AARHUS
UNIVERSITET

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TISYE1 – Lecture 1

Systems Thinking and Systems Engineering Practice

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Plan for the Lecture

› Introduction to systems engineering

› Motivation: Why it is important?

› Systems of systems and hierarchy within a system

› System engineering processes and life-cycles
› The ”Vee”-model

Engineering – a Definition

› The process of creating or inventing a system component, or process to meet desired needs.

› It is a decision-making process (often iterative) in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective.

ABET

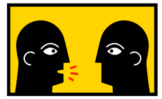
› Accreditation Board for Engineering and Technology

INCOSE: Systems Engineering

- Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems.

- It focuses on defining customers needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.

INCOSE
International Council on Systems Engineering



System Engineering

- SE integrates all the disciplines and specialty group into a team effort forming a structured development process that proceeds from concept to production to operation.

- SE considers both the business and the technical needs of all customers with the goal of providing quality product that meets the user need.

- SE facilitates the solution of complex problems by using a wide range of activities, tools, people in order to provide a system which delivers fulfilled needs to customers.

- What distinguishes engineering from systems engineering?

SE as a Career Path

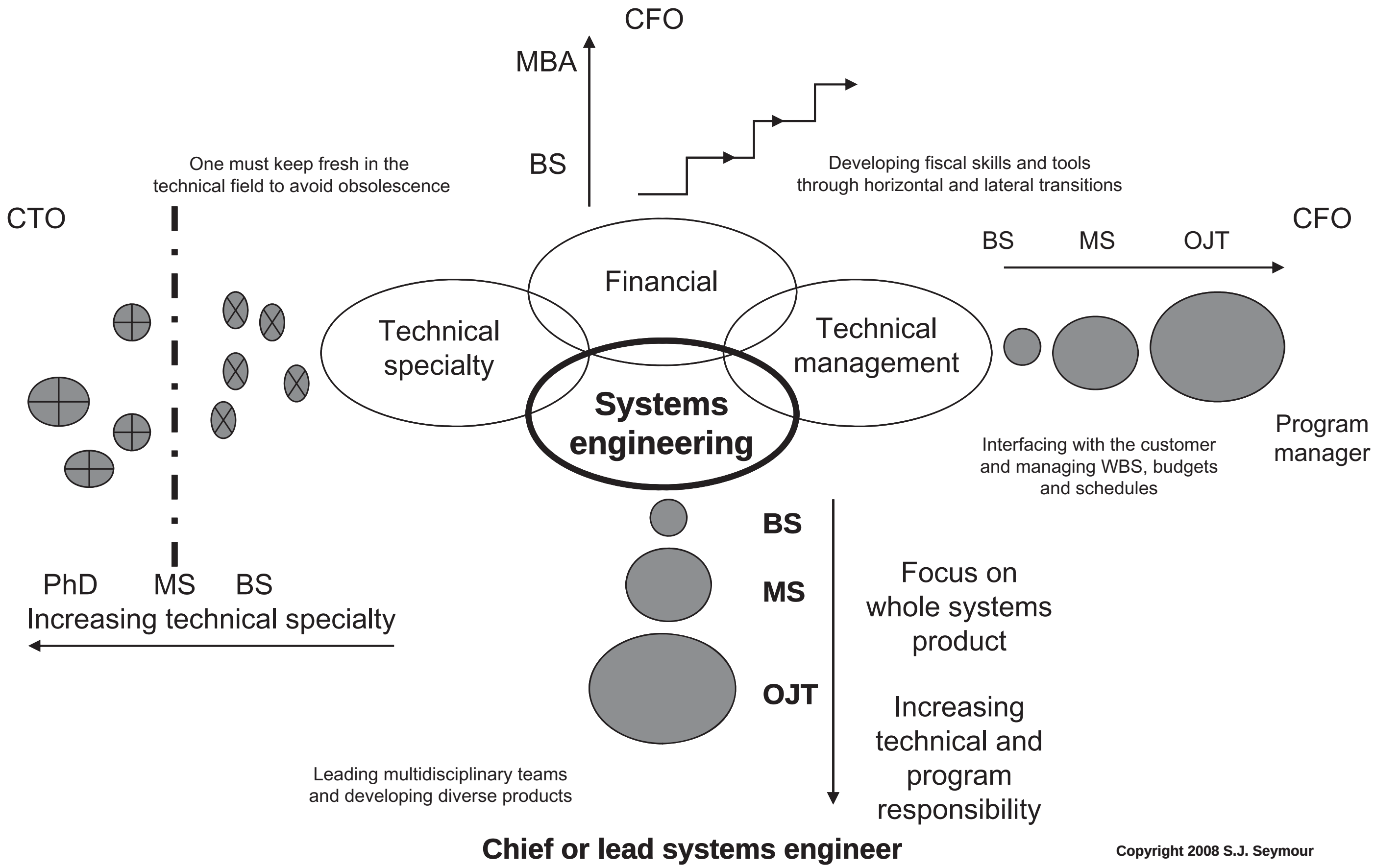


Figure 1.1. Career opportunities and growth.

› Kossiakoff, Sweet, Seymour, Biemer, Systems Engineering Principles and Practices, Wiley 2011

Definition of a System

- A combination of interacting elements organized to achieve one or more stated purposes

- An integrated set of elements, subsystems, or assemblies that accomplish a defined objective.

- These elements include products (mechanics, hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements.

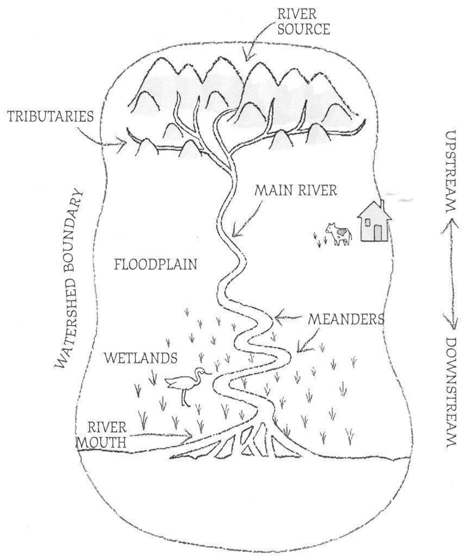
The Elements of a System

- Systems are composed of components, attributes, and relationships. These are described as follows:
- Components are the parts of a system
- Attributes are the properties (characteristics, configuration, qualities, powers, constraints and states)
- Relationships between pairs of linked components are the result of engineering the attributes of both components
  so that the pairs operates together effectively in contributing to the system's purpose(s)

- Systems can be modelled from models of its elements.

Which of These are Systems?

› What are their purpose; the main components; attributes and relationships?



Complexity and Systems

- Must be configured in such way that each major function is embodied in a separate component that can be specified, developed, built and tested as a an individual entity.

- The convenience of subdividing complex system into individual building blocks has a price…
- … that of integrating these disparate parts into an efficient, smoothly operating system
- Inter-component boundaries: Interfaces
- Functional relationships: Interactions
- Involves several engineering as well as other disciplines in its design.

- The task of analysing, specifying, and validating the component interfaces with the external environment is the province of the systems engineer.

Knowledge Domains

› Knowledge domains of the systems engineer and the design specialists

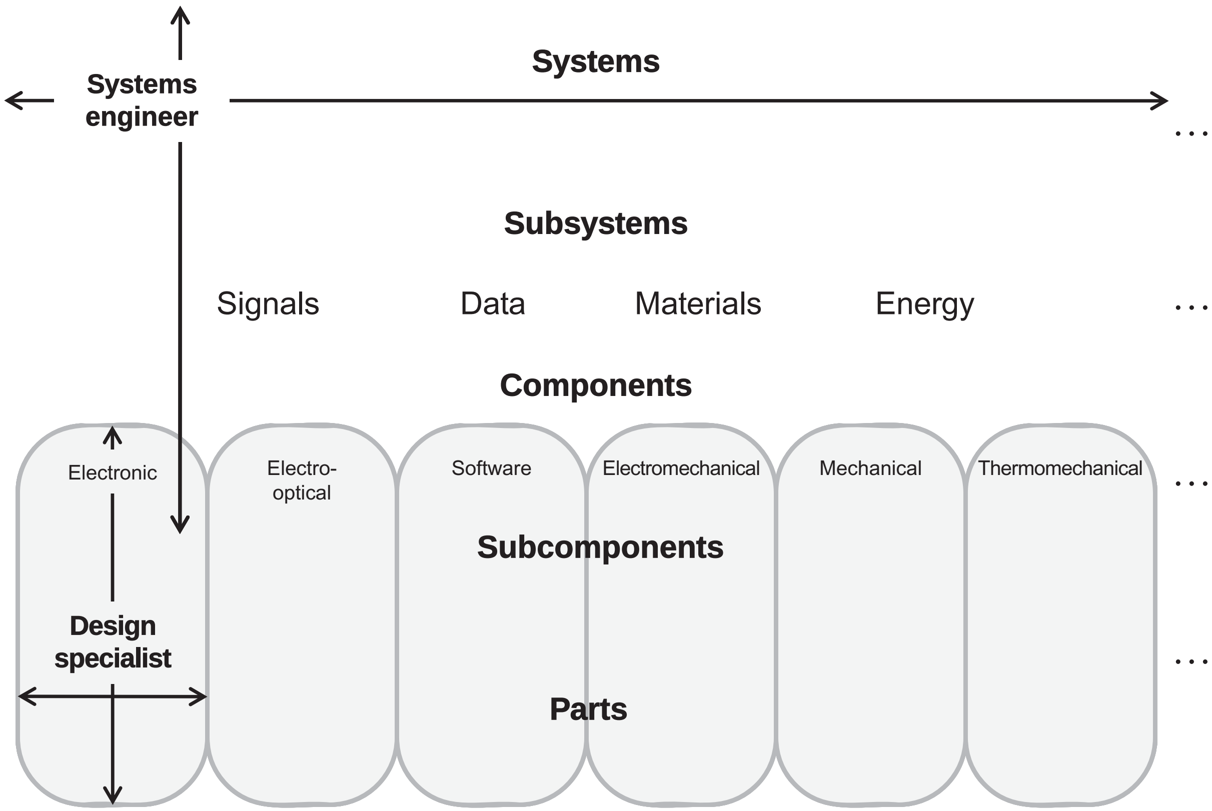


Figure 3.1. Knowledge domains of the systems engineer and the design specialist.

Systems, subsystems, components, …

TABLE 3.1. System Design Hierarchy

Systems					
Communications systems		Information systems	Material processing systems		Aerospace systems
Subsystems					
Signal networks		Databases	Material preparation		Engines
Components					
Signal receivers	Data displays	Database programs	Power transfer	Material reactors	Thrust generators
Subcomponents					
Signal amplifiers	Cathode ray tubes	Library utilities	Gear trains	Reactive valves	Rocket nozzles
Parts					
Transformer	LED	Algorithms	Gears	Couplings	Seals

Building Blocks

- **Functional blocks**
- Information
  - Signal
  - Data
- Materials
- Energy

- **Physical blocks**
- Electronics
- Electro-optics
- Electromechanical
- Mechanical
- Thermomechanical
- Software

Modularity

› Modularity is a measure of the degree of mutual independence of the individual system components.

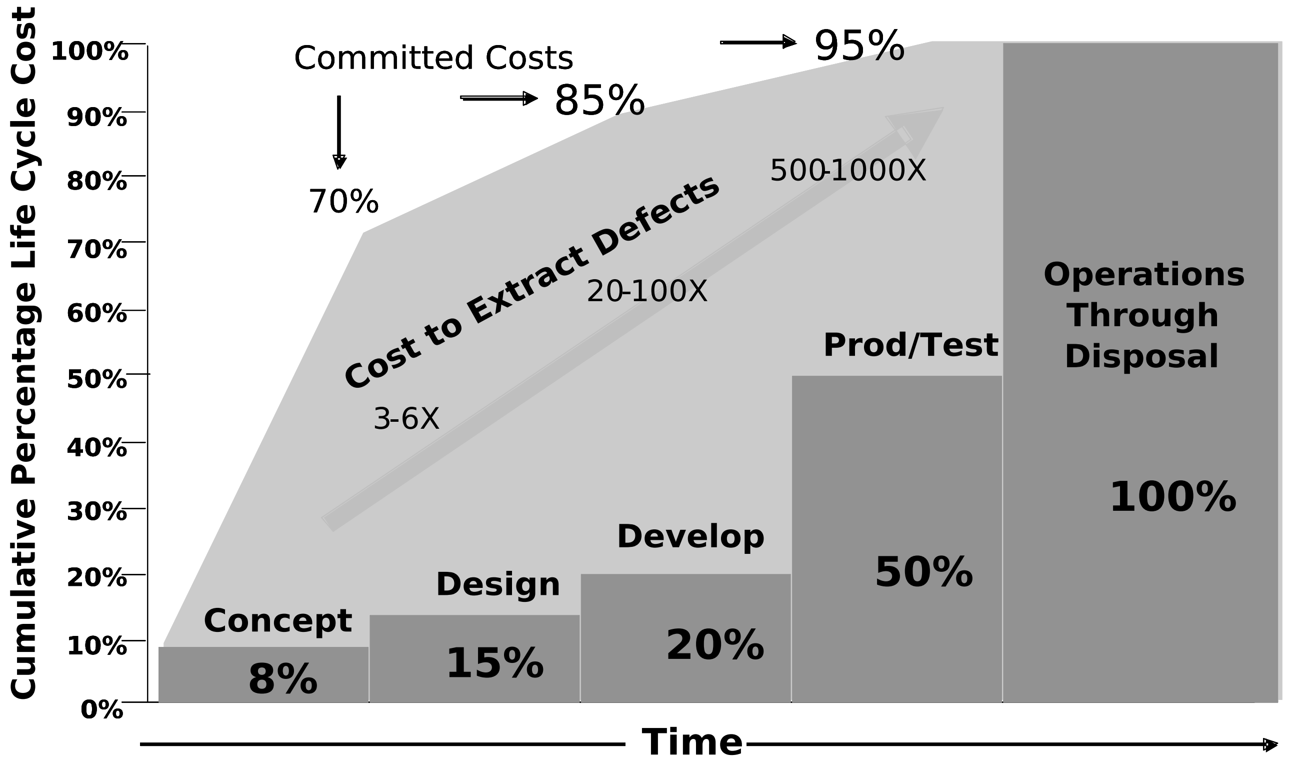
› Example: Car engine

Picture: wikipedia (Ford Modular engine)

Why Systems Engineering?

