Complex Systems

Lecture 03, v03

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BSEE

MSSE

INCOSE ESEP

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Complexity

- A complex system has many interrelated, interconnected, or interwoven entities and relationships
- Complexity is driven into systems by "asking more" of them
  - More function
  - More performance
  - More robustness
  - More flexibility
  - …
- It is also driven into systems by asking systems to work together and interconnect with increasing scale and scope
- Complex systems require a great deal of information to specify and describe
- Ways of measuring complexity
  - Based on the information content of the description of the system
  - Categorizing what the system does (a function-based approach)

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Complexity (continued)

- An idea closely related to complex is complicated
  - Takes into consideration the finite ability of the human to perceive and understand complexity
  - Complicated things have high apparent complexity
  - They are complicated because they stretch or overwhelm our ability to understand them
- Dealing with complexity is not new
  - Over the last century, systems and the context in which they operate have become more complex
  - This increasing complexity has strained our ability to comprehend systems
- Our job as architects is to train our minds to understand complex systems so that they do not appear to be complicated to us
- We should seek to build architectures that do not appear complicated to all the others who have to work on the system — designers, builders, operators
- The task of good architecture design can be summarized as follows
  - Build systems of the necessary level of complexity that are not complicated

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Decomposition

- Decomposition is the dividing of an entity into smaller pieces or constituents
  - It is one of the most powerful tools in our toolset for dealing with complexity
  - Break a problem down into smaller problems until each is tractable
- Sometimes defining decomposition is easy
  - When the system is made up of distinct elements
- Sometimes the system is modular
  - This suggests use of decomposition of the modular structure
- Sometimes the system is integral
  - Decomposition can then be somewhat arbitrary since there is no clear separation of components

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Decomposition (continued)

- The difficulty with breaking things apart is not in the breaking apart, but in the process of later bringing together the decomposed entities to build the whole
  - This process is often called integration
  - In the formal domain
    - Form aggregates
    - We have to worry about the physical/logical fit between the elements as they are brought together
  - In the functional domain
    - We decompose functions into more basic functions
    - In recombining the entities of function, we encounter emergence: the real challenge

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Hierarchy

- In a hierarchical system, the system entities belong to layers or tiers
  - Layers are ranked one above the other
- The top-most level of a system hierarchy is referred to as Level 0 (or Tier 0)
  - Below that, we refer to Level 1 (down), and Level 2 (down), and so on
- Hierarchy is can be used to understand and reason about complexity in systems
- What causes some tiers to be higher in the hierarchy than others?
  - They have more scope
    - Governors rank above mayors because they have more scope (a state is larger than a city)
  - They have more importance or performance
    - Black belts rank above brown belts because they perform to a higher standard and have greater skills
  - Their functions entail more responsibility
    - Presidents rank above vice presidents because they have more responsibility
- Hierarchy does not imply that a system element on a particular level is subordinate to any specific element at the next higher level
  - That observation only occurs when performing hierarchical decomposition

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Hierarchical Decomposition

- Often, decomposition and hierarchy are combined into a multilevel or hierarchical decomposition: a decomposition with more than two levels
- Organizing a hierarchical system in this way appeals to our desire to group things in sets of seven +/– two
- System classification scheme:
  - Simple systems
    - A system that can be completely described by a one-level decomposition diagram
    - There are generally no more than seven +/– two elements of form at Level 1
    - When you get to these elements, they are more or less atomic parts
  - Systems of medium complexity
    - A system can be represented by a two-level decomposition diagram
    - There are no more than (seven +/- two) parts — that is, no more than about 81 entities
  - Systems of complex complexity, or "complex" systems
    - A complex system has the same representational diagram as a medium-complexity system
    - At the second level (down) there are still only abstractions of things below
    - These are significantly harder to analyze, and more common

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Hierarchical Decomposition (continued)

