

Thinking Systemically

Achieving Sustainable Systems

Systems: Complex, Dynamic Processes

- ▶ Systems science provides a means of analyzing and understanding complex processes based on a few basic principles
- ▶ Complex systems behave in complex ways and may change or adapt over time
- ▶ When problems emerge there is an underlying positive feedback loop that may not be evident
- ▶ Such problems cannot be solved using linear causality thinking
- ▶ True sustainability involves whole systems thinking and design

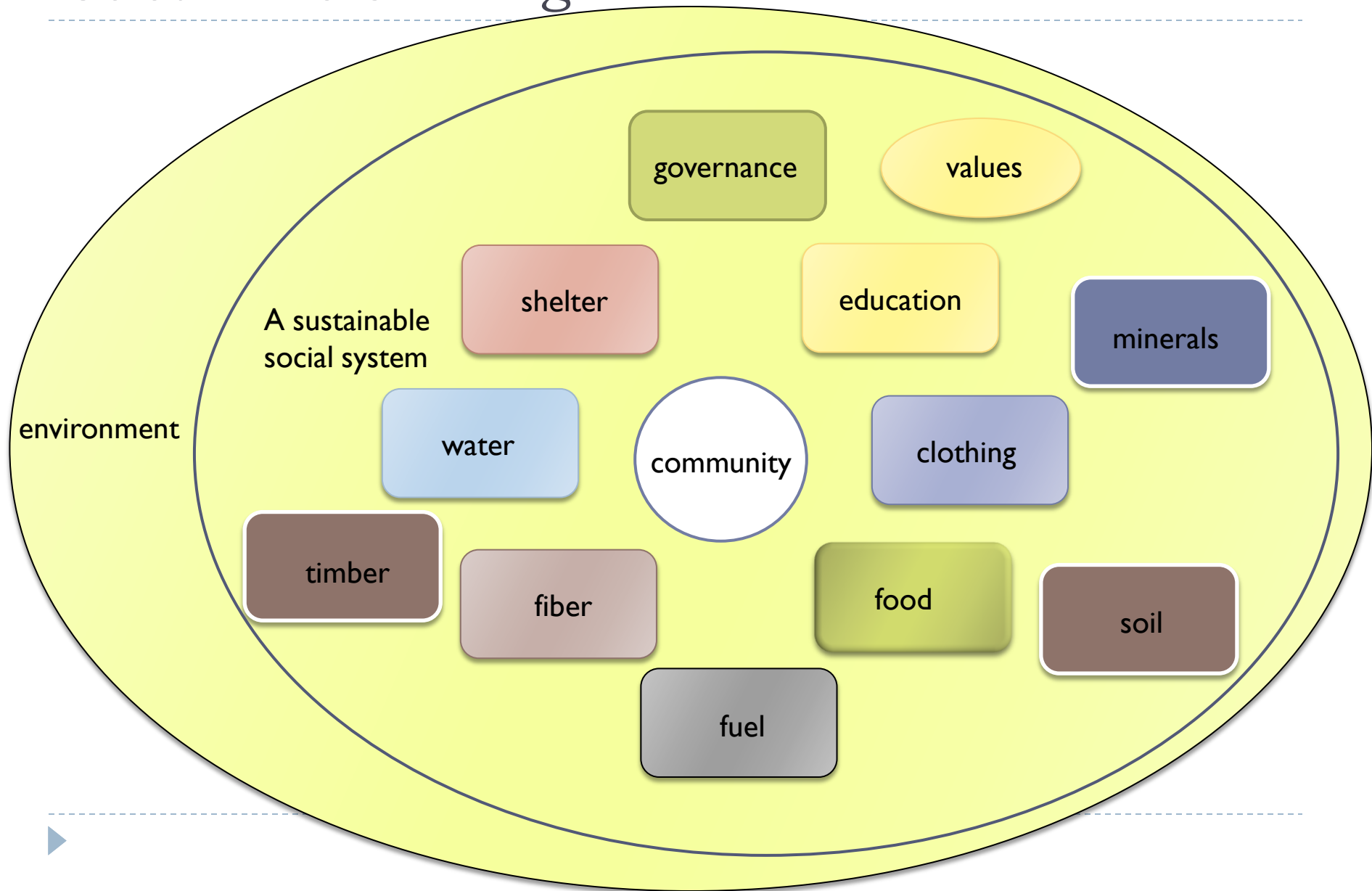


Permaculture: A Systems Approach to Sustainable Living

- ▶ The application of systems thinking and systems science to the design of living arrangements
 - ▶ Environment and climate
 - ▶ Buildings, design, orientation, construction
 - ▶ Water management
 - ▶ Food production
- ▶ What is Systems Thinking?
- ▶ What is Systems Science?
- ▶ What is Sustainability?
- ▶ Then we can understand Permaculture



Permaculture: The Systems Approach to Sustainable Living



What is Systems Thinking?

- ▶ Seeing the system as a functional whole and not just a collection of parts
- ▶ Seeing relations among the components and between a system and its environment as the basis of explanation
- ▶ Using various kinds of models to represent whole systems and their dynamical behaviors
- ▶ Testing understanding by playing ‘what-if’ games with the models to see:
 - ▶ if they behave the same way the system does under similar circumstances
 - ▶ if there are leverage points that can be used to move a system in a desired direction of behavior



What is Systems Science?

- ▶ The application of *scientific* thinking with *systems* thinking in order to understand how the world works
- ▶ Systems science discovers and studies the common principles that apply to all systems studied by specific sciences
- ▶ It defines a general property – systemness – that is found in objects of interest regardless of scale and complexity, e.g.:
 - ▶ Natural physical, chemical, biological systems
 - ▶ Social systems
 - ▶ Built systems, cultural artifacts
- ▶ It provides universal principles that can be applied to specific sciences to help them develop better explanatory models



What Is Sustainability?

- ▶ A property of systems is longevity
- ▶ Systems are internally organized so as to maintain themselves in spite of environmental contingencies
- ▶ Some kinds of systems are adaptable over time as the environment changes
- ▶ What are the properties of system organization and adaptation that lead to longevity?
- ▶ Real systems age ☹️
- ▶ But complex, adaptive systems can give rise to newer systems (e.g. living systems reproduce) 😊
- ▶ Life on Earth is a sustainable system as long as the Sun is stable!



