Architecture-Based Systems Engineering and Integration

By

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Outline

1.0 Why Architecture-Based Systems Engineering?
What does Architecting bring to the Systems Engineering Process?
2.0 DODAF views and Products
3.0 Four Aspects of Systems Engineering.
Five Phases of Systems Engineering Process.
4.0 Five System Architectures;
The 4+1 Software Architectures.
5.0 Merging Activities: Architecting, Engineering Integration, and Evaluation.
6.0 System Integration and Interfaces.
7.0 Conclusion

Why Architecture-Based Systems Engineering?

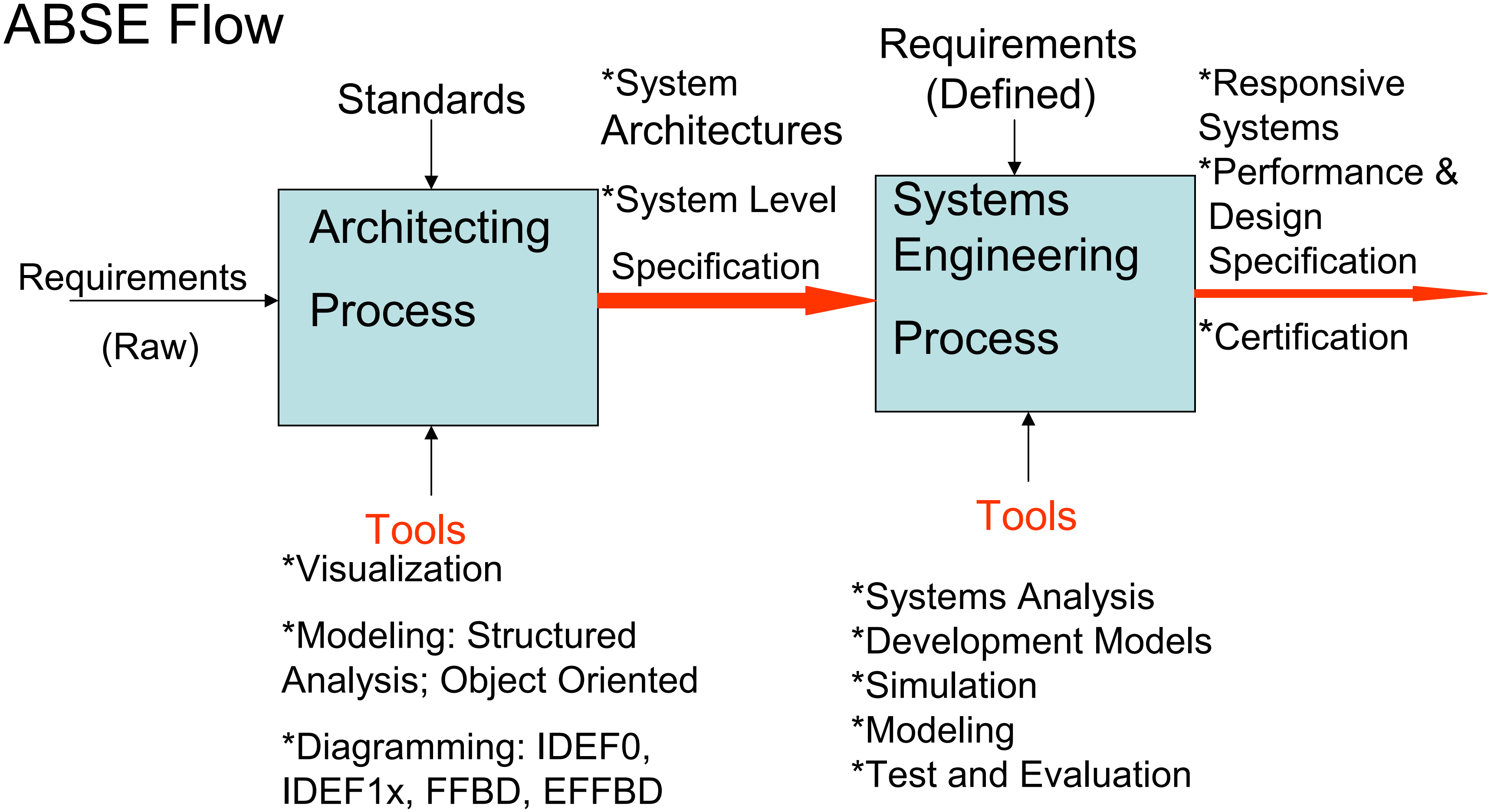
- DOD Systems Acquisition paradigm is moving away from acquiring products to acquiring Capabilities.
- Emphasis on using existing systems with new systems.
- Network Centric Operations demands flexibility and Interoperability between System-of-Systems.
- Coping with Complexity, uncertainty and cost of Engineering Effective Systems and Enterprises.
- Utilizing Information Technology to improve Productivity, integration, and build unprecedented Complex Systems.

Architecture-Based Systems Engineering

- Responding to these changes and challenges: We must systematically merge: Architecting activities, Engineering, Integration, and Evaluation of systems.
- The response is using the Systems Engineering approach of iterative top-down design and bottom-up integration of software and hardware.
- DOD has directed that DODAF be used to describe several Aspects of system architecture. DODAF consists of 26 views products.
- DODAF 1.0 does not provide guidance for detailed design, integration, or evaluation of systems.
- DODAF products can be used to create the System Architecture.

Architecture-Based Systems Engineering

ABSE Flow



Concept of Architecture

- The concept of architecture entered the domains of Software and Systems Engineering in recent decades
- Some people argue that the Software and System architecture are similar to that of civil architecture
- A building architecture is a detailed endeavor driven by the user that is meant to stay for many years. The drawings are very detailed to support the builder.
- Enterprise /System architecture must be more responsive to change & extensible: flexible, adaptable, and scalable than building architecture. It must be interchangeable / modular, & reusable.

Types of Architectures

There are two types of architectures:

(1) System Architecture of building real systems: Civil, Hardware, and Embedded systems architecture,

(2) Domain Specific Architectures: Software, supply chain, finance, insurance, business processes, security, C4ISR, avionics, weapon system.

** Architectures are preambles and part of the systems engineering process.

Architecture Framework

- Framework is the structural frame of reference,
- Architecture Framework e.g. DODAF or Zachman give the structure of the architecture.
- Framework does not give detailed guidance on how to design or implement architectures.
- Architecture (Framework +Design) = System Architecture

DODAF Linkages Among Views

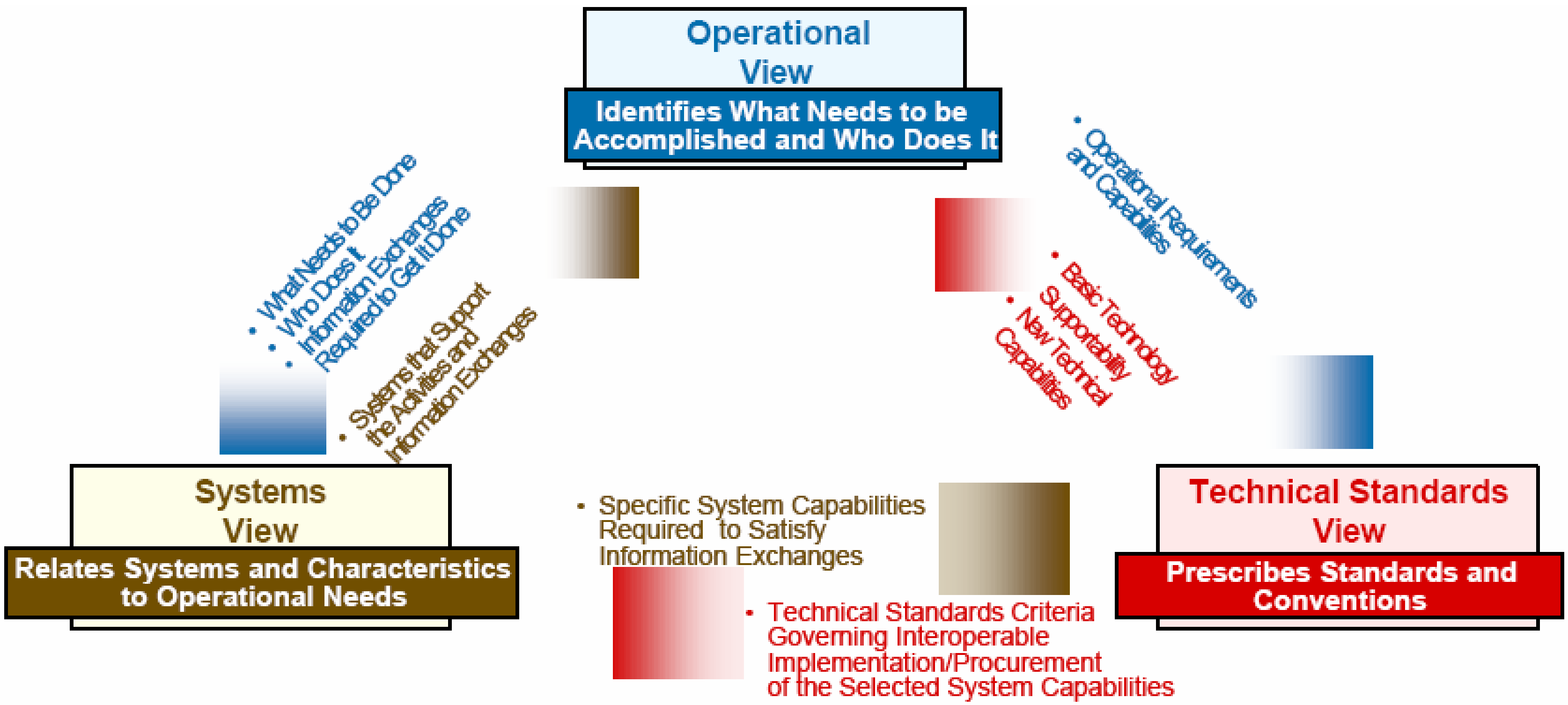


Figure ES-1. Linkages Among Views

System Architecture Must Have:

- Every system/enterprise must have an architecture
- An architecture must have:

  * Structure (Topology)/Organization,

  * Functionalities: Function Blocks, Modules

  * Connectivity: Linkages and interfaces-
    Function Blocks Diagram for a given set
    of events

Architecture-Based System Design Process

- Two approaches:
  (1) Structured Analysis (SA):
  using IDEF0, IDEF1x, DFD, FFBD, EFFBD
  (2) Object Oriented (OO):
  using UML or equivalent

Systems Engineering

Systems engineering is a multidisciplinary subject dealing with the integration of all parts of a system (hardware, software, and operator) into the real world environment. It provides rationalization for tradeoffs in meeting the requirements and building the system.

Systems Engineering Framework

Systems Engineering

Philosophical

- Theory
- Concepts
- Process: phases, steps, stages
- Development Models

Management & Business

- Planning, budgeting
- Costing
- Schedule control
- Configuration Control
- Program management
- System acquisition
- Political engineering

Technical & Engineering

- Effectiveness factors
- SEA
- Metrics
- Capability
- Performance
- Testing
- Reliability
- Maintainability

Operational

- Derivation of requirements
- Validation of requirements
- Testing
- Logistics
- Support
- Training

Systems Engineering Process

Systems Engineering Process deals with all aspects of system design, development, integration, evaluation, disposal, and management.

