ENES 489P Hands-On Systems Engineering Projects

Foundations for Model-Based Systems Engineering

Mark Austin

E-mail: austin@isr.umd.edu

Institute for Systems Research, University of Maryland, College Park

Topic 4: Model-Based Systems Engineering

Topics:

1. Goals for model-based systems dngineering

2. Basic system concepts (e.g., definition, emergent properties).

3. Basic models of System Structure (e.g., hierarchies, layers, networks).

4. Transformational and Reactive Systems.

5. Systems Engineering view of Modeling.

Model-Based Systems Engineering

Goals

Model-based systems engineering (MBSE) development is an approach to systems-level development in which

... the focus and primary artifacts of development are models (as opposed to documents).
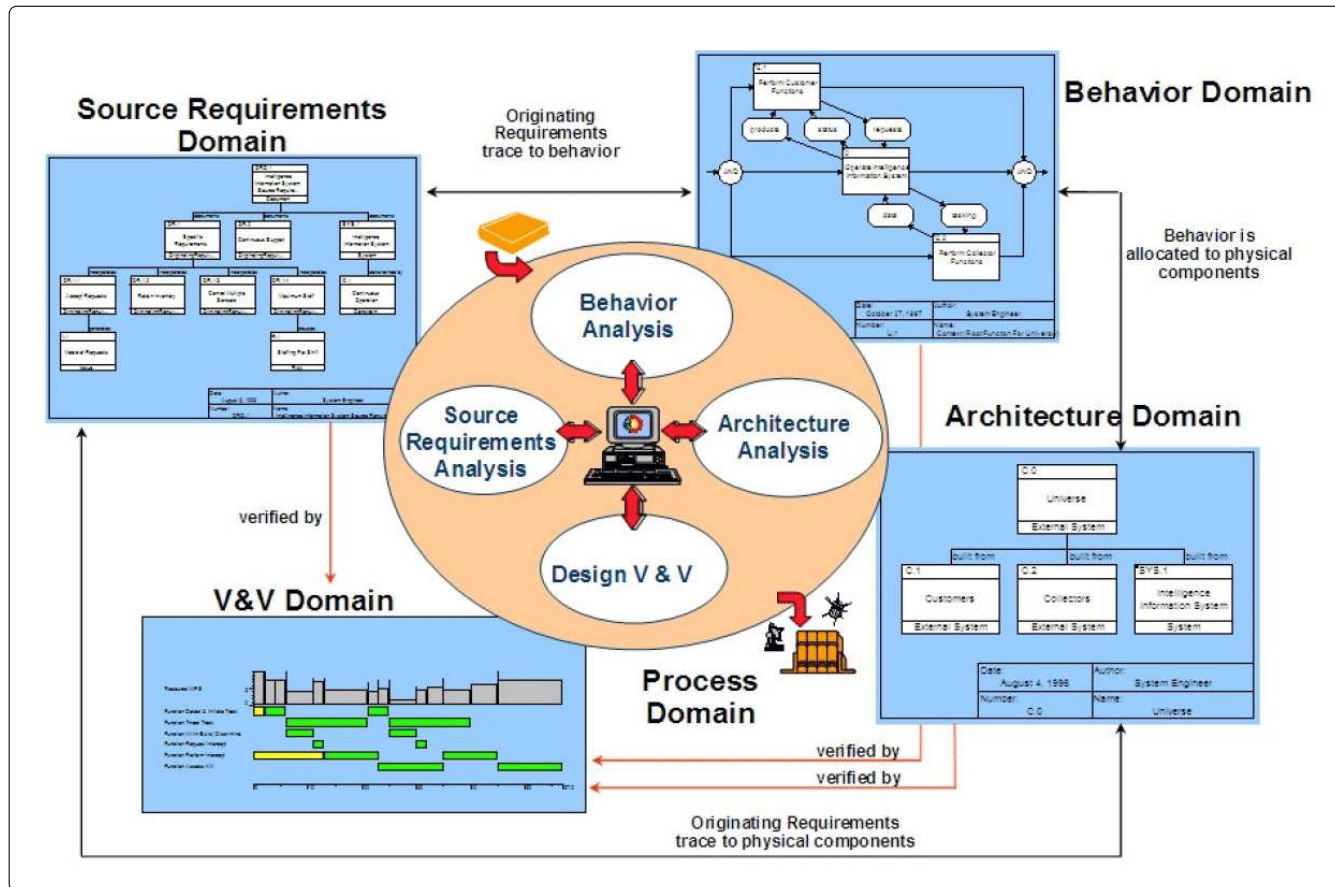
Approach and Benefits

MBSE procedures provide a formal basis for:

- Closing the gap between **what is needed** and **how the system will work**

- Assisting in the management of complex systems.

- Early and formal approaches to system validation and verification.

Model-Based Systems Engineering

Model-based systems engineering process at Vitech
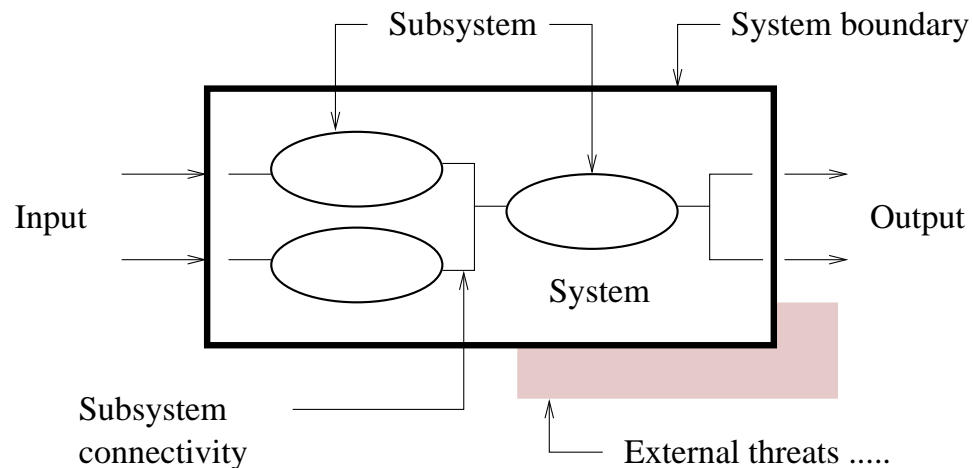
Basic System Concepts

Definition of a System

For our purposes, a system is:

... a collection of components (some of which can be modules and sub-systems) that are interconnected so that the system can perform a function which cannot be performed by the components alone.

