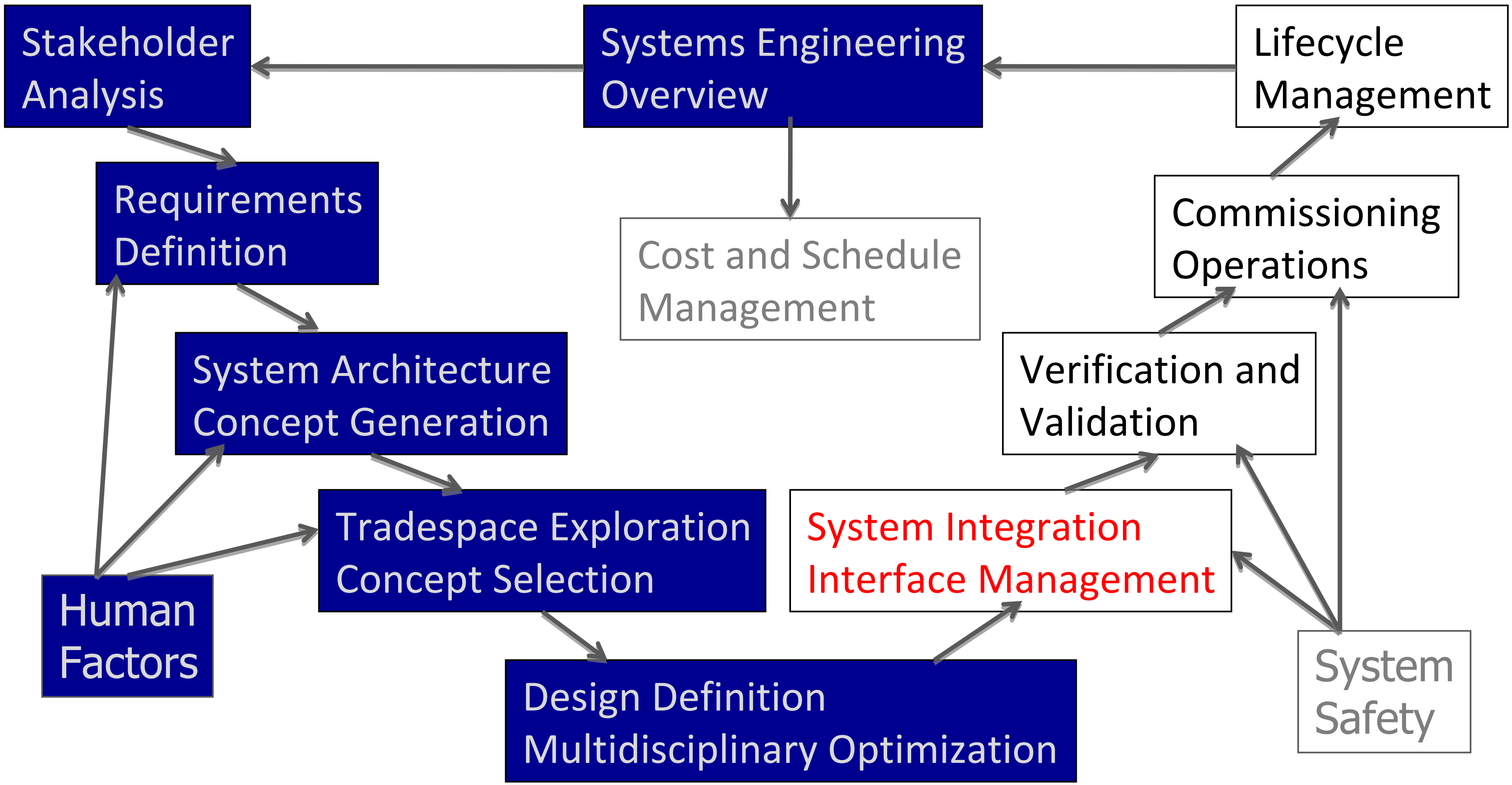
October 30, 2009

16.842 Fundamentals of Systems Engineering

Lecture 8 – Systems Integration and Interface Management

Prof. Olivier de Weck

V-Model – Oct 30, 2009



Outline

- Why is interface management important?
  - System failures due to interfaces
  - Working with partners and suppliers
- Interface Management
  - Types of Interfaces
  - Design Structure Matrix
  - Interface Control Documents (ICD) – NASA Approach
- System Integration
- Movie Clip: Apollo Lander – System Integration
  - From the Earth to the Moon (15 min)

Interface Failures

- Much effort is spent on designing individual parts of a system
  - Functionality, tolerances, mean-time-between-failure (MTBF)
  - Interfaces are often neglected and can be the “weak points”
    - Bottlenecks, Structural failures, Erroneous function calls

This photograph of a rocket explosion has been removed due to copyright restrictions.

This photograph of traffic accident has been removed due to copyright restrictions

As a result of its failure, the active inertial reference system transmitted essentially diagnostic information to the launcher's main computer, where it was interpreted as flight data and used for flight control calculations. On the basis of those calculations the main computer commanded the booster nozzles, and somewhat later the main engine nozzle also, to make a large correction for an attitude deviation that had not occurred.

Merging from side road
to main road (Russia 2007)

Ariane 501
Accident report (1996)

Working with Suppliers

Complex aerospace systems are increasingly designed (and built)
By geographically distributed teams, requiring careful definition of interfaces

