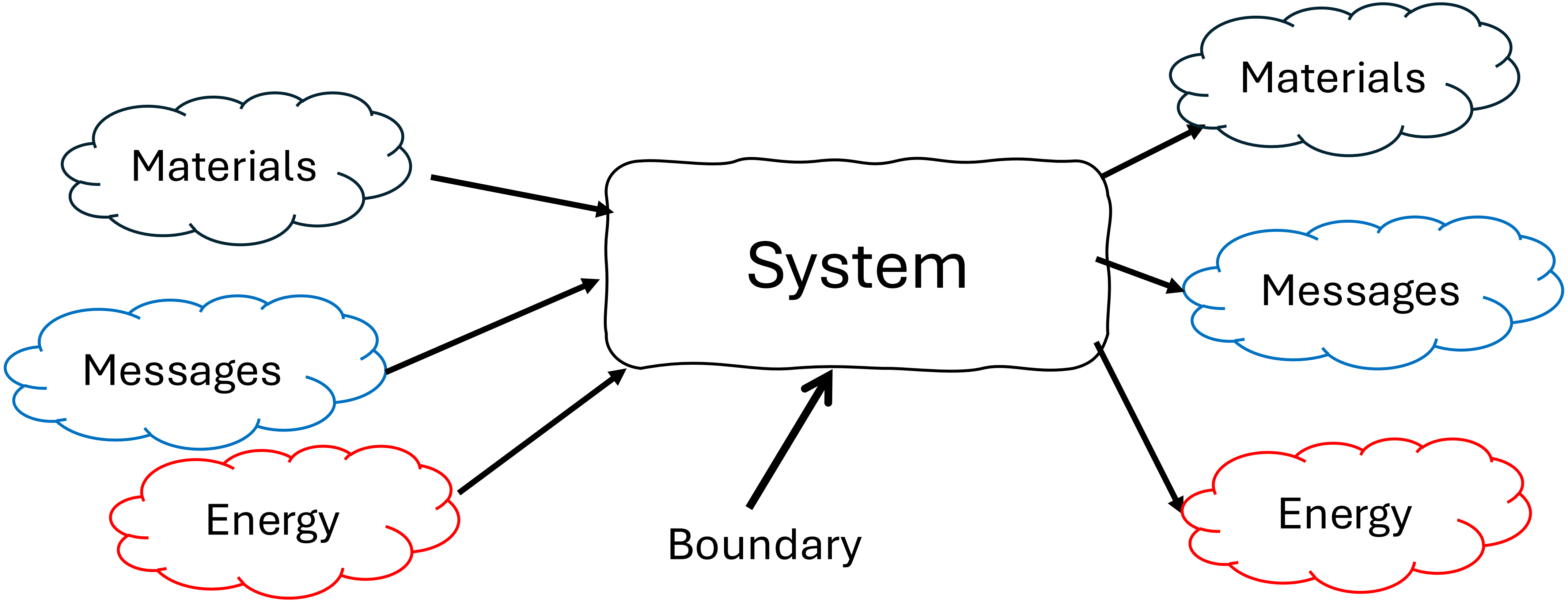


Input-Throughput-Output is a defining characteristic of systems.
Input / Output Categories are material, energy, and messages.
Throughput is the set of transition or transformation rules that map inputs to outputs.

- Inputs may transition or be transformed into outputs via algorithms.
- Throughput may be linear, non-linear, or chaotic at times.
- Throughput may be described by equation-based or agent-based models, causal loop diagrams, stock and flow diagrams, or other types of models.

Image Description

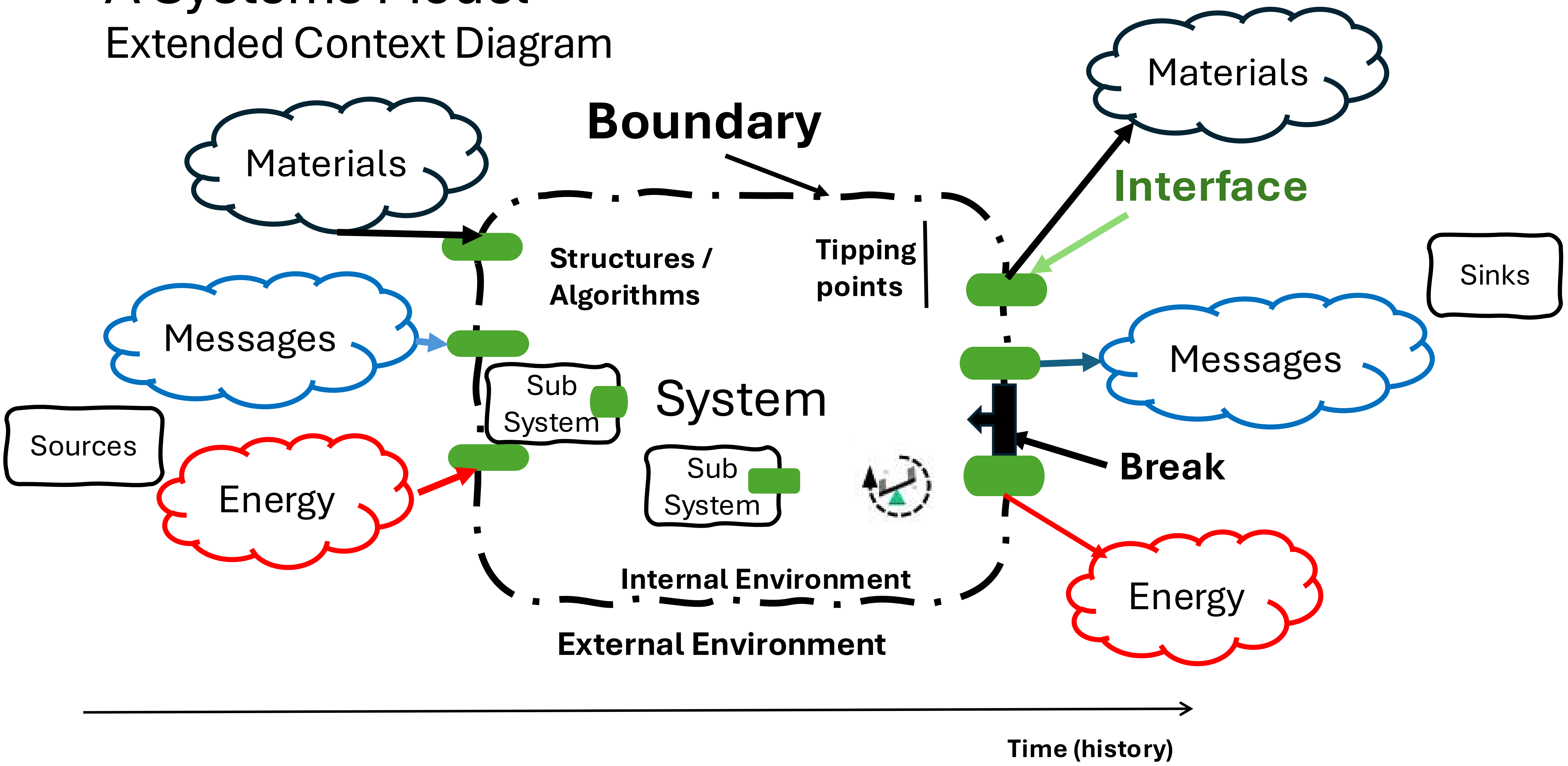
Expanded Context Diagram (Image)



Materials, Energy, and Messages are abbreviated MEM and are the fundamental categories of input and output.

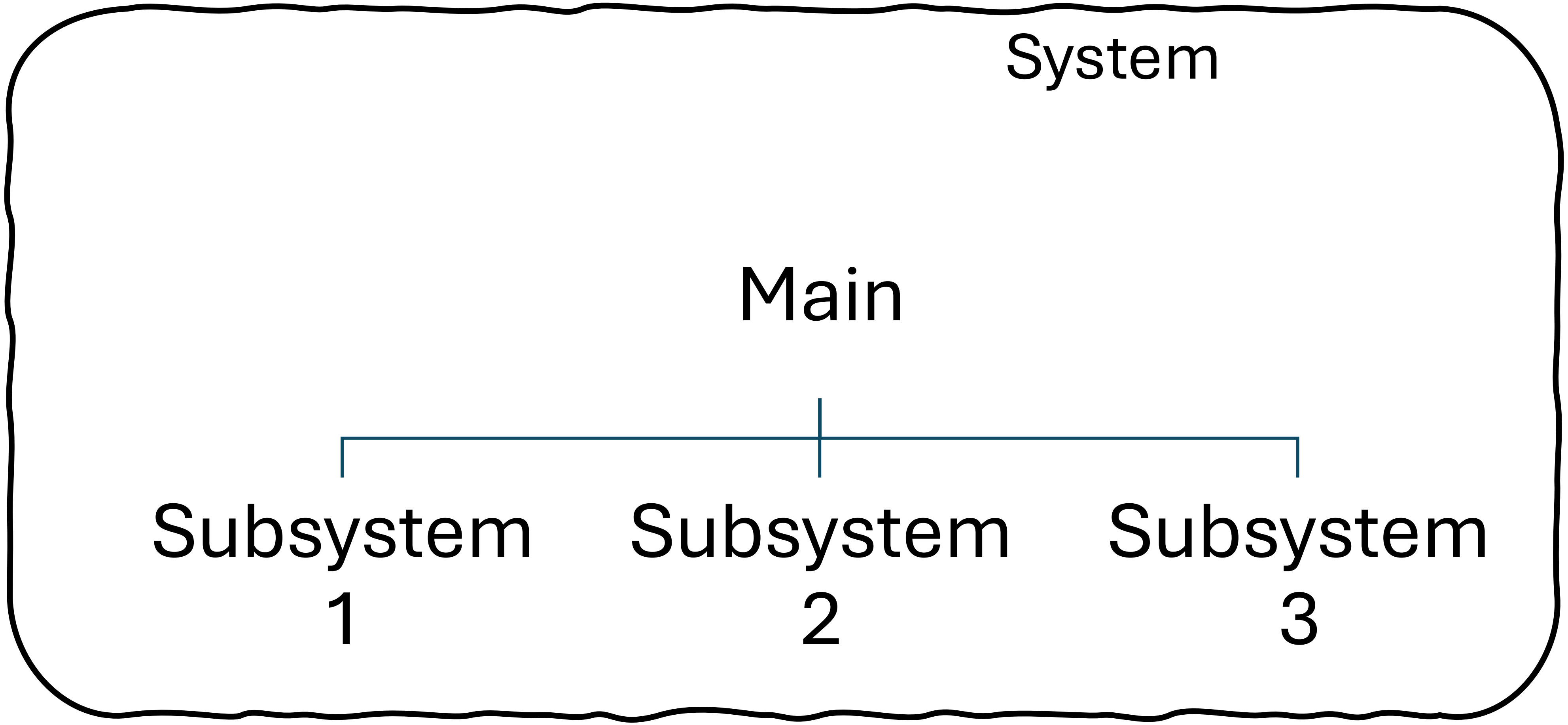
A Systems Model

Extended Context Diagram



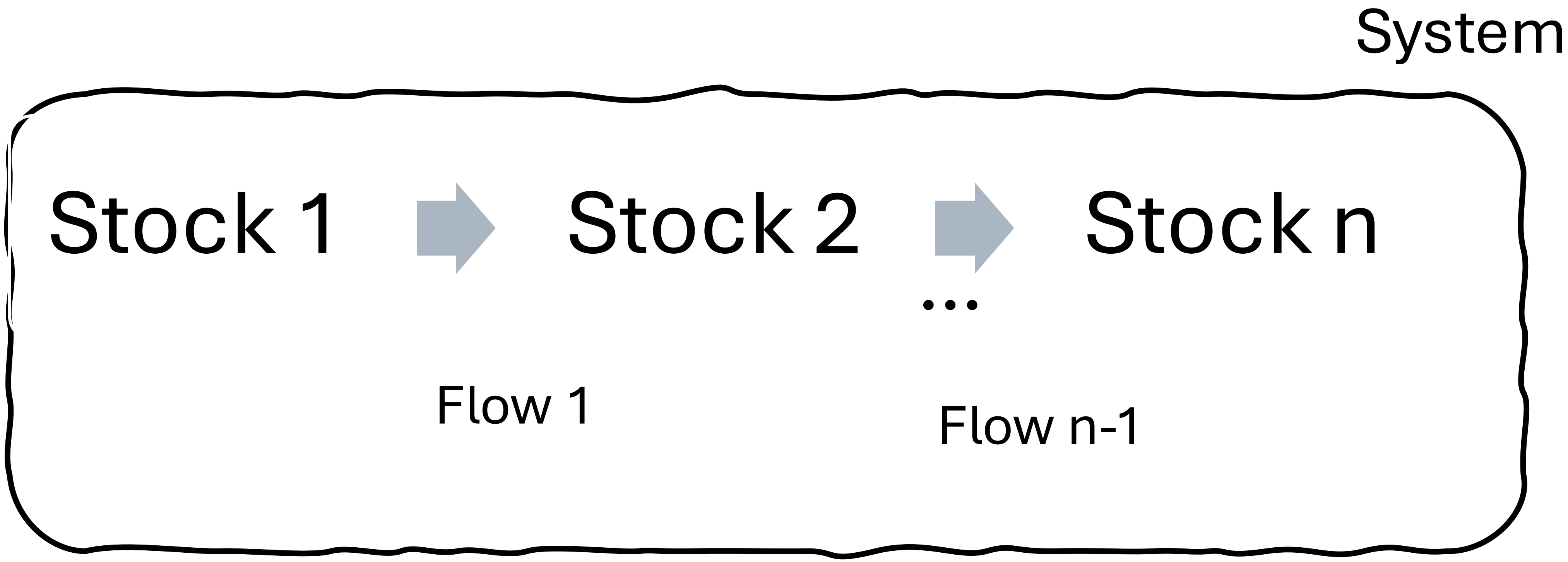
A Systems Model

Subsystems Within a System: An example of 3 subsystems



MEM flows from Main to Subsystems for processing as necessary.

A Systems Model
Stocks and Flows Within a System or Subsystem



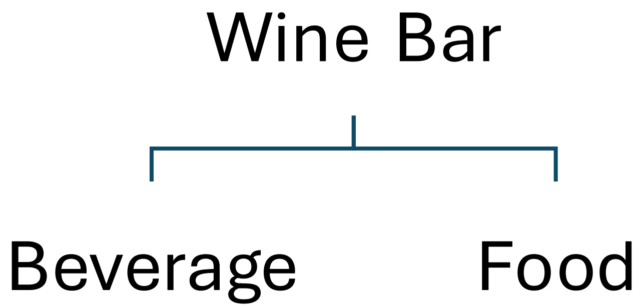
MEM flows from Stock 1 to Stock 2 to ... Stock n via Flows 1, 2, ... n-1

A stock is an accumulation of a resource: material, energy, or message

System

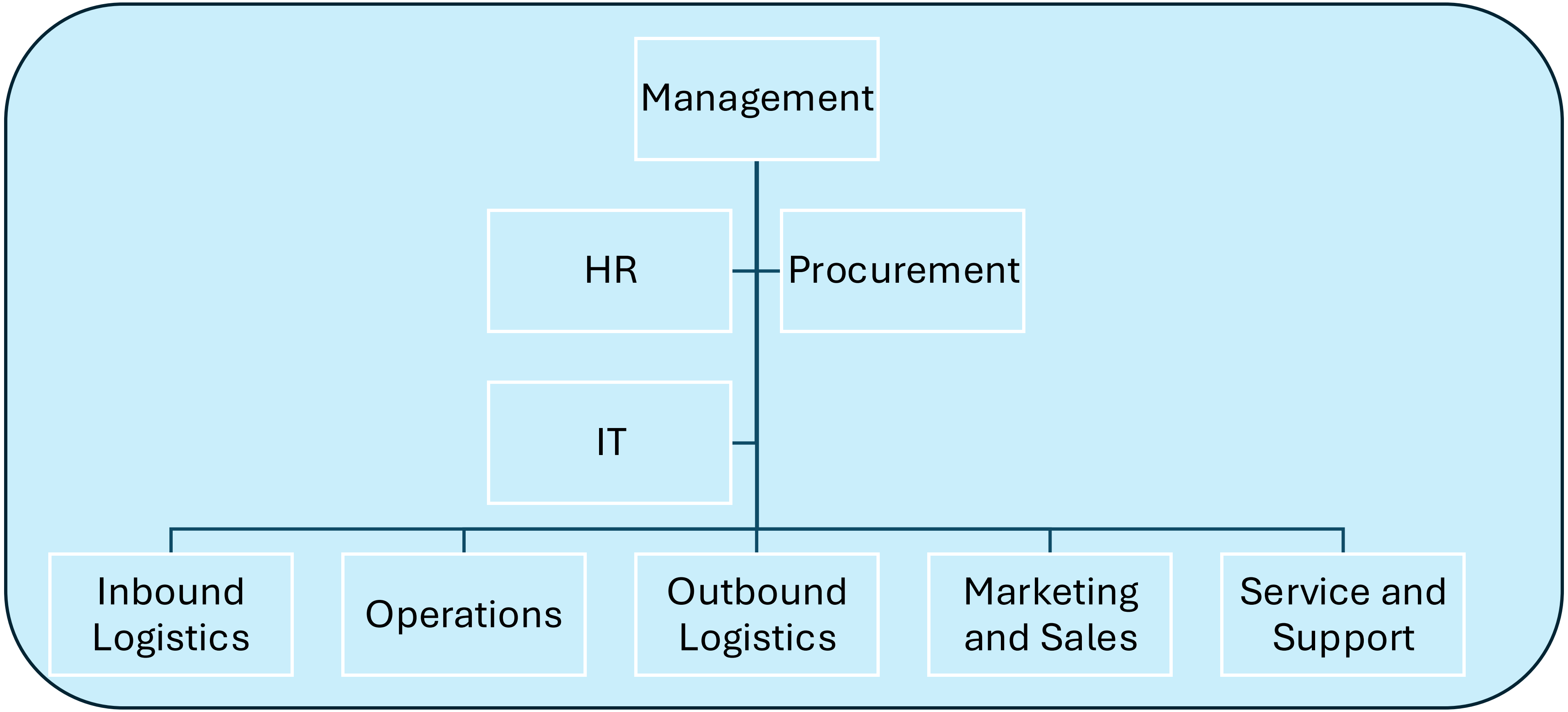
A Small Wine Bar Example

- This small wine bar is a system with several elements
  - Its boundary (a component) is the perimeter of the building.
  - Subsystems include the beverage and food service systems
  - The structure is a simple tree structure with the wine bar system at the top and the two subordinate subsystems
  - Interfaces include doors and windows
  - Algorithms for managing the system, HR, procurement, inbound logistics, operations, outbound logistics, sales and service and such describe behaviors. (adapted from Porter)



System

A Generic Business System Example



Subsystems are Management, HR, IT, ...

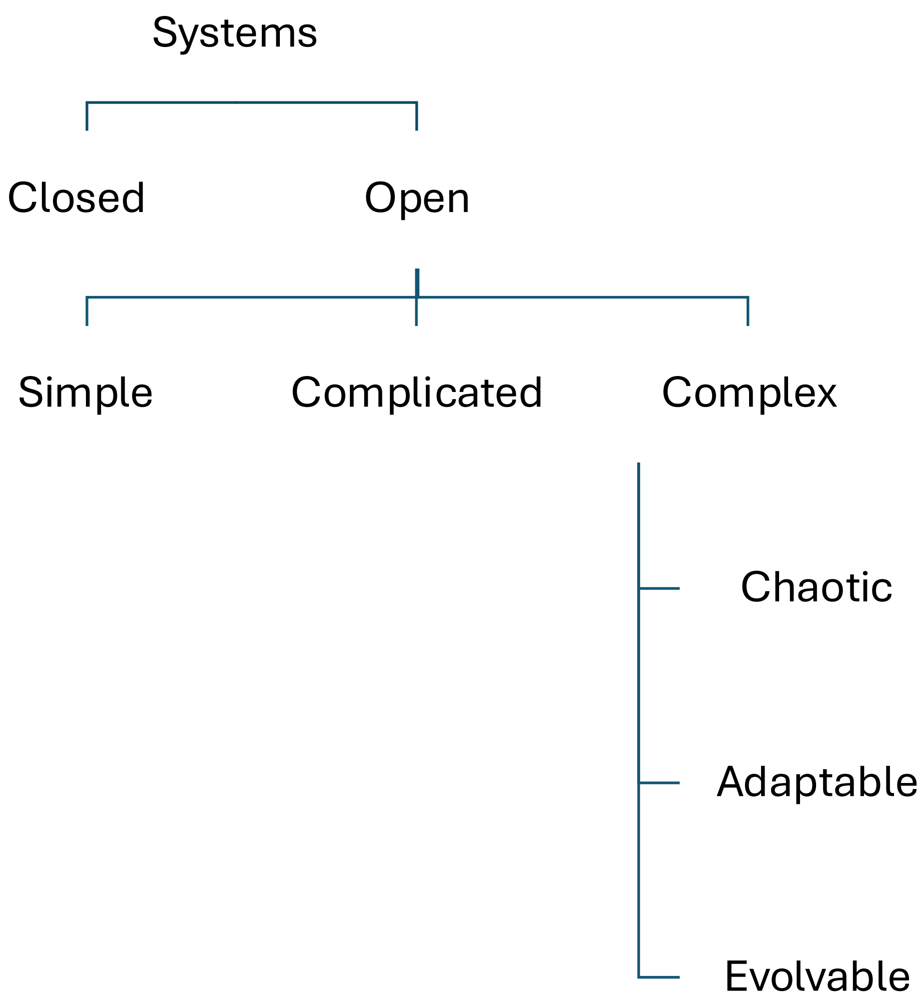
Adapted from Michael Porter

Systems

Four Basic Types of Systems with Examples

- Artificial
  - Artificial life
  - Buildings
  - Highways
  - Internet
  - Software
- Biological
  - Flora / Fauna
  - Ecosystems
- Natural
  - Atmosphere
  - Galaxies
  - Solar systems
- Social
  - Companies
  - Families
  - Military
  - Non-profits
  - Schools

Systems
Taxonomy



Systems
Taxonomy

- Closed systems
  - No exchange of material, energy, and messages with its environment
- Open systems
  - Exchange of material, energy, and messages with its environment
- Simple systems
  - Few parts, few linear interactions
- Complicated systems
  - Many parts, few interactions
  - Examples: Cars, airplanes, trains ..

Systems

Taxonomy

- Complex systems
  - Few to many parts, few to many nonlinear interactions
  - Examples: a jazz band, a business organization, a city, an ant colony, society
- Chaotic Systems
  - Dynamical systems exhibiting sensitive dependence on initial conditions (SDIC)
  - Examples: a pendulum, the weather
- Adaptive systems
  - Systems that learn and adapt
  - Examples: people, families, organizations, ecosystems, industries
- Evolutionary systems
  - Systems that are adaptable and undergo differentiation, selection, and replication
  - Examples: industries, species, the economy, technology, language

Systems

Theories and Disciplines That Make up Systems Science

- Chaos theory
- Complexity theory
- Cybernetics
- Evolution
- Information theory
- Network theory
- Psychology / neurobiology
- Social systems
- Systems dynamics
- Systems engineering

Mobus, G. E., & Kalton, M. C. (2015). *Principles of systems science*. Springer.

Components

Component

A component is a contributing element of a system but is not a functional system.

The boundary of a system is a component for example.

Boundary

- Separate a system from its environment
- May change, contract, disappear, evolve, expand, reappear, rearrange, … at times.
  - That is, boundaries may be nonstationary.
- May be conceptual, fluid, fuzzy, permeable, porous, regular, irregular, permanent, semipermeable, solid, temporary
- May be for protection, safety, containment
- May be thick, thin, have multiple layers
- May have breaks, tears, or holes in it.
  - That is, not an interface for normal I/O.
  - Consider a fence or wall with holes cut through it
- Includes one or more interfaces (i.e., entry or exit point) for material, energy, and messages.

Interface

- Interfaces are components on the boundary of a system
  - A door to a car or home is a simple interface
- Interfaces do not alter the content, shape, or size of the inputs or outputs
- Interfaces include information for entry/exit of material, energy, and messages.
  - Some considerations include cost, frequency, quality, quantity, shape, size, time, type …

Interface

- Entry/exit rules to/from a system may be described algorithmically
- Entry/exit may require going through several interfaces and steps
  - In each case, material, energy, or messages entering/exiting would not be changed.
  - However, whatever enters/exits must fit within the size of the interface.
- Potential inputs/outputs may be vetted, filtered, ... before entry/exit approved
  - Examples: Software logins are vetted before approval, entry to secure facilities or private facilities must be approved, organisms must be fit (vetted for life).

Interface

Algorithm Entry Example for Secure Facility

1. Drive a circular driveway to a gate (interface on a boundary)
2. Show credentials
3. Drive to a parking lot
4. Walk to the building
5. Enter door (interface on another boundary)
6. Stop for security
7. Place all carry-on belongings on a belt for security scanning (another interface)
8. Walk past security
9. Pick up belongings
10. Walk to office

Structures

Structure

The arrangement, organization, or interrelationships of agents, components, and subsystems within a system.

It is essentially a blueprint of a system.

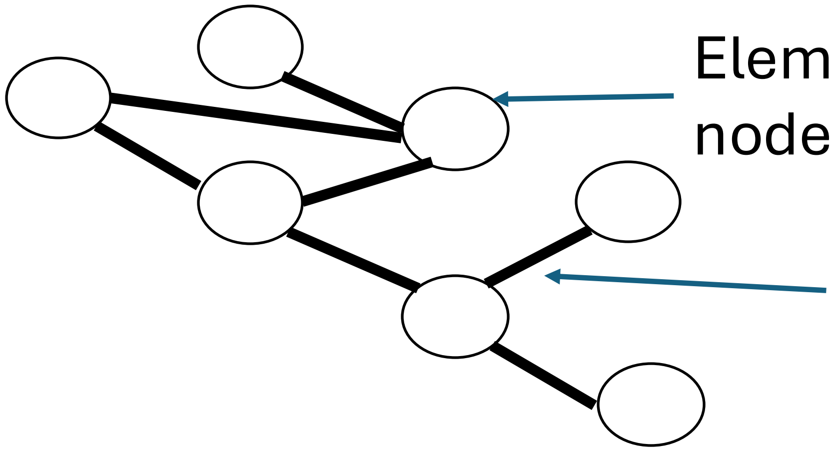
Structures

- A structure refers to the arrangement or network of relationships between agents, components, and subsystems within a system.
- Essentially defines how the parts are connected and interact with each other.
- Structures either store or reference stored resources.

Structures

Networks

A **network** is a set of elements (agents, components, nodes, parts) and links (relationships).



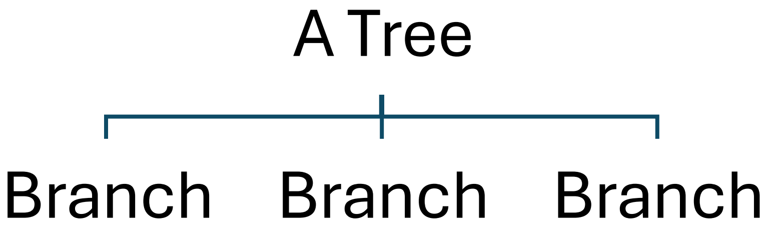
Elements (agents, components, nodes, parts ...)

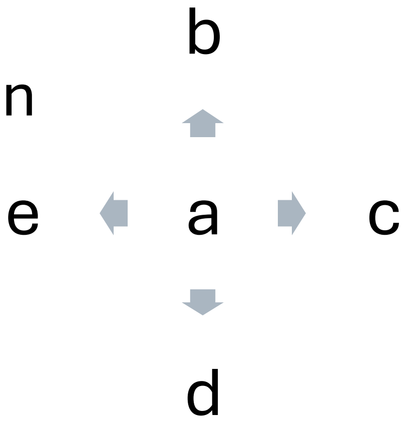
Links (relationships)

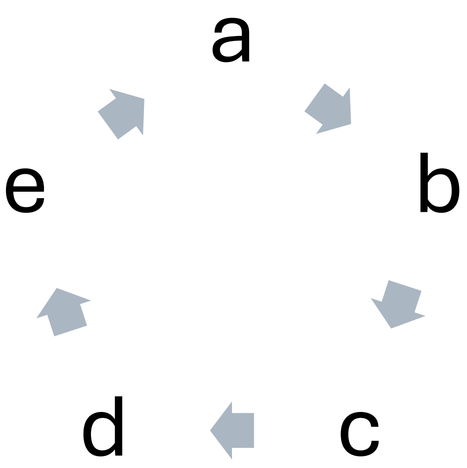
Structures

Network Typologies

1. Bus
2. Fully connected
3. Hierarchical (tree)
4. Linear (line)
5. Mesh
6. Ring
7. Star
8. Some combination





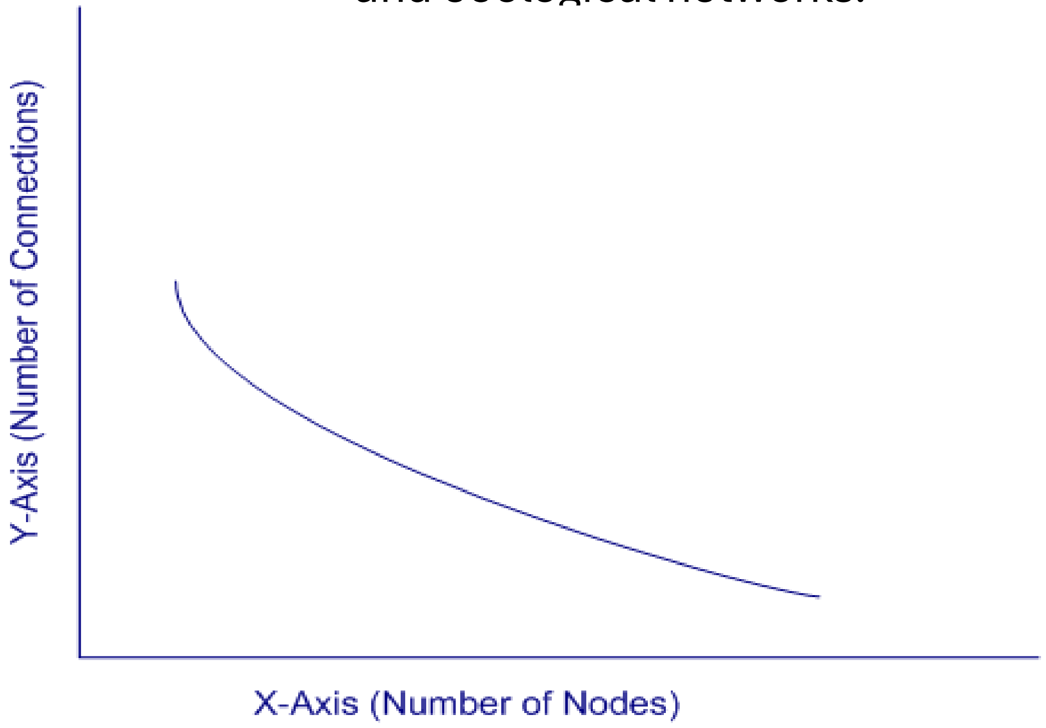


Networks
Scale Free

Scale free networks are characterized by a few nodes having large numbers of connections while most nodes have considerably fewer connections. This distribution follows a power law.

Examples of scale free networks include social networks, the Internet, and ecological networks.

Scale free networks are robust against accidental or random failure; however, they are vulnerable to targeted destruction.



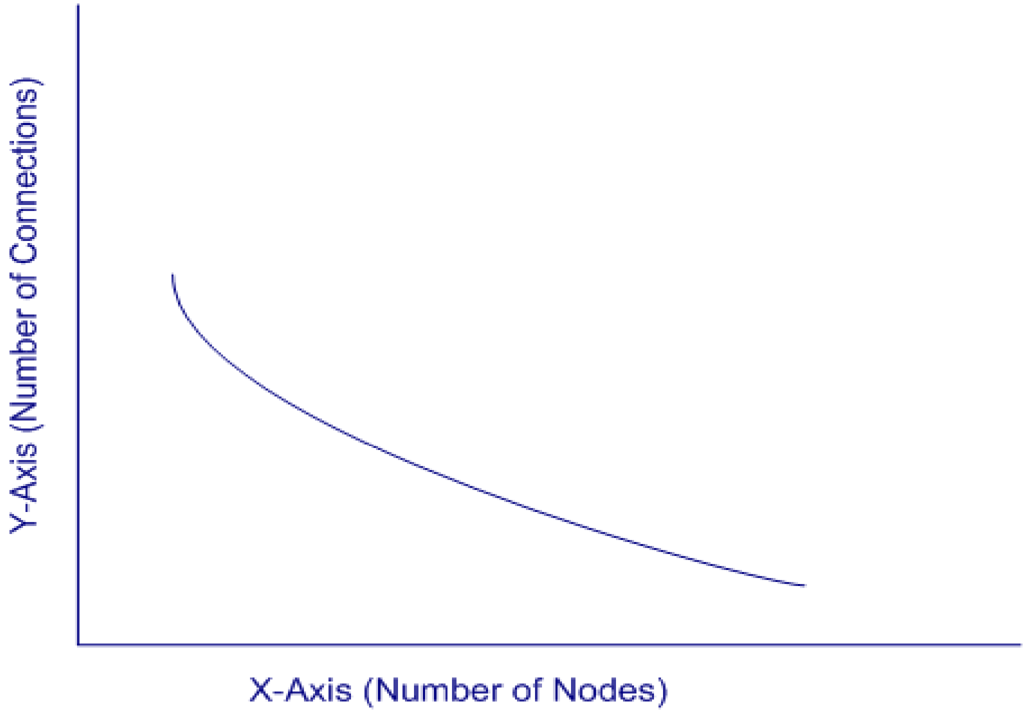
Buchanan, M. (2002). *Nexus: Small worlds and the groundbreaking science of networks*. W.W. Norton & Company

Networks

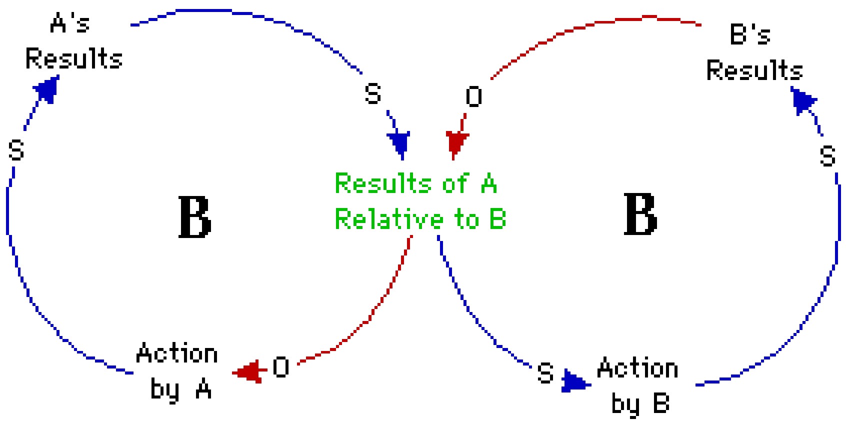
Scale Free

This graph represents the power law or a scale free network distribution.

In terms of human populations, non-behavioral attributes such as height or weight typically follow a bell shaped curve, while behavioral attributes such as wealth accumulation, popularity, and such follow the power law.