Systems may consist of products, people and processes.

Elements of a System

Basic System Concepts

Key points:

1. A boundary separates the system from its external environment (e.g., walls in a building; starting and finishing times for a numerical analysis).

2. Inputs are elements that enter the system (e.g., raw materials entering a manufacturing plant).

3. Outputs are the finished products and consequences of being in the system.

   New cars leaving a car assembly plant is an example of finished products.

   An example of "consequence of being" is the ability of a highway bridge system to carry traffic.

4. System threats are those things that can potentially affect acceptability of the system configuration – for example, a lack of knowledge, insufficient time to build, lack of finance etc...

Basic System Concepts

Dichotomies of System Classification

- **Artificial versus Natural**

  Artificial systems are man-made.

  Natural systems are not.

- **Physical versus Conceptual**

  Physical systems operate on matter (or from matter) in the physical environment.

  Conceptual systems exist abstractly as ideas, plans, or information.

- **Open versus Closed**

  Open systems interact with the surrounding environment through a boundary.

  Closed systems do not.
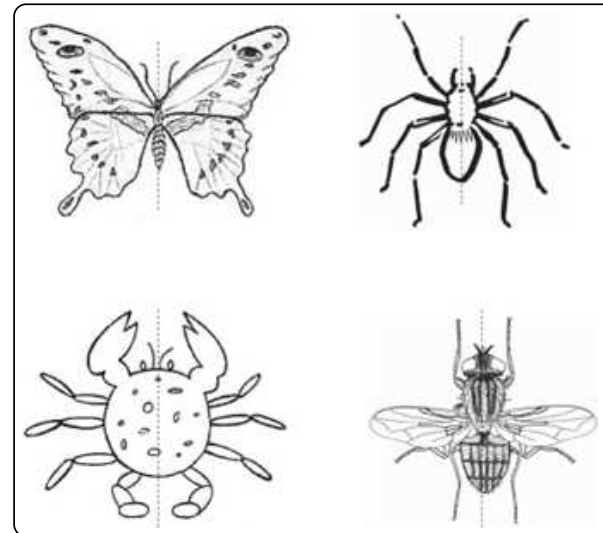
Basic System Concepts

Emergence and Emergent Properties

Emergence is the way in which complex systems and patterns arise out of a multiplicity of relatively simple interactions.

Parallel sand ripples caused by wind and water

Axes of symmetry in nature

Two examples from nature: (1) parallel lines in sand caused by water and wind; (2) axes of symmertry in crabs, butterflys and bugs.

Basic System Concepts

Example. Emergent Properties in Bridge Engineering.

Typical: Aesthetics, load carrying capacity, physical symmetries, resistance to aeroelastic flutter.

Warning. Failure to understand emergent properties can be catastrophic!
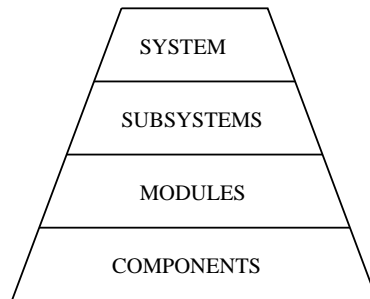
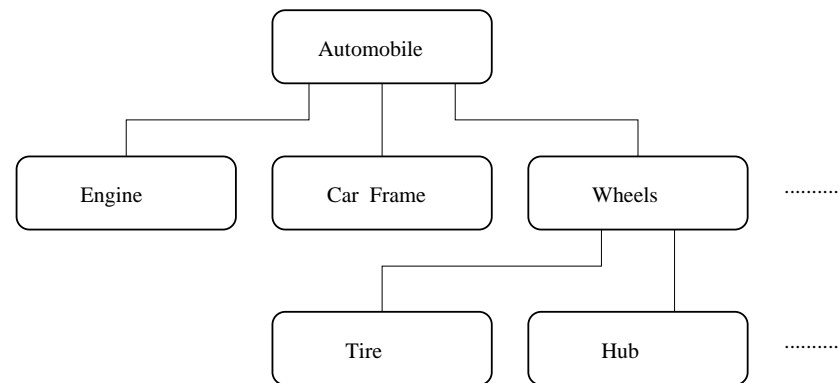Tacoma Narrows Bridge

System Structure

Hierarchy Structure

A hierarchy is ...

... an arrangement of items in which the items are represented as being above, below, or at the same level as one another.

Example

SYSTEM HIERARCHY   HIERARCHY OF SYSTEMS / SUBSYSTEMS IN AN AUTOMOBILE

System Structure

Benefits of the Hierarchy Structure

For designers the hierarchy structure is a powerful abstraction mechanism ...

- The hierarchy viewpoint enables a designer to visualize an entire related aspect of the system without the confusing detail of subparts and without the unrelated and distracted generality of super-parts.

- By reducing the distracting detail to a single object that is lower in the hierarchy, one can greatly simplify many system development operations.

  For example, simulation, verification, design-rule checking, and layout constraints can all benefit from hierarchical representation, which makes them much more computationally tractable.

