System Thinking

Lecture 02, v02

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BSEE

MSSE

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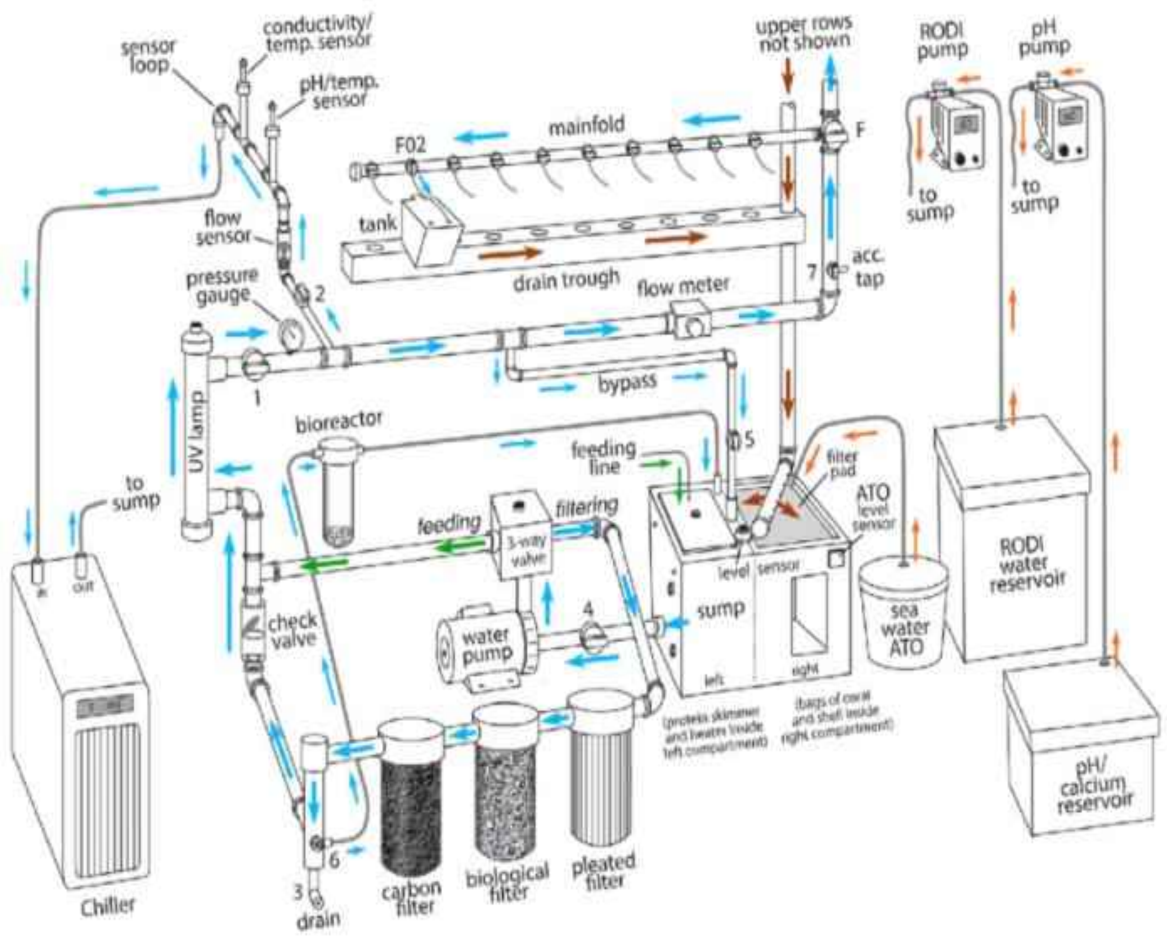
What is System Thinking?