- One rarely sees a single decomposition diagram more than two levels deep
- There are two reasons why such drawings are not frequently used
  - A three-level diagram could have as many as (seven +/– two) elements at the third level
    - Or as many as 729
    - This is far more than humans can routinely process
  - When we look down into the organization of a system, we find that we know the Level 1 elements fairly well
    - We more or less comprehend things on the next level (Level 2)
    - Beyond that (Level 3 and lower) our understanding and appreciation of the system organization is much less clear

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Two Levels (Tiers) of Decomposition

1 element at Tier 0

7 elements at Tier 1

49 elements at Tier 2

If fully populated, the number of entities quickly becomes overwhelming

Hierarchical Decomposition (continued)

- The designation of Level 0 as “the system” is somewhat arbitrary and depends on the viewpoint of the architect
- There are dozens of words to designate the layers below “the system”
  - modules, assemblies, sub-assemblies, functions, racks, online replacement units (ORUs), routines, committees, task forces, units, components, sub-components, parts, segments, sections, chapters, and so on
- Unfortunately, there is little consensus about how these terms are applied
  - One person’s assembly is another person’s component
- There are relatively fewer words for the levels above “the system”
  - People speak of systems of systems (SoS), family of systems (FoS), complexes, collections, etc
  - If needed, we will call these Level 1 (up) and Level 2 (up)

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Atomic Parts

- The term “atomic part” does not have an exact definition
- In mechanical systems, atomic parts are those that cannot easily be “taken apart”
- In information systems, the definition of “atomic part” is even fuzzier
  - A useful test is to call something an atomic part when
    - It possesses a fundamental semantic meaning (as does a word or an instruction)
    - It is a unit of data or information
  - These words, instructions, or data units would include details, of course
  - Because all information is an abstraction, defining meaningful abstractions of abstractions is necessarily more fuzzy
- Call it a part if it loses meaning when you take it apart

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Special Logical Relationships

- Class/Instance Relationship
  - More commonly used in software than in hardware
  - A class is a construct that describes the general features of something, and an instance is a specific occurrence of the class
  - The instance is often referred to as the instantiation of the class
  - The idea of class/instance is quite common
- The Specialization Relationship
  - Describes the connection between a general object and a set of more specific objects
  - Used extensively in design
  - Akin to the concept of inheritance in object-oriented programming
    - A class can be created starting from a more general class
    - From which some attributes and functionality are inherited
    - And to which new attributes and functionality are added
- Iteration
  - Iteration is commonly and very explicitly used in software engineering
  - Occurs when a process is performed several times <u>at the same level</u> of a hierarchy
  - Occurs when a routine or function uses itself at the same level
  - Occurs when entities or relationships are used in a self-similar way
- Recursion
  - Recurrence is commonly and very explicitly used in software engineering
  - Occurs when a process or object uses itself within the whole
  - Occurs when a routine or function uses itself
  - Occurs when an approach used at one level of a system is <u>used again at lower levels</u> within the system
  - Occurs when entities or relationships are used in a self-similar way

