The Principles of Systems Science

And General Systems Theory

The Concept of A System

- An identifiable whole – an entity or object
  - Bounded in some way
- Interacts with its environment in various ways
  - Inputs/Outputs (matter, energy, messages)
- Has internal organization
  - Processes inputs to produce outputs
- Subject to change over time
  - Growth, development, decay, dissolution

General Systems Theory

- Every identifiable object is a system of some kind
  - Simple vs. Complex
- All systems share properties (principles) that govern their form and function
- A scientific approach to the study of systemness can provide guidance in the study of specific kinds of systems, e.g. biological systems

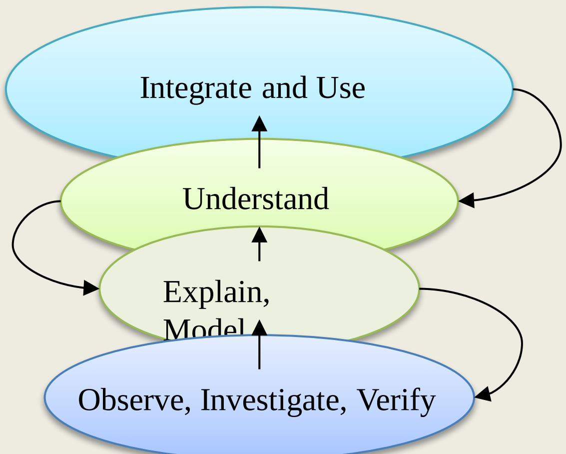
Science and Systems Science

TCORE 122D

Introduction to Science

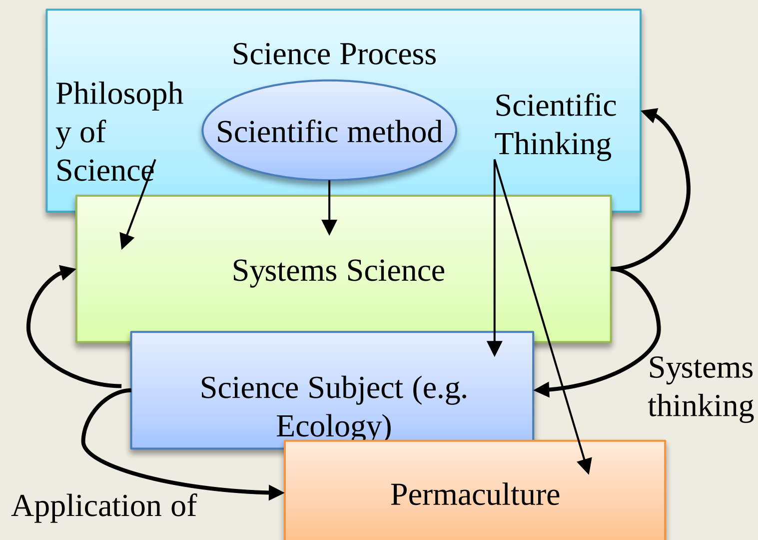
Relationships

The Science Process



Evidence, hypothesize, experiment, analyze, review

The Role of Systems Science



A Conceptual History of Science and Systems Science

- Psychology of causal thinking – built into our brains
- Backward causal relations to find explanations of why and how things happen
- First tentative scientific process came with control over fire and really took off with invention of agriculture – Became formalized with civilizations
- Inquiry:
  - What is inside? ⟶ Reductionism
  - How does this work? ⟶ Mechanism
  - Why does this happen? → Explanation → Understanding

“THING” – The Most Useful Word in any Language!

- Native (informal) Systems Thinking
  - There are “Things” in the world
  - Things are connected in various ways
  - Some things cause other things to change
  - Things may last a long time unless disrupted by some other thing
  - I’m a thing to other things like me!
  - I’m part of a larger thing that includes all other things

Formal Systems Science

- Early science focused on the successes obtained from reductionism – taking things apart
- Evolved to categorization – identification of similar/unlike things
- Evolved further to explanation of causes
- Systems thinking in the background in all sciences
- Methods of science applied to systemness itself
- Systems science has started to pervade all sciences

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 Complex 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 have internal regulation subsystems to achieve stability

Additional Principles for Complex Adaptive Systems (CAS)

- Several principles related to systems thinking, systems science, and systems development

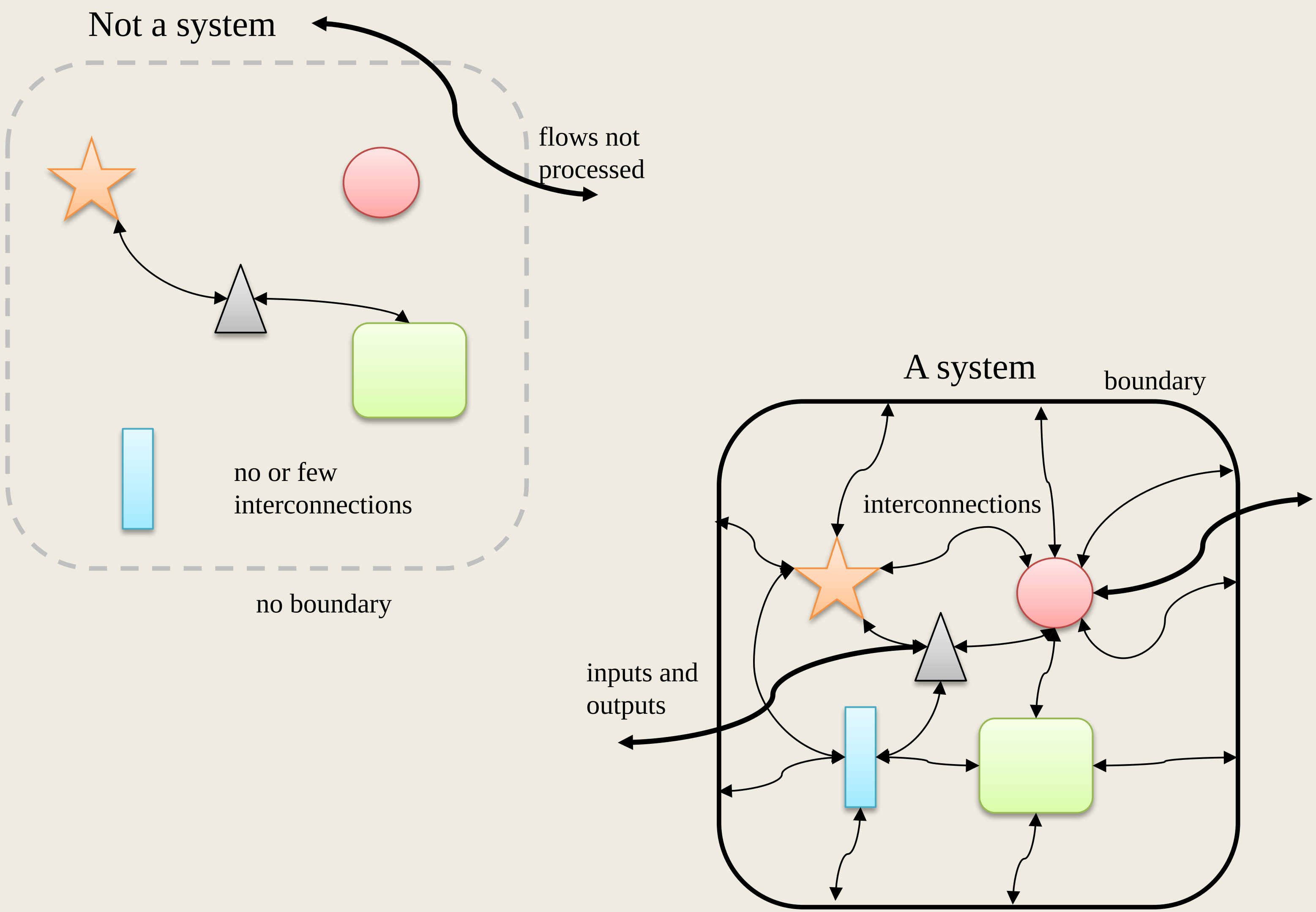
9. Systems can contain models of other systems
10. Sufficiently complex, adaptive systems can contain models of themselves (brains and mental models)
11. Systems can be understood (a corollary of #9) – Science as the building of models
12. Systems can be improved (a corollary of #6) – Engineering as 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.

Systemness


Not a system
flows not
processed
no or few
interconnections
no boundary
A system
boundary
interconnections
inputs and
outputs

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

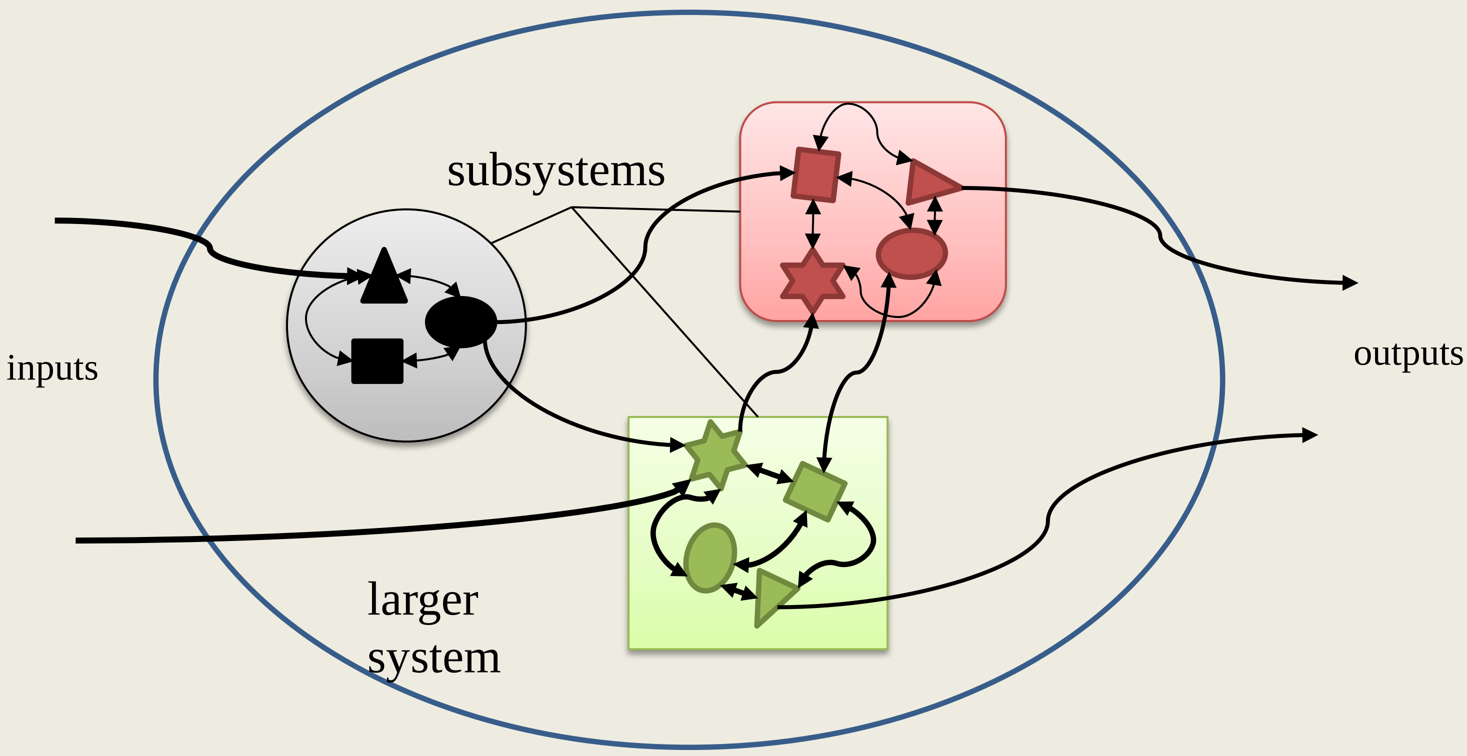


Figure 3. Systems are comprised of subsystems.