(1) Determination of requirements,
(2) Definition of system architectures,
(3) Establishing performance, reliability, and availability goals
(4) Tradeoff analysis: performance versus cost, reliability, support,
(5) Decomposition and partitioning of system, and system design,
(6) Integration of building blocks, interfaces, testing, and safety,
(7) Metrics to evaluate all these activities, evaluate the effectiveness of alternatives and options,
(8) System engineering management: system acquisition, project management, and risk analysis.

Partitioning Levels of System Architecture

There are five levels of architectures:

(1) <u>**System/Enterprise**</u> level → Conceptual Architecture
Expressing stakeholders needs, concerns, capability requirements, and strategy

(2) **Subsystem** level → Functional/Logical Architecture
Performance, functional connectivity, and interfaces

(3) **Module** level → Physical Architecture
Physical connectivity and interfaces

(4) **Function** Block level → Operational/Implementation Architecture

(5) **Subfunction** level → Bottom-up Integration and Interfaces Architecture

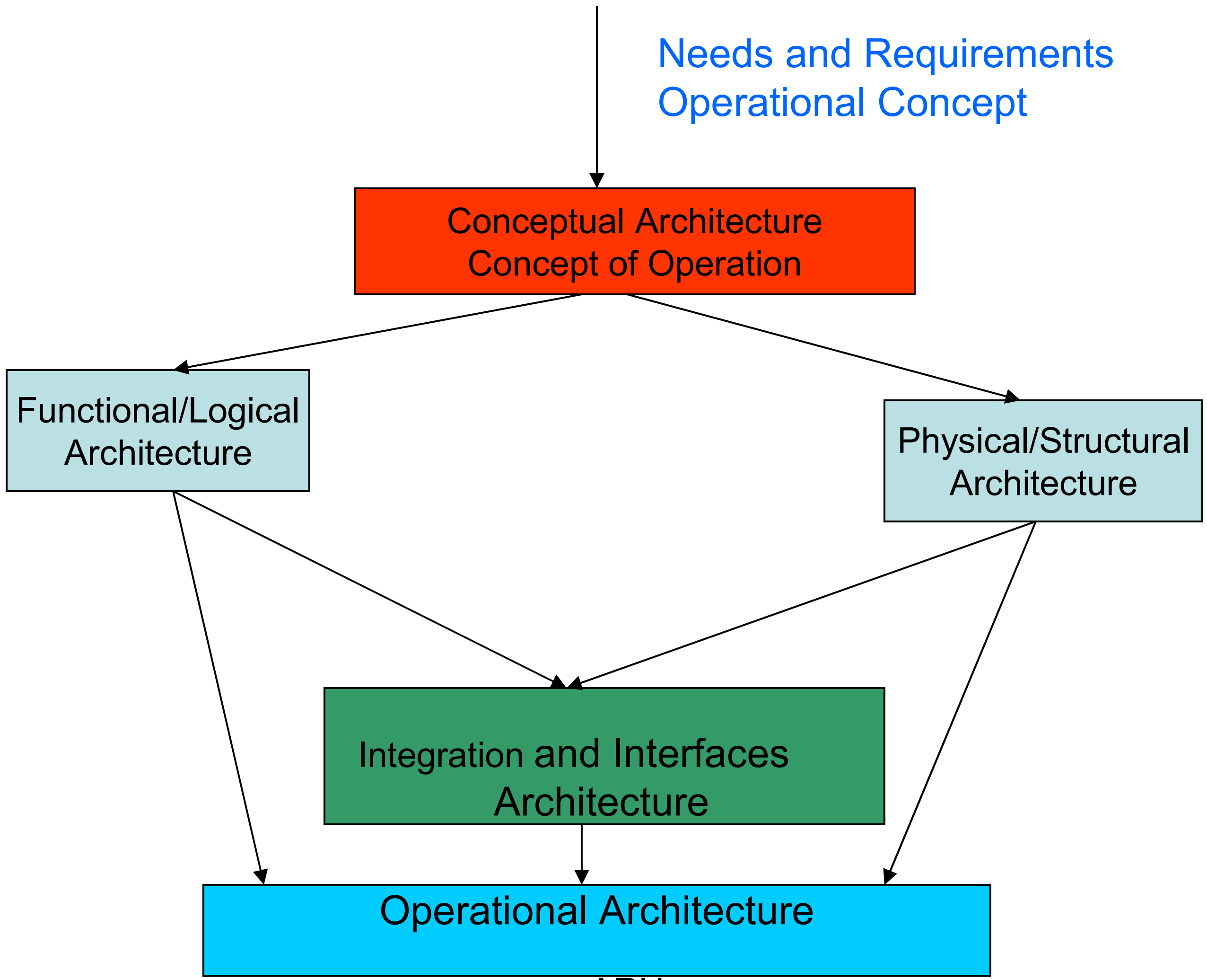
* Physical and functional connectivity are interfaces driven

** Functional and Physical architectures are performed concurrently

** The final architecture is achieved by iteration between these levels

** These architectures evolved into architecture Views: System, Operational, Technical and All

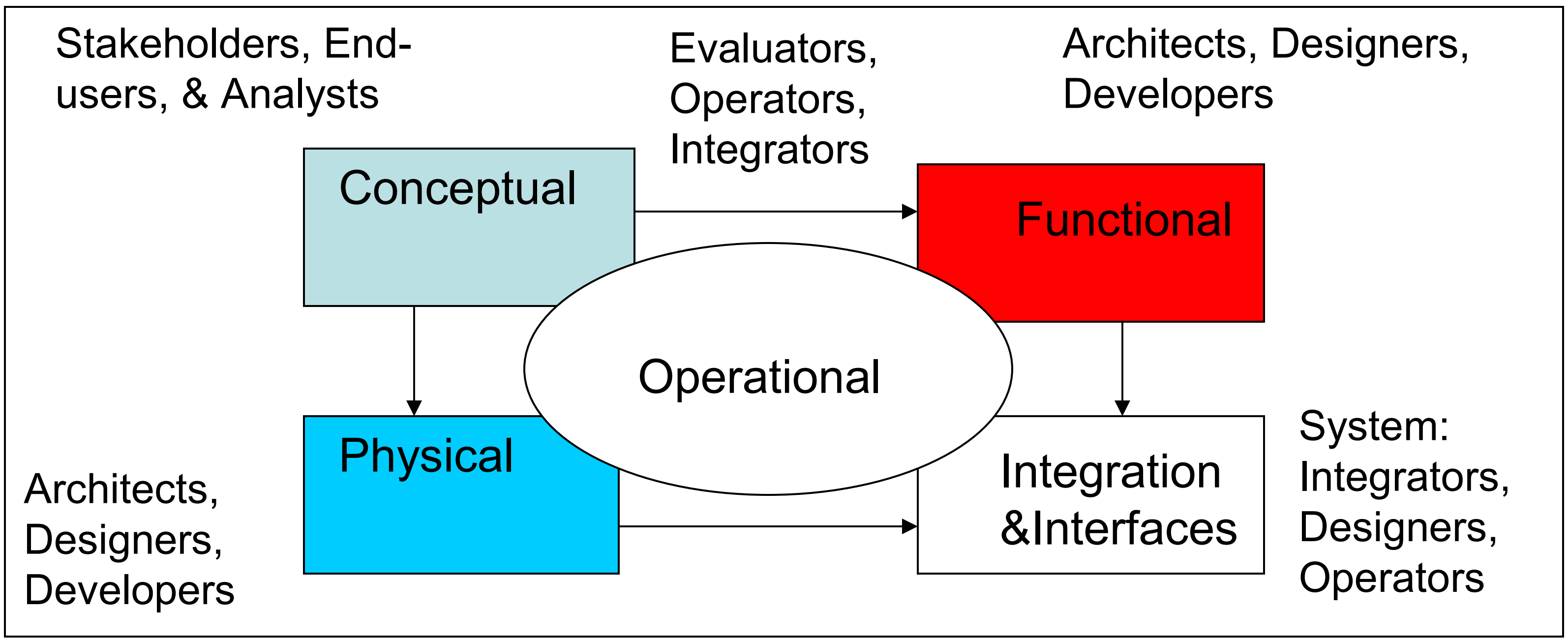
System Architectures Flow and Relationship



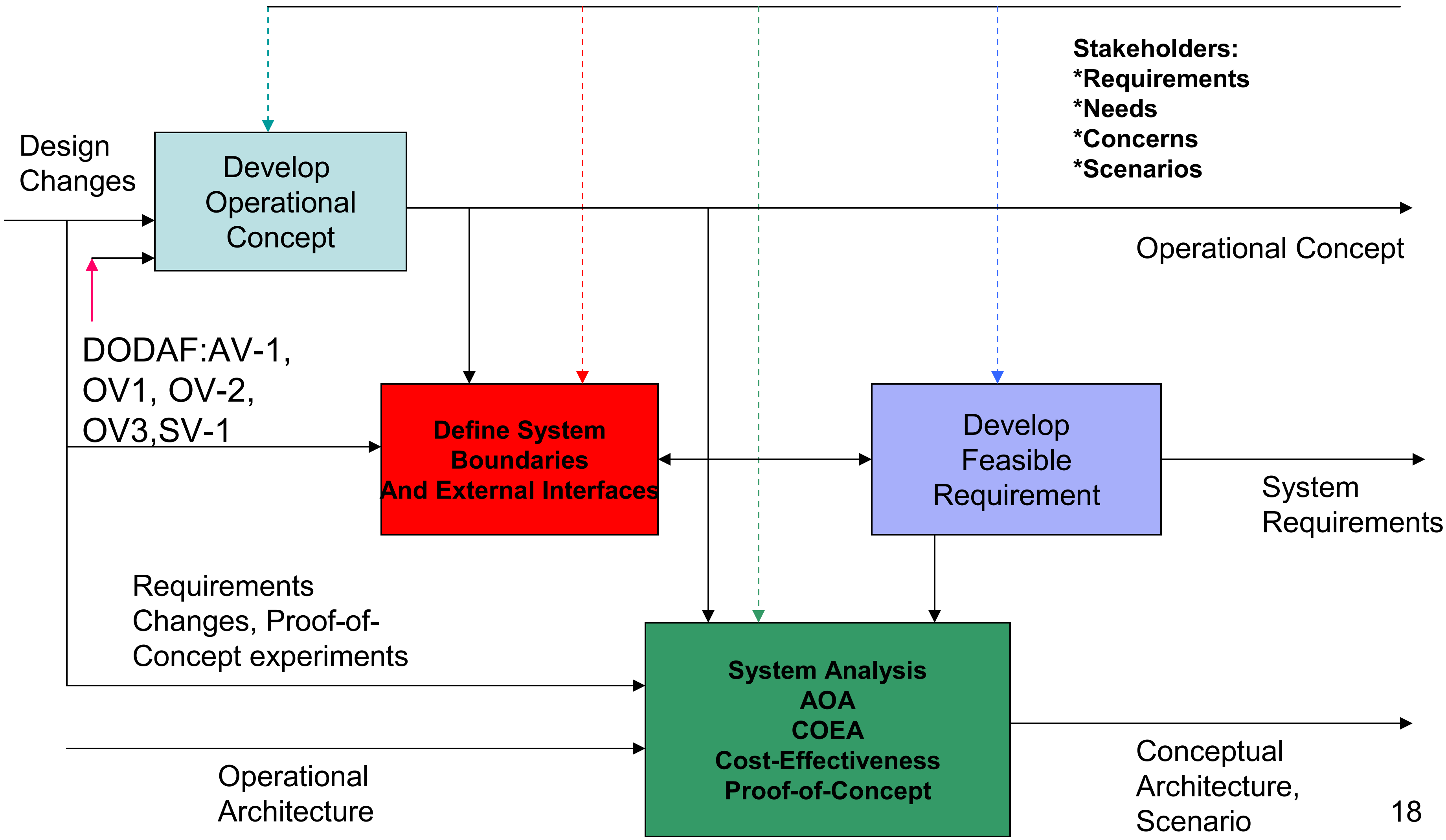
Architecture flow development in the engineering of a system

