Introduction to Model Based Systems Engineering

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RAM X

Huntsville SOCIETY OF RELIABILITY ENGINEERS

ISEEM Industrial and Systems Engineering and Engineering Management

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Summary

- Model Based Systems Engineering (MBSE) provides a new methodology to perform systems engineering.
  - The objective of systems engineering does not change, only the means.

- This session will review traditional systems engineering methodology and illustrate the MBSE analogs.

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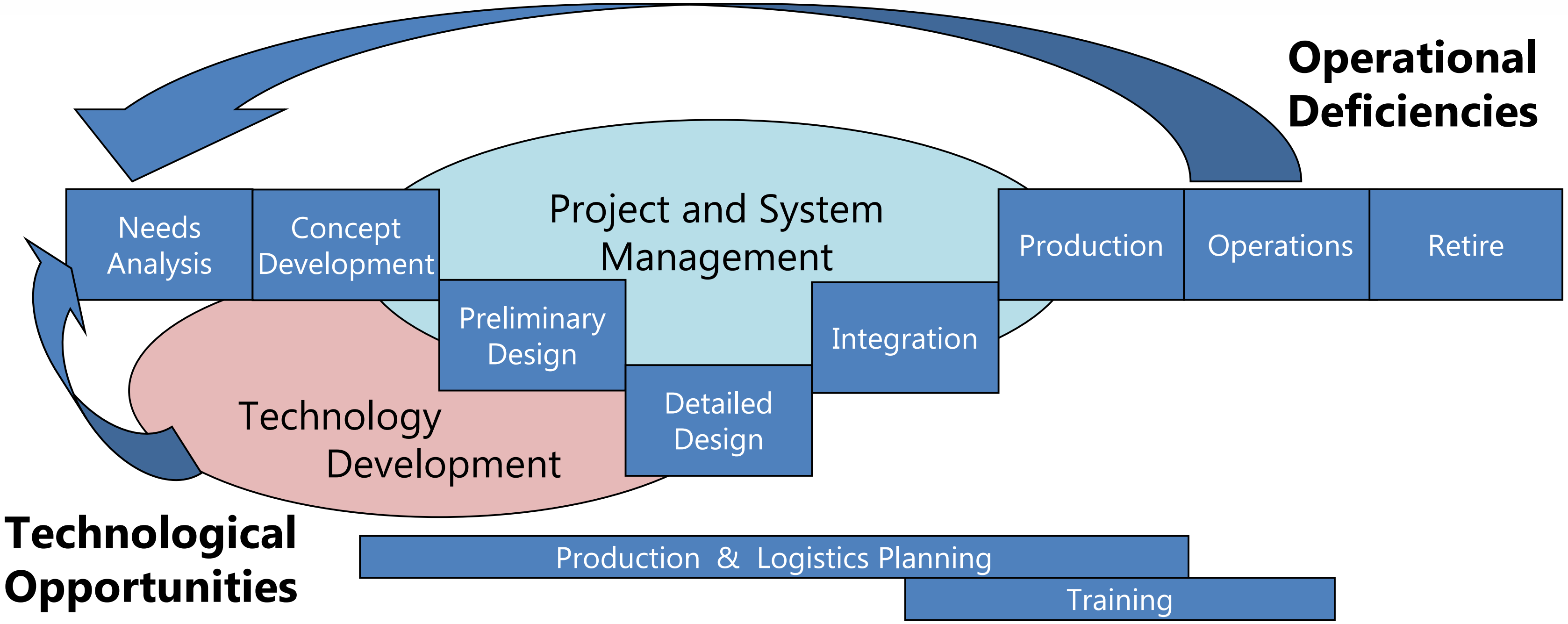
What System Engineers Do

- System engineers play an important role in designing and managing complex systems.
  - Systems engineers are concerned with the **whole system** and take a top-down, **interdisciplinary** approach to design and management.
  - System engineers are involved with a system throughout its **life-cycle**.
  - System engineers are **problem definers**, not just problem solvers.

(ref. Panitz, 1997)

Problem Definition

- The initial customer expectation for a new or enhanced mission or capability may be defined in response to a variety of reasons:
  - A current functional deficiency or existing operational deficiency,
  - A desire to leverage new technology breakthroughs to enhance mission capability or market positioning,
  - An evolving threat or competition, or
  - A response to improve the capability based on observed behavior of current systems and their operators or maintainers.



Successful systems are typically a marriage of technology development & operational deficiency.

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Technology Development or Operational Deficiency?

Q. Does the evolution of the light bulb indicate an advance of technology or a deficiency in lighting?

A. It depends on how you characterize an operational deficiency.

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Operational Deficiency

- A successful system brings the right technology to bear on an operational deficiency, where the operational deficiency is characterized from the operators' (customers') perspective.

- Military planners first realized they needed something better than helicopters and fixed-wing transports when they had malfunctioned and collided during a failed hostage rescue attempt in 1980 in the Iranian desert, killing eight soldiers. They wanted "*an aircraft that could combine the speed and range of a turboprop airplane with the vertical agility of a helicopter.*" (ref: Thompson, 2011)

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Who are the Customers?

- To "listen to the voice of the customer", we first need to identify the customer
  - Customer in this context is comprised of various stakeholders

- In most cases there are many customers &/or stakeholders
  - consumer/end user
  - regulatory agencies
  - manufacturing
  - marketing/sales
  - …

"Contrary to the traditional Engineering viewpoint of developing "widgets" … From the Engineer's perspective for the User to figure out how to use, the reverse should occur." (ref: Wasson, p. 99.)

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Two Dimensions of System Engineering

All disciplines

- Mechanical
- Electrical
- Electronic
- Control
- Aerodynamic
- Structural
- Thermal
- Acoustic
- Vibration
- Human Factors
- …

- Inception
- Design
- Production
- Operations
- Retirement

All Life Cycle Stages

System engineers integrate across time & across engineering disciplines.

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Representative Technical Artifacts for a Spacecraft Development

- **Needs, Goals, and Objectives**
- **Mission Requirements**
- **Operations Concept Document (incl. Ground Systems & Mission Operations Strategies)**
- Technical Measurement Plan & Reports
- **Systems Requirements Document**
- Flight Hardware, Software, & Ground Support Equipment Specifications
- **Ground System Requirements**
- **Mission Operations Requirements**
- Natural Environment Definition Document
- Requirements Validation Matrices
- Logical Decomposition Models (FFBDs)
- Functional Analysis Document
- **Master Verification Plan**
- Operations Procedures
- Activation and Inflight Checkout Plans
- User Manuals
- Operational Limits and Constraints
- Integrated Schematics
- Spares Provisioning List
- **Integrated Master Plan**
- Integrated Master Schedule
- **SEMP**
- **Systems Analysis Plan**
- **Software Management Plan**
- **Safety & Mission Assurance Plan**
- Configuration Management Plan
- Data Management Plan
- Mass Properties Control Plan
- Manufacturing and Assembly Plan
- Electromagnetic Compatibility/Interference Control Plan
- Spacecraft Systems Analysis Plan
- **Supportability Plan (incl. Training Plan)**
- Spacecraft Design Analysis Cycle Plans
- Disposal Plan
- Technical Review Plans
- Technology Development Plan
- Launch Operations Plan
- Payload-to-Carrier Integration Plan
- Technical Work Directives
- Engineering Change Requests/Notices
- Waivers
- **External Interface Requirement/Control Documents**
- Spacecraft to Payload Interface Requirement/Control Documents
- Spacecraft to Launch Vehicle Interface Requirement/Control Docs
- Spacecraft to Ground System Interface Requirement/Control Docs
- Launch Vehicle to Ground System Interface Requirement/Control Docs
- Ground System to Mission Ops Interface Requirement/Control Docs
- Instrumentation and Command Listing
- Interface Change Requests
- Technical Risk Reports
- Hardware/Software Configuration Items List
- Baseline Configuration Document
- Configuration Management Reports
- Specification Tree
- Drawing Tree/Engineering Drawing List
- Technical Data Electronic Exchange Formats
- Design Disclosure
- Technical Measurement Reports
- Mass Properties Reports
- Design Analysis Cycle Reports
- Technical Reports
- Trade Study & Decision Support Reports
- Verification Compliance Reports
- Validation Compliance Reports
- Integrated Spacecraft & Payload
- Integrated Spacecraft & Payload Acceptance Data Package
- Mission Operations System
- Ground System

(ref: Larson et.al., 2009)

- Technical artifacts primarily in the form of documents.
- Keeping all these artifacts mutually consistent and in synch throughout system development is essentially impossible.
- Omissions and inconsistencies often surface late in the life cycle.

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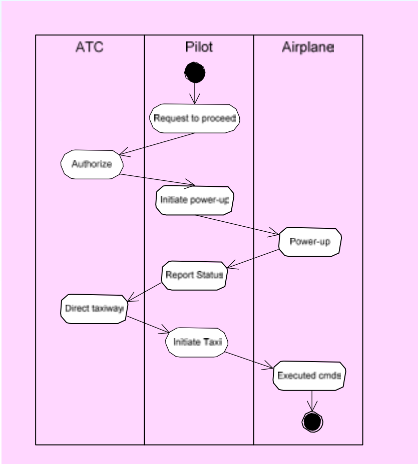
SE Practices for Describing Systems

Past

- **Specifications**
- **Interface requirements**
- **System design**
- **Analyses & Trade-offs**
- **Test plans**
- **…**

Future



Moving from document-centric to model-centric.

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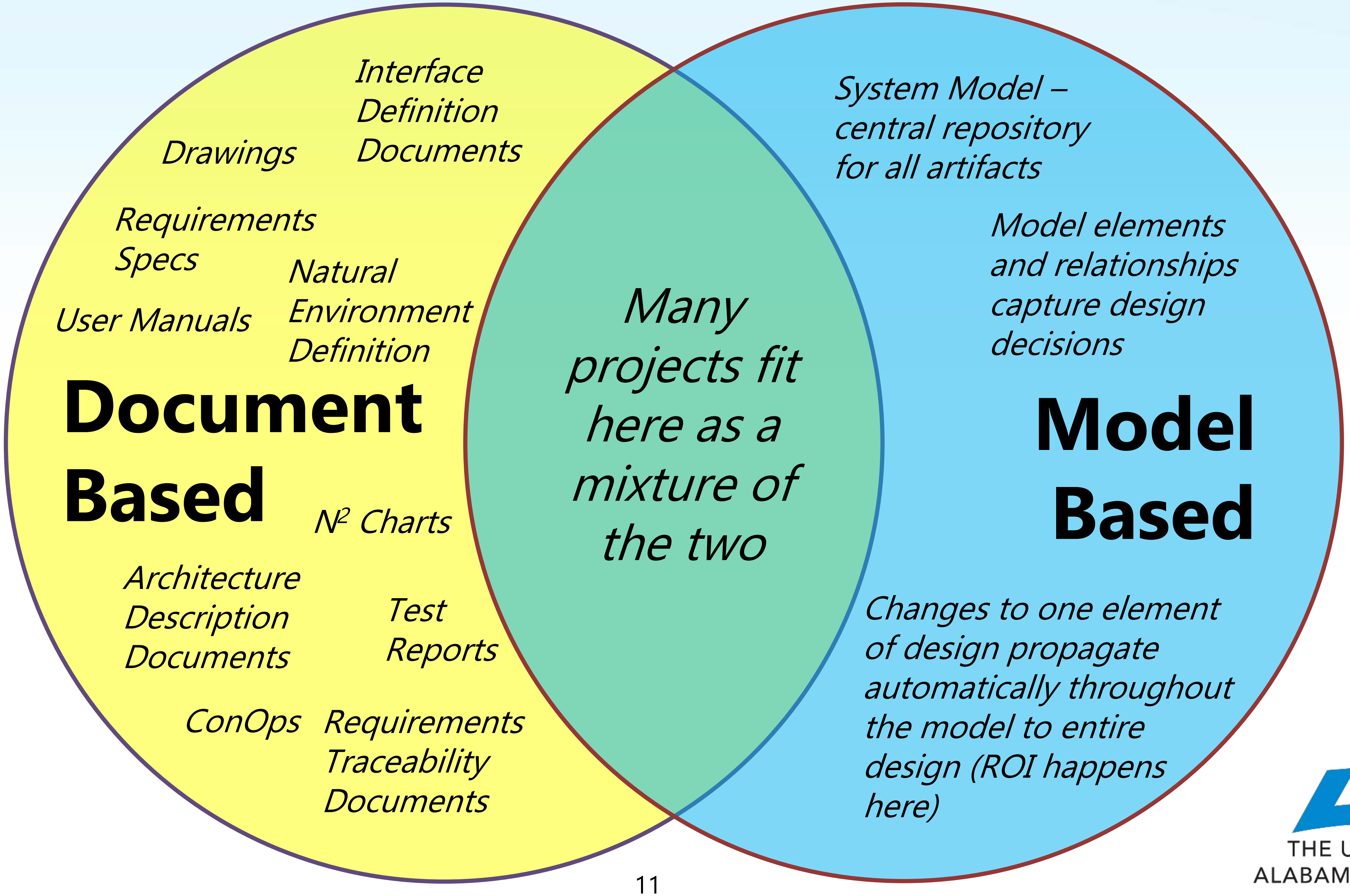
Traditional Document Based SE vs. MBSE