- It is an effective way to manage complexity and change.
- It minimises the risk associated with early business decisions.
- It reduces the time from prototype to (significant) market penetration.

Committed Life-Cycle Cost

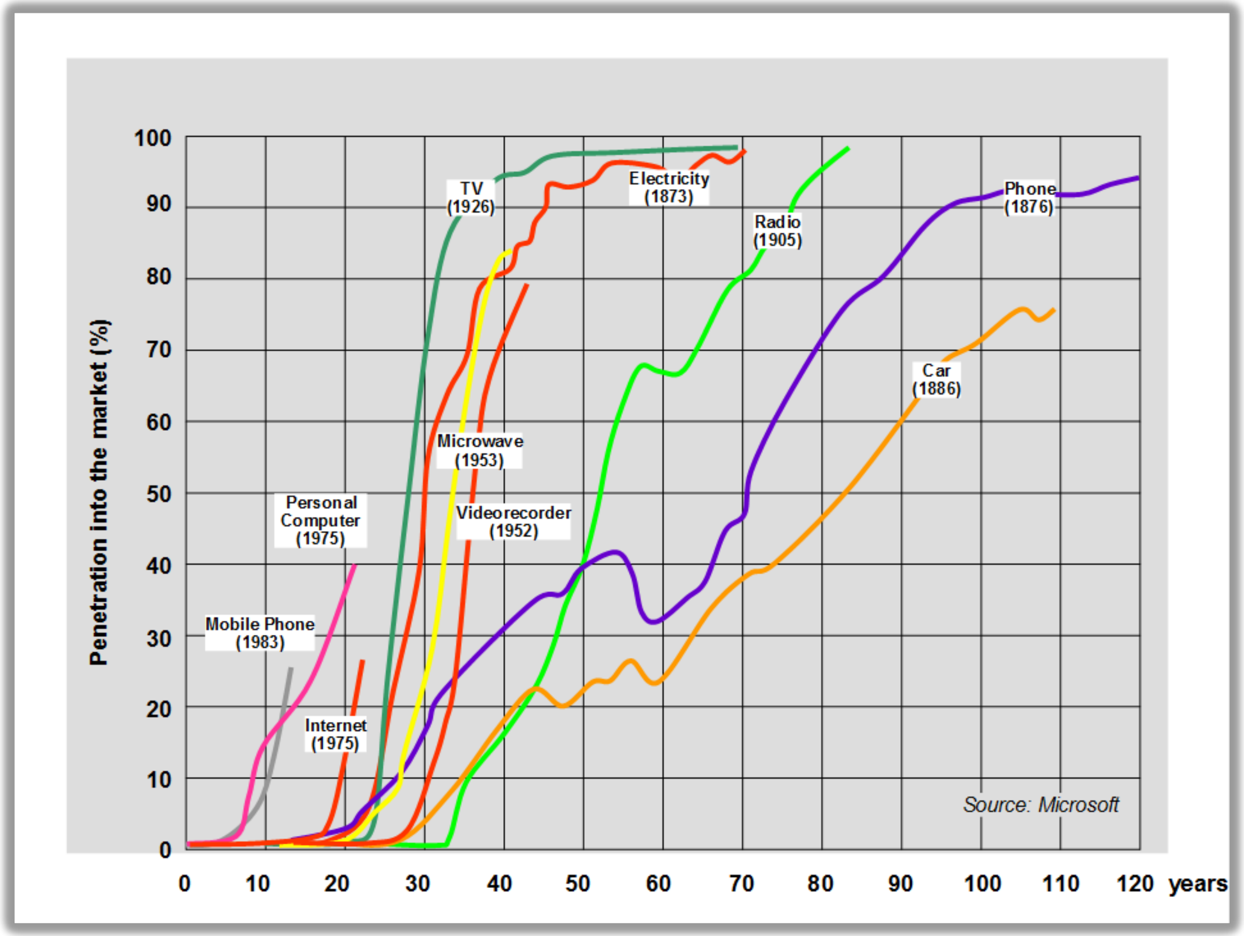


› Systems engineering emerged as an effective way to manage complexity and change.

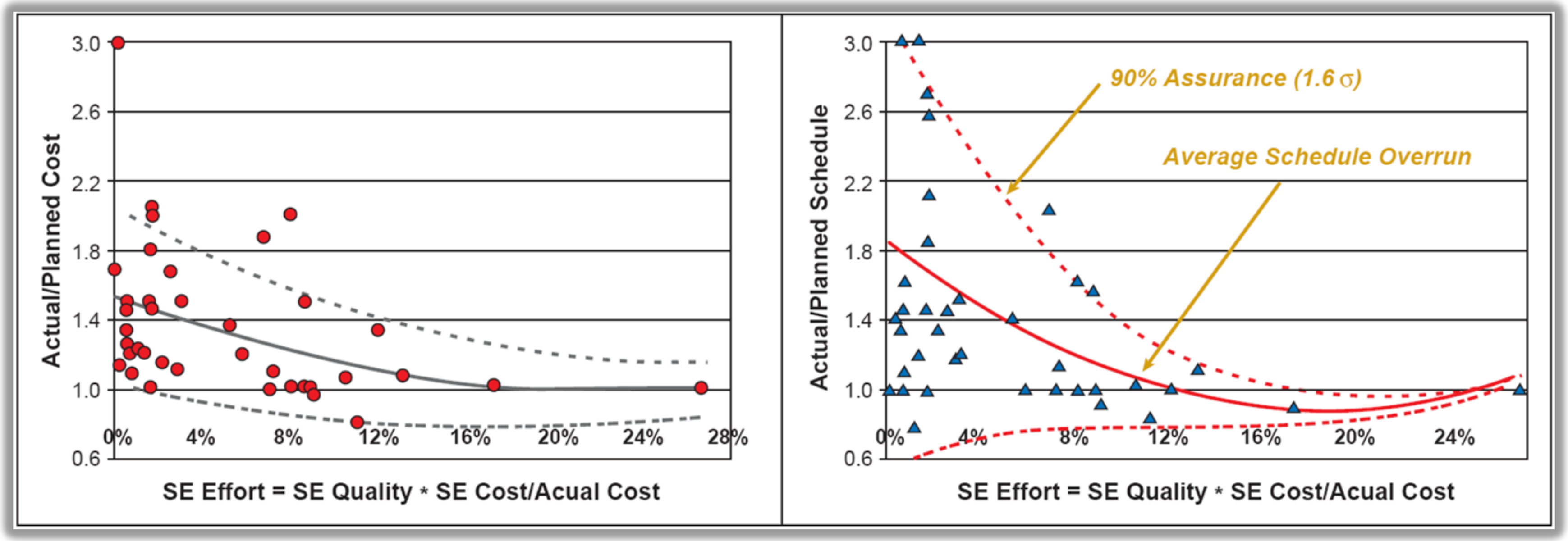
› Reducing the risk associated with new systems or modifications to complex systems continues to be primary goal of the systems engineer.

Market Penetration

› From prototype to market penetration



Value of Systems Engineering



- Cost and schedule overruns correlated with systems engineering effort
- Cost and schedule overruns decreases with increasing systems engineering effort.
- Variance in the cost and schedule overruns also decrease with increasing systems engineering effort.

Performance vs Cost

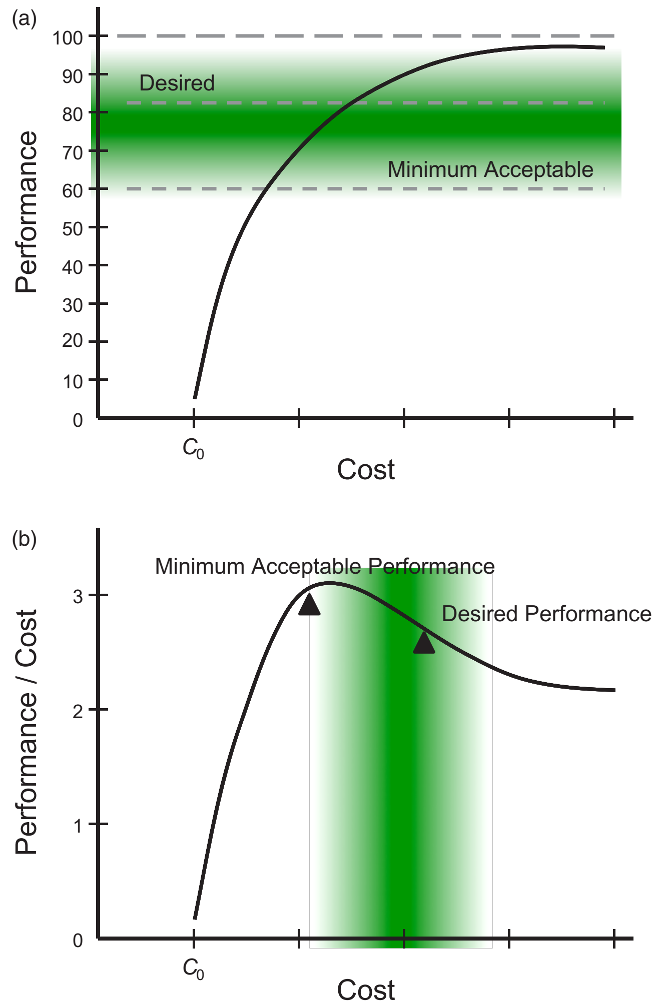


Figure 2.1. (a) Performance versus cost. (b) Performance/cost versus cost.

Systems of Systems (SoS)

- System-of-interest: the system whose life-cycle is under consideration (INCOSE).

- SoS are systems-of-interest whose system elements are themselves system.

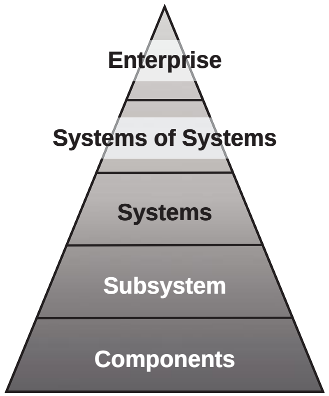
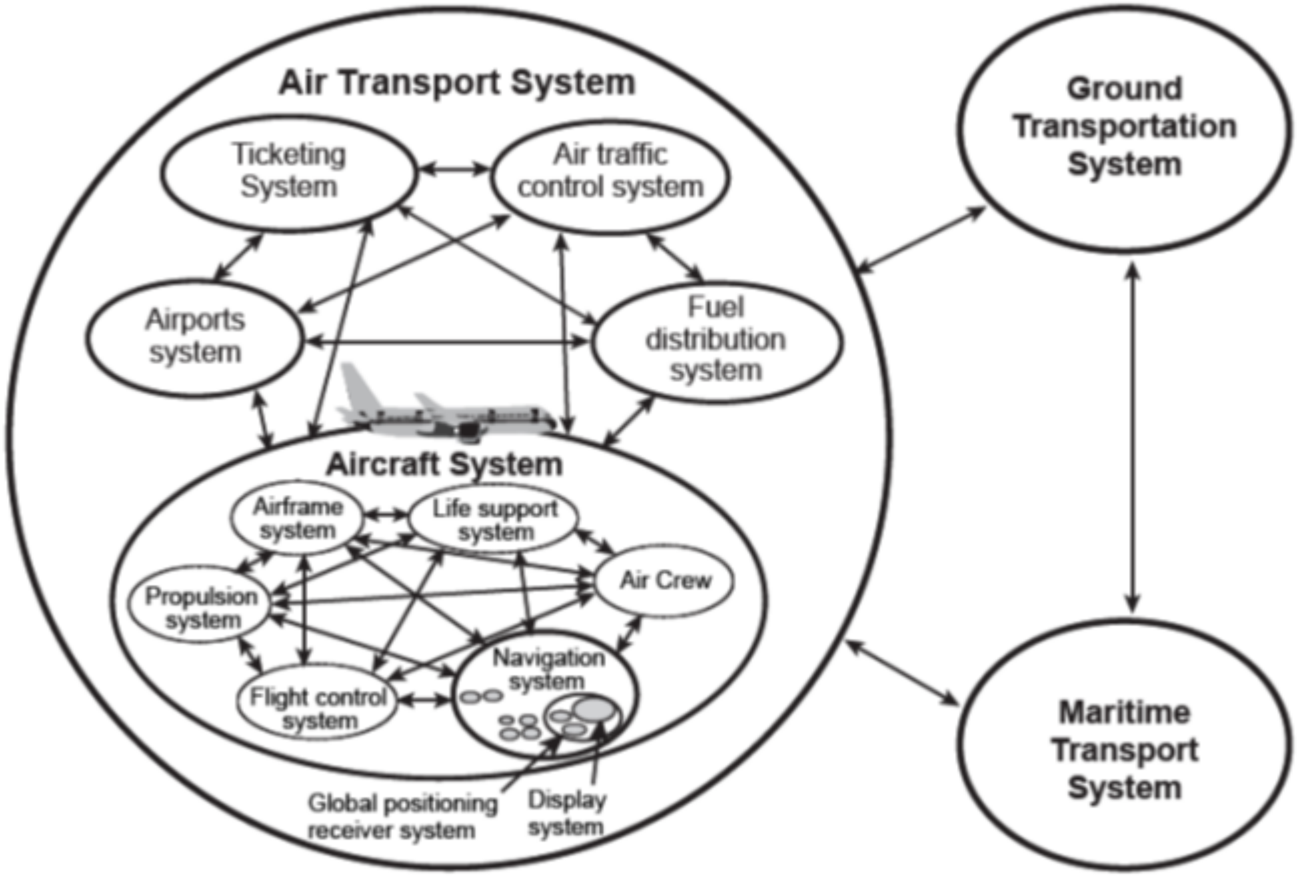


Figure 3.6. Pyramid of system hierarchy.