System Architecture Model

The relationship of the five kinds of system architecture:

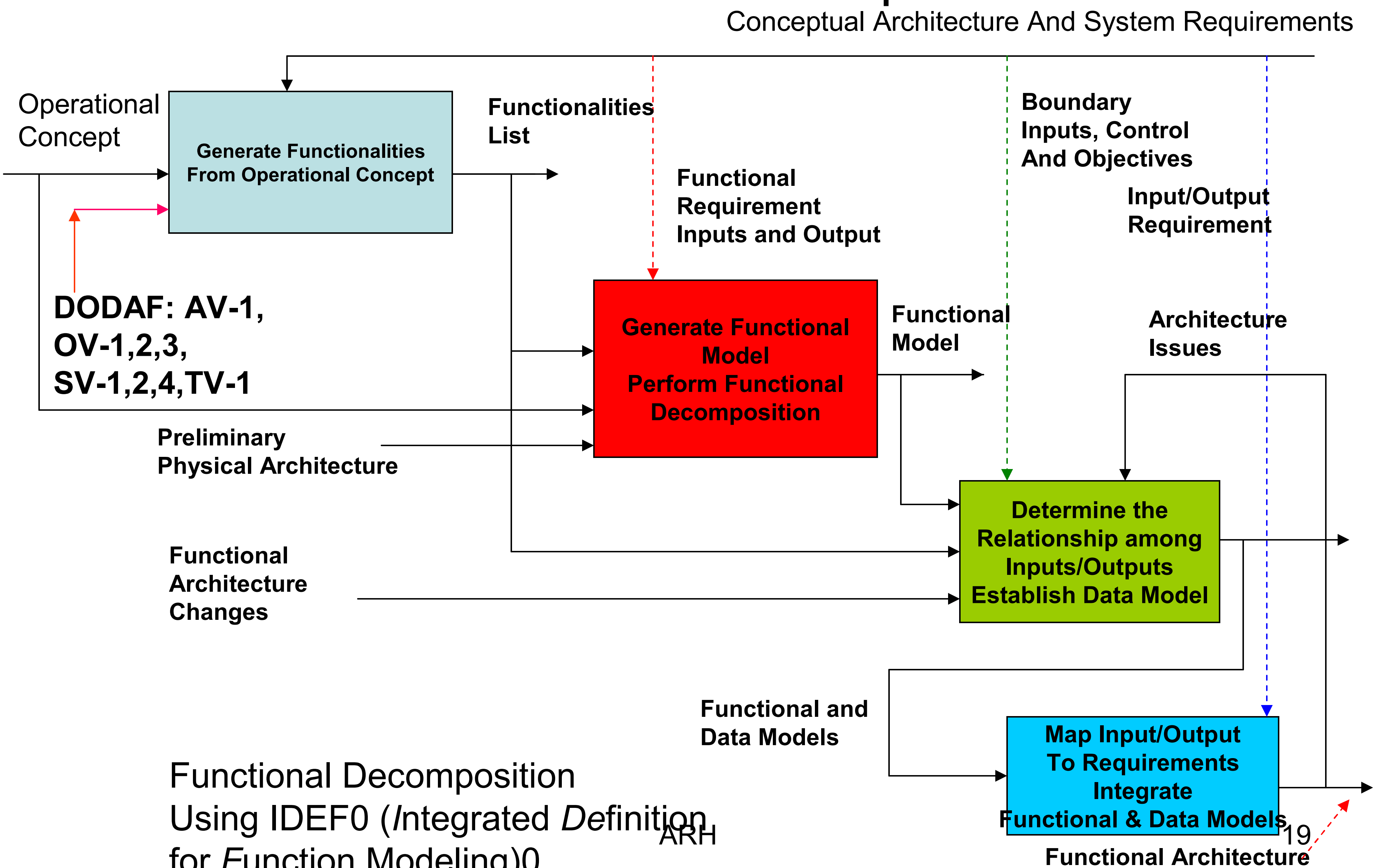


Conceptual Architecture Development Process



Iteration between the development levels

Functional Architecture Development Process

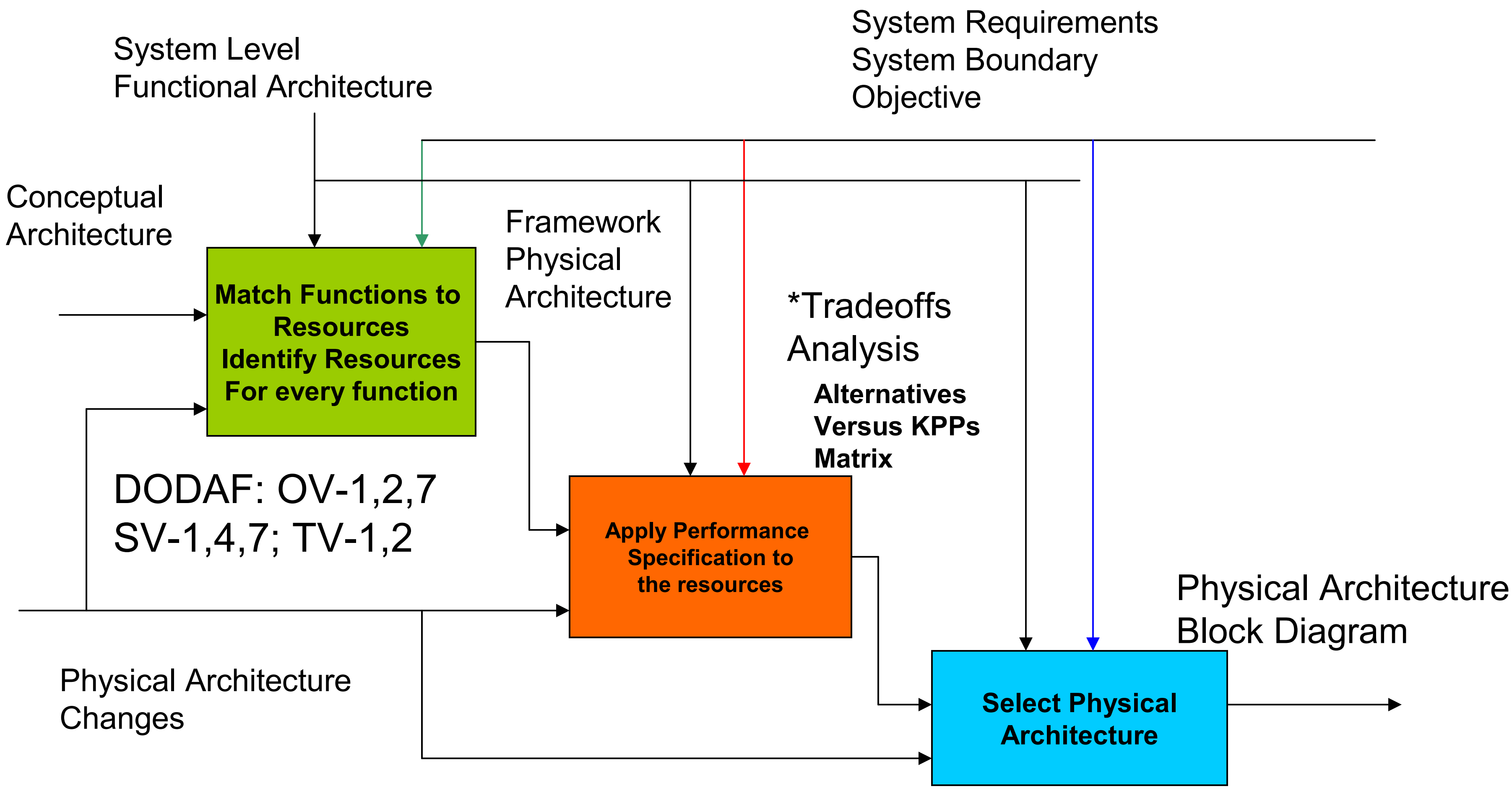


Functional Decomposition
Using IDEF0 (*I*ntegrated *Def*inition
for *F*unction Modeling)0