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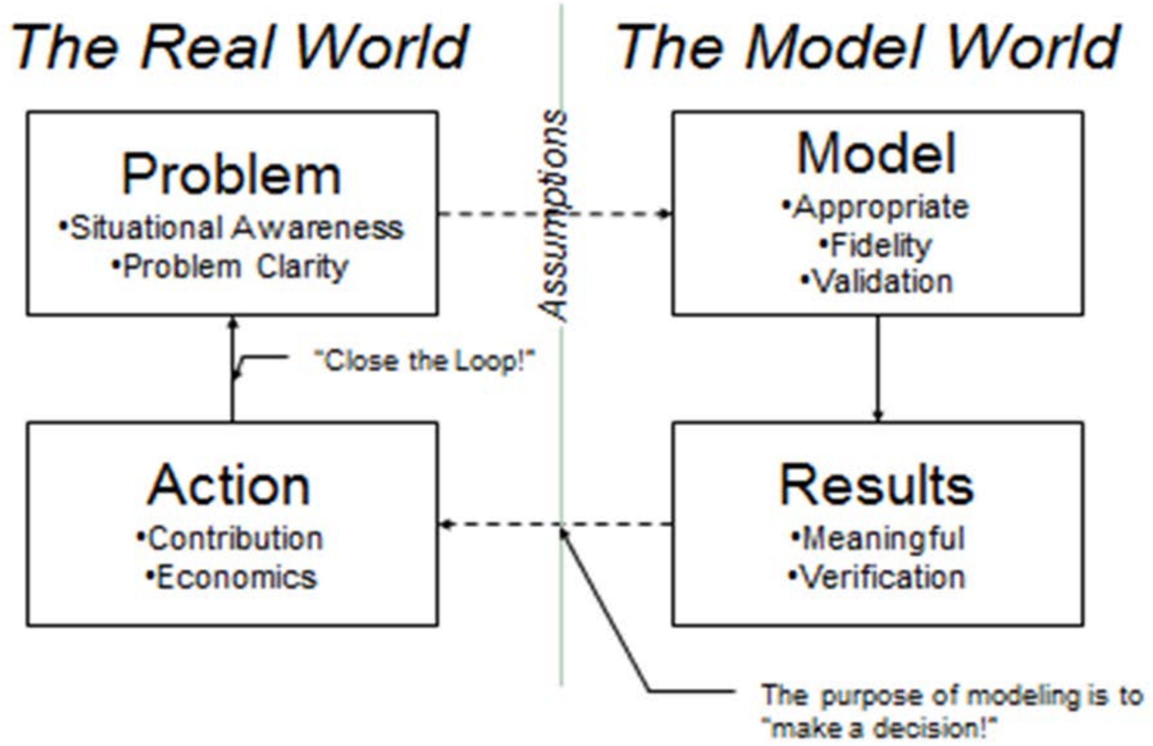
Models are a Means, Not an End

- "…essentially, all models are wrong, but some are useful." -- George E.P. Box, 1987.



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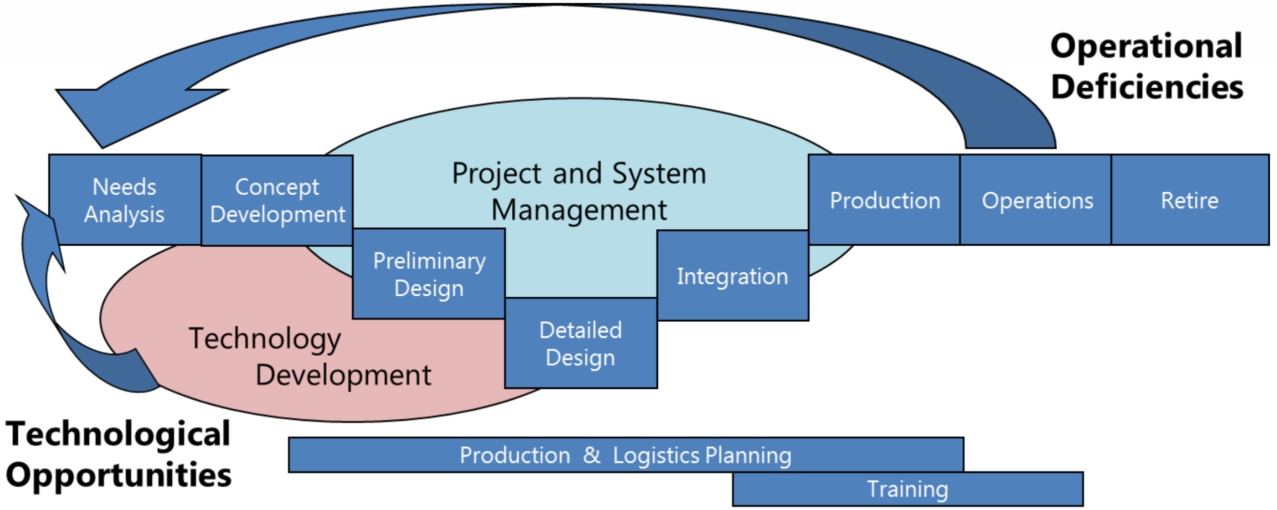
System Model Characteristics

- **Primary use is to *design* and *evaluate* a system that satisfies system requirements and allocates requirements to the system's components.**

- Used to enhance communication between stakeholders
  - Developer(s), operators, etc.
- Includes information on:
  - System specification & design
  - System analysis & evaluation
- Consists of elements that represent:
  - Requirements
  - Design elements & behaviors
  - Interrelationships (between the above)



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Why Build a System Model?

- **Specify and design a new or modified system**
  - Represent a system concept
  - Specify and validate system requirements
  - Synthesize system designs
  - Specify component requirements
  - Maintain requirements traceability
- **Evaluate the system**
  - Conduct system design trade-offs
  - Analyze system performance requirements or other quality attributes
  - Verify that the system design satisfies its requirements
  - Assess the impact of requirements and design changes
  - Estimate the system cost (e.g., development cost, life cycle cost)
- Train users on how to operate or maintain a system
- Support system maintenance and/or diagnostics

The system model can take many forms. The best form of the system model depends on the purpose for which it is constructed. Why is the model being built?

(ref: Friedenthal et.al., 2014)

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Two Aspects of a System Model

- **Structural**
  - The "what" of the system – what it is.
  - Identifies and defines the system elements, defines their properties, and identifies the relationships & interactions between system elements.
- **Behavioral**
  - The "how" of the system – how it functions.
  - Identifies the behavior of the system at the system level, between system elements, within system elements, and within operations of system elements.
- In general, both aspects are needed for system modeling. However, in some instances either may be sufficient depending on the purpose of the system model.

(ref: Holt & Perry, pp. 91-98)

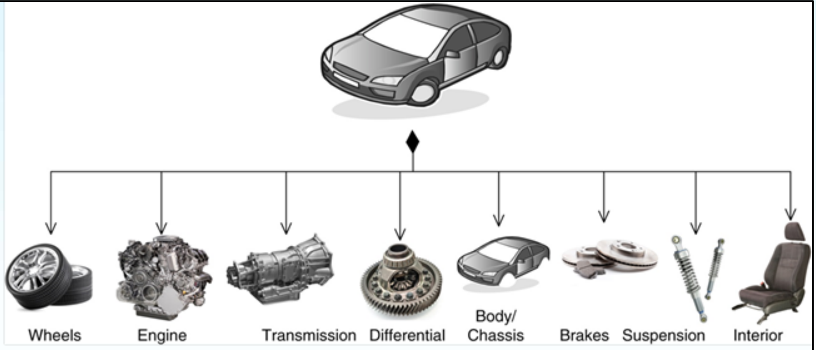

FIGURE 1.5
Automobile system decomposition into its components.

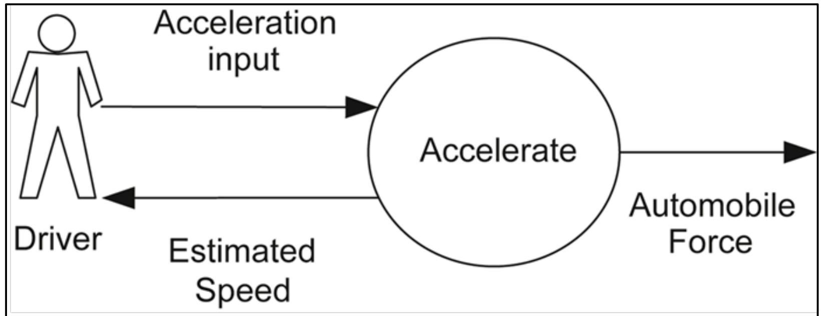

FIGURE 1.3
Specifying the functional requirements.

(ref: Friedenthal, et.al., 2014)

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Example: Structural Model

Automated Teller Machine

Example: Behavioral Model

Automated Teller Machine

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Integrated System Model Must Address Multiple Aspects of a System

Requirements ⟷

System Model

Functional/Behavioral Models

Start → Taxi → Ascend → Cruise →

Engine | Transmission | Propeller

Structural/Component Models

Mass Properties Model
Thermal Model
Reliability Model
Cost Model

Other Engineering Analysis Models

Performance Models

Control Input → Power Equations → Vehicle Dynamics →

(ref: Friedenthal et.al. 2009, p. 7.)

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Model–Based Systems Engineering (MBSE)

- "Model-Based Systems Engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." (ref: Friedenthal et.al., 2014)

- MBSE produces a system model contained in a model repository
  - System model includes system requirements, design, and evaluation information
  - The system model can provide a more complete, consistent, and traceable system design
  - Enhances the quality of traceability and change impact assessments

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System Modeling Languages

- SysML – most commonly used language for system modeling
  - Graphical modeling language with rules and syntax
  - Current version 1.4 – maintained by Object Management Group (OMG) http://www.omgsysml.org/
- Other Modeling Languages
  - UML – Unified Modeling Language
    - SysML is based on UML
    - Used for development in the field of software engineering
    - Current version 2.5 – maintained by OMG http://www.omg.org/spec/UML/
  - AADL – Architecture Analysis and Design Language
    - SAE Standard for Model-Based Engineering (SAE AS5506)
  - UPDM – The Unified Profile for DoDAF/MODAF
    - Many DoD customers want to see DoDAF views, even if not required
    - Current version 2.1 – maintained by OMG www.omg.org/spec/UPDM
  - Text modeling languages (Verilog, Modelica)

Systems Modeling Language – SysML

- What it **IS**
  - A *graphical* modeling language
  - Grammar
  - Vocabulary
  - A profile (an extension) of UML
  - Specification owned by OMG (www.omg.org)

- What it **IS NOT**
  - A modeling method
  - User must define the path to use SysML in design
  - Does not dictate that all graphical views be used
  - An independent language – a UML extension
    - Next version (2.0) will be a standalone language

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SysML Diagrams

- Five Basic Types: Structure, Behavior, Parametric, Package, and Requirements Diagrams
  - Structure Diagrams include Block Definition & Internal Block Diagrams
  - Behavior Diagrams include Use Case, Activity, Sequence, & State Machine Diagrams