System Structure

Layered Structure

A layered system is ...

... one where the hierarchy of system components is clustered into horizontal strata.

Example 1. Open systems interconnection (OSI) model for computer communications.
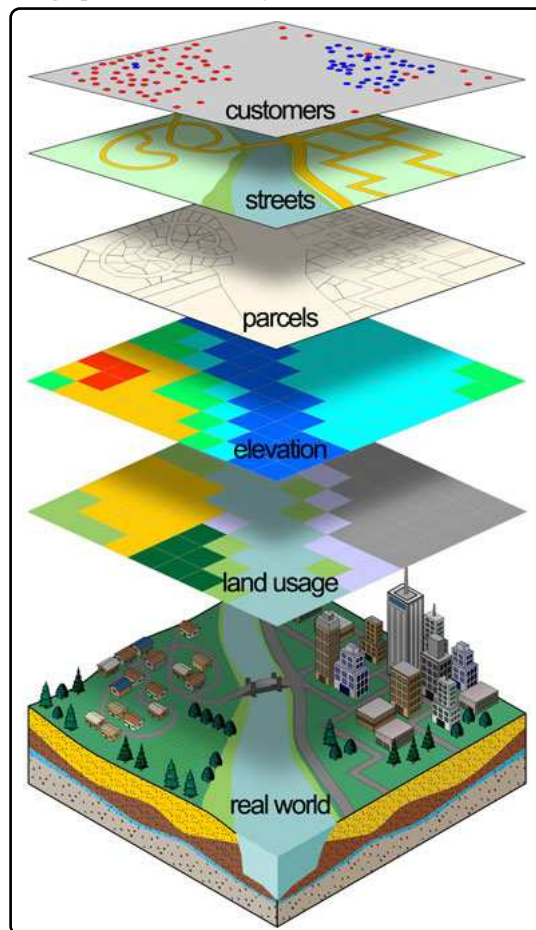
7	Application
6	Presentation
5	Session
4	Transport
3	Network
2	Data Link
1	Physical

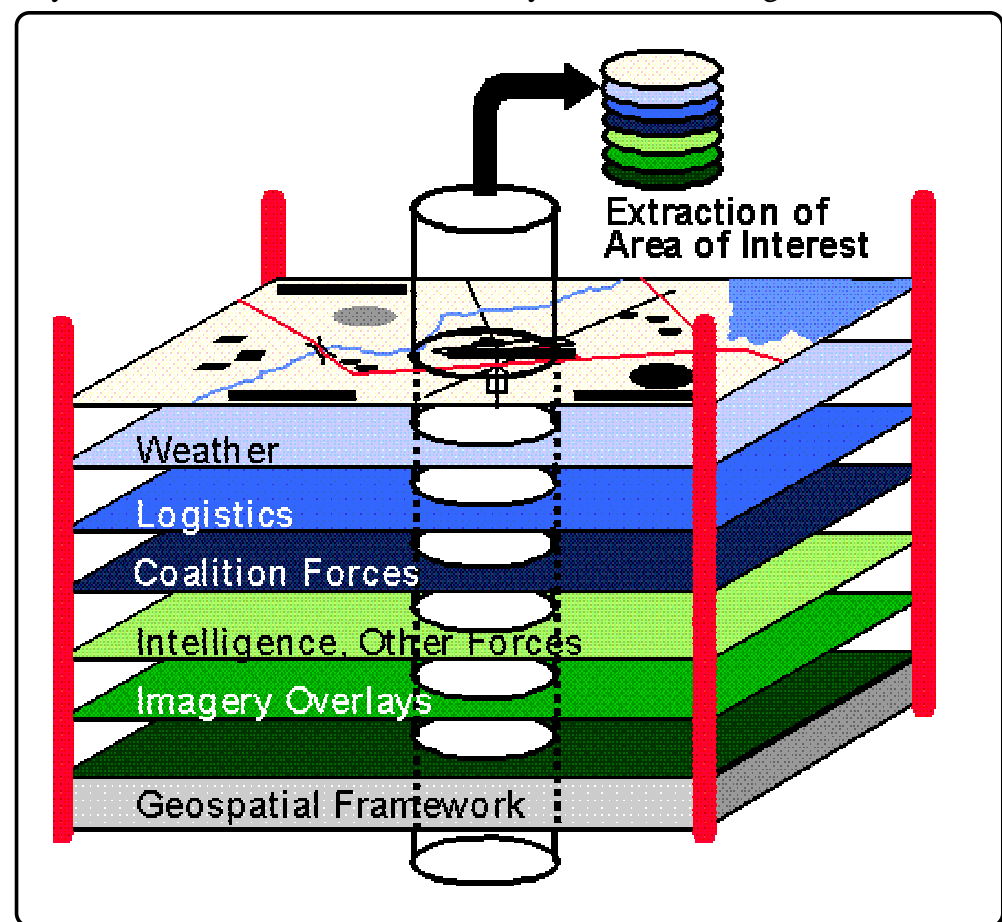Open Systems Interconnection Model for computer communications.

System Structure

Example 2. Layered organization of multi-dimensional attributes in spatial data.