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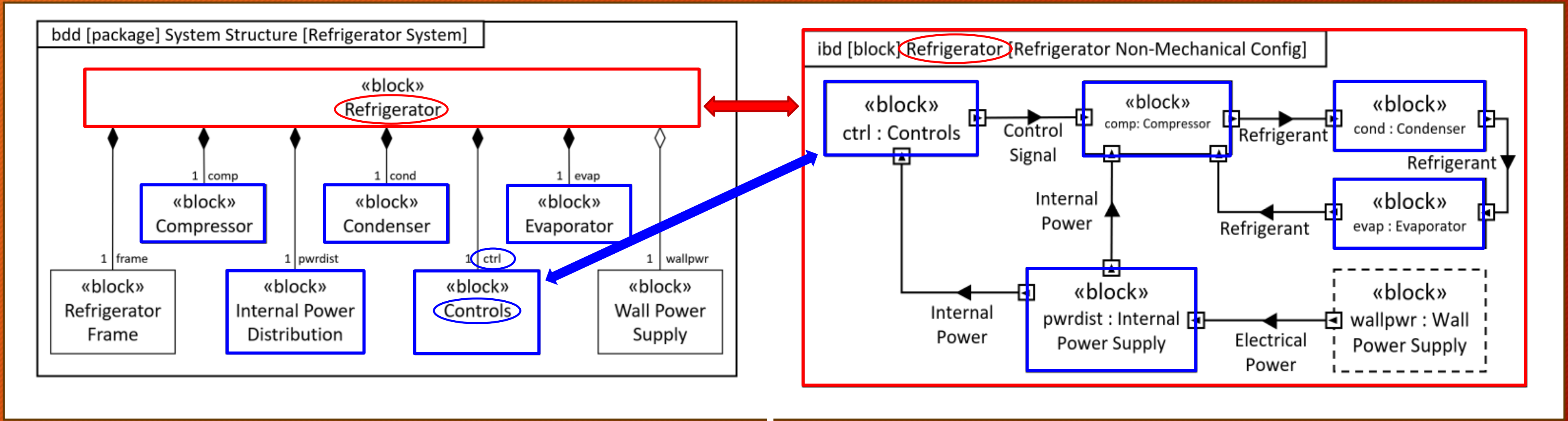
Class/Instance Relationships

A class is a construct that describes the general features of something, and an instance is a specific occurrence of a class

The instance is often referred to as the instantiation of the class

The idea of class / instance is quite common

In Systems Engineering the most common example is that of the definition of a block (class) and description of a particular usage of a block (an intance of that class)



- Serves like class definition in software
- Defines the properties of block types (properties are not shown in the above example)
- Used to “type” the usage of blocks in an IBD
- The example above shows the decomposition of the “whole” Refrigerator block into its component “parts” (represented by the black diamond)
- This BDD describes the “definition” of a “Refrigerator”
  - If any of the components defined here are missing in a deployment, then the system does not fit this definition of Refrigerator

- Serves like an object instance in software
- Describes the use of one or more of the block types described in a BDD
  - The IBD frame represents the “whole”
  - In this case, the frame is the Refrigerator
- The blocks inside the IBD frame represent the Refrigerator’s “parts” in one particular configuration (“usage” – meaning how they are arranged, or connected together)
- There could be other arrangements or configurations
- Parts indicate what “type” they are
  - **Ctrl : Controls** – says “ctrl is of type Controls”
- Parts inherit all the properties of their type