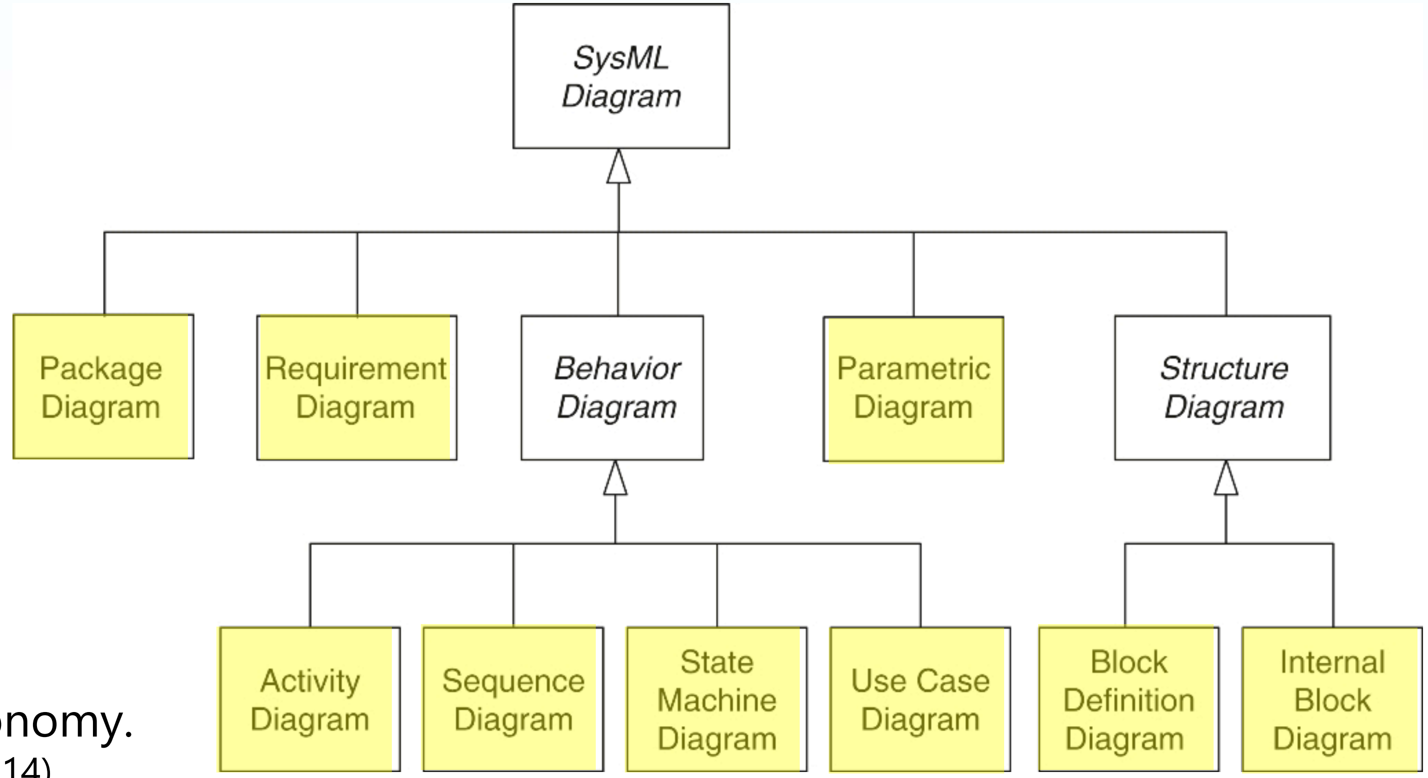

FIGURE 3.1
SysML diagram taxonomy.
(ref: Friedenthal et.al., 2014)

The Operational Concept

(ref: ANSI/AIAA G-043A-2012)

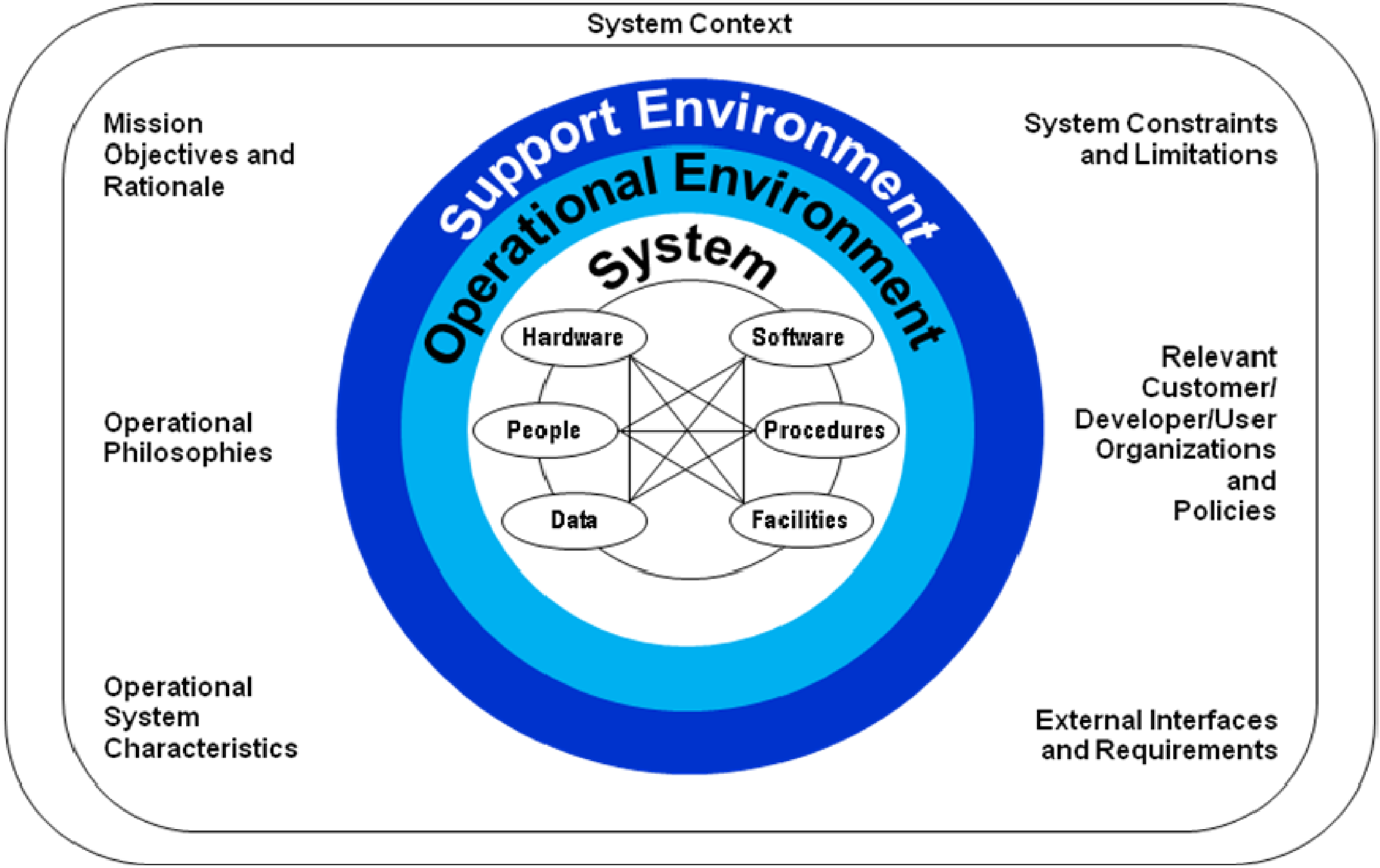

Figure 4 — An operational concept document describes the system and its context with both text and graphics in the user's terminology

- The ConOps communicates to all system stakeholders, ***in the user's language***, the desired characteristics of a system to be developed.

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ConOps Development Benefits

(ref: ANSI/AIAA G-043A-2012)

- The ConOps provides a mechanism to trigger questions and raise issues regarding **operator-related and user-related needs and associated design trades**. The effort to develop a ConOps can achieve a number of benefits to a program, as follows:
  - act as a catalyst to stimulate the development of *complete, consistent, testable requirements and designs with emphasis upon those attributes that shape the user-related elements of the system*;
  - provide guidance and clarification for the development of the subsequent system definition documentation (e.g., operational *system specifications* and interface control drawings);
  - form the basis for long range operational planning activities (i.e., staffing, facilities, training, security, safety, and logistics);
  - **describe the system behavior(s) that are needed** (give best and worst case); and
  - reduce cost overrun and schedule slips by defining more accurately the system earlier in the development stage; and decrease the chances that stakeholder dissatisfaction will terminate the project.

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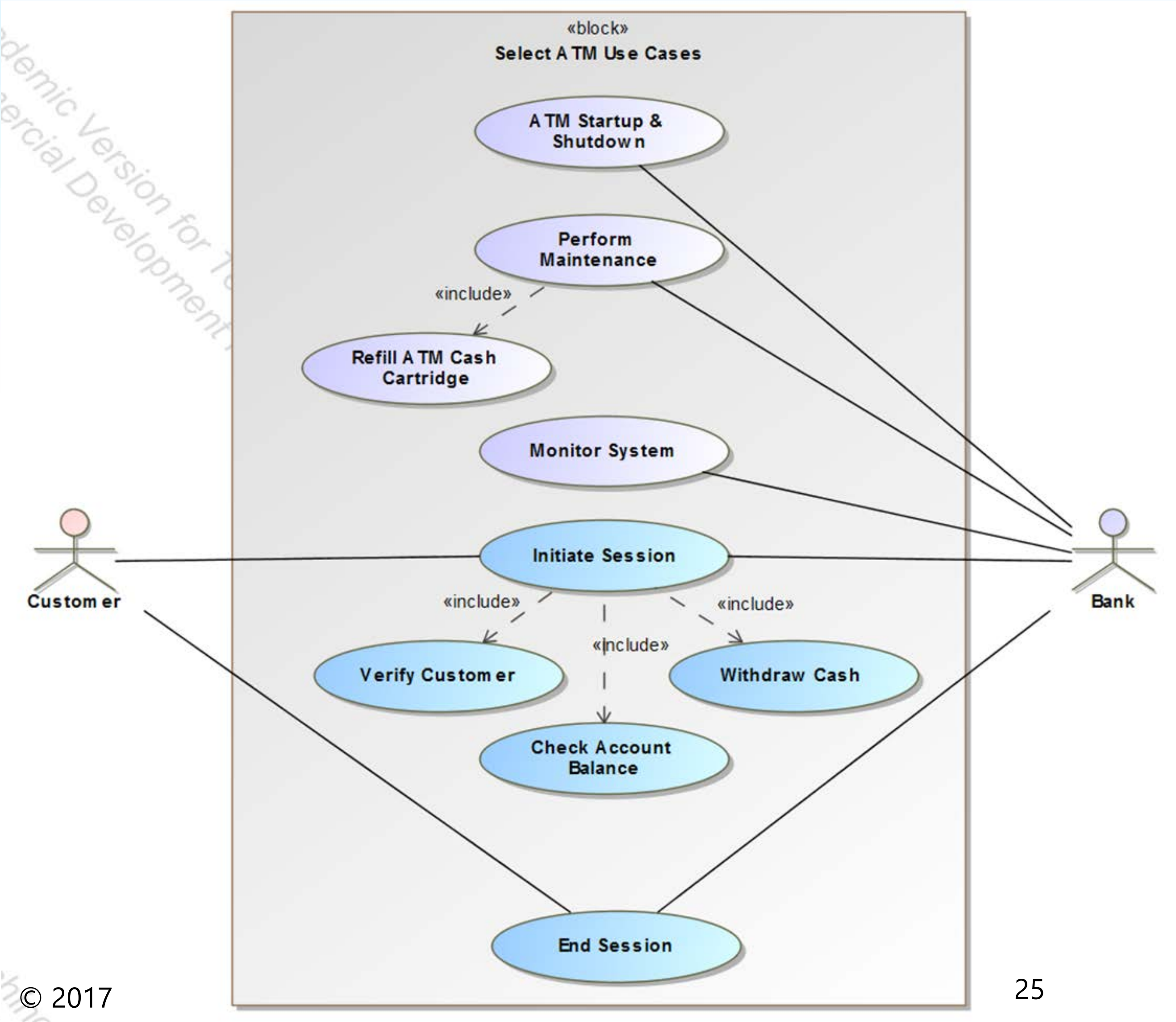
Use Case Diagrams



- Represents functionality in terms of how a system or other entity is used by external entities (i.e., actors) to accomplish a set of goals
  - Shows services the system performs.
  - Shows Actors that participate in the use cases.

- It's a good practice to use photos in place of stick figure actors to help customers identify with real life situations; this can be a very enlightening tool with stakeholders.