Success to the successful Archetype



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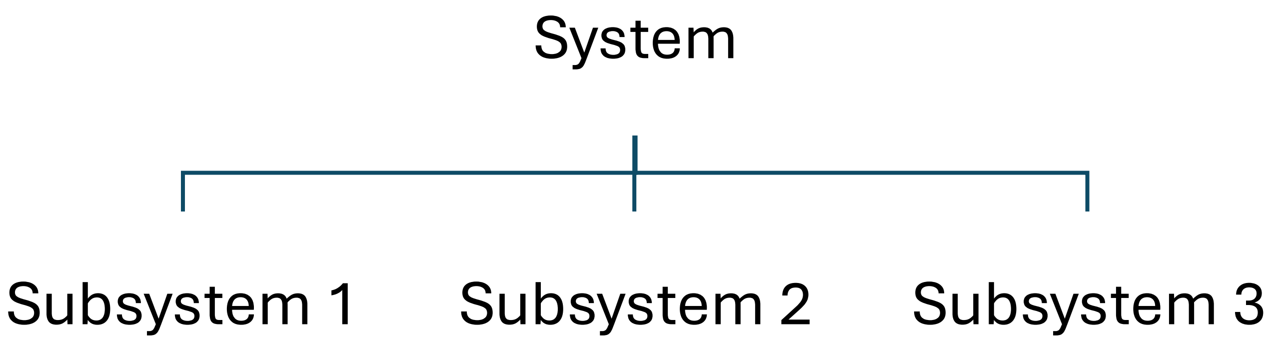
Structures

Hierarchical (tree) System with two Levels and Three Subsystems



Systems may be functionally deconstructed as practical.

System Boundary: Boundaries may be fixed, permeable, semipermeable, porous ...

Algorithms

Algorithm

A set of steps to do something such as performing a computation.

A recipe.

Algorithms are created and/or executed/followed by agents.

Algorithms

Definitions

- Algorithms in simple terms are recipes.
  - Algorithms are as Berlinski (2000) noted, “a finite procedure, written in a fixed symbolic vocabulary, governed by precise instructions, moving in discrete steps 1,2,3, …., whose execution requires no insight, cleverness, intuition, or perspicuity, and that sooner or later comes to an end.”
- Algorithms are a set of instructions to process input **data** to solve a problem or complete a task.

Algorithms

Relaxed Definition

- Generalizing by relaxing the conditions that algorithms are just about **data** and precision and more like a recipe for processing **material** or **energy** gives:
  - **An algorithm is a set of steps to do something**.
- Data and information can be generalized to messages.

That is, an algorithm is a set of steps, $A = \{s_1, s_2, \ldots s_n\}$ that transform input MEM to output MEM.

Algorithms

Rules are Information

- Algorithms are rules are information are messages
- Rules may be in the form of {If then else, Iteration, Assignment}
- For example:
  - If (customer walks in the door) then (greet), else (continue working)
  - Do (something) while (true)
  - Assign the value 2 to variable A
- Rules exist for the use or consumption of resources, where use means use without changing the resource and consumption means use and changing the resource
  - Resources such as cooking utensils are USED in cooking and can be reused.
  - Resources such as ingredients are CONSUMED in the cooking and cannot be reused.

Algorithms

Encode Rules to

- Obtain source inputs to the system / subsystems
- Manage system interfaces
- Navigate structures
- Store inputs (in stocks)
- Manage components and subsystems (in / out)
- Store intermediate MEM processing in stocks
- Transform inputs to outputs
- Store outputs (in stocks)
- Express outputs from the system / subsystems to sinks

Algorithms

Behavior

- A systems behavior can be described via structures and algorithms / programmatically).
  - ➢Structures and algorithms can be described in a tabular format (such as in relational data base)
    - Input MEM flows (external)
    - Output MEM flows (external)
    - Process MEM flows (internal)
    - Structural typology
  - ➢Behaviors may be described via causal loop diagrams, stock and flow diagrams, mathematically, or programmatically.
    - Systems dynamics

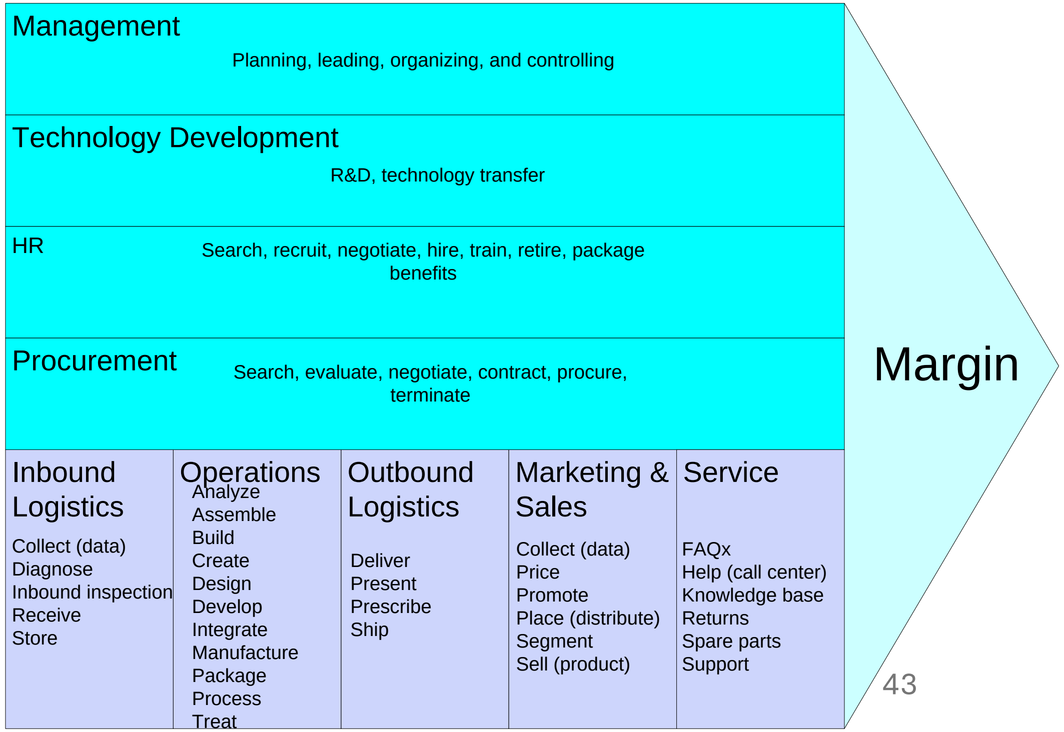
Algorithms

Examples from a Business Organization

Porter's value chain model includes these categories or processes, which can be described via algorithms.

- Management
- Technology
- Human Resources
- Procurement
- Inbound Logistics
- Operations
- Outbound Logistics
- Marketing and Sales
- Service

Generic Value Chain



Algorithms
Examples

- Algorithms can also describe:
  - Consumption of resources
  - Economic health (e.g., financial ratios)
  - Flow of material, energy, and messages
  - Internal and external system networks
  - Movement over time
  - Product/service design
  - Rules for interface function
  - Transformation (inputs to outputs)
  - Transition (inputs to outputs)
  - Use of resources

Algorithms

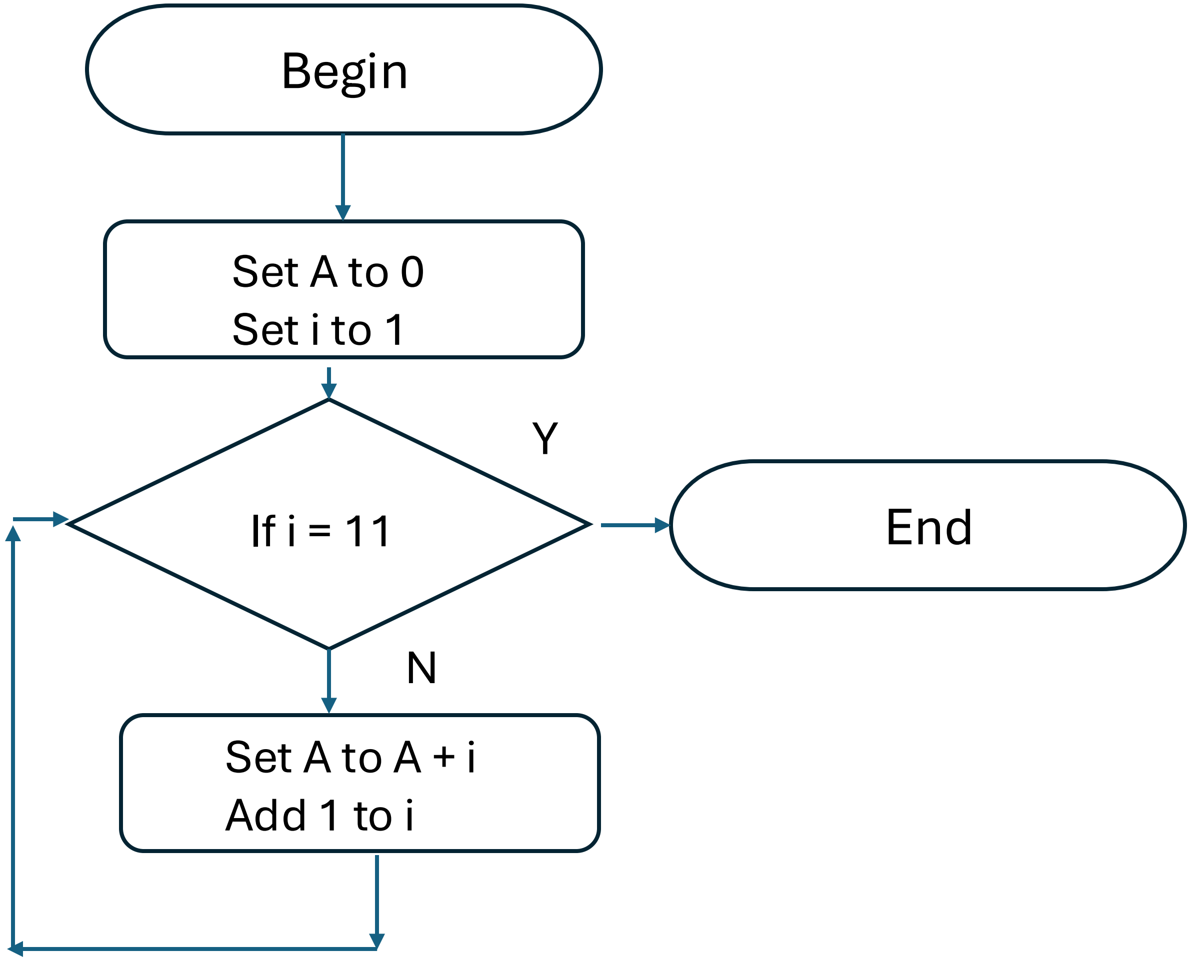
Expressed in Code

Algorithms (systems behavior) can be expressed in code, such as:

- C, C++
- JavaScript
- NetLogo
- Python
- Or almost any programming language

Algorithms

Flowchart for Summing the Numbers 1-10



Algorithms

Pseudocode for Summing the Numbers 1-10

```
Set A to 0
Set i to 1
Loop
    If i = 11, then Stop
    Set A to A +i
    Add 1 to i
End
```

An algorithm is a set of steps to do something. In this case:

$A = \{s_1, s_2, \ldots s_n\}$

S_1 = Set A to 0

S_2 = Set i to 1

And so on.

Algorithms

C Code for Summing the Numbers 1-10

Here is a simple C program that calculates the sum of numbers from 1 - 10:

```
#include <stdio.h>
int main() {
   int sum = 0;
   for (int i = 1; i <= 10; i++) {
      sum += i;
   }
   printf("The sum of numbers from 1 to 10 is: %d\n", sum);
   return 0;
}
```

This program initializes a sum variable to 0, then uses a for loop to iterate through the numbers 1 to 10, adding each number to sum. Finally, it prints the total sum.

Algorithms
Examples

- Artificial
  - Compute
  - Copy
  - Delete
  - Evolve
  - Insert
  - Read / Write
  - Search
  - Sort
  - Update
  - Transform

- Biological
  - Birth / Death
  - Develop
  - Evolve
  - Grow / Shrink
  - Movement
  - Reproduce
  - Transformation
  - Transition

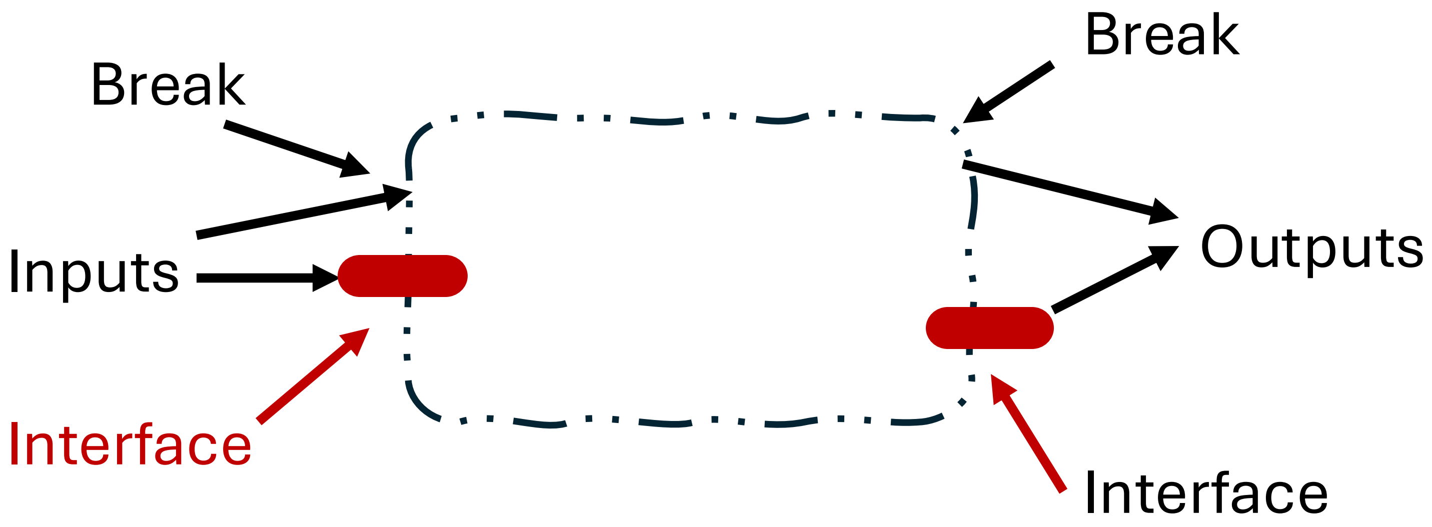
Algorithms
Examples

- Natural
  - Birth / death
  - Evolve
  - Grow / shrink
  - Merge / split
  - Movement
  - Transformation
  - Transition
- Social
  - Birth / death
  - Copy
  - Evolve
  - Grow / shrink
  - Merge / split
  - Transformation
  - Transition

Inputs-Throughputs-Outputs

Material, Energy, Messages (MEM)

- Inputs (material, energy, and messages) from external sources enter a system via its boundary interfaces or breaks in the boundary.
- Input material, energy, and messages are then transformed or transitioned to output material, energy, and messages while they flow through a system.
- Outputs (material, energy, and messages) to sinks exit a system via its boundary interfaces or breaks in the boundary.



Material, Energy, Messages Flow

Flow Possibilities

- One-to-many or divergent or one type of MEM may flow to multiple processes. For example, sugar may be used in creating multiple pastries.
- Many-to-one or convergent or many types of MEM may flow to one process. A bakery for example may take flour, sugar, salt, chocolate chips among other food products to make chocolate chip cookies.
- Many-to-many or multiple types of MEM flow to multiple processes. For example, flour, sugar, salt, and so on are used in multiple pastries.
- One-to-one or linear flow of a type of MEM to one process after another (think assembly line).
- Some flows cycle within a system or between systems, such as recycling of materials.

Materials, Energy, Messages

Examples

- Material to/from systems such as:
  - Chemical elements
  - Nutrients
  - Water
- Energy to/from systems such as:
  - Electricity
  - Heat
  - Sunlight
- Messages / information to/from systems such as:
  - Email
  - Expenses
  - Images
  - Light
  - Money
  - Music
  - Revenue
  - Sound
  - Videos

Throughput

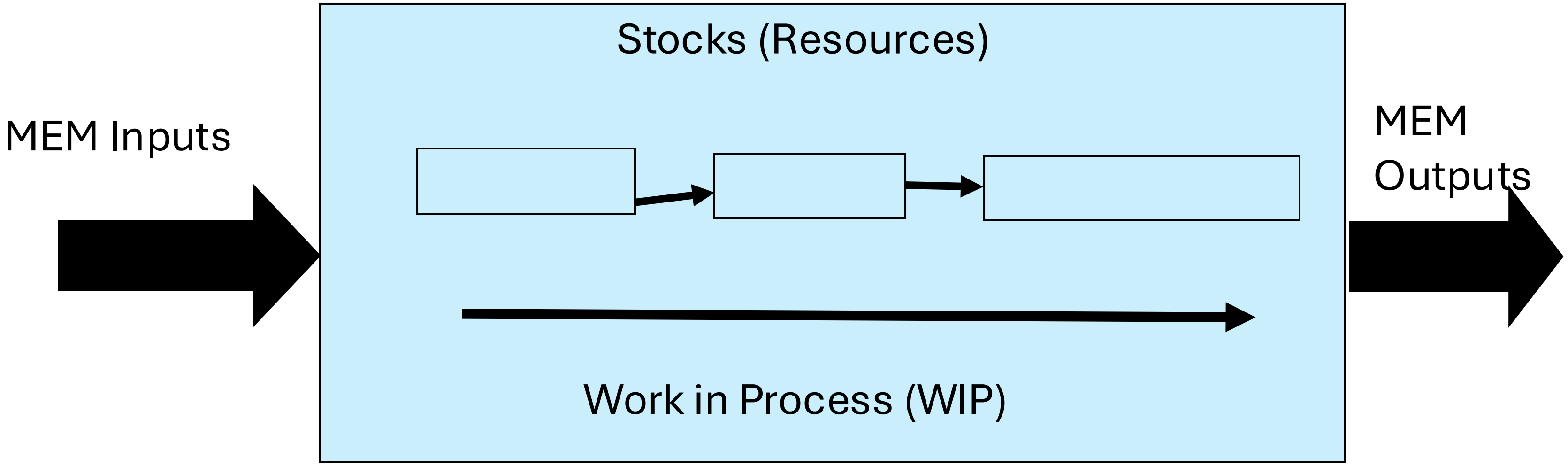
- Systems **input-throughput-output** material, energy, and messages
- Capacity is the maximum sustainable flow rate. In periods of heavy congestion, throughput is equal to capacity.
- Sometimes referred to as the flow rate
- For example:
  - A company may process or manufacture 100 units per month.
  - A university may graduate 250 PhDs per year
  - A software company may sell 50 apps per month
  - A router may process 1 million packets per second

Throughput

Cycle Time

- Cycle Time is defined in terms of Capacity.
- Examples:
  - Cycle time = 1/Capacity
  - If Capacity = 10 units /hour, then Cycle Time = 1/10 hour or 6 minutes.
- Throughput is typically less than Capacity given a maximum rate is not sustainable.

Throughput
Any Production System (Processing MEM)



Input = Output [– defects] (1st Law of Factory Physics)

Idle time - % of time a resource is not working

Throughput – the average number of processed MEM units per unit of time

Lead time –time needed to process a component of MEM

Throughput

Little’s Law

Little’s Law:
WIP = (Throughput) x (Lead Time)

- Little’s Law is a fundamental law of system dynamics
- Gives good results for a variety of scenarios
- *Throughput* (Units/time).

Example: A facility can produce 250 units / month, and the average lead time is 3 months. According to Little’s law the average WIP = 250 x 3 = 750 units.

Systems Dynamics

Systems Dynamics Concepts

- Stocks
- Flows
- Dynamics
- Cycles
- Feedback
- Tipping Points
- Resistance
- Archetypes

Stocks

- Stocks are quantities of resources (material, energy, and messages) in a system.
- Stocks accumulate or shrink over time by inflows and outflows of material, energy, messages.
- Stocks can be organized.
  - For example, data—a form of message—can be organized in structure like an array, linked list, tree, or graph, which can then be processed with an algorithm.
  - Material can be organized in a FIFO or first in, first out manner.

Stocks
Organization

Stocks can be organized in a variety of ways.

1. Hierarchical (network)
2. Color
3. Size
4. Type or other
5. Geography
6. Sequentially (alpha numeric)
7. Chronological

Stocks

Examples

- The total number of people in a city is a stock, affected by birth rates (inflow) and death rates (outflow).
- The number of widgets stored in a warehouse is a stock, influenced by production rates (inflow) and sales (outflow).
- The total amount of money in a bank account is a stock, influenced by deposits (inflow) and withdrawals (outflow).

Stocks

Examples

- CO_2, water vapor, methane, … in the atmosphere
- Employees in an organization
- Ice in a glacier
- Inventory
- Laptops in an organization
- Marine life in Glacier Bay
- National debt
- Population (people, ants, fish, cows, elephants, ..)
- Stock / bonds owned
- Savings account / credit card account
- Trees in a forest

Stock

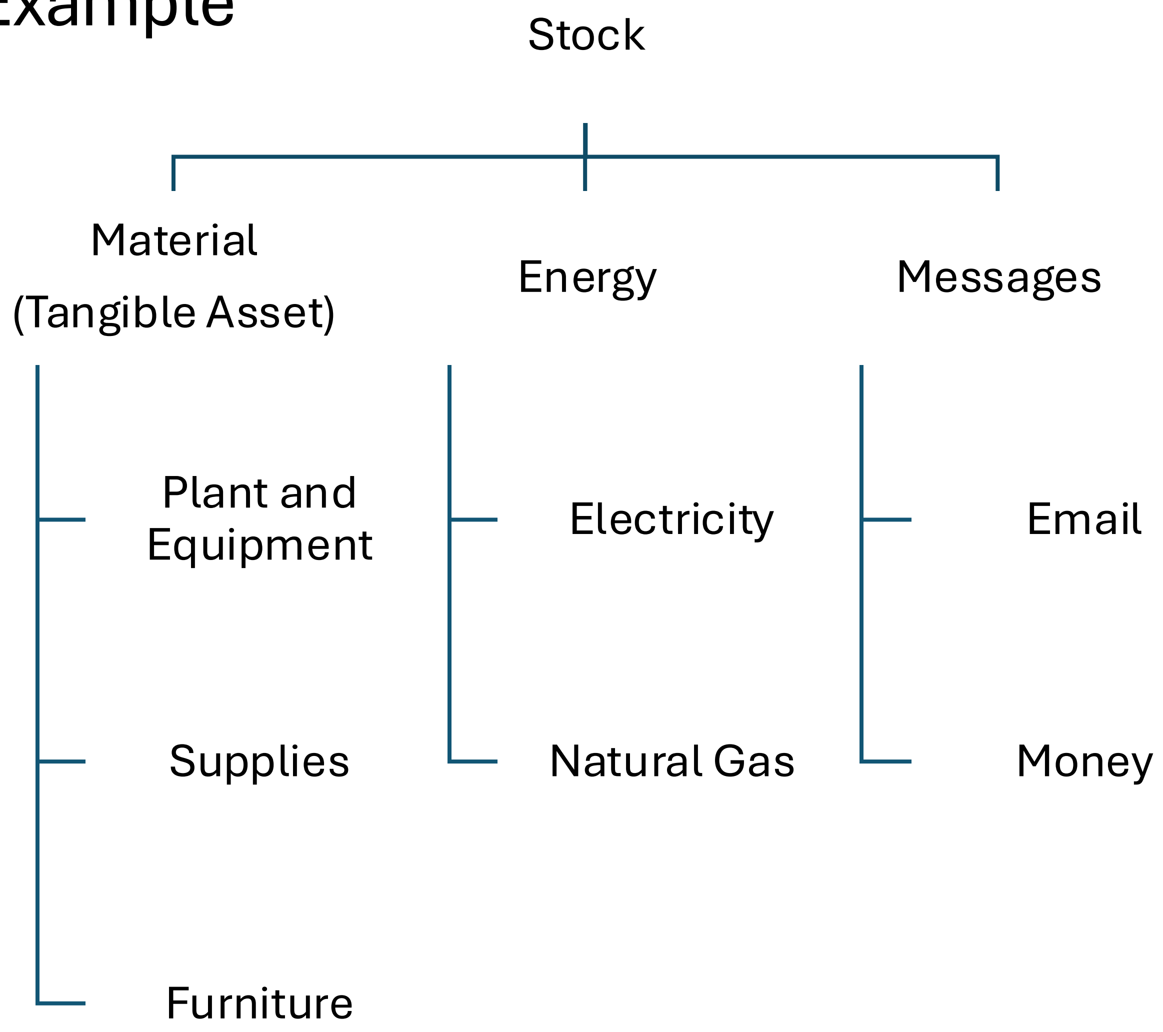
A Table Example in a Database

A Stock of Widgets

Primary Key	Name	Price	Qty	Supplier
W001	Wid001	$1.00	10	Acme
W002	Wid002	$1.50	0	Zyx
W003	Wid003	$.90	25	Zyx
W004	Wid004	$2.25	7	The ABC Co.

Stocks

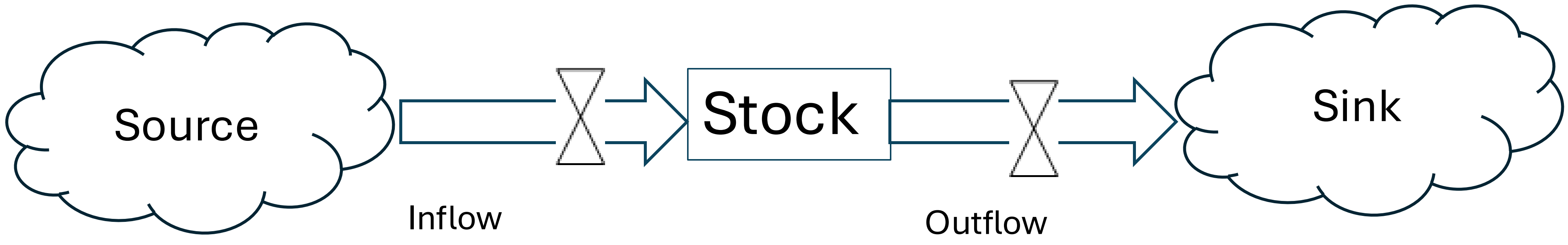
An Organization Example



Flows

- Inflow
  - A flow of material, energy, messages into a stock
  - Measurable (e.g., dollars / week, calories consumed / day, ..
  - May be linear or nonlinear
  - May vary in size, frequency, quantity, quality, shape
- Outflow
  - A flow of MEM from a stock
  - Can be measured (e.g., packets processed, instructions processed ....
  - May be linear or nonlinear
  - May vary in size, frequency, quantity, quality, shape

Stock and Flow Diagram
Birth Death Template



Dynamical Systems

- A dynamical system is any system (artificial, biological, natural, or social) that changes over time
- Dynamical systems evolve
- The present state determines future states
- Behavior is generally non-linear

Dynamical Systems

Examples

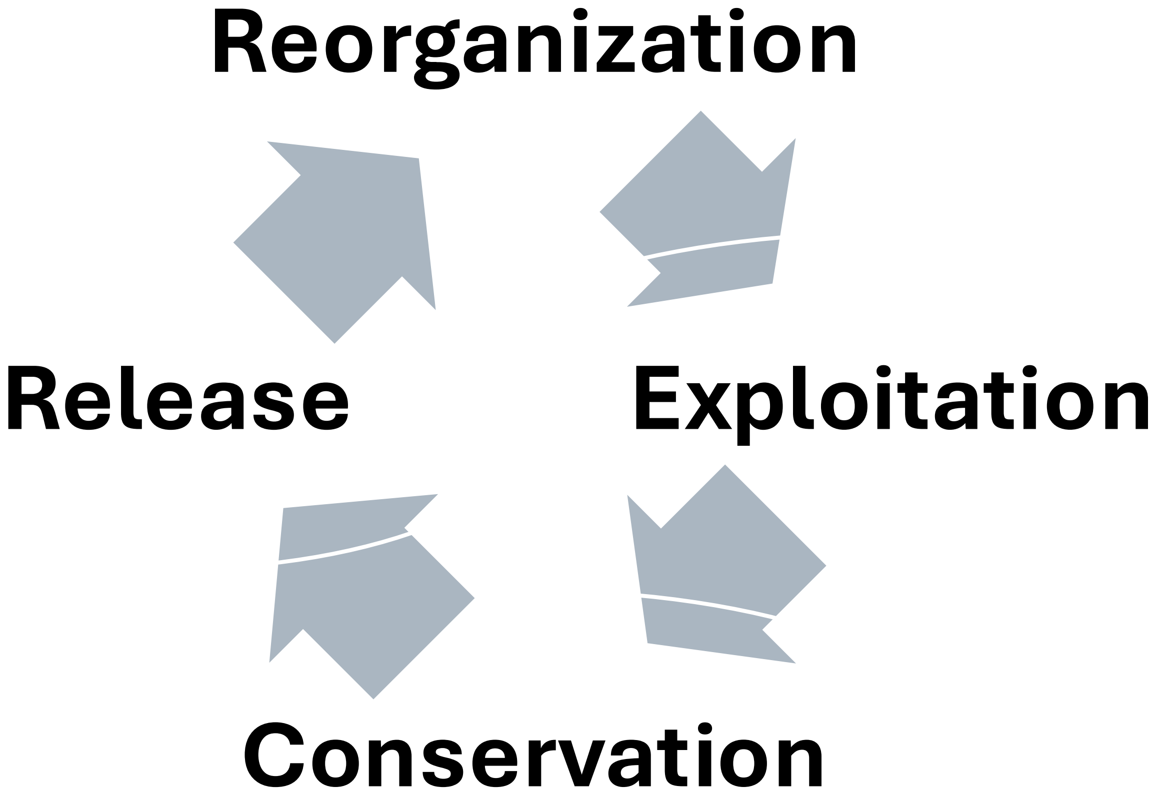
- Artificial systems
- Biological organisms
- Cancers
- Chemical reactions
- Economies
- Ecological systems
- Internet
- Pandemics
- Power grid
- Social systems
- Weather

Cycles

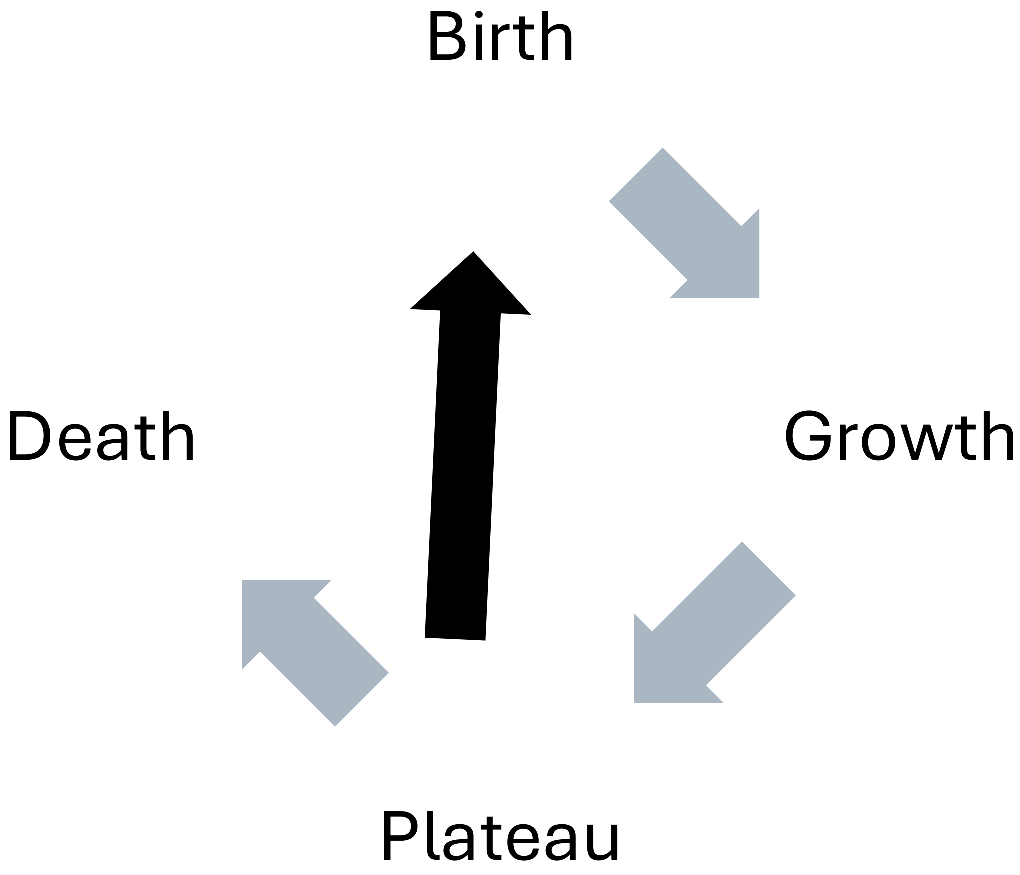
Some Common Cycles (Patterns)

- Adaptive cycle (conservation, release, reorganization, exploitation)
- Birth / death / lifecycle
- Economic cycles
- Escalation (war, conflict, revolution)
- Innovation cycles
- Limits to growth (overshoot and collapse)
- Negative feedback loops (goal seeking)
- Positive feedback loops (boom and bust)
- Tragedy of the commons (resource usage and depletion)