- We are surrounded by systems, and they are becoming increasingly complex
- System thinking can help us make these complex systems appear less complicated
- System thinking is not about "thinking systematically"
- System thinking is thinking about a system as a set of interrelated entities <u>*whose functionality (as expressed through the system's behavior) is greater than the sum of the functionality of the individual entities*</u>
- Understanding the emergence of such behavior is the goal — and the art — of system thinking
- System thinking can be used in a number of ways
  - To understand the behavior or performance of an existing system
  - To imagine what might be if a system were to be changed
  - To inform decisions or judgments that are of a system nature
  - To ensure that all the important implications of decisions are identified and considered
  - To support the design and synthesis of a system (the system architecture)
    - Architecture is an abstract description of the entities of a system and the relationships between those entities

What is System Thinking? (continued)

- Useful where scientific thinking and the scientific method are inappropriate
- Think about a question, circumstance, or problem explicitly as a system — as a set of interrelated entities
- Identify the important boundaries, dependencies, and relationships of systems and their components
- Adopt a holistic approach that complements reductionist activity



Attributes of a Systems Thinker

- Seeks to understand the big picture
- Observes how elements within the system change over time, generating patterns and trends
- Recognizes that a system's structure is instrumental in carrying behavior
- Identifies the circular nature of complex cause-and-effect relationships
- Surfaces and tests assumptions
- Changes perspective to increase understanding
- Considers an issue fully and resists the urge to come to a quick conclusion
- Considers how mental models affect current reality and the future
- Uses understanding of system structure to identify possible leverage actions
- Considers both short- and long-term consequences of actions
- Finds where unintended consequences emerge
- Recognizes the impact of time delays when exploring cause-and-effect relationships
- Checks results and changes actions if needed: "successive approximation"

https://opa.hhs.gov/sites/default/files/2020-07/508_OPA_Systems_Thinking_27Feb2020_SLIDES.pdf

System-Thinking-Related Tasks

1. Identify the system, its form, and its function
2. Identify the entities of the system, their form and function, and the system boundary and context
   a. System entities have form and function of their own
   b. Define the initial decomposition of the system into entities
   c. Identify potential entities of the system using holistic thinking
   d. Use focus to identify the important entities of the system
   e. Create or recognize abstractions for the entities
   f. Define the boundary of the system and separate it from the context

These tasks will be detailed throughout the remainder of this presentation

System-Thinking-Related Tasks (continued)

3. Identify the relationships among the entities in the system and at the boundary, as well as their form and function
   a. Formal and functional relationships
   b. External interfaces
4. Identify the emergent properties of the system based on the function of the entities, and their functional interactions
   a. The importance of the emergence of system-level behavior
   b. System failure
   c. Predicting the emergence of behavior
   d. Emergent behavior depends on entities and relationships

These tasks will be detailed throughout the remainder of this presentation

Identify the System, its Form, and its Function

Task 1

- Systems simultaneously have the characteristics of form and function
- Form is what the system is
  - The physical or informational embodiment that exists or has the potential to exist
  - Form has shape, configuration, arrangement, or layout
- Function is what the system does
  - The activities, operations, and transformations that cause, create, or contribute to performance
  - Function is the action for which a thing exists or is employed to do
  - Function is not form, but function requires an instrument of form

Identify the System, its Form, and its Function (continued)

Task 1

- Function consists of a process and an operand
  - The process is the part of function that is pure action or transformation, and thus it is the part that changes the state of the operand
  - The operand is the thing whose state is changed by that process
- Function is more abstract than form, and because it is about transitions, it is more difficult to diagram than form
  - Function is inherently transient; it involves change in the state of the operand (creation, destruction, or alteration of some aspect of status of the operand)
- Emergence of behavior occurs in the functional domain
- Function, performance, quality attributes ("ilities"), and emergencies (unanticipated and undesirable behavior) are all issues of functionality

Identify Entities of a System

Task 2

a. Recognize that system entities have form and function of their own
b. Define the initial decomposition of the system into entities
c. Identify potential entities of the system using holistic thinking
d. Use focus to identify the important entities of the system
e. Create or recognize abstractions for the entities
f. Define the boundary of the system and separate it from the context