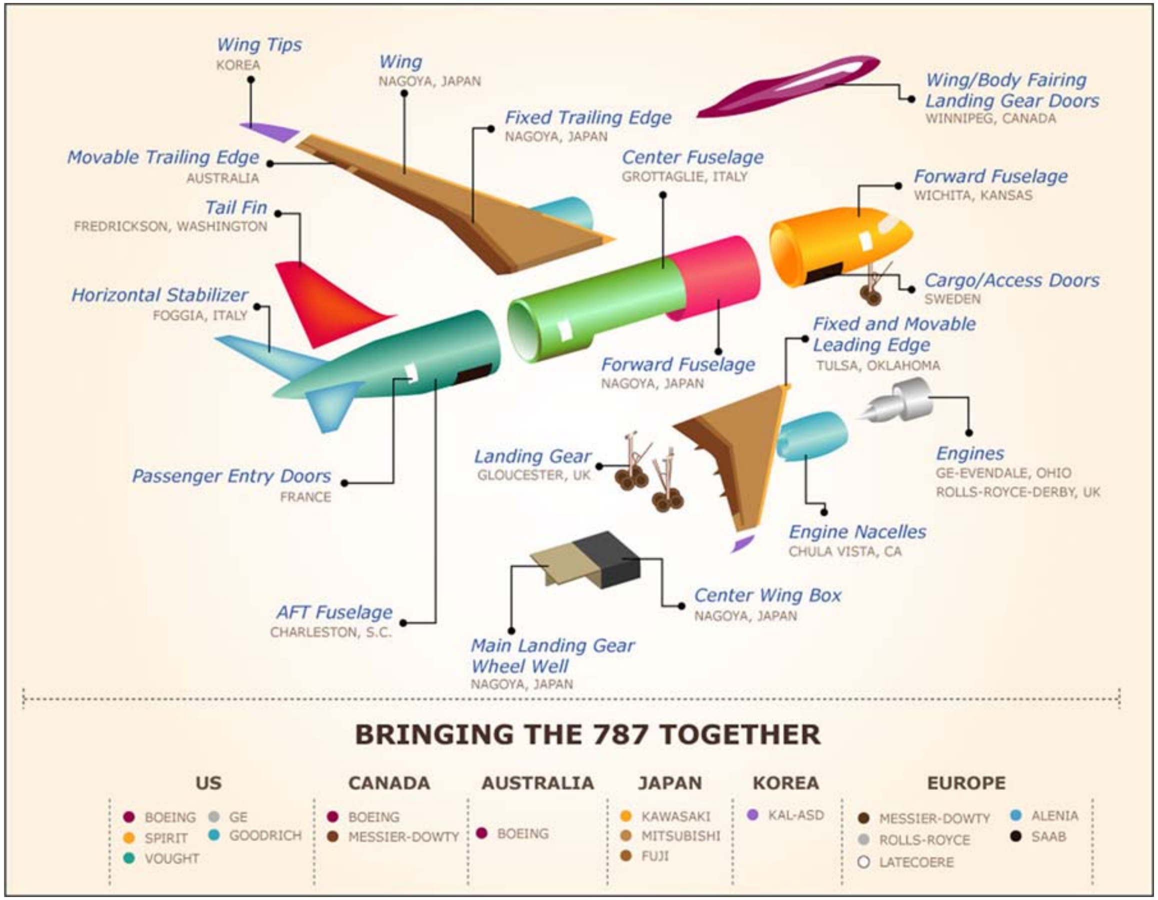