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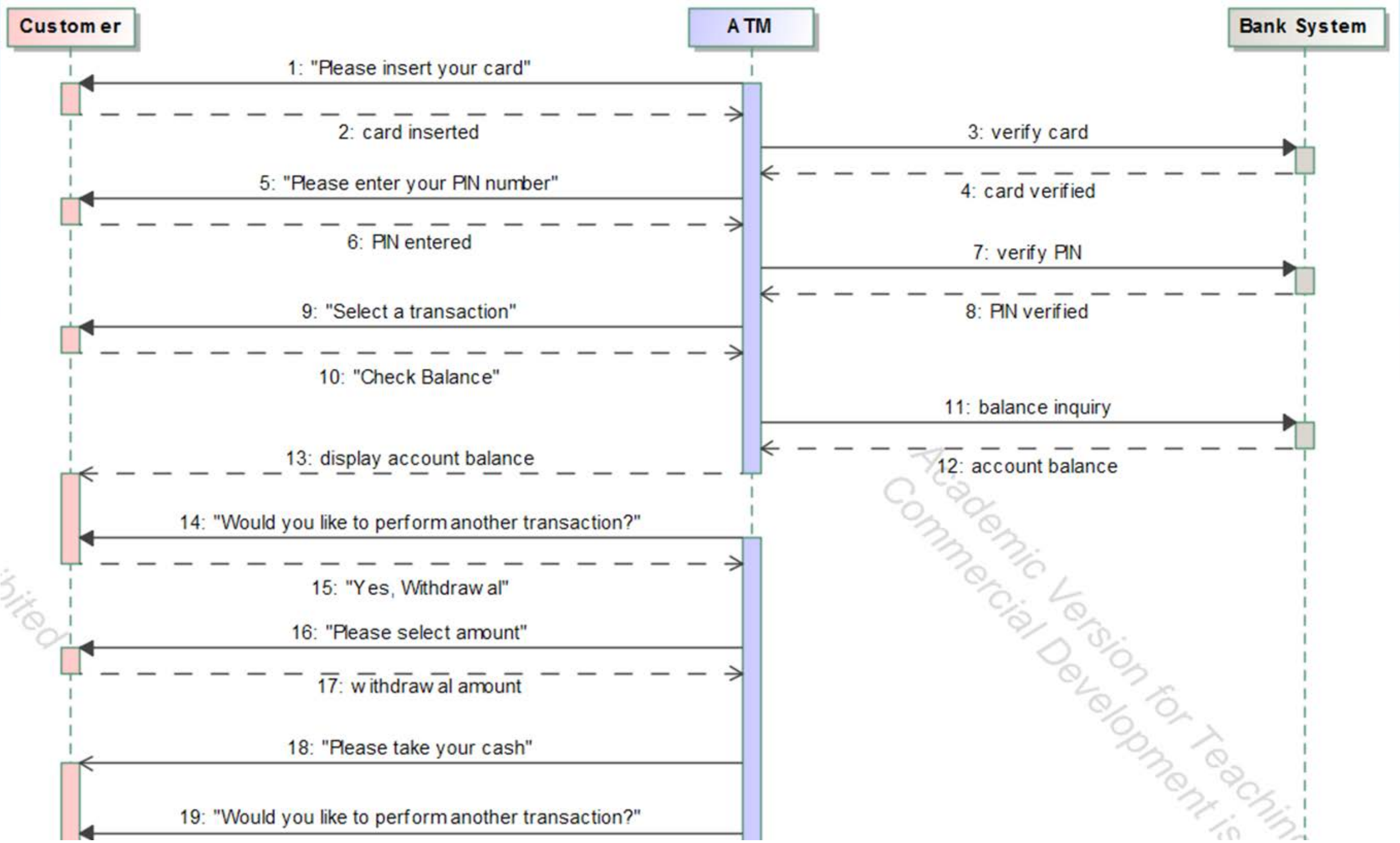
Sequence Diagrams

- Represents behavior in terms of a sequence of messages exchanged between parts
  - Focus of behavior is on how the blocks interact through calls and signals.
- Useful for test cases on event sequences.
- Requirements are often defined as sequence diagrams are developed.
- In modeling existing systems, missing requirements are often discovered at this stage.



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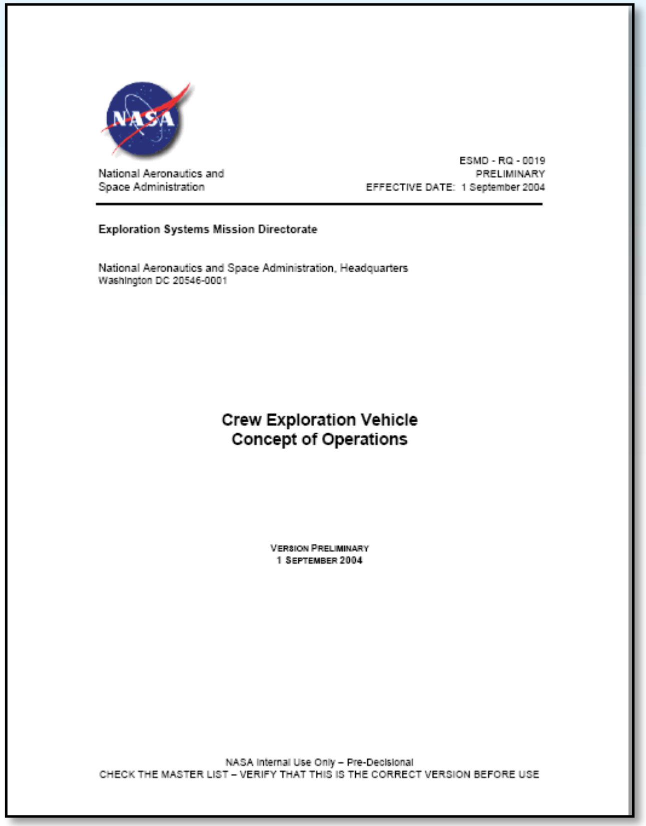
ConOps Anchors Requirements


National Aeronautics and Space Administration

ESMD - RQ - 0019
PRELIMINARY
EFFECTIVE DATE: 1 September 2004

Exploration Systems Mission Directorate

National Aeronautics and Space Administration, Headquarters
Washington DC 20546-0001

Crew Exploration Vehicle Concept of Operations

VERSION PRELIMINARY
1 SEPTEMBER 2004

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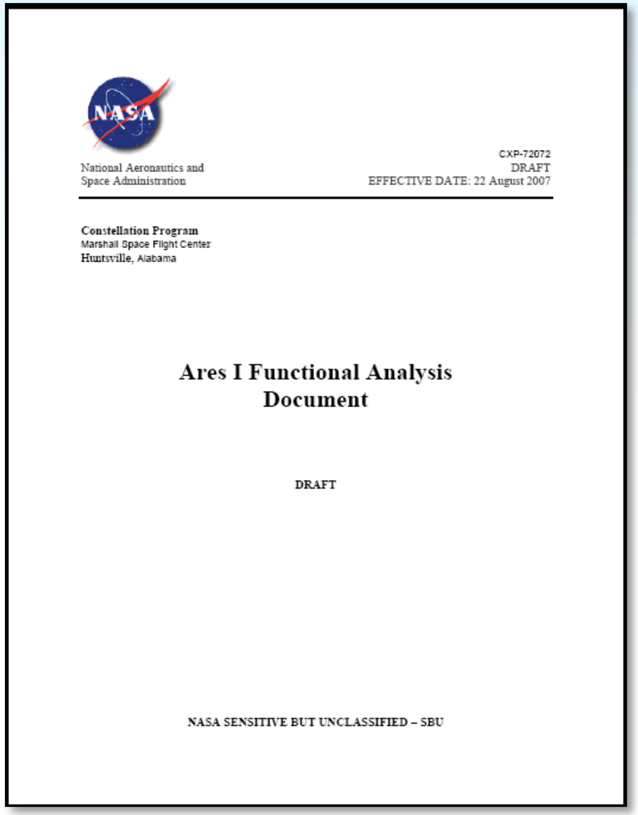
National Aeronautics and Space Administration

CXP-72072
DRAFT
EFFECTIVE DATE: 22 August 2007

Constellation Program
Marshall Space Flight Center
Huntsville, Alabama

Ares I Functional Analysis Document

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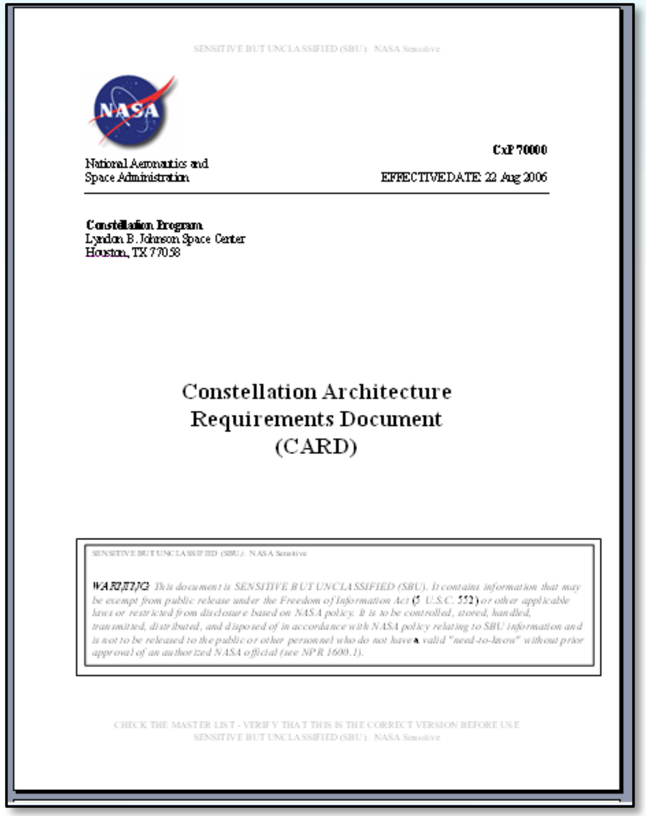
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National Aeronautics and Space Administration

CxP 70000
EFFECTIVE DATE: 22 Aug 2006

Constellation Program
Lyndon B. Johnson Space Center
Houston, TX 77058

Constellation Architecture Requirements Document (CARD)

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Operational Concept documents the mission scenarios, which provides the basis for the functions the system must perform.

Functional allocation and analysis provides the logical basis for system requirements.

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ConOps to FFBD to Requirements

CLV Concept of Operations

6.1 Launch Scrub Turnaround
In the event of a launch scrub turnaround, after the crew egresses the CEV, the CLV accepts the command to begin autonomous vehicle safing. The CLV facilitates the draining of propellants (if required) and vehicle safing.

Traces to

FFBD Function

ACON.2.16.4.9
Support CLV Scrub Turnaround

In the event of a launch scrub, the CLV supports the scrub turnaround. The CLV is returned to its pre-launch condition by safing the pyros, unloading of propellants, etc.

Traces to*

CLV Requirements

CLV.16
The CLV shall have an sufficient operational life to support 10 launch re-cycles.

CLV.90
The CLV shall be capable of consumable unloading at the launch site.

*Note – see FFBD traceability spreadsheets for all links

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Functional Analysis
(ref. Blanchard and Fabrycky, 2011)

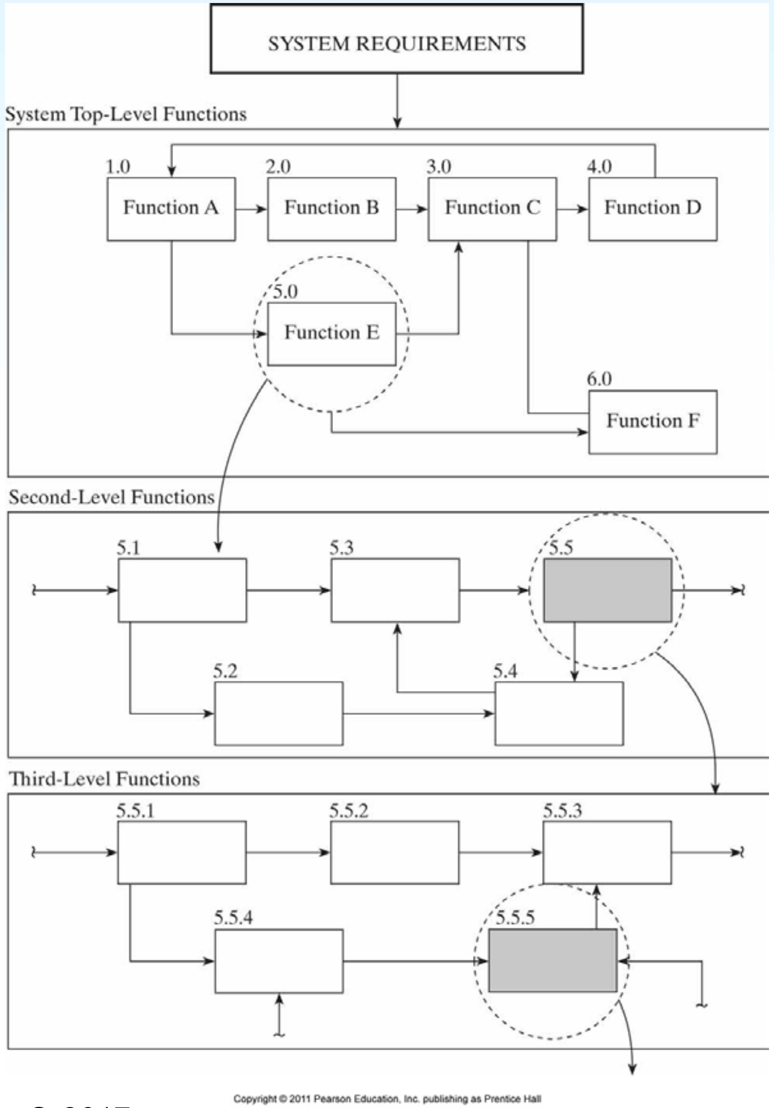

Figure 3.20 System functional breakdown

- The functional architecture is a *hierarchical model* of the functions performed by the system and the system's components.
- It includes the *flow* of informational and physical items from outside the system through the transformational processes of the system's functions and on to the waiting external systems being serviced by the system.
- Functional analysis is where the Operational Scenarios meet the System Architecture. Ideally, both are refined in lockstep.