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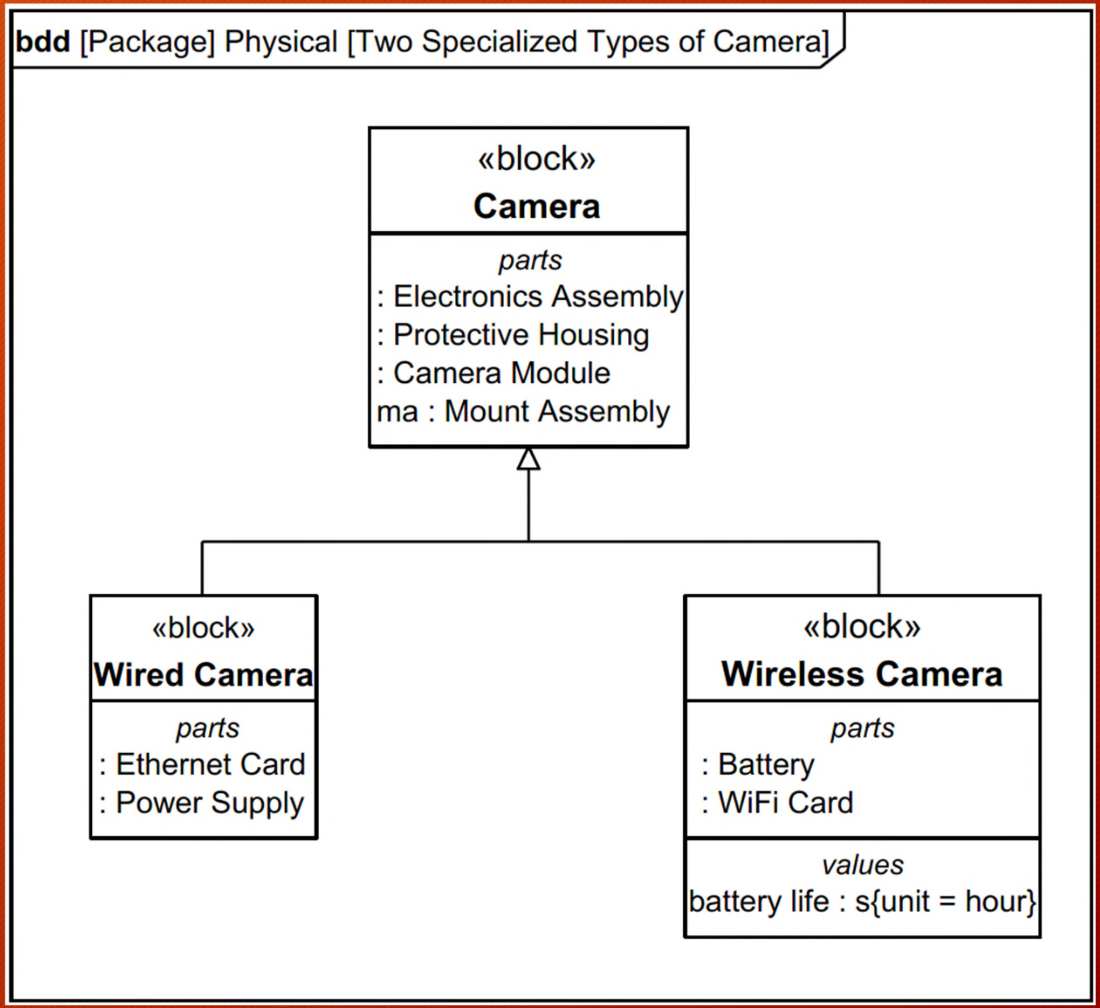
Specialization Relationship

- Describes the connection between a general object and a set of more specific objects
- Used extensively in design
- Akin to the concept of inheritance in object-oriented programming
  - A class can be created starting from a more general class
  - From which some attributes and functionality are inherited
- In this example, the superclass "Camera" is specialized into two subclasses
  - The "Wired Camera" class adds features, such as Ethernet Card, that specialize the subclass apart from the more general class "Camera"
  - Equivalently, the "Wireless Camera" defines parts, such as WiFi Card, that are unique to that subclass of Camera



