Module Purpose: System Hierarchy

- To show how one view of the system architecture is captured by the product breakdown structure (PBS).
- To describe the benefits and costs of creating a system hierarchy.
- To show how to capture all of the work necessary for a project by adding the non-product work to the PBS to create the work breakdown structure (WBS).
One View of the Architecture - The Product Breakdown Structure

The framework and interrelationships of elements of a system. Typically illustrated by both a pictorial and a decomposition diagram depicting the segments and elements and their interfaces and interrelationships.

Architecture is described by the System Hierarchy or Product Breakdown Structure (PBS)

Why Break a Product Down?

Breaking a large complex problem (project) into smaller pieces makes them easier to solve since the problems are smaller and specialists can focus on their functional areas.

But this process of reductionism creates some new problems. Namely,

- New interfaces are created between the pieces (subsystems), so they must be defined and managed.
- System resources (e.g., mass or power) must be allocated to the subsystems and these allocations must be accounted for; and
- System performance is also allocated to subsystems, so confidence must be established that if all of the subsystems perform as desired, then the system will perform as desired.

The creation of the system architecture, the description and management of interfaces, the allocation of resources and performances, and establishing confidence that these allocations are appropriate are all systems engineering responsibilities.
More Value to Creating A System Hierarchy

- Organizes the work required to complete a flight project.
- Contains all hardware items, software items, and information items (e.g., documents, databases).
- Provides the basis for functional analysis.
- Characteristics:
  - Top-down,
  - Product-based,
  - Lowest level maps to cognizant engineer or manager,
  - Branch points in hierarchy show how elements will be integrated.

Hierarchical Level Names and Examples

<table>
<thead>
<tr>
<th>Hierarchical Level Name</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission</td>
<td>Needs + Objectives + Operation of Everything Necessary to Meet the Objectives</td>
</tr>
<tr>
<td>System*</td>
<td>Total System = Spacecraft + Launch Vehicle + Ground Support Equipment + Communications Systems (TDRSS, etc.) + NASCOM + POC + Science Data Center + ... + Personnel</td>
</tr>
<tr>
<td>Segment</td>
<td>Spacecraft = Structure + Power + C&amp;DH + Thermal + ...</td>
</tr>
<tr>
<td>Element</td>
<td>Flight = Spacecraft Bus + Instruments + Launch Vehicle + ...</td>
</tr>
<tr>
<td>Subsystem</td>
<td>Power = Solar Arrays + Electronics + Battery + Fuses + ...</td>
</tr>
<tr>
<td>Component</td>
<td>Solar Arrays = Solar Cells + Interconnects + Cover Glass + ...</td>
</tr>
<tr>
<td>Part</td>
<td>Solar Cells</td>
</tr>
</tbody>
</table>

* Any given system can be organized into a hierarchy composed of segments and/or elements of succeedingly lower and less complex levels, which may in themselves be termed “systems” by their designers. In order to avoid misunderstandings, hierarchical levels for a given mission must be defined early.
System Hierarchy (1/2)

- **Hierarchy/Hierarchical Levels** - The relationship of one item of hardware/software with respect to items above and below in the relative order of things.

- **Mission** - An individual system or groups of systems operated to meet a specific set of objectives.

- **System** - A composite of hardware, software, skills, personnel, and techniques capable of performing and/or supporting an operational role. A complete system includes related facilities, equipment, materials, services, software, technical data, and personnel required for its operation and support to the degree that it can be considered a self-sufficient unit in its intended operational and/or support environment.
  - The system is what is employed operationally and supported logistically. (More than one system may be needed to conduct a mission.)

System Hierarchy (2/2)

- **Segment** - A grouping of elements that are closely related and which often physically interface. It may consist of elements produced by several organizations and integrated by one.

- **Element** - A complete, integrated set of subsystems capable of accomplishing an operational role or function.

- **Subsystem** - A functional grouping of components that combine to perform a major function within an element.

- **Component** - A functional subdivision of a subsystem and generally a self-contained combination of items performing a function necessary for subsystem operation. A functional unit viewed as an entity for purpose of analysis, manufacturing, testing, or record keeping.

- **Part** - A hardware element that is not normally subject to further subdivision or disassembly without destruction of designated use.
System Hierarchy Example - Space Shuttle

System hierarchy is also referred to as the Product Breakdown Structure (PBS).

How complicated it can get...

The yellow boxes represent the bottom-level end products.
**Work Breakdown Structure (WBS)**

**Definition**

- A hierarchical breakdown of the work necessary to complete a project. The WBS should be a product-based, hierarchical division of deliverable items and associated services.
- The WBS is based on the System Hierarchy or Product Breakdown Structure (PBS), with the specified prime products at the top, and the systems, segments, subsystems, etc. at successive lower levels.
- At the lowest level are products, such as hardware and software for which there is a cognizant engineer or manager.
- The WBS is built from the PBS by adding (at each level) the necessary service elements, such as management, systems engineering, integration and verification, and logistics support.