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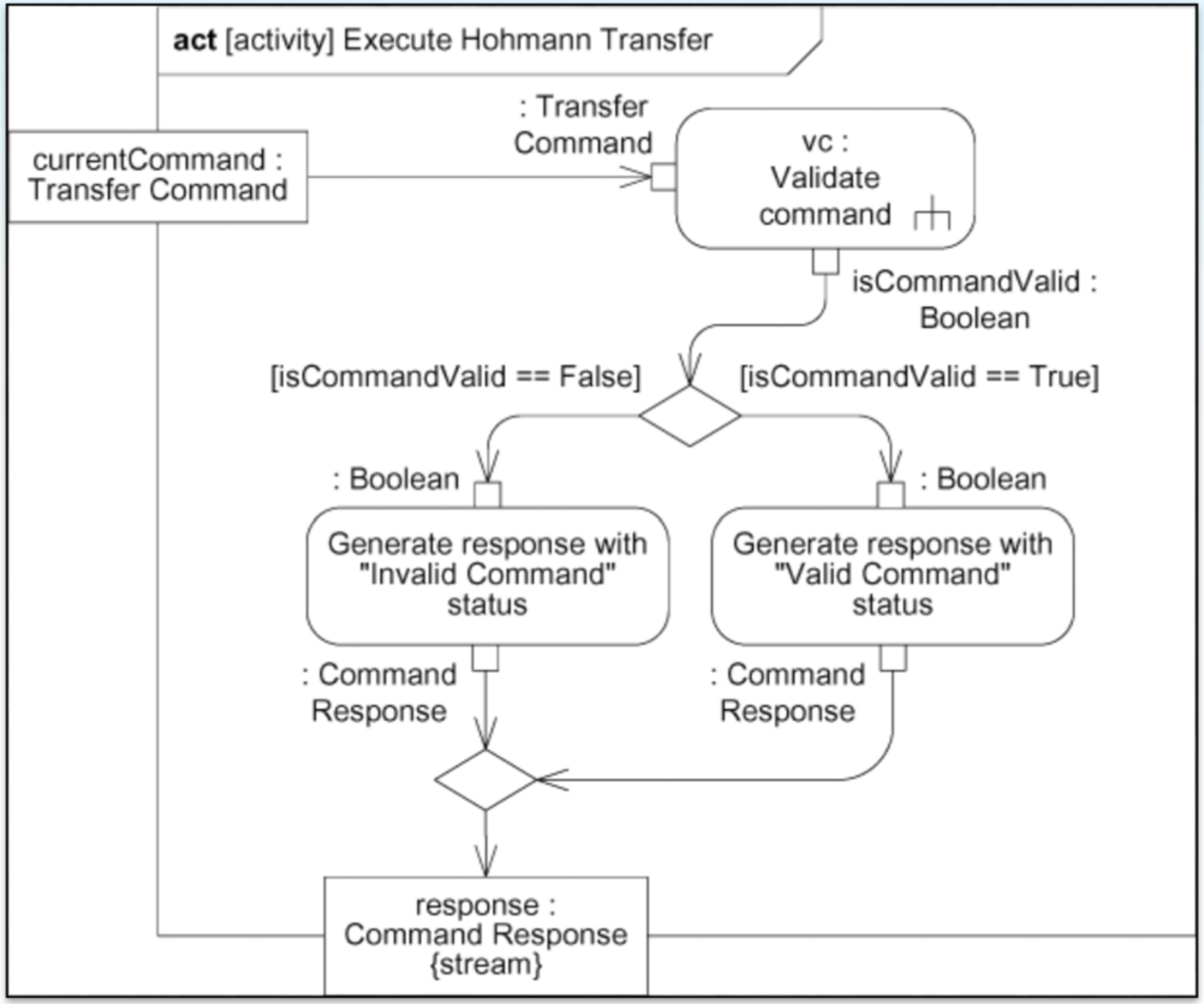
Activity Diagrams



(Image ref: Delligatti, Figure 6.10 on p. 100.)

- Represents behavior in terms of the ordering of actions based on the availability of inputs, outputs, and control, and how the actions transform the inputs to outputs
- Commonly used in analysis to understand desired behavior of system
- Missing requirements are often discovered when modeling behavior of existing systems via activity diagrams

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Operational Scenarios

(ref: ANSI/AIAA G-043A-2012)

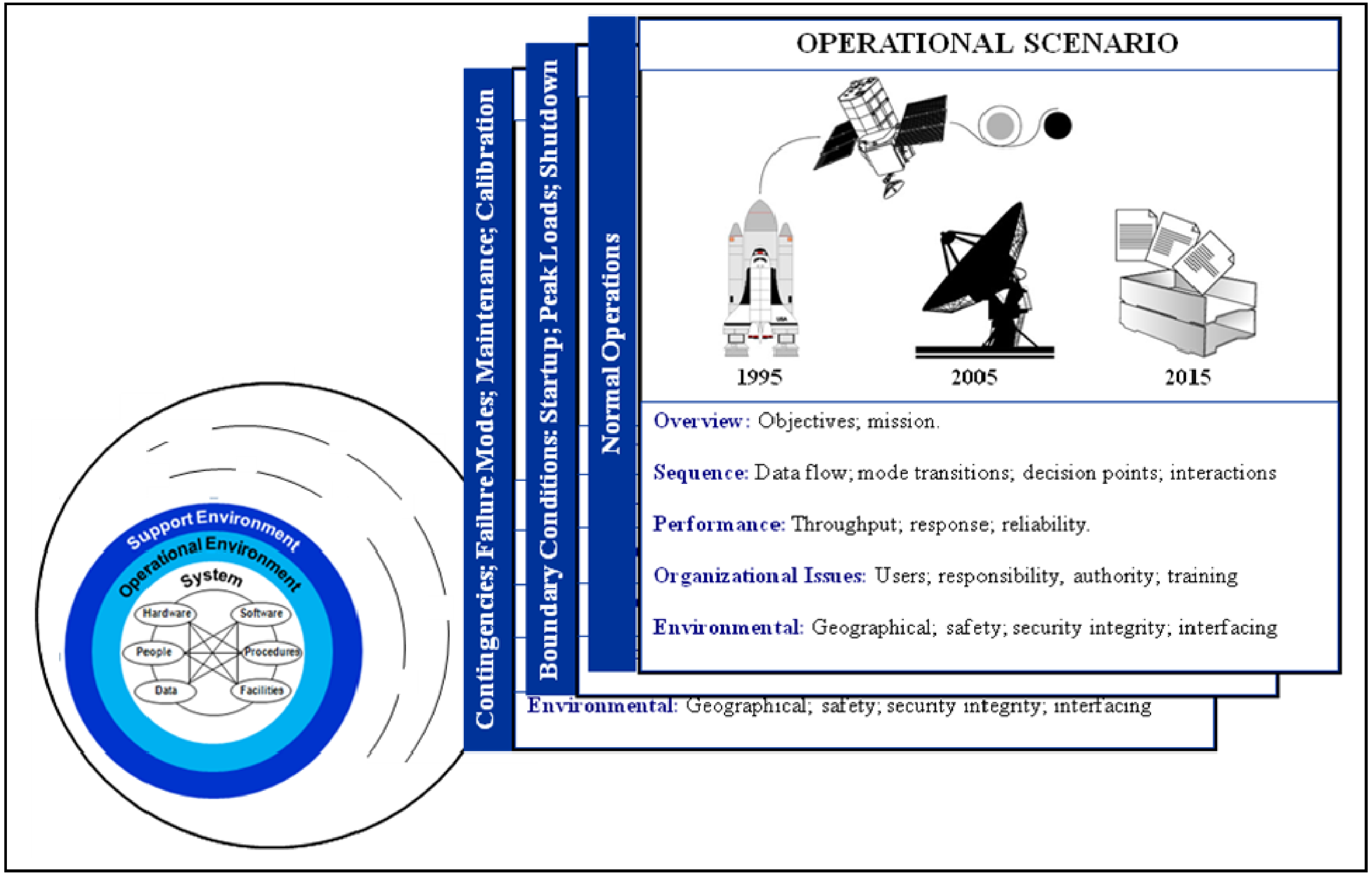

Figure 7 — The key to a successful operations concept document is the development of operational scenarios

- Describe the dynamic views of the system's operation, primarily from the users' points of view.
- Articulate how the system will *operate through various modes and mode transitions*, including its expected interactions with the external environment, outlining all important anticipated user, operator, tester, and maintainer interactions that provide the basis and framework for the system analysis and evaluation.

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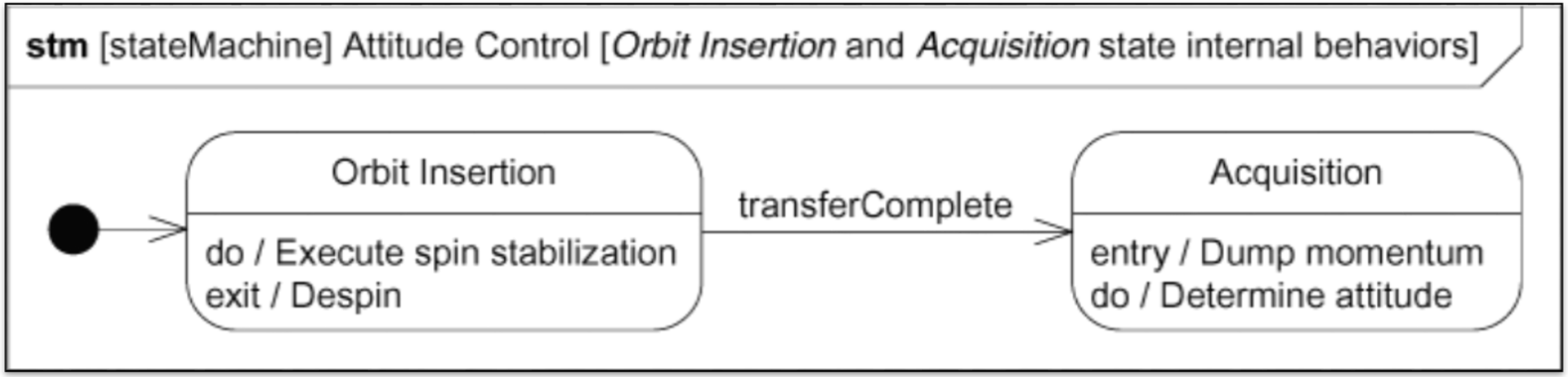
State Machine Diagrams

- Represents behavior of an entity in terms of its transitions between states triggered by events
- Useful in development stage of life cycle.
- Very helpful in functional requirements definition.
- Very useful in showing behaviors of multiple states that change in scenarios of operation of large scale systems.



(Image ref: Delligatti, Figure 8.2 on p. 159.)