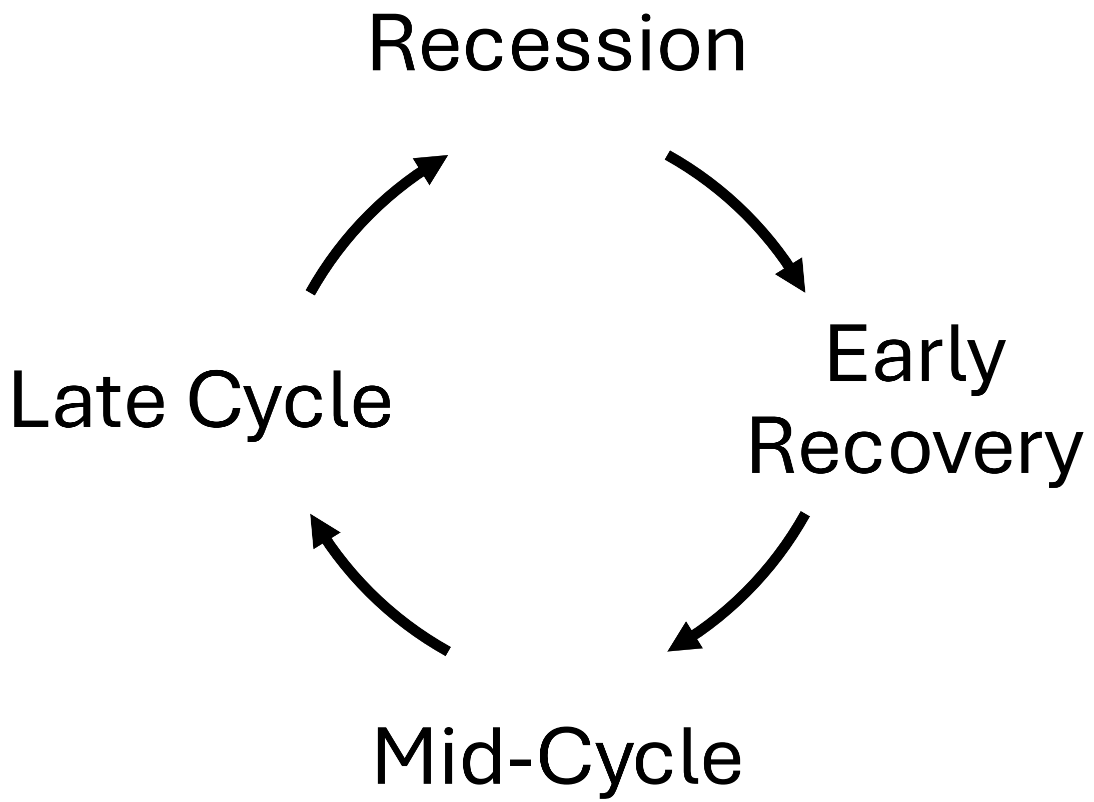
Adaptive Cycle



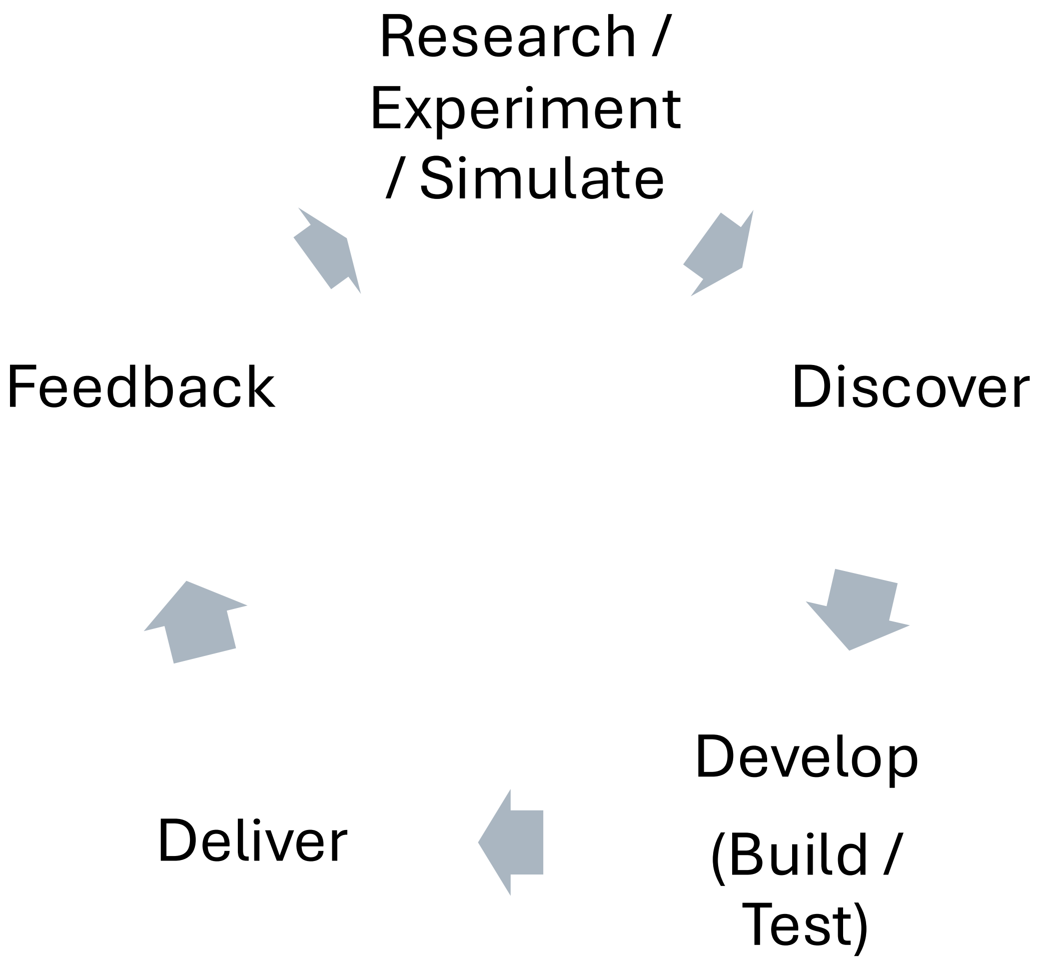
Birth Death Cycle



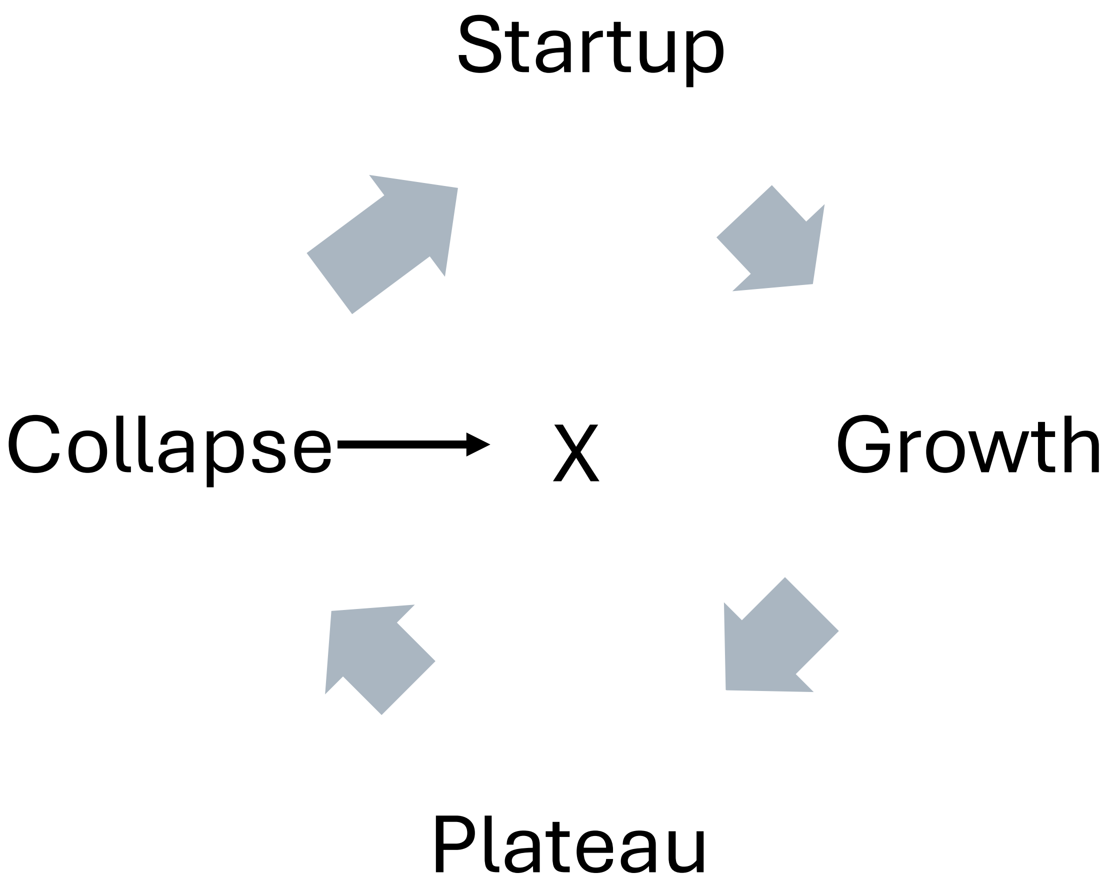
Economic Cycles



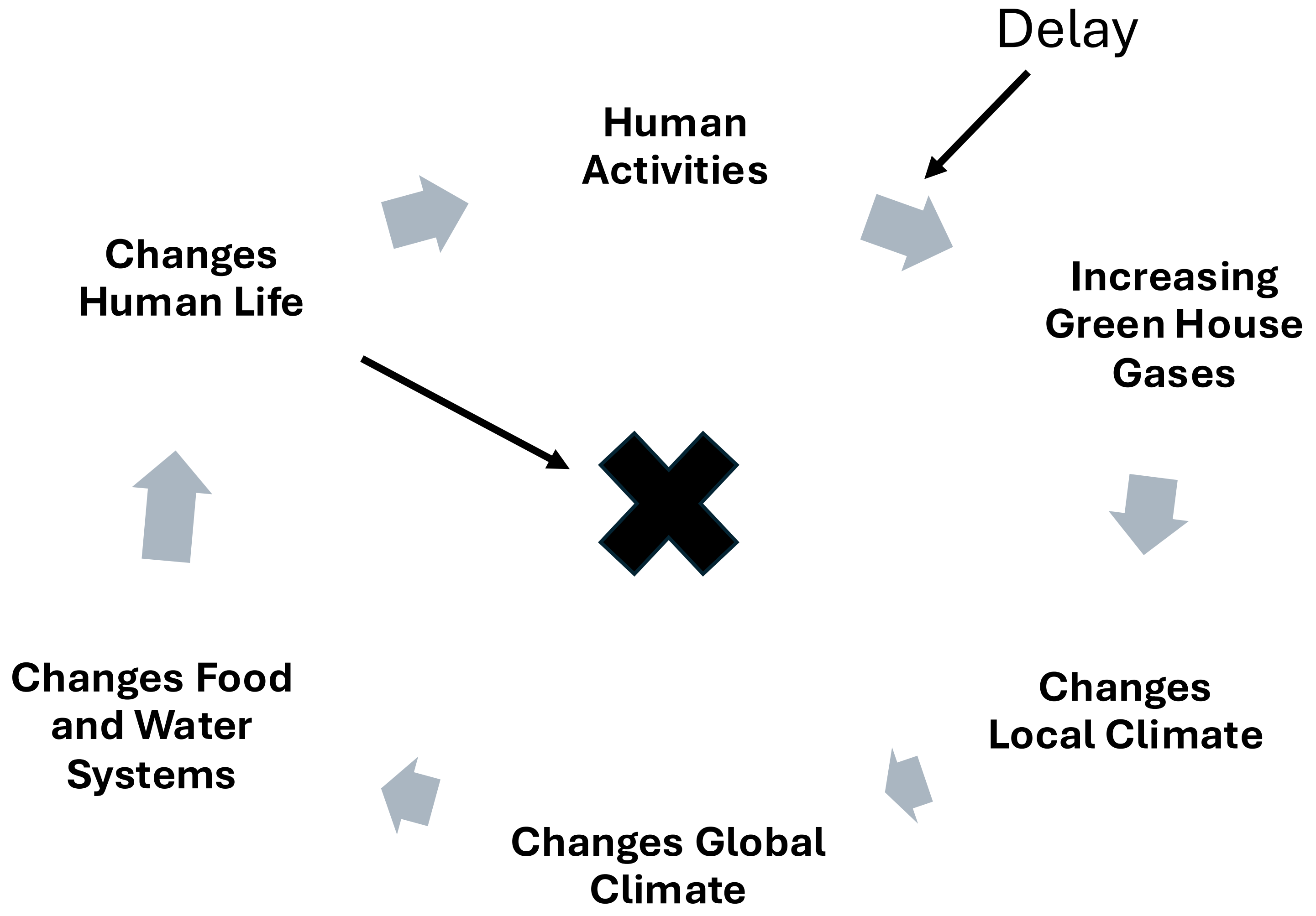
Innovation Cycle



Lifecycle



Climate Change Cycle



Tipping Points
Thresholds

- That point beyond which something becomes different, and at which point becomes difficult to reverse
- Example:
  - Heating water up to 99.9999 degrees Celsius is hot, but still water. The tipping point is the boiling temperature at which point, water changes from a liquid to a gas
  - A company continues to lose money but remains in business. If the company declares bankruptcy or is acquired, it tips.
  - Two countries declare war
  - A country elects / adopts a new and different political regime

Resilience

- The capacity of a system to absorb disturbance and re-organize so as to retain essentially the same function, structure, and feedbacks—to have the same identity.
- The opposite of resiliency is vulnerability
- Resilience is the capacity of a system to continually change and adapt yet remain within critical thresholds
  - Stockholm Resilience Centre
- Components
  - Robustness, redundancy, resourcefulness, response, recovery

Walker, B., & Salt, D. (2006). *Resilience thinking: Sustaining ecosystems and people in a changing world*. Island Press

Resilience

Examples

- An ecosystem is resilient to change if it can withstand storms, fire, or other perturbations
- A society is resilient if it can manage political instability, natural disasters, population growth, economic disasters, or other perturbations.
- A company is resilient if it can manage financial swings, increasing / decreasing numbers of customers, increasing competition, lawsuits, ….

Feedback

- Complex systems exhibit positive and negative feedback loops
- Positive feedback is an amplifying feedback
  - Example: customers recommending other customers
- Negative feedback is balancing or goal seeking feedback
  - Example: Maintenance of something

Negative Feedback Symbol

Positive Feedback Symbol

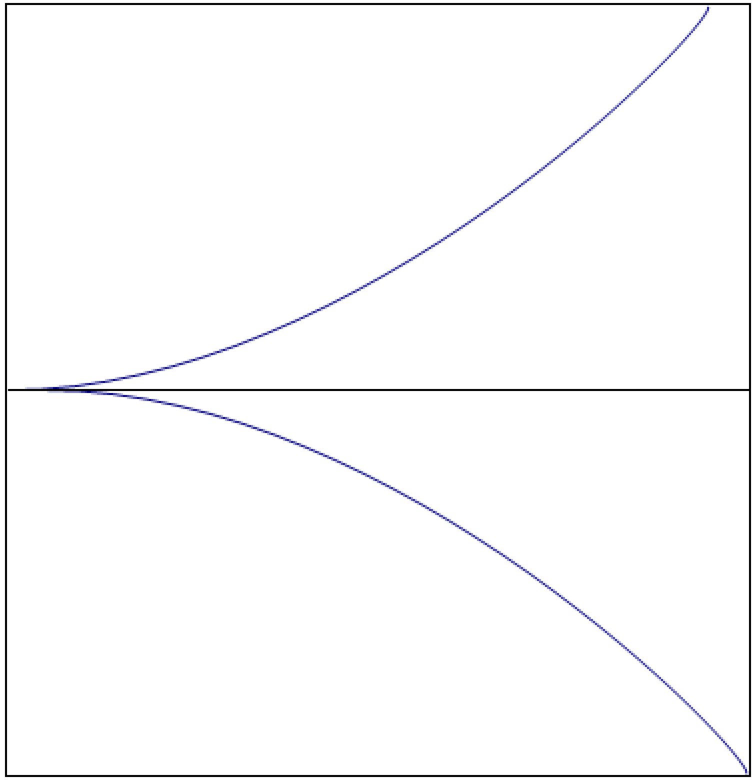
Examples

Positive Feedback Loop

- Banking
  - Stock as a Savings Account $$$$$
  - Inflows as (a) monthly deposit, and (b) earned interest.
  - Outflow as a withdrawal
  - A positive feedback loop (virtuous) exists as part of the **stock** (earned interest) inflows monthly into the **stock**. The larger the **stock**, the more earned interest.

Positive Feedback

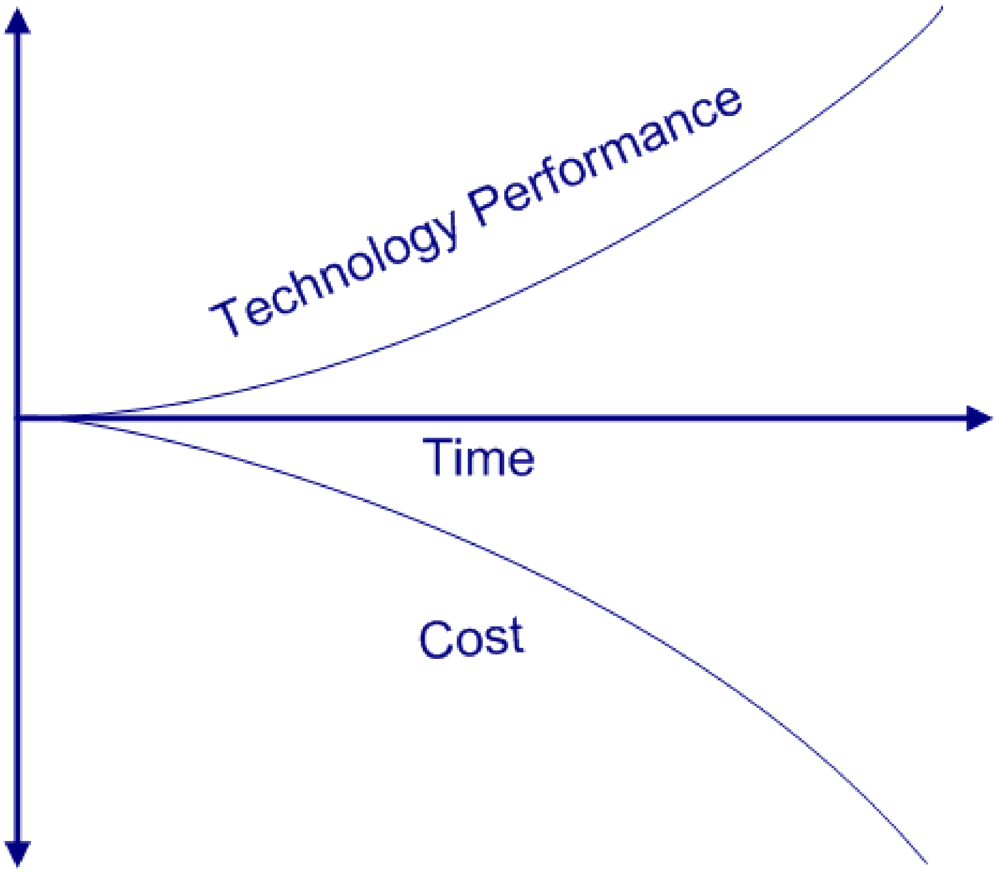
Behavior Over Time



Virtuous Cycle
(Exponential Growth)

Vicious Cycle
(Exponential Destruction)

Wright’s Law



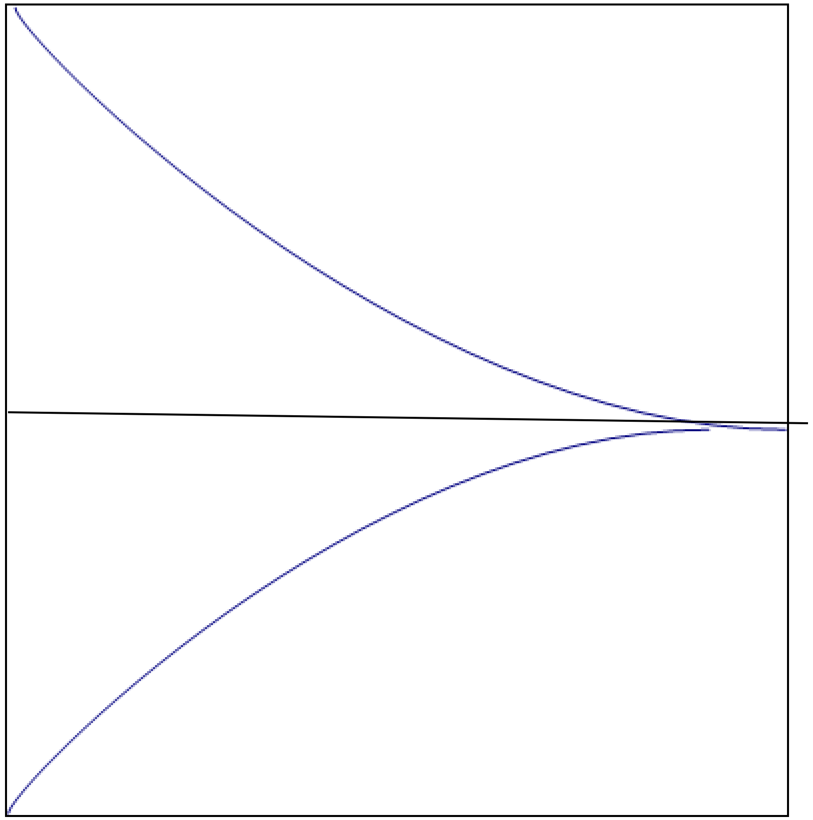
Learn from experience or learn by doing.

A generalized Moore’s Law. The performance of a technology increases while the cost decreases.

Think aerospace, biotechnology, communications, energy, information technology, medical technology, …

Negative Feedback

Behavior Over Time



Goal Seeking—from any direction. Behavior may oscillate around the goal until settling down

Archetypes

Common Behavioral **Patterns** in Systems

- Problem
- Positive Feedback
- Negative Feedback
- Birth Death Model
- Limits to Success (Limits to Growth)
- Escalation
- Drifting Goals
- Shifting the Burden
- Success to the Successful
- Tragedy of the Commons
- Fixes that Fail
- Growth and Underinvestment

Source: Senge, P. (2006). *The fifth discipline*. Doubleday.

What is a Problem?

- A simple definition of a problem is something to be *fixed* or something requiring *corrective action*.
- Another consideration is something that needs to be *improved* (or requires innovation).
- A requirement or *mandate* is yet another consideration as a problem.
  - For example, writing a required paper is a problem
- In each of these cases, there is a **gap** *between* the **current state** and the **desired state**.

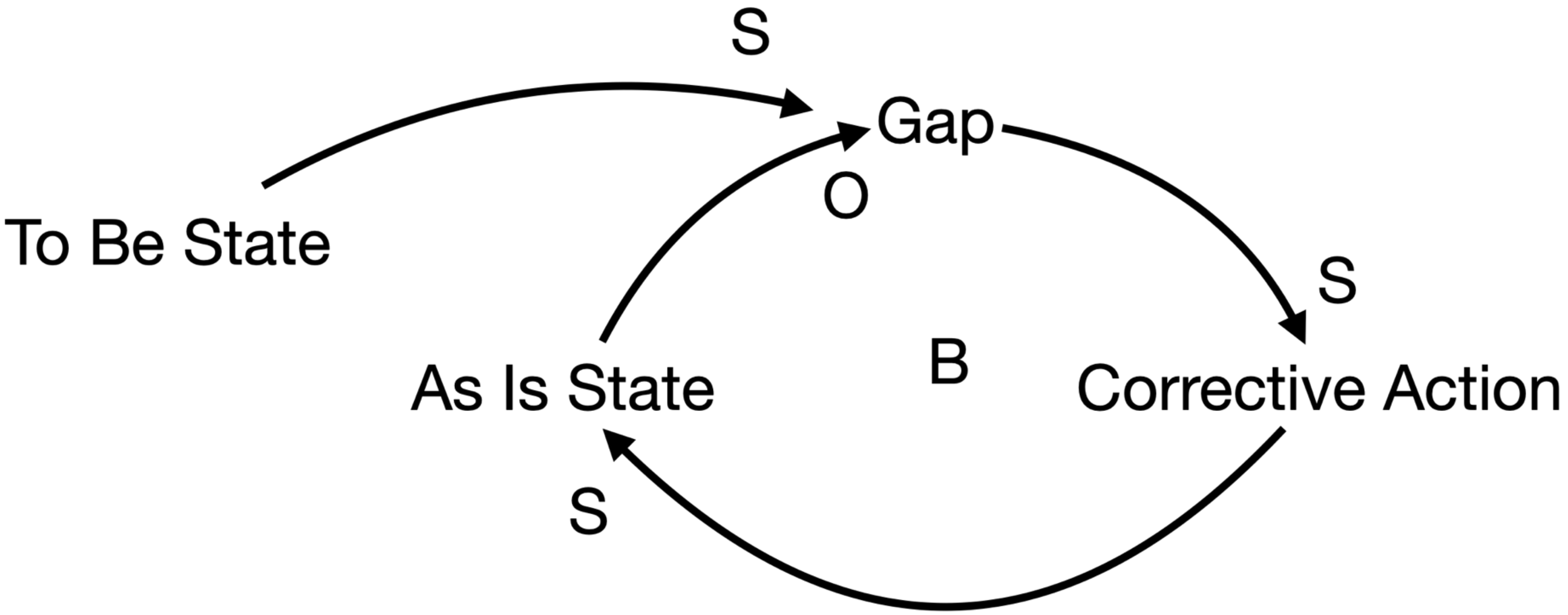
Whitten, J.L., & Bentley, L.D. (2007). *Systems analysis and design methods, 7th Ed*. McGraw-Hill.

Problem Archetype

Structure

A problem is the difference between the ***as is*** or current state and the ***to be*** or desired state.

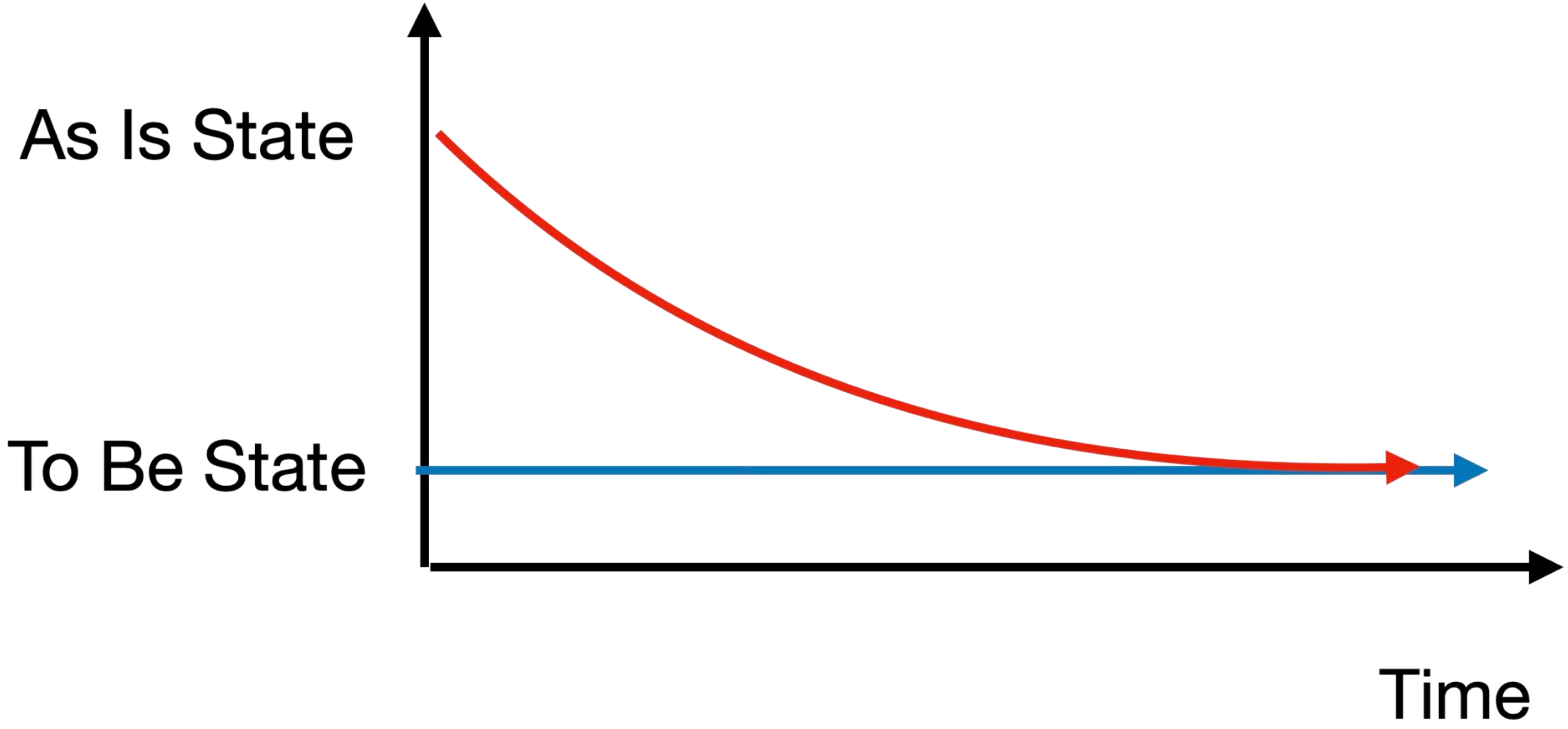
A problem can be something to fix or repair, an opportunity, or a mandate.



Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Problem

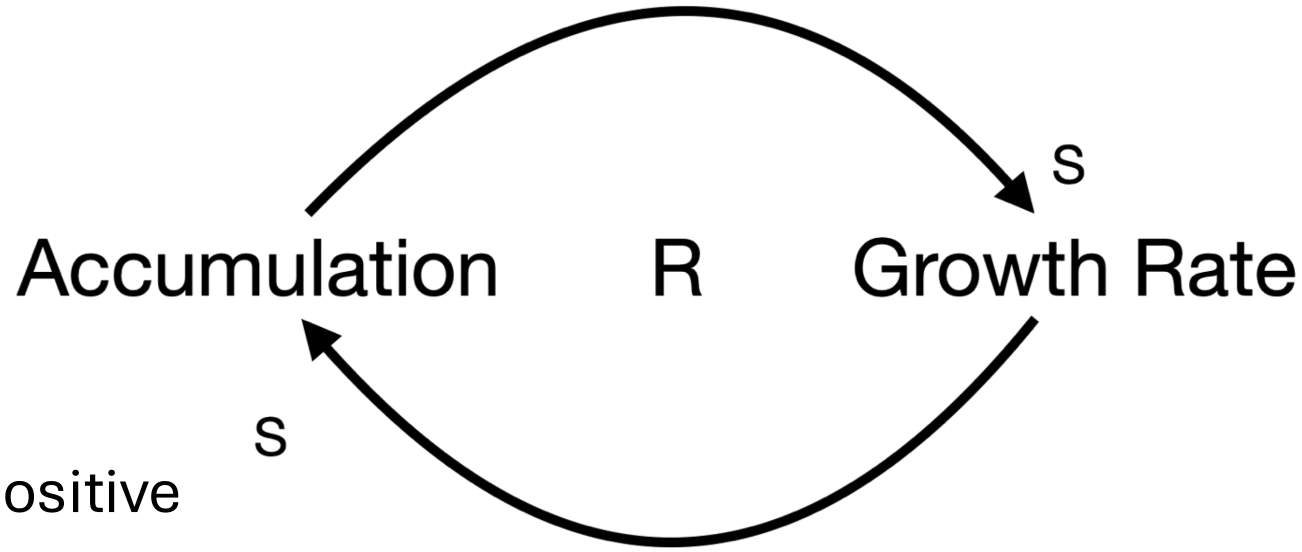
Behavior Over Time



Over time, corrective action drives the ***as is*** state to the ***to be*** state. Essentially, a negative feedback loop.

Positive Feedback Archetype

Structure



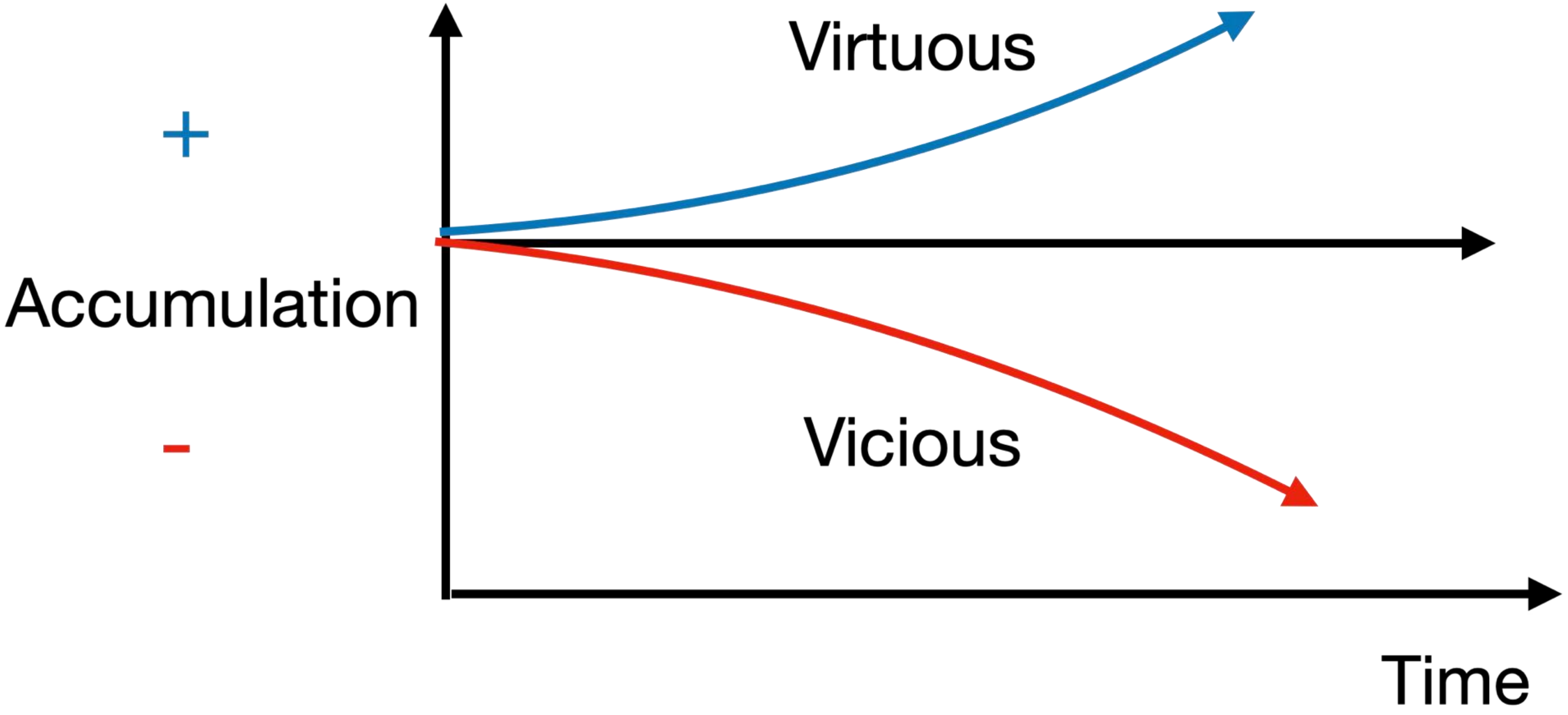
A positive feedback loop is either positive (virtuous cycle)

or a negative (vicious cycle), sometimes referred to as a doom loop.

Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Positive Feedback

Behavior Over Time



Virtuous and vicious are relative terms.

Positive Feedback

Applications / Examples

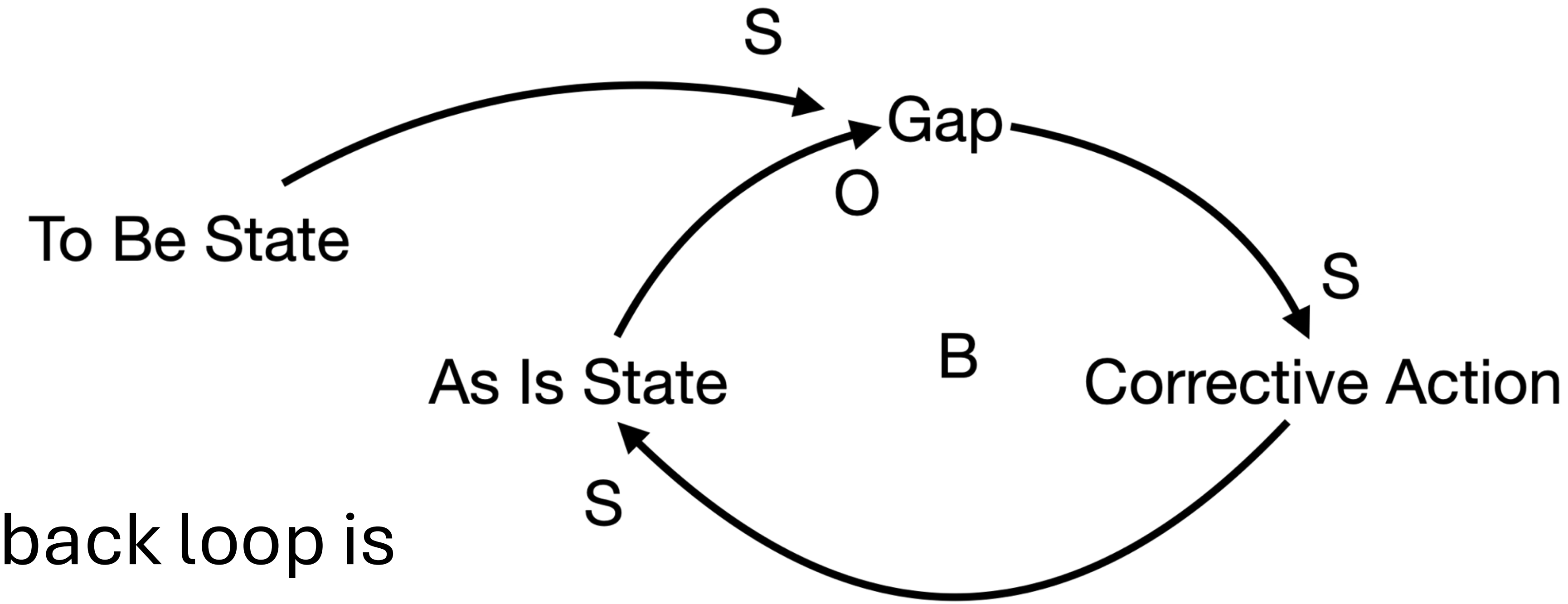
- A savings account with compound interest
- Climate change
- Cancer
- Pandemics
- Population growth

Notes: Rarely does positive feedback go unchecked for any length of time.