- SoS are defined as an interoperating collection of constituent systems that produce results unachievable by the individual systems alone.

Transport System-of-Systems

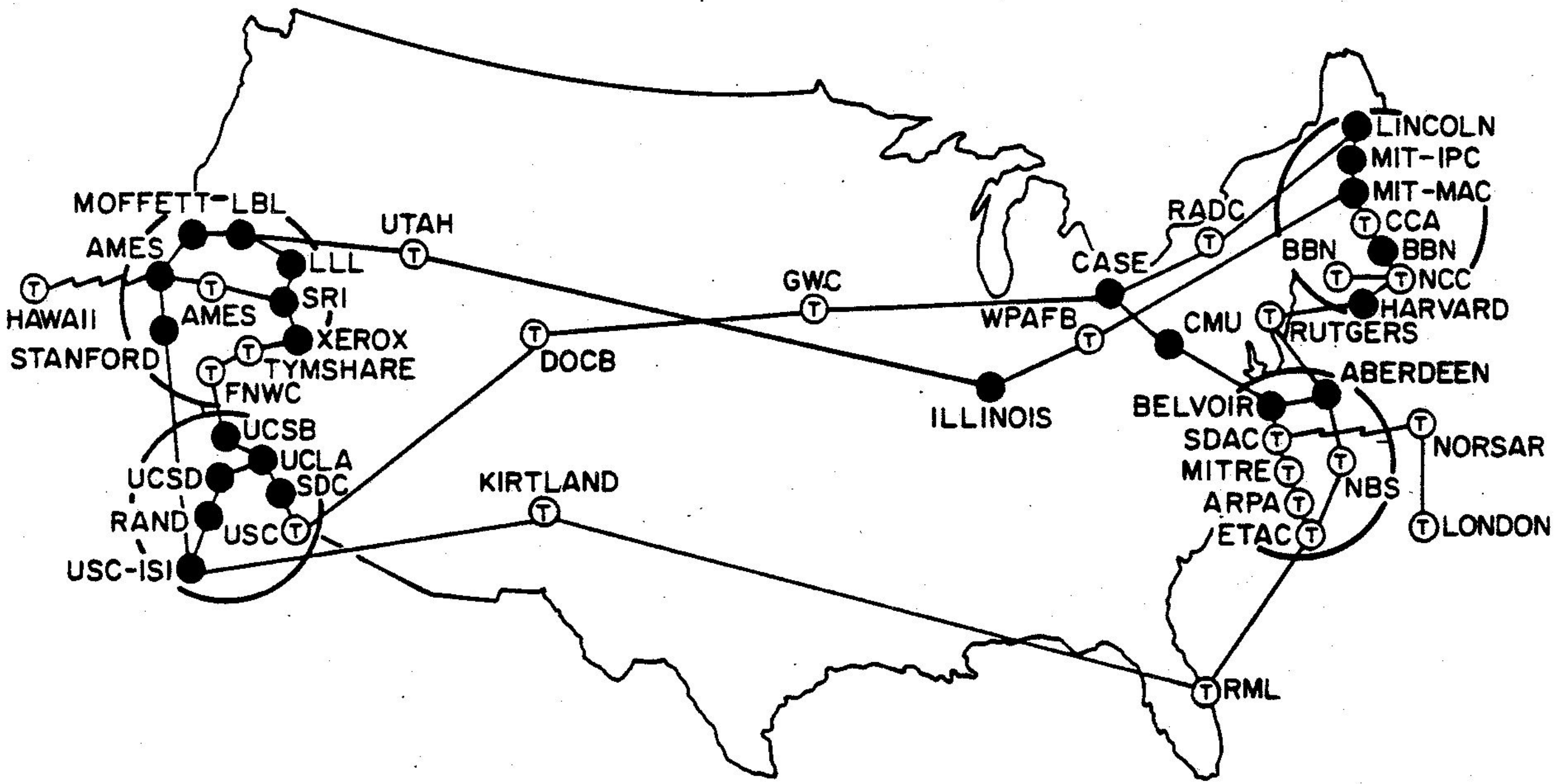


SoS Challenges

- System elements operate independently
- System elements have different life-cycles
- The initial requirements are likely to be ambiguous
- Complexity is a major issue
- Management can overshadow engineering
- SoS engineering is never finished

ARPANET – 1974

› Example of a networked communication system



› How could we describe ARPANET as a System of Systems?

Context Diagram

› Analysing the system boundaries

› Components pass around:
› Data
› Materials
› Activity
› Energy
› Signals

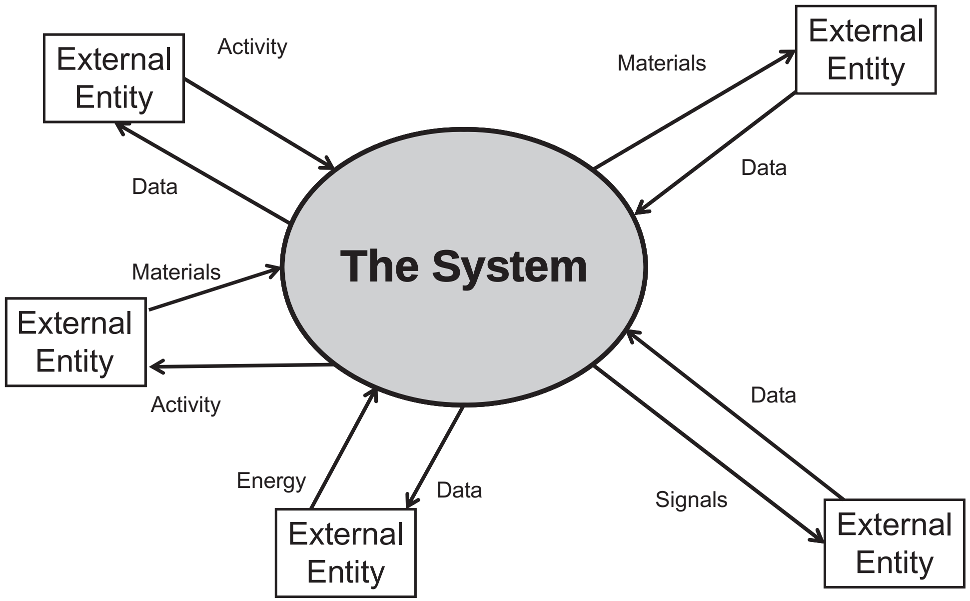


Figure 3.2. Context diagram.

Context Diagram Example

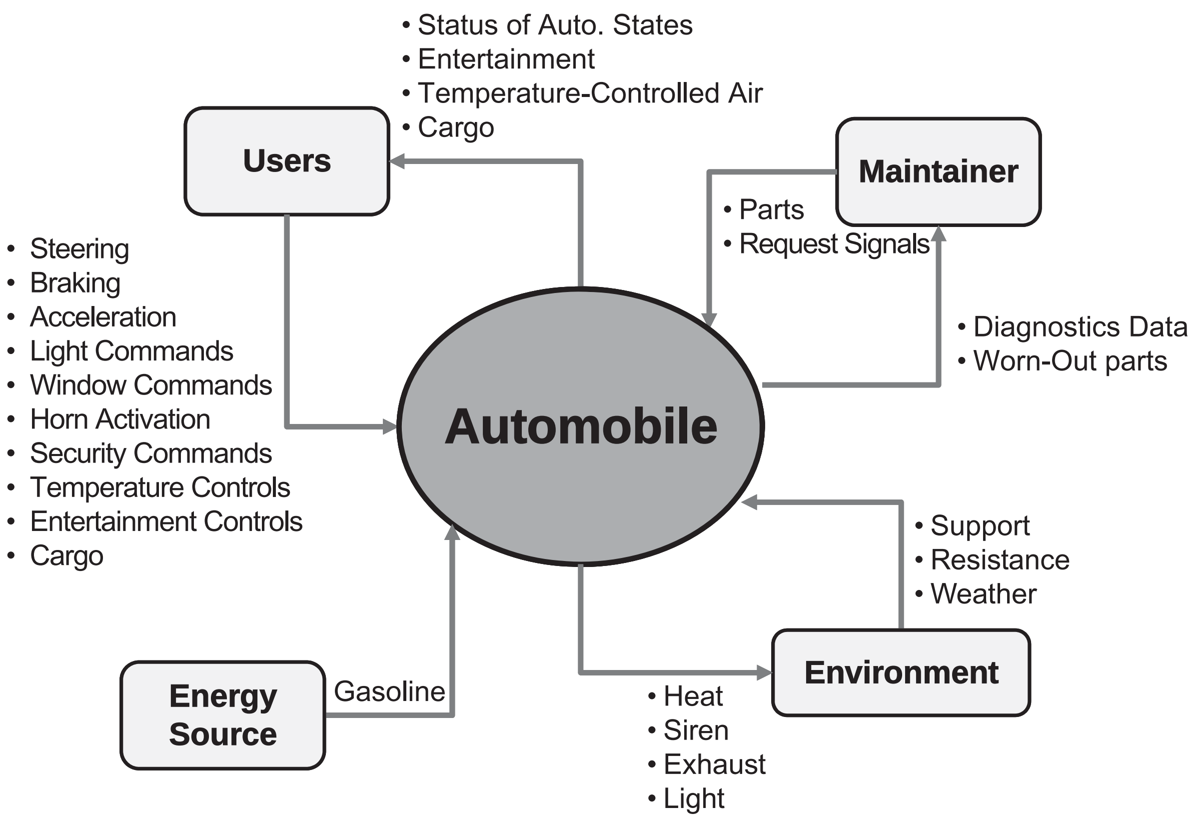


Figure 3.3. Context diagram for an automobile.