A First Look At Permaculture

- ▶ The term was devised by Bill Mollison and David Holmgren (Australia) in the 1970s to describe their application of systems ecology to designing sustainable living arrangements
- ▶ Systems ecology is the science that looks at ecology from a holistic perspective, but especially considers the flows of energy and material resources through an ecosystem
- ▶ Designing local communities according to the principles of systems that are at the heart of sustainability
- ▶ Combines organic food production, water management, “green” building practices, and many other aspects of a living system to achieve the goal



The Challenges for the 21st Century

- ▶ The growing evidence points to the possibility that we are running out of critical resources if we continue to live over-consuming lives
- ▶ Our reliance on high technology has been based on a faith that might not be justified in practice – technology alone cannot replenish dwindling non-renewable resources
- ▶ Permaculture, and systems science in general, represents a new way to look at technologies that have systemic purposes
- ▶ The goal is to allow people to live comfortable, fulfilling lives for many generations to come





The Principles of Systems Science



And the Keys to Sustainable Living

How Systems Science Works

- ▶ Survey **models** of specific systems, e.g. biological systems such as cells and organisms or social systems such as communities
- ▶ Seek **commonalities** in terms of explanations of how systems **function** and **evolve**
- ▶ Use **analytical methods** to find those commonalities
- ▶ Develop **languages** that can describe all systems regardless of specific domains, e.g. whether biological or physical
- ▶ Develop general principles that provide **causal explanations** regardless of the details of any specific system
- ▶ Develop **mathematical** descriptions of those principles such that they can be employed to discover new aspects of specific systems



What Principles are True of All Systems?

- ▶ Here are a set of principles that have been discovered to operate over all knowledge domains
 1. Systemness – the world is composed of systems of systems
 2. Systems are organized in structural and functional hierarchies
 3. Systems can be represented as abstract networks of relations between components
 4. Systems are dynamic processes on one or more time scales
 5. Systems exhibit various kinds and levels of complexity
 6. Systems emerge from proto-systems (unorganized, not complex) and evolve over time to greater organization and complexity
 7. Systems can encode knowledge and receive and send information
 8. Systems evolve internal regulation subsystems to achieve stability



Additional Principles

- ▶ Several principles related to systems thinking, systems science, and systems development
 - 9. Systems can contain models of other systems
 - 10. Sufficiently complex, adaptive systems can contain models of themselves (brains and mental models)
 - 11. Systems can be understood (a corollary of #9) – Science as the building of models
 - 12. Systems can be improved (a corollary of #6) – Engineering as an evolutionary process
- ▶ Lets look at the details



Principle 1 – Systemness, or What Makes Something a System

- ▶ A collection of many component parts (number and types) – objects,
- ▶ That interact with one another through various *interconnections* that have varying strengths
- ▶ That maintain structural integrity over time including:
 - ▶ Maintaining a *boundary* that demarcates the *system object* from the *environment*
 - ▶ Maintaining the interconnections in stable configurations
- ▶ That perform an overall *function* by accepting *inputs* from an environment and *processing* them into recognizable *outputs* (to the environment) as a result of the internal interconnections between the components.



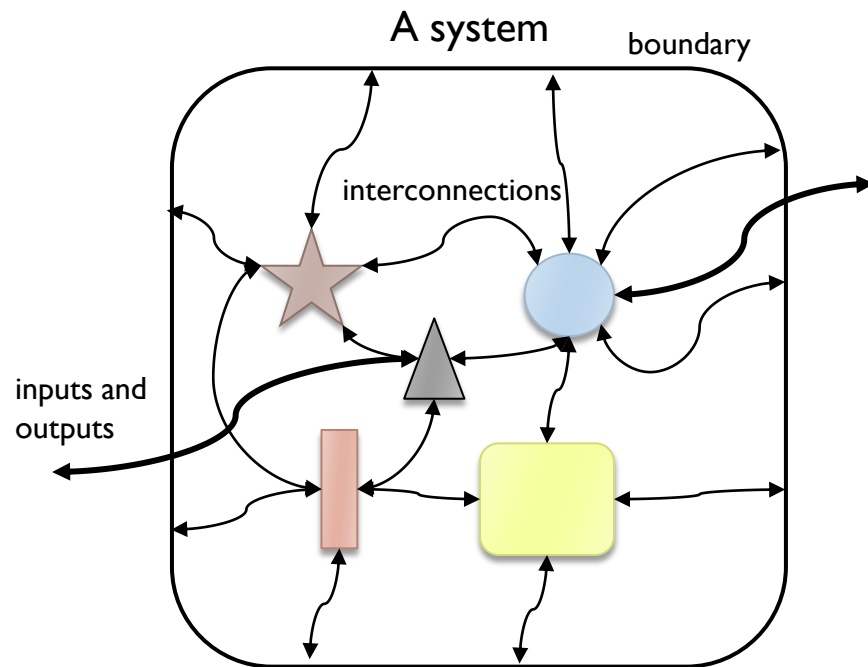
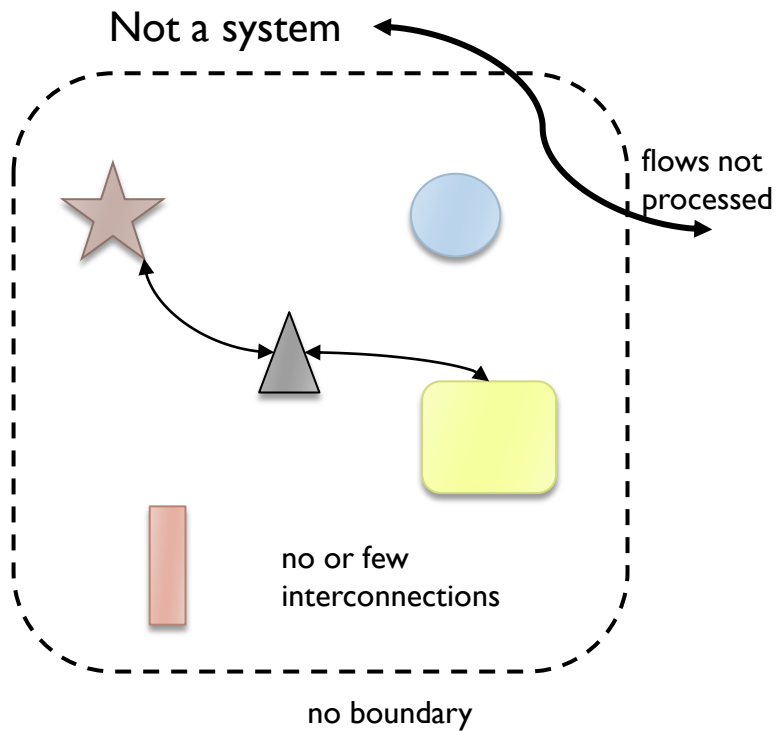


Figure 2. A non-system vs. a system.