As limits or constraints are reached, growth slows, stops, and may decline or take another dynamic path.

Negative Feedback Archetype

Structure

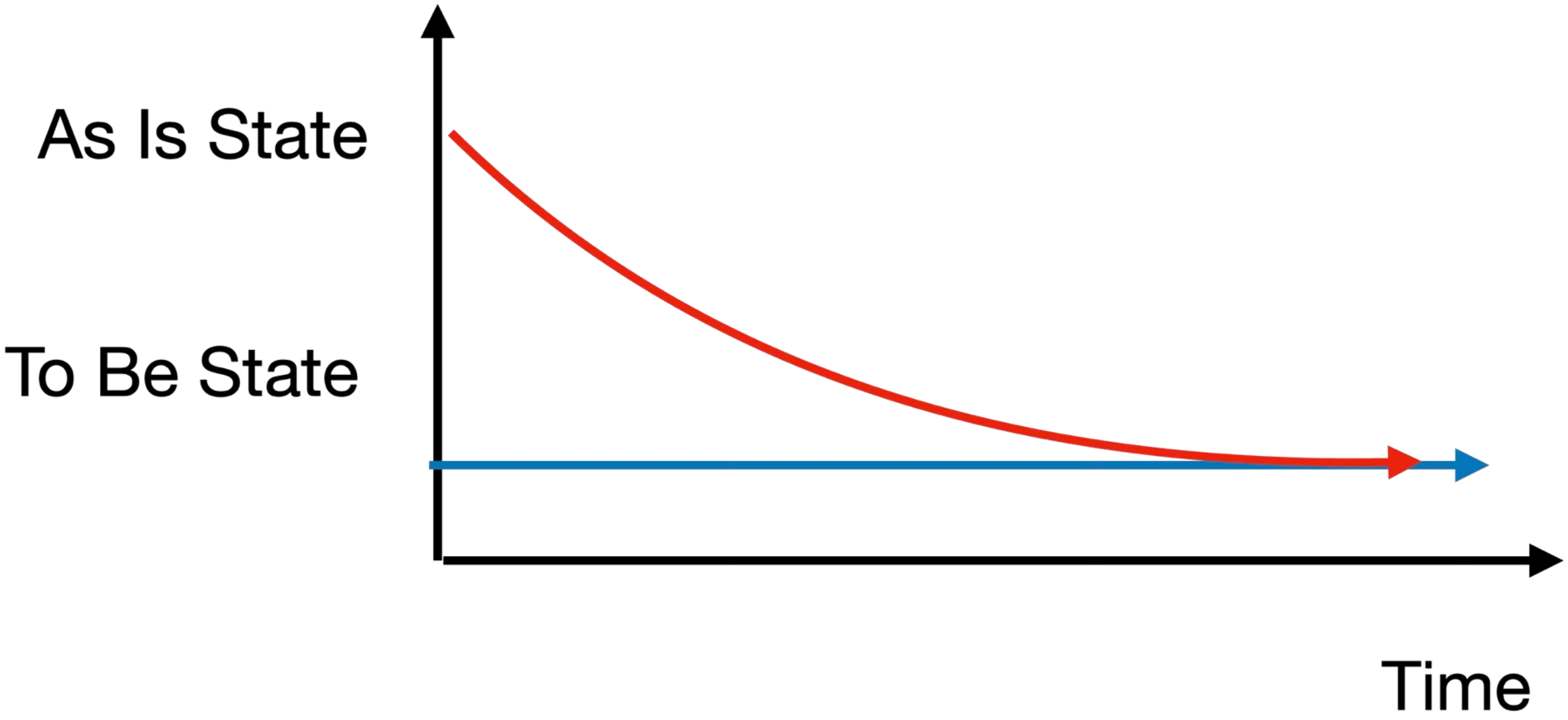


A negative feedback loop is a goal seeking or maintenance seeking loop.

Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Negative Feedback

Behavior Over Time



Over time, corrective action drives the ***as is*** state to the ***to be*** state.

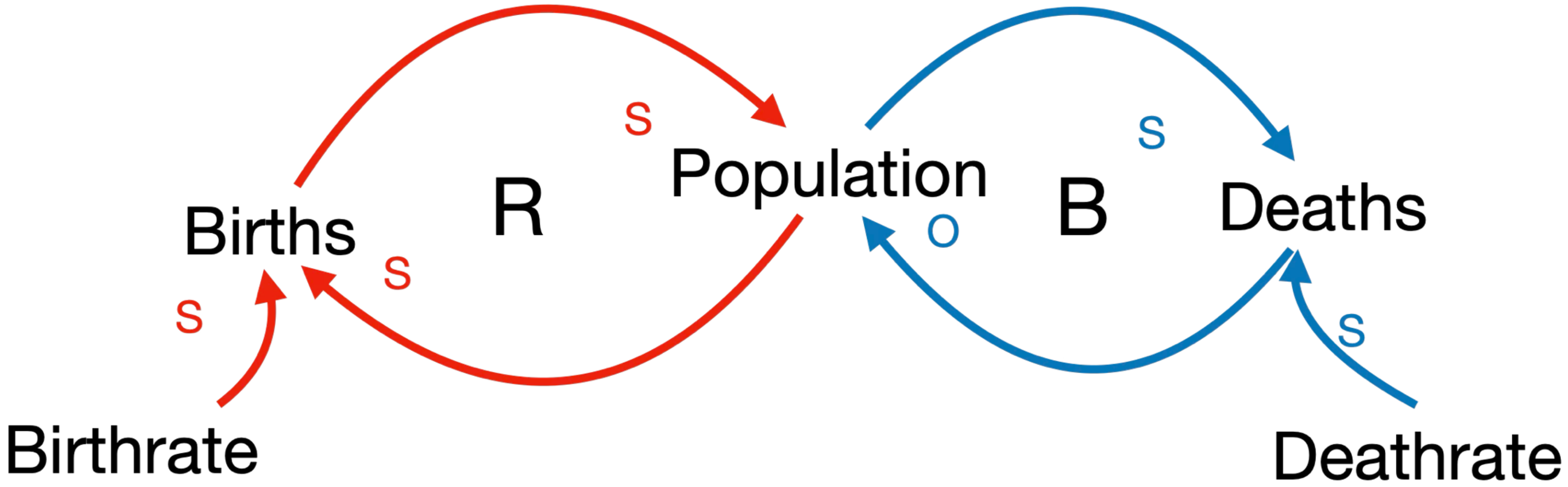
Negative Feedback

Applications / Examples

- Regulation of body temperature
- Regulation of hunger / thirst
- Regulation of inventory
- Maintenance or regulation of almost anything

Birth Death Archetype

Structure

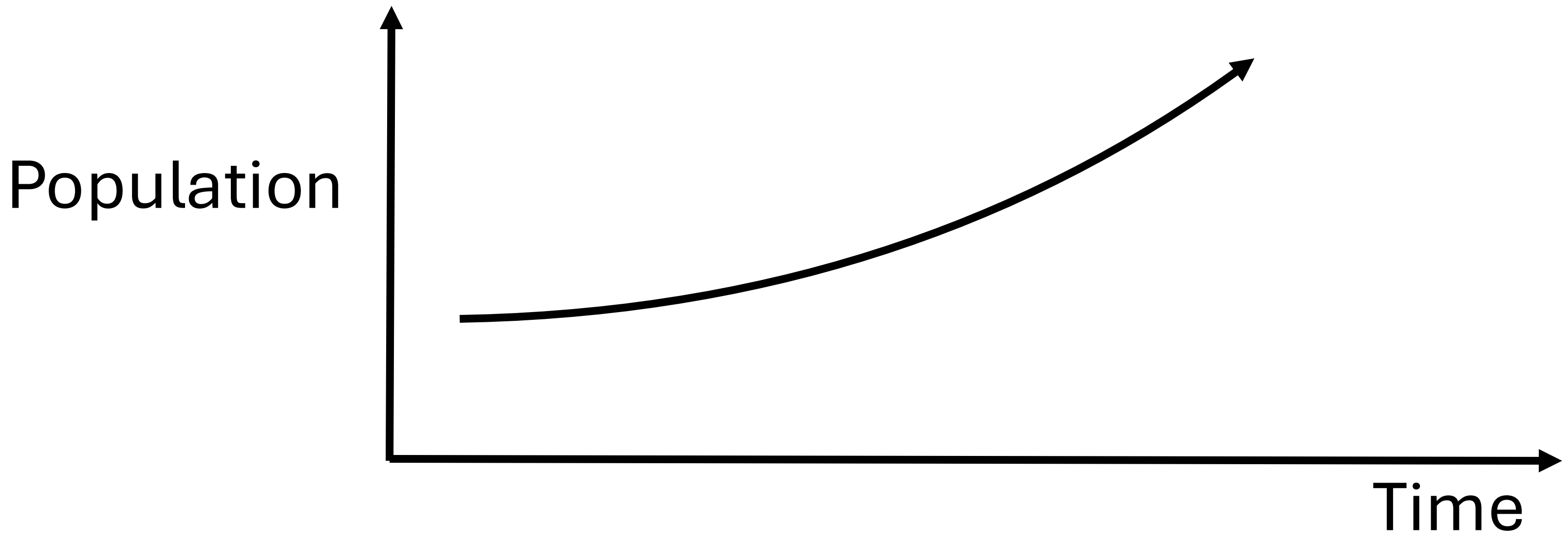


Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Birth Death

Behavior Over Time

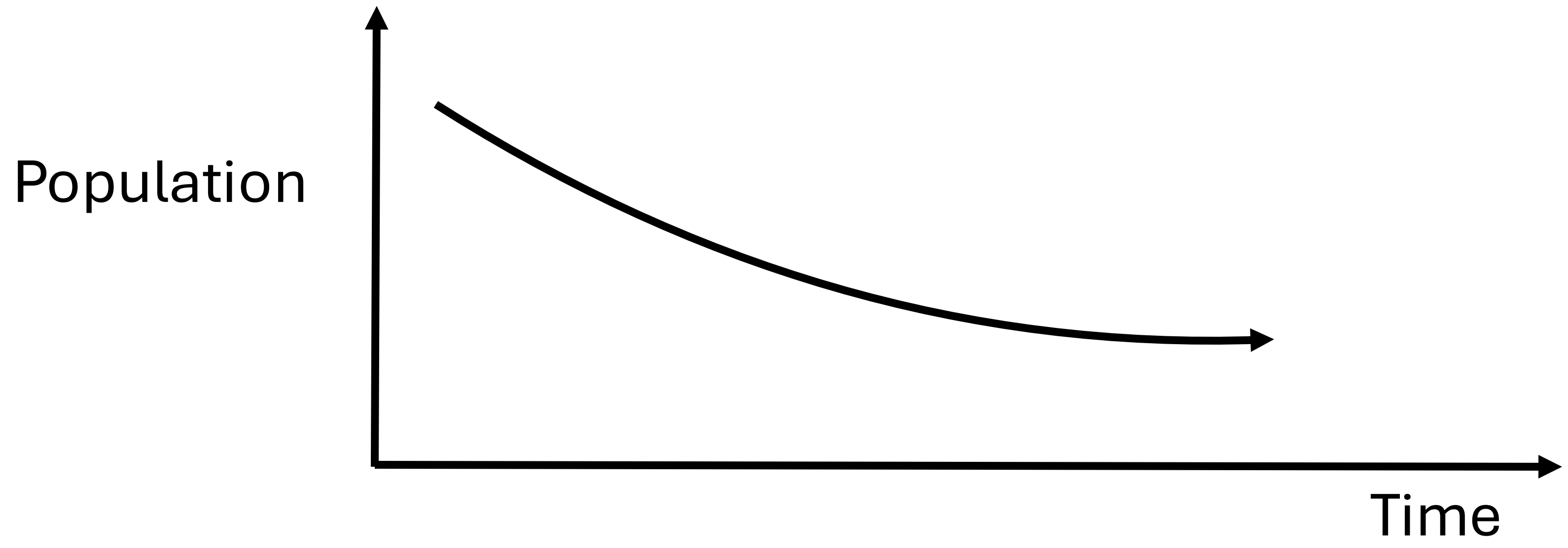
Number of births exceeds the number of deaths



Birth Death

Behavior Over Time

Number of deaths exceeds the number of births



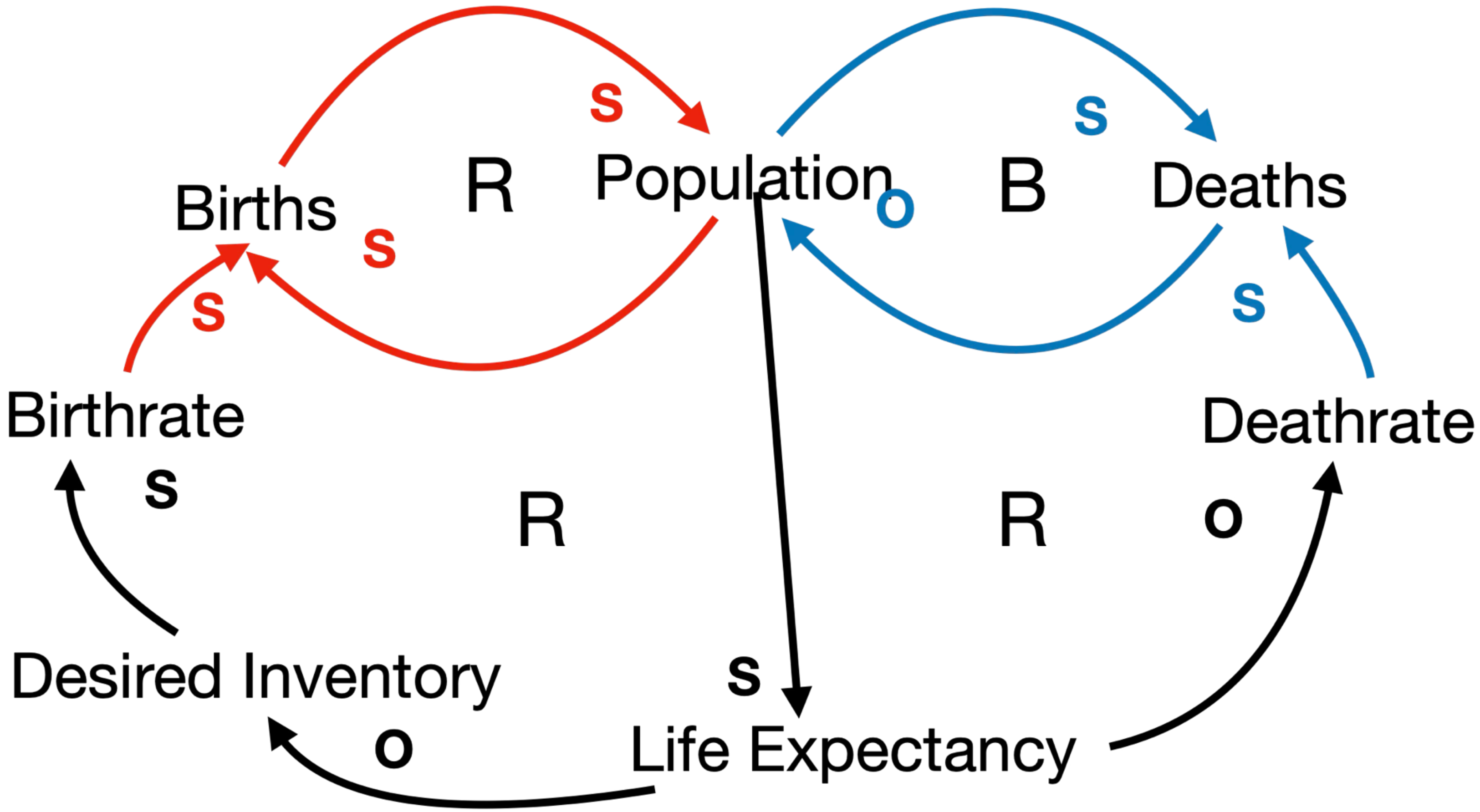
Birth Death

Applications / Examples

- Input-throughput-output systems
- Population of any artificial, biological, natural, or social system
- Suppliers –Products- Customers

Birth Death Archetype

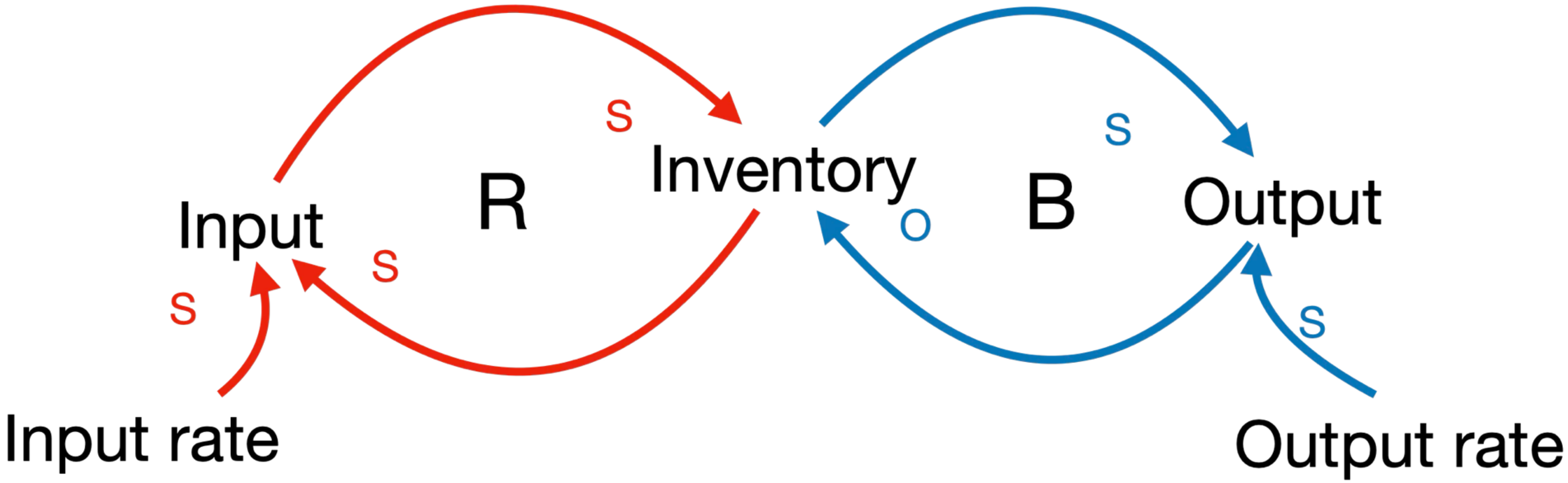
Structure of a Population of Almost Anything, Biological or Not



Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Input-Throughput-Output Archetype

Structure



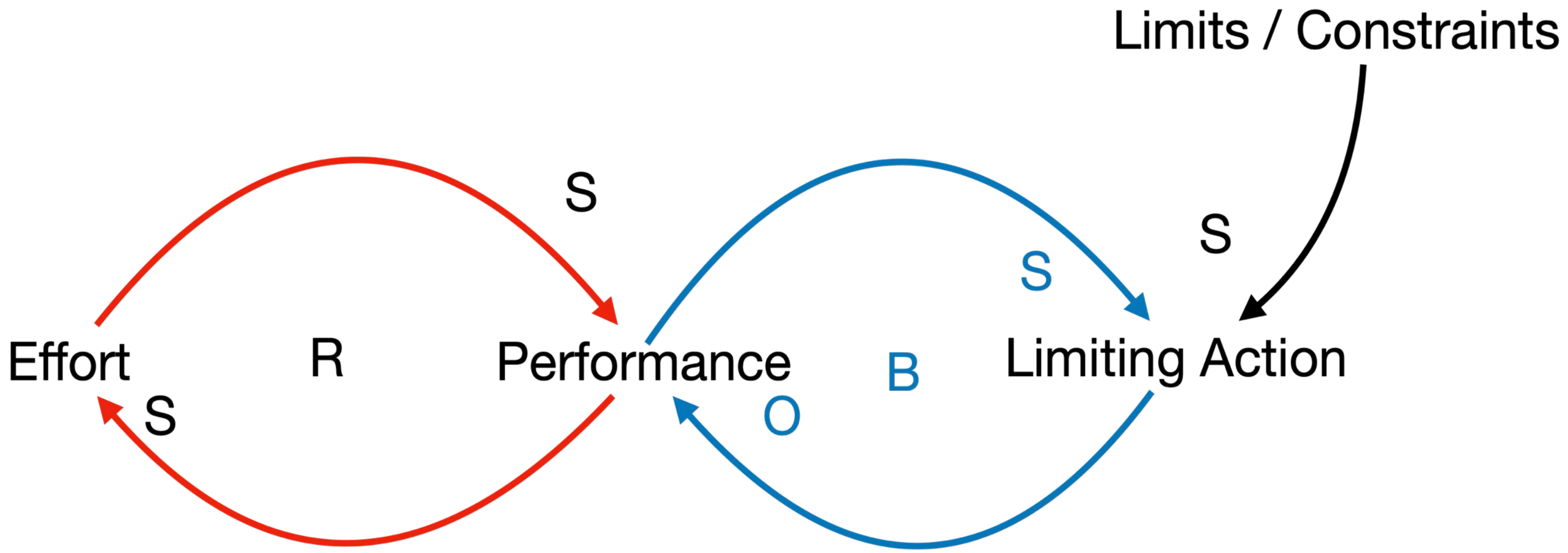
Input Categories: material, energy, and messages.

The Birth Death Model is the template.

Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Limits to Success Archetype

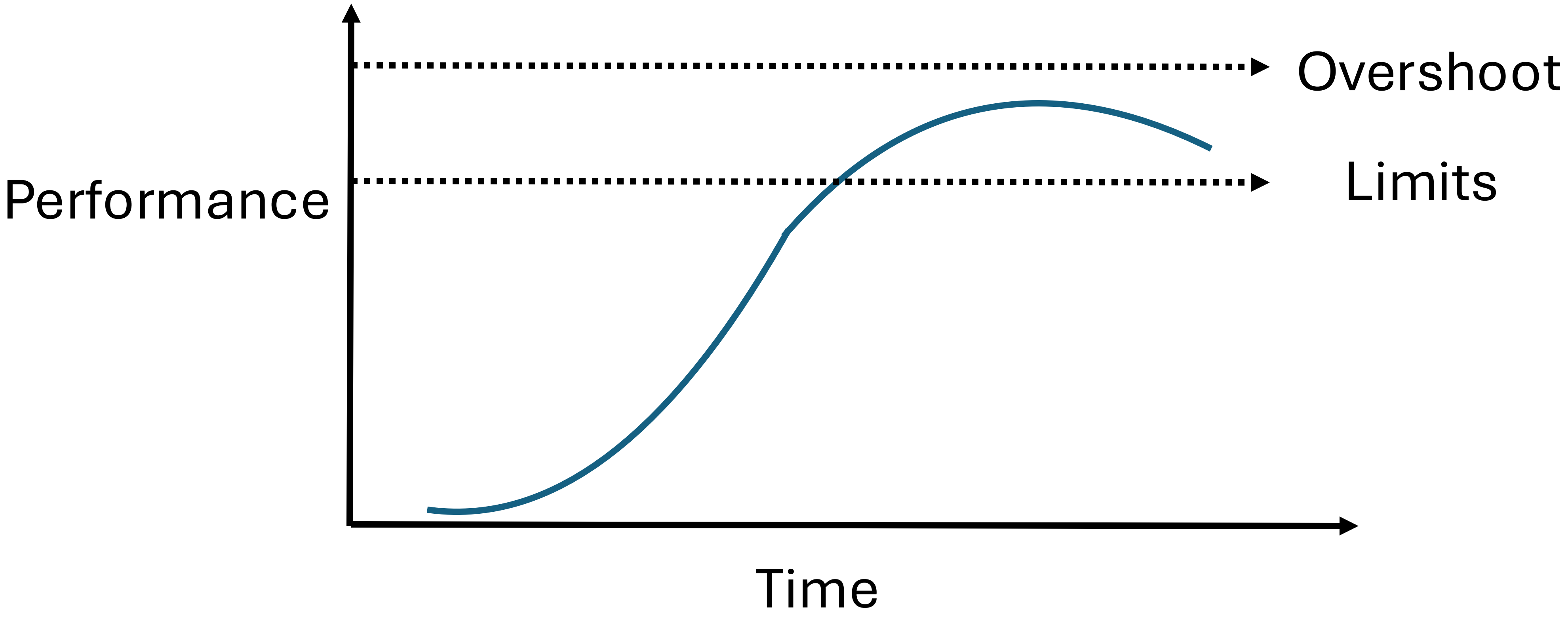
Structure



Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Limits to Success

Behavior Over Time



Adapted from: Braun, W. (2002). *The systems archetypes*.
https://www.albany.edu/faculty/gpr/PAD724/724WebArticles/sys_archetypes.pdf

Limits to Success

Applications

- Performance
    - Cities
    - Companies
    - Countries
    - Education Level Attainment
    - Financial Success
    - Sales / Marketing
    - Sports

Limits to Success

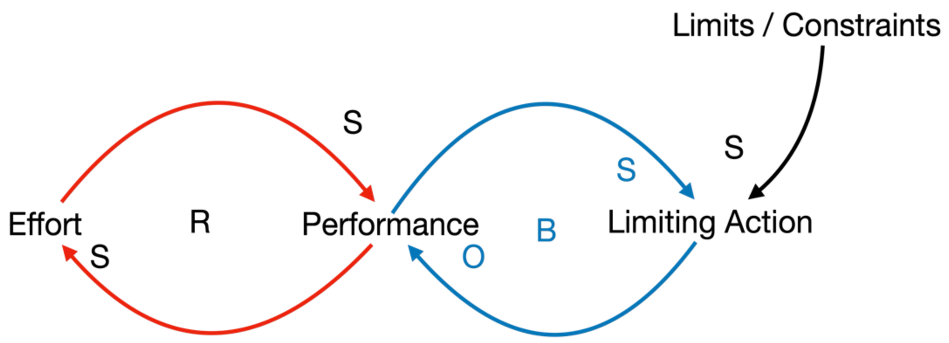
Examples

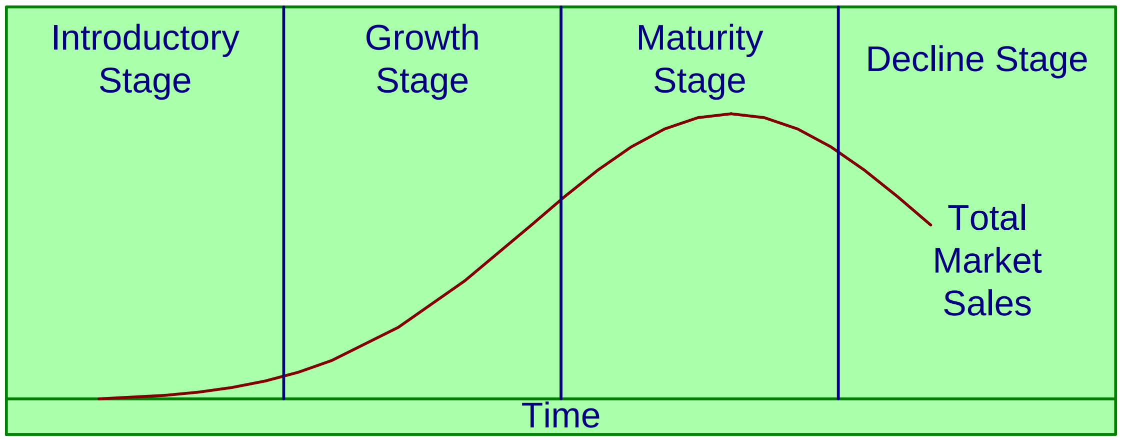
- The Product Life Cycle curve in marketing / sales
- Limits to the improvement of anything
  - Athleticism
  - Education
  - Products
  - Services
  - Skills

Limits to Success

Product Life Cycle Model or Pattern

- The product life cycle model (plan, do, check, act) is a special case of the more general limits to growth pattern or archetype. See below for the behavior over time.
- This is the behavior pattern for **marginal returns**. Early returns are productive, then over time become diminishing returns, and then potentially negative returns.





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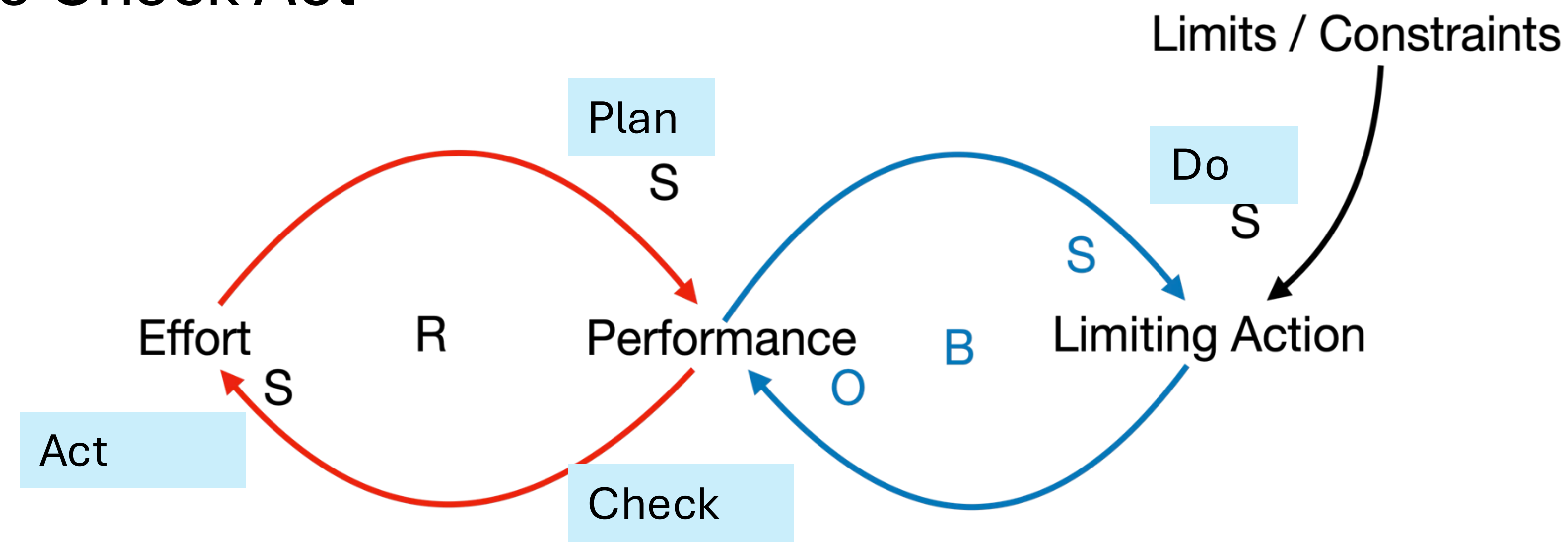
All causal loop diagrams created in Apple Keynote.

Limits to Success

Plan Do Check Act



There are limits to improvement such as the laws of physics, chemistry, biology, investment capital, time, mental models, and interest.

Improvements may start slow, speed up, slow to stop, oscillate about a line, or even decline as limits to improvements are reached

Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Limits

- Limits may constraint growth or progress
- Limits may be reduced or increased; if not static or fixed
- Limits may be physical, cognitive, imaginative
- Systems may be resource limited

Limits

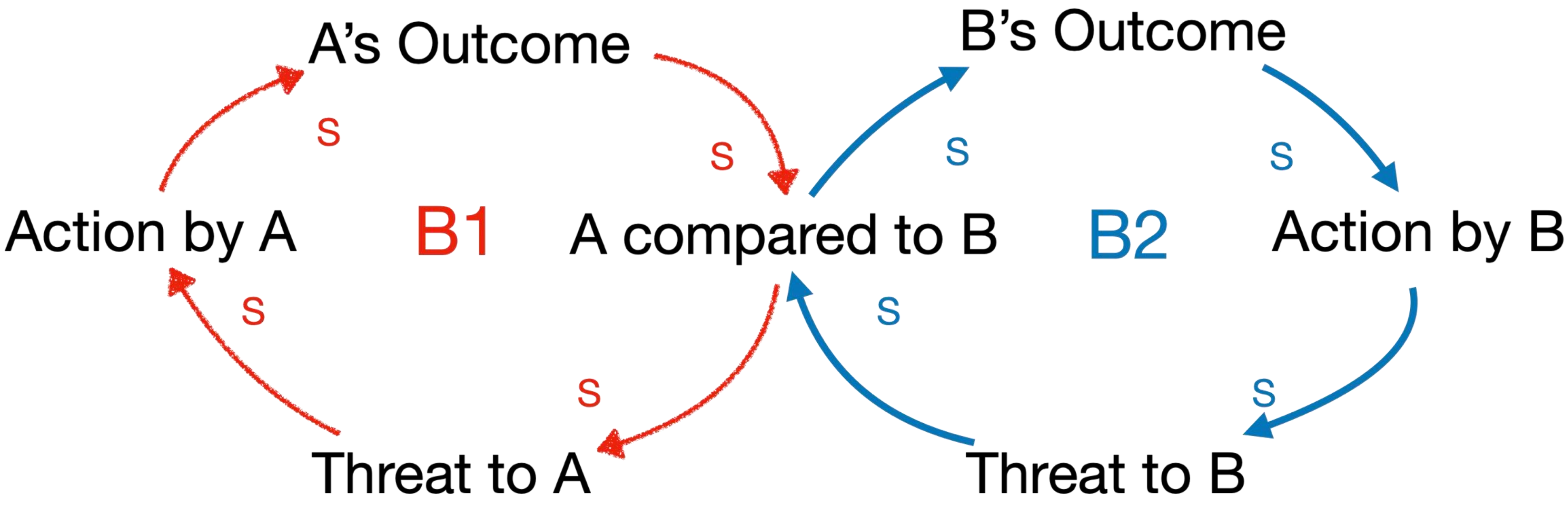
Approaches to Raising the Limit

- These approaches are based on a sales model for specificity
  - Increase sales to same type of customer by varying the price
  - Sell the same products to new customers
  - Develop and sell new products / services
  - Change the delivery system or approach
  - Expand into new territories or geographies
  - Change the industry structure (M&A)
  - Look outside the industry for opportunities

Baghai, M., Coley, S., & White, D. (1999). *The alchemy of growth*. Perseus.