System Entities have Form and Function of their Own

Task 2a

System Function	Entity Function	Entity Form	System Form
Provide power to vehicle	Power the drivetrain	Internal Combustion Powerplant	Engine
	Power the electrical system	Electrical Generator	
	Power the cabin cooling system	Compressor	
	Power the brakes	Vacuum Generator	

- Breaking up the functionality of a system into constituent functionality of the system's entities is called ***zooming***
- When the functions of the entities combine to produce the function of the system, the ***emergence*** of system behavior occurs
  - When a number of functions act in coordinated operations, a more dynamic and interactive system behavior emerges
- Breaking a system into smaller pieces of form is called ***decomposition***
- Integrating pieces of form into the form of the whole system is called ***aggregation***

Systems Thinking – Form or Function First?

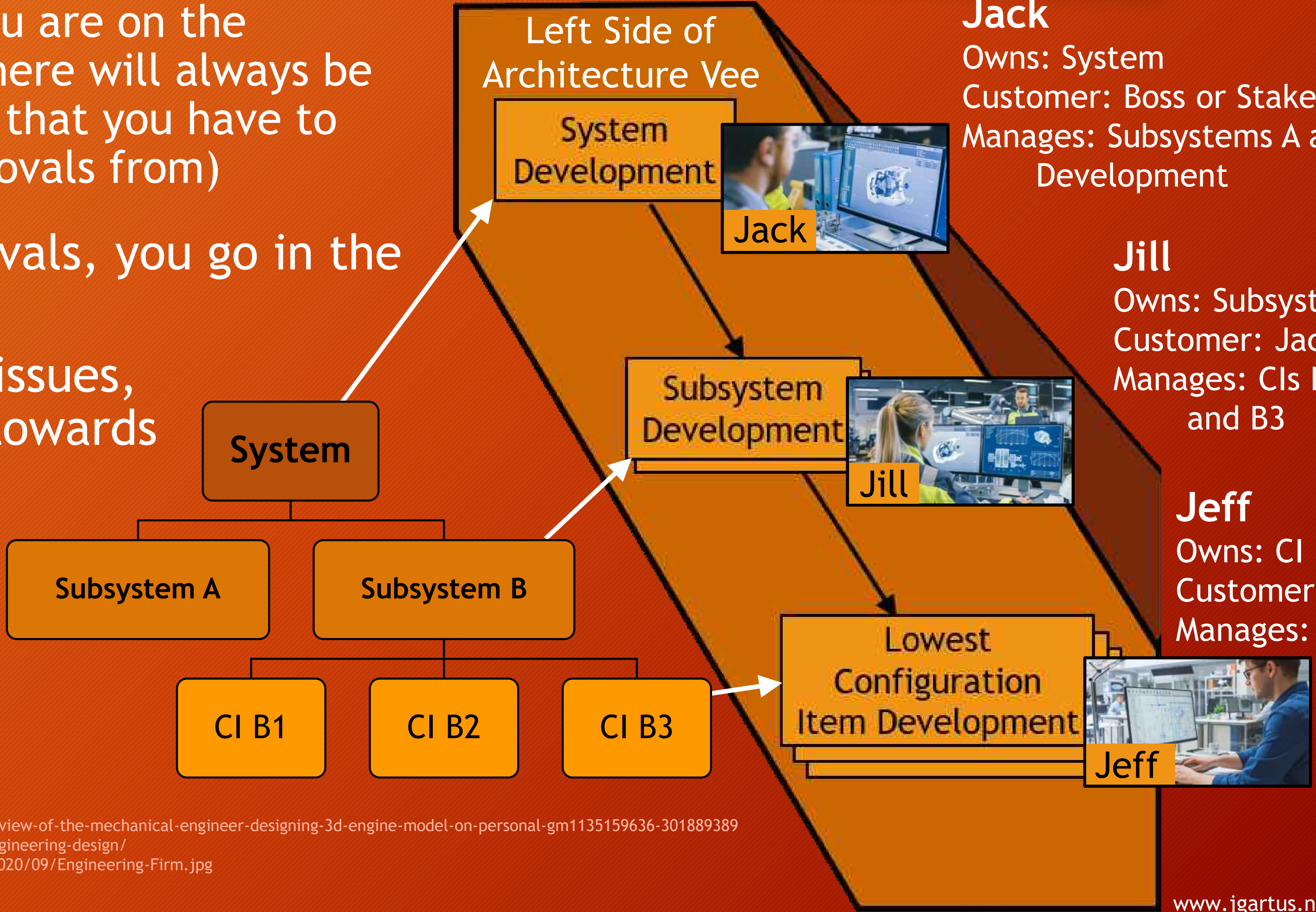
- Sometimes in system thinking, it is useful to think just about function and zooming
  - By placing less emphasis on form, we avoid biased thinking that tends to consider only the functionality that known parts provide
  - This kind of functional thinking is often used early in analysis and design of new or unique systems with which we don't have a great degree of familiarity with the functionality typically provided by the parts involved
- On the other hand, sometimes it is enough to reason about form and decomposition
  - This approach is useful when we are developing a "parts list"
  - Or when we are developing a variant to a known system such that we are already quite familiar with the functionality typically provided by the parts involved
- Reasoning about form or function separately is a convenience
  - It does not imply that both are not ultimately present or that they are not linked