The System Hierarchical Tree

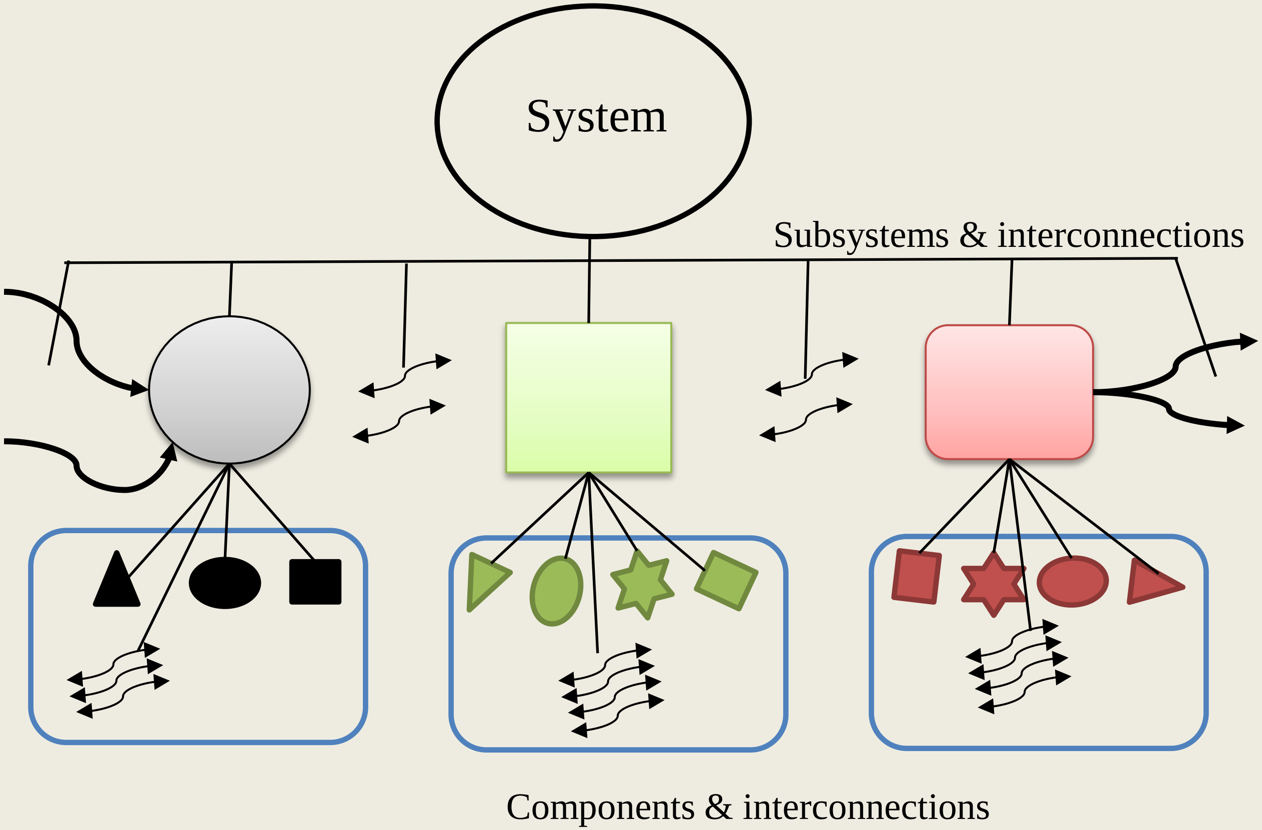
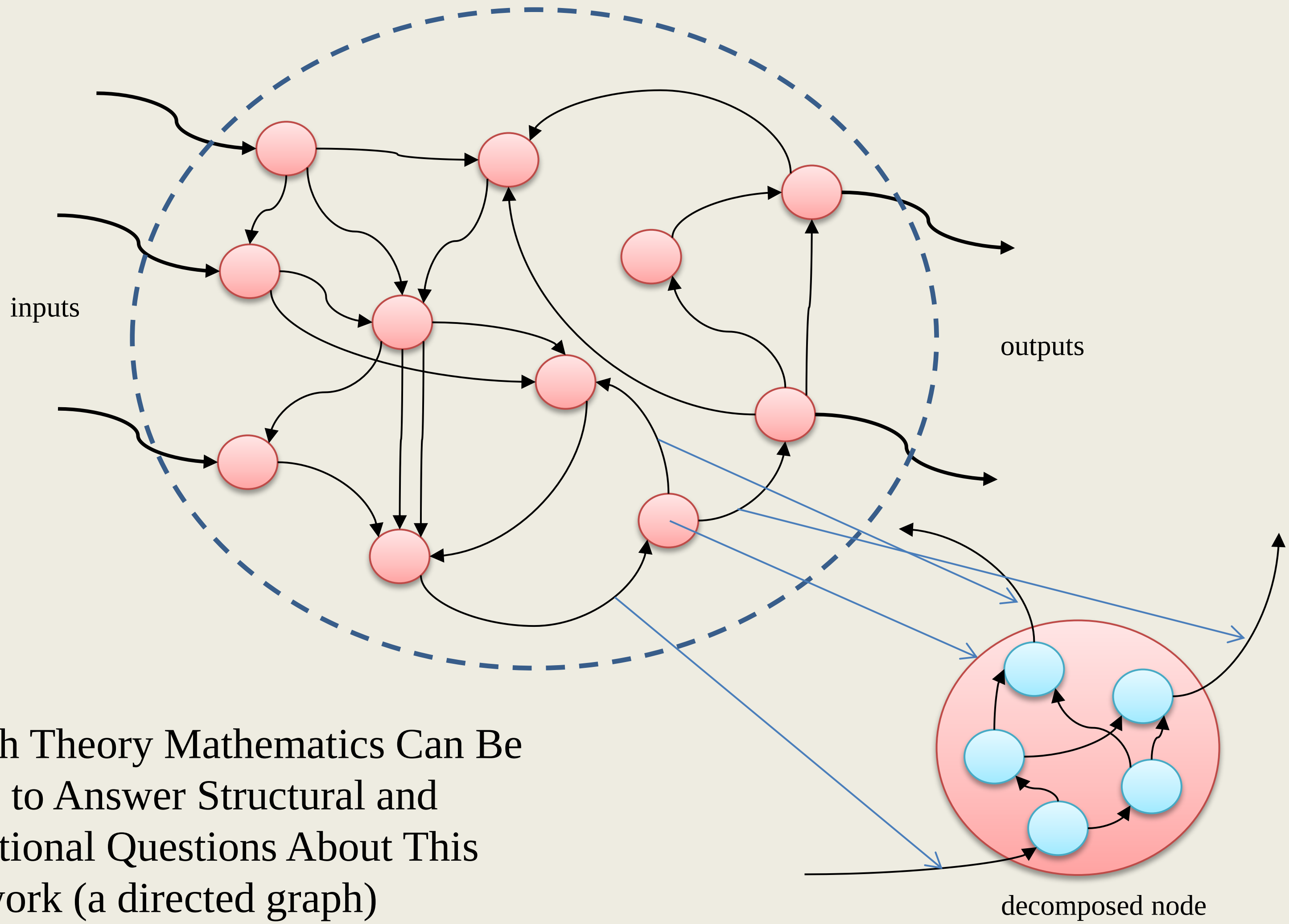


Figure 4. Systems, subsystems & components form a structural hierarchy.

Principle 3 - Systems Represented as 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 – their components (subsystems)
- Energy, Material, and Message 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

Causal Relations – Cont.

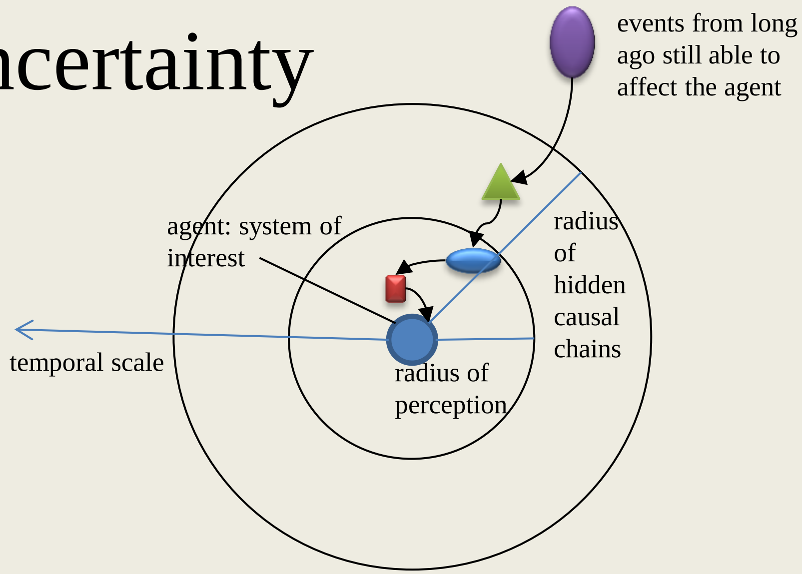
- Event *A* (e.g. an input) causes event *B* (change of state) if:
  - *A* precedes *B* by time Δt (on some scale)
  - *A* never succeeds *B* except after some long time interval, $n\Delta t$
  - *A* is connected to *B* by a force or a flow
- Event *A* occurring causes a change of state, event *B*, which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