Geographic Information System

Layers of Data / Information in Military Decision Making

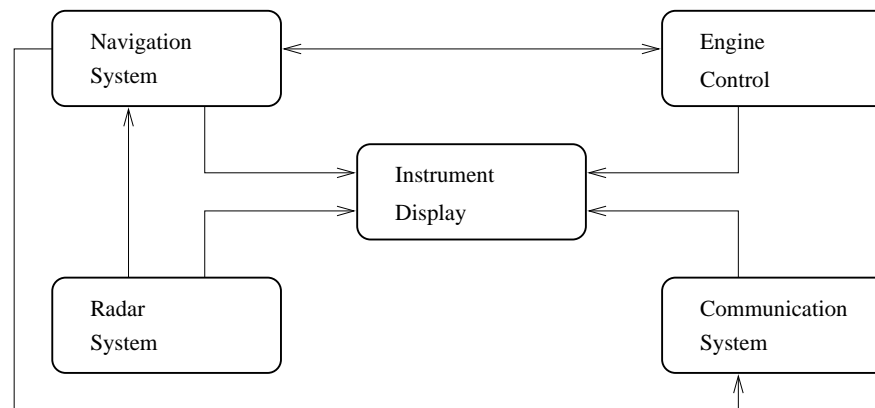# System Structure

Network Structure

A network is a ...

... set of elements (or modules or nodes or devices) that are connected by a set of interfaces (or links or communication channels). Formally, a network is a graph.

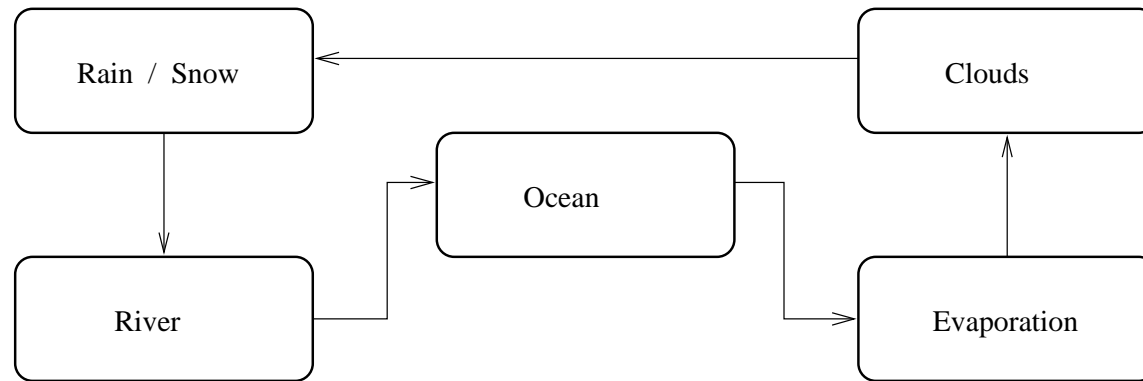The modules may be computers, mechanical machines, etc...

The interfaces may use a variety of communications media.

Example 1. Interacting subsystems in an aircraft.

System Structure

Example 2. The behavior of many man-made and natural systems can be modeled as networks having cyclic behavior, e.g., the water cycle.
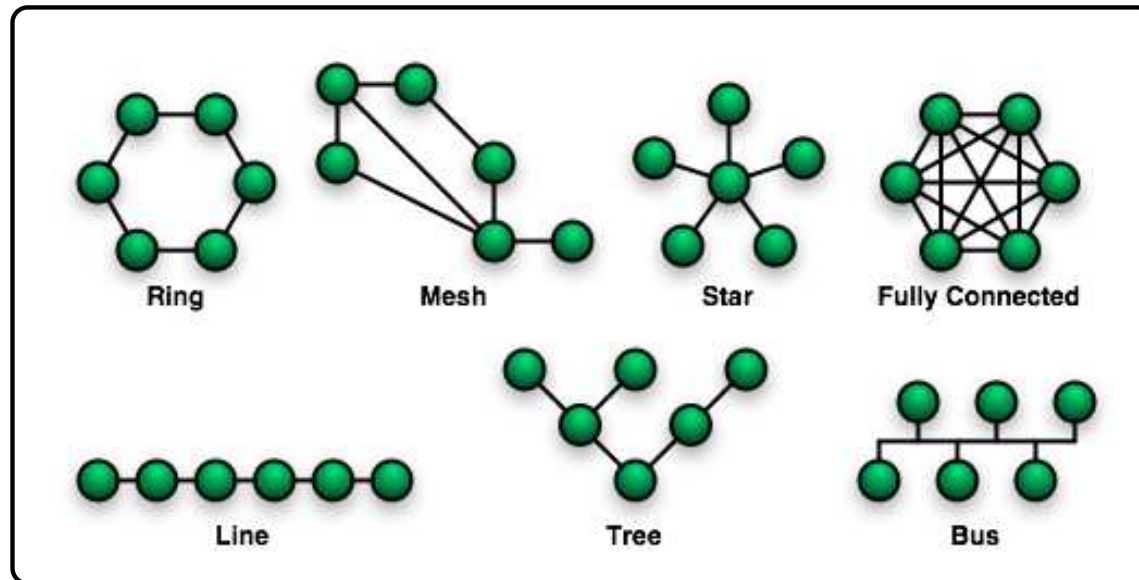
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  │              │ ◄────────────────────────────────  │              │
  │  Rain / Snow │                                     │   Clouds     │
  │              │                                     │              │
  └──────┬───────┘            ┌──────────────┐         └──────▲───────┘
         │                    │              │                │
         │                 ┌─►│    Ocean     │──┐             │
         ▼                 │  │              │  │             │
  ┌──────────────┐         │  └──────────────┘  │      ┌──────────────┐
  │              │         │                     └─────►│              │
  │    River     │─────────┘                            │ Evaporation  │
  │              │                                       │              │
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System Structure

Network Topology

A network topology describes the connectivity (or arrangement) of nodes on a network.

Common network topologies include star, ring, line, bus, and tree configurations:

System Structure

Network science seeks to discover the common principles, algorithms, and tools that govern network behavior across a wide range of domains.

**Fundamental questions about networks:**

- How big is the network?

- How many hops does it take for a random node A to be connected to node B?

- What is the shortest distance (in terms of edges or cost) from node A to node B?