"A Practical Guide to SysML" by Friedenthal, Moore, and Steiner

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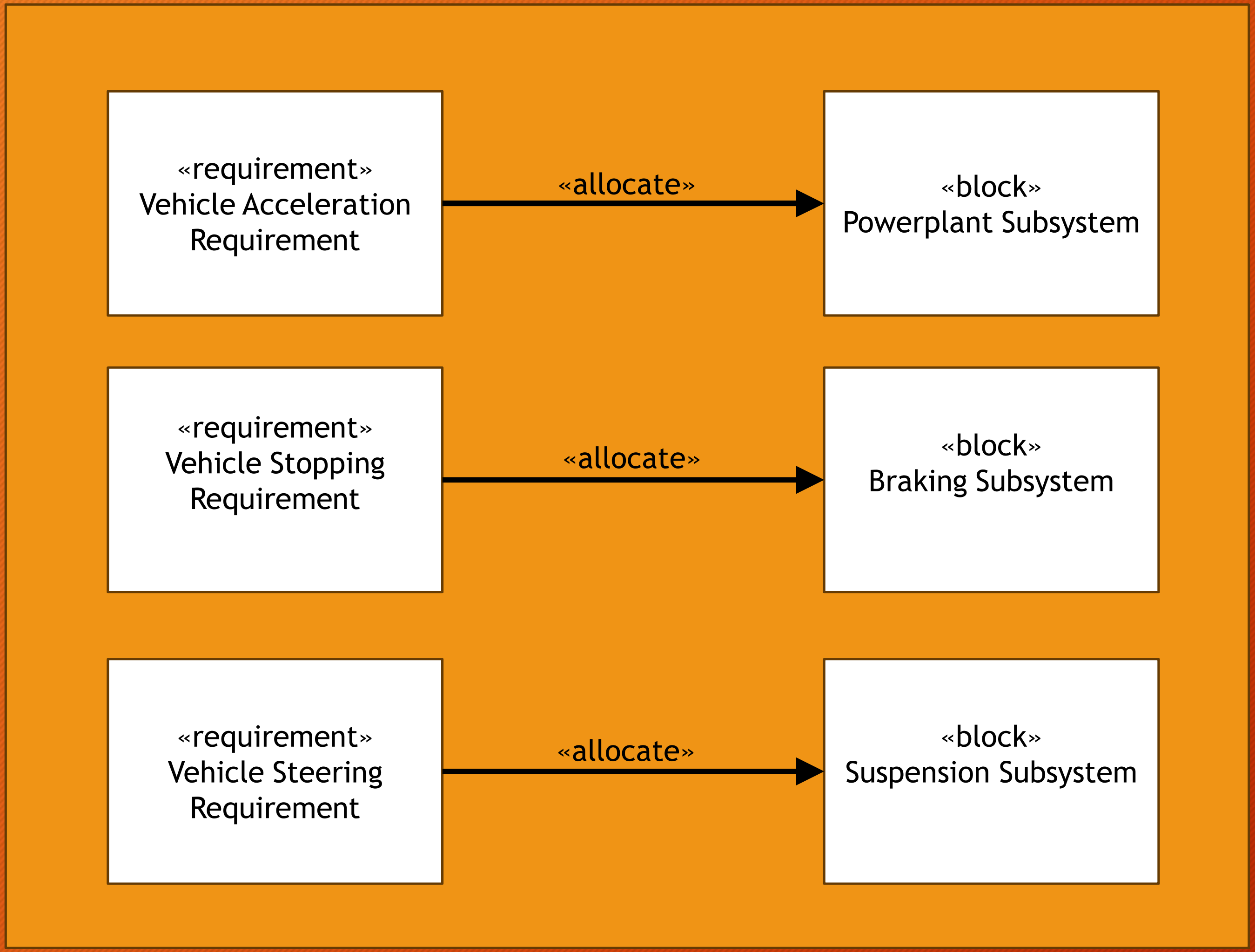
Iteration



- Occurs when a process is used at one level of a system and then is used again, repeatably, at the same level within the system
- In the example shown, the same process is used multiple times to allocate a system requirement to be implemented by a specific system component within the same level of the system hierarchy