Definitional Problem

- ▶ It is hard to find a “non-system”!
 - ▶ An arbitrarily chosen volume of outer space – no boundary
 - ▶ An artificially contained volume of gas molecules – no function
- ▶ The difference between simple systems and non-systems
 - ▶ Add an input of heat and a measuring sensor for pressure to the contained volume of gas and it becomes a simple system with a function of relating heat (temperature) and pressure and producing information for an observer!
- ▶ Problem: If just about everything is a system then isn't the concept meaningless?
- ▶ Epistemological Answer: Because everything is a system, systems thinking is a way to know the world.

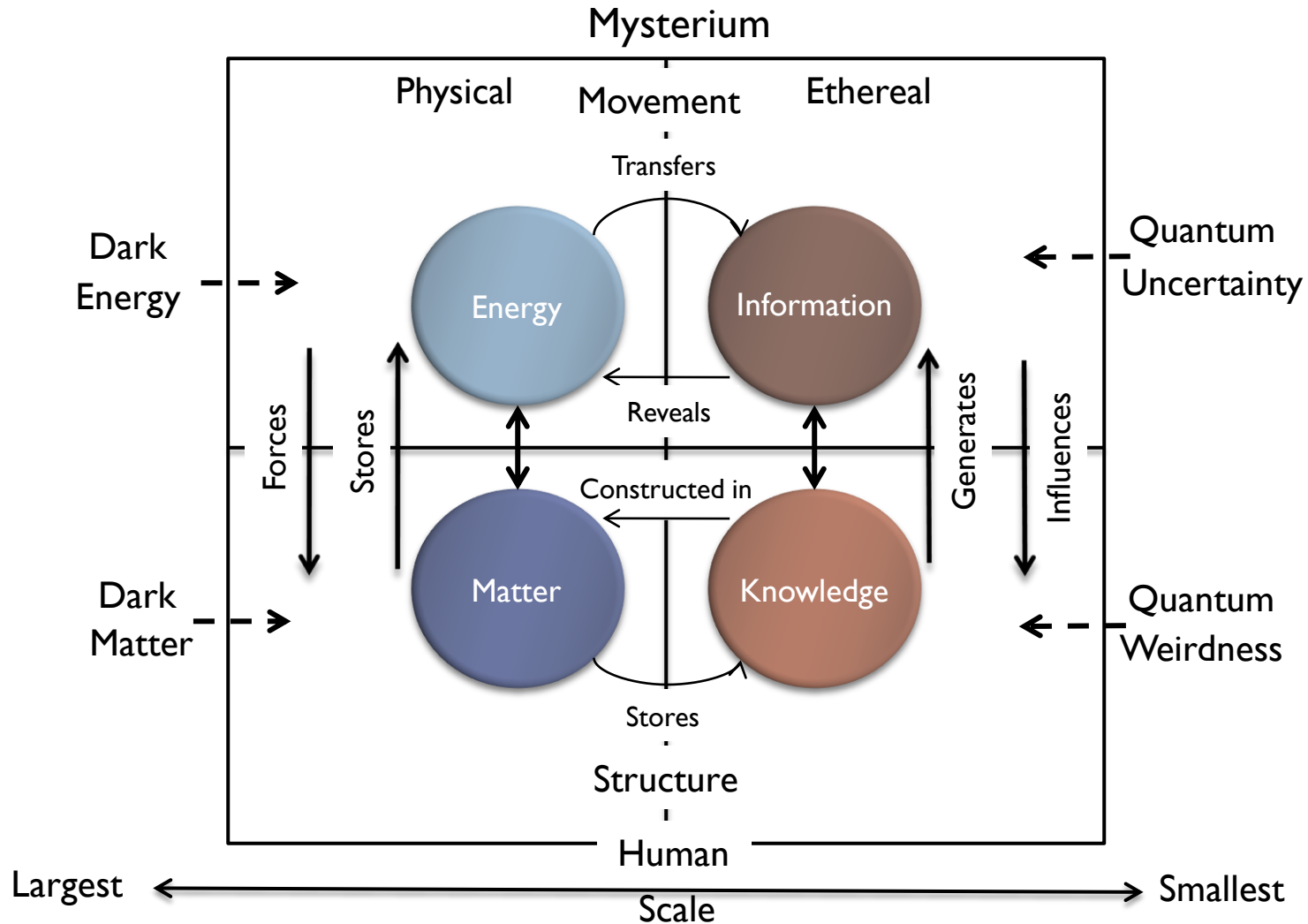


An Ontological Side Trip

- ▶ **Four Aspects of the Physical Universe – What Exists**
 - ▶ **Matter** – Substance with attributes of mass and momentum
 - ▶ **Energy** – That which changes the position/momentum of matter over time; the capacity to do work
 - ▶ **Knowledge** – Structure (of matter) that anticipates energy flow
 - ▶ **Information** – Message that conveys “a difference that makes a difference”*
- ▶ All that exists involves these four aspects
- ▶ We understand systemness in terms of the interactions between these four aspects.

* Gregory Bateson, (1972). *Steps to an Ecology of Mind: Collected Essays in Anthropology, Psychiatry, Evolution, and Epistemology*. University Of Chicago Press.

The Systems Ontological Perspective



Relations of the Existential Aspects (I)

▶ The Physical

▶ Matter and Energy

- ▶ Matter can be converted to energy, $E = mc^2$
- ▶ Energy moves (forces) matter
- ▶ Matter is measurable directly
- ▶ Energy is measured by its effects on matter
- ▶ Matter can store energy (e.g. chemical bonds)

▶ The Ethereal

▶ Knowledge and Information

- ▶ Knowledge is embodied in the structural arrangements of matter
- ▶ Information is the measure of how a message receipt affects the structural arrangements of matter – “news of difference”
- ▶ $K = 1/I$ and $I = -\log(Pm)$: Both are probabilistic in nature
- ▶ Newly acquired knowledge generates information when it causes changes in system behavior



Relations of the Existential Aspects (II)

▶ Structure

▶ Matter and Knowledge

- ▶ The structure of a system – how the components of matter are arranged and exchange energy – encodes the history of exchanges with the environment, the messages received, as memory
- ▶ The arrangement reflects *a priori* expectations of messages (conveyed by energy), what the system expects in future exchanges

▶ Movement

▶ Energy and Information

- ▶ Energy flows from material node to node, transversing space
- ▶ Energy forces matter to move relative to other matter
- ▶ Modulated energy conveys messages from node to node
- ▶ Communication is the transport of energy through a channel conveying a message



Relations of the Existential Aspects (III)

▶ Scale

- ▶ The four aspects are discerned at all scales of time and space
- ▶ At the largest scales of space and time the Universe is ruled by the forces of gravity (dark matter) and dark energy
- ▶ At the smallest scales of space and time the Universe is ruled by quantum effects
 - ▶ Uncertainty
 - ▶ Weirdness
- ▶ The Laws of Nature describe how all of these aspects relate to one another on all of these scales



Principle 2 - Systems are Organized in a Structural Hierarchy

- ▶ A system is a *subsystem* of a larger system
- ▶ A system contains components that may be, themselves, subsystems
- ▶ Systems decompose through a subsystem tree
- ▶ Roughly akin to the material composition hierarchy, e.g. organism – cells – molecules – atoms – subatomic particles, etc.