- From a design standpoint, what are the pros/cons of each network structure?

More interesting questions:

- What does nature do? Why?

- What kinds of relationships exist between real-world networks?

- How vulerable are networks to attack? And how does this change with network structure?

System Structure

Real-World examples of network connectivity
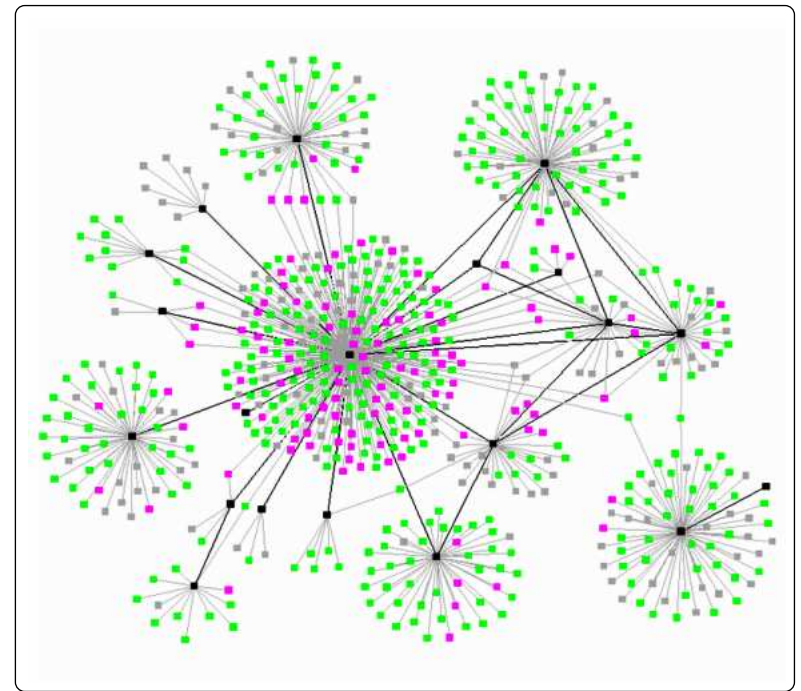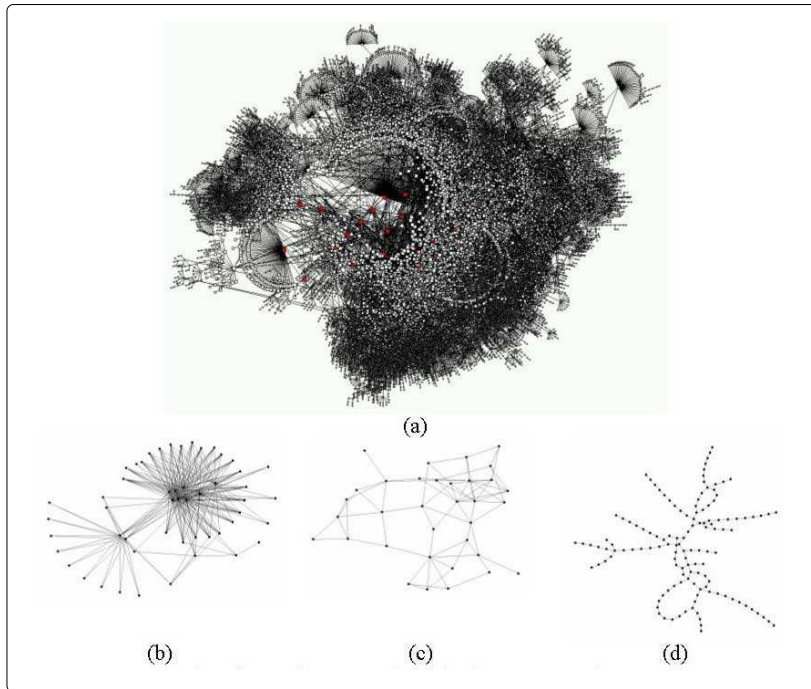
Right. Nodal connectivities in four different real-world networks: (a) the Internet; (b) social networking; (c) a random graph; (d) track configuration in a metro system.

Left. Connectivity in a typical scale-free network (e.g., air transportation networks).
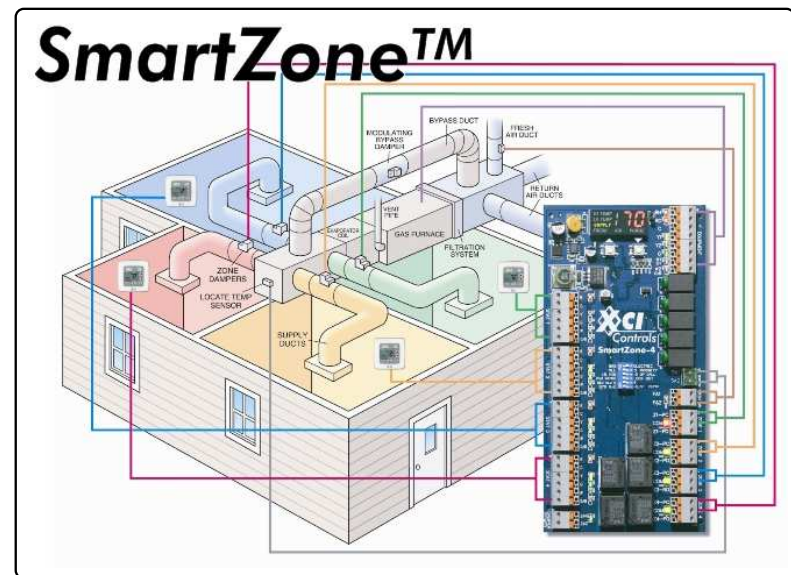
System Structure

Networks of Networks

Many large scale systems are intertwined networks of networks.