One Person's Subsystem is another Person's System

- All systems are composed of entities that are also systems, and all systems are entities of larger systems
- Our initial reference for "the system" is arbitrary
- Because the initial choice of "the system" in these hierarchies is arbitrary, all systems must be made up of systems, which are made up of smaller systems, and so on
- What matters is that we choose a system boundary that is useful, so that we focus our system-thinking on the most important part of the problem
- In practice, definition of the entities and boundary is important and often challenging
- There are five issues the systems thinker faces:
  - Defining the initial decomposition into entities
  - Identifying the potential entities using holistic thinking
  - Narrowing down to the consequential entities using focus
  - Creating abstractions for the entities
  - Defining the boundary of the system, and separating the system from context

One Person's Subsystem is another Person's System (continued)

- No matter where you are on the Architecture Vee, there will always be someone above you that you have to answer to (get approvals from)
- To get those approvals, you go in the upward direction
- To solve technical issues, you go downward towards your lower-level developers



Jack
Owns: System
Customer: Boss or Stakeholder
Manages: Subsystems A and B Development

Jill
Owns: Subsystem B
Customer: Jack
Manages: CIs B1, B2, and B3

Jeff
Owns: CI B3
Customer: Jill
Manages: Nobody

Images:
Jack: https://www.istockphoto.com/photo/close-up-back-view-of-the-mechanical-engineer-designing-3d-engine-model-on-personal-gm1135159636-301889389
Jill: https://www.rangeroilfieldproducts.com/oilfield-engineering-design/
Jeff: https://www.huntersure.com/wp-content/uploads/2020/09/Engineering-Firm.jpg

Define the Initial Decomposition into Entities

Task 2b

- The level of difficulty encountered in defining the entities, and therefore the internal boundaries, of a system depends on whether the system is made up of distinct elements, is modular, or is integral
- Distinct Elements
  - Sometimes the system is made up of clearly distinct entities, and the decomposition is obvious
  - Unambiguous decomposition into entities is a trait of systems that really are made up of discrete entities that are brought together and defined as a system (example: a fleet of ships)

Define the Initial Decomposition into Entities (continued)

Task 2b

- Modular Systems
  - The decomposition is more challenging but still relatively clear
  - Modules are relatively independent, especially in function
  - Internal relationships are dense within a module
  - Relationships between modules are weaker or less dense
- Integral Systems
  - Integral systems are the most difficult to decompose
  - Integral systems cannot be easily divided and keep their function intact
  - They are often highly interconnected systems, some of which are simultaneously also components of other systems
    - Example: the components in the steering mechanisms of a car (tires, wheels, suspension, steering gears, column) are highly connected, and are components of other systems (ride quality, drive)
  - Truly integral mechanical elements and integrated circuits are examples of integral elements
  - Many information systems are highly integral