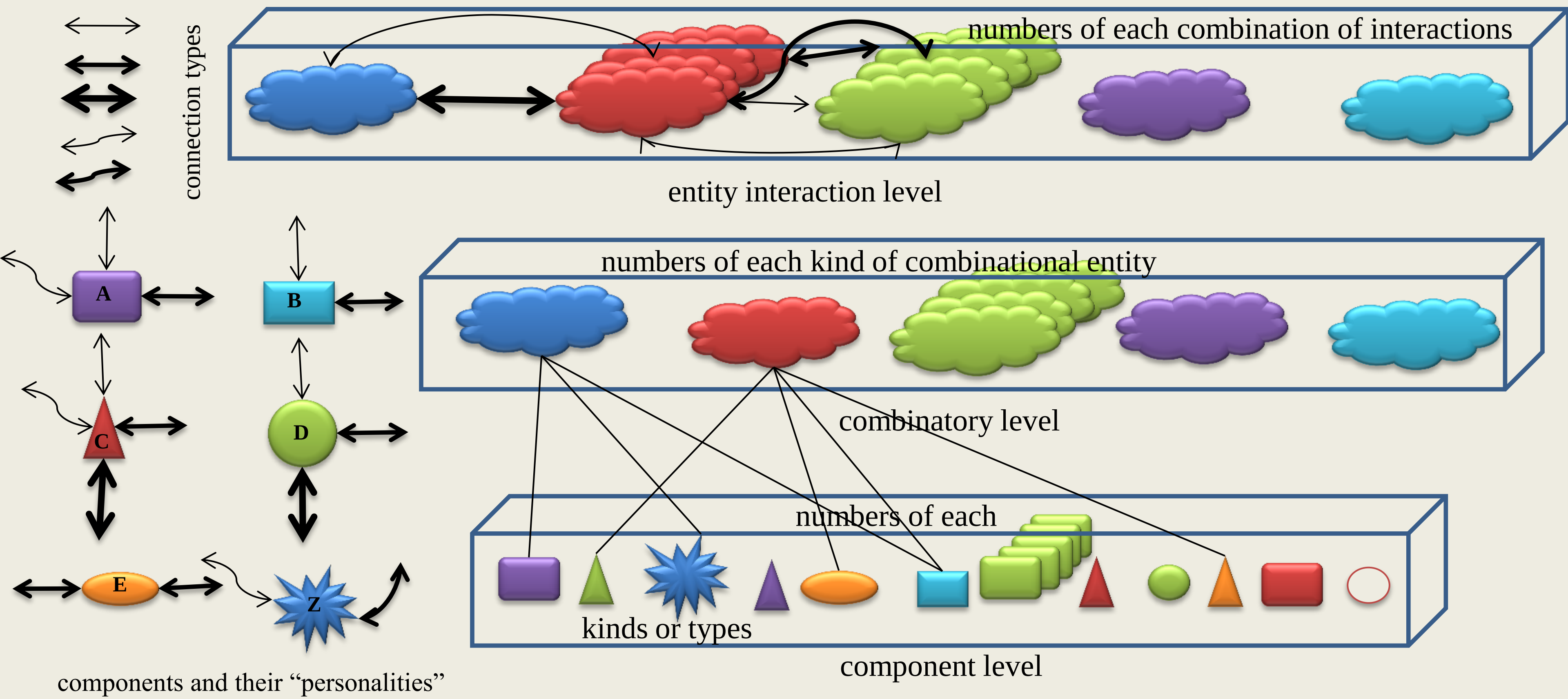
Dynamics Over Time Tell a Story

- 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

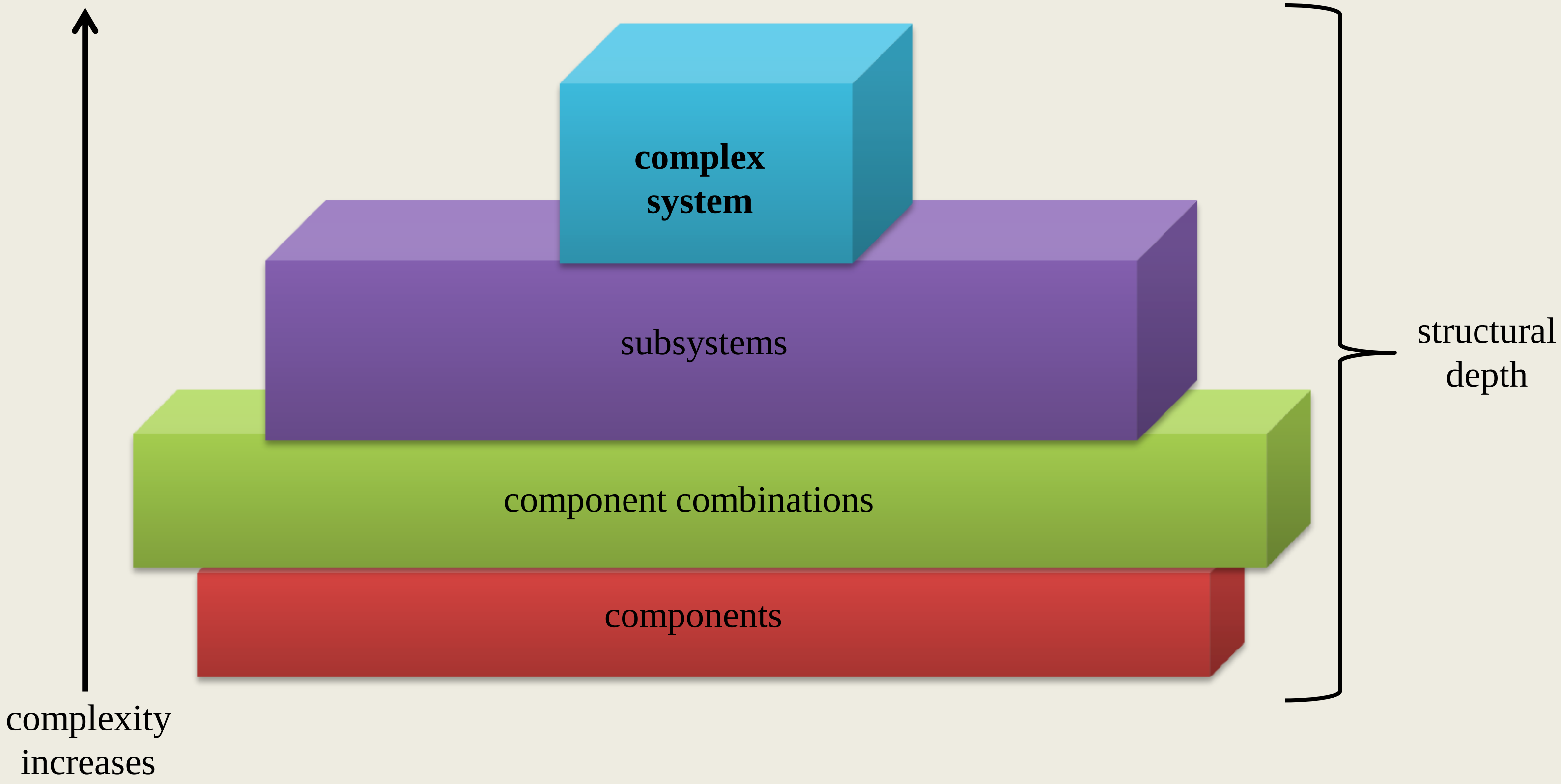
Principle 5 – Systems Can Be Complex

- Levels of Organization refers to the system structural hierarchy
- The deeper the hierarchy the more complex the system of interest
- Complexity can be an index of:
  - the number of components
  - the number of types of components (personalities)
  - the number of interconnections
  - the strength of those interconnections
- Complexity (of behavior) can arise from non-linear interactions between components

Levels of Organization – Basic Complexity

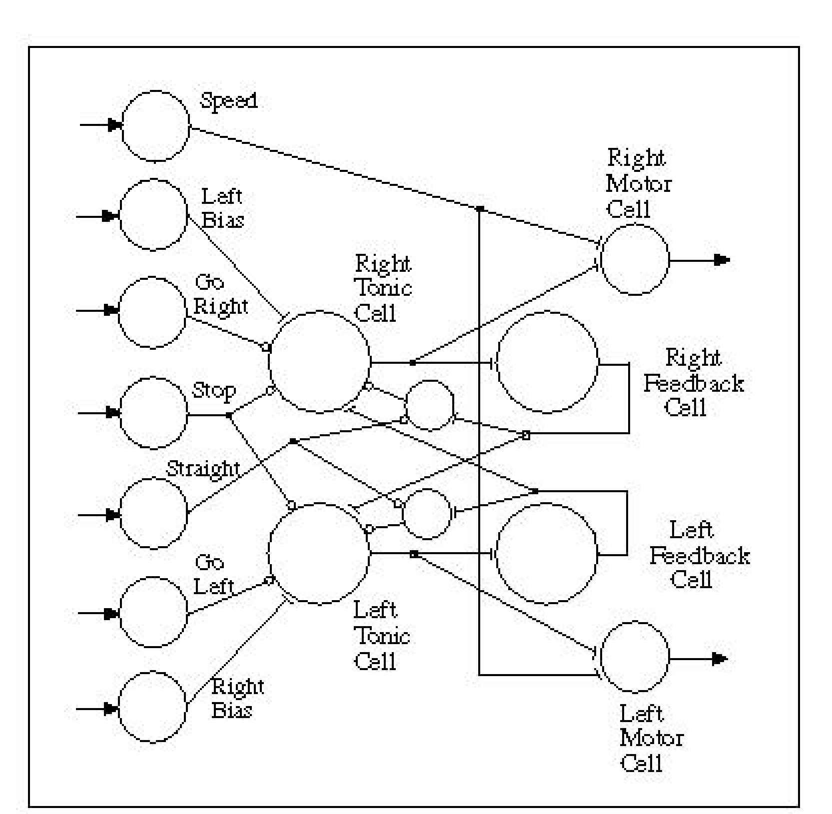


Levels of Organization - Depth



Complex Behavior – Example Robot Brain

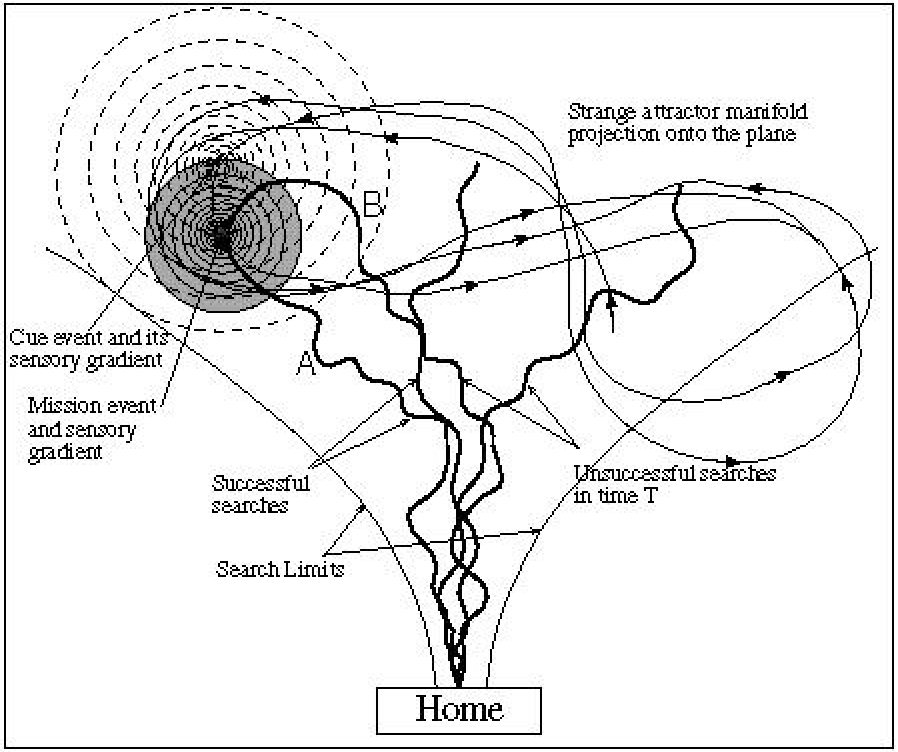
Mobile **A**utonomous **V**ehicle for **R**esearch in **I**ntelligent **C**ontrol



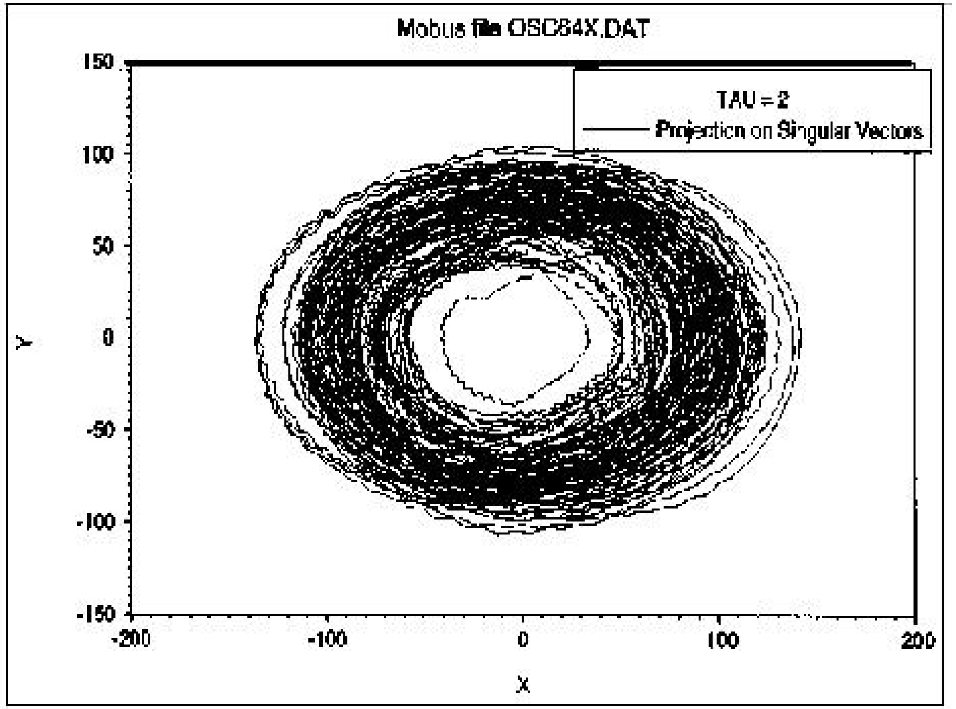
central pattern generator neural network

The MAVRIC robot learned to avoid harmful signals and approach rewarding signals. It followed a “drunken sailor walk” search to find targets.

Complex Behavior – Example Robot Brain (cont.)



drunken sailor walk (chaotic) search



phase space plot of chaotic attractor generated by the MAVRIC CPG

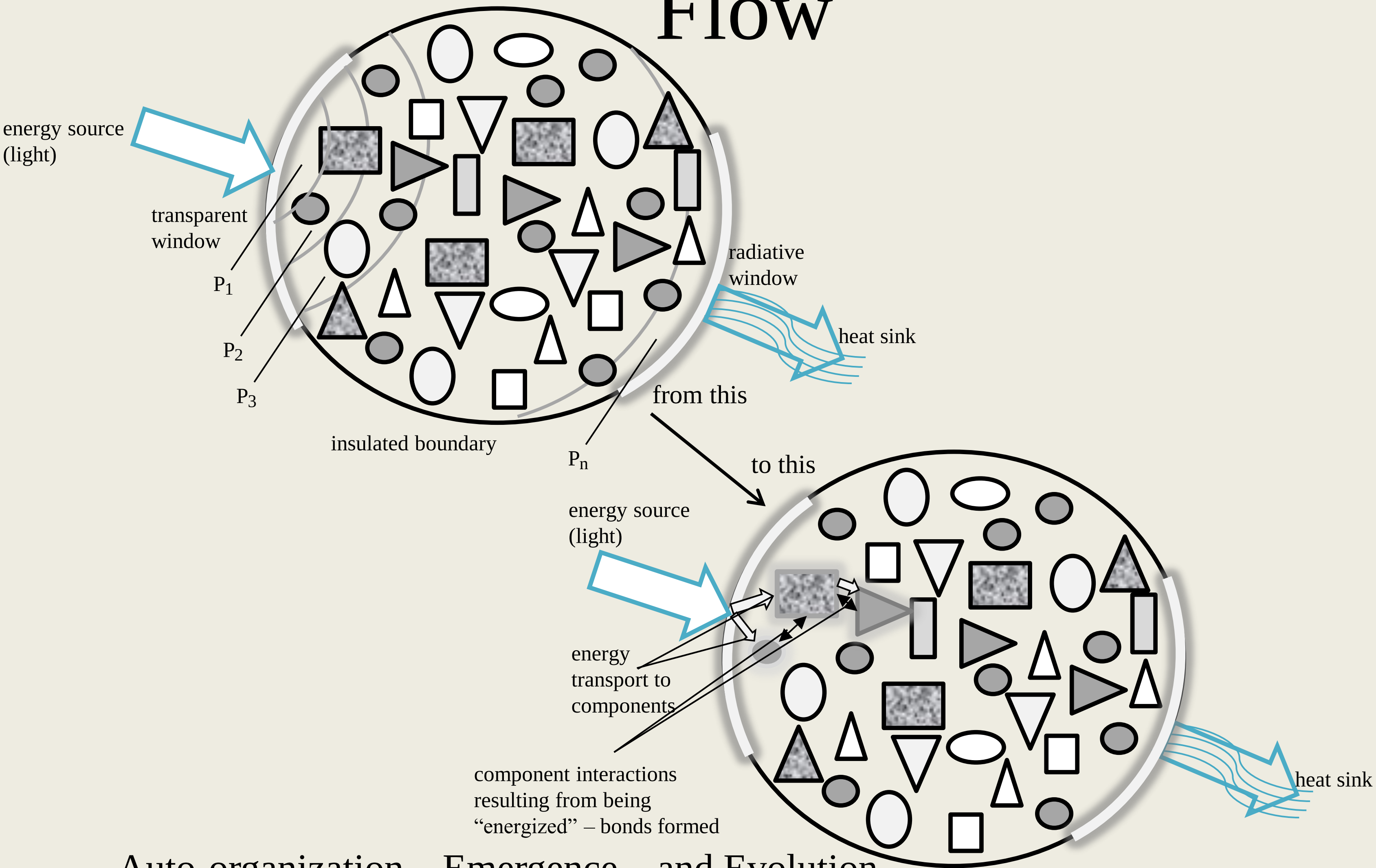
Complexity – The Downside

- Greater complexity in a system requires more subsystems devoted to regulation (see Principle 8)
- Non-linear behaviors of subsystems can be a source of uncertainty and lack of control
- Complexity is often increased to compensate for problematic situations
  - A problem can be defined as an unfavorable cost-benefit condition, e.g. cost >> benefit
  - Problems can be solved, but usually by finding new resources and technological (structural and functional) advances
  - If the new resources are limited, then the solution of a problem leads to more problems later on
- The Law of Diminishing Returns – Marginal cost of solving a problem with marginal return of diminishing value