Environments

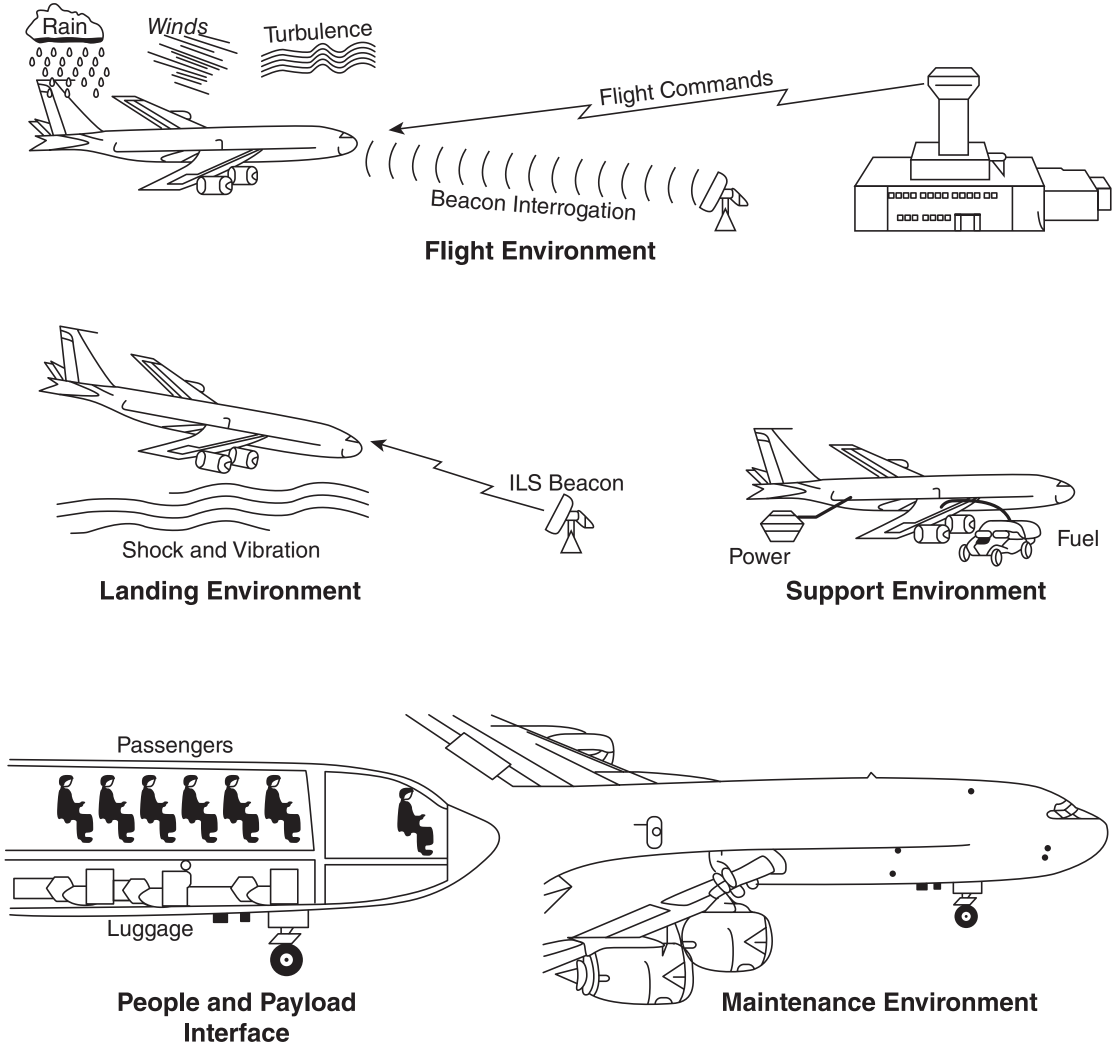


Figure 3.4. Environments of a passenger airliner. ILS, instrument landing system.

Interactions

› Functional interfaces and physical interactions.

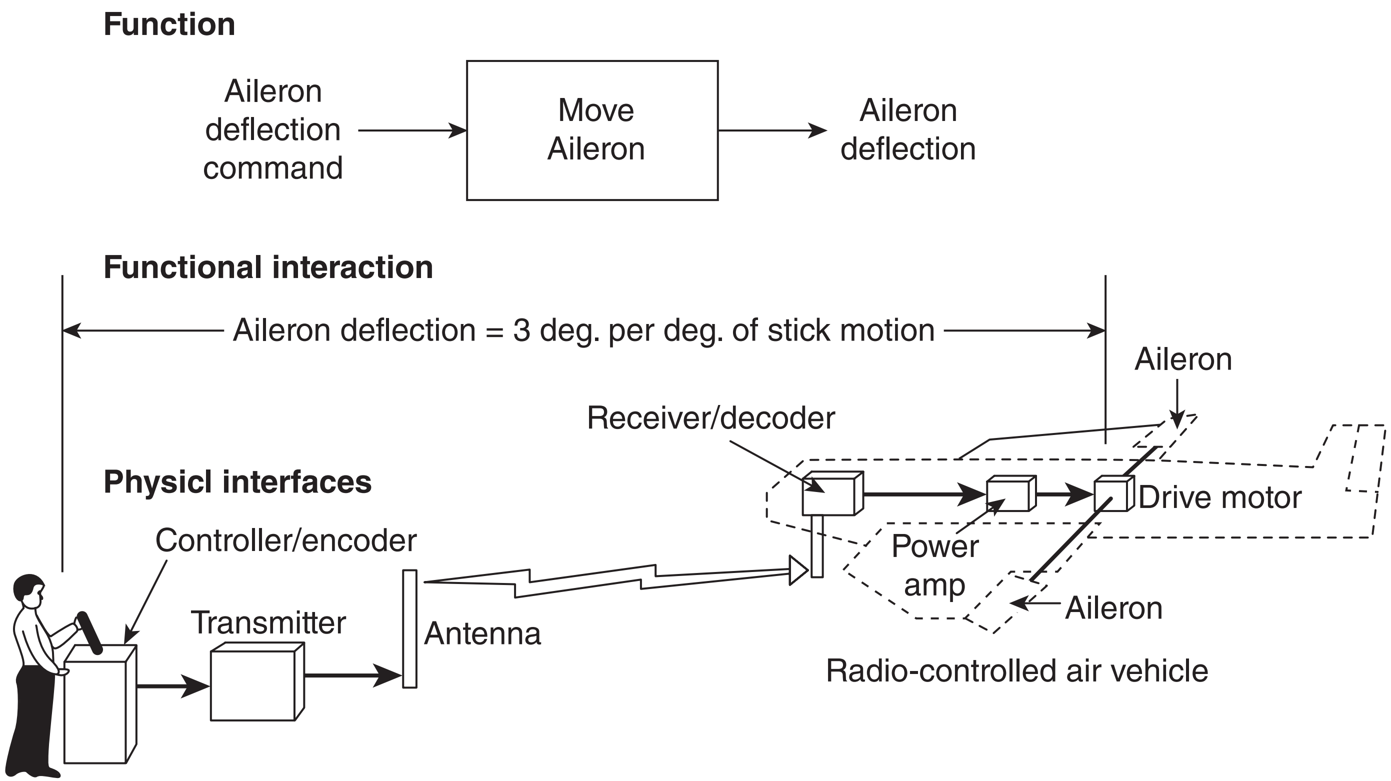


Figure 3.5. Functional interactions and physical interfaces.

Interface Elements Examples

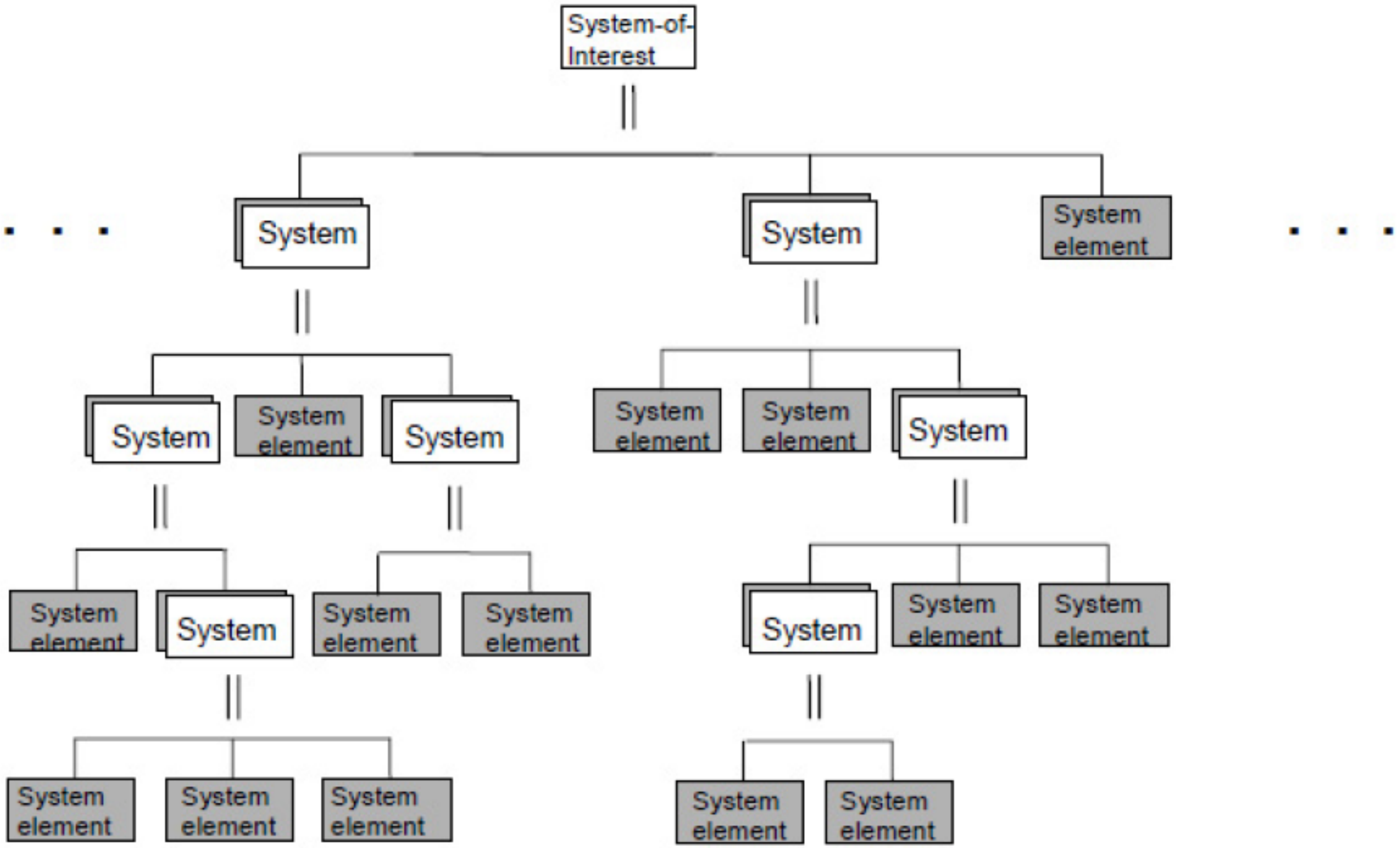
TABLE 3.4. Examples of Interface Elements

Type	Electrical	Mechanical	Hydraulic	Human–machine
Interaction medium	Current	Force	Fluid	Information
Connectors	Cable switch	Joint coupling	Pipe valve	Display control panel
Isolator	RF shield insulator	Shock mount bearing	Seal	Cover window
Converter	Antenna A/D converter	Gear train piston	Reducing valve pump	Keyboard

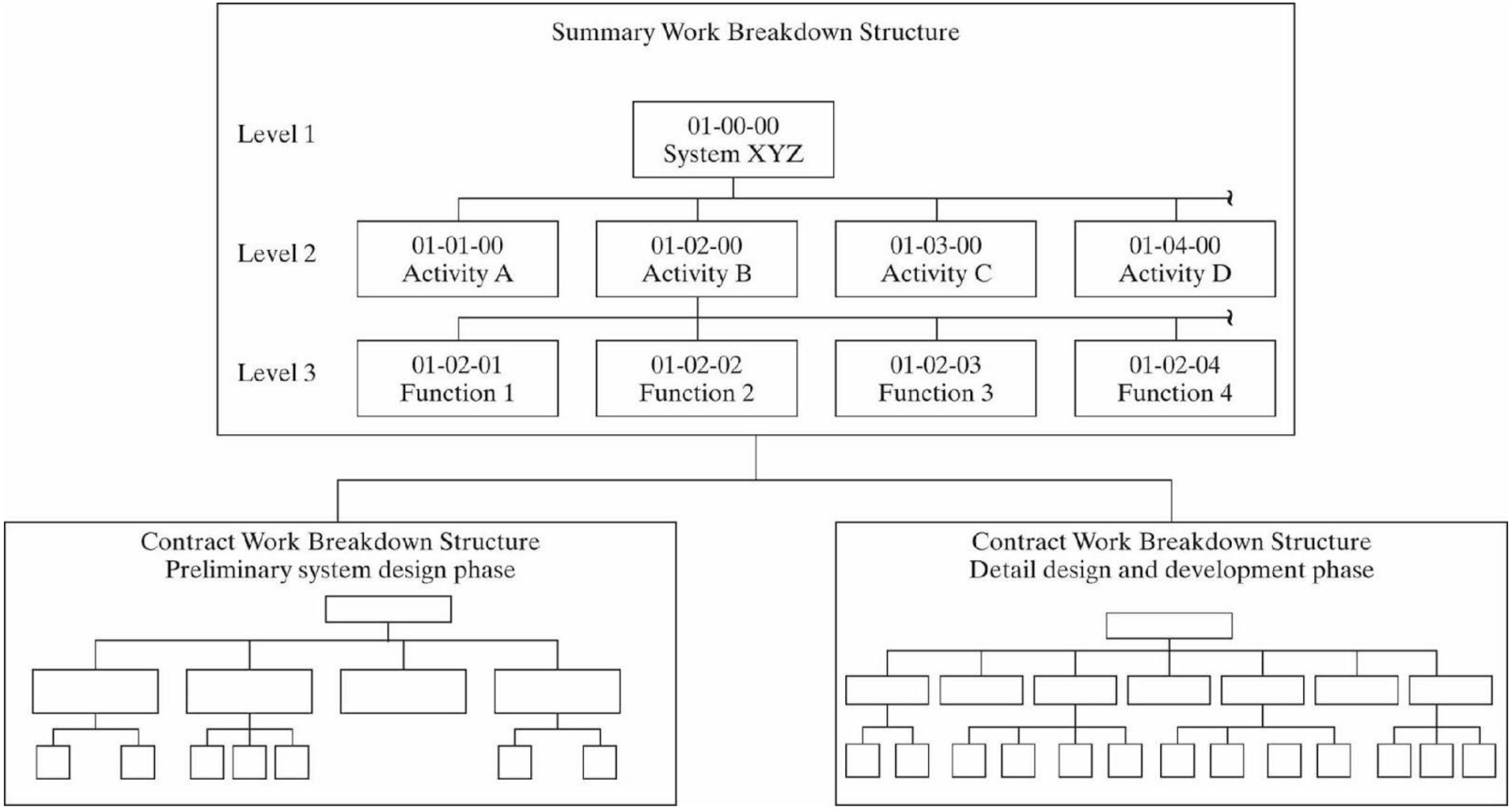
Hierarchy within a System

- System/product hierarchy

- Tier n:
- Tier n+1 . . .
- Tier n+2
- …



Work Breakdown Structure (WBS)