Understanding the relationships among the networks and their combined behaviors can be very challenging.

Example 1. Buildings have intertwined network structures for:

- The arrangement of spaces,

- Fixed circulatory systems (power, hvac, plumbing), and

- Dynamic circulatory systems (flows of energy through rooms; flows of material).

Example 2. Cascading failure of networks caused by earthquakes.

Christchurch, New Zealand, 4.30 am, September 4, 2010. A magnitude 7.2 earthquake rolls into town ....


20% of homes are uninhabitable. Many transportation links are damaged. Street flooding in low-lying areas → Widespread power outages → Disruption of many services.

System Structure

Planning for disaster relief needs to look at the connections between network models.

Basic questions:

- What kinds of dependencies exist between the networks?

- How will a failure in one network impact other networks?

- What parts of a system are most vulnerable?

- Does it make sense to stockpile supplies of water and food?

- How much should we spend to prepare for an inevitable attack?

Waterway Network

Transportation Network

Information and Communications

Emergency Services
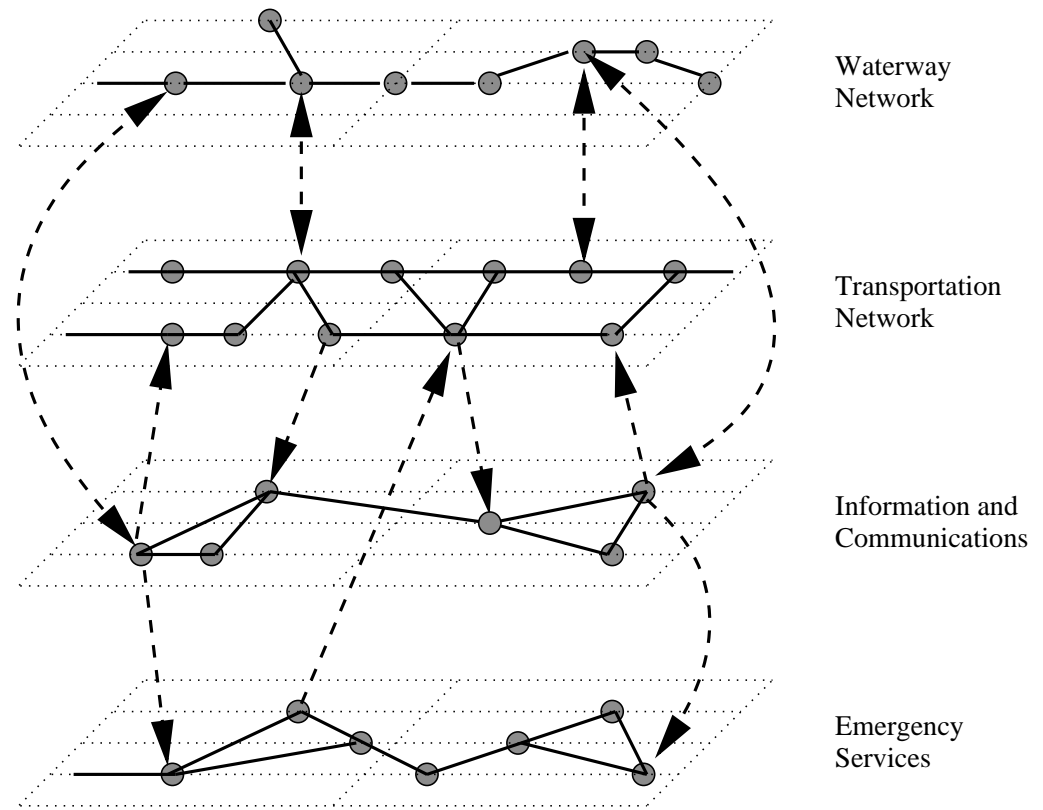
Transformational Systems

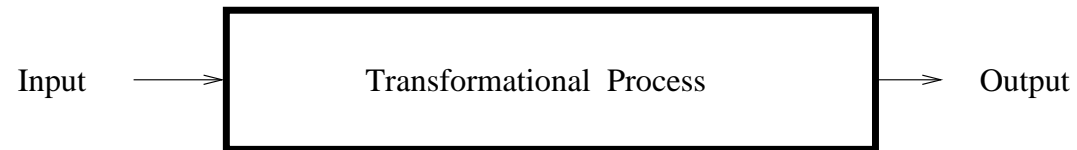**Definition.** A transformational system ...
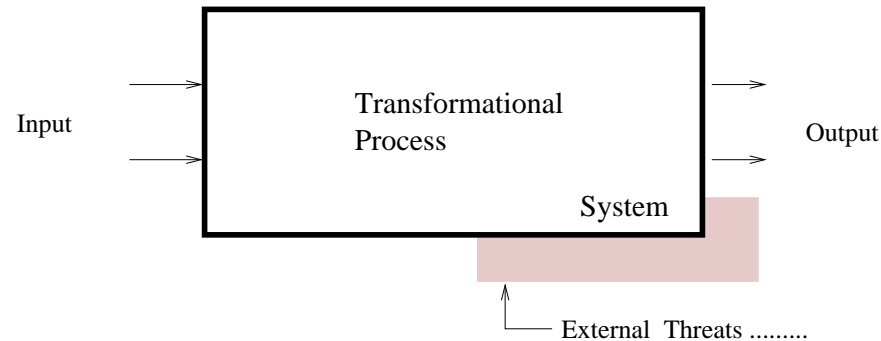
is ...

... a process that receives one or more system inputs I from an external environment, transforms them with process T, and then releases them as system outputs O to an external environment.

A transformational system generates an output and then terminates.