Identify Potential Entities Using Holistic Thinking

Task 2c

- Holism insists on the intimate interconnection of things — on the idea of the whole
  - To think holistically is to think deliberately about the whole
  - Holistic thinking seeks to identify all of the entities (and other issues) that might be important to the system
  - We think holistically in order to bring into view all aspects of the system at hand, taking into account the influences and consequences of anything that might interact with the system
  - We use holism to expand our thinking about the problem or issue at hand
  - By thinking as widely as is feasible about what might be important to the system, we increase the chances that we will move something into consideration that will ultimately be important
  - Holistic thinking gets issues onto the “radar screen”

Principle of Holism

- Holism holds that all things exist and act as wholes, not just as the sum of their parts
- Its sense is the opposite of that of reductionism, which suggests that things can be understood by carefully explaining their parts
- To think holistically is to encompass all aspects of the system at hand, taking into account the influences and consequences of anything that might interact with the system
- To think holistically is to think about all the things (entities, relationships, and so on) that may be important to the question, circumstance, or problem at hand

Principle of Holism (continued)

- There are various methods to help stimulate holistic thinking
  - Structured and unstructured brainstorming
  - The development of frameworks to ensure that relevant issues have been considered
  - Thinking from various perspectives
  - Thinking explicitly about context
- Every system operates as a part of one large system or several larger systems, and each is itself composed of smaller systems
- Think holistically about all of these relationships, and develop architectures that are in harmony with the larger, smaller, and peer systems
- The desired outcome of holistic thinking is a longer list of all the potentially important entities to consider in defining the system and its context

Use Focus to Identify Important Entities of the System

Task 2d

- At any given time, there are tens or even hundreds of issues identified by holistic thinking that could impact the system under consideration
  - This is too many for any individual or small team to simultaneously understand
  - The number of identifiable issues that will influence a system at any point is beyond one's ability to understand
  - One must identify the most critical and consequential issues, and focus on them
  - To sustain close consideration of the important issues at any moment, one must be prepared to leave other issues behind
- The objective of this step is to cut down the list of everything generated in holistic thinking to a shorter list of things that are truly consequential
  - Process or filter this larger set of issues to identify those that are important to that day or that activity
  - Focus on the hard issues, and avoid the temptation to address the easier ones first
  - Failure rarely occurs in aspects on which you focus

Use Focus to Identify Important Entities of the System (continued)

Task 2d

- The pivotal step in focusing is defining the question, circumstance, or problem at hand and articulating what is important about it
  - What is important to you and your stakeholders?
  - What outcomes are important?
  - Is the emergent behavior of the system important?
  - Is satisfaction of some specific set of criteria important?
- Begin to reason through the entities in the whole and ask a simple question that is very difficult to answer:
  - Is this entity important in determining the emergent behavior, and thus, the outcome that is of interest?

Use Focus to Identify Important Entities of the System (continued)

Task 2d

- The human brain can only reason about a finite number of things simultaneously, while remaining able to understand their interaction
  - This manageable number is conventionally thought of as seven +/– two
  - Be aware of the longer list of things that are potentially important, and then prioritize up to seven of them at any time to really focus on
  - When the circumstances change, swap in another set of issues to reason about
- Ultimately, perform a sanity check to make sure that
  - The entities still under consideration are broad enough to cover the important question, circumstance, or problem
  - But small enough so that they can be carefully examined with the resources at hand

Create or Recognize Abstractions for the Entities

Task 2e

- Define or recognize the appropriate abstractions to represent the entities in the system
- An abstraction is defined as
  - An expression of quality apart from the object
  - A representation <u>*having only the intrinsic nature*</u> rather than the detail
- Create useful abstractions in order to
  - Bring to the surface important details about the entity
  - Hide, within the abstractions, any details and complexity that you do not need to consider

Create or Recognize Abstractions for the Entities (continued)

Task 2e

- Create abstractions
  - Of form and function with the important information represented on the surface, and with less important details concealed
  - That allows for representation of appropriate relationships at the right level of decomposition or aggregation
- Create the minimum number of abstractions that will effectively represent the important aspects of the system at hand
- When creating abstractions, loop back many times to the focus issue to ensure the abstractions capture the important issues