› From: Blanchard and Fabrycky, 2011

Space Transportation System

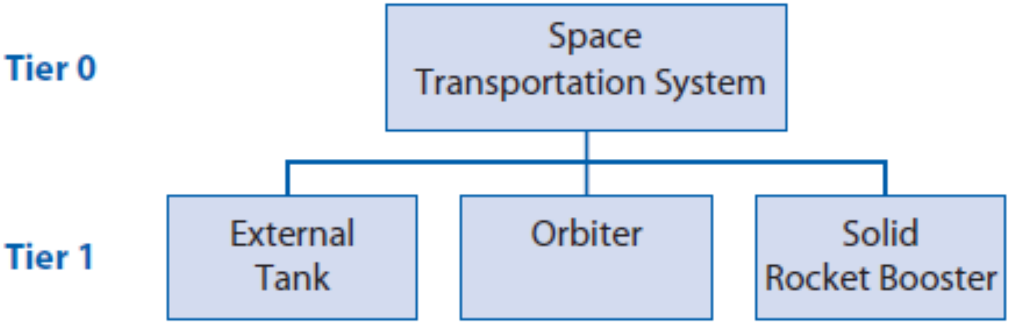


Figure 2.3-2 Product hierarchy, tier 1: first pass through the SE engine

› From: NASA Systems Engineering Handbook

Space Transportation System

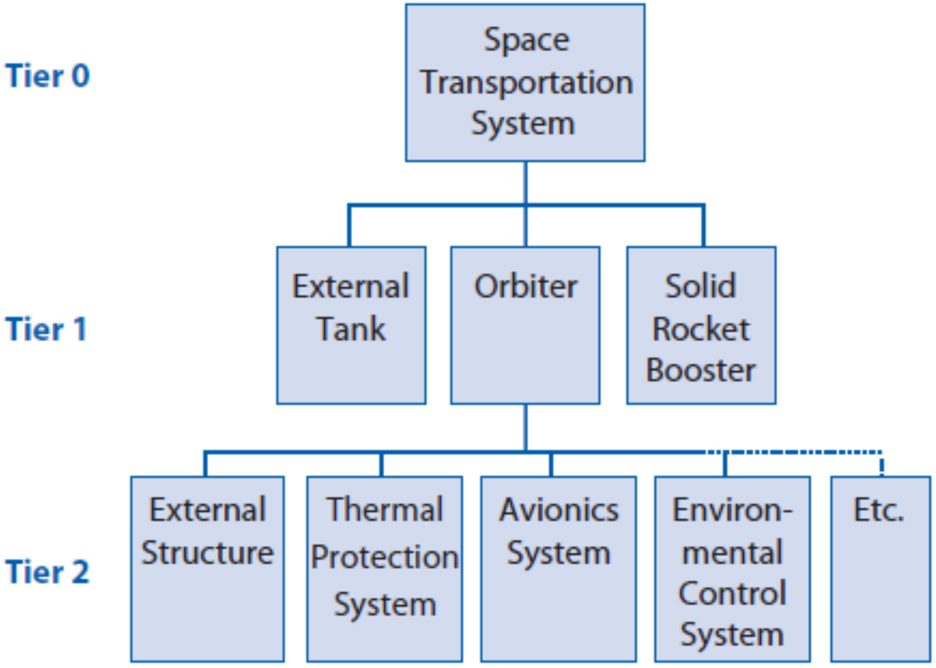


Figure 2.3-4 Product hierarchy, tier 2: orbiter

› From: NASA Systems Engineering Handbook

Space Transportation System

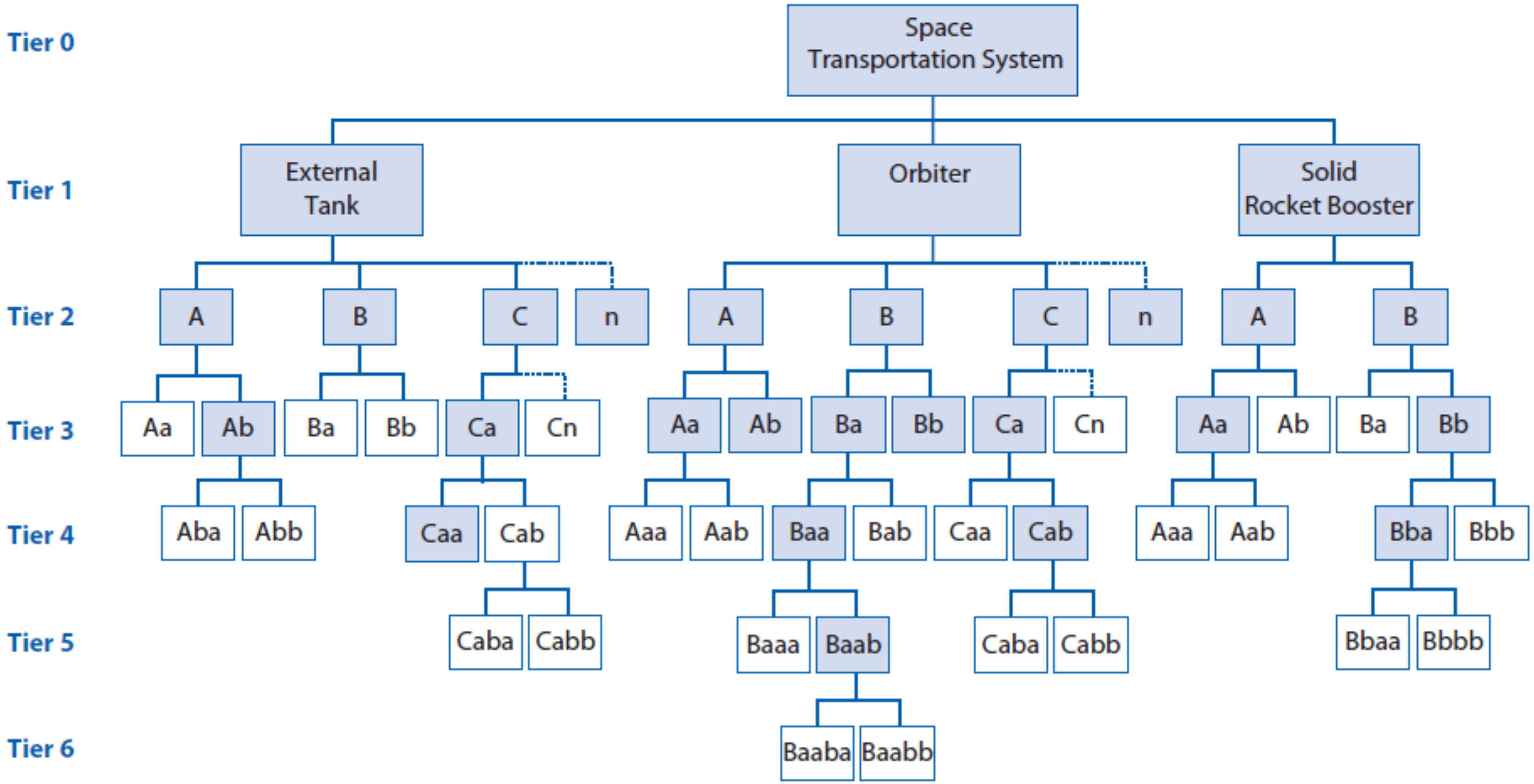
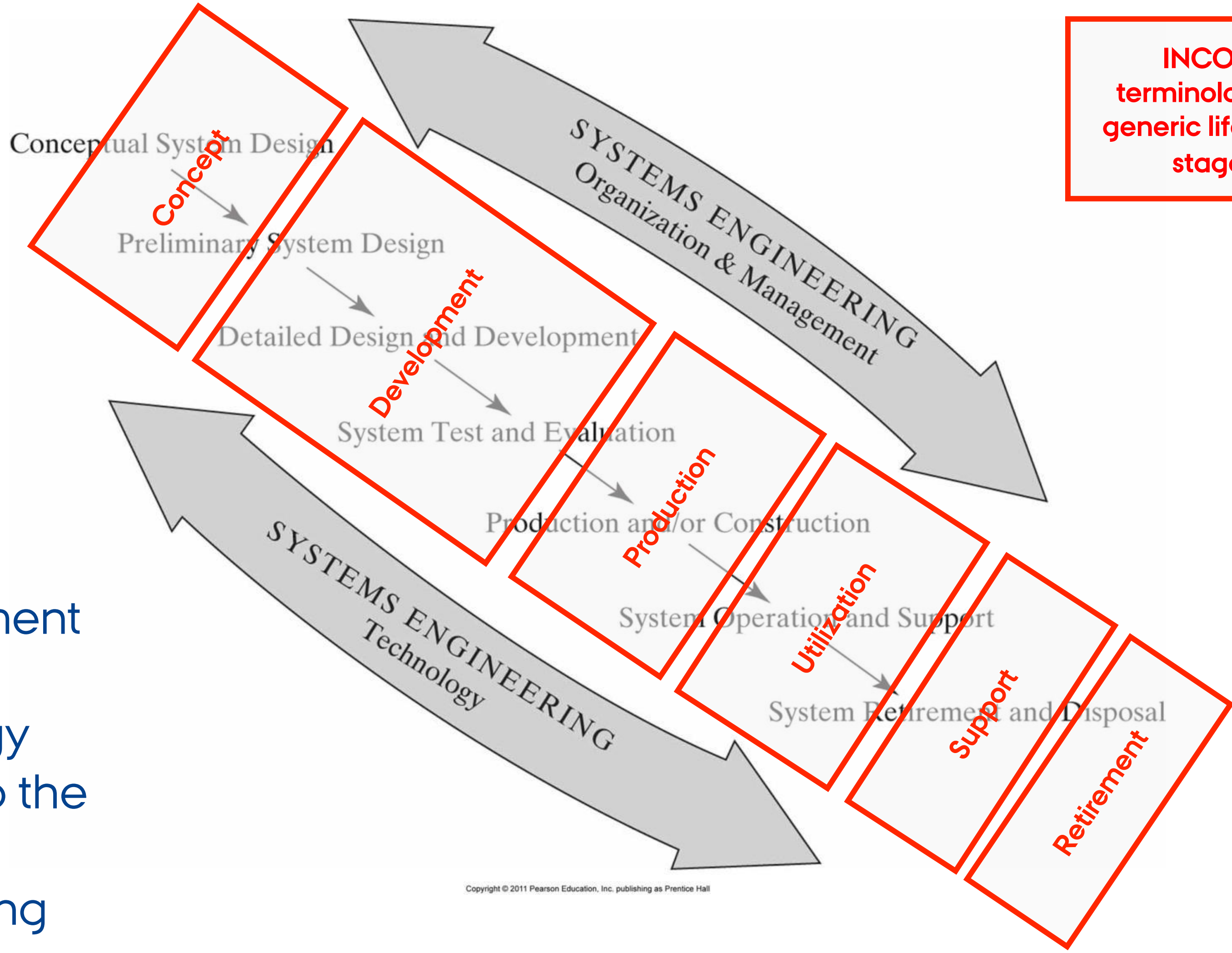


Figure 2.3-6 Product hierarchy: complete pass through system design processes side of the SE engine

› From: NASA Systems Engineering Handbook

Systems Engineering Process



INCOSE terminology for generic life-cycle stages

- Management and technology applied to the systems engineering process

From: Blanchard and Fabrycky, 2011

Generic Life-Cycle Stages

<table>
<tr><th>LIFE CYCLE STAGES</th><th>PURPOSE</th><th>DECISION GATES</th></tr>
<tr><td>CONCEPT</td><td>Identify stakeholders' needs
Explore concepts
Propose viable solutions</td><td rowspan="6">Decision Options
– Execute next stage
– Continue this stage
– Go to a preceding stage
– Hold project activity
– Terminate project</td></tr>
<tr><td>DEVELOPMENT</td><td>Refine system requirements
Create solution description
Build system
Verify and validate system</td></tr>
<tr><td>PRODUCTION</td><td>Produce systems
Inspect and test [verify]</td></tr>
<tr><td>UTILIZATION</td><td>Operate system to satisfy users' needs</td></tr>
<tr><td>SUPPORT</td><td>Provide sustained system capability</td></tr>
<tr><td>RETIREMENT</td><td>Store, archive, or dispose of the system</td></tr>
</table>

INCOSE
International Council on Systems Engineering

Decision Gates

- Decision Gates (control gates, milestones, reviews) represent major decision points in the system life cycle.