Principle 6 – Systems Emerge and Evolve

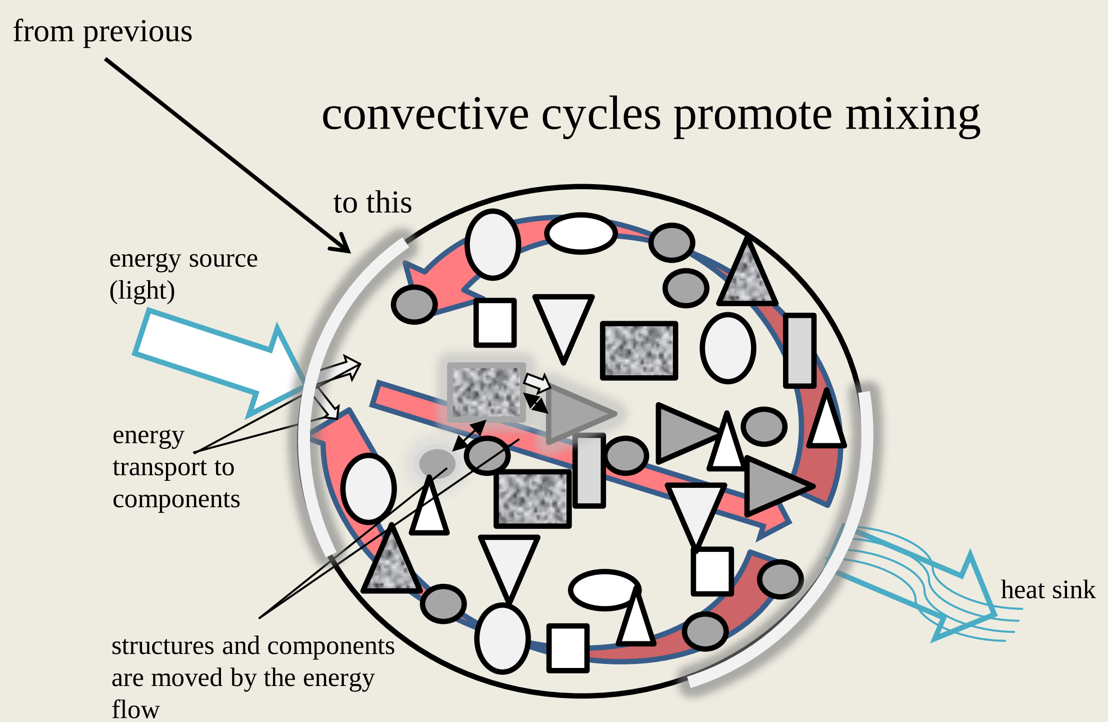
- From disorganized atomic components to organized processes
- Energy flow needed to do work of building and moving structures
- More complex structures that are stable in a particular environment emerge
  - Competition with other complex structures
  - Cooperation with other complex structures
- Auto-organization proceeds as long as energy is available

Auto-Organization Starts With Energy Flow

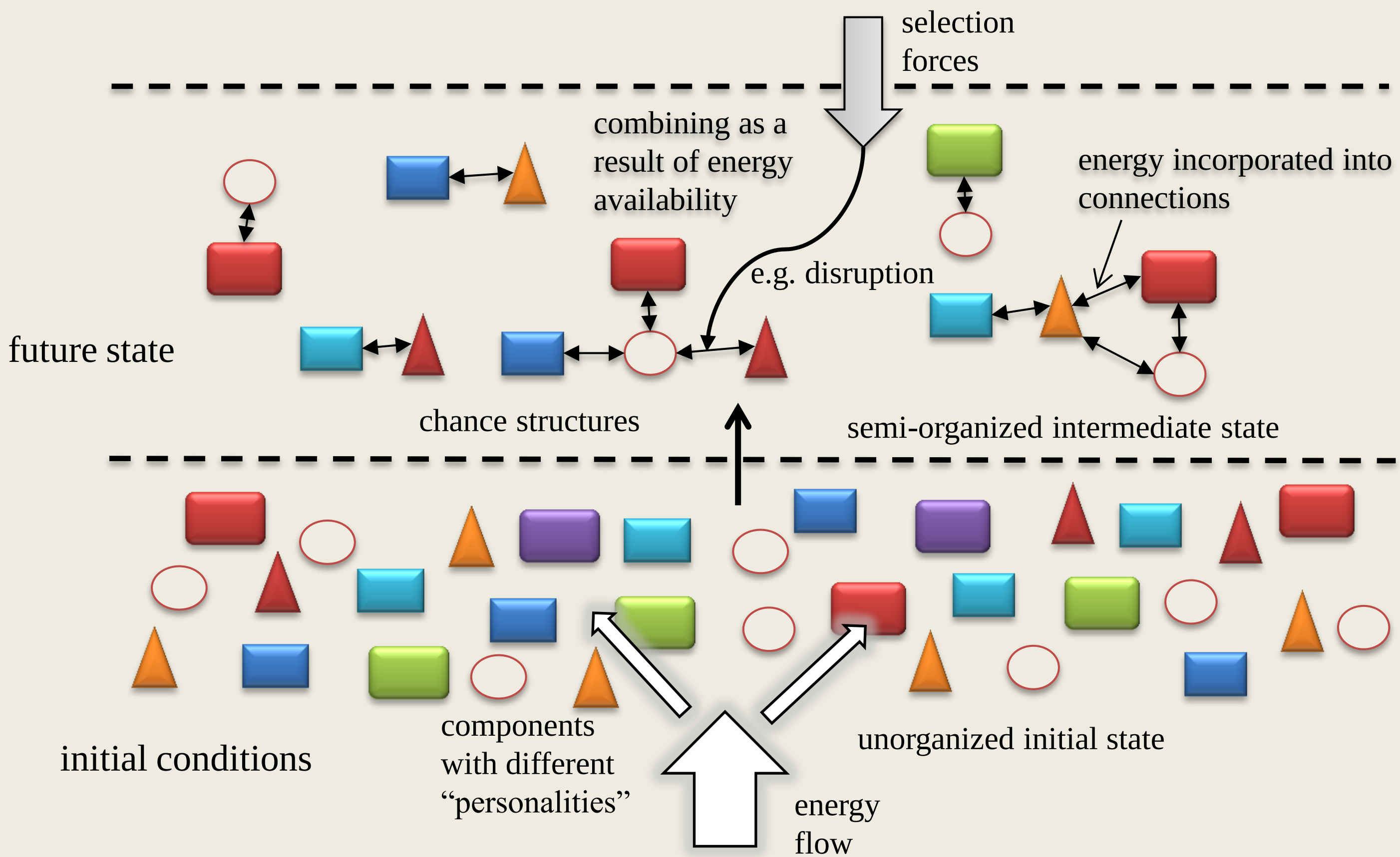


Auto-organization – Emergence – and Evolution

Dynamic Structures and Movement



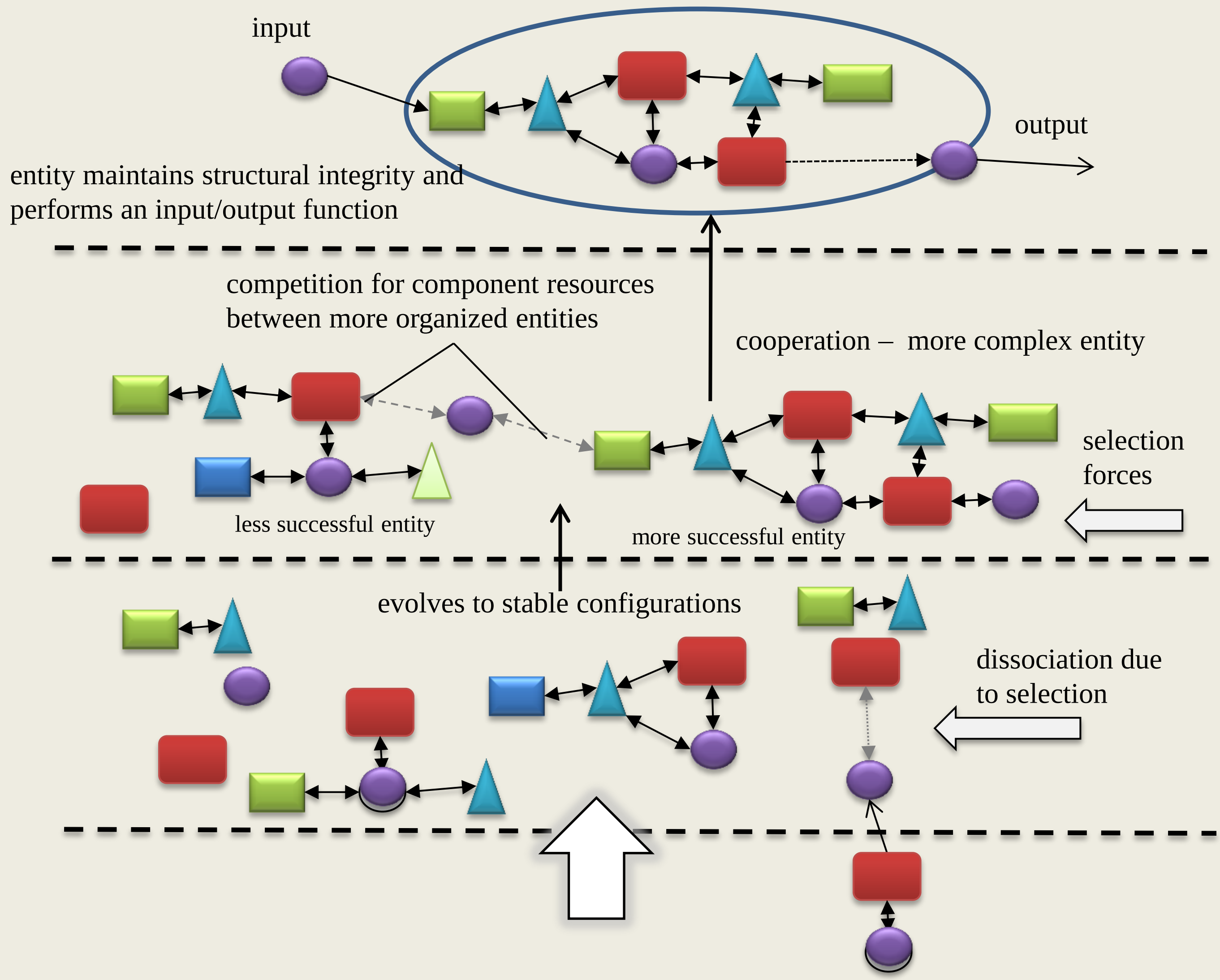
Auto-Organization Leads to Greater Complexity



Components Interact and Form Structures

- Auto-Organization is a dynamic process of making and breaking interconnections
- Components are mixed by energy fluctuations, as shown above
- Some interconnections are inherently stronger and will persist longer
- Stable configurations in light of “selection forces” obtain in time
- Unstable configurations decay and provide components for new attempts at auto-organization