**Relationship Between PBS and WBS**

The Product Breakdown Structure shows the components from which the system was formed.

The PBS reflects the work to produce the individual system components.

The Work Breakdown Structure shows all work components necessary to produce a complete system.

The WBS reflects the work to integrate the components into a system.
**Work Breakdown Structure (WBS)**

- A Work Breakdown System (WBS) is used for:
  - Task or work package planning and scheduling
  - Cost estimating or budget formulation
  - Product development documentation, e.g., documentation tree, systems engineering management plan (SEMP), drawings
  - Project status reporting and assessment

- The WBS should include:
  - All the work in the project life cycle, in-house and/or contracted
  - Hierarchical relationships of all work products
  - A companion dictionary to describe the content

- When should you have a WBS?
  - Pre-phase A; conceptual design phase; early mission/project formulation

**NASA Standard WBS at Level 2**

```
Space Flight Project

Project Management 01
  Systems Engineering 02
  Safety & Mission Assurance 03
  Science / Technology 04
  Payload(s) 05
  Spacecraft 06
  Mission Operations 07

Launch Vehicle / Services 08
Ground System(s) 09
Systems Integration & Testing 10
Education and Public Outreach 11
```

Standard Level 2 WBS Elements for Space Flight Projects
Example: NASA’s SOFIA Project PBS and WBS

PBS

Sofia Project

Observatory Sys.

Airborne Facility

Science Instrument

Labs/Offices

Mission Planning Syst.

Ground Support Sys.

Facility GSE

System Hierarchy Module

WBS

Sofia Project

Manager

Systems Engineering

Project Integration & Test

Operations and Logistic Planning

Science Support

Mission Assurance

Observatory System

Ground Support System

Plant and Learn Opportunity

Pause and Learn Opportunity

View the James Webb Space Telescope (JWST) WBS & Dictionary Baseline document for example implementation.

(JWST WBS & Dictionary (Baseline).pdf)
Techniques for Developing a WBS

- Takes several iterations through the life of the project, since the full extent of the work is not obvious at the outset.
- Develop System Hierarchy / PBS first, from the top down
- Develop WBS by adding appropriate services, such as management and systems engineering to the lower levels
- Use a similar structure as a starting point for all product elements of the WBS at all levels
- Repeat for all levels, starting with project level
- Involve people who will be responsible for the lower level WBS elements.
- Document assumptions, e.g., common spacecraft computer and software; all operations development costs under mission ops; testbeds and prototype hardware contained within hardware element etc.

Module Summary: System Hierarchy

- A product breakdown structure (PBS) captures the hierarchy of the system and is one representation of the system architecture.
- Creating a system hierarchy is valuable since it breaks a complex problem into smaller pieces that will be easier to tackle.
- But this reductionism, or decomposition has a price:
  - New interfaces are created between the pieces (subsystems), so they must be defined and managed.
  - System resources (e.g., mass or power) must allocated to the subsystems and these allocations must be accounted for; and
  - System performance is also allocated to subsystems, so confidence must be established that if all of the subsystems perform as desired that the system will perform as desired.
- The work breakdown structure (WBS) extends the PBS in that it captures all of the work necessary for a project by adding the non-product work necessary for a successful project (e.g., integration, test, logistics support, systems engineering and management).
Backup Slides
for System Hierarchy Module

Note slides 26-28 demonstrate some common errors in PBS and WBS structure. The pilot students found these useful, so they could be included in the body of the lecture.

NASA Space Flight Project
Standard WBS Dictionary (1/4)

- **Element 1 – Project Management**: The business and administrative planning, organizing, directing, coordinating, analyzing, controlling, and approval processes used to accomplish overall project objectives, which are not associated with specific hardware or software elements. This element includes project reviews and documentation, non-project owned facilities, and project reserves. It excludes costs associated with technical planning and management and costs associated with delivering specific engineering, hardware and software products.

- **Element 2 – Systems Engineering**: The technical and management efforts of directing and controlling an integrated engineering effort for the project. This element includes the efforts to define the project space flight vehicle(s) and ground system, conducting trade studies, the integrated planning and control of the technical program efforts of design engineering, software engineering, specialty engineering, system architecture development and integrated test planning, system requirements writing, configuration control, technical oversight, control and monitoring of the technical program, and risk management activities. Documentation products include requirements documents, interface control documents (ICDs), Risk Management Plan, and master verification and validation (V&V) plan. Excludes any design engineering costs.