Create or Recognize Abstractions for the Entities (continued)

Task 2e

- Loop back to the holism issue if it is found that something is missing from the holistic view
- Abstractions are not unique
  - There may be other abstractions of the same entities that are also completely valid
  - Which abstraction is the right one to choose depends on the nature of the question, circumstance, or problem at hand
  - You usually cannot make universal abstractions
- The outcome is a set of abstractions that are important to the system but have not yet been defined to be in the system
- In other words, the system boundary has not yet been drawn

Define the Boundary of the System

Task 2f

- In defining the entities of "the system," it will often be necessary to define a boundary of the system
  - The boundary makes it clear what is "in the system" and what is outside it
  - All engineered systems have boundaries
- Humans tend to define systems to be of limited extent, either because
  - We are simply not able to consider a more extensive set of entities (a human capability limitation)
  - We believe it is not useful to do so (a human judgment)
- In defining the boundary of the system, we separate the system from its context
- Context is what surrounds the system
  - It is the entities that are "just on the outside of the system" but are relevant to it
  - Between the system and the context sits the system boundary

Define the Boundary of the System (continued)

Task 2f

- In drawing the system boundary, consider including
  - The entities to be analyzed (if the goal is understanding)
  - What is necessary to create the design (if the goal is design)
  - What we are responsible for implementing and operating (if the goal is delivery of value)
  - Formal boundaries, established by law, contract, or other legal regime
  - Traditions or conventions that distinguish the system from context
  - Interface definitions or standards that we must respect, including supplier relationships
- When a relationship crosses a boundary, it defines an external interface between the system and the context
- These external interfaces are critical for the system’s interaction with its context

Identify the Relationships Among the Entities

Task 3

Identify the relationships among the entities in the system and at the boundary, as well as their form and function

a. Form and Function of Relationships
b. External Interfaces

Identify the Relationships Among the Entities (continued)

- The relationships between a set of entities can have two characters:
  - Functional relationships
  - Formal relationships
- Functional relationships are relationships between entities that do something
  - They involve operations, transfers, or exchanges of something between the entities
  - They are sometimes called functional relationship interactions to emphasize their dynamic nature
  - During interactions, operands are exchanged by the entities or acted on jointly
- Formal relationships are relationships among the entities that exist stably for some period of time
  - Formal relations often include a connection or a geometric relationship
  - Formal relationships are sometimes called structural to emphasize their static nature

Identify the Relationships Among the Entities (continued)

Task 3a

- In general, a functional relationship usually requires a formal relationship
  - The formal relationship is the instrument of the functional relationship
  - These formal and functional relationships can be represented in an **N-Squared matrix**
- Formal relationships tend to be more concrete
  - They are a good starting point for thinking about relationships in general
  - When examining formal relationships, try to understand the functional relationship that each enables
  - The formal relationships are important primarily because they are instruments of the functional relationships

Because emergent behavior occurs in the functional domain,
it is the functional interactions that are of primary importance