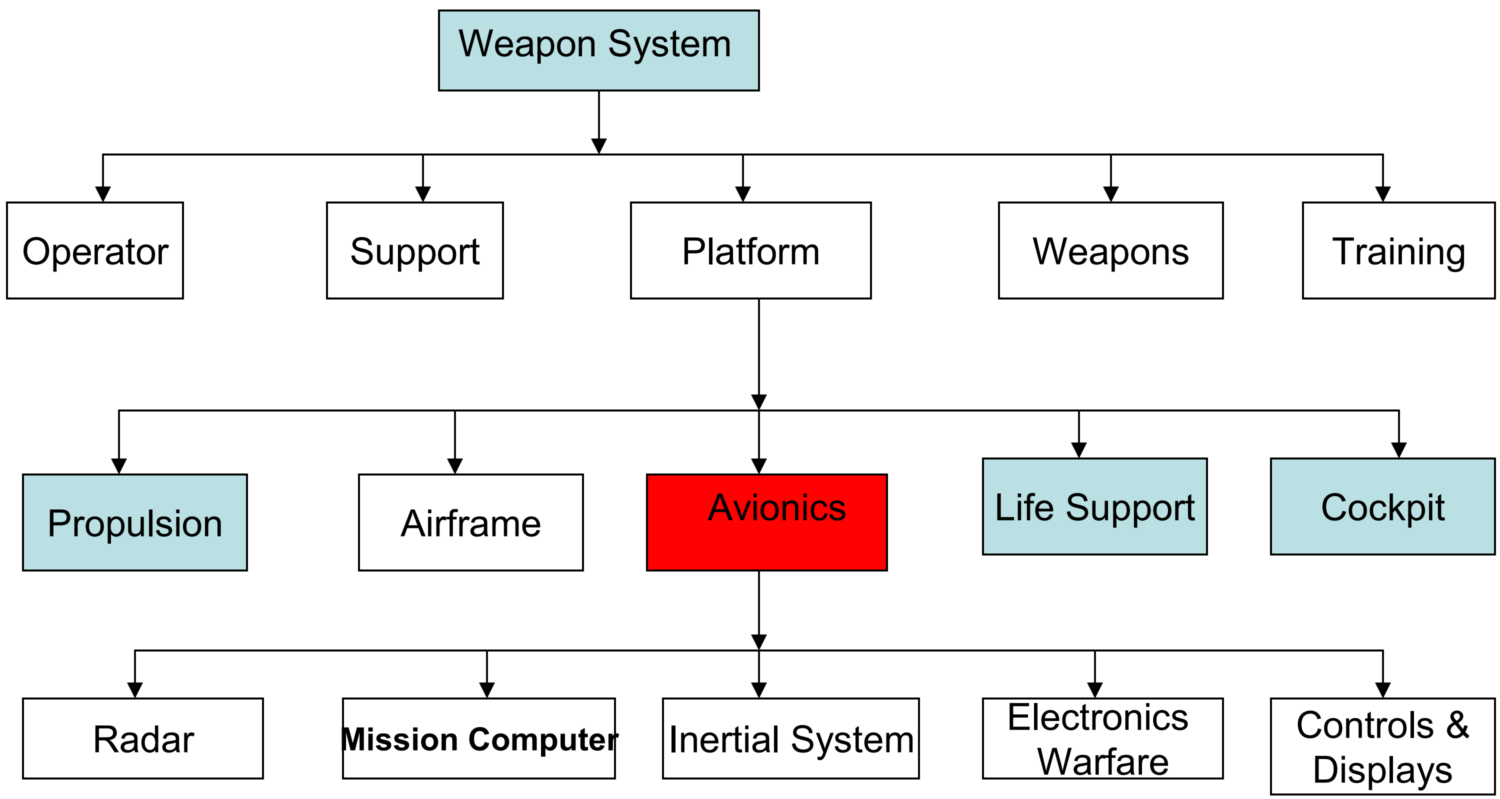
Physical/Structural Architecture

- The physical architecture gives the physical resources to perform the system functions. It is developed concurrently with the Functional Architecture.
- It identifies resources to form the structural architecture. Physics-Based simulations provide insights into the physical architecture
- Physical architecture is a description of the partitioned elements of the system without their performance specifications.
- It accounts for all the nonfunctional attributes: Reliability, availability, security, scalability, reusability.

Physical Architecture Development Process



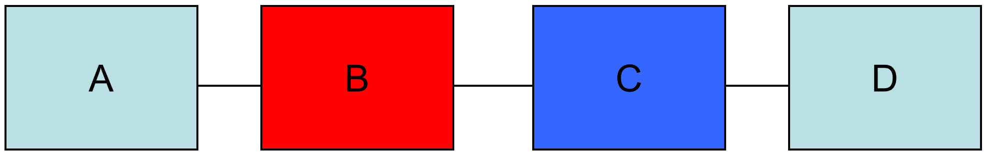
Physical Architecture of a Weapon System



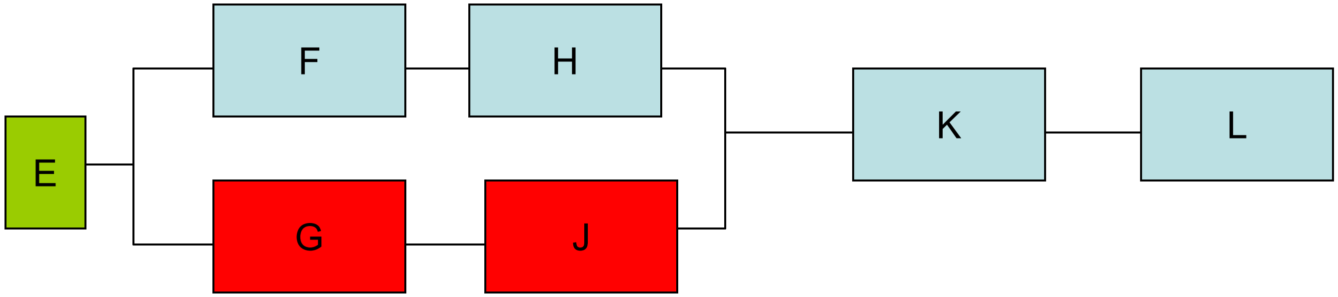
Work Breakdown Structure is similar to the physical architecture (WBS)