Escalation Archetype

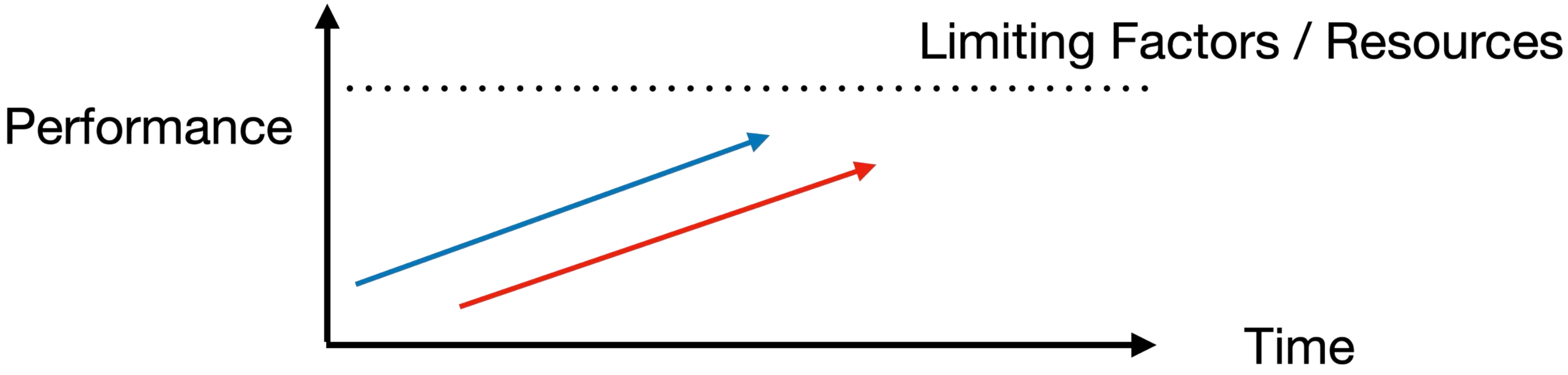
Structure



Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Escalation

Behavior Over Time



Competing parties track may track each other for some time, but given limiting factors or resources

- Performance diverges
- Performance converges
- One party wins
- Both merge
- Parties switch places on performance
- Performance oscillates over time
- War

Adapted from: Braun, W. (2002). *The systems archetypes*. https://www.albany.edu/faculty/gpr/PAD724/724WebArticles/sys_archetypes.pdf

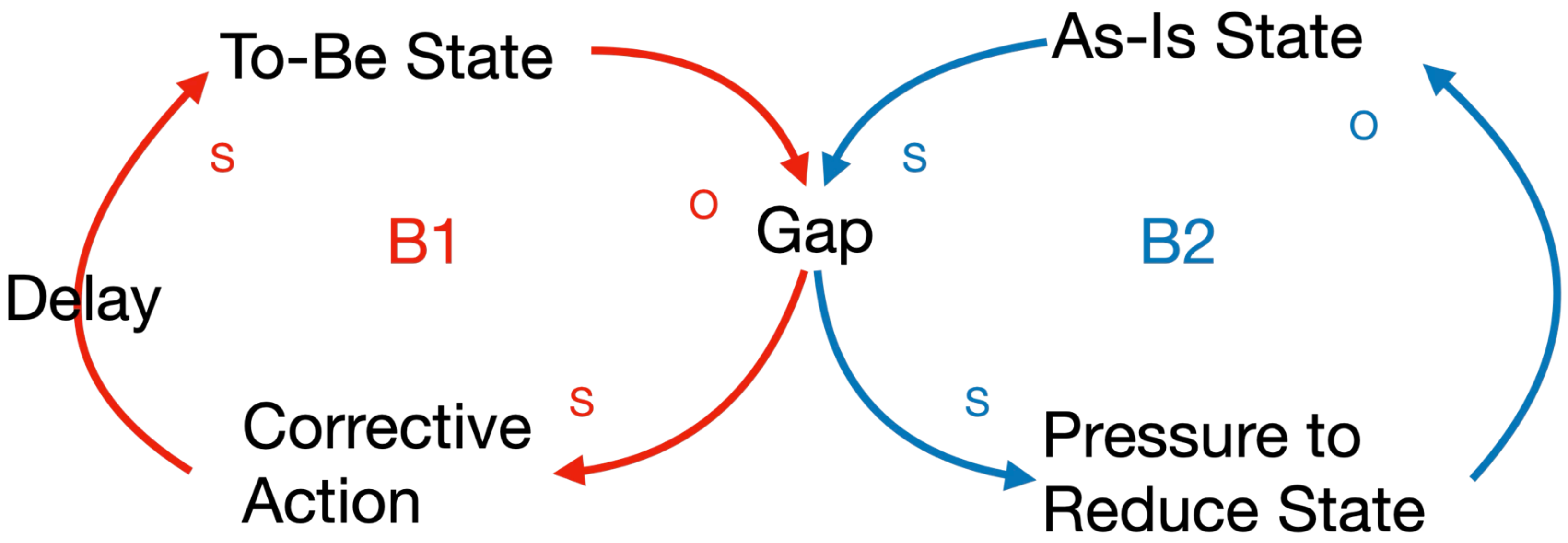
Escalation

Applications

- Competition
  - Countries
  - Companies
  - Organisms
  - People
  - Political Parties
  - Sports Teams

Drifting (Eroding) Goals Archetype

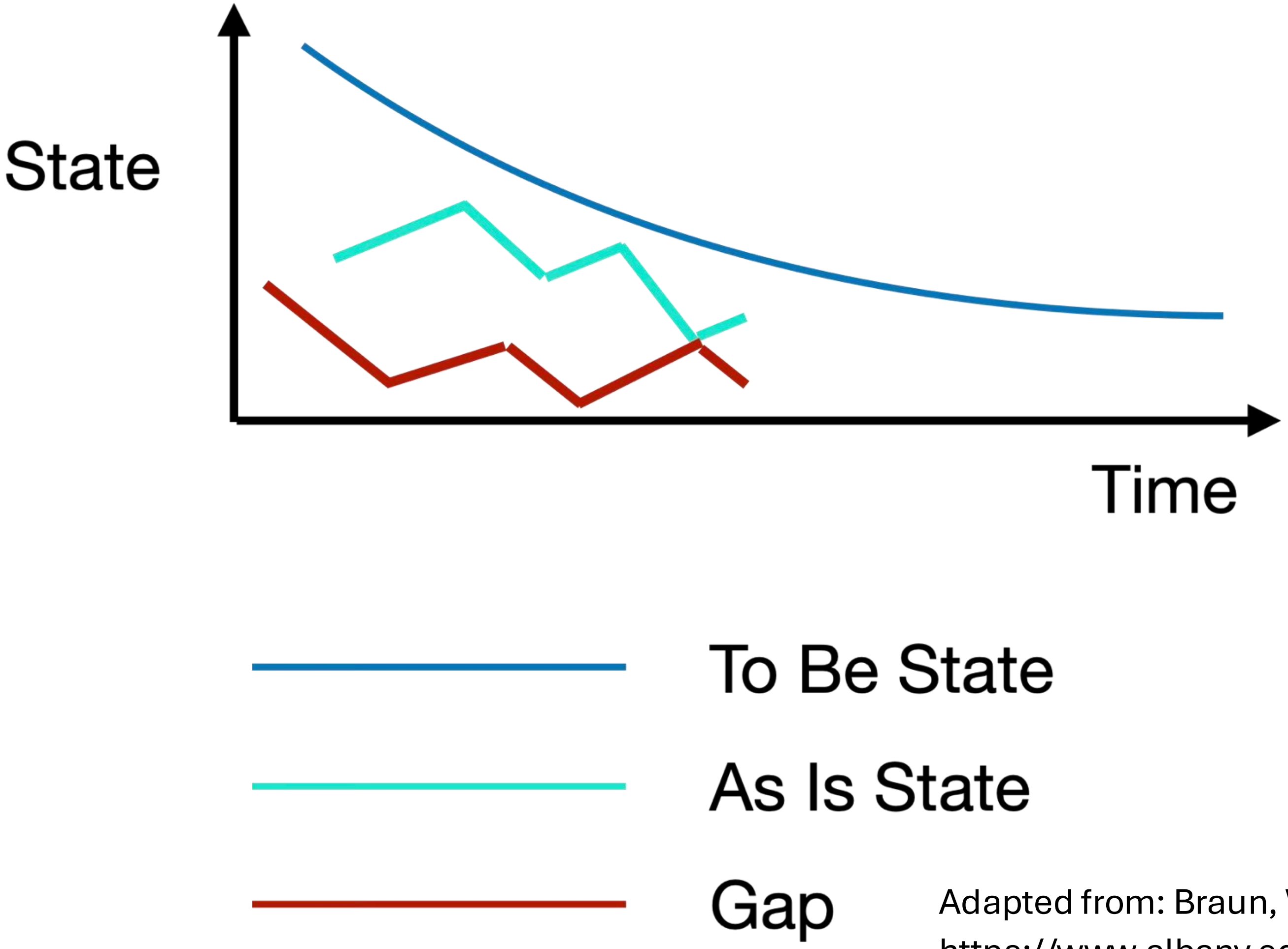
Structure



Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Drifting Goals

Behavior Over Time



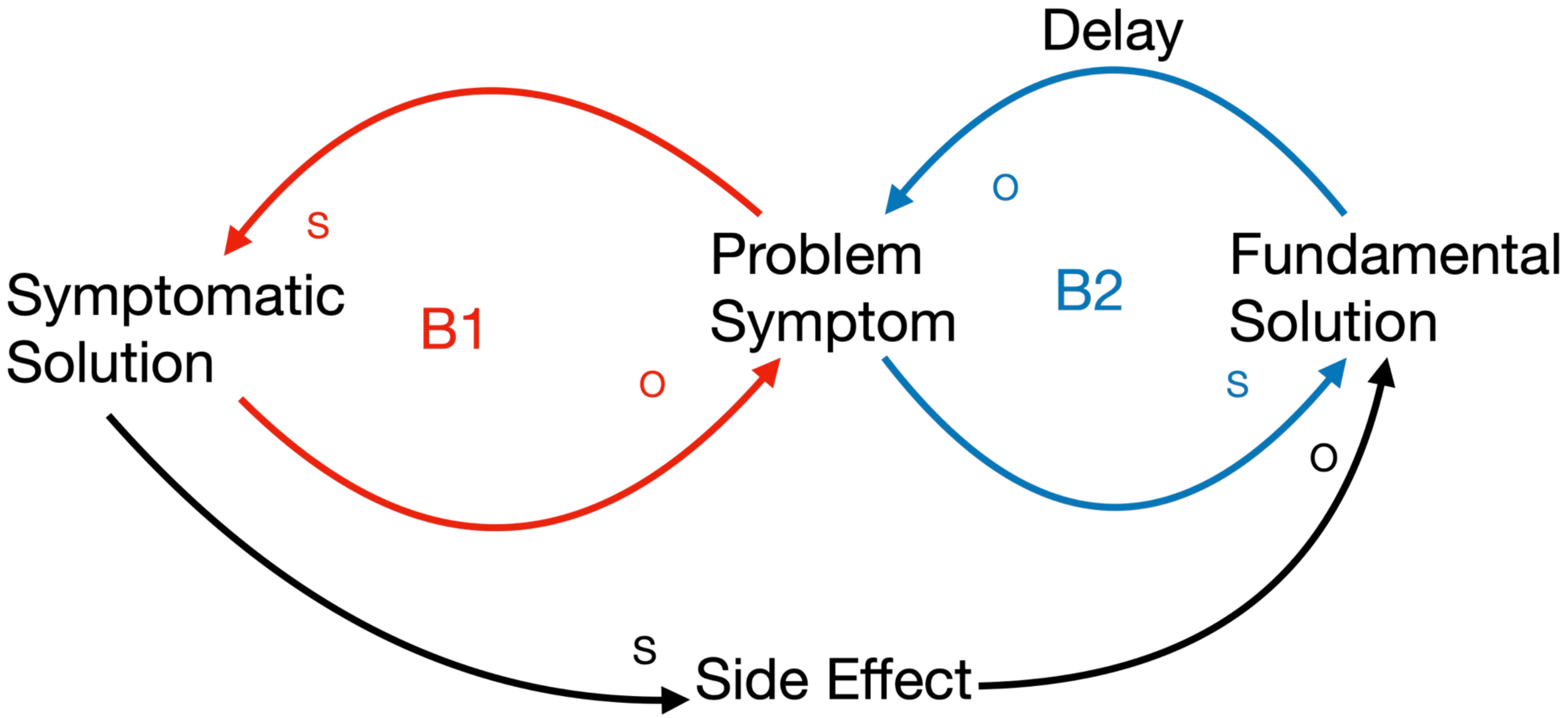
Adapted from: Braun, W. (2002). *The systems archetypes*. https://www.albany.edu/faculty/gpr/PAD724/724WebArticles/sys_archetypes.pdf

Drifting Goals
Applications / Examples

- Deficits
  - Increasing budget deficit limits
- Lowering expectations
  - Reducing personal expectations in life
  - Reducing expectations of others
- Lowering quality
  - Reducing the quality of ingredients in a product
  - Reducing the quality of a product or service
  - Reducing the quality of education

Shifting the Burden Archetype

Structure



Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
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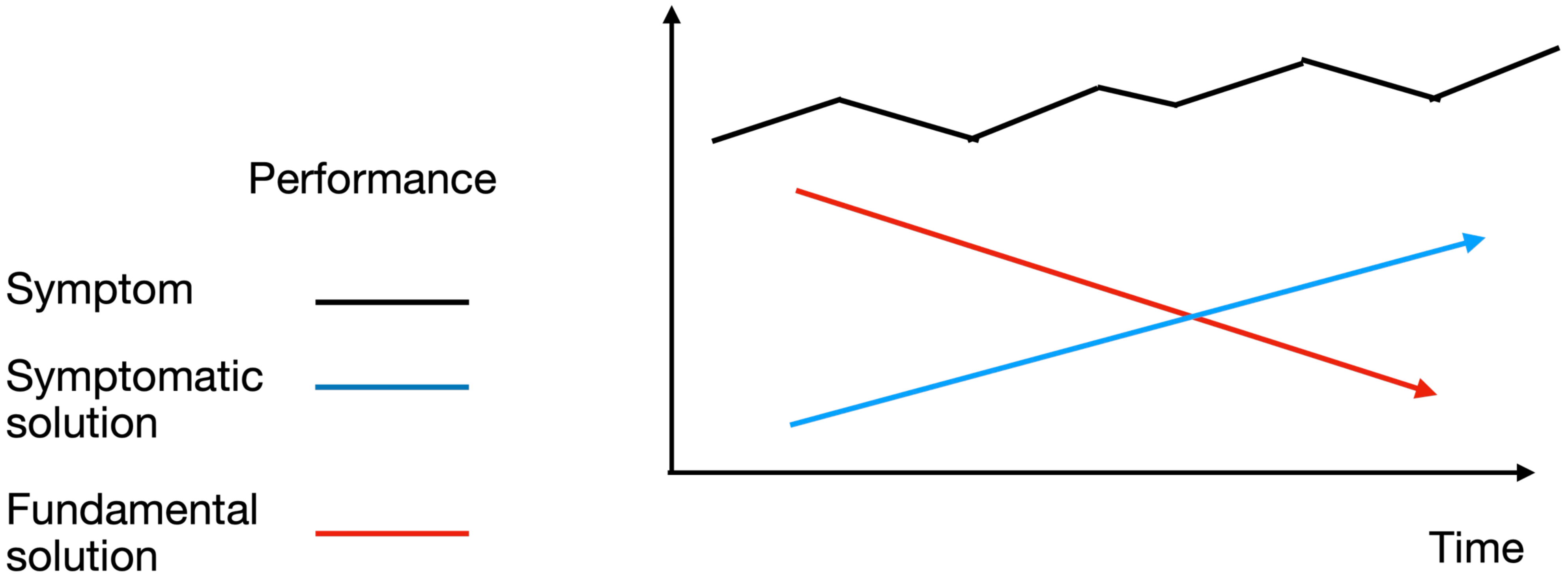
Shifting the Burden

Behavior Over Time



Adapted from: Braun, W. (2002). *The systems archetypes*. https://www.albany.edu/faculty/gpr/PAD724/724WebArticles/sys_archetypes.pdf

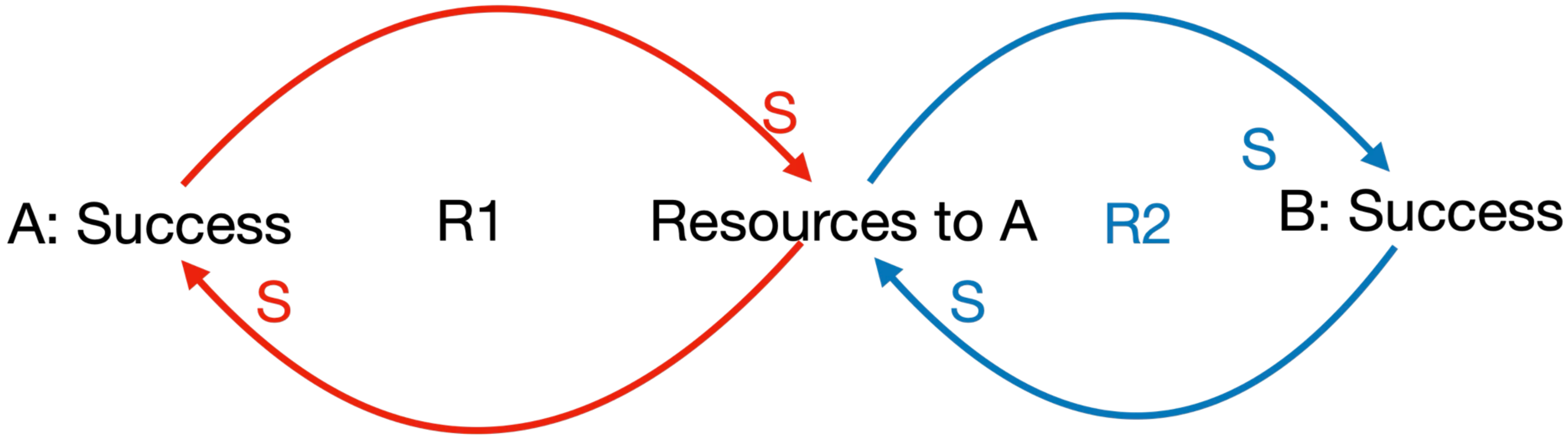
Shifting the Burden

Applications / Examples

- Outsourcing
  - Outsourcing competencies rather than building your own
- Retaining consultants
  - Instead of developing internal talent
- Borrowing money
  - To cover deficit spending
- Self medication
  - Instead of seeking medical professional advice

Success to the Successful Archetype

Structure



Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
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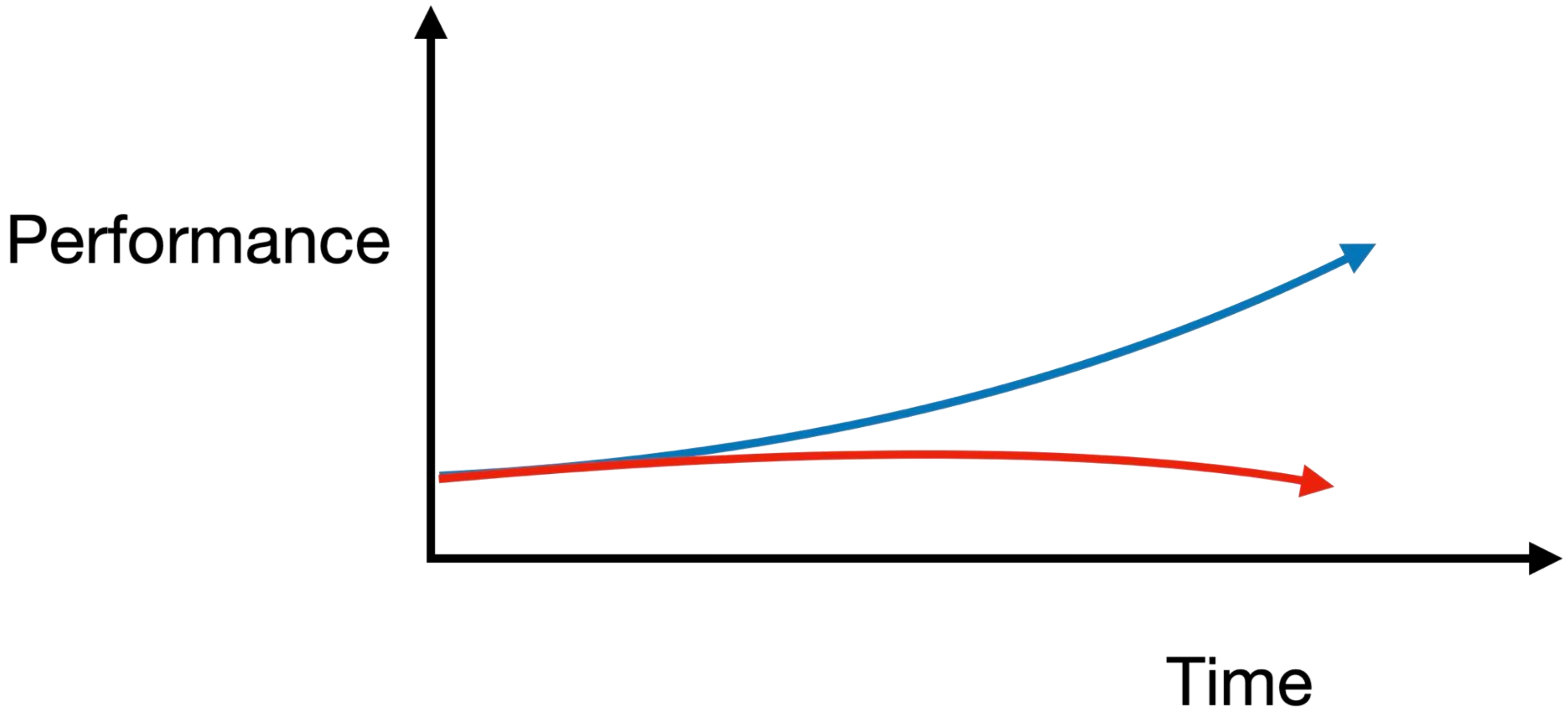
Success to the Successful

Behavior Over Time



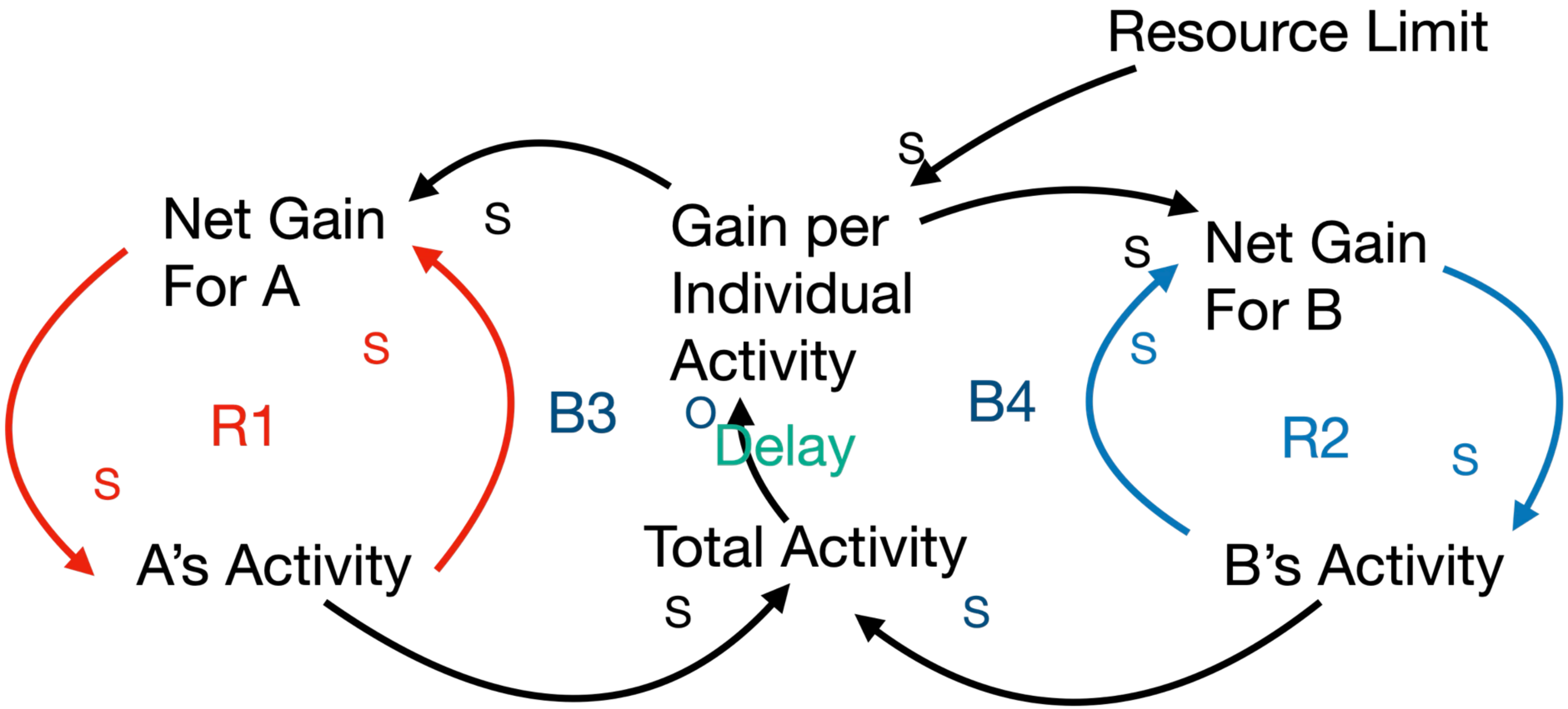
Success to the Successful

Applications

- Economic Success
- Educational Attainment
- Entrepreneurial Success
- Political Success
- Promotional Success
- Social Success
- Survival Success
- Technological Success

Tragedy of the Commons Archetype

Structure



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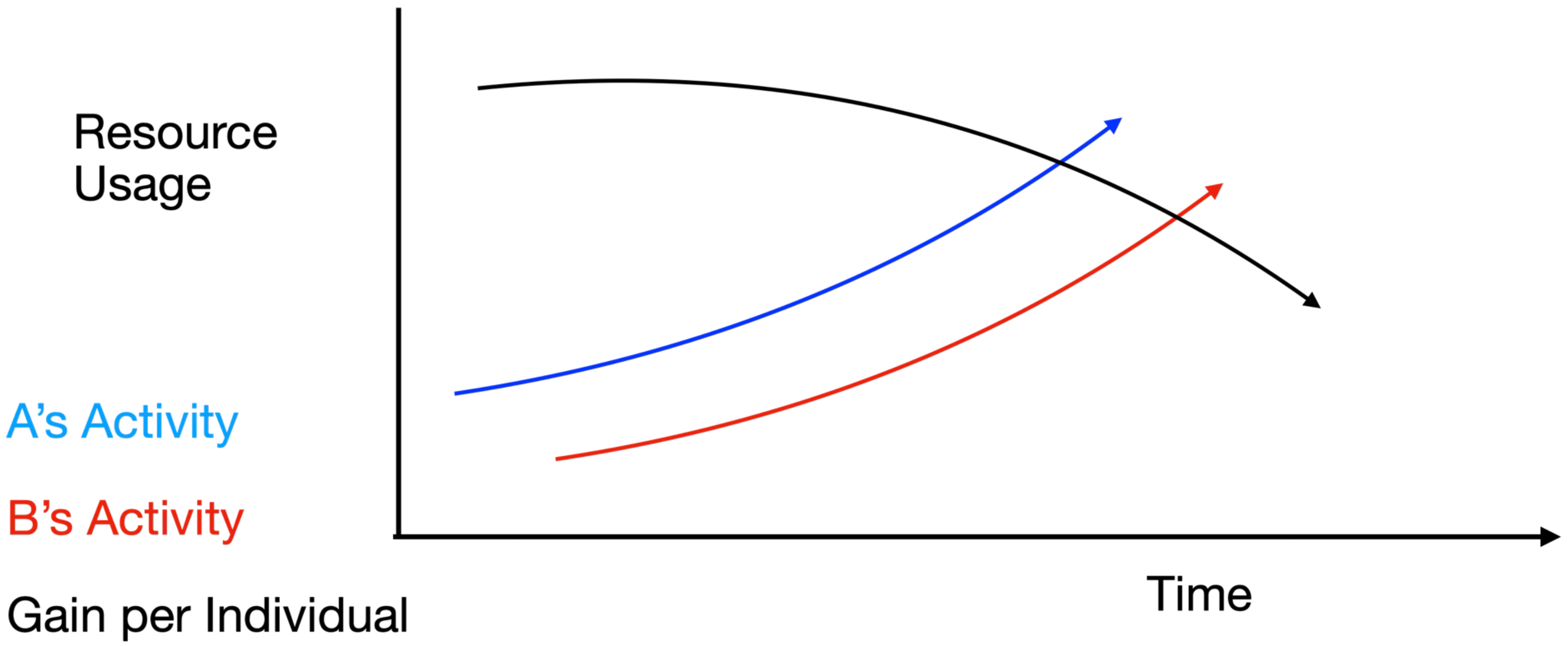
Tragedy of the Commons

Behavior Over Time



Adapted from: Braun, W. (2002). *The systems archetypes*. https://www.albany.edu/faculty/gpr/PAD724/724WebArticles/sys_archetypes.pdf

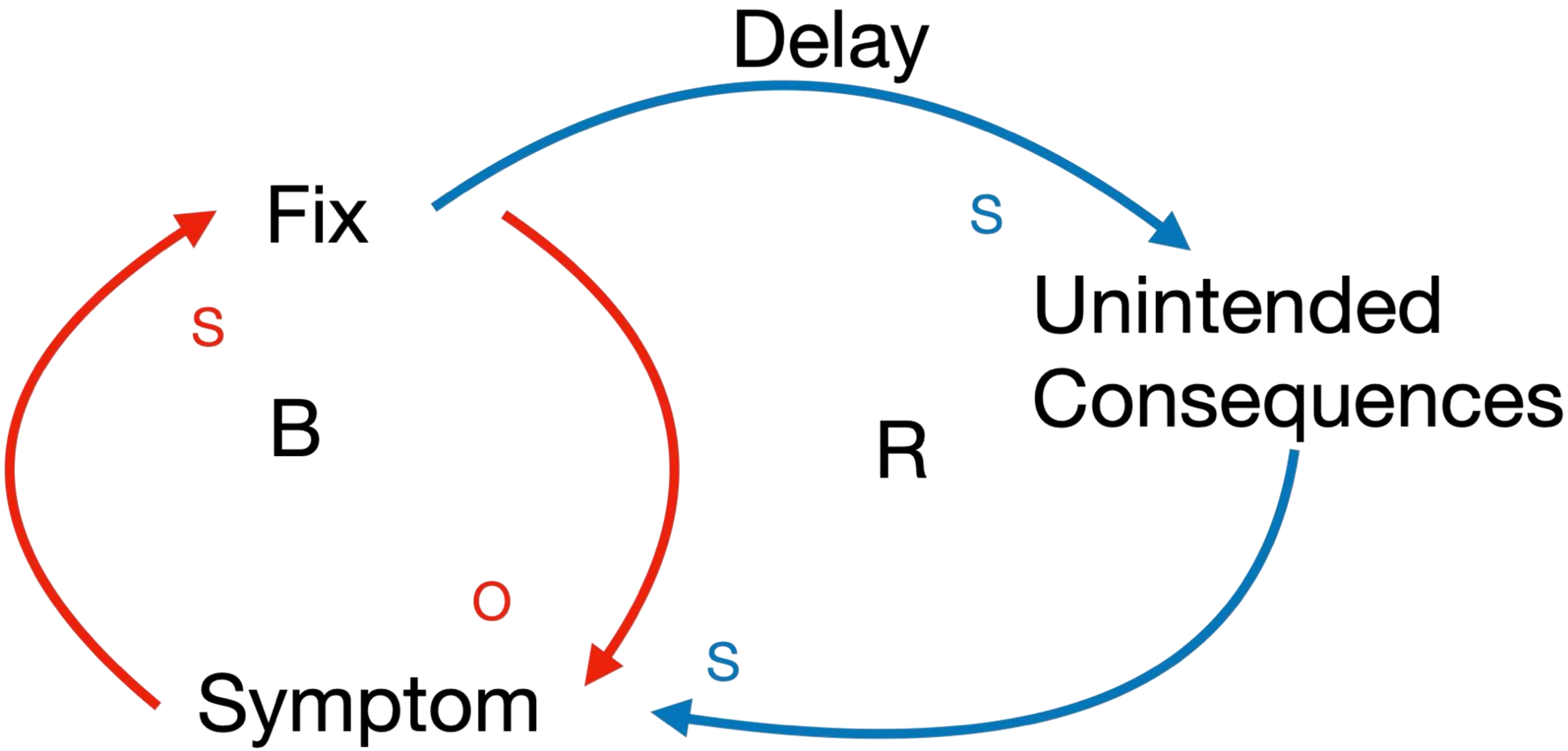
Tragedy of the Commons

Applications / Examples

- Climate change
- Collapse of a resource (fisheries, water, land, law firm)
- Depletion of ground water
- Traffic congestion

Fixes That Fail Archetype

Structure



Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
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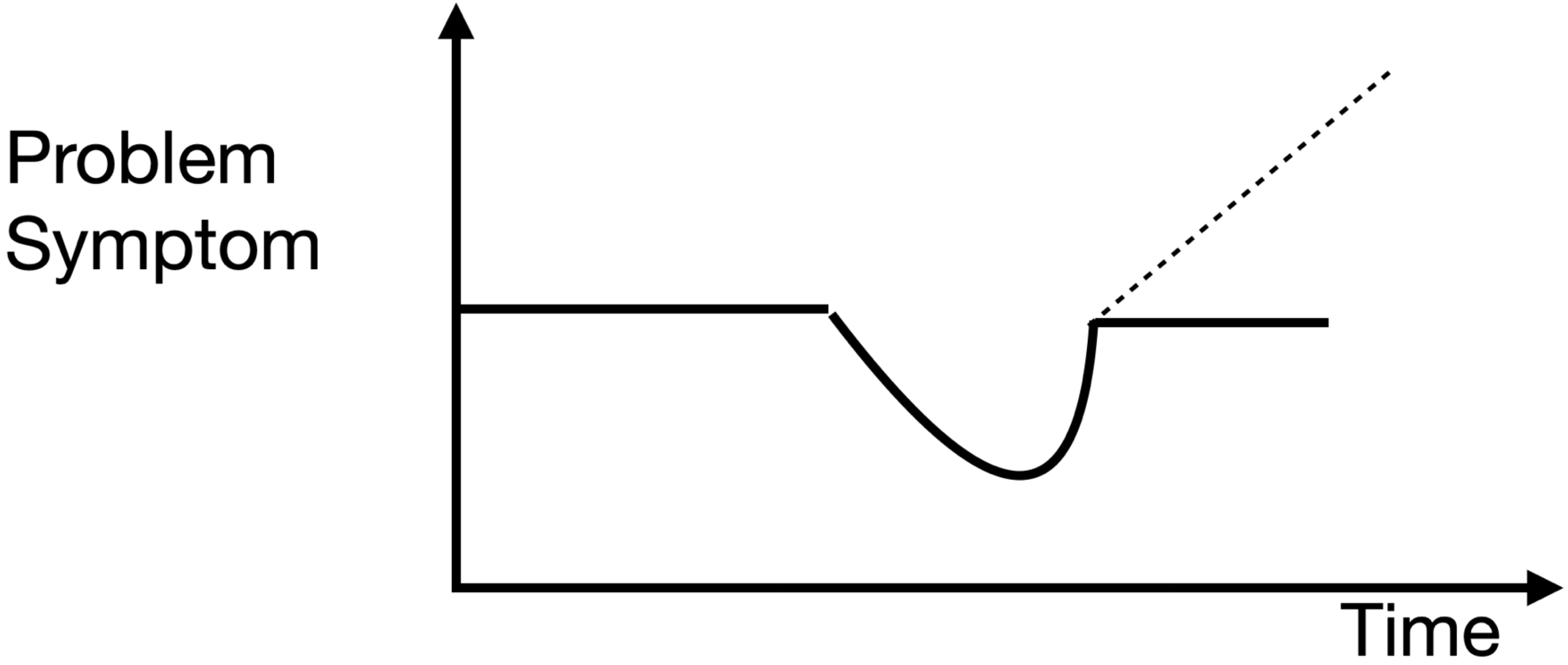
Fixes That Fail

Behavior Over Time



Adapted from: Braun, W. (2002). *The systems archetypes*.
https://www.albany.edu/faculty/gpr/PAD724/724WebArticles/sys_archetypes.pdf

Fixes That Fail

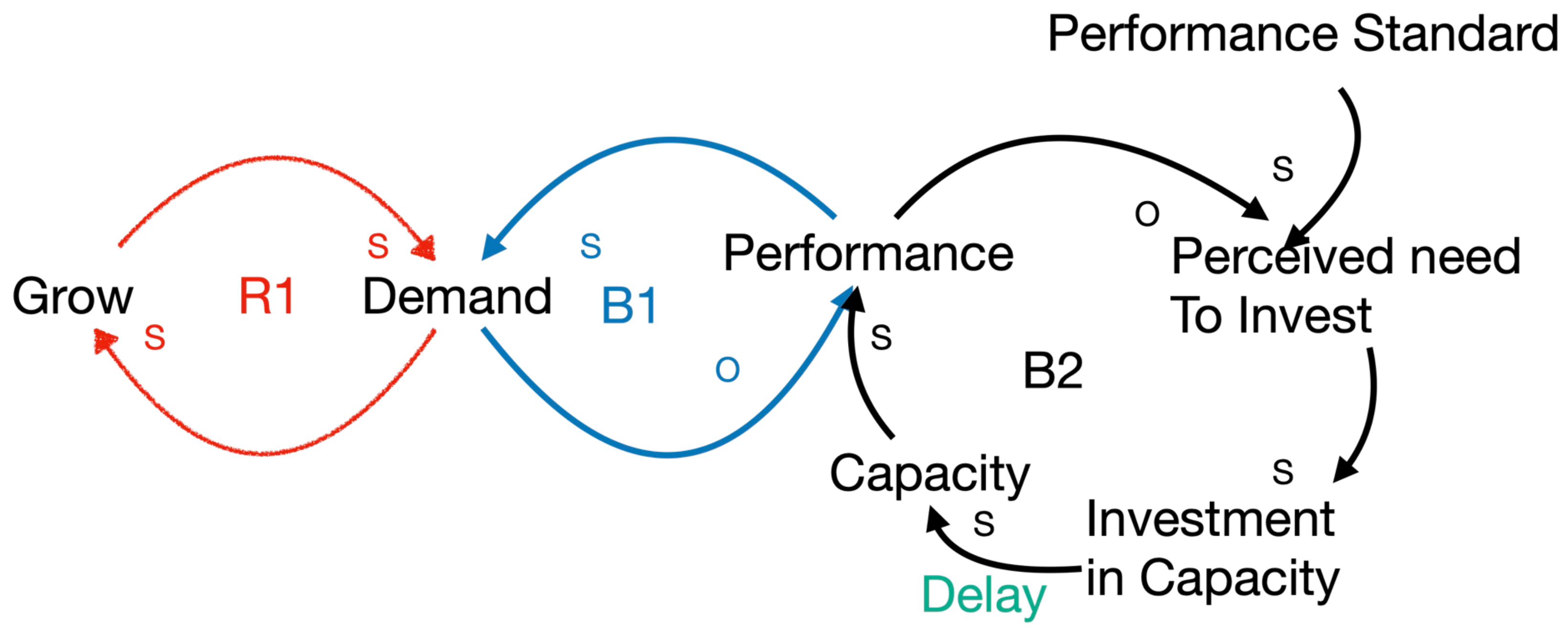
Applications / Examples

- Building more roads
  - But this tends to add more drivers
- Reducing maintenance
  - Money saved in the near term, costs more in the long term
- Replace skilled workers with less skilled workers
  - Money saved in the near term, costs more in the long term

The fix is not necessarily the solution.