Systems Composed of Subsystems

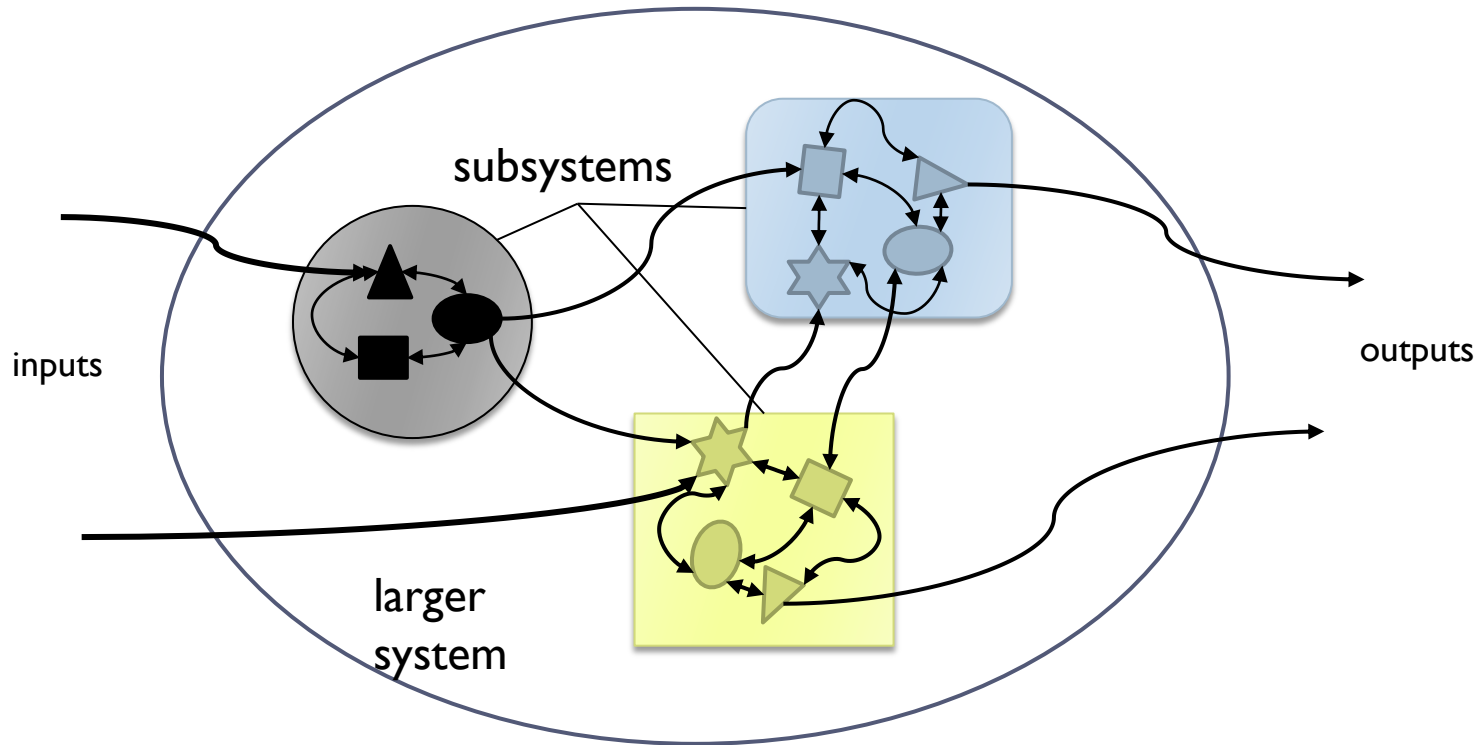


Figure 3. Systems are comprised of subsystems.