Reliability/Availability Block Diagram

Example of a Physical/Structural architecture

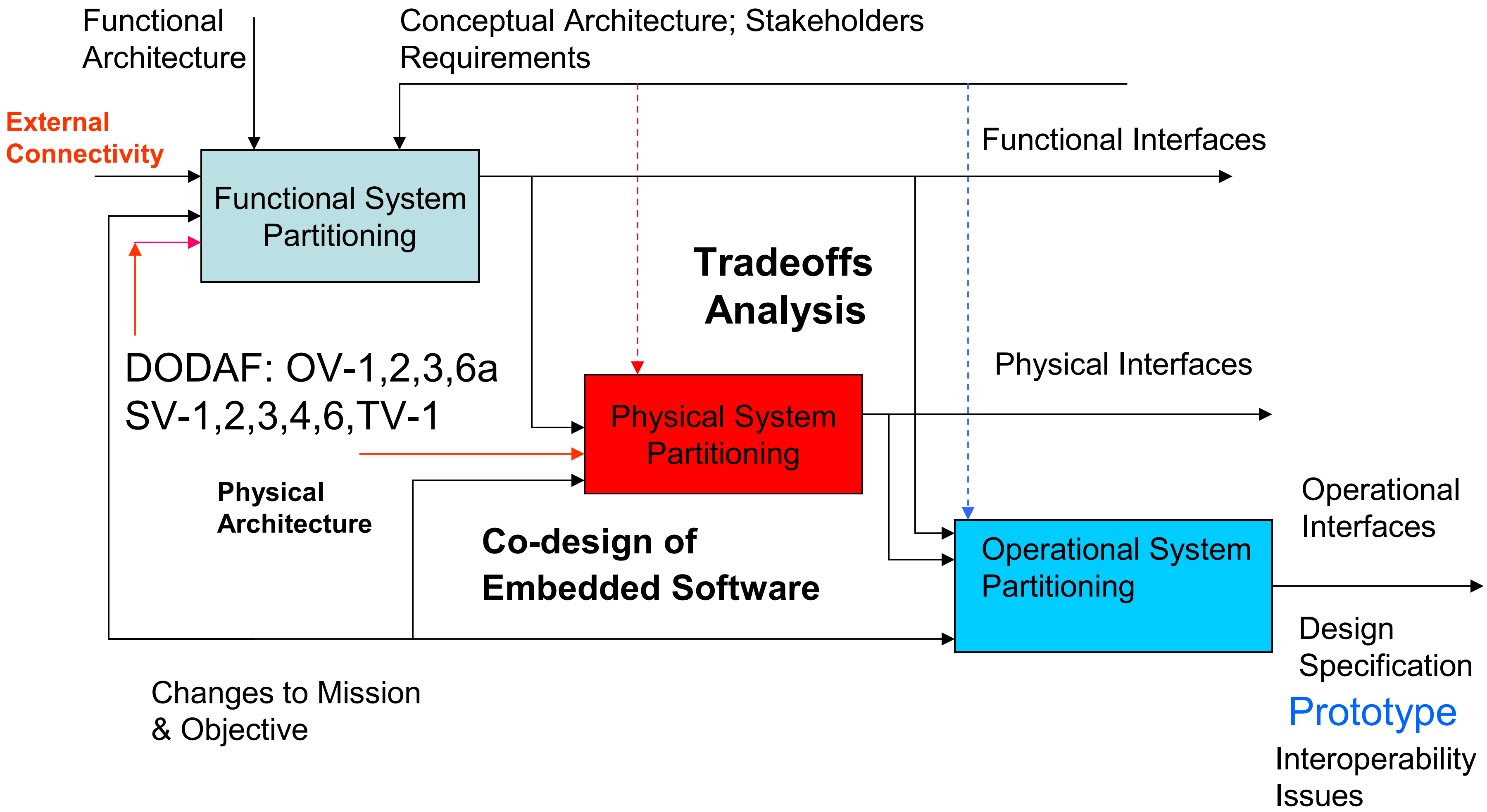


Series Architecture

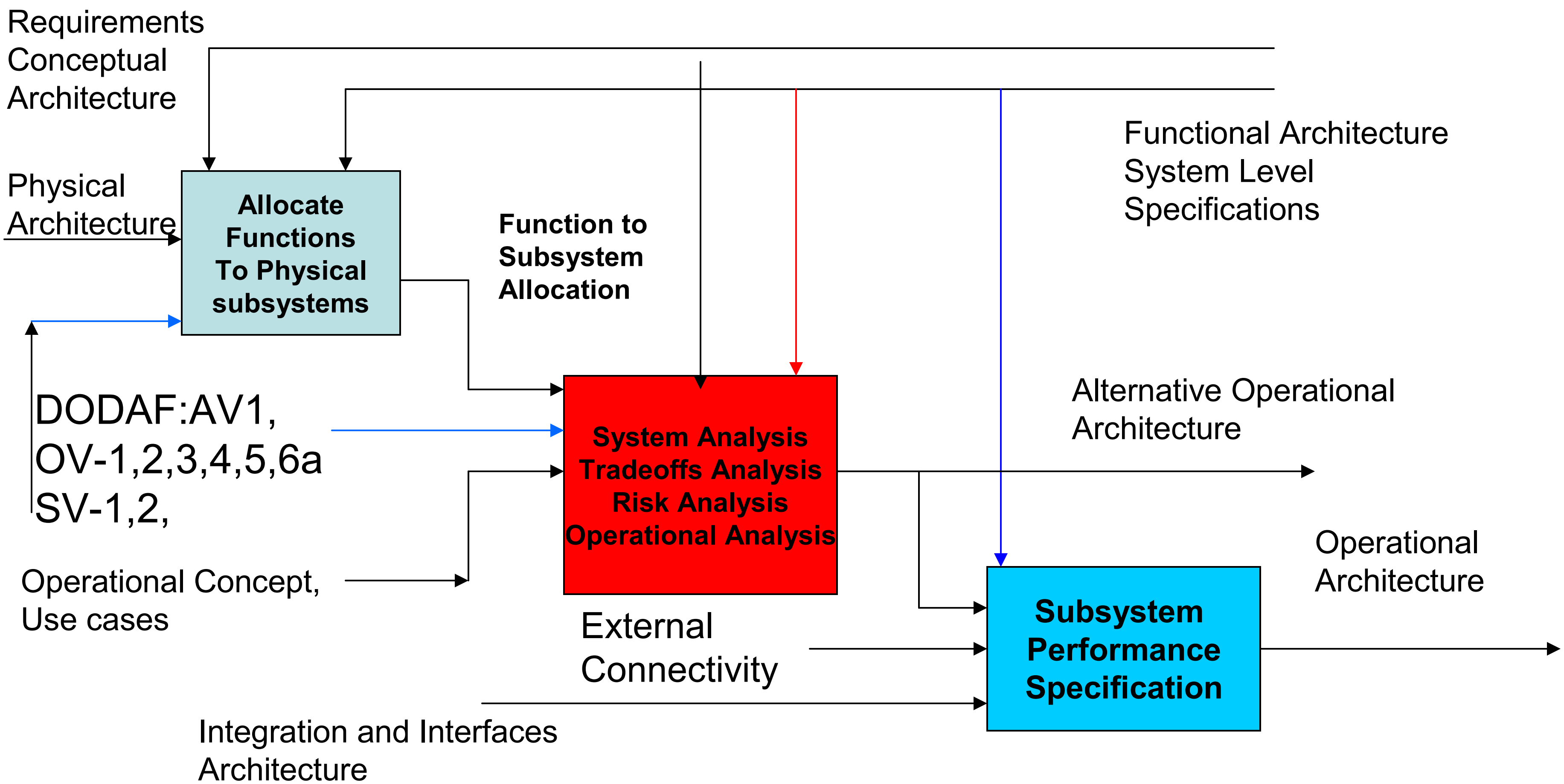


Series parallel Architecture

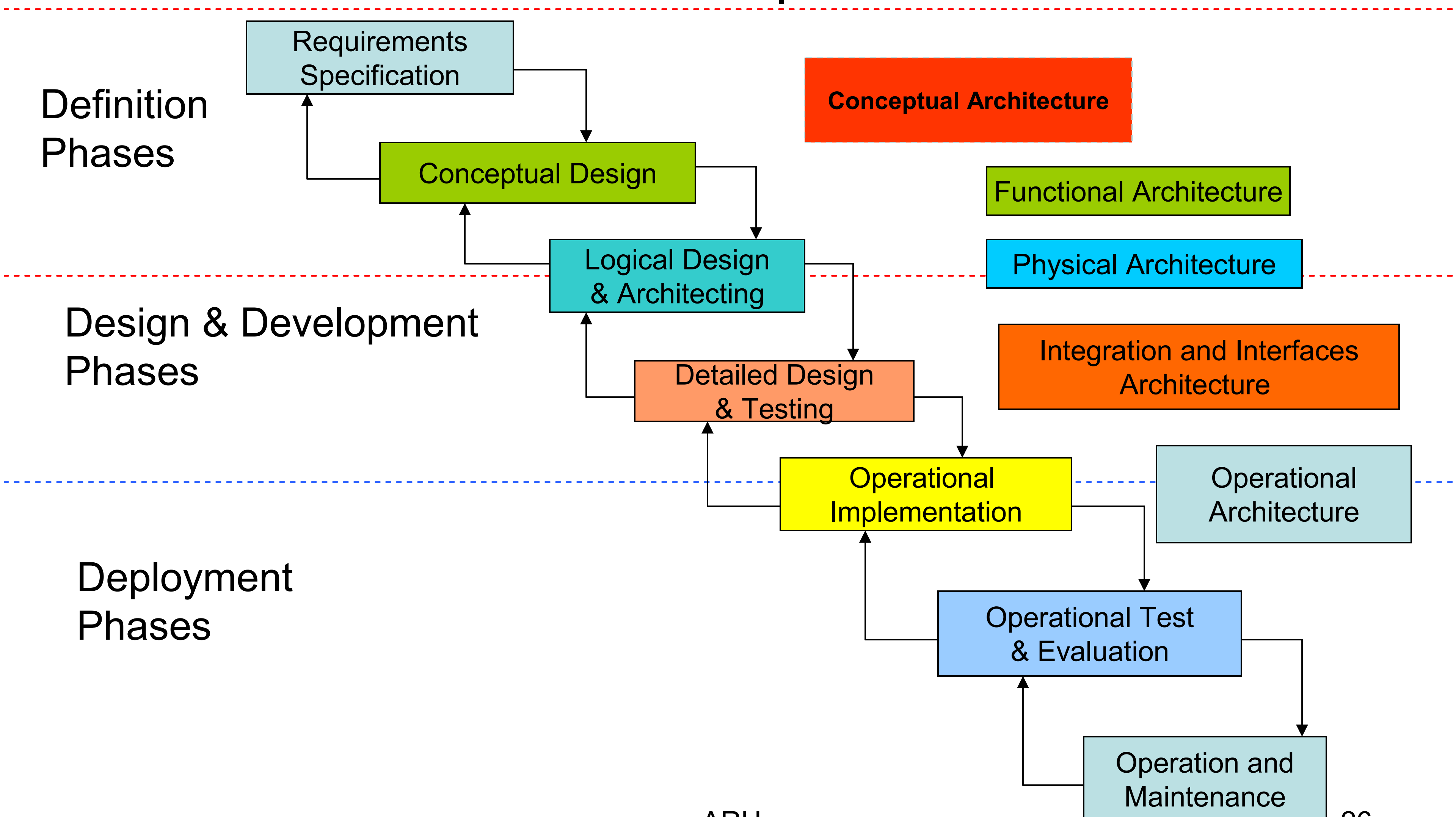
Development Process of Integration and Interfaces Architecture



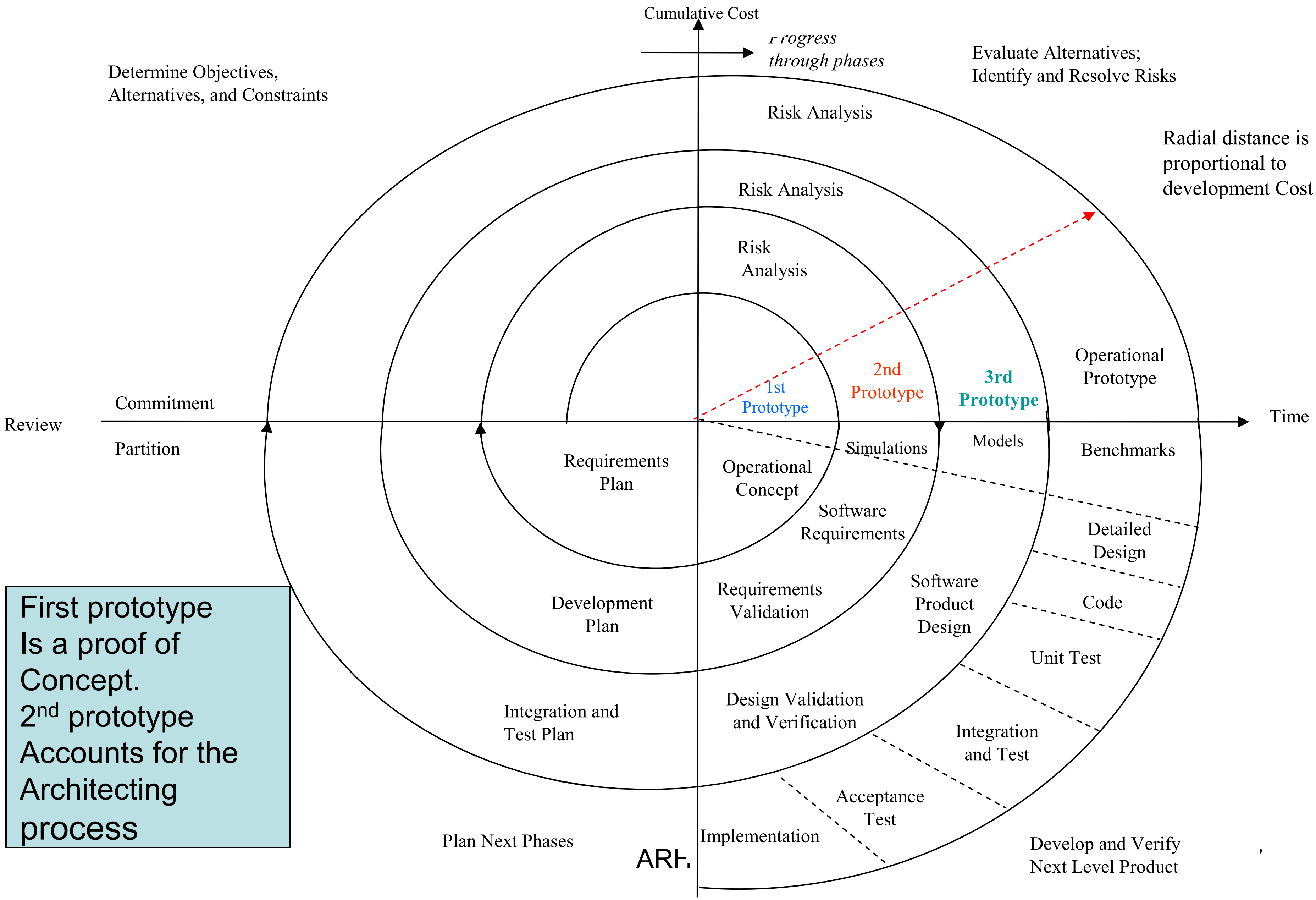
Development of Operational Architecture



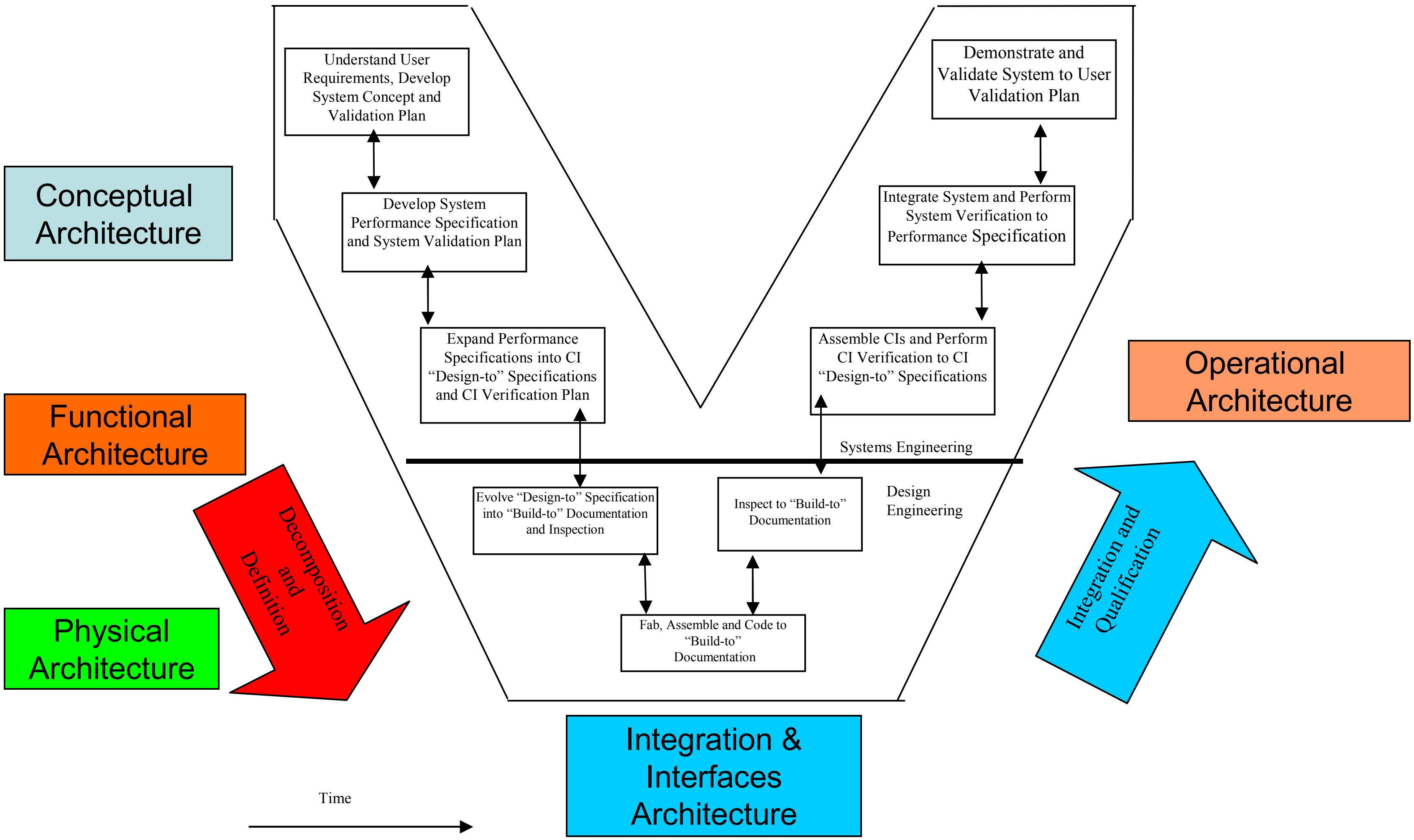
Systems Engineering Process
Seven Phases for Acquisition/Production