- Objectives:
- Ensure business and technical baselines are acceptable and will lead to satisfactory verification and validation
- Ensure that the risk of proceeding to the next step is acceptable
- Continue to foster buyer and seller teamwork

- What are good questions to answer at a decision gate?

SE Activities and Documents

TABLE 2.2. Systems Engineering Activities and Documents

Context diagrams	Opportunity assessments	Prototype integration
Problem definition	Candidate concepts	Prototype test and evaluation
User/owner identification	Risk analysis/management plan	Production/operations plan
User needs	Systems functions	Operational tests
Concept of operations	Physical allocation	Verification and validation
Scenarios	Component interfaces	Field support/maintenance
Use cases	Traceability	System/product effectiveness
Requirements	Trade studies	Upgrade/revise
Technology readiness	Component development & test	Disposal/reuse

Programs vs Projects

Programs	Projects
• Programs create outcomes. • Program is a set (or portfolio) of projects. • Management is concerned about managing the *right projects.*	• Deliver outputs, discrete “chunks” of change. • Pursues defined project objectives. • Management is concerned about managing the *project right.*

Program Life-Cycle

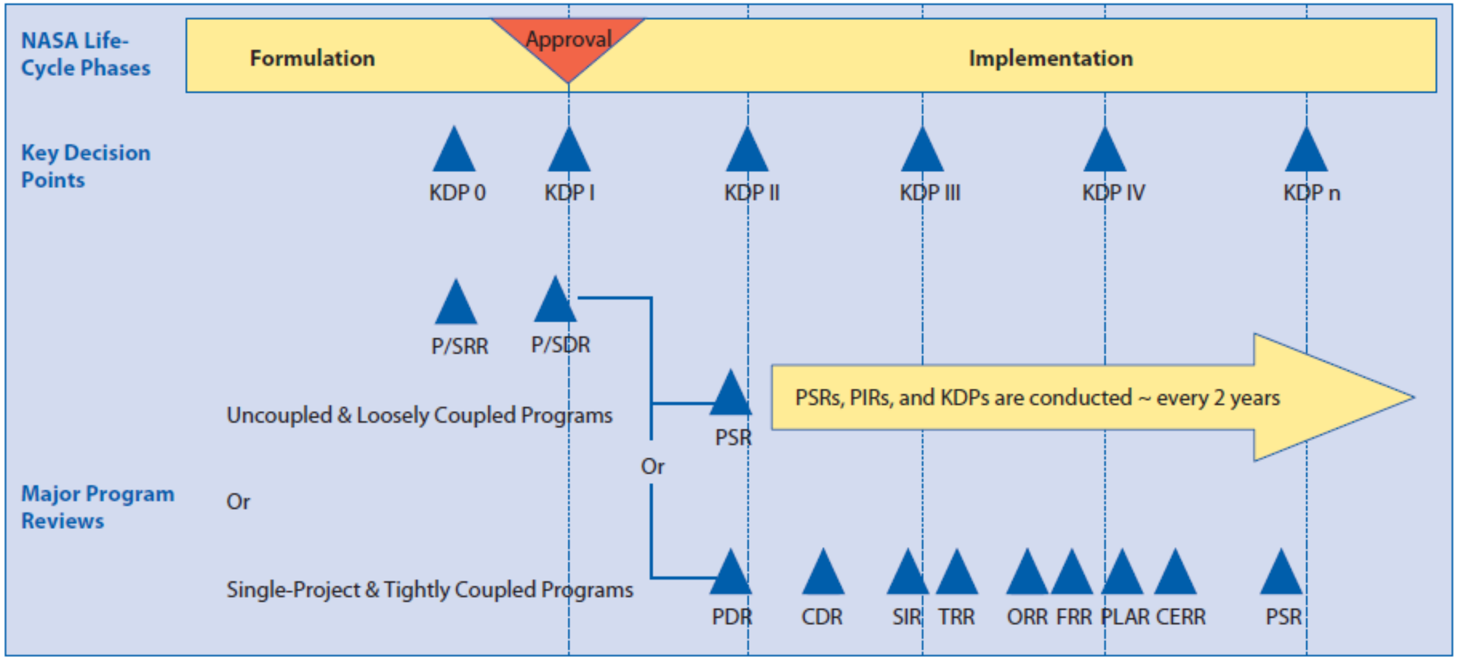


Figure 3.0-1 NASA program life cycle

CDR	Critical Design Review	PLAR	Post-Launch Assessment Review
CERR	Critical Events Readiness Review	PRR	Production Readiness Review
DR	Decommissioning Review	P/SDR	Program/System Definition Review
FRR	Flight Readiness Review	P/SRR	Program/System Requirements Review
KDP	Key Decision Point	PSR	Program Status Review
MCR	Mission Concept Review	SAR	System Acceptance Review
MDR	Mission Definition Review	SDR	System Definition Review
ORR	Operational Readiness Review	SIR	System Integration Review
PDR	Preliminary Design Review	SRR	System Requirements Review
PFAR	Post-Flight Assessment Review	TRR	Test Readiness Review
PIR	Program Implementation Review		

› From: NASA Systems Engineering Handbook

Project Life-Cycle

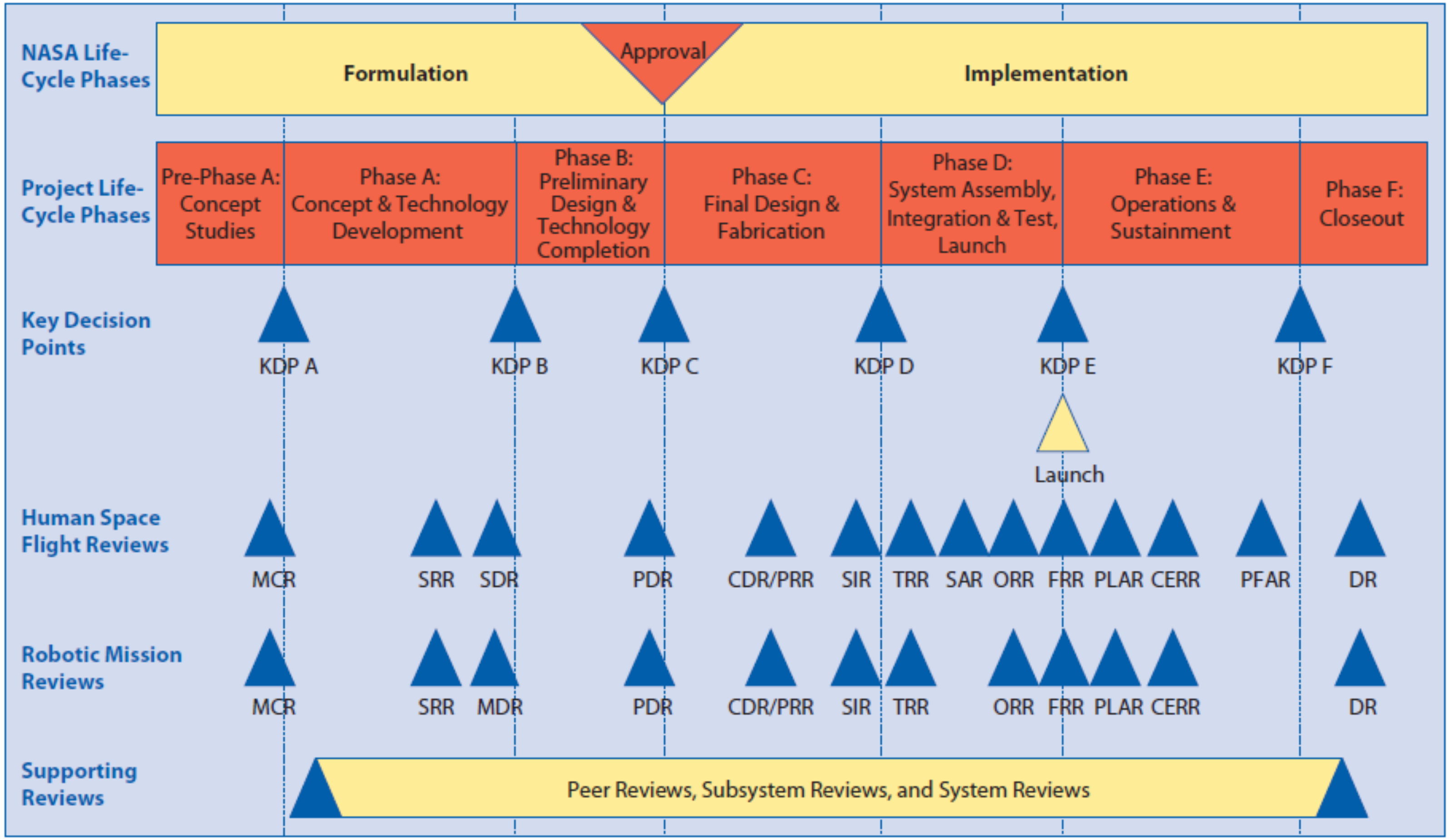


Figure 3.0-2 NASA project life cycle

› From: NASA Systems Engineering Handbook

Scope of SE Life Cycles

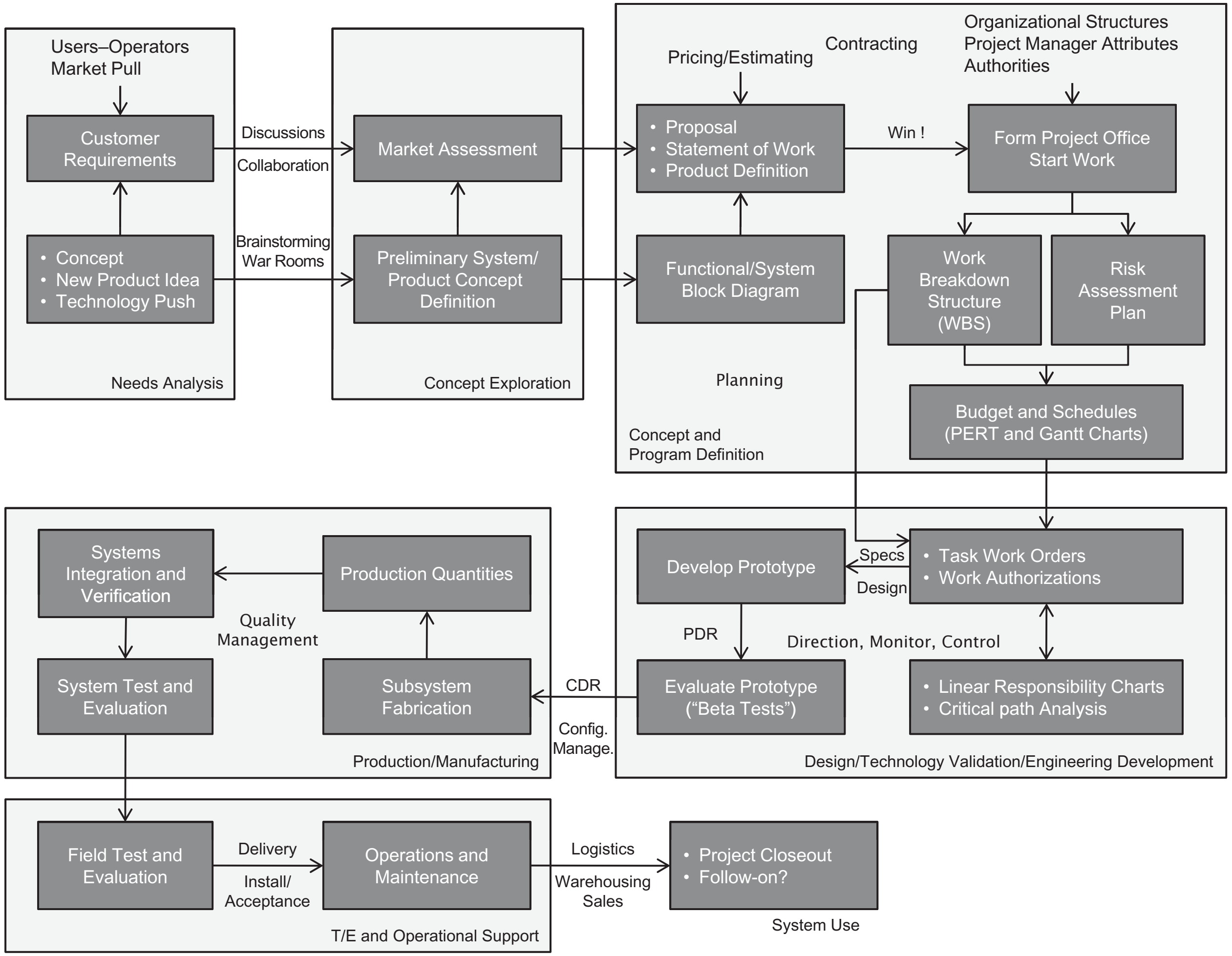
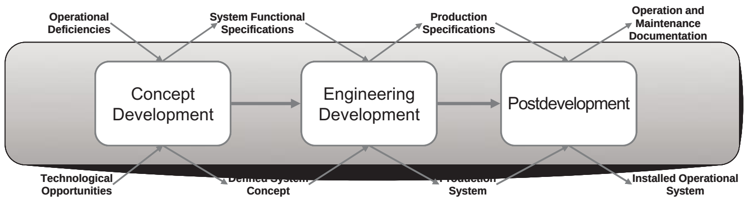
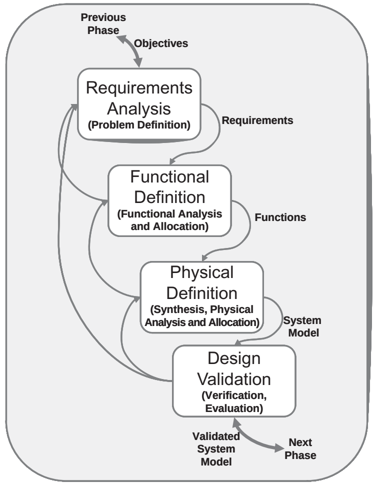


Figure 2.7. Life cycle systems engineering view. PERT, Program Evaluation and Review Technique; PDR, Preliminary Design Review; CDR, Critical Design Review.