The System Hierarchical Tree

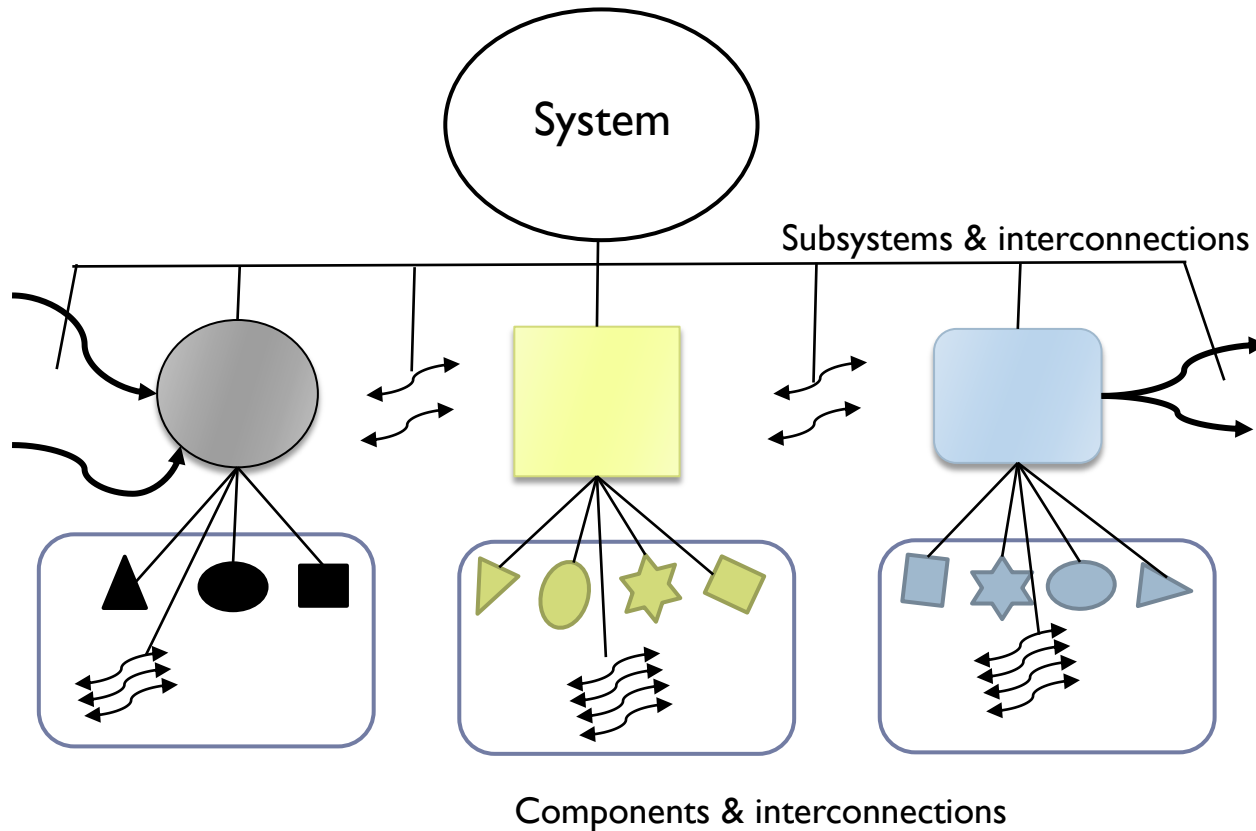


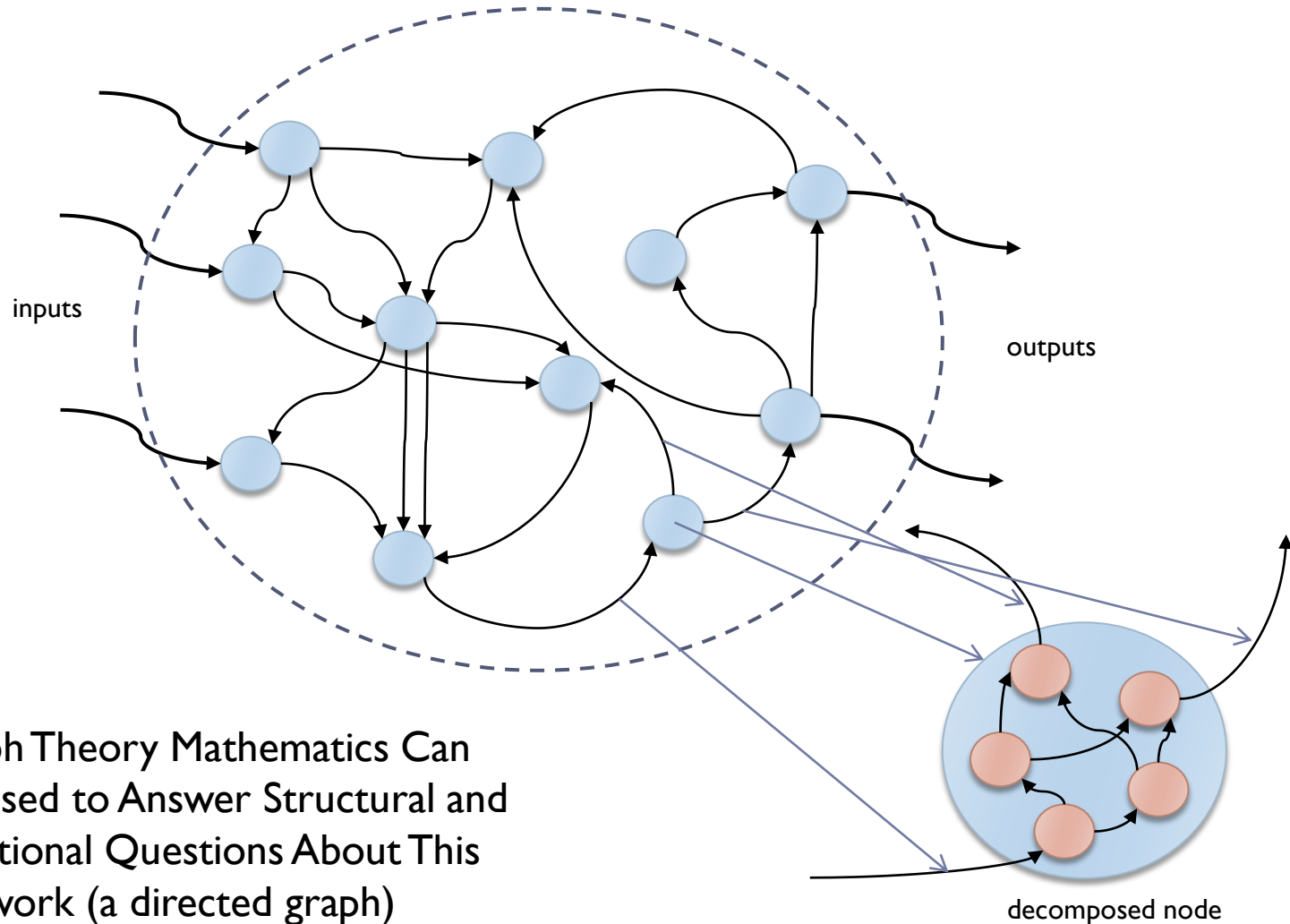
Figure 4. Systems, subsystems & components form a structural hierarchy.

Principle 3 - Systems Can Be Represented in an Abstract Way – Networks of Networks

- ▶ Systems are, in reality, composed of networks of components
- ▶ Systems can be **represented as a network** comprised of:
 - ▶ Nodes – representing components
 - ▶ Links – representing the interconnections
- ▶ Network representations are powerful tools for analyzing and modeling systems.
- ▶ Nodes have properties that can take on variable values over time
- ▶ Some properties of nodes are exposed to other nodes and constitute the “personality” of a component
- ▶ Links can be flows of matter, energy, or information, or forces that bind or repel.