Spiral Model



Vee Model



CI-Configuration Item

Systems Engineering Interactive Model

System Definition

Requirements/Objectives
Requirements Analysis
Mission Analysis
System Performance
Preliminary Conceptual Design

Requirements Loop

System Development

- System Effectiveness Analysis
- MOEs, MOPs
- Functional Requirements
- Tradeoffs Analysis
- Technology Base
- System Design and Architecturing
- System Integration

Design Loop

System Deployment

- Detailed Design and Testing
- Transform System Architecture into Real World Entities: Functional and Physical
- System Design Specifications and Standards
- Operational Implementation
- Operational Test and Evaluation
- Operation and Maintenance

Conceptual Architecture

Functional Architecture

Physical Architecture

Integration &Interfaces Architecture

Operational Architecture

Software Architecture

- Software architecture deals with the design and implementation of the high-level structure of software.
- A model of five views called (4+1) is used to describe the software architecture:

  (1) Logical View,

  (2) Process View,

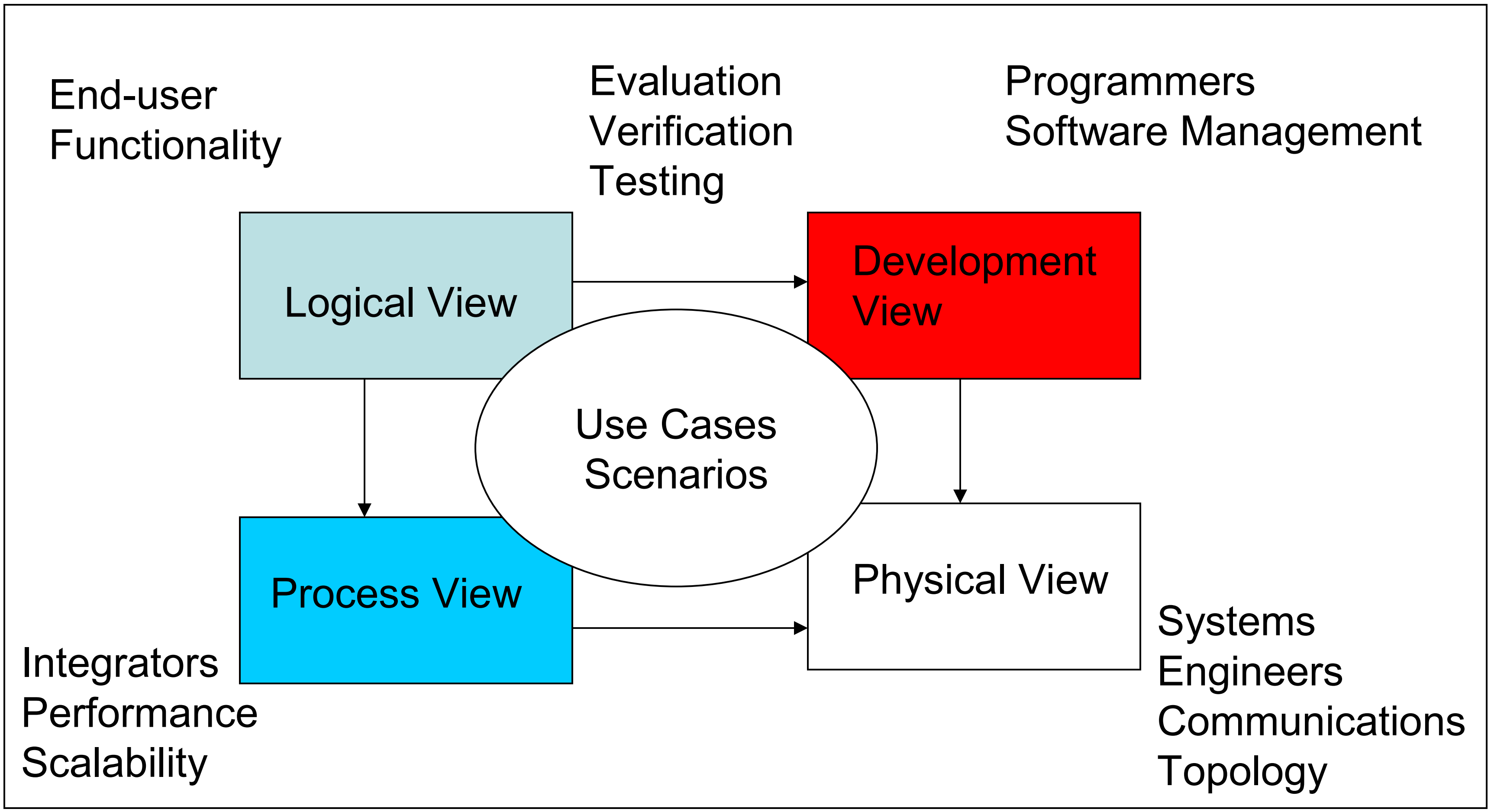
  (3) Development View,

  (4) Physical View

  (5) Use Case view

Software Architecture Model

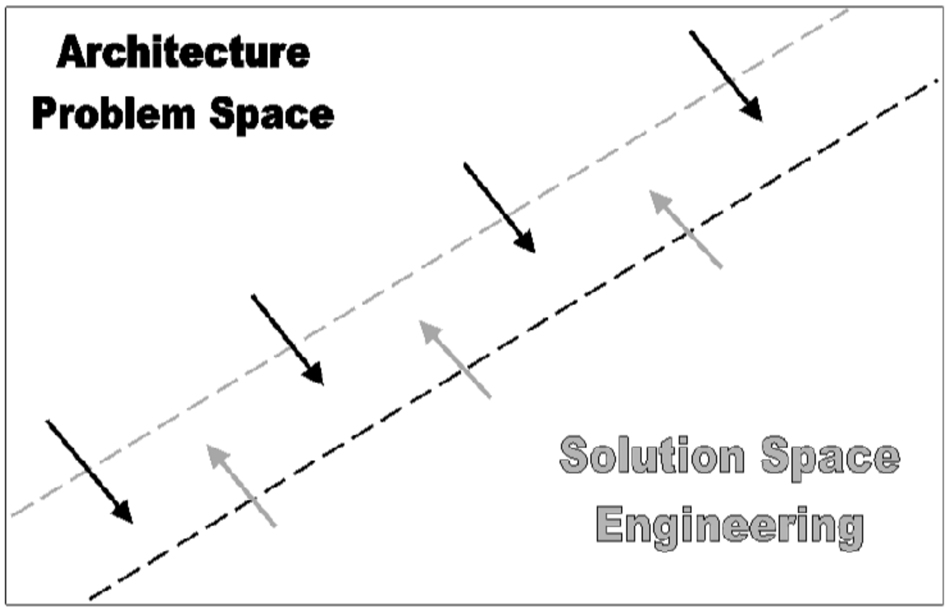
Four + One View Model



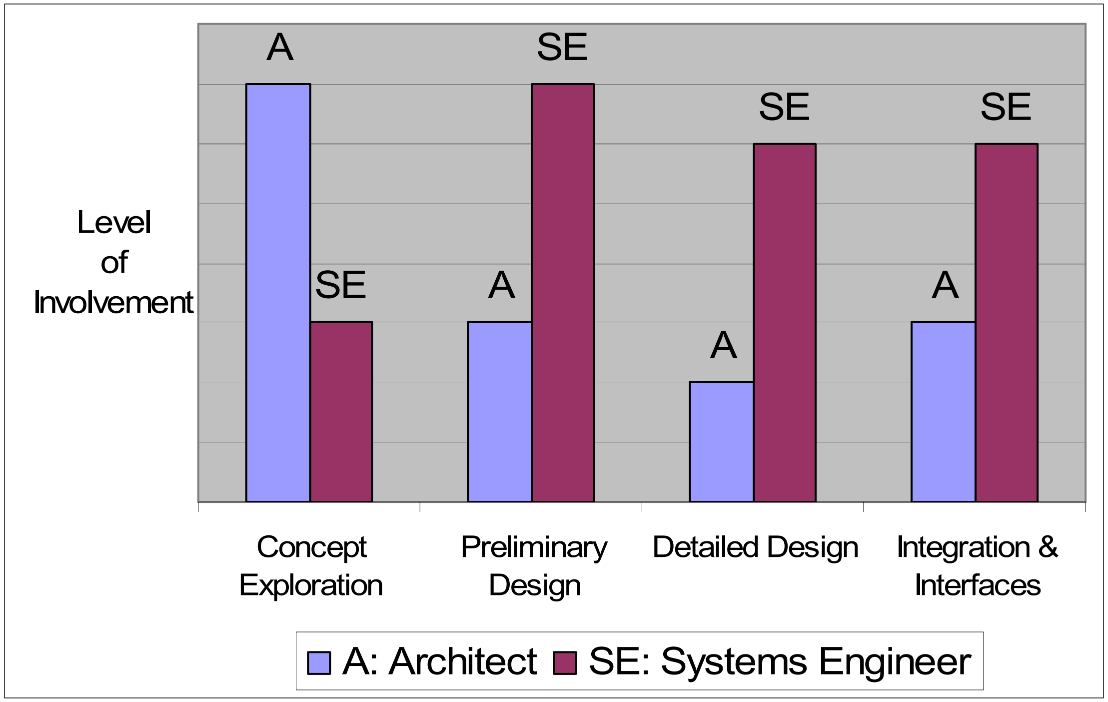
Merging Architecting Into the Systems Engineering Process

Partitioning Level	Software Architecture Views	Systems Engineering Process: 5Ds	System Architecture Views	DoDAF: C4ISR Views
System	**Logical Architecture**	**Definition Phase**	**Conceptual Architecture**	**ALL View**
Subsystem Cluster	Process Architecture	Design Phase	Functional Architecture	Operational View
Module	Development Architecture	Development Phase	Physical Architecture	Systems View
Function Block	Physical Architecture	Deployment Phase	Integration & Interfaces Arch.	Technical View
Subfunction	Use Cases Architecture	Disposal Phase	Operational Architecture	
Component Element				

Architect and Systems Engineer Spaces



Level of Architecting Involvement in the Systems Engineering Process



System Integration and Interfaces: Why is it important?