- **Element 3 – Safety and Mission Assurance**: The technical and management efforts of directing and controlling the safety and mission assurance elements of the project. This element includes design, development, review, and verification of practices and procedures and mission success criteria intended to assure that the delivered spacecraft, ground systems, mission operations, and payload(s) meet performance requirements and function for their intended lifetimes. This element excludes mission and product assurance efforts directed at partners and subcontractors other than a review/oversight function, and the direct costs of environmental testing.
Element 4 - Science/Technology: This element includes the managing, directing, and controlling of the science investigation aspects, as well as leading, managing, and performing the technology demonstration elements of the Project. The costs incurred to cover the Principal Investigator, Project Scientist, science team members, and equivalent personnel for technology demonstrations are included. Specific responsibilities include defining the science or demonstration requirements; ensuring the integration of these requirements with the payloads, spacecraft, ground systems, and mission operations; providing the algorithms for data processing and analyses; and performing data analysis and archiving. This element excludes hardware and software for onboard science investigative instruments/payloads.

Element 5 - Payload: This element includes the equipment provided for special purposes in addition to the normal equipment (i.e., GSE) integral to the spacecraft. This includes leading, managing, and implementing the hardware and software payloads that perform the scientific experimental and data gathering functions placed on board the spacecraft, as well as the technology demonstration for the mission.

Element 6 - Spacecraft(s): The spacecraft that serves as the platform for carrying payload(s), instrument(s), humans, and other mission-oriented equipment in space to the mission destination(s) to achieve the mission objectives. The spacecraft may be a single spacecraft or multiple spacecraft/modules (i.e., cruise stage, orbiter, lander, or rover modules). Each spacecraft/module of the system includes the following subsystems, as appropriate: Crew, Power, Command & Data Handling, Telecommunications, Mechanical, Thermal, Propulsion, Guidance Navigation and Control, Wiring Harness, and Flight Software. This element also includes all design, development, production, assembly, test efforts, and associated GSE to deliver the completed system for integration with the launch vehicle and payload. This element does not include integration and test with payloads and other project systems.

Element 7 - Mission Operations System: The management of the development and implementation of personnel, procedures, documentation, and training required to conduct mission operations. This element includes tracking, commanding, receiving/processing telemetry, analyses of system status, trajectory analysis, orbit determination, maneuver analysis, target body orbit/ephemeris updates, and disposal of remaining end-of-mission resources. The same WBS structure is used for Phase E Mission Operation Systems but with inactive elements defined as “not applicable.” However, different accounts must be used for Phase E due to NASA cost reporting requirements. This element does not include integration and test with the other project systems.

Element 8 - Launch Vehicle/Services: The management and implementation of activities required to place the spacecraft directly into its operational environment, or on a trajectory towards its intended target. This element includes launch vehicle, launch vehicle integration, launch operations, any other associated launch services (frequently includes an upper-stage propulsion system), and associated ground support equipment. This element does not include the integration and test with the other project systems.
Element 9 – Ground System(s): The complex of equipment, hardware, software, networks, and mission-unique facilities required to conduct mission operations of the spacecraft systems and payloads. This complex includes the computers, communications, operating systems, and networking equipment needed to interconnect and host the Mission Operations software. This element includes the design, development, implementation, integration, test, and the associated support equipment of the ground system, including the hardware and software needed for processing, archiving, and distributing telemetry and radiometric data and for commanding the spacecraft. Also includes the use and maintenance of the project testbeds and project-owned facilities. This element does not include integration and test with the other project systems and conducting mission operations.

Element 10 – Systems Integration and Testing: This element includes the hardware, software, procedures, and project-owned facilities required to perform the integration and testing of the project’s systems, payloads, spacecraft, launch vehicle/services, and mission operations.

Element 11 – Education and Public Outreach: Provide for the education and public outreach (EPO) responsibilities of NASA's missions, projects, and programs in alignment with the Strategic Plan for Education. Includes management and coordinated activities, formal education, informal education, public outreach, media support, and website development.
Rules for the NASA Standard WBS

1. The Project Name will be WBS Level 1.

2. The title of each WBS Level 2 element can be modified to facilitate project-unique titles, but the content of each must remain the same. If the linkage of the project-unique title to the standard title is not intuitive, the project-unique title is cross-referenced to the standard.

3. If the set of standard WBS Level 2 elements does not comprise an exhaustive set of WBS elements, additional WBS elements may be added horizontally (i.e., at Level 2) as long as their content does not fit into the content of any existing standard WBS elements.

4. For each standard WBS Level 2 element, the subordinate (children) WBS elements at Level 3 and lower will be determined by the project.

5. The Level 3 and lower elements can differ from project to project but will include only work that rolls up to the standard WBS Dictionary definition of the Level 2 element. (See back-up for definitions.)

6. If there is no work to fit into a standard WBS element, then an inactive placeholder element (and an inactive placeholder financial code) will be established.