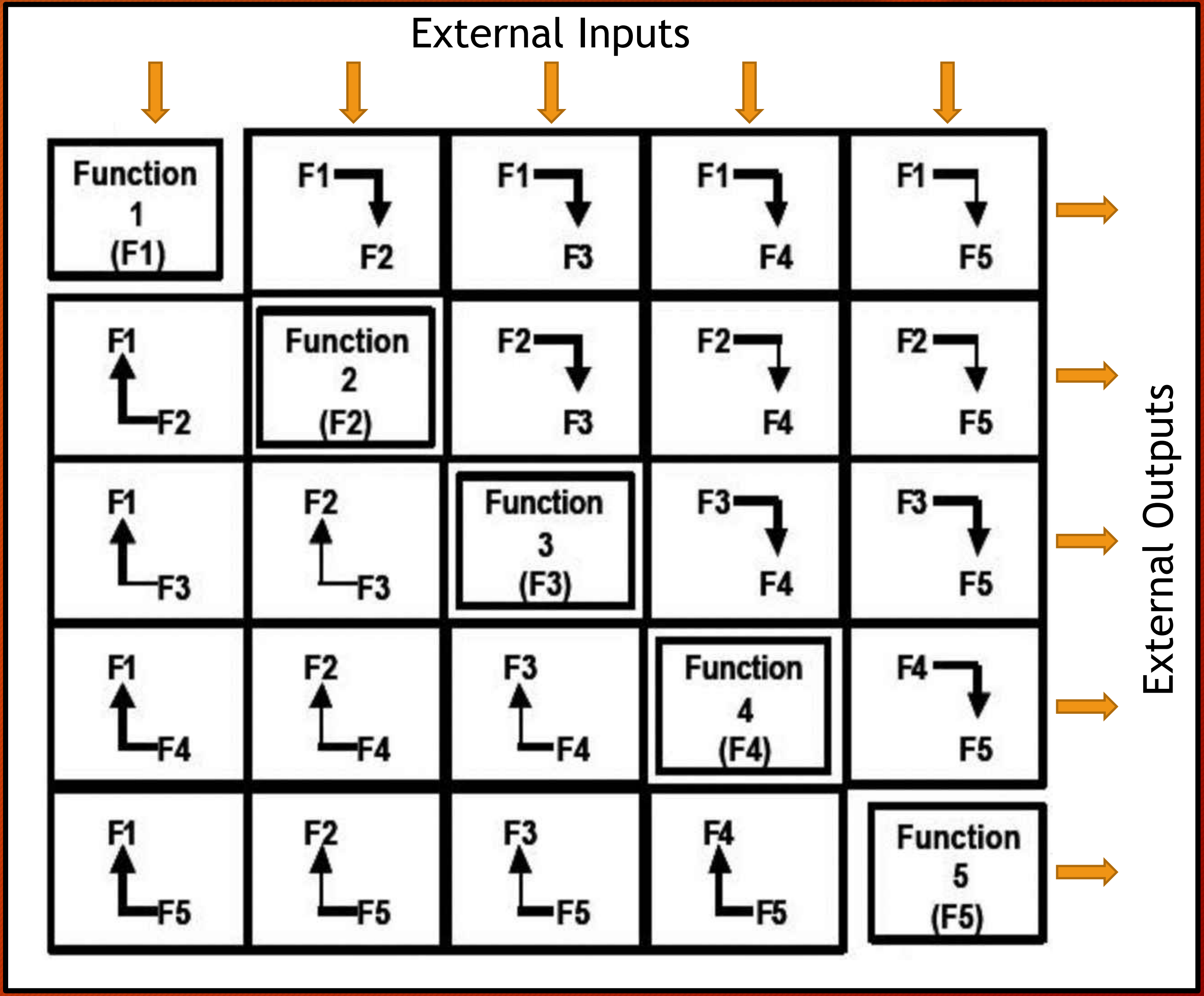
Identify the Relationships Among the Entities (continued)

Task 3b

- External interfaces of the system
  - Formal and functional relationships that exist across the boundary of the system
  - They exist between entities in the system and its context
- In the N-Squared matrix, external interfaces are indicated as any relationship outside the part of the matrix reserved for the system
- In common engineered systems it is impossible to define a system that is not connected somehow to entities beyond its boundary by external interfaces
- In general, some of the entities of a system will have both formal and functional relationships with context entities outside the system
  - Such relationships occur across external interfaces

N-Squared Matrix

- Represents interfaces between system entities
- Functions are indicated along the diagonal of the matrix
- External inputs enter functions from top row
- External outputs exit functions from right column
- Internal inputs enter functions from top or bottom of the function
- Internal outputs exit functions from right or left of the function
- Non-diagonal cells represent interfaces
- A blank cell indicates lack of an interface among the intersecting functions



https://en.wikipedia.org/wiki/File:10_N2_Diagram.jpg

Identify the Emergent Properties

Task 4

Identify the emergent properties of the system based on the function of the entities, and their functional interactions

a. The importance of emergence of system-level behavior
b. System failure
c. Predicting emergence of behavior
d. Emergent behavior depends on entities and relationships