Growth and Underinvestment Archetype

Structure



Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

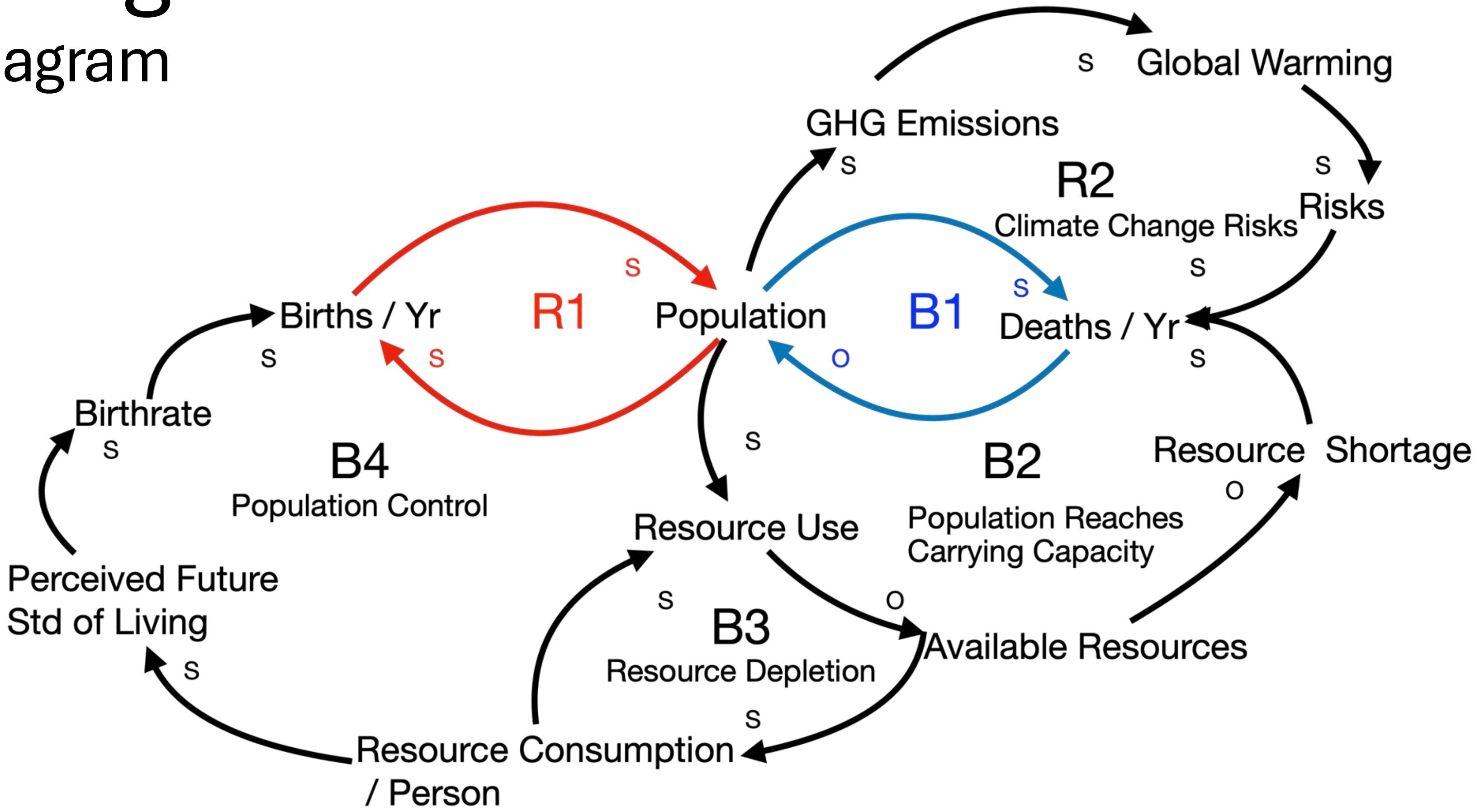
Growth and Underinvestment

Applications and Examples

- Demand and supply become significantly out of balance and investment to meet demand lags creating more problems.
- This is a difficult archetype to find applications in the real world as sometimes, drifting goals is a better and more appropriate fit.

Climate Change

A Causal Loop Diagram



Source: https://www.edrawsoft.com

Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Complex Adaptive Systems

Complex System

A complex system is a group of "agents" existing far from equilibrium, interacting through positive and negative feedbacks, forming interdependent, dynamic, evolutionary networks, that are sensitive dependent, fractionally organized, and exhibit avalanche behavior (abrupt changes) that follow power-law distributions.

Fichter, L.S., Pyle, E.J., & Whitmeyer, S.J. (2010). Strategies and Rubrics for Teaching Chaos and Complex Systems as Elaborating, Self-Organizing, and Fractionating Evolutionary Systems. *Journal of Geoscience Education*. *58*(2)

Complex Adaptive Systems

Complex adaptive systems (CAS) are “composed of elements or agents that learn or adapt in response to interactions with other agents.”

Holland, J. H. (2014). *Complexity: A very short introduction*. Oxford University

Principles of Complex Systems

Possible Additions / Subprinciples to Mobus (2022)

1.1 Systems may be composed of agents
1.2 Systems may be composed of components
1.3 System / subsystems are interdependent
4.1 Systems exist within limits
4.2 Systems have thresholds or tipping points
5.1 Dynamic behavior may be described algorithmically
12.1 Systems are resilient
12.2 Systems are robust
12.3 Systems are resistant
12.4 Systems are sustainable over a near term

See Mobus (2022) for the list of 12 principles.

Additional Principles

Biological and Social Systems

1. Biological and social systems react to threats and opportunities (material, energy, and messages) in their external environment.
2. Artificial, biological and social systems contain internal strengths and weaknesses (agents, internal resources, flow efficiencies, capabilities, strategies,…)

A set of principles specific to artificial, biological, natural, and social may be derived from the set of general principles noted by Mobus (2022). Something to develop.

Principles of Complex Systems (cont)

- Another list of systems principles is found at this link to the Systems Engineering Body of Knowledge.
- These sets of principles are good approaches to thinking about systems.
  - https://www.sebokwiki.org/wiki/Principles_of_Systems_Thinking

Additional Concepts

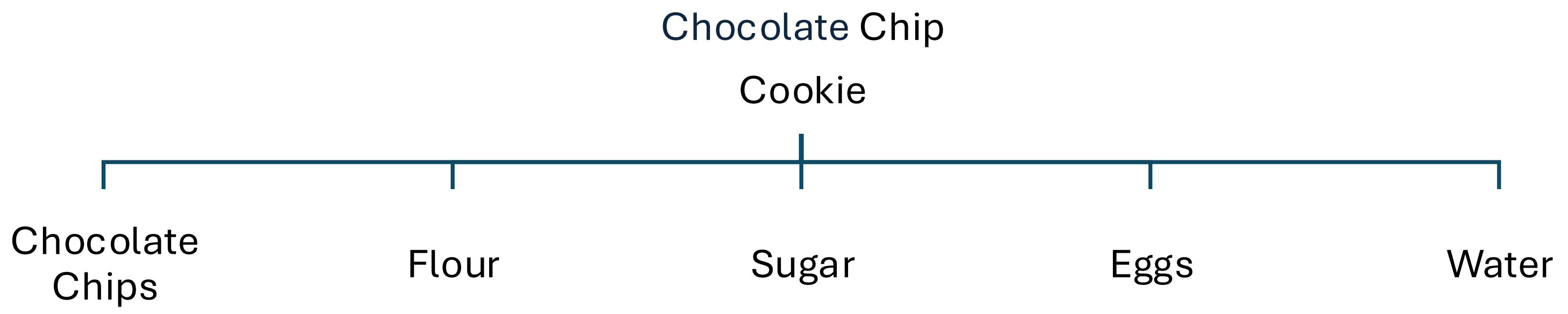
- Abstraction
- Equifinality
- Multifinality

Abstraction

- A focus on essential characteristics and ignoring non-relevant details of something: an idea, a problem, an object ...
- Examples from mathematics
  - The symbol *n* can represent any positive integer from 1 to whatever
  - a + b = b + a for any two integers
  - ab = ba for any two integers

Equifinality

Equifinality is convergence from multiple points or approaches to one final state.



Multifinality

- Divergence from a single state to multiple states.
  - See http://environment-ecology.com/general-systems-theory/379-systems-thinking.html
  - See https://oecd-opsi.org/systemic-governing-applied-systems-thinking-in-practice/

Agents

- An agent is a biotic or abiotic entity that is interactive, can make decisions, and can create or execute / follow an algorithm.
- System elements are referred to by different names such as agent, component, element, entity, object, part, or unit.
- Agents detect, process, and effect material, energy, messages
- An agent's behavior is described by a set of algorithms
- Agents may be tagged or identified, such as a manager, a cat, a dog, a star system, a tree, an app
- Agents may be aggregated into meta-agents, such as a management team, a set of cats or dogs, a galaxy

Relationships

- Describe connections and flows (links) among the parts of the system and subsystems as well as from sources and to sinks external to the system.
- Flows along these links include:
  - Material
  - Energy
  - Messages

Relationships

Types

- Strong / weak
- Attract / repel
- Competitive / cooperative
- Necessary
- Synergistic
- Redundant

Relationships

Among Parts of Systems

- Precedence (order)
- Specialization (is-a)
- Inclusion (is contained in)
- Use (used and reusable)
- Consumed (used and not reusable)
- Transformation (changes to)
- Composition (is part of)
- Transitional (becomes)
- Associative (other)

Source: DMR / Fujitsu

Relationships

Precedence Examples

1. Input raw materials
2. Store as inventory
3. Subassembly
4. Finished goods inventory
5. Sale to customer

Precedent relationship are equivalent to path dependent.

Relationships

Specialization (is-a)

- A dog *is a* mammal
- Helium *is an* element
- IBM *is an* organization
- Microsoft Word *is* software
- Our sun *is a* star

Relationships
Inclusion (is contained in)

- Blood *is contained* in a human body
- Books *are included* in a library
- Hydrogen and oxygen atoms *are contained* in H2O or water
- Information i*s contained* in starlight
- Our sun is *included* in the Milky Way galaxy

Relationships
Use (used and reusable)

- Dishes *are used* in preparing and eating dinner
- Software *is used* to describe behavior in systems
- Telescopes *are used* to observe celestial objects

Relationships

Consumed (used and not reusable)

- Firewood *consumed* in a fireplace
- Fuel *consumed* in producing energy
- Ingredients *consumed* in cooking dinner

Relationships

Transformation (changes to)

- A caterpillar *transforms* into a butterfly.
- Fuel *is transformed* into energy
- Raw materials *are transformed* into finished products
- Sunlight *is transformed* into energy

Relationships

Composition (is part of)

- Hydrogen atoms *are part of* a water molecule
- Subroutines *are part of* a software application
- Tires *are part of* a car

Relationships

Transitional (becomes)

- Boiling water *becomes* steam
- Stellar gas *becomes* a different celestial object over time

Relationships

Associative (other)

- Agent A *consults with* Agent B
- Attorney B *represents* Citizen C
- Doctor D *treats* Patient P
- Electrical energy E *heats* a home
- Material M *flows from* source Src to sink Snk
- Material M *flows from* stock S1 to stock S2
- Material M *is 95% recyclable*
- Message M *flows from* source Src to sinks Snk (1, ..., n)

Relationships

Data

- One to one
- One to many
- Many to one
- Many to many

Relationships
Interderpendencies

- Agents are interdependent with other agents
  - Agents may trade with other agents
  - Agents may cooperate with other agents to achieve something
  - Agents may consult with other agents
  - Agents may provide inputs to other agents
  - Agents may express outputs to other agents

Relationships

Social

- Business
- Collaborative
- Competitive
- Family
- Friendship
- Interpersonal
- Professional
- Romantic

Complex Adaptive Systems
Properties and Mechanisms

- Tags (Mechanism)
- Aggregation (Property)
- Nonlinearity (Property)
- Diversity (Property)
- Flows (Property)
- Building Blocks (Mechanism)
- Internal Schema (Mechanism)

Holland, J. H. (1995). *Hidden order: How adaptation builds complexity*. Basic Books.

Tags

Mechanism

- Tags are a mechanism that facilitates the formation of aggregates
- Examples: flags, titles, religion, role, size, color, type, shape…
- Provide a basis for filtering, specialization, cooperation, selection
- The mechanism behind hierarchical organization

Aggregation

Property

- An approach to simplifying complex systems
- For example, we aggregate similar things into categories—schools, buildings, food—and then we treat them as a single abstract unit.
- Aggregation is an approach to constructing models
  - Aggregate sales of companies into GDP
  - A forest is an aggregation of different type of trees and such
  - Organizations of similar types can be aggregated into corporations, non-profits, and so on
  - Stars can be aggregated or classified into white dwarfs, binary, ...
  - Software can be aggregated into operating systems, apps, ...

Aggregation

Information Organization Patterns

- Alphanumeric
- Chronological
- Color
- Geography
- Hierarchical
- Size
- Type

Agents can be aggregated in a few possibilities.

Examples of types: clusters of managers, technical staff, ...

Organization charts are organized by hierarchy

May organize by the size of cities, countries, ..

Nonlinearity

Property

- A nonlinear function of one or more variables
- Not a linear sum of variables such as $w = ax + by + cz$
- Exponential growth and decline are examples of nonlinearity
- A community example could be a YouTube video going viral

Diversity
Property

- The variety of agents within a system
- A city may contain hundreds to thousands of different types of businesses
- A country may contain several regions
- A city may contain a variety of communities
- A community may contain a variety of populations
- Diversity is maintained via innovation (positive feedback)
- Diversity is lost by selection (negative feedback)

Diversity

Property

- Diversity in complex adaptive systems arises by chance and imperfection, recombination, and in social sciences by innovation and foresight.
- Diversity means more than simply having a range of different individuals, strategies, or populations.
- From the perspective of the entire system, diversity means having a greater range of options for responding to environmental change and a corresponding higher likelihood that a solution to a particular problem will be found.

Norberg, J., & Cumming, G. S. (Eds.) (2008). *Complexity theory for a sustainable future*. Columbia University

Flows

Property

- A transfer of material, energy, or messages across a network of agents within a system
- For example, electronic mail flows across a set of computers, from source to target via connections
- Money flows across a set of agents from a source (company, agency, ...) to employees to retailers .....
- Packages flow across a network of suppliers, delivery services, and customers.

Building Blocks
Mechanism

- Reusable objects (components, parts, subsystems, and such) that can be combined and recombined in new ways, which determine a systems appearance
- Building blocks in smartphones include apps, chips, screens
- Examples of community building blocks include organization charts, document templates, contracts, meeting sites, and such.
- All objects are composed of one or more of the 94 elements in nature.

Internal Models or Schema

Mechanism

- Structures within agents enabling the prediction and anticipation of consequences
- Internal models develop from interactions with the environment
- An example of a community internal model would be a set of response rules (if then else) for processing environmental signals

Complex Adaptive Systems

Some Properties

- Adaptable
- Emergence
- Exhibit positive / negative feedback
- Environment
- Life cycle
- Mitigation
- Possibly evolvable / co-evolvable
- Sensitive dependence on initial conditions

Other Systems Thoughts

- Adaptable and flexible systems are more robust than non-adaptable systems
- Systems may be sustainable in the short term, but not in the long term
- Systems that exhibit replication, variation, and selection will evolve.
- Systems that self-organize, evolve

Emergence

- Emergence refers to new structures, patterns, and properties as complex systems continue to self-organize and evolve.
- Emergence refers to the existence or formation of collective behaviors — what parts of a system do together that they would not do alone.
  - Source: https://necsi.edu
- Examples
  - Hurricanes
  - Storms
  - Water (Combines two atoms of hydrogen and one of oxygen)

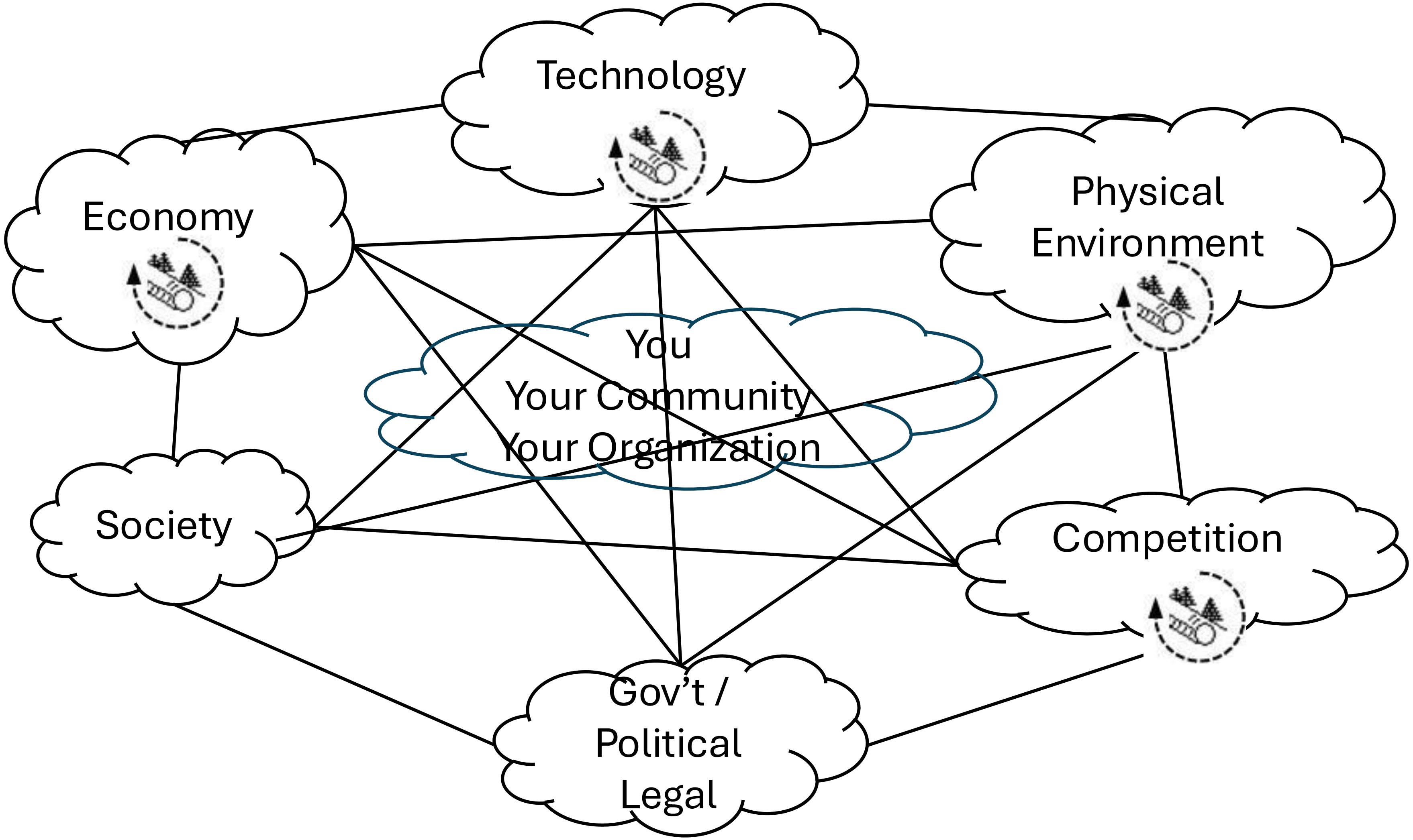
The Environment (for Social Organizations)

A complex network

- The external environment for social organizations is the economy, technology, government / legal / military, social systems, the physical environment, and competitive systems.
- Each of these systems is itself, a complex adaptive system.
- Each of these complex adaptive systems interacts with each other via material, energy, and messages.
- The technology environment changes the fastest with government / legal / and military systems changing the slowest. In between are the economy, the physical environment, society, and competitive systems.

The Environment (for Social Organizations)

A complex network



Note: Each of these systems is a complex adaptive system.

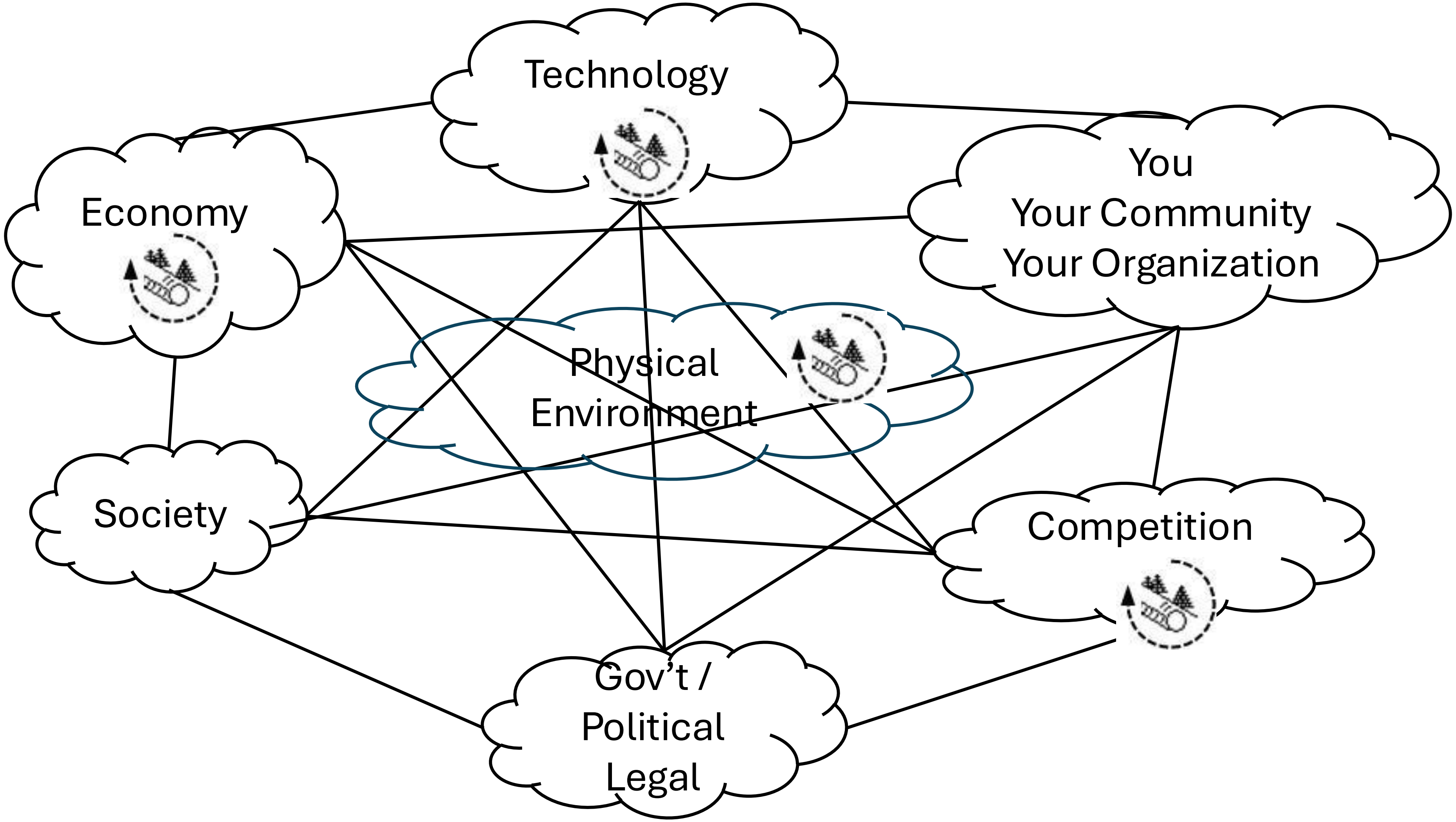
The Environment (for the Physical Environment)

A complex network

- The external environment for the physical environment is the economy, technology, government / legal / military, social systems, local social organizations / community, and competitive systems.
- Each of these systems is itself, a complex adaptive system.
- Each of these complex adaptive systems interacts with each other via material, energy, and messages.
- The technology environment changes the fastest with government / legal / and military systems changing the slowest. In between are the economy, local organizations / community, society, and competitive systems.

The Environment (for The Physical Environment)

A complex network



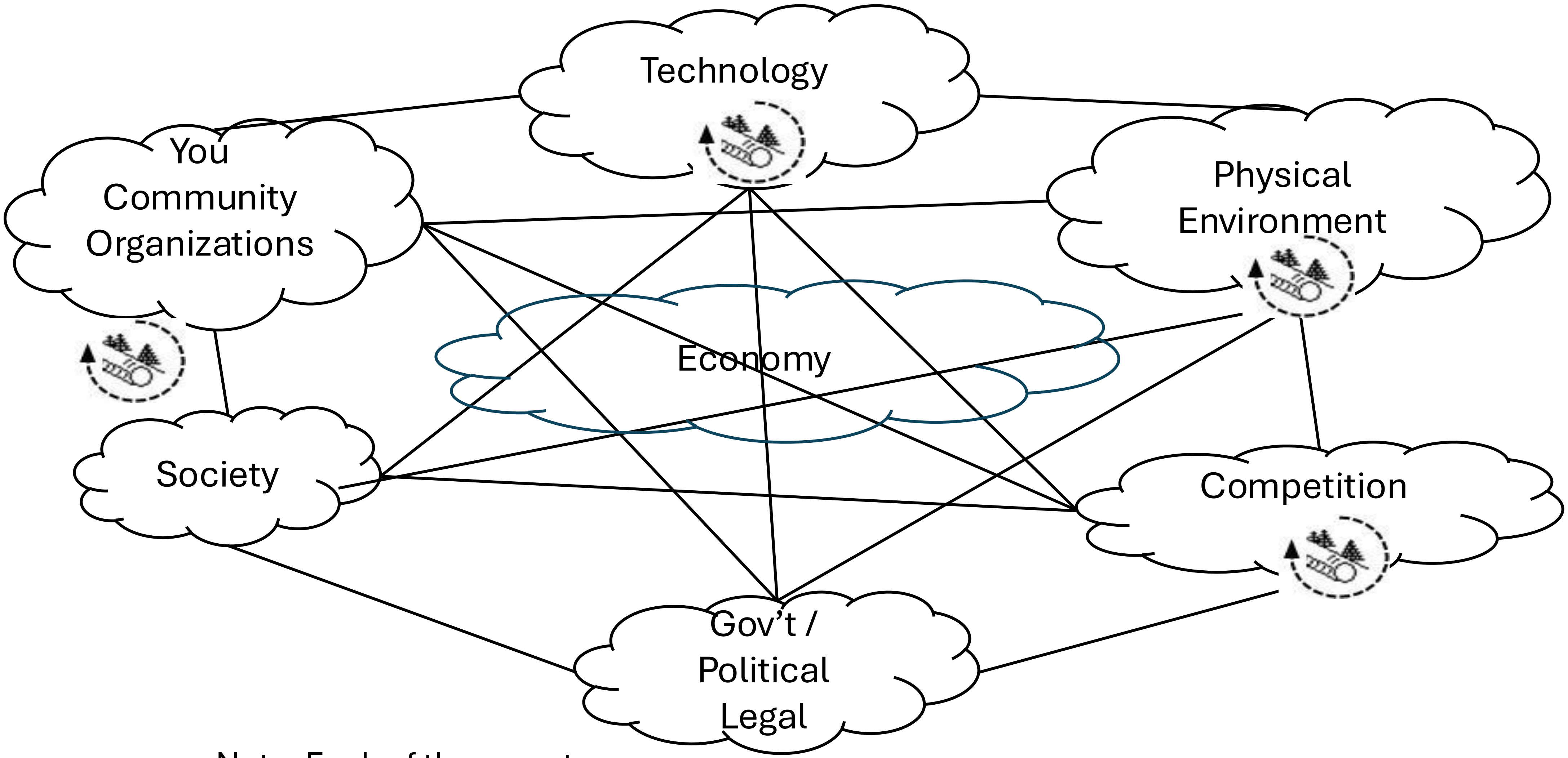
Note: Each of these systems
is a complex adaptive system.

The Environment (for the Economy)
A complex network

- The external environment for the economy is technology, government / legal / military, social systems, local social organizations / community, the physical environment, and competitive systems.
- Each of these systems is itself, a complex adaptive system.
- Each of these complex adaptive systems interacts with each other via material, energy, and messages.
- The technology environment changes the fastest with government / legal / and military systems changing the slowest. In between are the economy, local organizations / community, society, and competitive systems.

The Environment (for the Economy)

A complex network



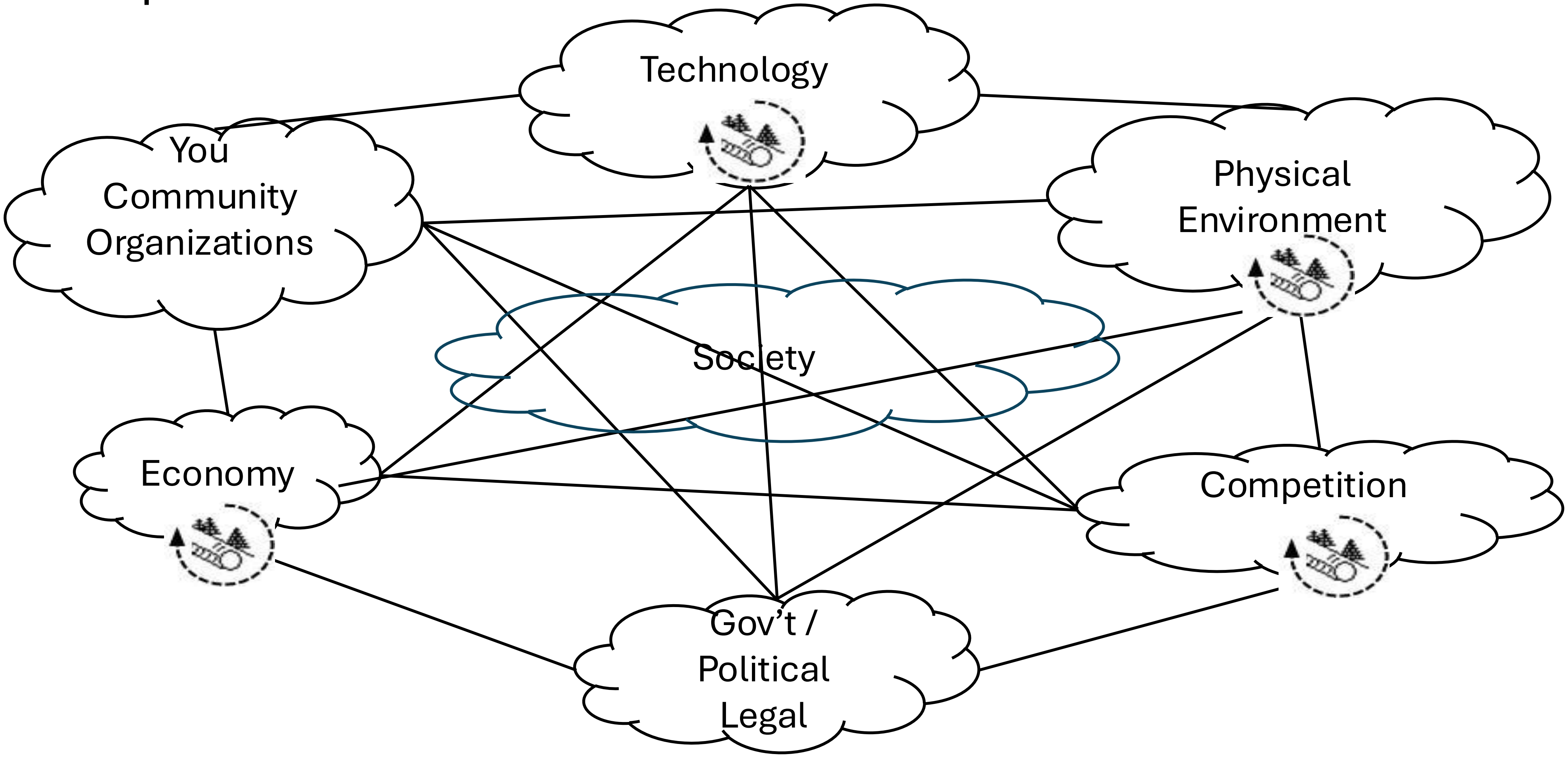
Note: Each of these systems
is a complex adaptive system.