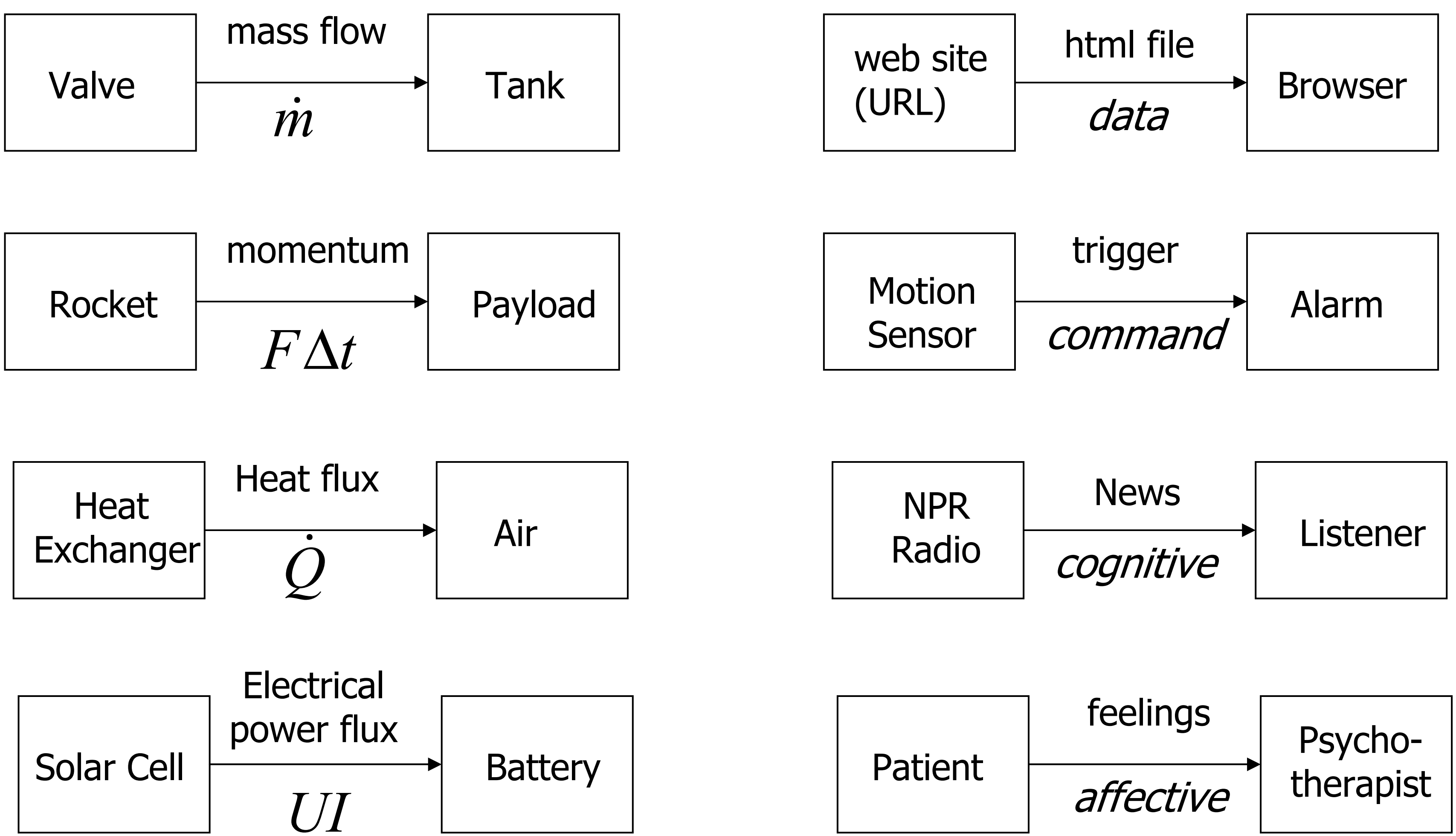