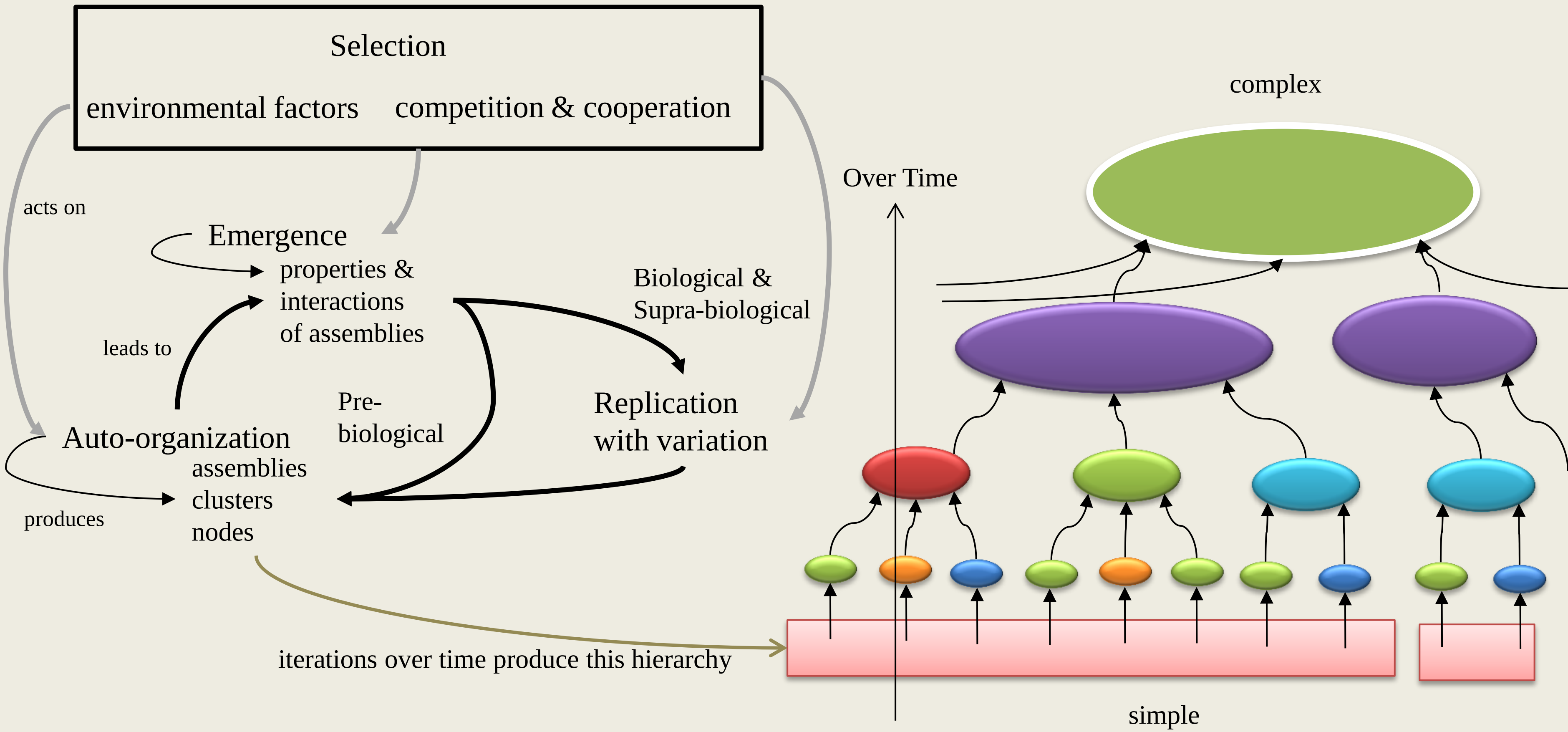
Emergence of Forms with Functions



Entities with Structural Integrity and Functions Emerge

- Emergent Behavior – Entities perform functions that interact with other entities
- Emergent Form – Entities, collectively, form networks of interactions with many other entities
- Emergent Properties – Entities produce form and behavior not predicted by the nature of the components (example: water properties not predicted by nature of oxygen or hydrogen)
- Properties can be analyzed and understood retrospectively but not prospectively
- The “whole” is not just the sum of the “parts”

Evolution – the Process of Increasing Complexity Over Time



Principle 7 – Systems Produce Information and Knowledge

- Complex systems can produce messages:
  - Flows of energy (sometimes matter) that are modulated to encode a message
  - The message is 'about' the state of the sending system
  - The message is interpreted by the receiving system
- Messages that are 'unexpected' convey information or tell the receiver system that something about the sender has changed – information is a function of the expectation of a message by the receiver, not a function of the sender
- An informational message causes the receiving system to adjust – make a structural change internally to accommodate the new state of affairs
- The adjustment comes in the form of changing the receiver's expectations for receiving that kind of message in the future

Information

- Proportional to the receiver's *prior probability* of a particular message state arriving at time *t*
- Information is a measure of surprise to the receiver!
- Information is "News of difference that makes a difference."
- Information tells you something you did not previously know
- $I_t = -log_2 P(x_t)$ Information is equal to the inverse log of the probability of the x_{th} event at time *t*
- The information in an event of probability 0.5 is 1 *bit*

Knowledge

- Knowledge is constituted in a receiving system’s internal structure, how it is organized internally
- The more knowledge a system possesses the less information it receives from a message
- The more you know the less you can be surprised
- It is the inverse function of information

Learning

- A receiving system that has the capacity to make internal structural changes that "encode" the information value of messages are adapting to their environments
- The brains of animals are able to make changes in the wiring patterns between neurons in response to sensory inputs correlated with internal "states"
- Such pattern changes represent changes in perceptions and conceptions and can lead to modified behavior
- If the changes are reinforced and persist across time then we call such real-time adaptations "learning"
- The more one learns the less surprising the world will be

Principle 8 – Complex Systems are Self-Regulating

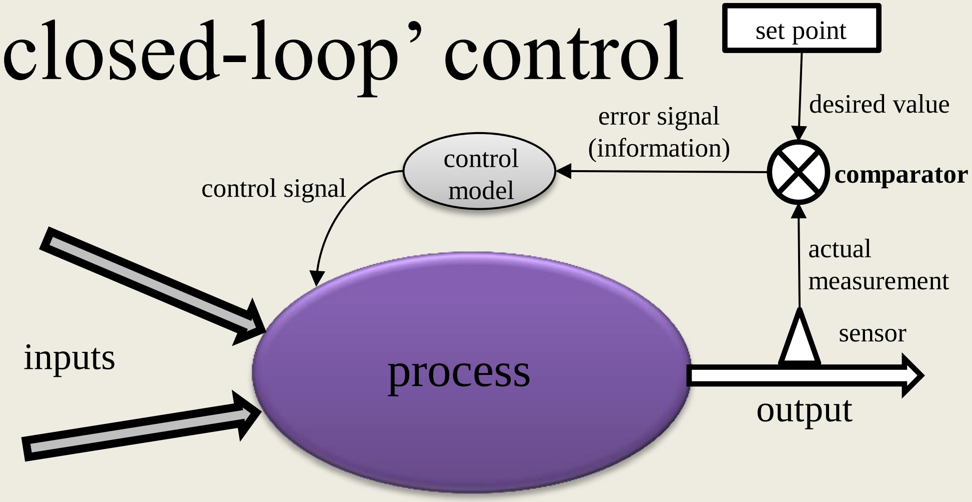
- Sufficiently complex, dynamic systems can use information and knowledge to maintain stability in spite of a volatile environment
- Principle 8.1 – Things can go wrong
  - Inputs are subject to noise and disruption
  - Components wear out and/or act stochastically
  - Systems need to use information to self-correct and possibly adapt to changes in the environment
- Principle 8.2 – Feedback and Feedforward
- Principle 8.3 – The coordination of complex systems
- Principle 8.4 – The adaptation of complex systems
- The hierarchical control subsystem

P 8.1 – Things Can Go Wrong

- Uncertainty
  - Random noise
  - Non-stationary stochastic processes
    - Trends away from long-term norms
    - New elements coming into the environment
  - Chaotic processes
  - Example: Climate and Weather
- Entropic Decay – Second Law of Thermodynamics
  - All real physical systems require energy input to maintain form and function
  - All work results in some loss of energy to waste heat, which cannot be used to do more work
- Systems have to be self-maintaining to remain stable over time

P 8.2 – Self Regulation - Cybernetics

- Systems can use internal information (messages) and knowledge to self-regulate
- Feedback of information regarding a subsystem's behavior can be used to bring the subsystem into expected performance
- A standard 'closed-loop' control

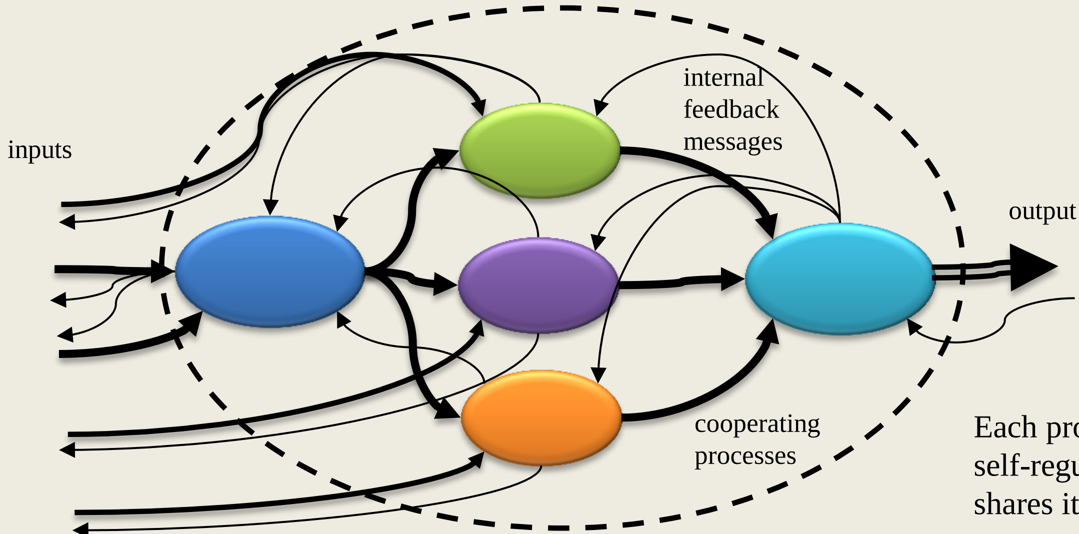


Closed-Loop Control

- A standard, ideal or desired value for the measurement of an output (product) attribute is determined and set
- A sensor measures the actual, real-time value of the attribute
- A comparator device determines how close or far the actual measurement is from the desired set point
- The result is an error signal that can take on zero, positive, or negative error levels
- A control model, and decision processor uses the error to compute a countervailing action (command) that is sent to the main process to cause it to adjust its internal conditions – to reduce the error back to zero

Emergence of Cooperating Processes

- Outputs from some processes are inputs to other processes
- Processes send messages to each other to coordinate inputs and outputs
- The collective of processes emerges as a loosely organized system



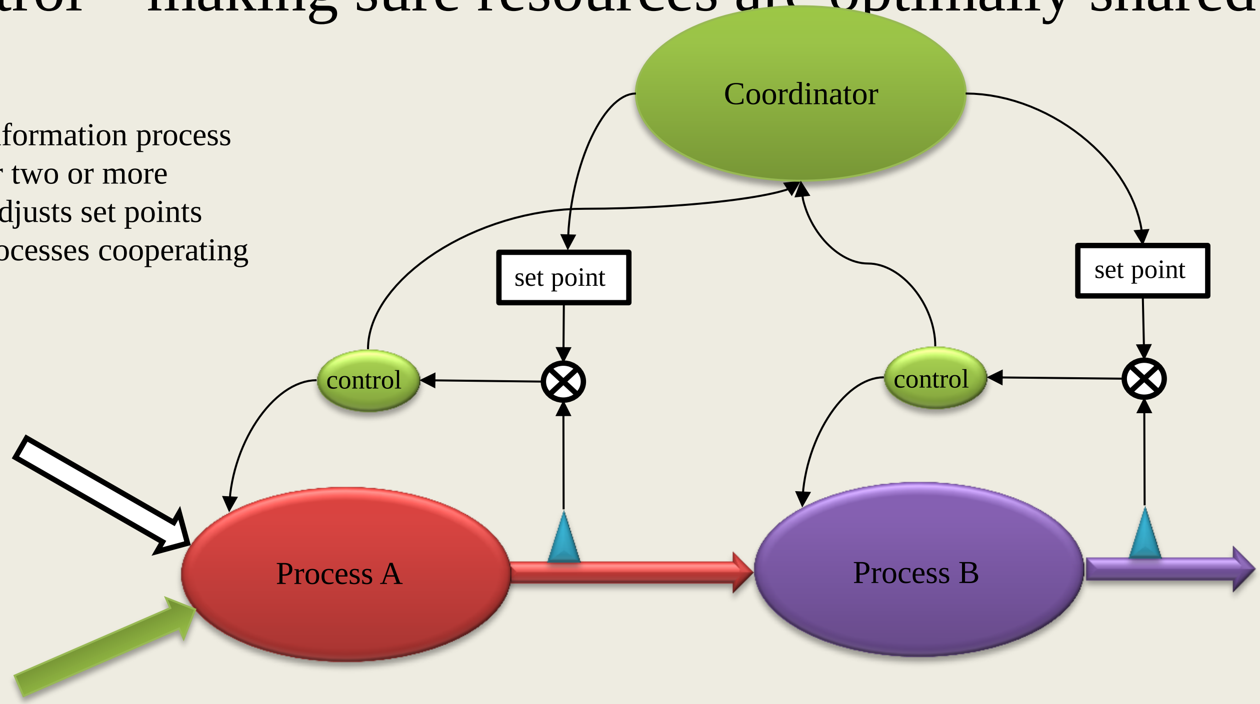
A Market of Cooperating Processes

Each process has an internal self-regulating controller and shares its signals with other processes.