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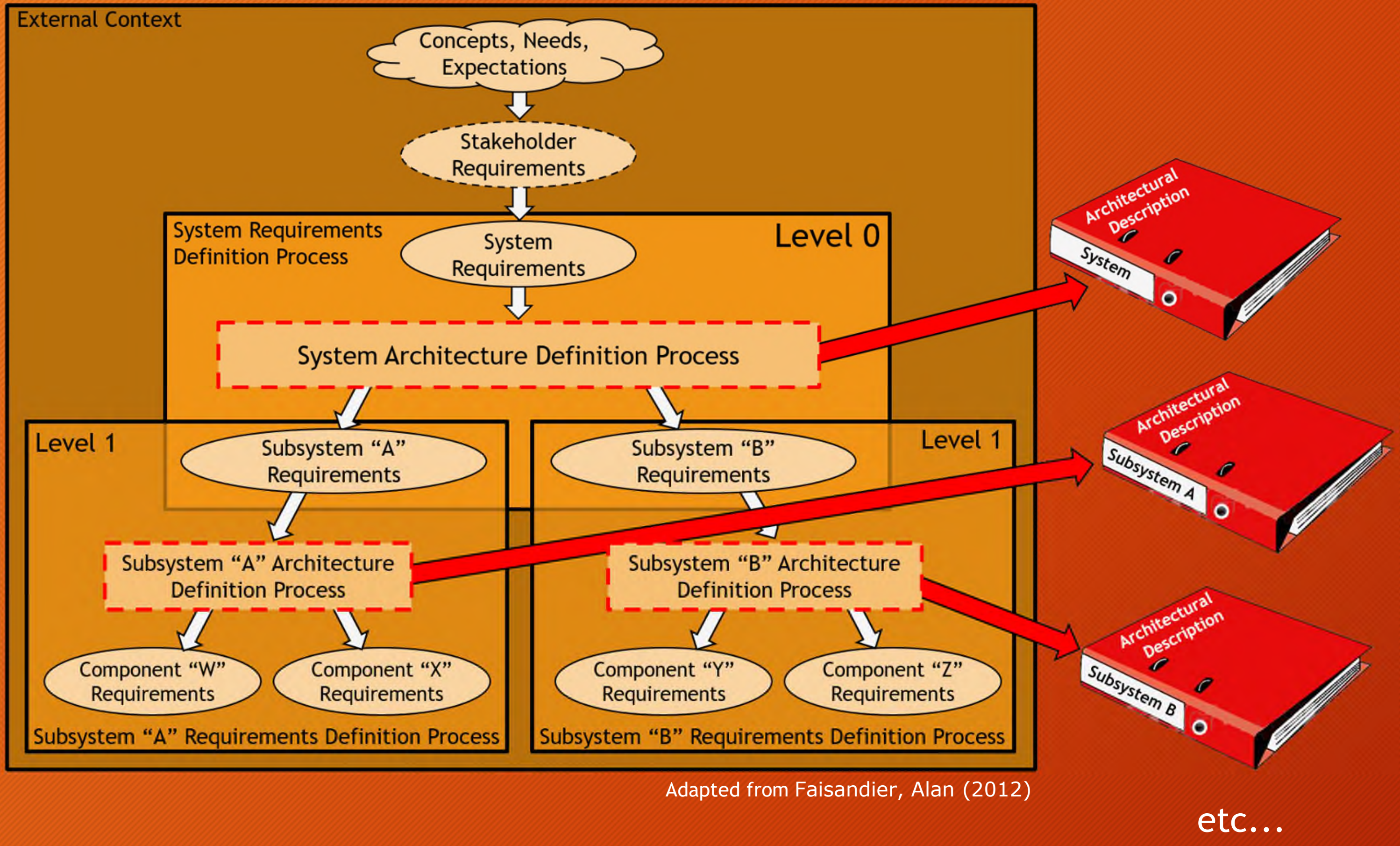
Recursion



Adapted from Faisandier, Alan (2012)

- Occurs when an approach used at one level of a system is used again at other levels within the system
- In the example shown, the Architecture Definition Process is repeated at each level of the system hierarchy, as well as within each element of a given level of the hieararchy

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Reasoning Through Complex Systems

v02

- Top-down Approach
  - Refers to the direction in which you approach a system
  - Start from the goals of a system and proceed to the concept and then the high-level architecture
  - Then develop the architecture in increasing detail until you reach the smallest entities of interest to you
  - This method follows the "left-hand side" of the systems engineering VEE model
- Bottom-up Approach
  - Think about the artifacts, capabilities, or services that are available in the lowest-level entities
  - Build upward from them, predicting emergence
- Outer-In Approach
  - Start at both top and bottom
  - Work toward the middle
- Middle-Out
  - Start at some arbitrary point in the system hierarchy
  - Try to reason one or two levels up or down
- There is really no top or bottom to truly complex systems
  - In reality we end up applying a middle-out approach

Good architects should be able to apply all of these approaches

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Zig-Zagging

- Zigzagging
  - When reasoning about a system, alternate between reasoning in the form domain and reasoning in the function domain
  - Start in one domain
  - Work as long as is practical
  - Then switch to the other domain
- This alternating pattern of thinking continues down through all levels of the system design

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