The Environment (for Society)
A complex network

- The external environment for society is technology, government / legal / military, the economy, local social organizations / community, the physical environment, and competitive systems.
- Each of these systems is itself, a complex adaptive system.
- Each of these complex adaptive systems interacts with each other via material, energy, and messages.
- The technology environment changes the fastest with government / legal / and military systems changing the slowest. In between are the economy, local organizations / community, society, and competitive systems.

The Environment (for Society)

A complex network



Note: Each of these systems
is a complex adaptive system.

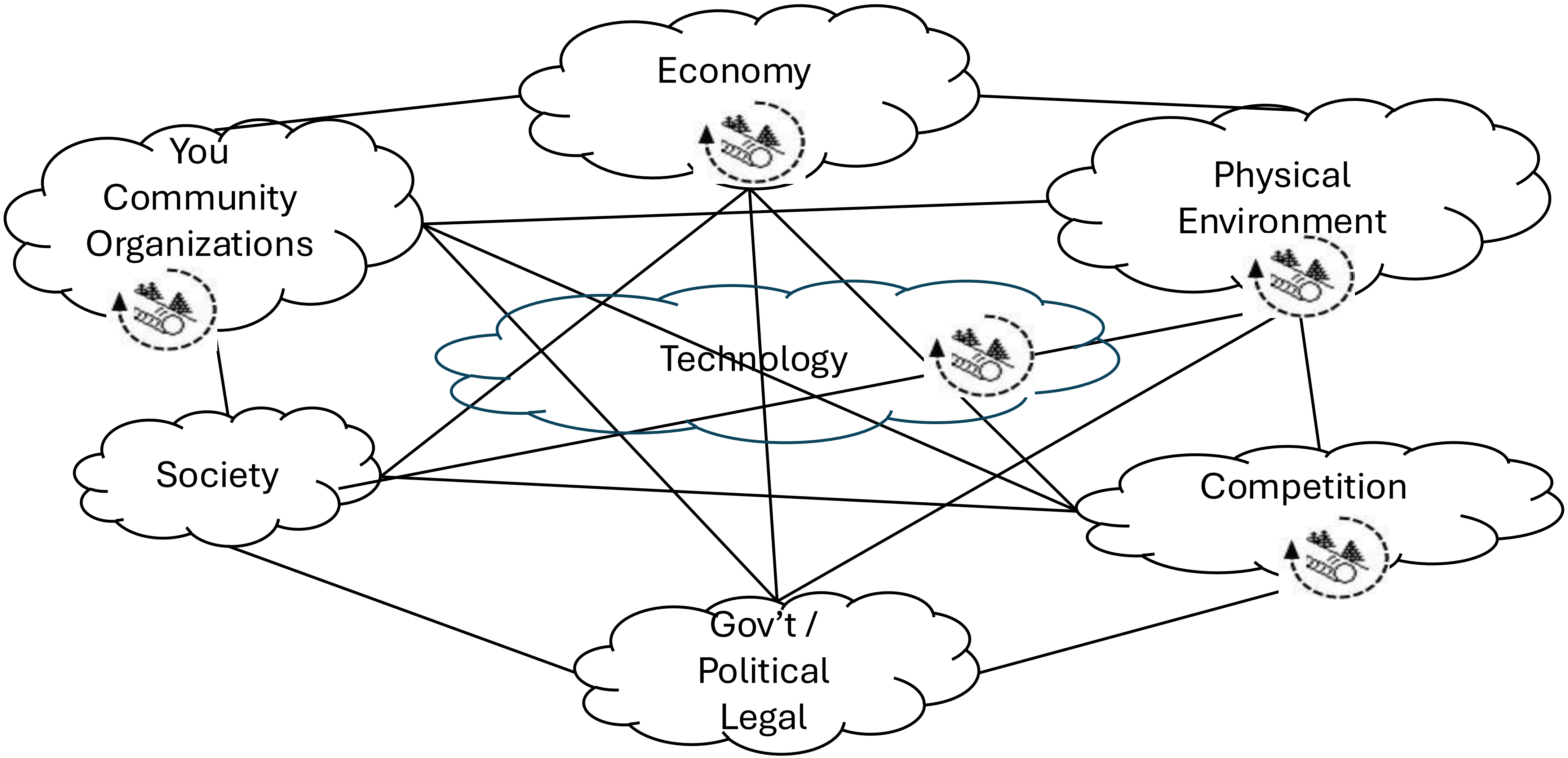
The Environment (for Society)

A complex network

- The external environment for society is technology, government / legal / military, the economy, local social organizations / community, the physical environment, and competitive systems.
- Each of these systems is itself, a complex adaptive system.
- Each of these complex adaptive systems interacts with each other via material, energy, and messages.
- The technology environment changes the fastest with government / legal / and military systems changing the slowest. In between are the economy, local organizations / community, society, and competitive systems.

The Environment (for Technology)

A complex network



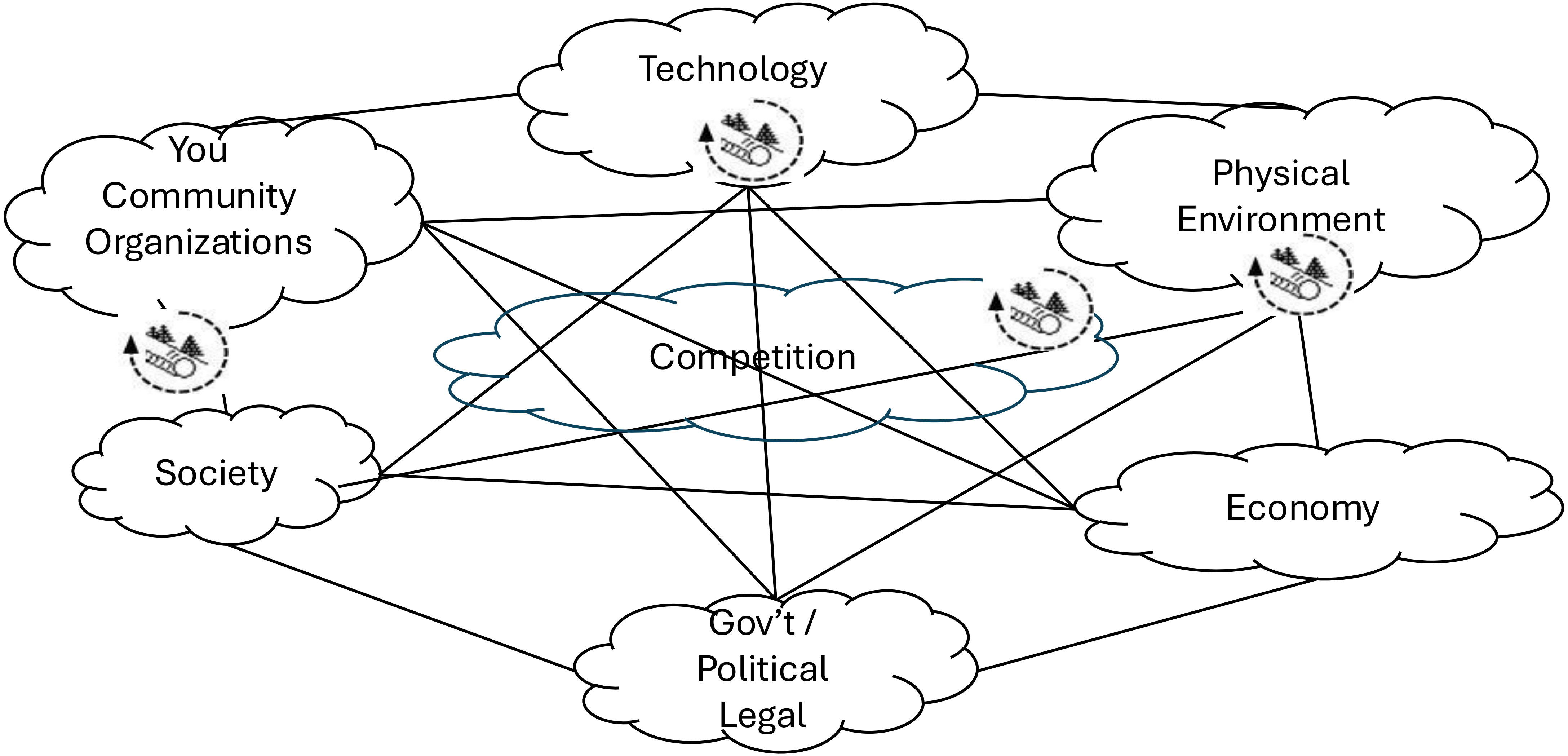
Note: Each of these systems is a complex adaptive system.

The Environment (for Competition)

A complex network

- The external environment for competition is technology, government / legal / military, social systems, local social organizations / community, the physical environment, and the economy.
- Each of these systems is itself, a complex adaptive system.
- Each of these complex adaptive systems interacts with each other via material, energy, and messages.
- The technology environment changes the fastest with government / legal / and military systems changing the slowest. In between are the economy, local organizations / community, society, and competitive systems.

The Environment (for Competition)
A complex network



Note: Each of these systems is a complex adaptive system.

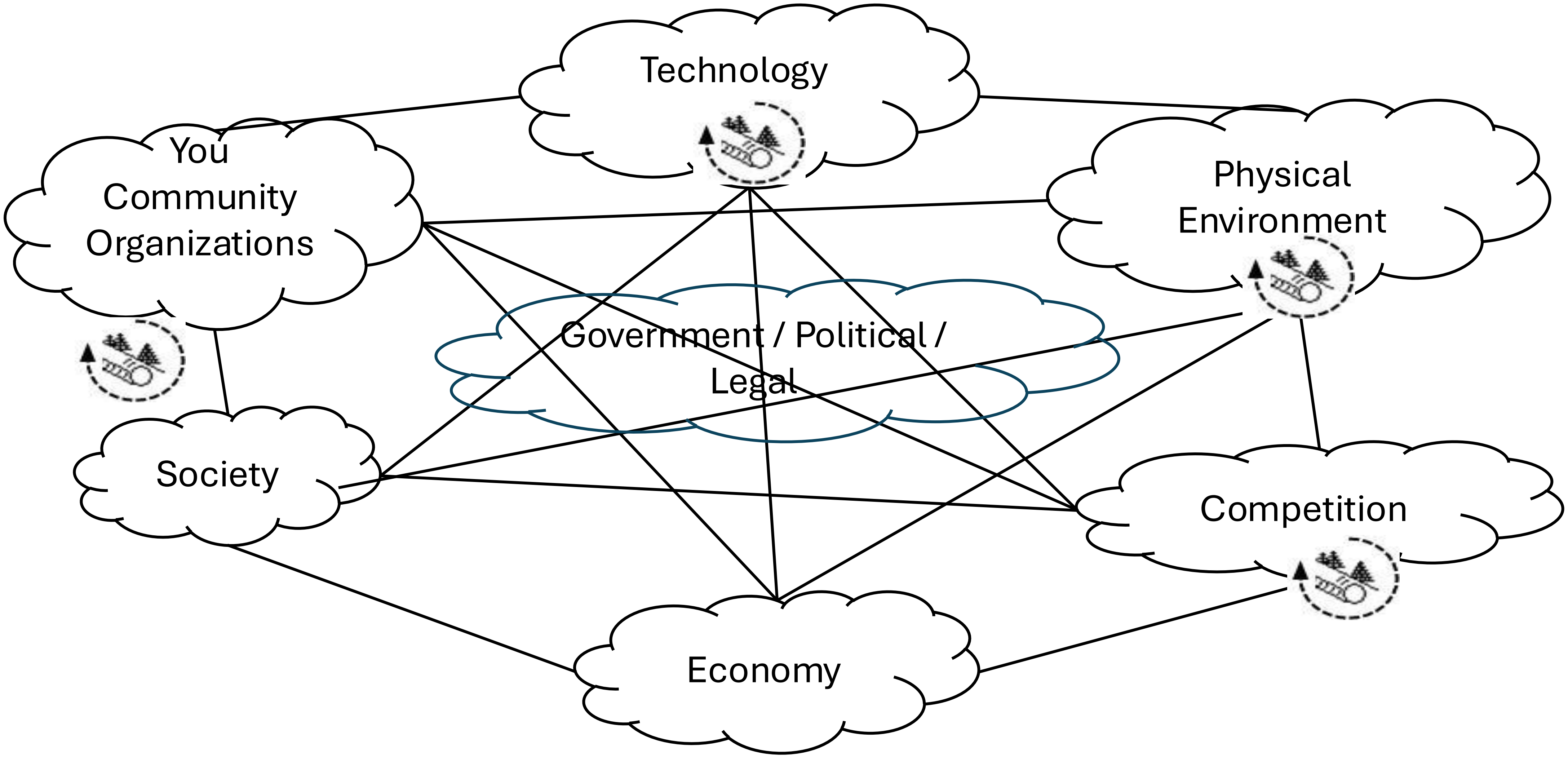
The Environment (for Government)

A complex network

- The external environment for government is technology, social systems, local social organizations / community, the physical environment, the economy, and competitive systems.
- Each of these systems is itself, a complex adaptive system.
- Each of these complex adaptive systems interacts with each other via material, energy, and messages.
- The technology environment changes the fastest with government / legal / and military systems changing the slowest. In between are the economy, local organizations / community, society, and competitive systems.

The Environment (for Government)

A complex network



Note: Each of these systems is a complex adaptive system.

Sensitive Dependence on Initial Conditions

A property of chaotic systems that describes how small differences in initial conditions can lead to significant differences in the future.

Also known as a butterfly effect.

SDIC means that specific predictions are impossible

Systems Model

- Applying the reporters' questions to material, energy, and messages (information +) leads to:
  - Who: Vendor, provider, supplier …
  - What: Product, service
  - Where: source and sink
  - When: Frequency, time, date,
  - Why: Rationale, goals, objectives
  - How Much: Cost, time

Systems Model

Material
Energy
Messages

Supplier
Product, service, quantity, quality, size, shape
Source, sink
Frequency, time, date
Rationale
Cost

For each MEM, there are several elements.

Systems Are Constrained

Theory of Constraints

- All systems have constraints or limits.
- A constraint is something that prevents a system from achieving goal.
- Systems have at least one constraint and possibly more but a limited number.
- Constraints may be internal or external.
- An internal constraint exists when demand is more than a system can produce.
- An external constraint exists when a system can produce more than the demand.
- Types of (internal) constraints are categorized by materials, energy, messages) (MEM).
  - Examples: Lack of skilled agents, limited resources, outdated equipment, outdated policies, and so on
- Reducing constraints may improve systems performance.
- Think about a chain being as strong as its weakest link.

Evolutionary Systems

Evolution

Definition

Evolutionary change is any process that leads to increases in complexity, diversity, order, and / or interconnectedness.

In other words, evolution occurs when a system changes via repeated cycles of reproduction / replication / propagation with variation, selection, and amplification.

Three types of evolution are elaboration, self-organization, and fractionation.

Evolution may be planned (intentional) or unplanned (unintentional).

Fichter, L.S., Pyle, E.J., & Whitmeyer, S.J. (2010). Explanding evolutionary theory beyond Darwinism, with elaborating, self-organizing, and fractionating complex evolutionary systems. *Journal of Geoscience Education*. *58*(2), 58-64.

Evolution

Definition

Elaboration evolution is an algorithm—a general evolutionary algorithm with three key cyclical steps: (a) **reproduction / replication / copying / propagation** with **variation / differentiation**, (b) **selection**, and (c) **amplification / retention**. **Repeat**.

Self-organization and fractionation are described by different algorithms such as attraction, common interests, or forces such as gravity, electromagnetism, and the two nuclear forces.

Algorithms also describe selection and amplification processes as well as mechanisms such as crossover and mutation.

Beinhocker, E. D. (2010). *Evolution as computation: Implications for economic theory and ontology.* Retrieved from http://www.santafe.edu

Evolution

Definition

- A gradual process by which artificial, biological, natural, and social systems undergo changes over time and possibly many generations
- Basic evolutionary processes are propagation with variation, selection, and retention / inheritance.
- If something exists, it is because of evolution
- The outcome of evolution generates the emergence of new species, technologies, ideas, functions and so on often leading to increased complexity and diversity.
- Mechanisms include
    - Innovation, market competition, economic factors, feedback in artificial evolution.
    - Genetic variation, natural selection, sexual selection, mutations in biological evolution
    - Climate, weather, heat, fusion reactions, gravity, strong and weak nuclear forces in natural systems
    - Innovation, competition, strategic planning, leadership, feedback in social systems

Evolutionary Systems

Types

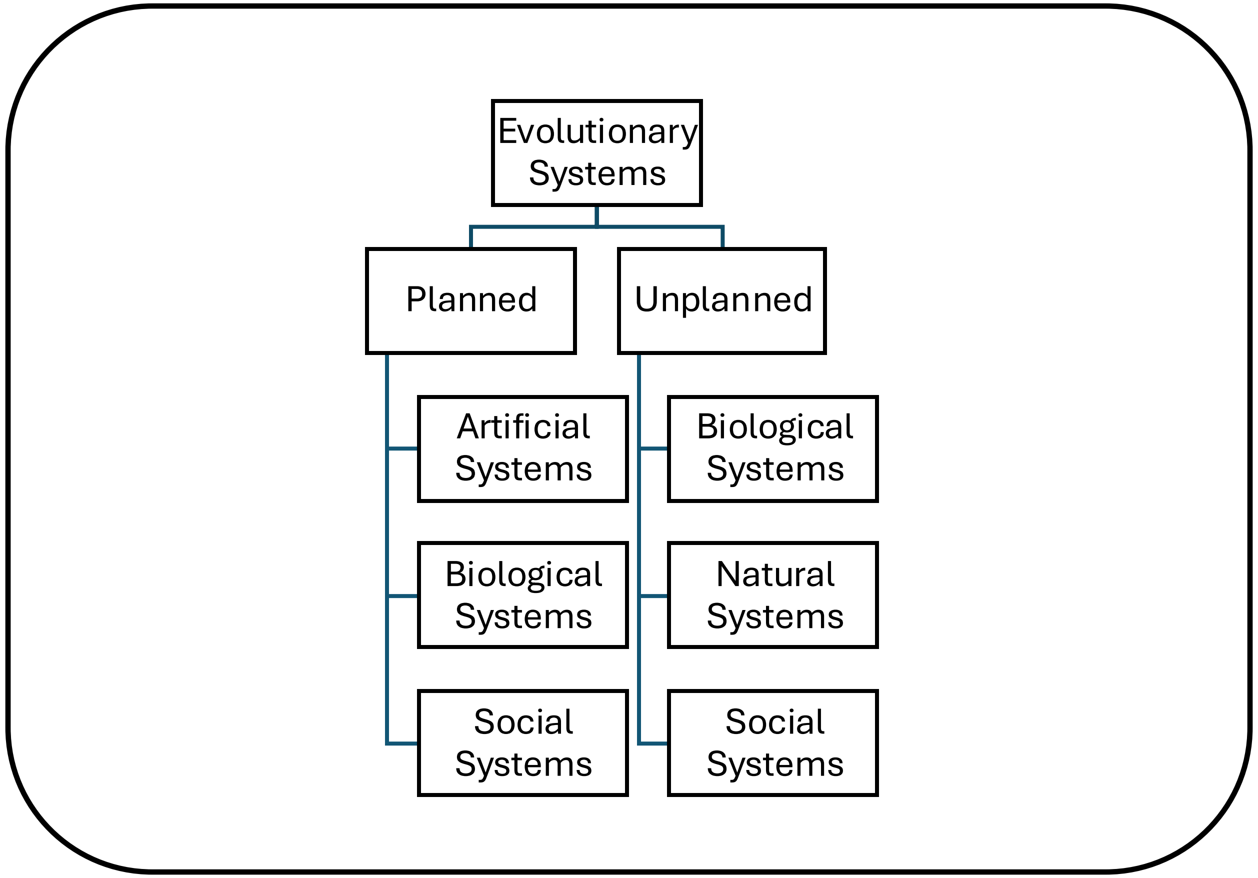
- Artificial (Artificial Life, Artificial Societies, Cities, Software
- Biological (Flora, Fauna)
- Natural (Atmosphere, Earth, Solar System, Universe, ...)
- Social (Civilizations, Political Parties, Organizations, ...)

Evolutionary Systems
Examples

- Artificial life (elaboration)
- Cities (elaboration, self-organization)
- Culture / religion (elaboration, self-organization)
- Economies (self-organization)
- Ecosystems (elaboration, self-organization)
- Ideas (elaboration, self-organization)
- Language (elaboration, self-organization)
- Life (elaboration, self-organization)
- Organizations (elaboration, self-organization)
- Religion (elaboration, self-organization)
- Software (elaboration)
- Technology (elaboration)

Evolution Systems

Planned and Unplanned Systems



Evolution

- Once something comes into existence (origin), its performance is evaluated based on its fitness.
  - If fit, it lives to be reproduced, replicated, or copied and possibly varied, and then the cycle repeats.
  - If unfit, it dies
- Origin could be from an idea, an experiment, self-organization, a plan or many other possibilities. The origin object must be subject to the laws of physics and chemistry.
- Not everything possible will exist given limits of time and resources. The possibility space >> time and resources.

Elaboration Evolution

Differentiation

- Differentiation / variation occurs from planned or intentional changes in artificial, biological, and social systems.
  - Mechanisms include experimentation, discovery, problem solving, sexual selection.
- Differentiation / variation occurs from unplanned or unintentional changes in biological, natural, and social systems.
  - Mechanisms include crossover, mutation, and variations in reproduction or replication.

Elaboration Evolution

Selection

- Selection is a process that acts to reduce diversity or numbers (negative feedback)
  - Natural and sexual selection are examples in biology that act to reduce the diversity of life
  - Decision making is a selection process in artificial, planned biological, and social systems.

Elaboration Evolution

Amplification

- Amplification is a process that acts to increase diversity or numbers (positive feedback)
  - Reproduction in biology acts to increase the diversity of life
  - Decision making is a process that acts to increase diversity in artificial, planned biological, and social systems.
  - Retention and heredity are key factors in biology while retention of resources is a key factor in artificial, natural, and social systems.

Self-Organization Evolution

- Selection works on self-organization evolution as well as elaboration evolution.
  - If something is created via self-organization such as a new social system or celestial object, selection acts on it for fitness.
    - If it is fit for its purpose, it may survive. If not, its existence ends.
- Self-organization is achieved via a change in internal structure or function as a response to changes in its internal and/or external environment.
  - The outcome may be an increase in internal complexity resulting in new / improved structures and behaviors.
- Examples of self-organization include countries, cities, organizations, stars, planets, comets, ….

Fractionation

- Selection works on fractionation evolution as well as elaboration evolution and self-selection
  - If something is created via fractionation such as a refined sugar or oil, selection acts on it for fitness.
    - If it is fit for its purpose, it may survive. If not, its existence ends.

Evolutionary Systems

Information Theory

- Data, information, and knowledge, are retained (in part) in social systems as they evolve.
  - Similar to DNA, which is also a form of information
  - As social systems evolve via differentiation, selection, and amplification / retention, information is retained in part
  - Example: A new form of organization such as an LLC may retain information about suppliers, products, services, customers, government agencies, and so on.

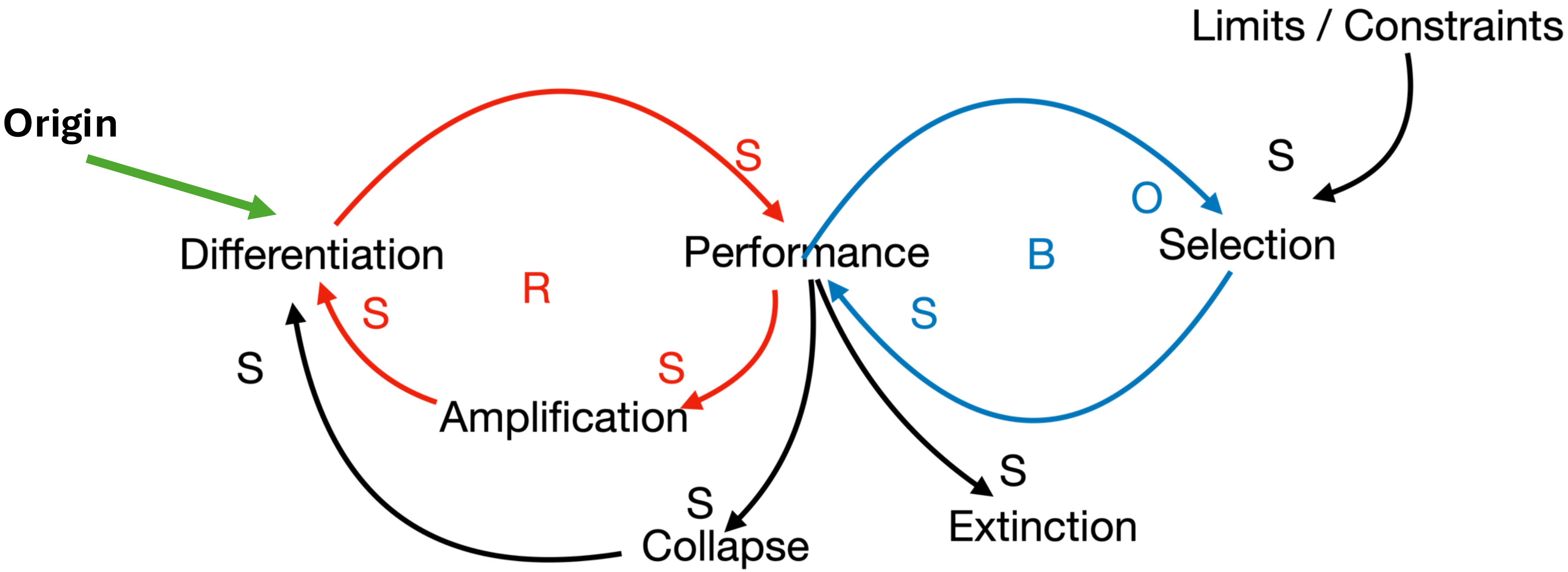
Evolutionary Systems

Resource Theory

- Resources are retained (in part) in social and natural systems as they evolve.
  - As social systems evolve via differentiation, selection, and amplification / retention, resources are retained in part
  - Example: A new form of organization such as an LLC may retain resources such as information and communications equipment, furniture, artwork, and so on.
  - There are 94 elements in the known universe, and they are combined, recombined, and recycled over time.
- Resources may be available to social and artificial systems in open-source libraries such as public libraries, government libraries, Github, and many others.

Evolutionary System

Concept Model



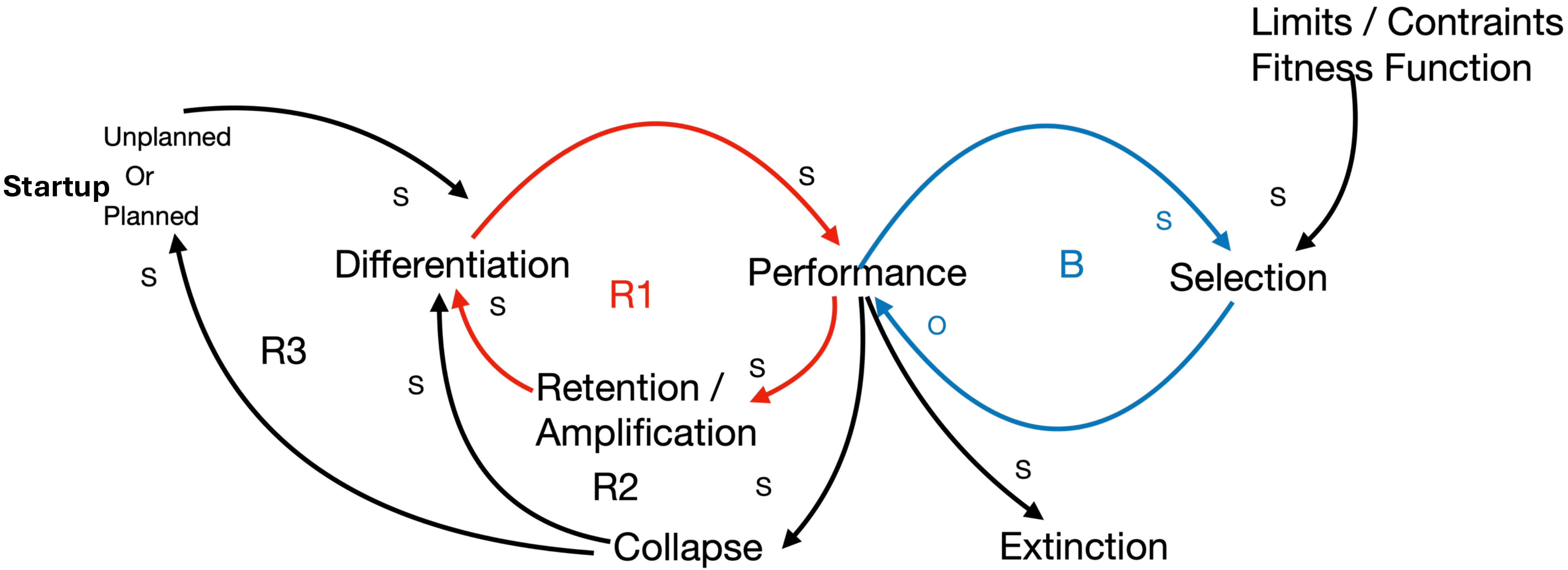
Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Evolutionary Speciation

- Speciation is a bifurcation of an existing system with isolation outcomes such as:
  - Behavior
  - Genetic
  - Geographic
  - Reproductive / replication / propagation
  - Social
  - Temporal
- A system transforms or transitions into two separate systems
- Essentially a system reaches, then exceeds, a tipping point, which is a point that something becomes something else.

Evolutionary System

Expanded Concept Model



Adapted from: Senge, P. (2006). *The fifth discipline*. Doubleday.
All causal loop diagrams created in Apple Keynote.

Evolutionary Systems

Categories of Differentiation

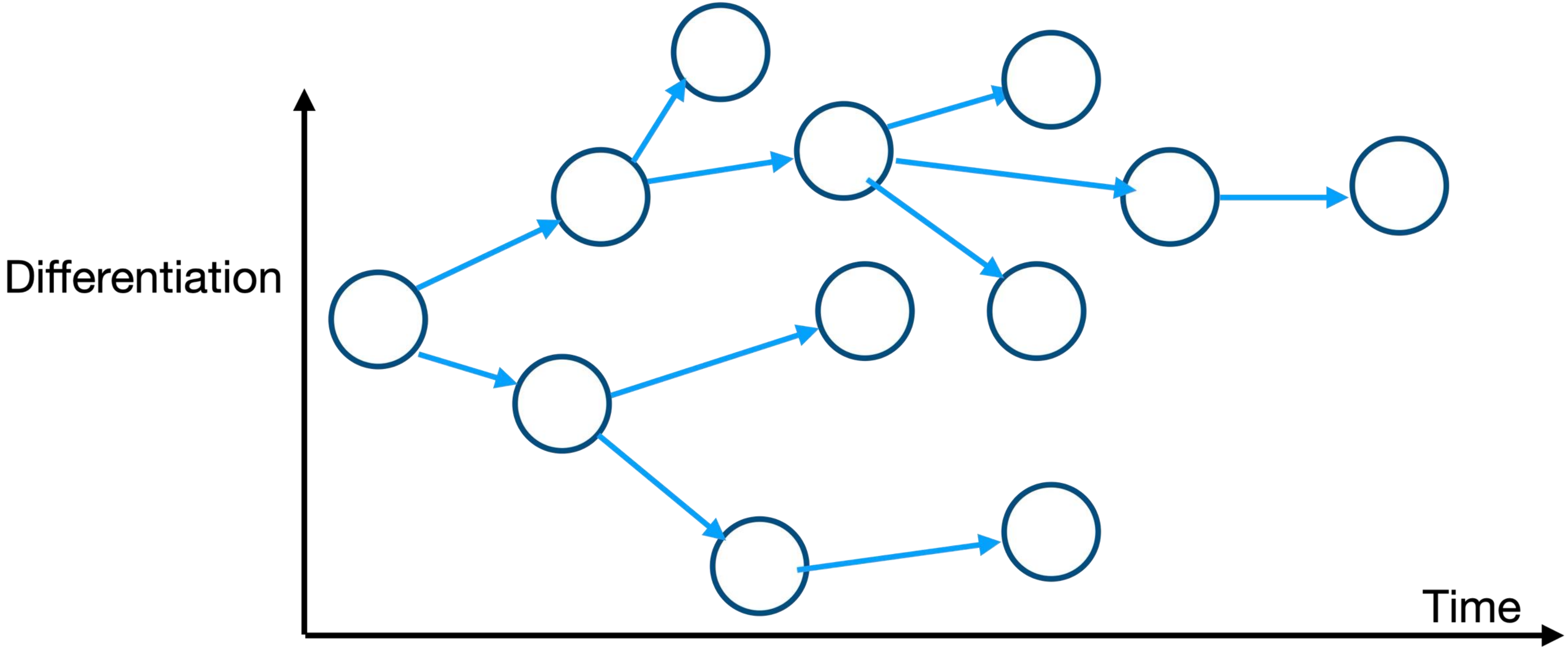
Unplanned
Origin / Emergence
Adaptation
Cultural Change
Environmental Pressures
Experimentation
Mutation
Self Organization

Planned
Adaptation
Adoption
Cultural change
Dialectical change
Experimentation
Innovation
Mitigation
Reproduction
Self Organization
Social Cognition
Teleological

Differentiation may be planned or intentional or unplanned or unintentional.

Evolutionary System (Concept Model)

Behavior Over Time

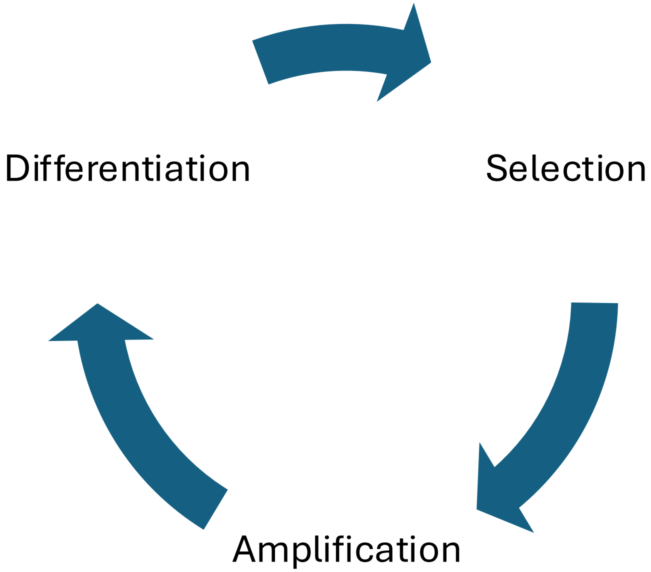


Examples of Evolutionary Systems

- Self-organizing evolution examples
  - Cities (settlements to large cities)
  - Human development (embryo to adulthood)
- Fractionation evolution examples
  - Crude oil to refined gasoline
  - Raw sugar to refined sugar

Evolutionary Systems

Elaboration evolutionary systems are complex adaptive systems with additional processes



Beinhocker, E.D. (2006). *The origin of wealth*. Harvard Business School.