P 8.3 - Coordination Above Cooperation

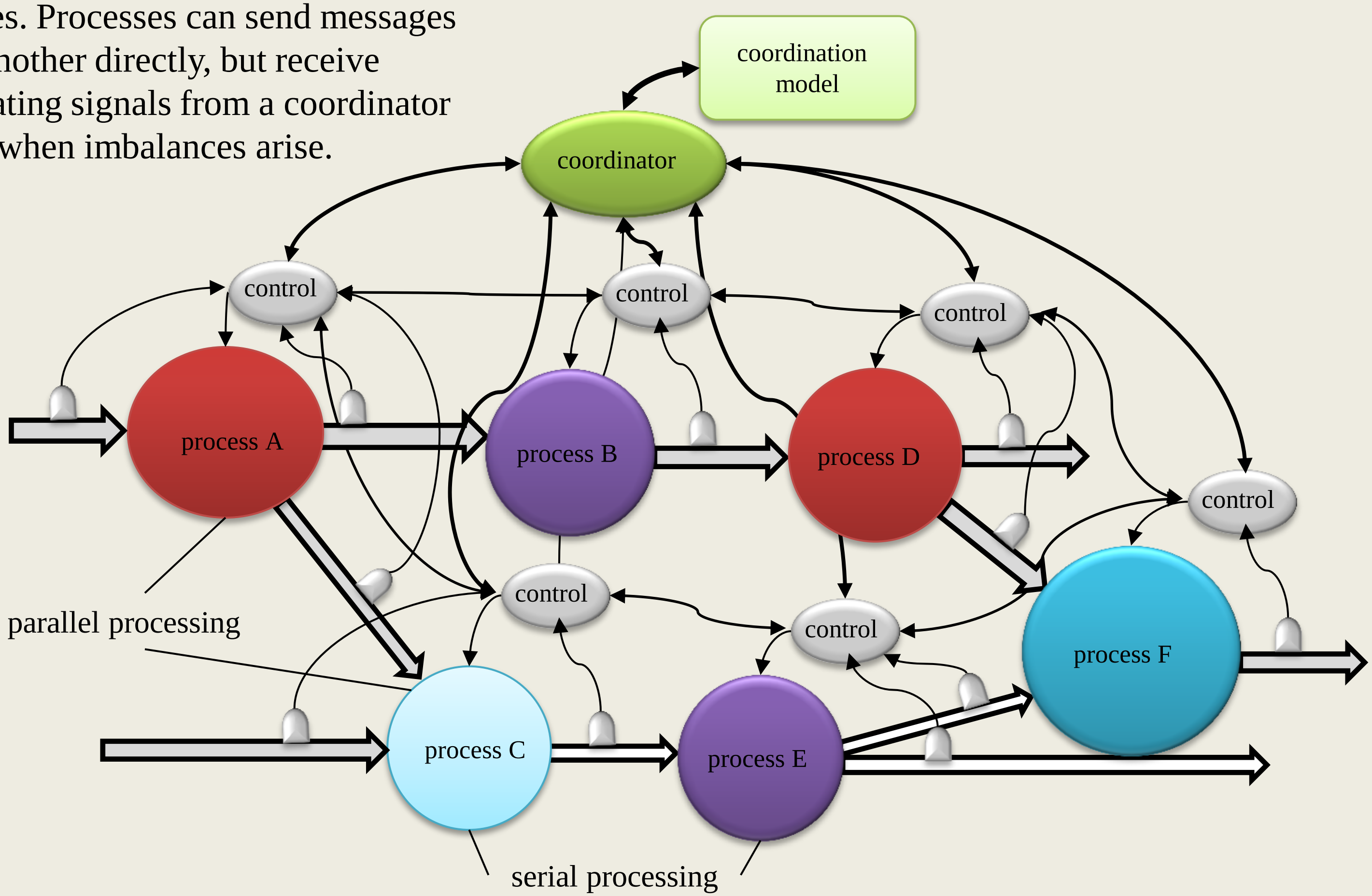
- Cooperating systems can evolve to incorporate a more reliable and dedicated coordinator
- An information processor whose job is to maintain balance between processes
- Logistic control – making sure resources are optimally shared

A coordinator is a special information process that acts as a controller over two or more subsystems (processes). It adjusts set points and control rules to keep processes cooperating smoothly.



A More Complex Set of Coordinated Processes

More elaborate coordination models are required to handle complex, cooperating processes. Processes can send messages to one another directly, but receive coordinating signals from a coordinator process when imbalances arise.

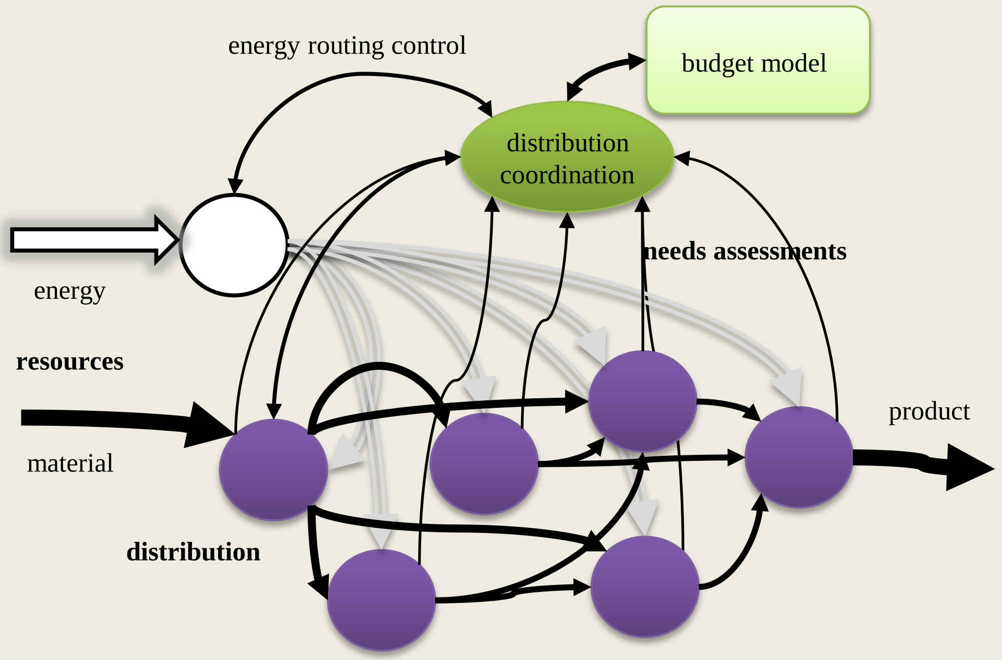


Internal Coordination is Logistical Control

- A coordination model is used to specify the input/output relations between all of the processes
- Sufficiently complex systems may further divide the coordination task between multiple coordinator processes – this requires a supra-level coordinator to coordinate the inferior-level coordinators
- Coordination hierarchies can be found
  - in living cells – metabolism control
  - whole organisms – central nervous system
  - organizations – management
  - states - government

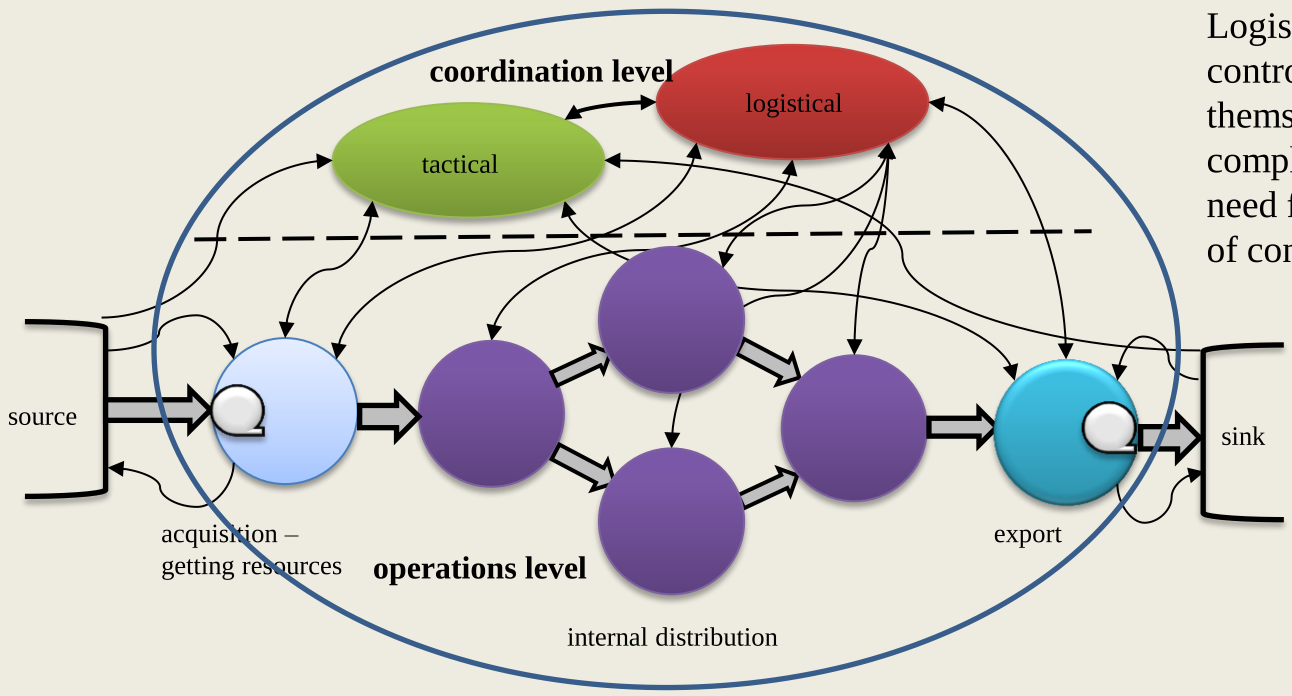
An Example of a Logistical Control – Distribution of Resources

A distribution coordinator uses a budget model to route resources (like energy) to the processes.



Coordinating With the External World – Tactical Control

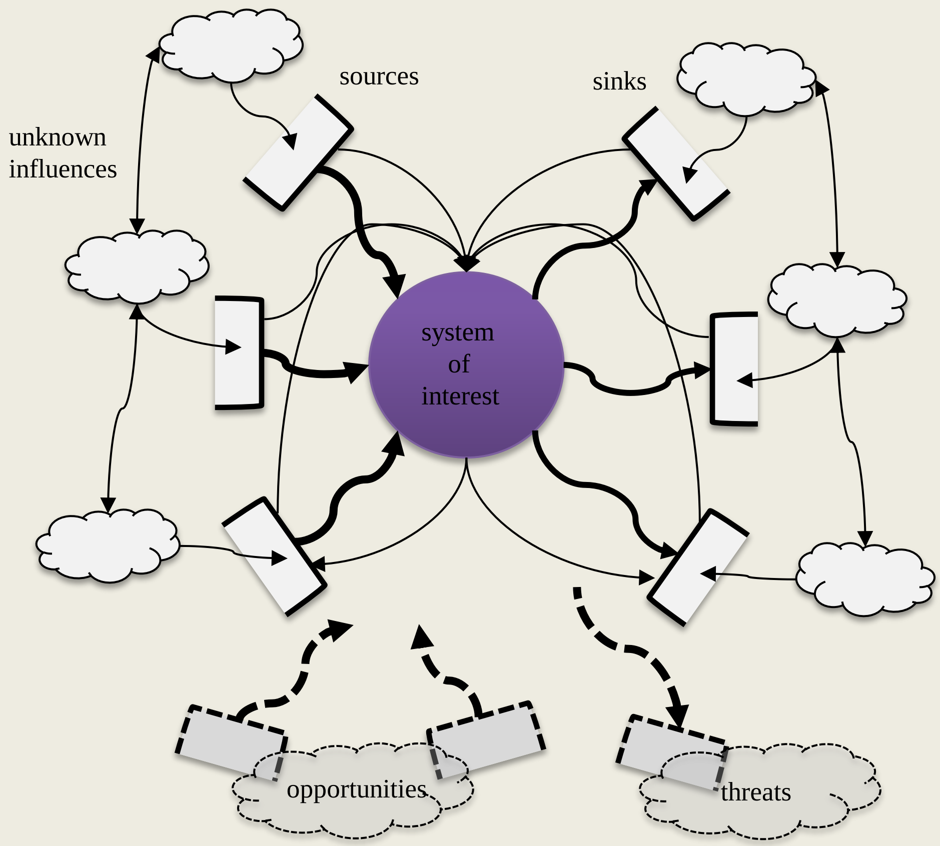
- A tactical controller is similar to a logistical controller but must act to coordinate the system's activities with the environmental entities that are sources and sinks (also threats and opportunities)



Logistical and tactical controllers must cooperate themselves. At some level of complexity this implies the need for an even higher level of control.