7. A single WBS will be used for both technical/business management and reporting.

8. The management assigned to each WBS element may differ from project to project.

Common WBS Errors (1/3)

• **Error 1: Functions without products.**
  - The WBS describes functions not products.
  - This makes the project manager the only one formally responsible for products.
Common WBS Errors (2/3)

- **Error 2**: Inappropriate branches
  - The WBS has branch points that are not consistent with how the WBS elements will be integrated.
  - Inappropriate to separate hardware and software as if they are separate systems to be integrated at the system level.
  - This makes it difficult to assign accountability for integration and to identify the costs of integrating and testing components of a system.

![Diagram of WBS structure with distributed information system, software, and hardware branches.]

Common WBS Errors (3/3)

- **Error 3**: Inconsistency with PBS
  - The WBS is inconsistent with the PBS.
  - This makes it possible that the PBS will not be fully implemented, and complicates the management process.

![Diagram showing the Work Breakdown System and Product Breakdown System with substructures like Telescope Assembly, Optics/Mirror, and other elements.]
Additional information for WBS module related to organizational structure

Relationship Between WBS and Organization

- Organizational structure for a program and/or project usually aligns with the WBS. Although the staffing of the functions can be addressed in a variety of ways based on the culture and size of the organization.

- Good reference on engineering organizational structures: “Systems Engineering Management” by Benjamin Blanchard (chapter 7)
  - Matrix organization structure (section 7.3.3)
  - Producer organization (combined project-functional structure) (section 7.3.4)

- Examples:
  - Exploration Systems (see next chart)
Organizational Structure for Exploration

Level 1
- NASA Headquarters
  - Exploration Systems Mission Directorate
  - Washington, DC

Level 2
- Constellation Program Office
  - Johnson Space Center (JSC)
  - Houston, TX

Level 3
- CEV/Orion Project Office
  - JSC
  - Houston, TX
- Atlas 1 Launch Vehicle Project Office
  - MSFC
  - Huntsville, AL
- Launch Systems Project Office
  - KSC
  - Florida

Level 4
- Prime Contractor
  - Lockheed-Martin
- Subcontractor
  - National
- Suppliers
  - National
- Service Module
  - GRC
  - Ohio
- Launch Escape System
  - LaRC
  - Virginia

Example for NASA human spaceflight effort. Reflects derivation of authority from HQ to Program to Projects. Requirements flow in same top-down direction.

Organizational Structure of Level 2 Box

Constellation Program

Program Manager
- J. Harley
- Deputy Manager
- M. Fryer

Office of the Program Manager
- Office of the Program Systems Engineer (M.)
- Chief Engineer (M.)
- Chief Medical Officer (M.)

Chief of Staff
- Associate Program Manager NASIC
- Special Assistant Integration Headquarters
- Special Assistant for Technology Integration
- Assistant for Strategic Communications

Program Planning & Control Office
- Crew Exploration Vehicle Project
- Exploration Launch Projects
- Ground Operations Project
- Mission Operations Project
- EVA Systems Project
- Lunar Lander Project

Test and Verification Office

Operations Integration Office

Systems Integration Office

Safety, Reliability & Quality Assurance Office

Advanced Projects Office

Counter signatures:
- Jeffrey M. Hanley, Manager
- [Signature]
**Constellation Program**

**Systems Engineering & Integration (SE&I)**

**SE&I Director**
Chris Hardcastle

**Deputies**
Charlie Lundquist - Transition & Integration
David Petri - Planning & Performance

**CoS Organization**
Jason Weeks (A)

**Secretary**
Tina Cobb (C)

**Secretary**
LaNell Cobarruvias (C)

---

**Technical Staff**
CoS/CX P. - John Baker (M)
Chief Architect: Bret Drake**
Verification: John Kennedy

SI/Time Phased Capability: Keith Williams
Avionics & Disl: Jeff Stephenson

---

**SECB**

**Supportability/Operability/Affordability**
Kevin Watson / TBD

---

**Technical Staff**
Program Technical Integration
Chief: Margarita Sampson
Deputy: Nancy USA
Deputy: Kerri Knotts **

SW & Avionics Integration Office
Chief: Monte Goforth
Deputy: Dan Hendel
CSP/MSWG
DBI/SGWG

Analysis, Trades & Architecture
Chief: Neil Lemmons
Deputy: Deb Ludwig (A)
AIG

Process, Requirements & Interface Management Office
Chief: Michele Digiuseppe
Deputy: Debbie Nash

---

**Notes:**
- **M** = Matrixed
- **A** = Acting
- **C** = Contractor
- **TBD** = To Be Determined
- **** = Post LAT 2 Team Assignment

---

Space Systems Engineering: System Hierarchy Module