Transformational Systems

Classification: Single Input/Single Output (SISO)

Input $\longrightarrow$	Transformational Process	$\longrightarrow$ Output

Classification: Multiple Input/Multiple Output (MIMO)

Input 1 $\longrightarrow$		$\longrightarrow$ Output 1
	Transformational Process	
Input 2 $\longrightarrow$		$\longrightarrow$ Output 2
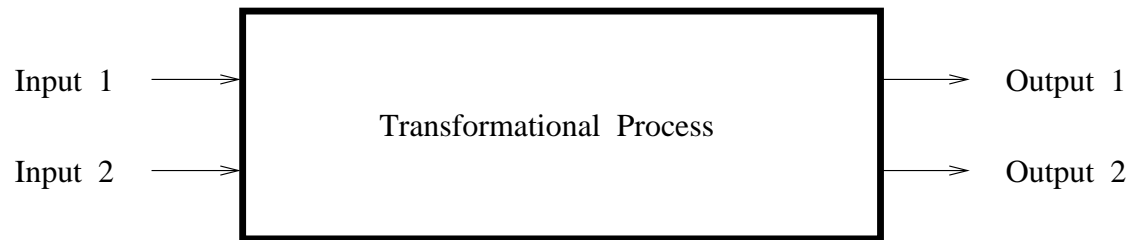
Reactive Systems

A reactive system is ...

... a system that, when turned on, is able to create desired effects in its environment by enabling, enforcing, or preventing events in the environment.
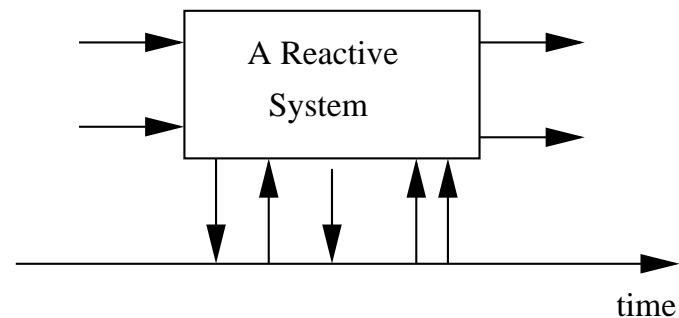
Reactive systems are involved in a continuous interaction with the environment. The environment:

... generates input events at discrete intervals through one or more interfaces and the system reacts by changing its state and possibly generating output events.

Reactive Systems

Typical Classifications

Many reactive systems are:

- **Real-time systems**

  A real-time system is a system in which the correctness of a response depends on the logical correctness and time at which the response is produced.

- **Safety-critical**

  Malfunctioning of the system could lead to a loss of life or property.

- **Embedded systems**

  Software to support a real-time system is often embedded within the system hardware.

- **Control systems**

  Control systems enforce a desirable behavior on their environment.

Reactive Systems

Key Characteristics

- They have behavior defined by continuous, non-terminating, interaction with the surrounding environment.

- If the system terminates during its availability time, then usually this is considered a failure.

- Reactive systems are required to respond to external stimulli as and when they occur. Therefore, reactive systems must be able to respond to interrupts, even when they are doing something else.

- It follows that behavior of a reactive system is often defined by a set of interacting processes that operate in parallel.

- Often, reactive systems will need to operate in real time, and be subject to real-time constraints.

Reactive and Transformational Systems

Side-by-Side Comparison (Adapted from Wieringa, 2003)

Transformational System	Reactive System
May interact to capture more data.	Highly interactive.
Terminating process.	Non-terminating process.
Non-interupt driven.	Interrupt driven.
Output not state dependent.	State-dependent response.
Output not defined in terms of the environment.	Environment-oriented response.
Sequential process.	Parallel processes.
Usually, no stringent time requirements.	Usually, stringent time requirements.

System Engineering View of Modeling

Systems engineers are ..

... the keepers of the processes, methods and tools needed to establish and maintain a shared vision of the system problem definition and solution.