Importance of the Emergence of System Behavior

Task 4a

- System-level emergent behavior is the magic of a system
- As the entities of a system are brought together, system-level behavior emerges as a result of combination of
  - The function of the entities
  - The functional interactions among the entities
- A system is a set of entities and their relationships, whose functionality is greater than the sum of the individual entities
  - This second phrase focuses purely on the emergence of system-level behavior
  - "Greater functionality" is delivered through emergent behavior
  - Nothing "emerges" in the domain of the form of the system
  - Form is linear, function is non-linear

Importance of the Emergence of System Behavior (continued)

Task 4a

- It is this property of emergence that gives systems their power
- Striving to understand and predict emergent behavior is the primary goal (and challenge) of system thinking
- Form enables the function of the entities
  - Formal relationships are instrumental in functional interactions
- This implies that both form and formal relationships (structure) are important to consider in predicting emergent behavior
- The formal relationships are important in guiding a certain specific functional interaction that leads to a specific system-level emergent behavior

System Failure

Task 4b

- System success and system failure often hinge on the emergence (or lack thereof) of desirable behavior
- Another way to understand the importance of emergent behavior is to think what might happen if the anticipated behavior does not occur
- This can happen in two ways:
  - The anticipated desirable behavior can fail to occur
  - Undesirable unanticipated behavior can occur
- Trying to understand and anticipate such system failures is also a goal of system thinking

Predicting the Emergence of Behavior

Task 4c

- It is hard to predict a-priori what behavior will emerge from the combinations of the functions of the various entities of a system
- Emergence depends on the function of the entities enabled by form, and on the functional relationships enabled by the formal relationships
- System success occurs when
  - The anticipated, desirable behavior emerges
- System failure occurs when
  - The anticipated, desirable behavior fails to emerge
  - Some unanticipated and undesirable behavior emerges
- The appearance of unanticipated, desirable behavior may be nice to see, but may also have no impact on determining system success or failure
  - If it has no impact on meeting the established goals of the system

Predicting the Emergence of Behavior (continued)

Task 4c

There are three ways to predict emergence

- Based on similar experiences in the past
  - This is prediction based on precedent
  - Look for identical or very similar solutions in our experience
  - Implement them with at most small changes
- Conduct experiments
  - Try putting together the entities with the proposed relations to see what emerges
  - This can range from tinkering to very highly structured prototyping
  - Spiral development is a form of experiment in which some of the system is first built to check emergence before the rest of the system is built in later spirals
- Perform modeling
  - If the function of the entities and the functional interaction can be modeled, then it may be possible to predict emergence from a model

Predicting the Emergence of Behavior (continued)

Task 4c

- Predicting emergence is at the crux of system thinking
- Predicting emergence is needed for a system that is
  - Without precedent
  - Cannot be experimented on
  - Cannot be reliably modeled
- The need to predict emergence arises routinely in new product development (unprecedented systems) for which experimentation and modeling are not easy
  - In these situations, humans must reason about emergence based on available information
- This reasoning may be informed
  - Partially by precedent (observing results in similar but not identical systems)
  - Partially by experiments and incomplete modeling
  - But the projection about emergence ultimately depends on human judgment

Emergent Behavior Depends on Entities and Relationships

Task 4d

- The emergence of behavior from a system depends on the functionality of the entities and their functional interactions
  - The form enables the function of the entities
  - The formal relationships are instrumental in functional interactions
  - This implies that both form and formal relationships (structure) are important to consider in predicting emergence
- The formal relationships are critical to the emergence of behavior
  - They guide a certain specific functional interaction that leads to a specific system-level emergent behavior

References

1. Crawley, Edward; Cameron, Bruce; Selva, Daniel (2016). *System Architecture: Strategy and Product Development for Complex Systems*, Pearson Higher Education Inc, Hoboken, NJ