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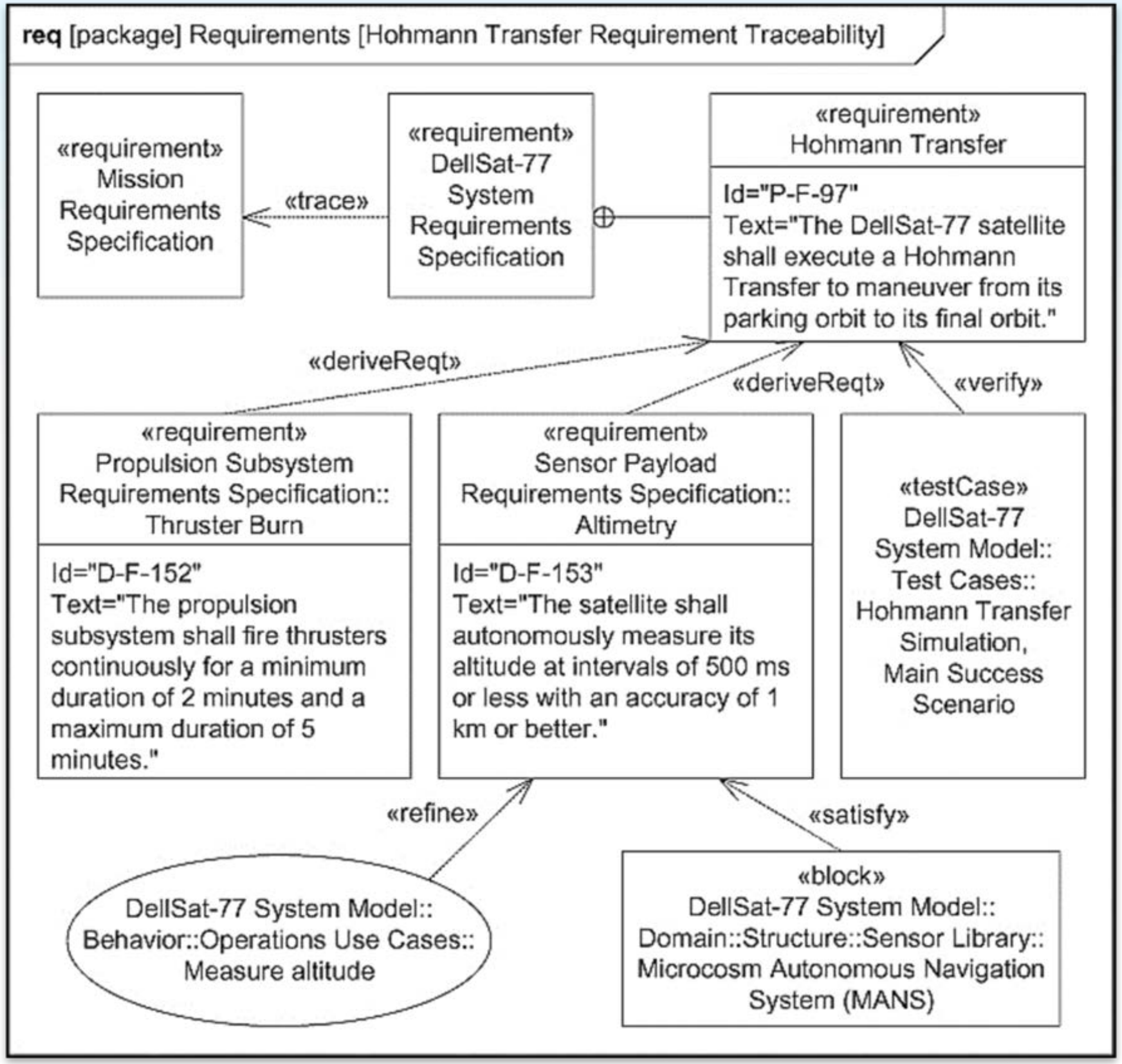
Requirements Diagrams



- Used to show text-based requirements
- Relationship between requirements can be shown
  - trace, containment, derive, refine, etc.
- Relationships to other model elements can be shown
  - satisfy, trace, verify, etc.
- Comment: In a project in which MBSE is being introduced, requirements diagrams can be key to making customers comfortable with the advantages of MBSE in impact analysis.

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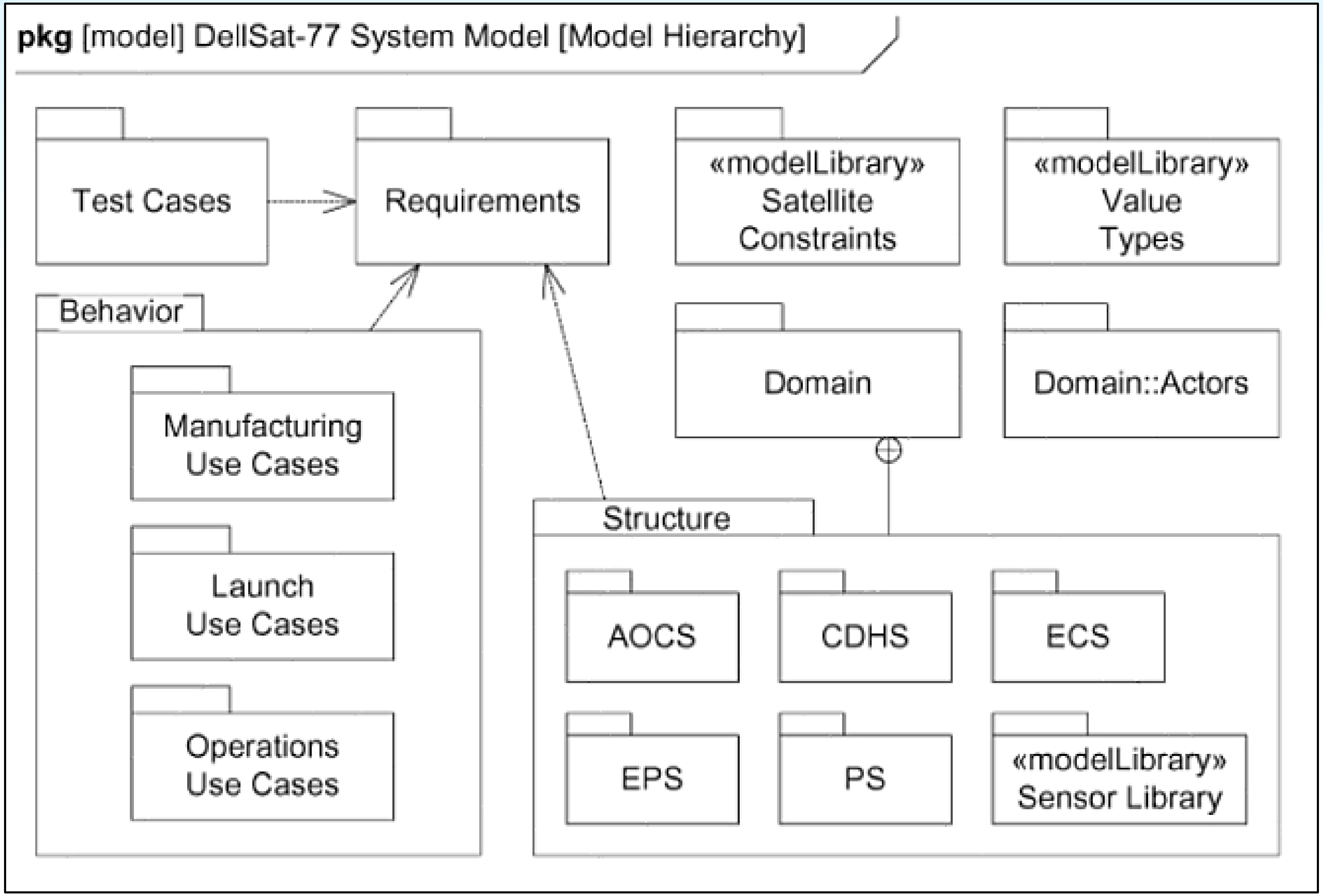
 (Image ref: Delligatti, Figure 11.1 on p. 203.)

Package Diagrams



(Image ref: Delligatti, Figure 10.1 on p. 191.)

- Displays the way that the integrated system model is organized from the various models comprising it.
- May show the dependencies between packages and their model elements.

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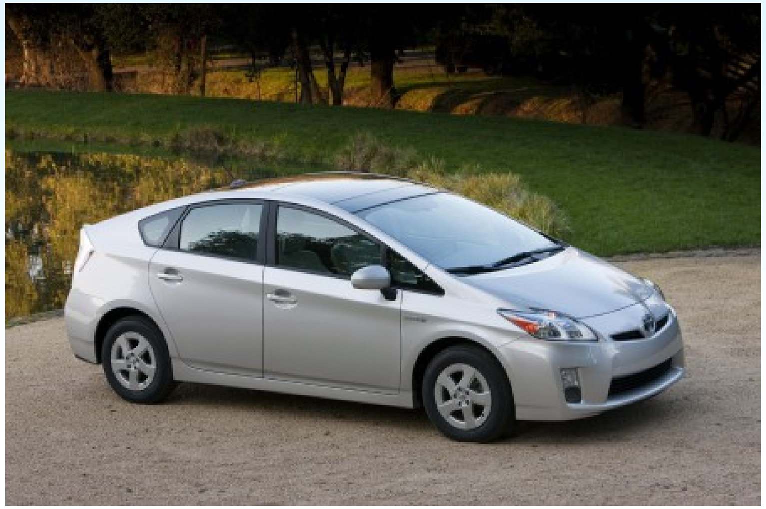
Typical Systems



Hybrid Car

Boeing 787 Dreamliner

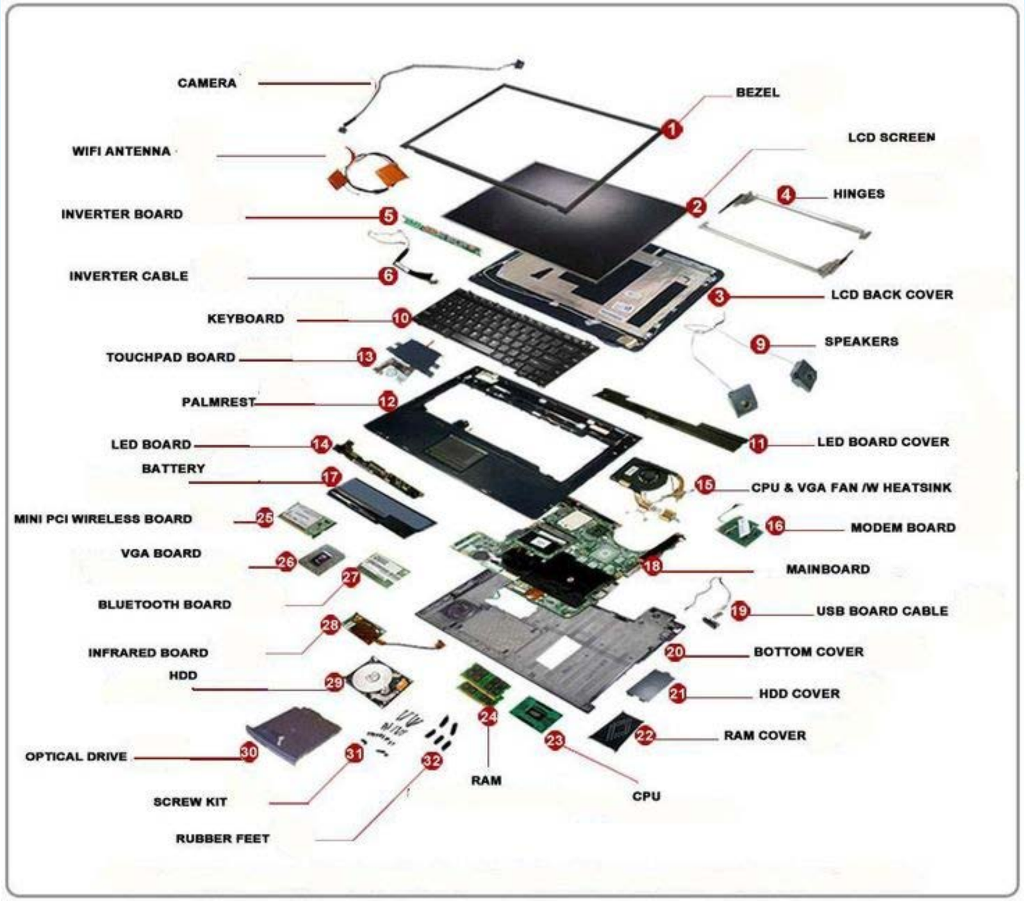
DC Metro subway train

Personal Computer (PC)

(ref: Muratore, 2010.)

Systems are Comprised of Components

Personal Computer (PC)



PC contains many components, including a mainboard that is in turn made of components (printed circuit board, various integrated circuits & electronic parts).