Abstract Network Representation



Graph Theory Mathematics Can
Be Used to Answer Structural and
Functional Questions About This
Network (a directed graph)

Principle 4 – Systems are Dynamic Processes

- ▶ **Systems are always in motion:**
 - ▶ Relative to one another
 - ▶ Internally
- ▶ **Energy and Material Flows**
- ▶ **Principle 4.1 – Causal Relations**
- ▶ **Principle 4.2 – Multiple Time Scales**
- ▶ **Principle 4.3 – Radius of Effect**
- ▶ **Principle 4.4 – All Objects are Processes at Some Time Scale**



P4.1 – Causal Relations

- ▶ Processes appear to be continuous at larger scales of time and space
- ▶ At a much finer scale we observe discrete events or changes of state
- ▶ Processes can be described/characterized as state changes
- ▶ Causality involves a change of state of the system based on prior states and input events
 - ▶ With no inputs processes decay or fall apart over time
 - ▶ With inputs (esp. energy) processes proceed and may either grow in size/complexity, or obtain a steady state



State Changes

▶ State Spaces

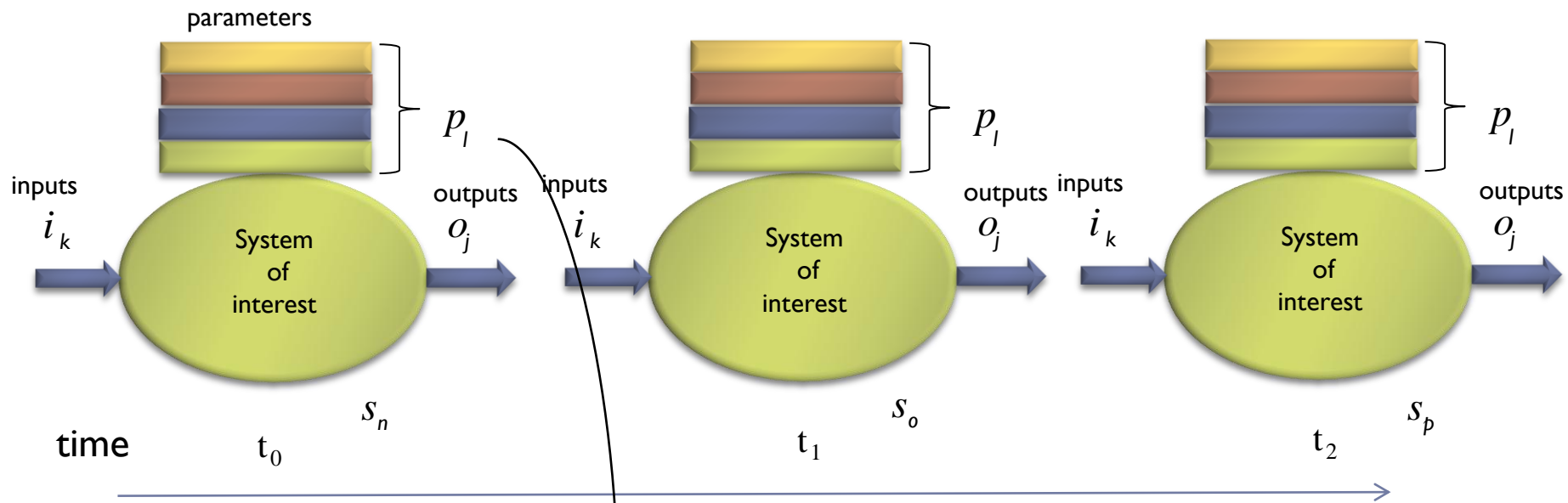
- ▶ Quantifiable parameters simultaneously measured at an instant in time
- ▶ Causal relations between parameters constrain values to certain levels relative to one another – the state of a system

▶ Phase Spaces

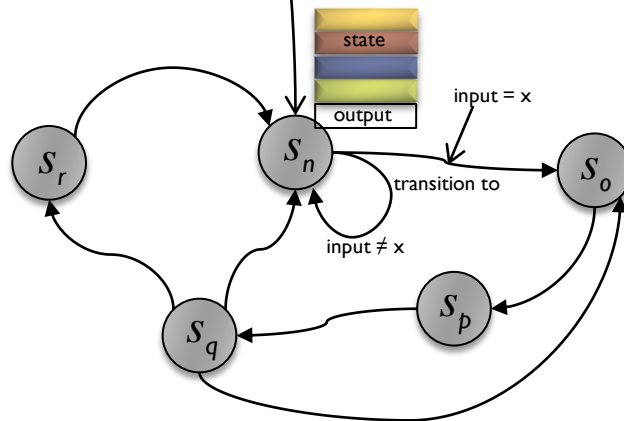
- ▶ A space in which all allowable states are represented by single points
- ▶ A trajectory defines how a system moves from one state to the next (or another)



Example of State Space Representation



At each interval of time (e.g. $\Delta t = t_1 - t_0$) the parameters and outputs will be altered by the inputs.



A state transition diagram – the system will transition from state n to state o on input x , otherwise it will remain in state n . State o will have different parameter measures and output.

Causal Relations

- ▶ Event A (e.g. an input) causes event B (change of state) if:
 - ▶ A precedes B by time Δt (on some scale)
 - ▶ A never succeeds B except after some long time interval, $n\Delta t$
 - ▶ A is connected to B by a force or a flow
- ▶ Event A occurring causes a change of state, event B , which can act as an input to another system/process producing a causal chain: $A \xrightarrow{\Delta t} B \xrightarrow{\Delta t} C$, events separated by Δt
- ▶ Mutual or Circular Causality: $A \rightarrow B \rightarrow C \rightarrow A$
- ▶ Multiple Causality: $A \rightarrow B \xrightarrow{X \rightarrow Y} C \rightarrow (B \ \& \ Y \text{ or } B \text{ OR } Y)$
- ▶ Stochastic Causality: $A \xrightarrow{P=x} B \xrightarrow{P=y} C$ (A causes B with probability, x)