Differentiation Approaches
via Innovation

- Develop new or improved products, services, and processes
- Acquire and/or develop new technologies for internal transformation
- Hire and/or retain more qualified talent.

Adaptation

Adaptation is successful change to either external forces or internal capabilities

An adaptive system is one that can sense changes in its external environment and alter its internal operations to compensate for it.

Successful adaptation does not imply remaining or improving on current position; rather it could devolve into a lessor position.

Mobus, G. E. (2022). *Systems science: Theory, analysis, modeling, and design*. Springer.

Adaptation

- Reduce costs and improve delivery time by
  - Digitize processes (where possible)
  - Digitize products (where possible)
  - Establishing virtual teams / telework
- Reduce the number of supply chain vendors
- Change the nature of relationships
- Modularize the internal environment
- Simply existing structures
- **Experiment,** learn, and act

Adaptation

- There are limits to adaptation to external forces and internal capabilities.
- If a system cannot sense changes in its environment and respond to them, then the system may well collapse. For example:
  - If a company does not see a threat in its environment such as a disruptive technology, then it may not have time to adapt if it were possible.
  - Kodak for example, seemingly did not see or act on the threat of digital photography.
  - If outside temperature increases above or decreases below the temperature at which an organism can live, it will likely collapse and die.
  - If a family cannot adapt to a changes in the economy, such as a loss of employment, the family may well collapse.

Adaptation

Adaptation is an algorithm

```
Set T = 90 degrees
Iterate T by 5 degrees while T <= 150 degrees
        Seek shade and shelter
        Sweat
        Drink fluids
        Rest
        If ok
                then adapted          // at this point in time
                else non-adapted      // may collapse and die from heat stroke or exhaustion
End
```

Adaptive Capacity

- The outcome of having different options and having the potential to switch between them.
  - A system can lack adaptive capacity if change between options is not possible, even if they exist.
    - Example: an overregulated organization
  - The willingness to change may exist; however, suitable options may not.
    - Example: A bankrupt organization may want to continue; however, it may not be possible.

Norberg, J., & Cumming, G. S. (Eds.) (2008). *Complexity theory for a sustainable future*. Columbia University.

Mitigation

A system's effort to reduce the effects of a problem or situation

Examples:

Civilization applying technology to mitigate a changing climate.
A couple going to counseling to keep their relationship alive
A software application being ported to a faster computer

Collapse

Collapse

Some say the world will end in fire.

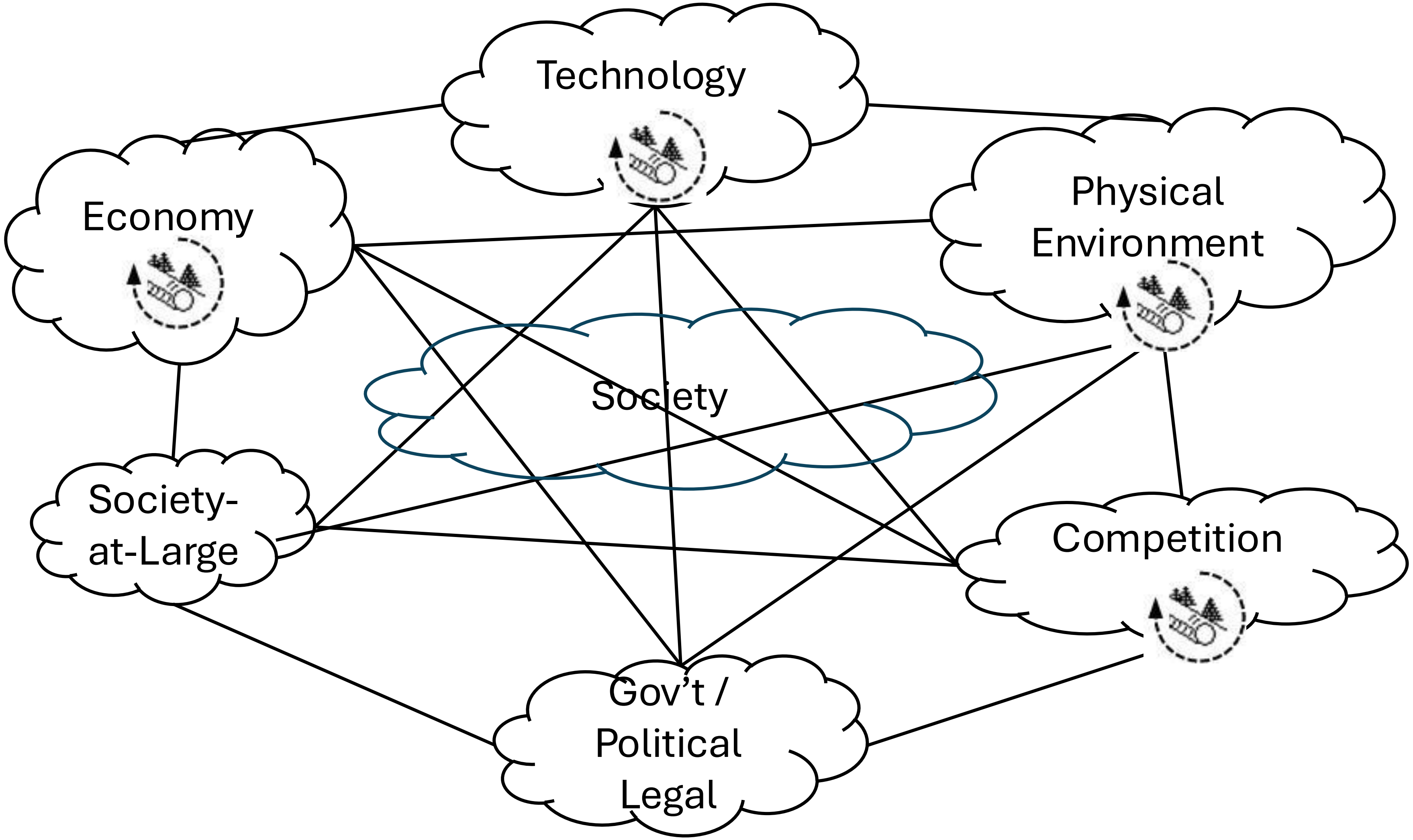
Some say in ice.

Robert Frost

Collapse

- All systems collapse for a variety of reasons.
  - Threats from the external environment may overwhelm a system
  - Weaknesses within a system may cause it to collapse
- Collapse is not necessarily catastrophic; the outcome may be a simpler or less complex system.

System Model



Collapse

- Systems are dependent on their environment (independent variables).
- Systems are dependent on supplies (within a range) of MEM.
- Changes (perturbations) to MEM flowing into a system may result in threats or opportunities
- Changes (perturbations) to MEM flowing out of a system may result in threats or opportunities

Collapse

- Exogenous perturbations to a social system may cause it to fail and collapse
  - Physical environment (climate change, pests / bugs / disease; viral pandemics such as SARS
  - Economics (The law of diminishing returns, economic conflict, disruption of MEM from suppliers
  - Competition (conflict, war, disruption of MEM)
  - Technology (unable to keep up with advanced technology)
  - Political (war, conflict, terrorism)
  - Society-at-large (disruption of MEM flows)

Collapse

- Exogenous perturbations to a social system may cause weaknesses in it to fail and possibly collapse
  - Weaknesses include a lack of resources, resiliency, talent, leadership, interest, finances, energy to survive, apathy, racism, inequality, polarization, among many others.
  - Example: A rapidly spreading viral pandemic could create panic leading to economic shutdowns (with a loss of jobs, income, status, opportunity, ...); constraints on personal freedoms (including social mobility, social interactions, ...); resource shortages (food, water, electricity, clothing, ...); and so on.

Essentially systems fail or collapse when a system-threatening situation cannot be solved.

Collapse

- Exogenous perturbations to a social system may cause it to fail and possibly collapse. Some questions:
  - What challenges might climate change bring?
  - What challenges might a major cybersecurity war bring?
  - What challenges might another world war bring?

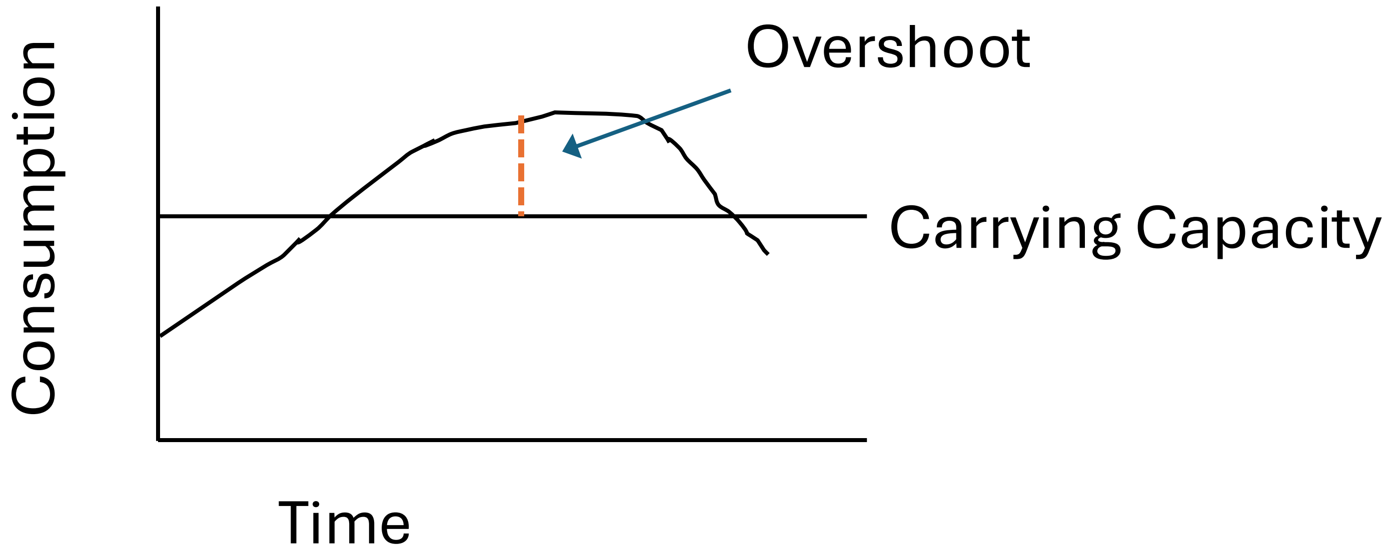
Essentially systems fail or collapse when a system-threatening situation cannot be solved.

Collapse

- Endogenous weaknesses in a social system may cause it to fail and possibly collapse. Some questions:
  - What challenges might a decline in food / water supplies bring?
  - What challenges might increasingly political, social, economic, educational, technological fragmentation and polarization bring?
  - What challenges might a regime change bring?
  - What challenges might over population bring?
  - What challenges might another civil war bring?

Essentially systems fail or collapse when a system-threatening situation cannot be solved.

Collapse (overshoot)



Overshoot occurs when a population exceeds the carrying capacity of its environment. Note: The carrying capacity varies depending on factors in the environment such as the availability of food and water, climate change, ...

Collapse

Overshoot

The world's population is consuming earth's resources at more than 1.7 times faster than it can regenerate.

Source: Earth Overshoot Day

Essentially systems fail or collapse when a system-threatening situation cannot be solved.

Collapse

- A collapse is the rapid rearrangement of a large number of links, including their breakdown and disappearance.
- The things that collapse (everyday objects, planes, ecosystems, companies, empires, and so on) are always networks.
- Examples
  - Nodes are people and links are familial relationships (e.g., death or divorce)
  - Nodes are countries and links are trade agreements.

Bardi, U. (2017). *The Seneca Effect* (The Frontiers Collection). Springer International Publishing. Kindle Edition.

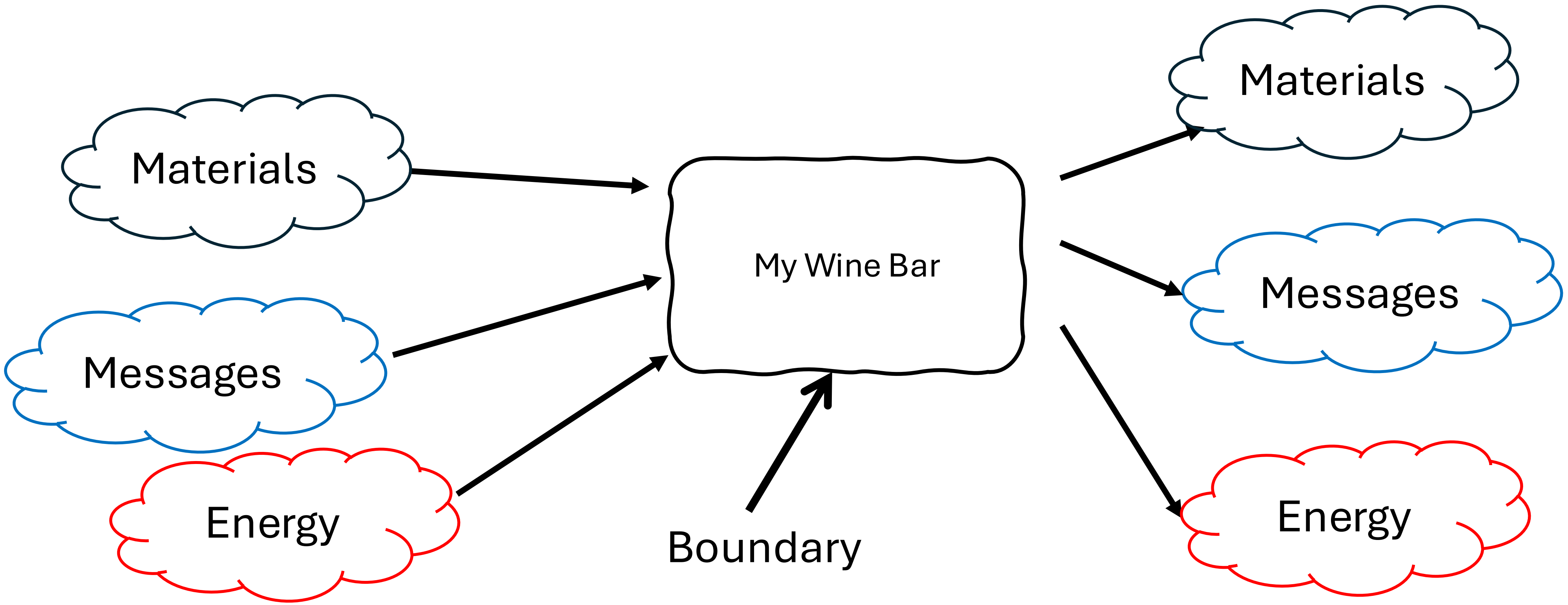
Collapse

- One way to look at the tendency of complex systems to collapse is in terms of "tipping points" or phase transitions.
- This concept indicates that collapse is not a smooth transition; it is a drastic change that takes the system from one state to another.

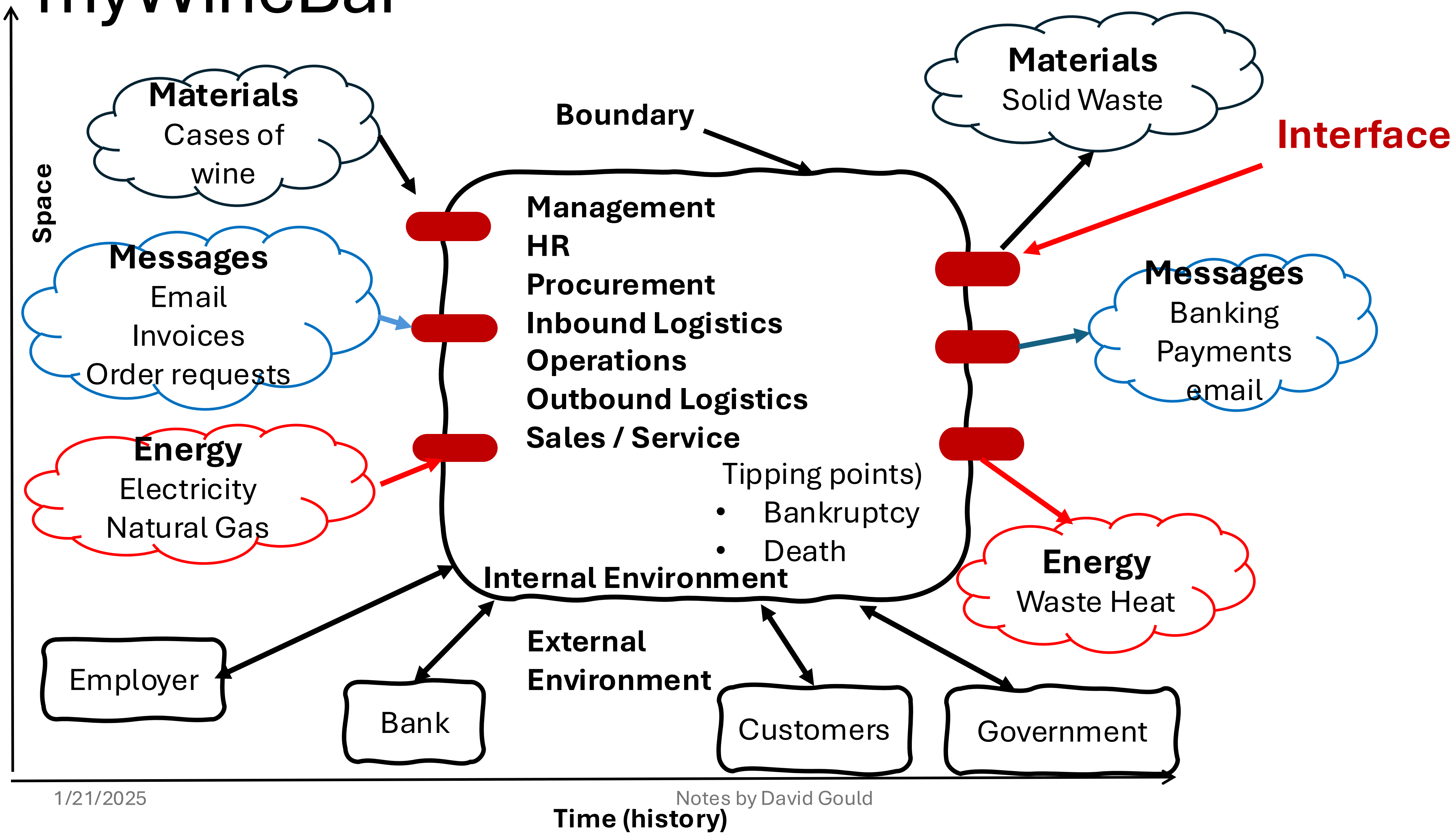
Bardi, U. (2017). *The Seneca Effect* (The Frontiers Collection). Springer International Publishing. Kindle Edition.

myWineBar

myWineBar
Context Diagram



myWineBar


Materials
Cases of wine
Boundary
Materials
Solid Waste
Interface
Space
Messages
Email
Invoices
Order requests
Management
HR
Procurement
Inbound Logistics
Operations
Outbound Logistics
Sales / Service
Messages
Banking
Payments
email
Energy
Electricity
Natural Gas
Tipping points)
• Bankruptcy
• Death
Energy
Waste Heat
Internal Environment
External Environment
Employer
Bank
Customers
Government
Time (history)

myWine Bar
(with applied principles from Mobus (2022))

Systems may be composed of subsystems
- myWineBar is functionally decomposed into beverage and food subsystems.

Systems exhibit behavior; that is, they are nonstationary
- myWineBar is in an expansionary phase

Systems have a history
- myWineBar was founded 10 years ago and is still in the same location.

Systems are bounded
- myWineBar has only one location in a mid-sized city.

Systems are dynamic
- At times, myWineBar is stable, other times, growing, and sometimes shrinking. Currently, myWineBar is in an expansionary or growth phase.

Systems interact with other systems
- myWineBar interacts with suppliers and customers, government agencies

myWineBar
(with applied principles from Mobus (2022))

Systems process information (some may process material or energy)
- myWineBar processes required MEM for operations

Systems are composed of networks
- Internal networks among operational agents as well as external networks among suppliers, customers, …

Systems regulate themselves through negative feedback
- myWineBar requires maintenance in terms of the number of agents, types of products sold, financial stability

Systems develop; systems evolve
- Development / evolution in response to environmental conditions

Systems have a life cycle (origin or startup, growth, mature, decline)
- Founded 10 years ago and in the growth stage

Systems will collapse at some point and die
- Not there yet

Input Messages

- Banks/Credit Unions
- Cable / Internet
- Commercial
  - News
  - Advertisements
- Government
  - Federal
  - State
  - County
  - City
- Insurance
- Management Company
- Suppliers

Add properties such as frequence, volume, cost, regulations, policies,

Input Materials

- Food and Wine
- Mail
- Packages

myWineBar

Add properties such as frequency, volume, cost, regulations, policies,

Input Energy

- Electricity
- Natural Gas
- Sunlight

myWineBar

Add properties such as frequency, volume, cost, regulations, policies,

Output Materials

- Outgoing mail and packages
- Solid Waste
- Waste Water / Sewage

Add properties such as frequency, volume, cost, regulations, policies,

Output Energy

Waste Heat

Add properties such as frequency, volume, cost, regulations, policies,

Output Messages

myWineBar

- Bank/Credit Union
- email
- Insurance
- Taxes
- Telephone Calls

Add properties such as frequency, volume, cost, regulations, policies,

Boundary and Interfaces

- The myWineBar boundary is the perimeter of the building
- Material Interfaces include:
  - Garage doors
  - Person doors
  - Windows
- Energy Interfaces include:
  - Electrical outlets
  - Windows
- Messages Interfaces include:
  - Internet connection points
  - Telephone connection points

Flows and Stocks

Flows and stocks of material, energy, and messages can be described in terms of their properties or attributes and stored in a database for subsequent processing.

Material Flow

Flow from Wine Distributor to My Wine Bar

Primary Key	**Name**	**Supplier**	**Customer**	**Frequency**	**Size**	**Cost**	**When**
InMat01	Rose	Wine Inc.	My Wine Bar	Weekly	1 case	$100	Mondays
InMat02	Pinot Grig	Wine Inc	My Wine Bar	Weekly	2 cases	$150	Tuesdays

Material Flow

Flow from My Wine Bar to Walk-in Customer

Primary Key	Name	Supplier	Customer	Frequency	Size	Cost	When
InMat01	Rose	My Wine Bar	Wine Bar Customer	On request	1 glass	$10	Varies
InMat02	Pinot Grig	My Wine Bar	Wine Bar Customer	On request	1 glass	$10	Varies

Energy Flow

Flow from Electric Utility to Wine Bar

Primary Key	Name	Supplier	Customer	Frequency	Size	Cost	Timing
InFlowE1	Electricity	Electric Utility	My Wine Bar	24/7	50 KWH	$100/mo	Continuous
InFlowE2	Natural Gas	Wine Bar	My Wine Bar	24/7	1000 Cubic Feet	$200/mo	Continuous

Message Flow

Message Flow from Electric Utility to Wine Bar

Primary Key	Name	Supplier	Customer	Frequency	Size	Cost	Timing
inMsg01	Invoice	Wine Inc.	My Wine Bar	Weekly	1 page	0	Varies
InMsg02	Order	Wine Inc	My Wine Bar	Weekly	1 page	0	Varies

myWineBar

Database Possibilities

- Input MEM flows
- Throughput MEM flows
- MEM Stocks
- Output MEM flows
- MEM models

Can be described in tabular format and added to a database for processing

Algorithm

Customer Service

1. Begin
2. Take Wine Bar customer’s order
3. Search for bottle of wine in cabinet (stored FIFO)
4. Pour a glass of wine
5. Serve to customer
6. Receive payment from customer
7. Is wine bottle empty?
8. If yes, toss into trash
9. If no, return wine bottle to wine cabinet
10. Customer requests another glass of wine?
11. Yes, go to step 3
12. No. Close

Multifinality

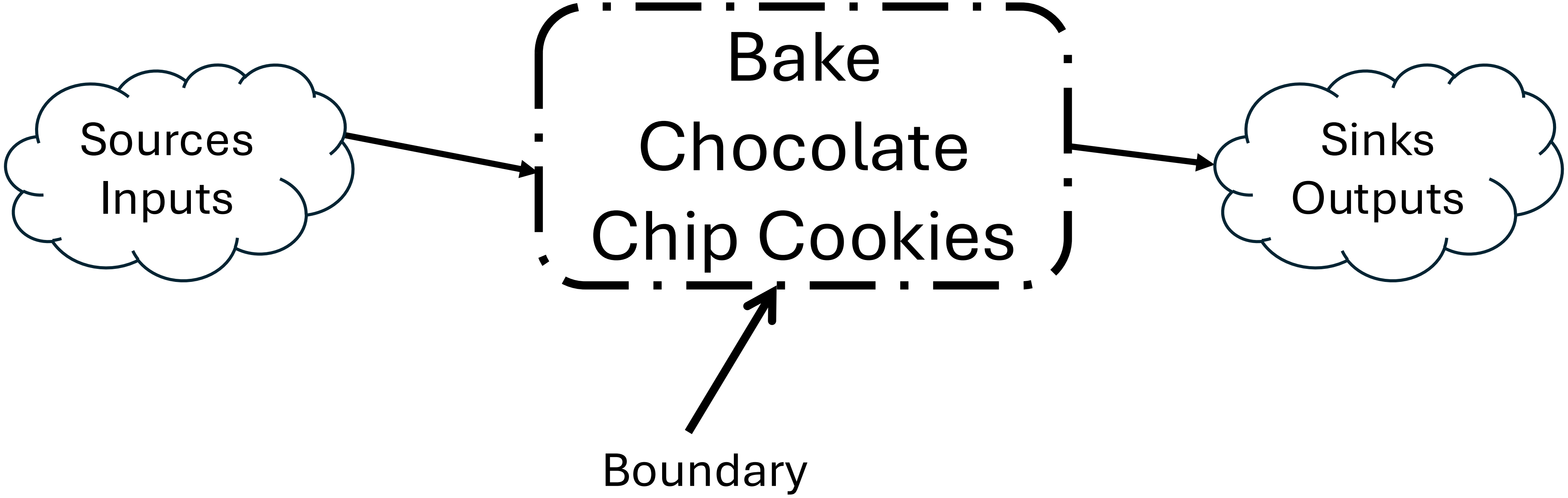
A Wine Bar Example

- A "profit making system" from the perspective of management and owners
- A "distribution system" from the perspective of the suppliers
- An "employment system" from the perspective of employees
- A ”shopping system" from the perspective of customers
- An "entertainment system" from the perspective of customers
- A ”workplace” from the prospective of remote employees
- A "social system" from the perspective of residents and customers
- A "dating system" from the perspective of single customers

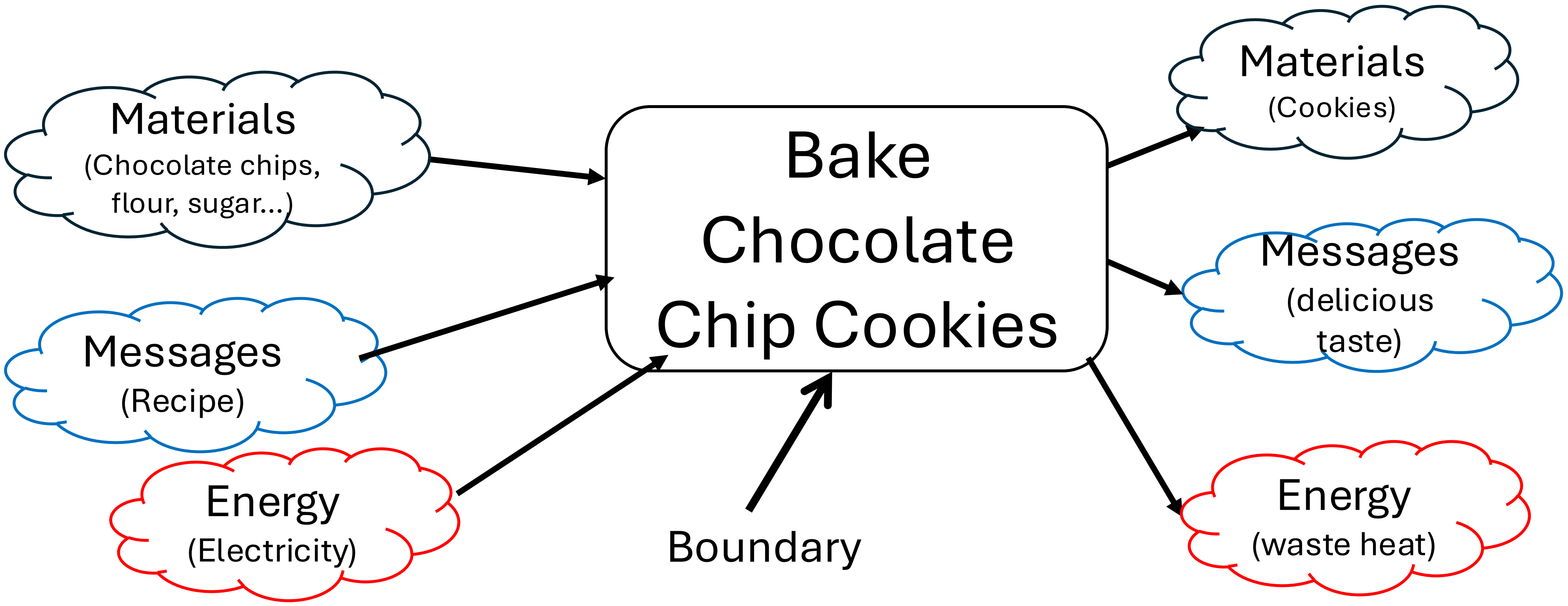
Chocolate Chip Model

An Image Description of a Cookie

Context Diagram



An Image Description of a Cookie
Context Diagram (Expanded)



Chocolate Chip Cookie System

Inputs

- Resources Used
  - Baking sheet
  - Mixing bowl
  - Oven
  - Spoon
- Resources Consumed
  - Chocolate Chips
  - Eggs
  - Flour
  - Salt
  - Sugar

Resources are supplied from the external environment.
Some resources are consumed; some are used.
Baking pans, the oven, … are used. Ingredients are consumed.

Algorithm

A Very Simple Algorithm

1. Get package of chocolate chips
2. Put chocolate chips in mixing bowl
3. Add cup of flour
4. Add ½ cup of sugar
5. Add 1 egg
6. Mix ingredients
7. Spoon onto baking sheet until sheet is full
8. Put baking sheet into oven at 300 degrees
9. Bake for 10 minutes
10. Remove baking sheet
11. Put cookies onto plate
12. Turn oven off
13. Eat cookies

Chocolate Chip System

- Outputs
  - Chocolate Chip Cookies
  - Dirty dishes
  - Waste heat

Definitions

Definitions

- Adaptation:
  - A successful change to either external forces or internal capabilities
- Agent:
  - A biotic or abiotic entity that is interactive, can make decisions, and can create and/or execute/follow an algorithm.
- Aggregation:
  - A set of objects with some common characteristics
- Algorithms
  - Algorithms are as Berlinski (2000) noted, “a finite procedure, written in a fixed symbolic vocabulary, governed by precise instructions, moving in discrete steps 1,2,3, ..., whose execution requires no insight, cleverness, intuition, or perspicuity, and that sooner or later comes to an end.”
  - An algorithm is a set of steps to do something such as performing a computation.
  - Algorithms are information or messages

Definitions

- Becomes:
  - A transitional change in state or into something else, such as water transitioning or becoming steam.
- Collapse:
  - The rapid rearrangement of a large number of links or nodes in a system.
- Data:
  - Attributes or properties of an object (something)
- Evolution:
  - Any process that leads to increases in complexity, diversity, order, and / or interconnectedness.
- Function:
  - A mathematical relationship that takes inputs and produces a single output based on those inputs.

Definitions

- Information
  - Information is processed data; that is data that has been analyzed and provides some meaning.
  - Examples: 1492 is data; 1492 processed is when Columbus discovered America
- Knowledge:
  - What we know from what we have learned / experienced.
- Messages:
  - Signals, data, information, … transmitted between parts of a system, for communication purposes.
  - Examples: Data between a system and its subsystems, hormones signaling a response, a scent, spectrums within light waves.
- Mitigation:
  - A system's effort to reduce the effects of a problem or situation

Definitions

- Network:
  - A set of nodes and links
- Perturbations:
  - Variations in inputs, which may be measurable.
- Property:
  - Characteristics of an object such as weight, size, color
- Problem:
  - Something to be fixed or repaired, an opportunity, or a mandate.
- Resilience:
  - A systems ability to recover from a disturbance or perturbation
- Resistance:
  - A systems ability to withstand a disturbance or perturbation with little deformation.

Definitions

- Robustness:
  - The output from a system or algorithm varies little when some of the inputs vary (Csete and Doyle 2002). Because shocks are specific examples of variation in inputs, robustness can be interpreted as reduced sensitivity of outputs to shocks; if outputs are related to the continued functioning of the system, then robustness and resilience are related.
    - Source: John M. Anderies, Carl Folke, Brian Walker, and Elinor Ostrom

Definitions

- Set:
  - A collection of objects or elements
- Stocks:
  - Accumulations of resources: material, energy, messages over time, based inflows and outflows.
- Structure:
  - An arrangement and organization of parts
- Sustainability:
  - Capable of meeting the needs of the present generation without compromising the ability of future generations to meet their own needs

Definitions

- System
  - A set of elements and their relations that exhibit behavior.
  - Elements may be agents, components, or subsystems.
  - Behavior of elements and relations is expressed in algorithms.
  - Relations include the interconnections, interactions, or dependencies among the elements
  - The arrangement or pattern of elements and their relations make up the structure of the system.
- Table:
  - A set of rows and columns
- Tag:
  - A mechanism that facilitates the formation of aggregates
- Transformation:
  - A deep or even radical state of change.
  - Example: a caterpillar transforming into a butterfly or raw wood being transformed into furniture.

Definitions

- Transition:
  - Something becoming something else.
  - Example: Heated water becoming steam
- Tuple:
  - A set of rows in a table

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  - http://www.accelerating.org
- Chaos Theory
  - http://library.thinkquest.org/3493/noframes/chaos.html
- International Society for the Systems Sciences
  - http://isss.org/world/
- ISEE Systems
  - http://www.iseesystems.com/
- Santa Fe Insitute
  - http://www.santafe.edu
- Seminars about Long Term Thinking
  - http://www.longnow.org/projects/seminars/
- Systems Engineering Body of Knowledge
  - https://www.sebokwiki.org/wiki/Principles_of_Systems_Thinking

Software Modeling Resources

- iThink
  - https://www.iseesystems.com/store/products/ithink.aspx
- Netlogo
  - https://ccl.northwestern.edu/netlogo/
- Stella
  - https://www.iseesystems.com/store/products/stella-architect.aspx
- Vensim
  - https://vensim.com/software/

Notes

The Zachman Framework and other approaches provide a relatively easy way to think about modeling systems.

Start with a List of Things (what), Processes (how), Networks (where)

Then add additional details and new row and column models as necessary,

Most of the models in these slides are descriptive rather than prescriptive. Prediction using simple systems is relatively easy; prediction of complex adaptive systems may not be possible if sensitive dependence on initial conditions is present.

Notes

Modified Zachman Framework (model MEM, not just data)

Level	What (MEM)	How (function)	Where (network)
Contextual	Lists of MEM items	Lists of functions, algorithms, goals	Lists of locations, places
Conceptual	Relationships	Relationships	Relationships
Logical	Schematic	Schematic	Schematic
Physical	Relative Specifics	Relative Specifics	Relative Specifics
Implementation (as necessary)			

Additional columns of who, when, and why may be added as necessary

Close

Thank you!