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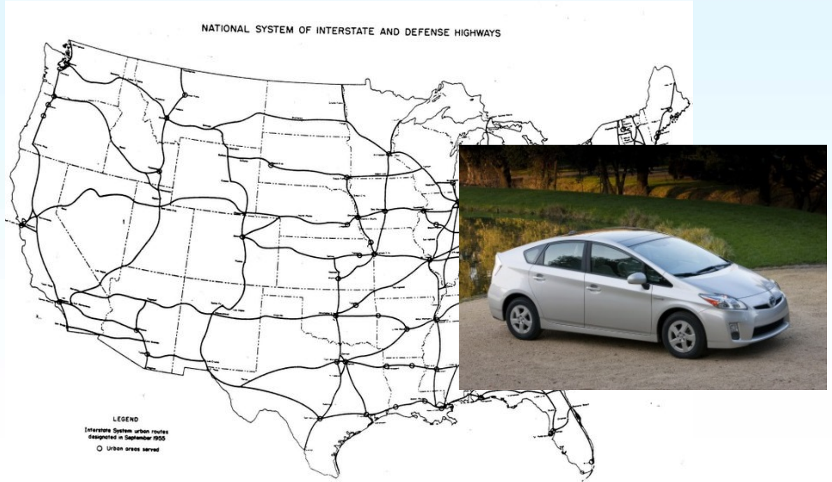
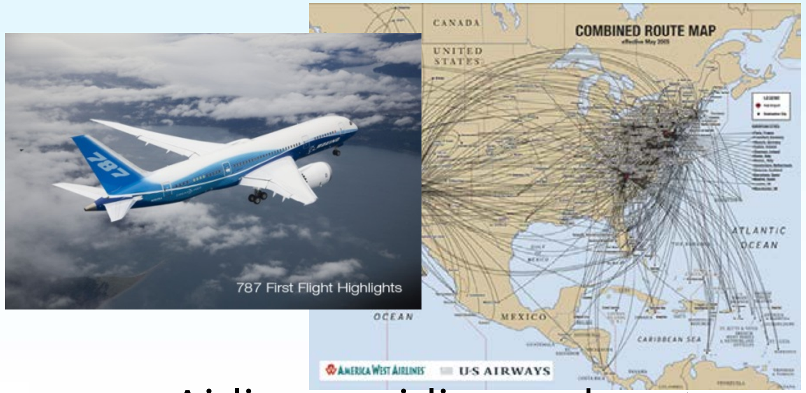
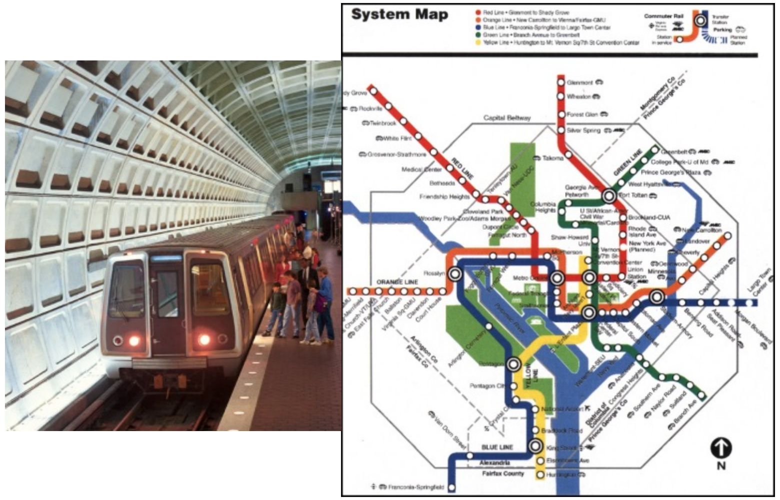
Systems are Often Components of Larger Systems



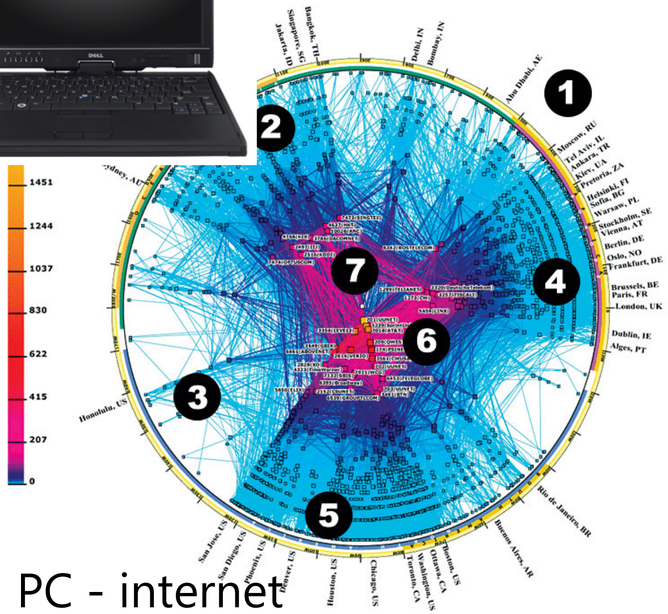
Car – highway system



Airliner – airline and routes



Subway train – subway system



PC - internet

(ref: Muratore, 2010.)

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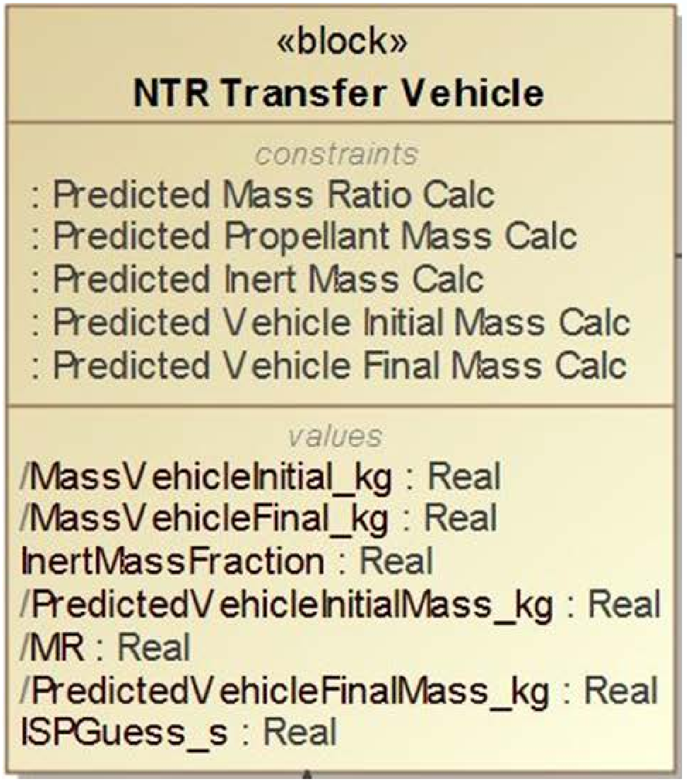
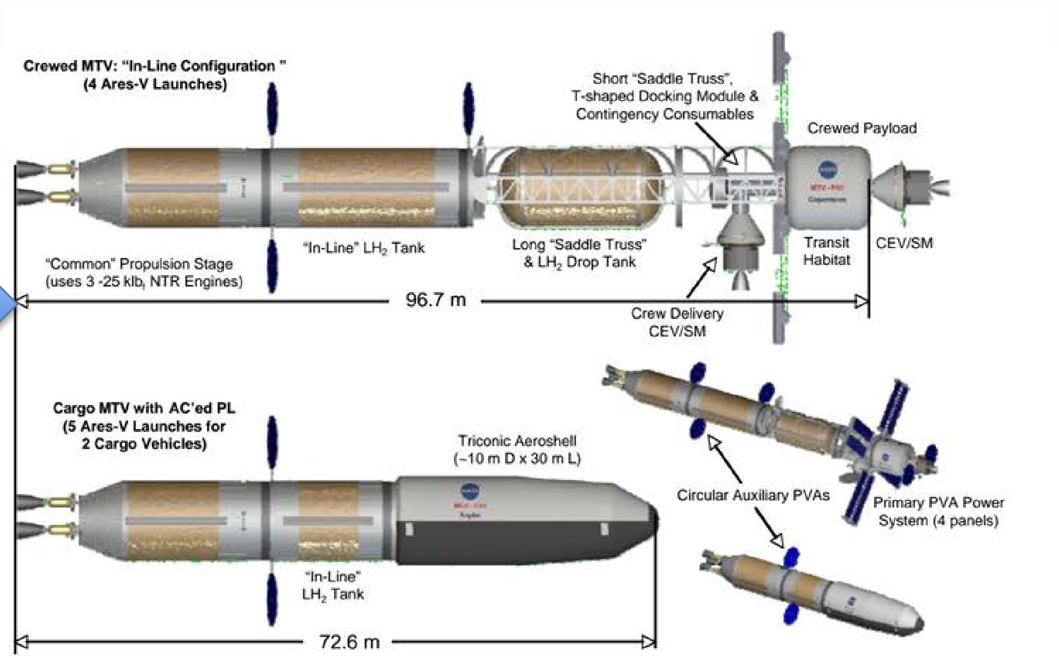
Block Definition Diagrams

- Displays system elements as blocks and identifies value types
- Shows relationships between system elements
  - Examples are system hierarchy trees and classification trees





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Parts

- Consider an automobile system. If the automobile is defined as the block, the wheels, engine, etc. are the parts, which may themselves be comprised of parts.

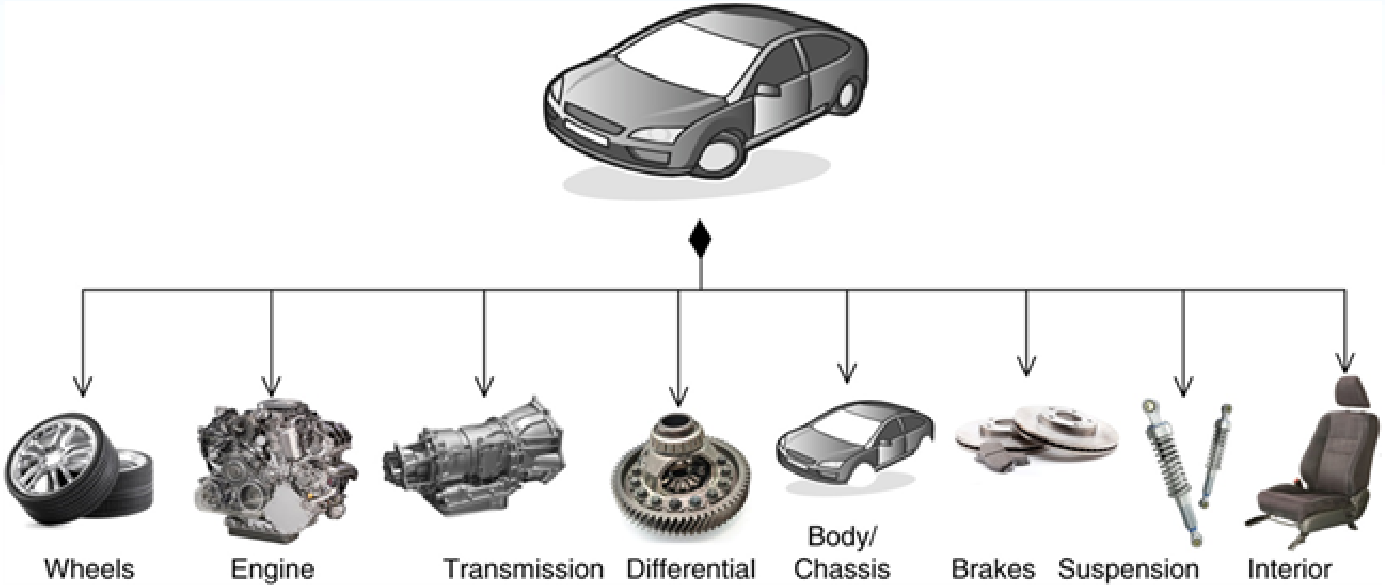

FIGURE 1.5
Automobile system decomposition into its components.

«block»
Automobile

parts

wheels: Wheel [4]
engine: Engine [1]
transmission: Transmission [1]
differential: Differential [1]
body/chassis: Body&Chassis [1]
brakes: Brakes [1]
suspension: Suspension [1]
interior: Interior [1]

(image ref: Friedenthal et.al., 2014)

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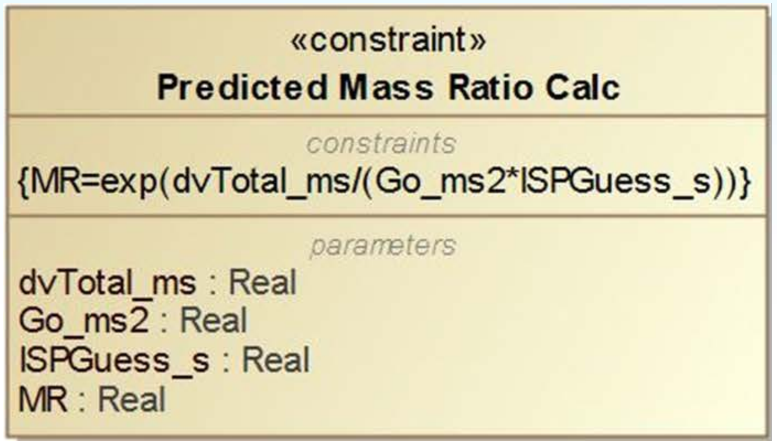
Parametric Diagram

- Used to evaluate system parameters
  - equations
  - inequalities
- Support engineering modeling and analysis
  - performance,
  - reliability,
  - availability,
  - power,
  - mass,
  - cost,
  - etc.



$$MR = \frac{M_i}{M_f} = EXP\left(\frac{\Delta V}{g_o * ISP}\right)$$

- Represents constraints on property values, such as F=m*a, used to support engineering analysis
- Can be used for trade studies of candidate architectures; this is a key feature and benefit of MBSE.