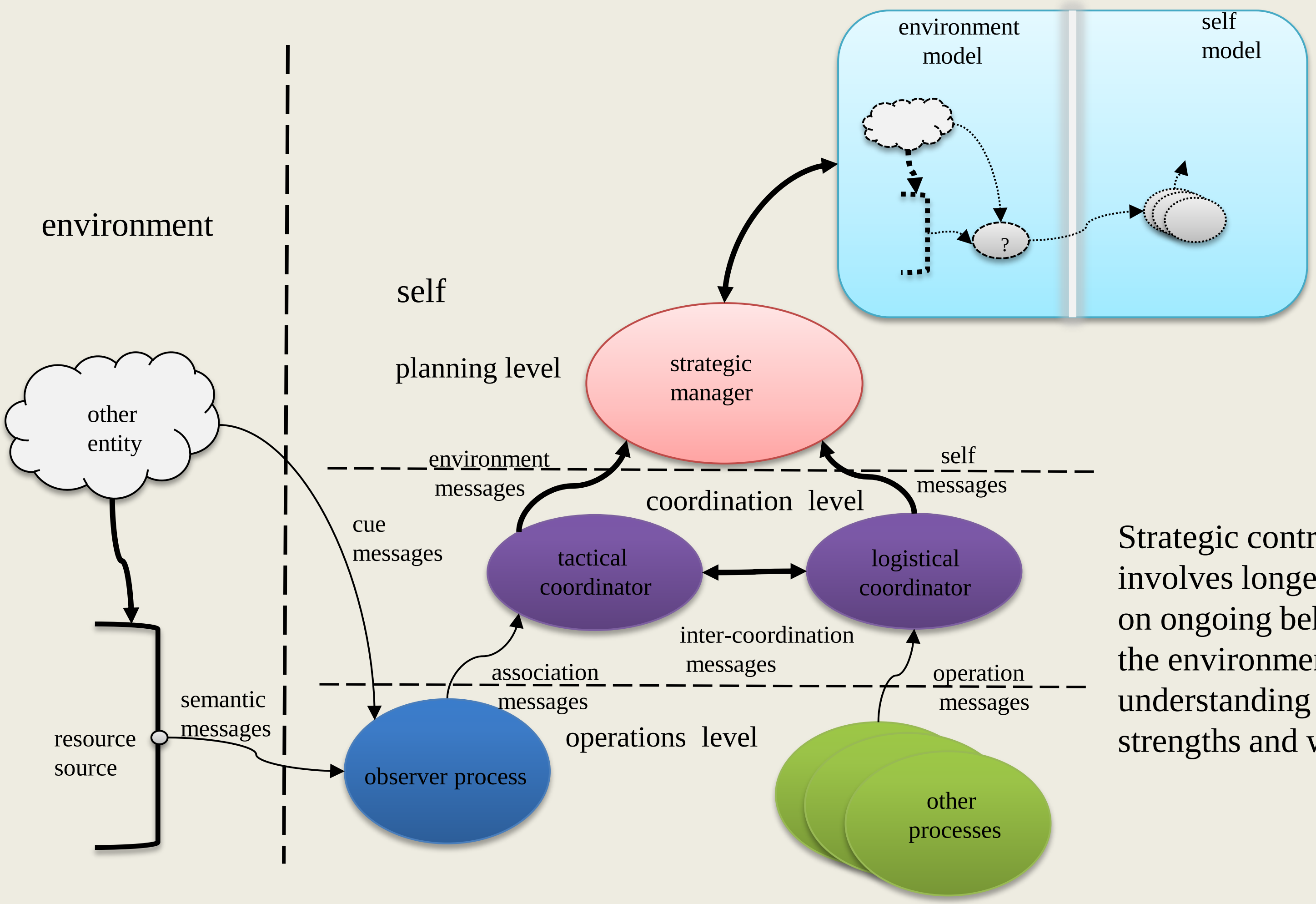
P 8.4 – Complex Systems in Complex, Changing Environments

- Combining the stochastic, possibly chaotic, and hidden nature of real environments



Systems that deal with multiple sources and sinks, including unknown possibilities, e.g. opportunities and threats, are subject to high degrees of uncertainty. Influences on sources and sinks that are not known to or observed by the system add even more uncertainty to stability.

Strategic Control for Planning and Long-term Coordination



Strategic control (management) involves longer-term planning based on ongoing behaviors of entities in the environment and an understanding of the self (e.g. strengths and weaknesses).

The Hierarchical Control Model

- This model is ubiquitous
- Complex systems in complex environments
- Uncertain and ambiguous dynamical processes
- Natural systems, including human societies, have evolved toward this structure
- Information and Knowledge are used to obtain stability in the face of an unstable world
- The human brain is possibly the most successful examples of a hierarchical control system in action

Principle 9 – Systems Can Contain Models of Other Systems

- The brain is a system – an adaptive system.
  - Neurons and their interconnections
  - Neural clusters and coordinated excitation
  - Clusters of clusters constitute higher-order concepts
- Brains take in sensory information
- Build models as part of development
- Recognize repeating patterns and strengthen the connections between neurons that constitute the perceptual or conceptual models
- Can manipulate the conceptual models to try different interrelations in a completely abstract way.

System Model

- Since a system can be represented as a network it is possible to construct a computer model of the system and use various computational methods to study the system.
  - Graph Theory is a mathematical approach to analyze properties of networks
  - Flow networks is another (variation) for studying the dynamics of networks
  - System dynamics is a special application of flow networks that allows a computer to simulate the long-term behavior of a system
- Modeling allows us to test our understanding of the system. Used to anticipate the future.

Systems that Contain Models of Other Systems

- Models are abstractions so will never be a “complete” representation of the real system
- Models must capture the relevant features of a system – this means what aspects of the system that have meaning to the modeler
- To be efficient (and fast) a model must not get bogged down in unnecessary details
- Our brains (and all animal brains) contain models of other systems in their environment, the interactions between which constitute a model of the world
- All interacting systems contain models of the systems with which they interact whether they learn it or inherit it

Mental Models

- Our brains are evolved to learn representations of models in the form of neural networks
  - The strength of connections between certain neurons that represent components and interconnections in the perceptual field constitutes a network representation of a system
  - A concept is a certain pattern of coordinated firing of neurons in various parts of the brain, which serves to unify the component representations into a structural whole
  - Our brains recognize systemness in the world and build conceptual models that are then subject to mentation:
    - Tracking perceptual inputs with our metal models
    - Simulating different situations (contemplating)
  - The brain is organized so as to represent a structural hierarchy, from perceptual elements to whole concepts
  - It treats the whole world of its experience as one large meta-system.

The Brain as a System Modeler

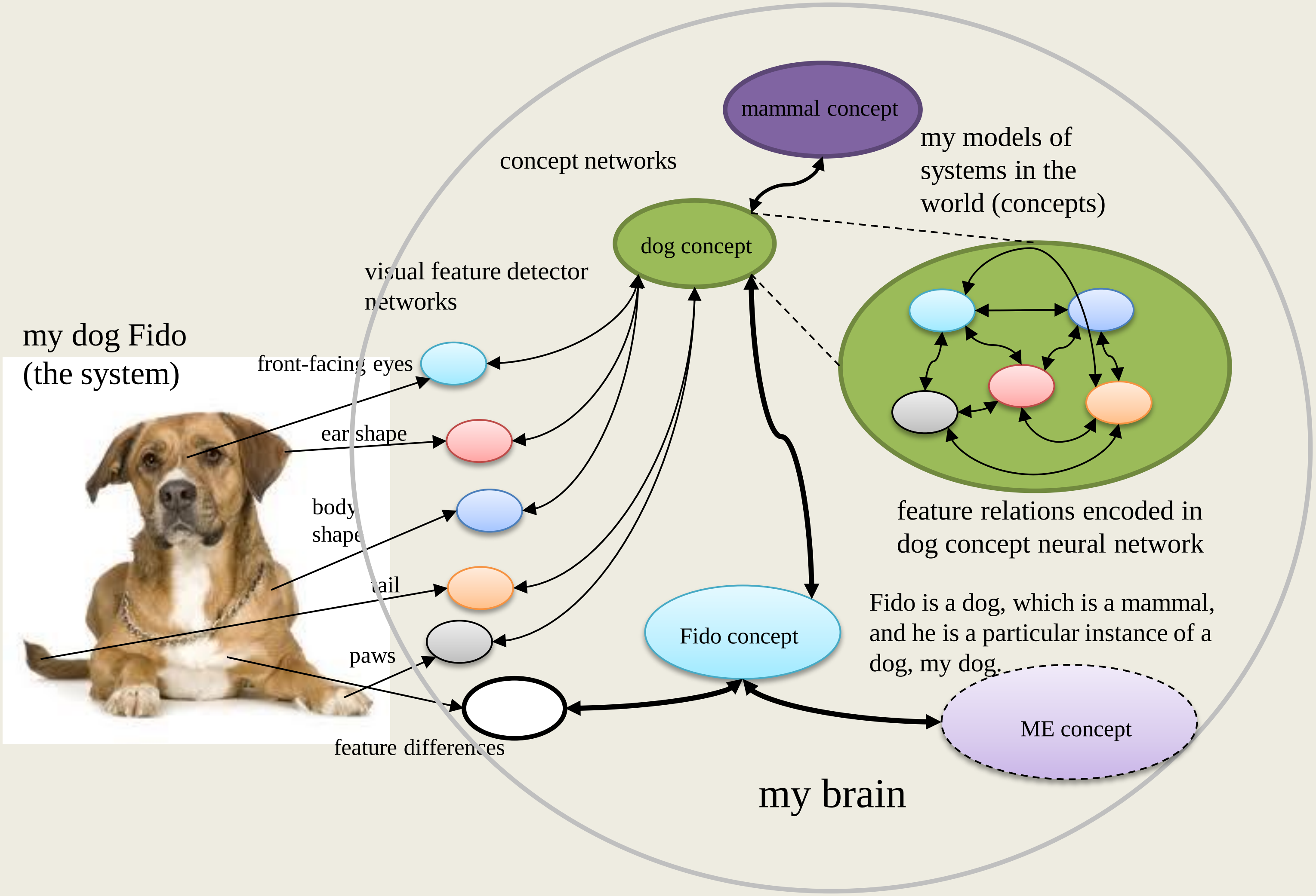


Figure 5. The brain builds conceptual models that have the hierarchical structure of systems.