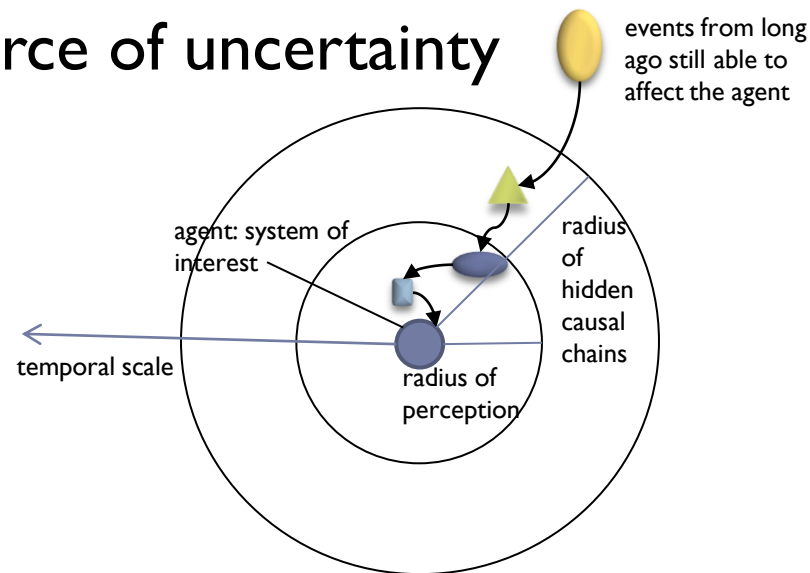
P4.2 – Multiple Time Scales

- ▶ Activity (movement and composition changes) occurs on many time scales roughly correlated with the size of components
 - ▶ Atomic – on the order of attoseconds (10^{-18} sec.)
 - ▶ Molecular – on the order of femtoseconds (10^{-15} sec.)
 - ▶ Computer circuit switching – on the order of picoseconds
 - ▶ Nerve impulses – on the order of milliseconds
 - ▶ Digestion – on the order of hours
 - ▶ Weather changes – on the order of days and weeks
 - ▶ Human life span – on the order of tens of years
 - ▶ Species longevity – on the order of hundreds of thousands of years
 - ▶ Continental drift – on the order of millions of years



P4.3 – Radius of Effect

- ▶ The system of interest, or agent, has a limited range of perception (how far away it can be from an event that will affect it)
- ▶ Causal chains can go back far in time and distant in space and still have an impact
- ▶ Major source of uncertainty



P4.4 – All Objects are Processes

- ▶ A rock at the atomic level of interaction is a chemical process operating over very long time scales
- ▶ A rock, not having usable energy or material inputs is undergoing a long process of decay
- ▶ Processes, if examined at a lower scale (higher resolution in a microscope), are made up of objects that seem to have form and solidity
- ▶ But at a yet higher resolution, these solid objects are found to be processes themselves!



Systems Are Always in Flux

- ▶ **Dynamics of the Environment**
 - ▶ Stochastic – unpredictable in detail
 - ▶ Non-stationary – long term changes in statistical properties
 - ▶ Chaotic – sensitive to initial conditions, no two systems follow same trajectory
- ▶ **Systems respond to their environments**
- ▶ **Environments respond to their component systems**
- ▶ **Adaptive systems are those that have complex, often redundant mechanisms for dealing with changing environments while maintaining a core constancy**
 - ▶ Life as the quintessential example of adaptive systems
 - ▶ Homeostasis and Autopoiesis examples



Dynamics Continuing Over Time Tell a Story

- ▶ Dynamic behavior is described by a sequence of statements about the changing state
 - ▶ Input triggers cause state changes
 - ▶ Subsequent states depend on prior states and current inputs
 - ▶ The story line describes causal sequences
 - ▶ Systems end up in a final state at the end of observation
- ▶ Complex systems tell complex stories
- ▶ All languages employ a lexicon of symbols to represent things, events, causal relations, etc.
- ▶ In describing the on-going story of a system's dynamics we employ a formal language



System Dynamics Language

- ▶ A language consists of:
 - ▶ Lexicon – words that serve purposes
 - ▶ nouns – objects
 - ▶ verbs – actions
 - ▶ modifiers – descriptors, temporal, quantifiers, etc.
 - ▶ Syntax – Grammar rules
 - ▶ how symbols can be combined to convey thoughts
 - ▶ Semantics – Meaning
 - ▶ Pragmatics – Context
- ▶ The language can be used to express meaning in context
- ▶ There is a mapping from real things and behaviors:
 - ▶ to an abstract verbal representation – text, narrative
 - ▶ to an abstract graphical representation – pictures
 - ▶ to an abstract numerical representation – mathematics and computer programs



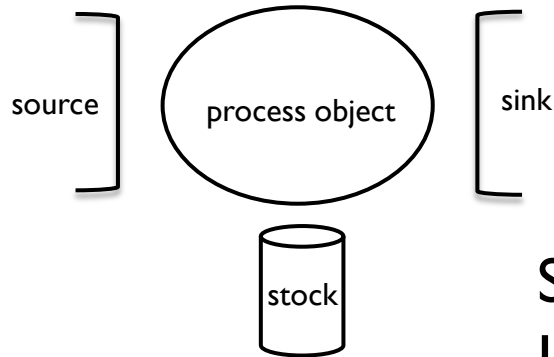
Describing the Dynamics of Systems

- ▶ Each process converts its inputs into outputs
- ▶ Each flow has a rate measure
 - ▶ can vary over various time scales
 - ▶ stochastic
- ▶ Each stock has a level measure
- ▶ Conversions can be represented by mathematical functions
 - ▶ Product per unit time = $f_t(\text{input}_1, \text{input}_2, \dots, \text{input}_n)$
 - ▶ $\text{input}_i = \text{units of measure} / \text{unit of time}$
 - ▶ $\text{waste}_j = \text{units of measure} / \text{unit of time}$
- ▶ All equations have to conform to the physical laws of conservation and decay



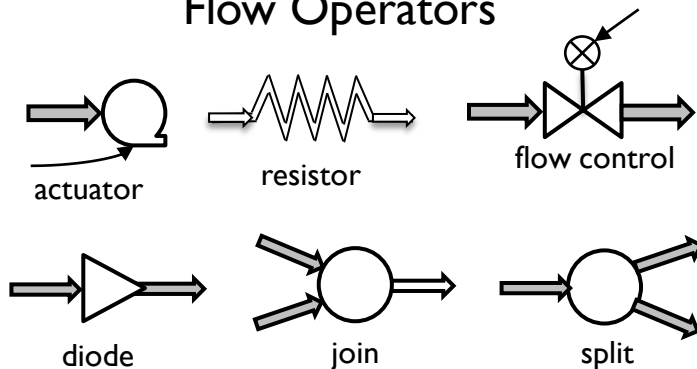
A Graphical Language for Describing Systems Dynamics