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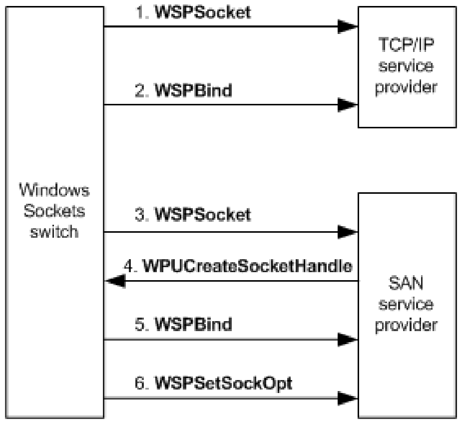
Hardware & Software Interfaces

- Physical object on a hardware object boundary
  - Spigot
  - HDMI jack
  - Fuel nozzle
  - Gauge
  - etc.

- Interaction point on a software object boundary
  - TCP/IP socket
  - Message queue
  - Shared memory segment
  - Graphical user interface
  - Data file
  - etc.



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Internal Block Diagrams (IBDs)

- IBDs are created in conjunction with BDDs to further describe blocks
  - IBDs show connections, flows, and/or services between parts of blocks and external references (think configuration)

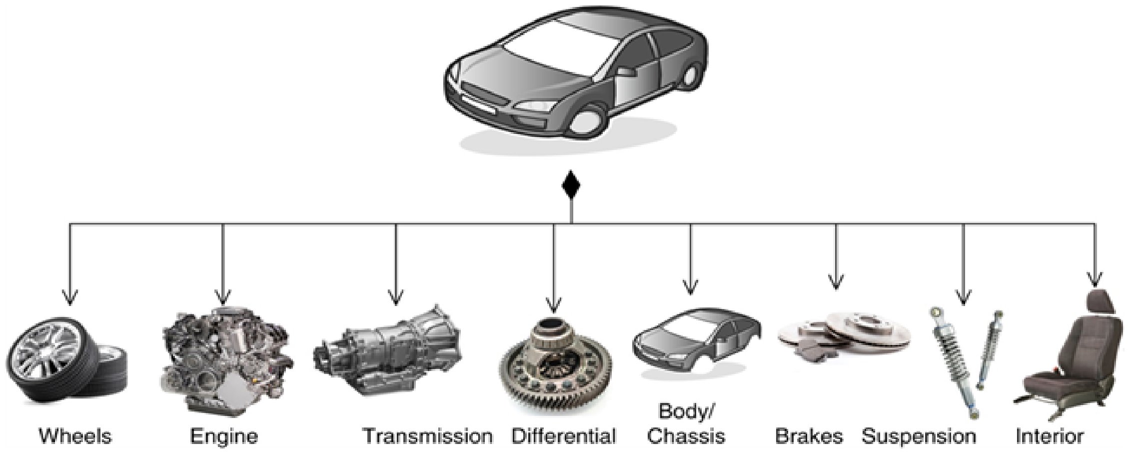

FIGURE 1.5
Automobile system decomposition into its components.

(image ref: Friedenthal et.al., 2014)

- IBDs and BDDs show complimentary views of blocks
  - BDDs show structure of a set of blocks
  - IBDs show relationships of parts internal to a block
- In the diagrams on the left, the BDD would depict that the automobile is comprised of all the parts, while the IBD would depict how the parts interact.
  - i.e. the engine has a both a rigid structural and a rotating structural interaction with the transmission.

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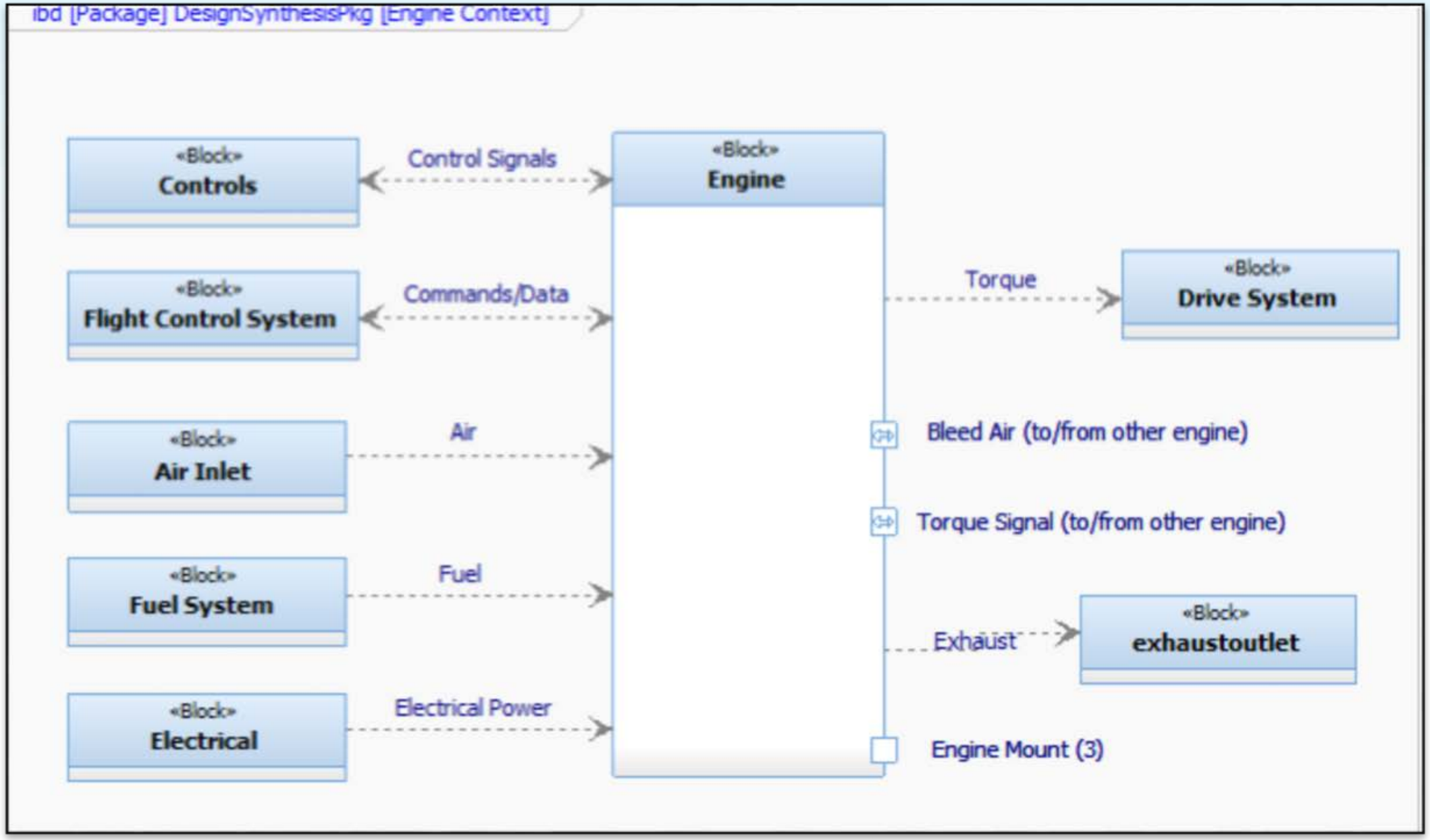
Internal Block Diagrams

- Represents interconnection and interfaces between the parts of a block
  - Shows the internal structure of a single block.
  - Shows interfaces of internal parts of a block.



(Image courtesy of Cheryl Hawkins.)

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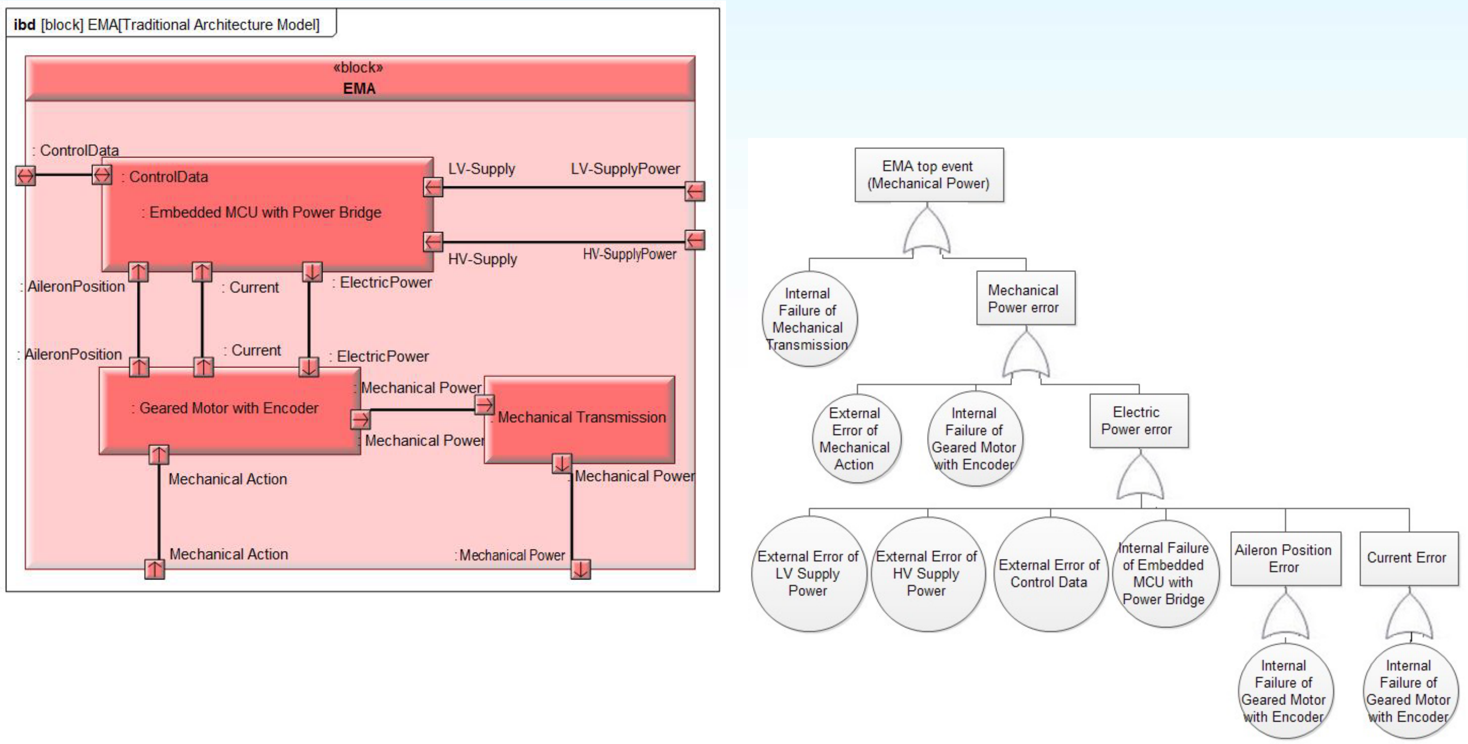
RAM Applications

- Research has shown that system models developed in SysML possess the requisite information to develop:
  - Reliability Block Diagrams (ref: Liu et.al., 2013)
  - Fault Trees (ref: Izygon et.al., 2016)
  - Failure Mode & Effects Criticality Analyses (ref: David et.al., 2010, Izygon et.al., 2016)
  - Hazard Propagation Models (ref: Zhou et.al., 2014)



(image ref: Mhenni, et.al., 2014)

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General Diagram Comments

- A diagram is a **view** of the model, not the model itself.
  - Similar to a picture of a mountain – the photograph is not the real geographical feature but a view of it
  - Different diagrams show different views and serve different purposes
- No diagram should be used to show every detail of a model; views should be specific to purpose.
- If an element doesn't exist on a diagram, that does not mean the element doesn't exist in the model.
- It takes many views, or diagrams, of the model to convey desired behavior of a system.

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Remarks

- System behavior described in ConOps & functional analysis in traditional systems engineering practice.
  - Traditionally captured in hierarchy of Systems Requirements documents.
  - Described in SysML by Use Case, Sequence, Activity, & State Machine with associated Requirements diagrams.

- System architecture and physical interactions traditionally described by drawing trees & mathematical models.
  - Traditionally described by geometric models & mathematical models with selected parameters controlled in interface description & control documents.
  - Described by Block, Parametric, and Internal Block diagrams.

- Selected systems analysis methods such as Reliability Block Diagrams lend themselves well to implementation in SysML.

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