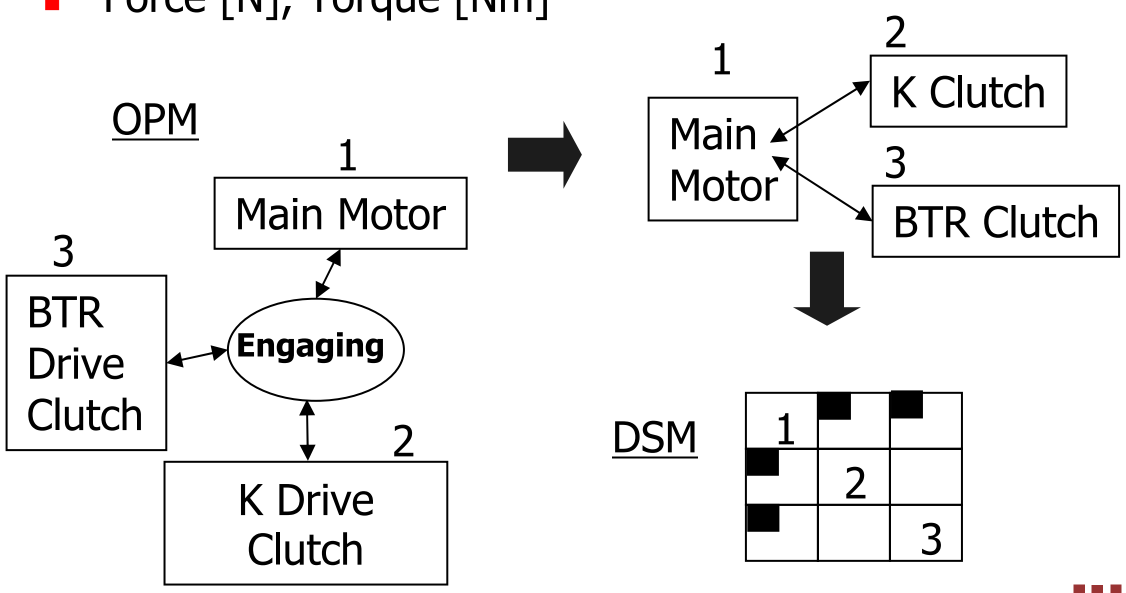
Image by MIT OpenCourseWare.