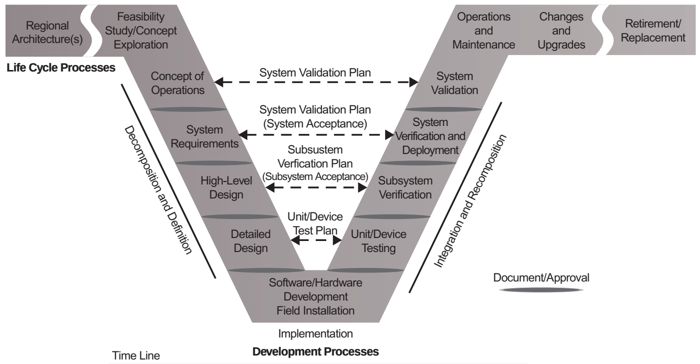
System Engineering Process Models



Waterfall



"Vee"



Spiral

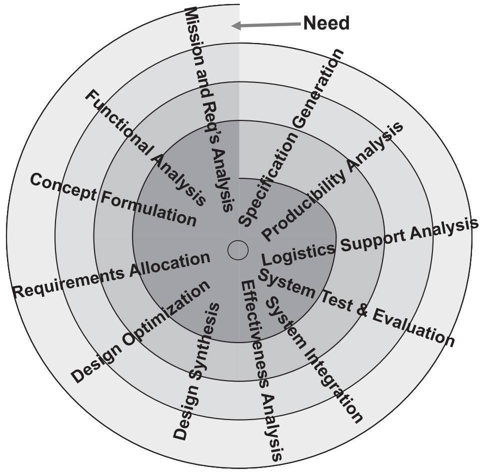


Figure 2.6. Examples of systems engineering approaches.

The Spiral Process Model

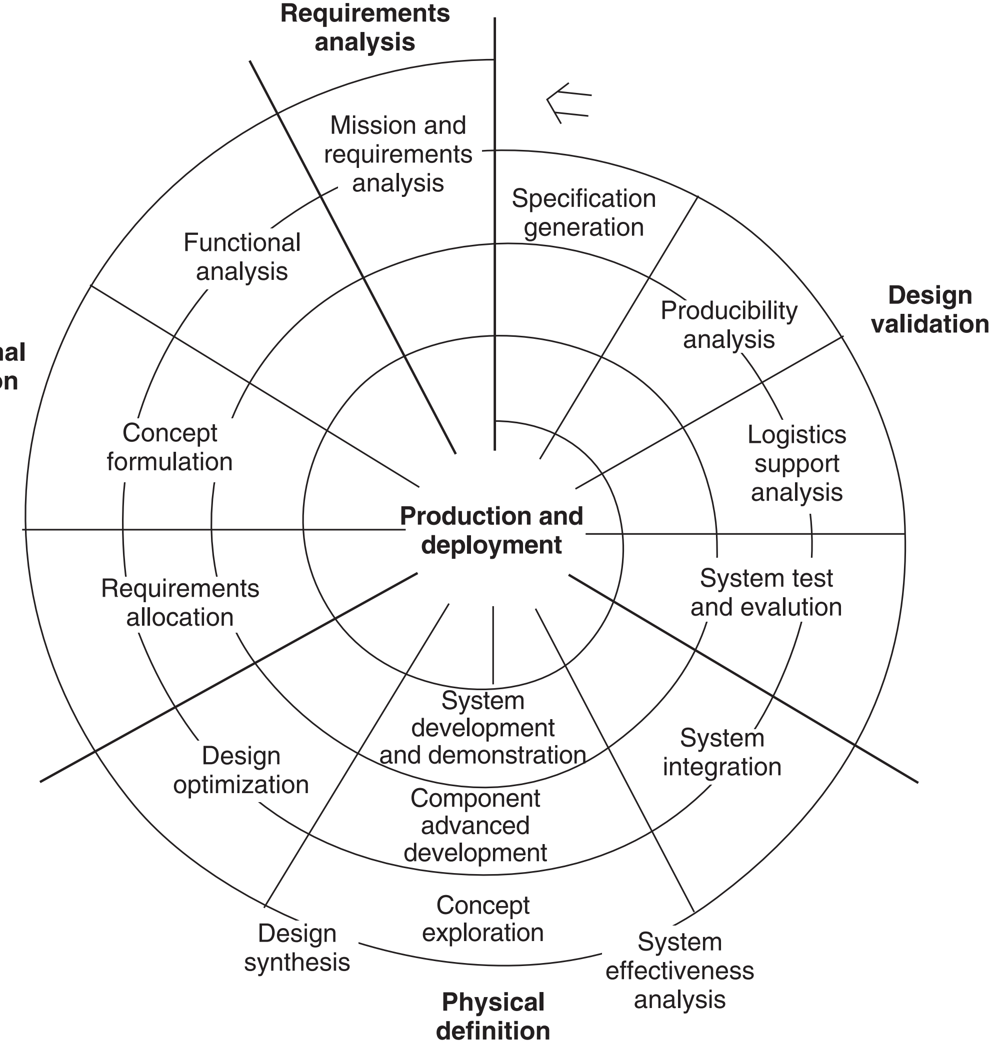


Figure 4.13. Spiral model of the system life cycle.

The "Vee" Process Model

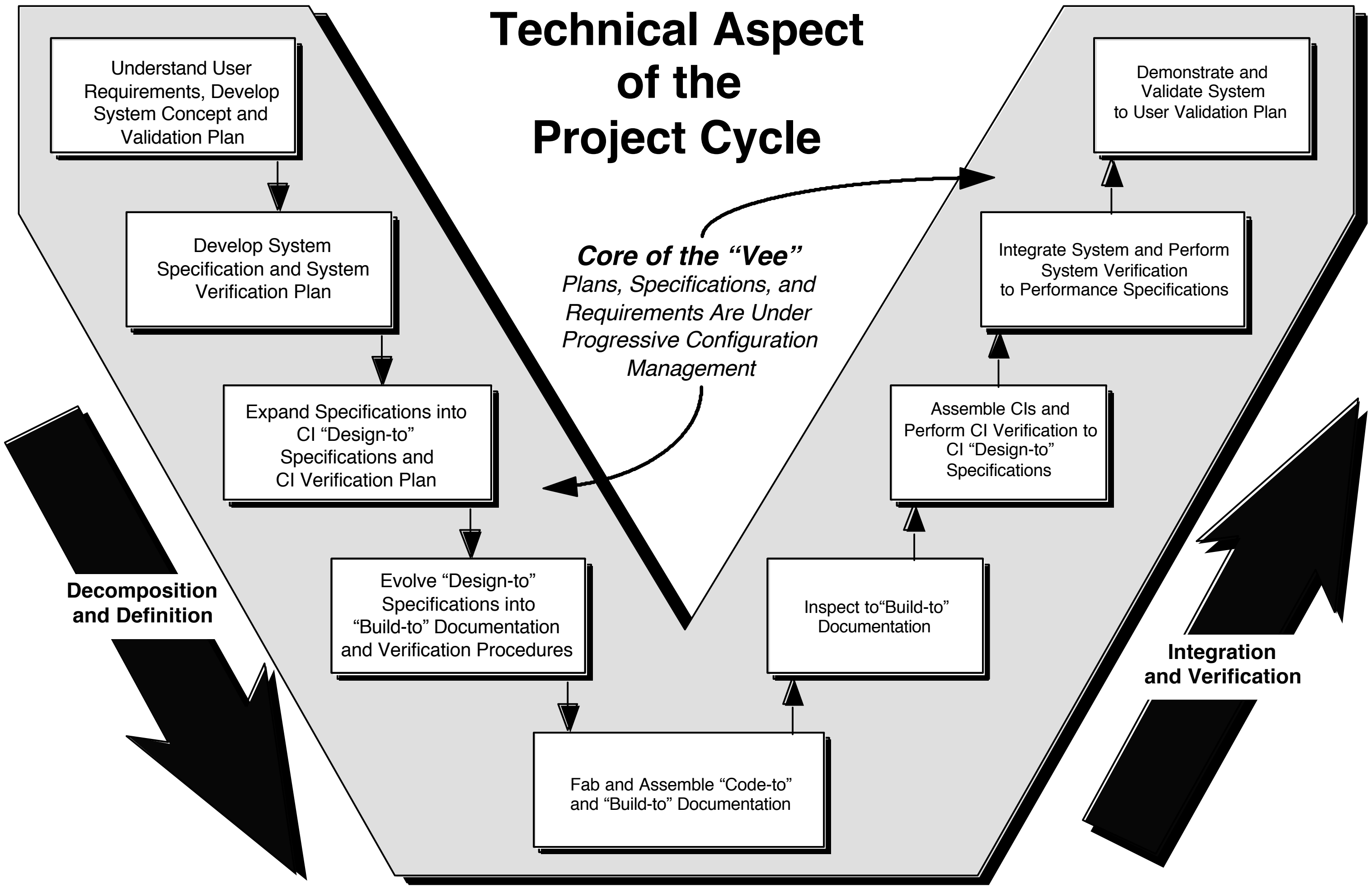
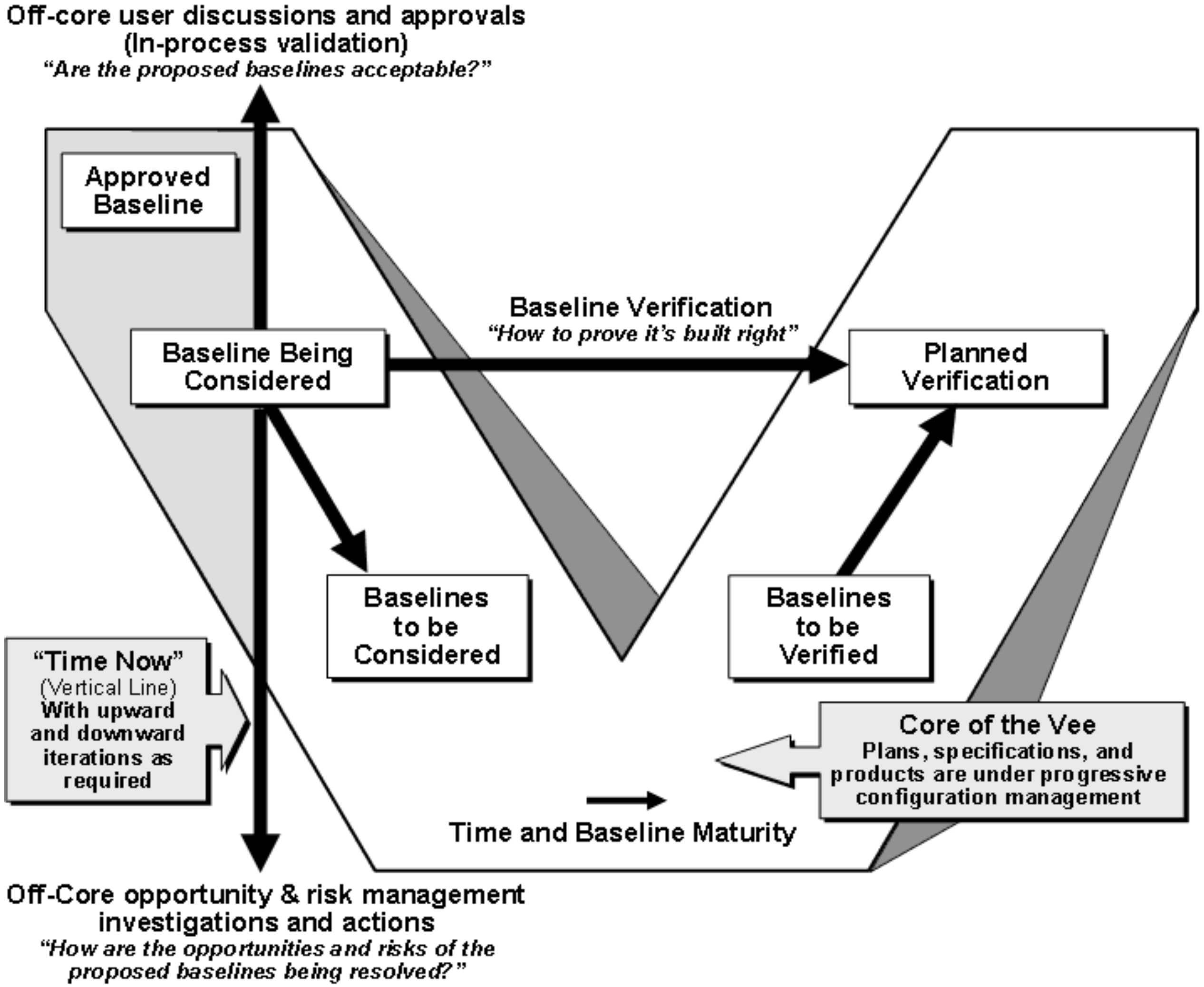