Process Framework

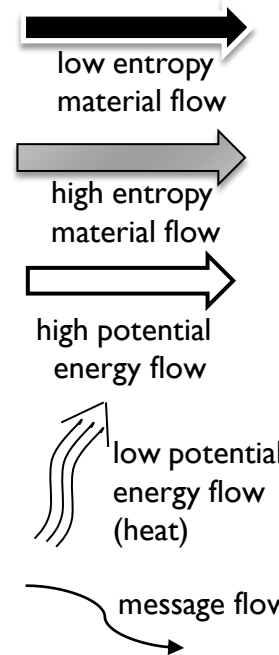


System Dynamics Language Lexicon – Semantic Objects

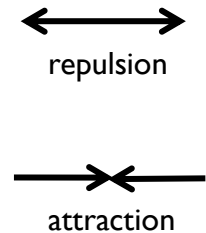
Flow Operators



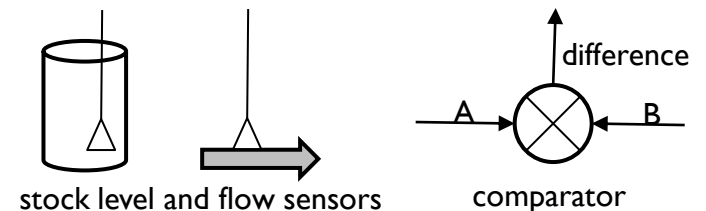
Flows



Forces



Message Modulators

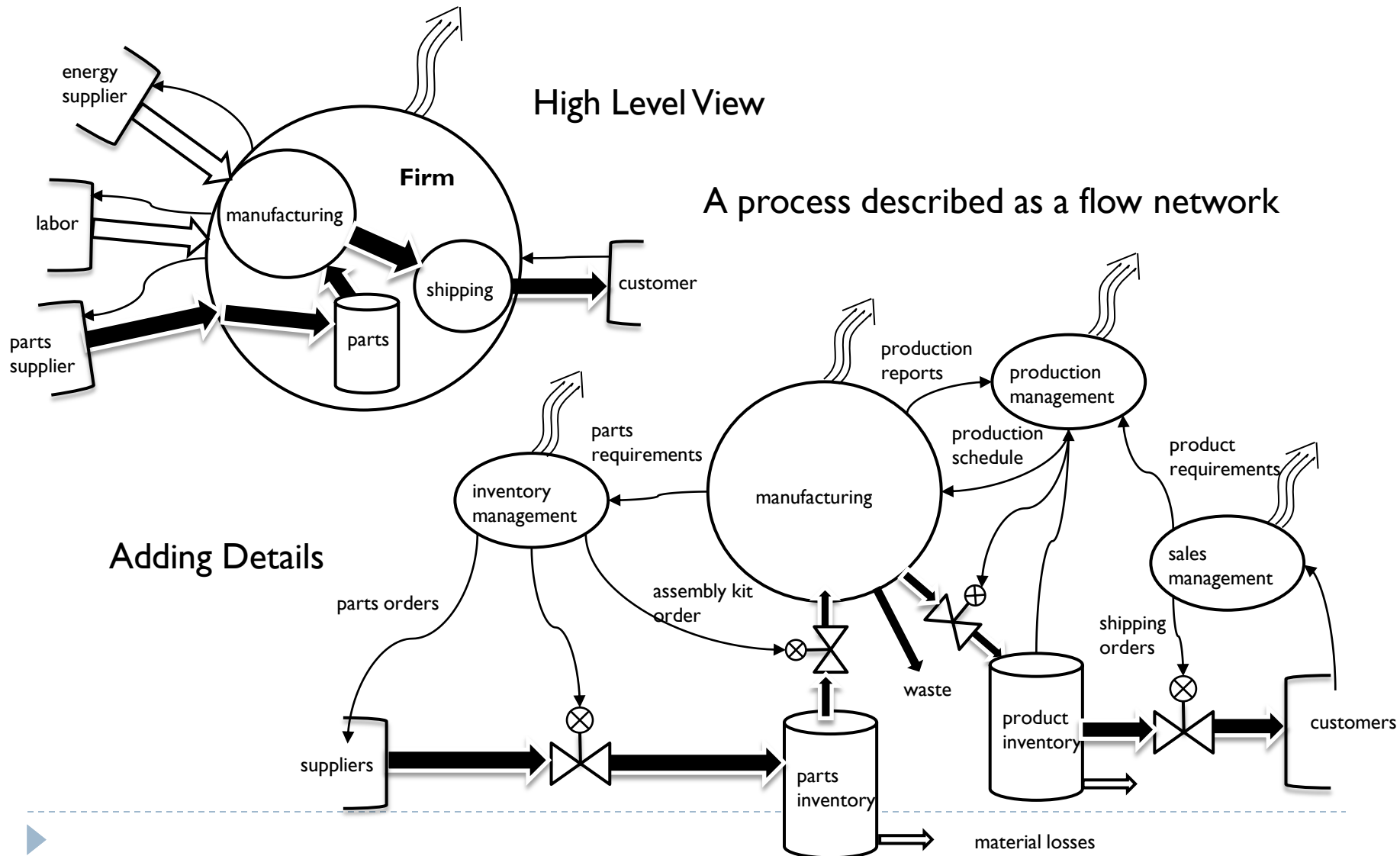


Example of Verbal Description

- ▶ A specific 'firm' is an economic process that manufactures products using energy, labor, and material parts inputs. It temporarily stores component parts as they are shipped in. It temporarily stores finished product in preparation for shipping to customers on demand. A manufacturing control system keeps track of orders for product, the state of product inventory, and issues orders to manufacturing to replenish stocks as needed.
 - ▶ The firm is comprised of a manufacturing sub-process, a parts inventory and a product inventory, and three management (information) processes, inventory, manufacturing, and sales.
-



Example of a Visual Description Language



Example of a Numerical Representation

- ▶ A computer code for computing the behavior of the firm

Process: Firm {

time constant: 1 day;

inputs {

energy {

range: 4000 to 7000 kw;

type: electricity;

}

labor {

type: human;

range: 6 to 8 hrs/person;

}

:

:// etc.



Numerical Model cont.

Sub-process: Manufacturing {

inputs: labor, energy, parts;

```
function: manufacture (product_units_needed) {  
  while (product_count < product_units_needed) {  
    product_unit = .25 * labor + .75 * parts + .13 * electricity;  
    product_count = product_count + product_unit;  
  }  
  output product_count;  
}
```

Sub-process: ProductionManagement {

inputs: product_inventory, sales;

```
function: product_inventory {  
  if product_inventory > 0 then {  
    output product_unit;  
    product_inventory = product_inventory - 1;  
  }  
  if product_inventory < 10 then production_management_notify(product);  
}
```



Translations From One Language to Another

- ▶ All formal descriptions and stories should be inter-convertible
- ▶ Stories about how a system behaves under various input circumstances (i.e., the dynamics of the environment) are scenarios
- ▶ Scenarios can be used to make predictions about system behaviors
- ▶ The formal descriptions are called models – more on those later



Thinking Systemically

- ▶ End of Part I
- ▶ Principles 5 – 12 in Part II