- System Integration is a critical part of the Systems Engineering Process, it brings the decompositions together.
- Interfaces are the keys to a successful Integration.
- The recognition and identification of Interfaces are very important in building responsive, robust, and Effective systems.
- Interfaces occur at the boundaries of the building Blocks of the system: functionally, physically, and operationally.
- The capability of recognizing and counting the interfaces will ensure the success of the architecting and engineering process.

The Binary Interfaces Model

- We build systems to give outcomes. System behavior is described by its outcomes.
- We will use a binary building blocks model to determine and count interfaces.
- Given a system whose functionality is achieved by integrating (merging) **n** = three building blocks: A, B, C.
- The number of possible outcomes is "$\mathbf{2^n}$"=$\mathbf{2^3}$= **8**.
- The outcomes are represented by:

(1) Events (Euler, or logical) Diagrams,

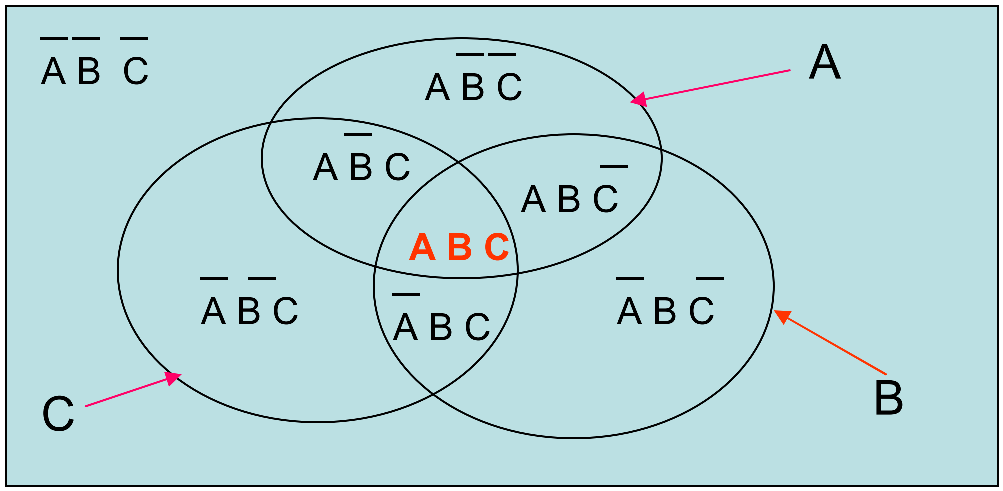
(2) Network (Decision tree),

(3) Truth table,

(4) Combinatorial mathematics.

Binary Model of Interfaces

- When the functionalities of A,B, and C merge new functions are created and are represented by the events (logic) diagram



Interfaces occur when two or more functionalities are merged, we call them mathematical intersections of order two or more. For this example:
There are three second order interfaces: $A\,B\,\bar{C}$, $A\,\bar{B}\,C$, $\bar{A}\,B\,C$

and a third order interface: A B C

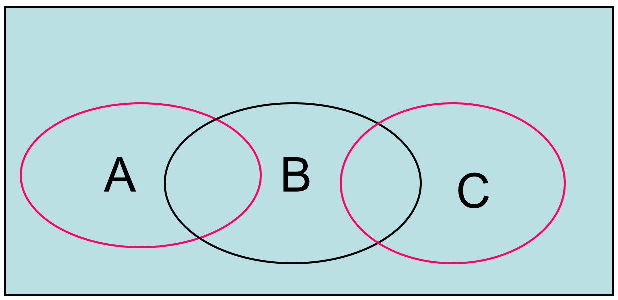
Subsumed Interfaces

- As we integrate systems not all interfaces are recognized and accounted for.
- The question is what happens when interfaces are subsumed?
- Subsumed interfaces are either absorbed by other interfaces, or they are neglected. This can happen when functionalities are not merged properly, poor coupling, low amplification, or by **organizational design**.
- The impact of subsumed interfaces is serious degradation in system effectiveness.

Logically Integrated System versus System with Subsumed Interfaces

The area of the function is proportional to its: **Design Limitation=1-Design Adequacy**

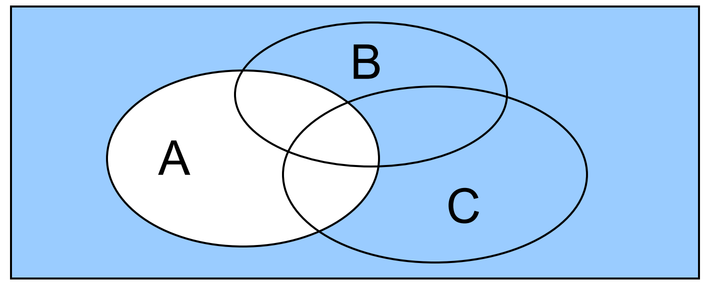
System S1: 2 Subsumed Interfaces



Design Limitation= A+B+C-AB-AC
Design Adequacy=1-A-B-C+AB+AC

A=B=C	Adequacy
0	1.0
.1	.72
.2	.48
.3	.28
.4	.12
.5	0
.7	0
1.0	0

System S2: Logically Integrated

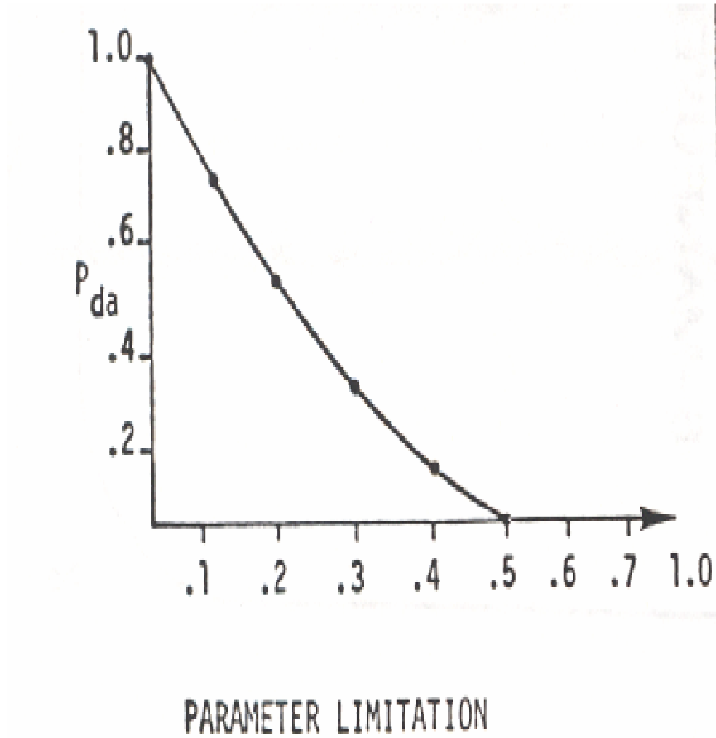


Design Limitation=A+B+C-AB-AC-BC+ABC
Design Adequacy=1-A-B-C+AB+AC+BC-ABC

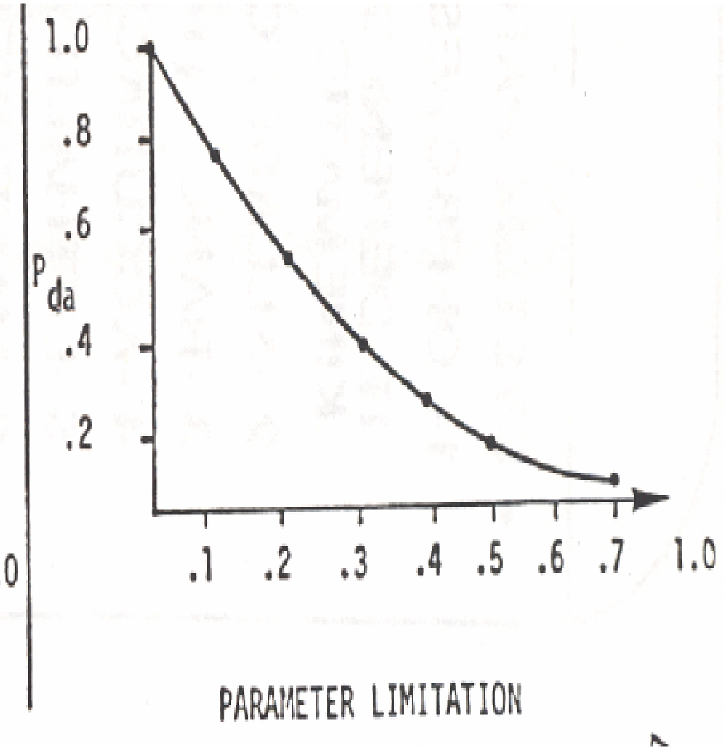
A=B=C	Adequacy
0	1.0
.1	.729
.2	.512
.3	.343
.4	.216
.5	.125
.7	.027
1.0	0

Comparing Two Systems

System S_1 with subsumed Interfaces



System S_2 Logically Integrated



Conclusion

• Architecting is a major contributor to the engineering of responsive systems. It strengthens the systems engineering process and provides critical insights into the stakeholder and user requirements.

• System architecture and software architecture should be congruent.

* Interfaces are the keystones of system integration.

* Merging the architecting, engineering, integration, and evaluation into the Systems Engineering process will provide a comprehensive and a balanced approach to deal with the complexity of building effective systems.

Architecture-Based Systems Engineering and Integration

Backup

Next Generation Systems

- Traditional Systems Engineering and Systems Acquisition are focused on Vertical (Stovepipe) System design.
- System acquisition have moved away from the traditional model to acquiring **Capabilities**.
- Next generation systems must be flexible, scalable, interoperable, and adaptable/agile. Therefore, the design of Future Systems should be based on "**Capability Building Blocks**"
- Current and Future Network Centric Operations requirements mandate Interoperability.
- Current and future systems are software intensive. Software is embedded into systems and intermingled within System-of-Systems.

** We need a comprehensive approach to build systems, whose architectures are compatible with the systems engineering process.

System Architecture Model

The system architecture model is the model of function and form that defines the physical structure, functional flow, interfaces, and the connectivity of the system

Architecture Implementation

- **Architecture Implementation Principles**
- Architecture framework
  - DoDAF
  - Zachman
- Implementation methodology of software
  - SOA
  - Data driven
  - Client/Server
  - Model driven architecture (MDA) using UML
  - Event driven architecture (EDA)
  - Component-based architecture
  - Aspect Driven Architecture
  - Domain Driven Architecture

Input/Output of System Design Activities During Architecting and Engineering

Design Activity	Input	Output
(1) Conceptual System Design	Stakeholders Needs & Concerns Operational Concept	Requirements Conceptual Architecture Concept of Operation
(2) Functional System Design	Requirements Conceptual Architecture	Functional Architecture System Level Specification
(3) Physical System Design	Requirements Conceptual/Functional Architecture	Physical Architecture System Level Specification Performance Specification
(4) Integration & Interfaces Subsystem, Module, Function Block	Functional & Physical Architecture Performance Specification	Integration & Interfaces Architecture Design Specification KPPs
(5) Operational System Design And Risk analysis	Requirements Functional Architecture Physical Architecture Interfaces	Operational Architecture Performance Specification Risk management
(6) Evaluation and Testing of system design	Integration &Interfaces & Operational Architecture;	Design Parameters Tradeoff &Feedback

Conceptual Architecture

- The conceptual architecture is a high level abstraction of the requirements.