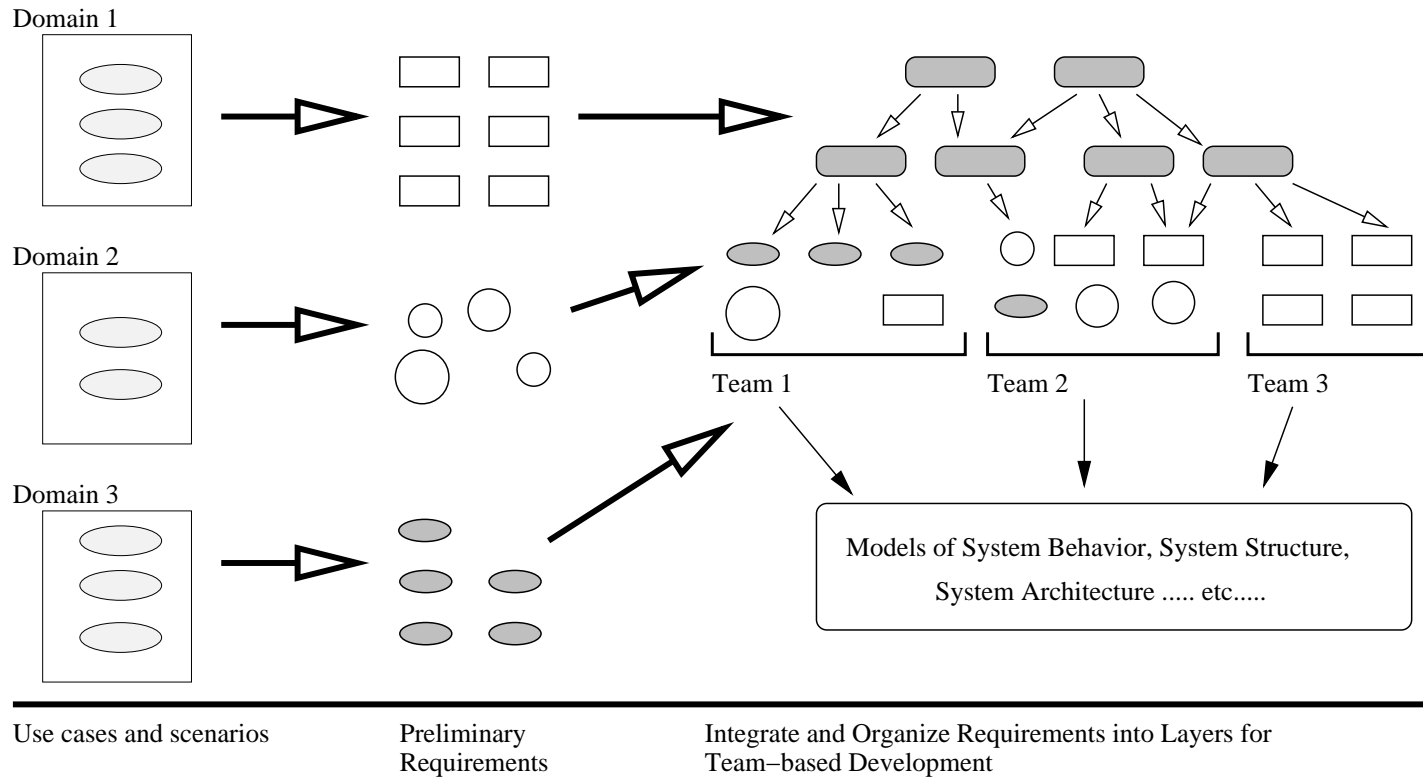This process is complicated by the

- technical,

- social,

- regulatory, and financial aspects

of a complex design being too broad and detailed for a single individual to master. Hence, by necessity,

... system development is a team activity involving multiple stakeholders, their design concerns, viewpoints, and ways of doing things.

System Engineering View of Modeling

Pathway from Functions to Representations in Multiple-Stakeholder Design

Domain 1

Domain 2

Domain 3

Team 1   Team 2   Team 3

Models of System Behavior, System Structure,

System Architecture ..... etc.....

Use cases and scenarios   Preliminary
                                 Requirements

Integrate and Organize Requirements into Layers for
Team–based Development

System Engineering View of Modeling

Networks of Processes and Models in Systems Engineering
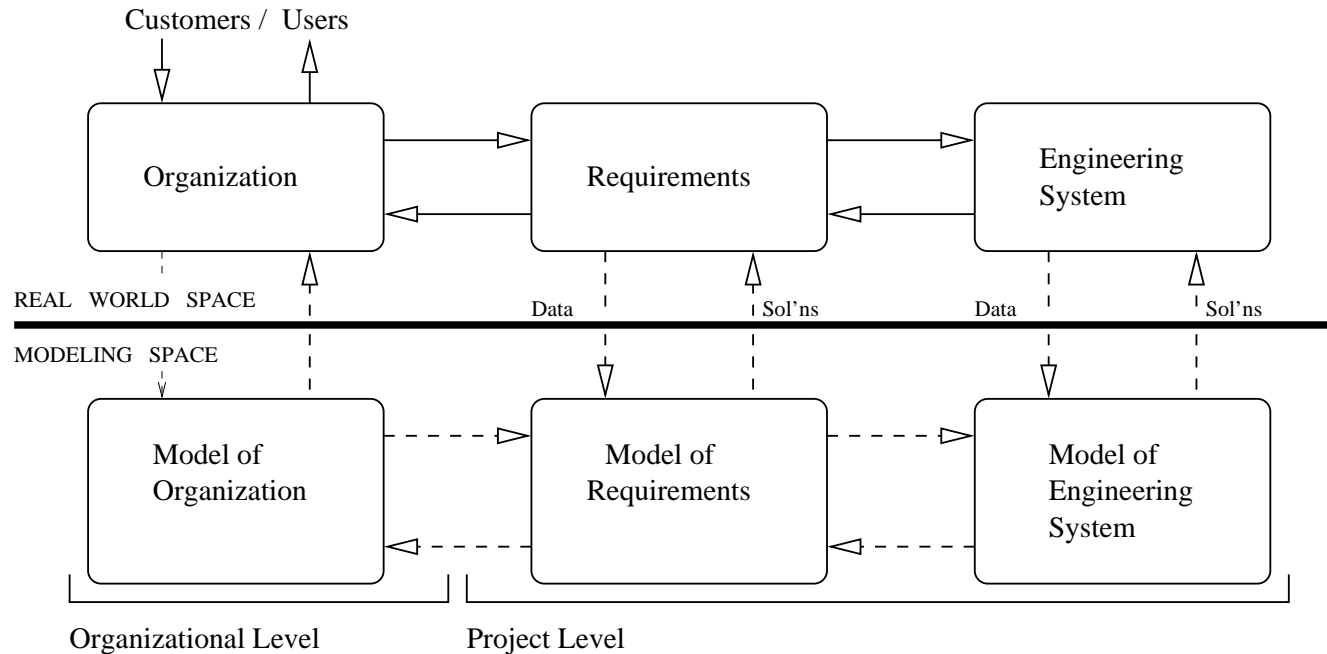
System Engineering View of Modeling

Systems Engineering Modeling and Process Requirements

Customers / Users

| Organization | Requirements
−− Legal agreement | Engineering
System |

REAL WORLD SPACE

MODELING SPACE

Data   Sol'ns   Data   Sol'ns

Strategy
Businesss processes
Resoucrces
Staff

Capture
Representation
Organization
Evaluation
Allocation / Flowdown
Traceability
Validation / Verification
Management

Behavior
Cost
Assembly
Maintenance
Retirement

Organization   Project