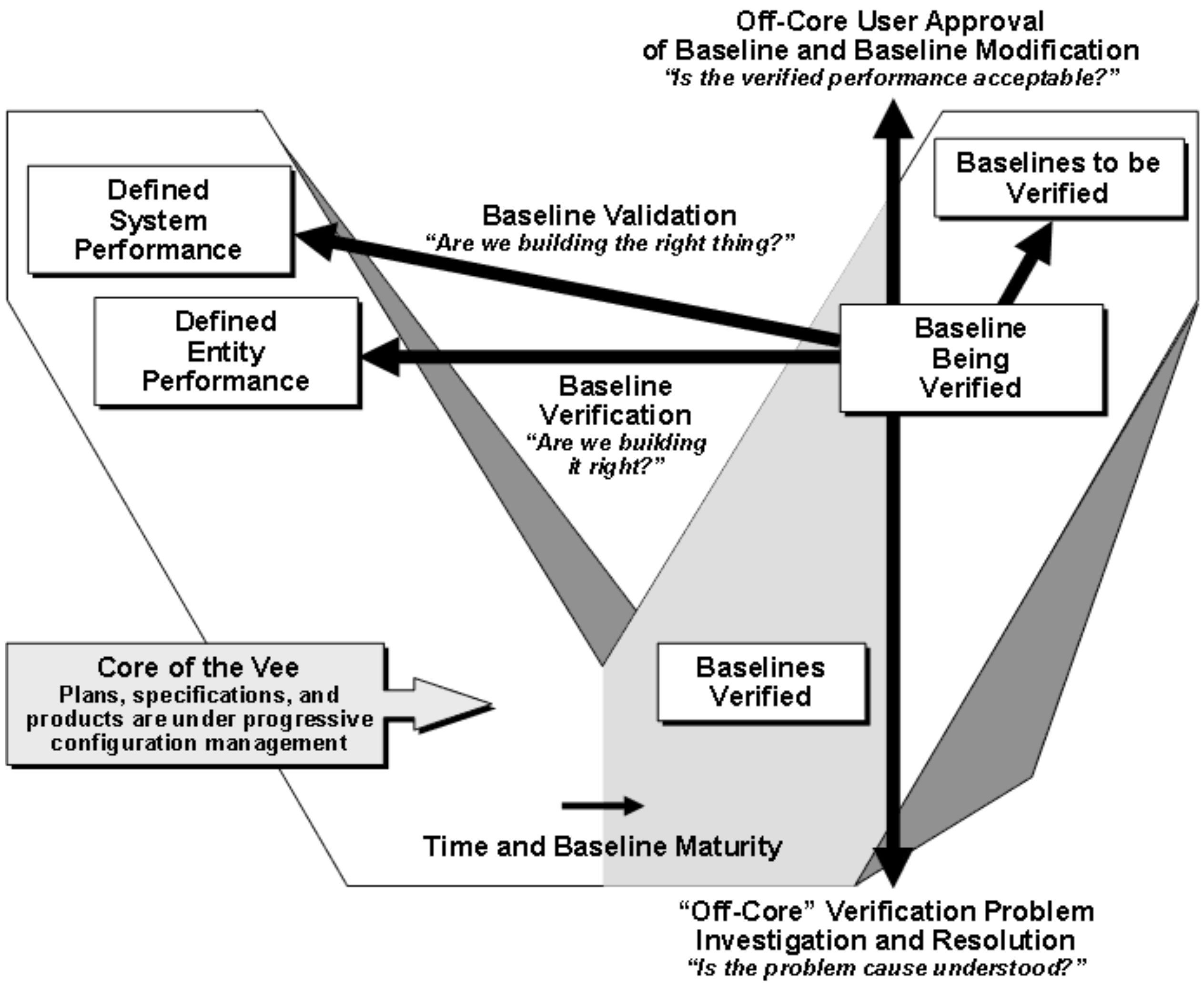
Figure 1 – The Technical Aspect of the Project Cycle (The "Vee")

› From: Forsberg and Mooz, System Engineering for faster, cheaper, better

Left Side of the "Vee" Process Model



Right Side of the "Vee" Process Model



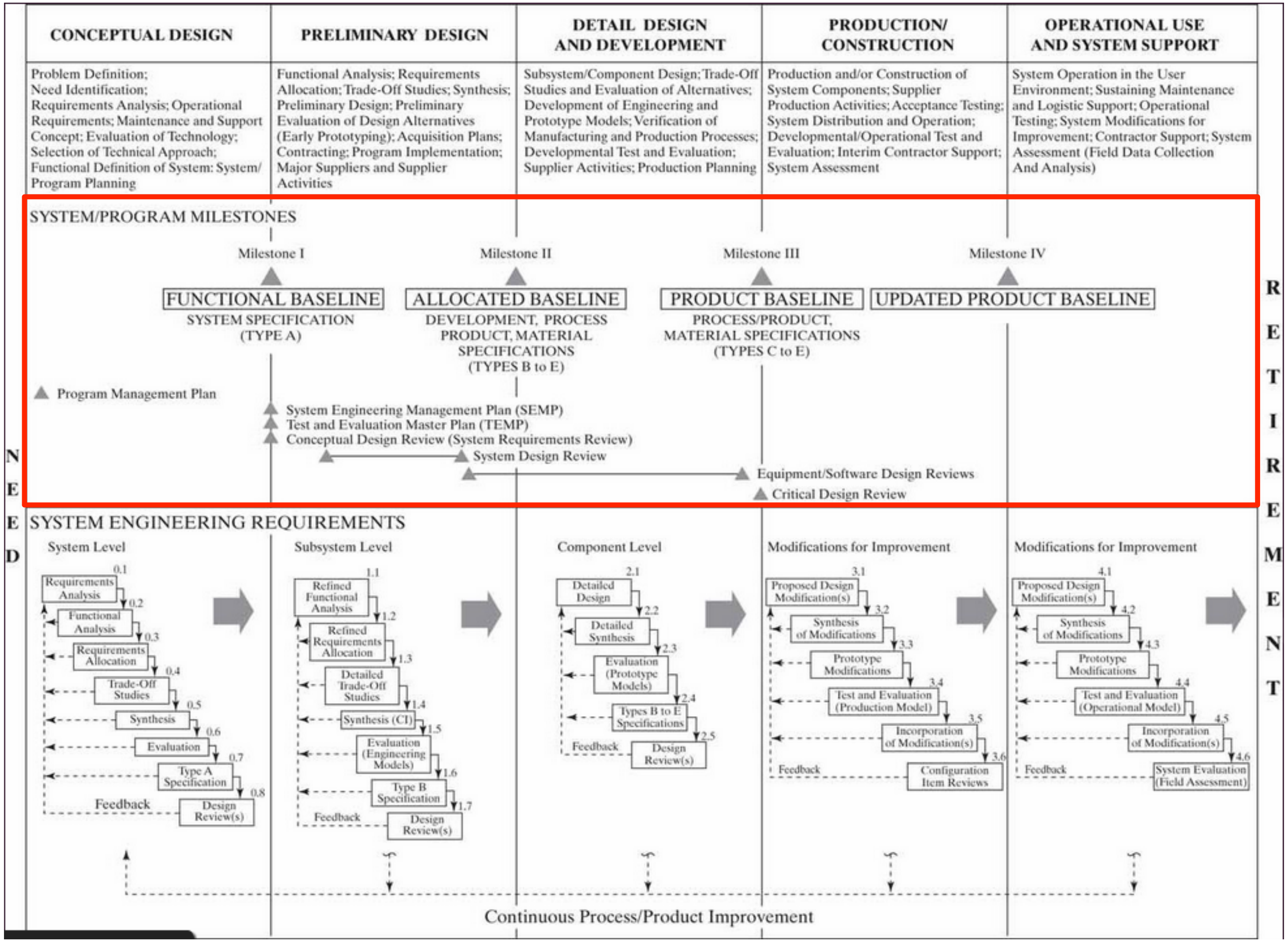
Baselines

- “The gate-controlled step-by-step elaboration of business, budget, functional, performance, and physical characteristics, mutually agreed by buyer and seller, and under formal change control.” (INCOSE)

- “… can be modified between formal decision gates by mutual consent through the change control process.” (INCOSE).

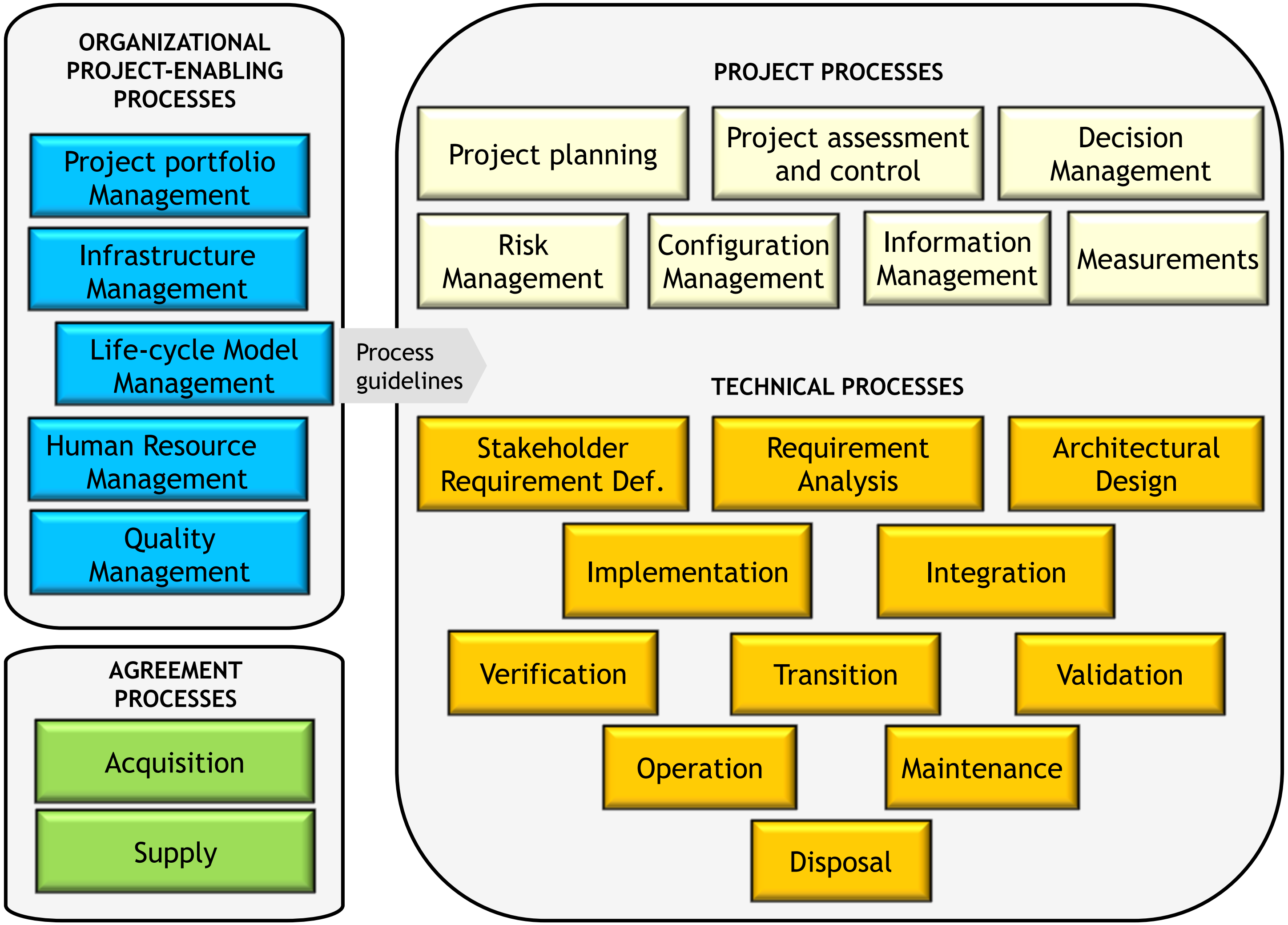
- Some examples of specific types of baselines include:
- Functional Baseline: initial specifications established; contract etc.
- Allocated Baseline: state of work products once requirements are approved
- Developmental Baseline: state of work products
- Product Baseline: contains the releasable contents of the project
- others (based upon proprietary business practices)

Baselines in the SE Life-Cycle



› From: Blanchard and Fabrycky, 2011

INCOSE: System Life-Cycle Processes



INCOSE: Process Context Diagram

- Process overview
- Purpose, description, Inputs , Outputs, Process Activities, Common approaches