  Virtual Simulation provides insights into the conceptual architecture.
- It is obtained by partitioning the requirements based on the stakeholders needs, concerns, and requirements.
- The conceptual architecture establishes the system/enterprise design requirements based on: Input/Output, Performance and cost tradeoffs, and mission analysis.
- Proof-of-concept experiments are used to support the Conceptual Architecture.

* In software engineering conceptual architecture can be derived from "use cases", scenarios, and activity diagrams.

Functional/Logical Architecture

- The **functional architecture** contains the system functions, configuration units, building blocks and components. It is represented by a directed network.
- It is a logical representation of what the system must do ?, it provides a decomposition of the system objective. Physics-based simulations give insights into the functional architecture
- A logical model of transforming inputs into outputs using control information-flow throughout the functional decomposition. It defines the functions and the data flows.
- It is derived using an IDEF0 model, FFBD, DFD, or “OO” UML methodology.

** Functions express activities, actions

*** Form follows function, Physical follows functional

*** Fit follows form which follows function: **Function, Form, Fit**

Functional Decomposition

- Several system features are used to partition a system into building blocks

(1) At the top level systems operate in modes. Modes lead to partition the system into subsystems.

(2) Each subsystem is partitioned into modules based on grouping of functions.

(3) Modules that have multiple inputs and outputs are partitioned by tracing the input to the output to establish the function.

(4) Partition each function block into subfunctions: Circuits/Applications.

(5) The lowest level of the functional architecture identifies devices and activities such as, transmit output, receive input, store output, format input, amplify input.

Relationship Among DODAF Views

The operational view provides the information exchanges, interoperability levels, and performance parameters required to support a mission or task

The systems view defines system attributes, and provides the basis for comparing system performance against operational requirements.

The technical view defines the standards to the implementation criteria for fielding an interoperable system.

The three views and their interrelationships are designed for deriving measures such as interoperability, performance and measuring the impact of these metrics on operational mission and task effectiveness

Many data elements of the products are used in more than one product and there are several mapping relationships between products.

Integration and Interfaces Architecture

- **Integration is a** bottom-up process of assembling the system from its components. Engineering-Based simulations and mockups provide **insights** into the integration and interfaces architecture.
- Integration is a hierarchical process. At the top level, it is the merging of subsystems functionally and physically. At the subsystem level it is the merging of modules functionally and structurally.
- Integration and Interfaces Architecture merges the functional, physical, and conceptual architectures.
- Interfaces are critical parts of the systems.
- Interoperability is based on system-to system interfaces; it is a major driver in architecting SoS& FoS.

Operational Architecture

- The operational architecture brings together through scenarios the requirements decomposition (conceptual architecture) with the **functional**, physical, and **integration and interfaces** architectures.

- Scenarios are used to develop the operational architecture. It identifies the system's internal and external interfaces, connectivity, and nodes.

- It provides sufficient details to evaluate system performance, performance tradeoff analysis, and risk analysis.

- Operational architecture describes the **mission, tasks, operational elements**, and information flows required to accomplish or support system functions

- It is concerned with interoperability and human interfaces. It defines and analyzes functional activation and control structure. Engineering-Based Simulation provides insights into the operational architecture.

Integration and Interfaces Architecture Continue

- Interfaces are connections for tying the system parts to each other, and creating new functions and nodes.
- There are internal interfaces of merging one system part to another. External interface is the connection of the system to another system- Interoperability.
- Integration and interfaces are united activities in building systems.
- Interfaces are the basic building blocks of the system integration process.
- There are several types of interfaces: Electrical, logical, physical, environmental, communications, thermal, social (human interfaces).
- Interfaces are the mathematical intersections of the interacting functions that create new functions, or activities.   .

Products of Architecture Views

- Each view is described by a set of products, e.g., graphics, diagrams, tables, scripts.
- Each product contains “data” that describes some aspect of the architecture, e.g., functionality, structure, connectivity.

Issues:

(1) Are the products consistent?

(2) What are the relationships among the products?

(3) Does the group of products contain all the information that define an architecture?

Products of Architecting

- Architecting is a key upfront activity and is strongly tied to the customer and user (stakeholder).
- Architecting is a major part of the definition and design phase of the Systems Engineering Process
- **Architecting Products To Systems Engineering**

(1)Provide visualization of needed capability based on requirements

(2)System Conceptualization and Innovation

(3)Interfacing with stakeholders

(4)Provide Architecture Framework: DODAF

(5)Generate and balance operational views and systems views

(6)Identify Standards

(7)Provide capabilities road-map

(8)System partitioning: functional, Physical, Logical, and Operational

(9)Define System boundaries

(10)Identify tradeoffs space: Cost, Capability, Support, Reliability, availability, and Risk

(11)Identification of interfaces (external and internal)

(12)Modeling/operation analysis

Products of Systems Engineering

System Definition, Design, Development/Production, Deployment, and Disposal.

(1)Visualization of what a system should look like: Engineering the System

(2)Tradeoff studies – AOA - CE, CB, Risk

(3)Requirements decomposition/Functional Decomposition, traceability

(4)System and design specification, and Configuration Management

(5)Detailed system analysis and identification of capability drivers

(6)Detailed system partitioning

(7)Detailed System integration and interfaces; codesign issues

(8)System Acquisition

(9)Resource allocation (scope)

(10)Integrated Logistics Support (ILS)

(11)Select metrics: MOEs, MOPs

(12)Data exchange and collaboration

(13)Test and Evaluation Plan

(14) Management of the Systems Engineering Process

Systems Engineering Attributes

- Systems Engineering is the integrating mechanism across the technical efforts related to the design, development, acquisition, integration, manufacturing, verification, deployment, operations, support, disposal, and user training of systems and their life cycle processes.
- Systems Engineering develops technical information to support the program management decision-making process in meeting: Cost, Schedule, Performance and Risk.

"ALL Views" Two Views

Framework View	Product Name	General Description
AV-1	Overview and Summary Information	Purpose, scope, stakeholders, user, environment description, analytical assessment
AV-2	Integrated Dictionary	Data repository with definitions of terms used in all products

Operational View
Nine Views

Framework Product	Product Name	General Description
OV-1	Graphic high Level Operational Concept	**High-level graphical & textual description of operational concept**
OV-2	Operational node Connectivity Description	Operational nodes, operational activities at each node, connectivity and information exchange need-lines between nodes
OV-3	Operational Information Exchange Matrix	Information exchanged between nodes, and the relevant attributes of that exchange
OV-4	Organizational Relationship Chart	Operational role, or other relationships among organizations
OV-5	Operational Activity Model	Capabilities, operational activities, relationships among activities, inputs, and outputs. May show cost.
OV-6a	Operational Rules Model	Describes sequence and timing of operational activities - identifies business rules that constrain operation
OV-6b	Operational State Transition Description	Describes sequence and timing of operational activities identifies business process response to events
OV-6c	Operational Event Trace Description	Describes sequence and timing of operational activities traces actions in a scenario or sequence of events
OV-7	Logical Data Model	Data requirements documentation and structural business process rules of the Operational View

Systems View
Seven Views

Framework Product	Product Name	General Description
SV-1	Systems Interface Description	Identification of systems nodes, systems, items, and their interconnections within and between nodes
SV-2	Description of Systems Communications	Systems nodes, systems, and system items and their related communications lay-downs
SV-3	Systems-Systems Matrix	Relationships among systems, system-type interfaces Planned vs. existing interfaces
SV-4	Systems Functionality Description	Systems Functions and data flow among them
SV-5	Operational Activity to Systems Function Traceability Matrix	Mapping systems to capabilities, functions and Operational activities
SV-6	Systems Data Exchange Matrix	Systems data elements exchanged between systems and the attributes of that exchange
SV-7	Systems Performance Parameters Matrix	Performance characteristics of elements for a given timeframes)

Systems View
Six Views

Framework Product	View Name	General Description
SV-8	Systems Evolution Description	Planned migration of systems to more efficient suite, or Evolving a current system to future implementation
SV-9	Systems Technology Forecast	Time table of emerging software & hardware products Technologies and that will impact future architecture
SV-10a	Systems Rules Model	Describes systems functionality constraints due to some aspect of systems design or implementation
SV-10b	Systems State Transition Description	Describes systems functionality: identifies responses of a system to events
SV-10c	Systems Events Trace Description	Describes systems functionality: identifies system changes due to critical sequences of events of the Operational View
SV-11	Physical Schema	Physical implementation of the Logical Data Model entities: message formats, file structure, physical schema

Technical Standards View Products
Two Products

Framework Product	Product Name	General Description
TV-1	Technical Standards Profile	Listing of standards that apply to System View elements in a given architecture
TV-2	Technical Standards Forecast	Description of emerging standards and potential impact on current System View Elements within a set of timeframes

Tailoring the Views

- Not all software architectures need all five views. Not relevant views can be omitted from the architecture description. For example, the physical view can be omitted if there is only one processor, also, the process view can be omitted if there is only one program. For very small system it is possible to merge the logical with the development view.
- Similarly, in the DODAF not all views are essential. In general, AV-1,AV-2, Ov-1,OV-2,OV-3, SV-1, and SV-4 are essential. The remaining products are supporting views.

Logical Software Architecture & Process Software Architecture

- The Logical Architecture supports the functional requirements; it describes the “Object Oriented” system decomposition using: Class, Collaboration diagrams and the sequence diagram.

- The Process Architecture gives Process partitioning into Tasks; it describes how processes communicate and interact. It accounts for the nonfunctional attributes: performance, availability, reliability, security, and scalability. Activity diagrams are used to describe this view

Development Software Architecture

- The Development Architecture describes the actual software modules of the system and its interaction with the environment. Packages, subsystems, and class libraries are considered modules.
- The Development view gives the layers of the system:

  (1) User Interface layer,

  (2) Presentation layer,

  (3) Application Logic,

  (4) Business Logic.

* The Development Architecture is given by module and subsystem diagrams.

Physical Software Architecture

- The Physical Architecture is a mapping of Software onto the Hardware. It describes how the applications are installed into the hardware, and how it executes in a network environment. It takes into account the non-functional requirements of the system: reliability, performance, availability, reuse, scalability. Deployment diagrams are used to represent the Physical Architecture.

The "Plus One" View
Use Case Architecture

- The Use Case View is putting it all together. The elements in the four views are shown to work together by using a set of scenarios. The scenarios are abstractions of the most important functionalities (requirements). Scenarios are expressed by using Objects and Interaction diagrams

General formula of Interfaces

The total number of interfaces: $(2^{n} – n – 1)$

The number of second order interfaces: $C^{n}_{2} = \frac{n!}{(n-2)!\ 2!}$

The number of third order interfaces : $C^{n}_{3} = \frac{n!}{n(-3)!\ 3!}$

The total number of possible outcomes:

$$2^{n} = \sum_{m=0}^{n} C^{n}_{m}$$

** A System that contains all intersections is called Logically Integrated