Principle 10 – *Sufficiently* Complex, Adaptive Systems Can Contain Models of Themselves

- As we saw in Principle 8 it is possible that complex adaptive systems can contain models of anything
- This can include a model of the entity itself
- Models are, by necessity, a much reduced version of the real system
- All models are approximations of the real system
- The human brain has a built-in model of the person
- Consciousness is, at least to some degree, a phenomenon resulting from an individual having a self-model that is constantly being updated
- A model of the self allows us to anticipate our own actions in the future under different conditions

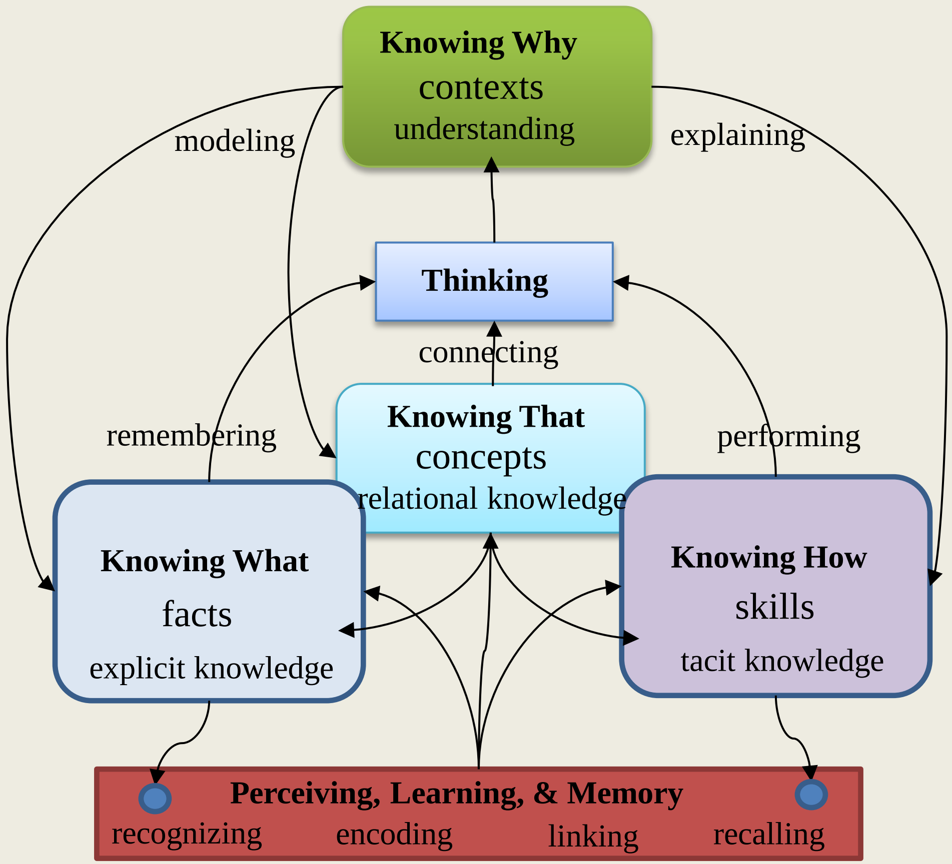
Principle 11 – Systems Can Be Understood

- Combining Principles 2 and 4
  - Systems Analysis – Methods for Decomposing Existing Systems to Build Models
  - Testing Hypotheses – Operating Models Under Different Assumptions
  - Playing 'What-If' Games
- Science as the process of understanding systems
  - Reductionism - Derivation
  - Constructionism – Synthesis and Integration
  - Causality – Comprehending dynamics
  - Prediction – Future Thinking

Principle 12 – Systems Can Be Improved

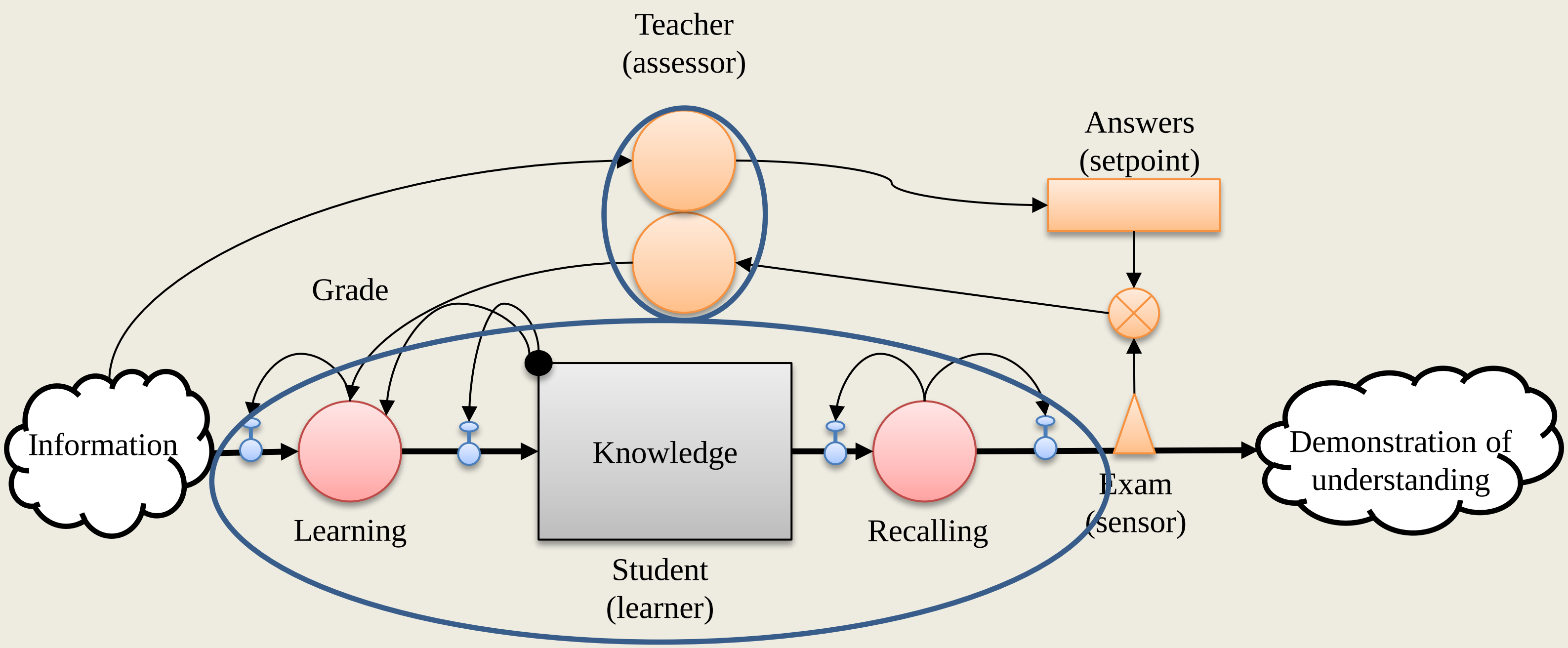
- Systems Design – Intentional Revision
  - A uniquely human activity?
  - Design as an Evolutionary Process
    - Affordance – the capacity to see alternate uses of existing objects
    - Incorporation – how to fit pieces together to obtain revised functionality
    - Incremental improvement – few “breakthroughs”
    - Breakthroughs are typically serendipitous
    - Trial and error
  - Design as an intentional process – Engineering
- Systems Engineering
  - A process that applies systems science principles and systems management to the development of complex artifacts
  - Life-cycle (dust-to-dust) design

The System of Knowledge and Knowing



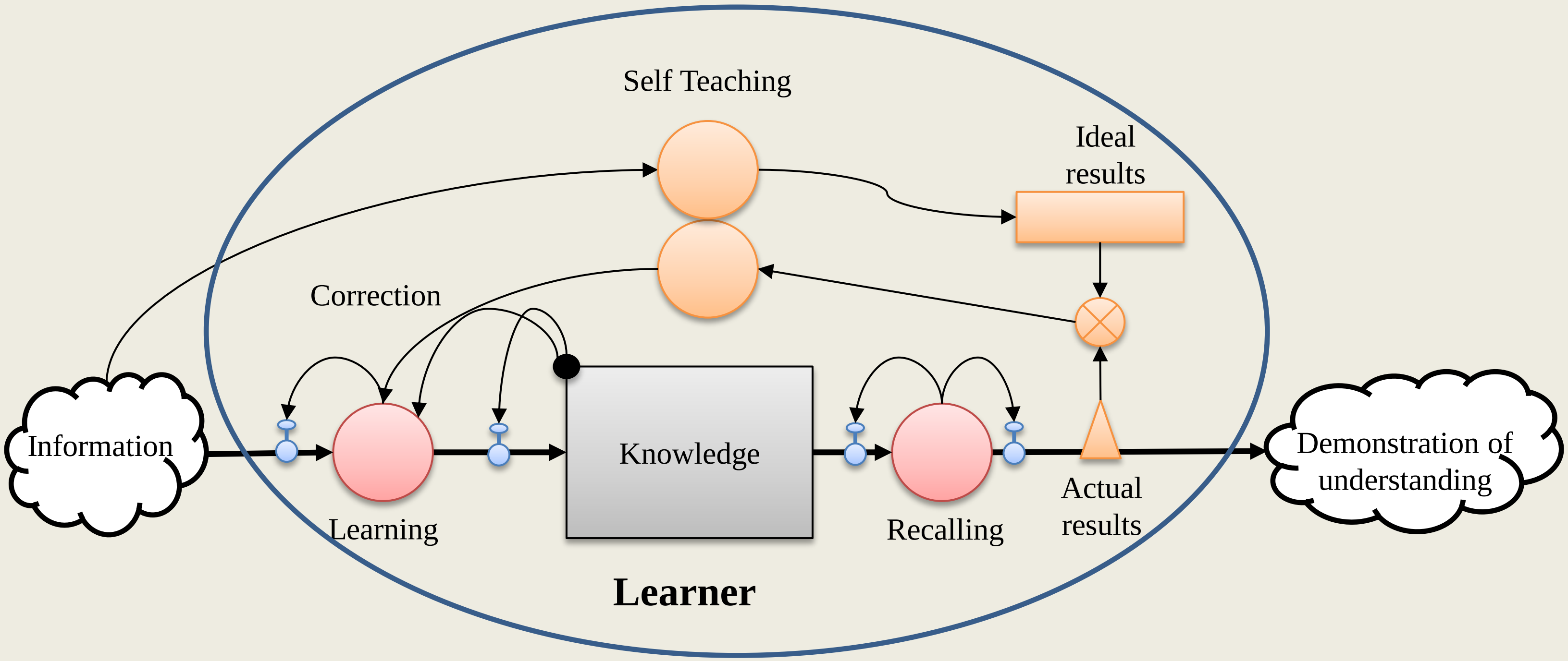
Cognitive Capabilities

Learning as a Dynamic System

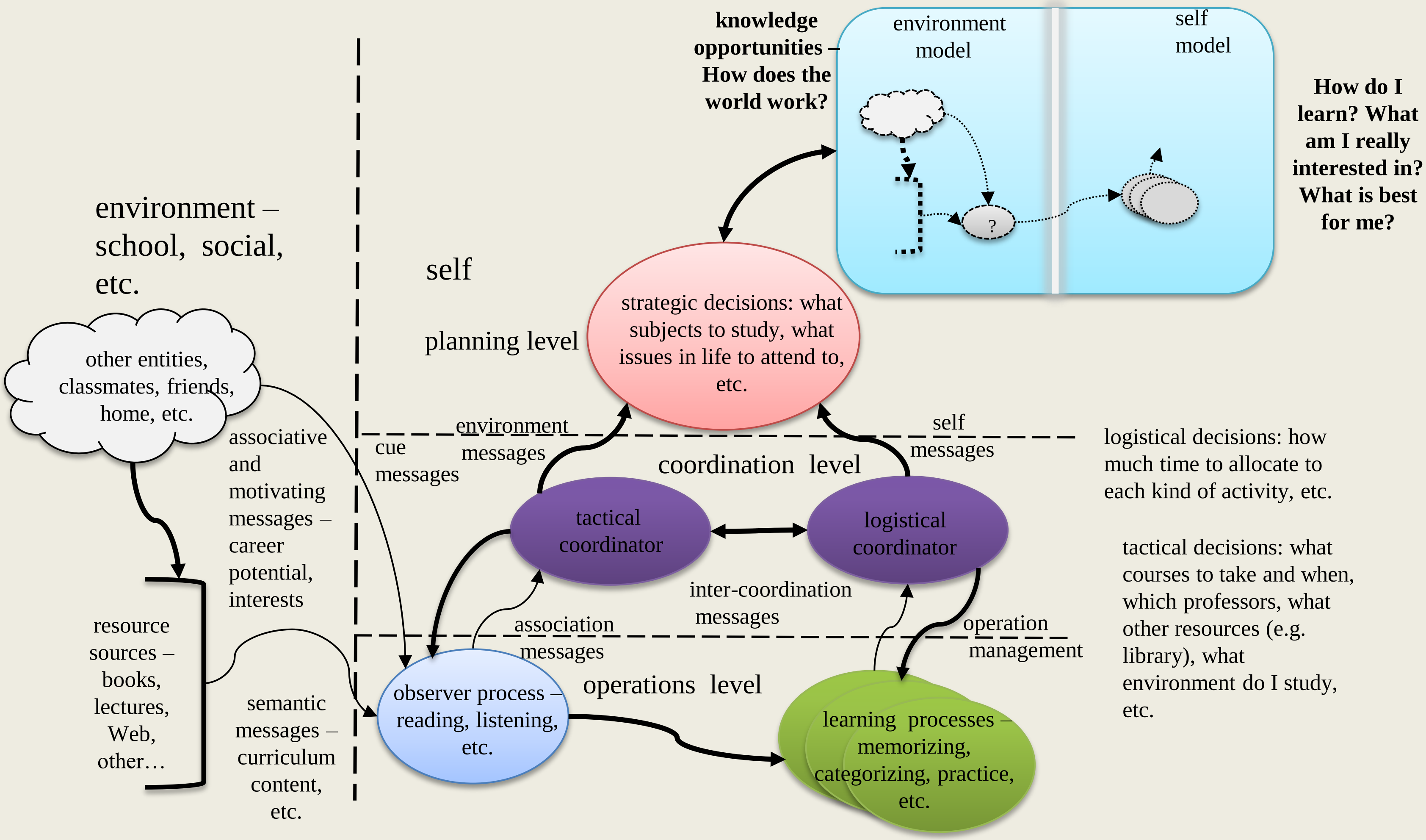


Life-long Learner and Self Managment

- The teaching function moves into the mind of the learner



Meta-Learning & Meta-Knowledge



Hierarchical Management Applied to Learning