Types of Interfaces



Physical Connection

- Two parts are in direct physical connection if they
  - touch each other
    - examples: rollers, brake pad & disk, finger & touchscreen
  - have a reversible connection between them
    - examples: electrical connectors, USB port/cable, latch mechanism, bolts & nuts
  - are permanently connected to each other
    - examples: rivets, spot-welded
- Quantifiable interaction
  - Force [N], Torque [Nm]

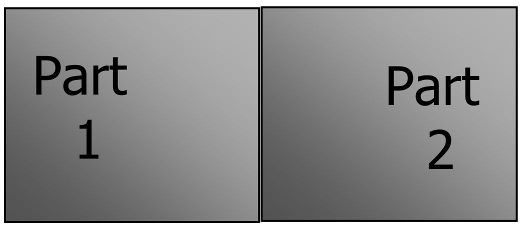


Important Note: physical connection implies symmetric entries in the DSM

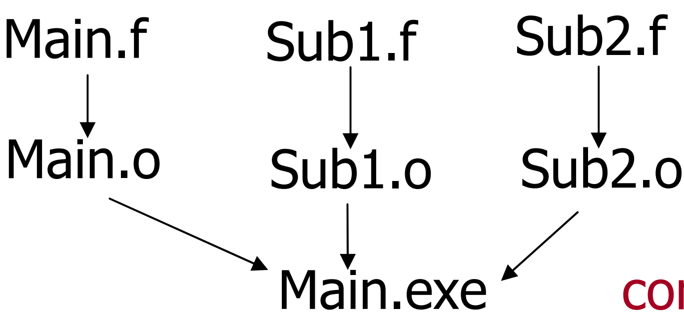
(action=reaction)

Examples Physical Connection

Irreversible structural links



welding



compiling

Reversible structural links

Strut 1

bolting

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Strut 2

RJ-45 jack

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connecting

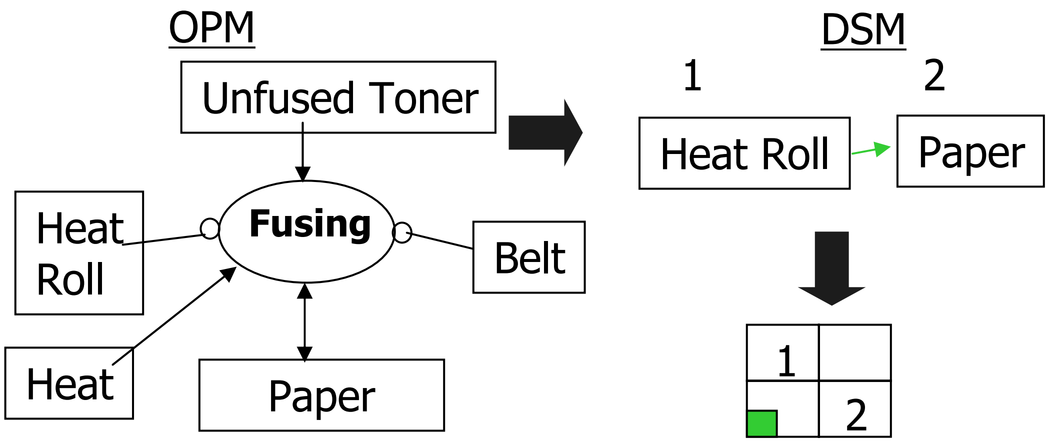
plug

Energy Flow

- Energy Flow is present if there is a net exchange of work between two components
  - Power = dW/dt [J/s=W]
- Can take on different forms
  - Electrical Power (most common in products)
    - DC Power (12V, 5V, 24V,…), Power = Current * Voltage
    - AC Power (120 V 60Hz, 220V 50Hz, …)
  - Thermal Power
    - Heat flux: dQ/dt
    - Conduction, Convection, Radiation
  - RF Power
    - Microwaves (2.4 GHz, 5.8 GHz,…)
  - Mechanical Power
    - Linear: Power = Force * velocity
    - Rotary: Power = Torque * angular rate
- Energy Flow typically implies a physical connection (but not always !)
  - Wires, conducting surface

Energy Flow (cont.)

- Energy Flow is typically directed
  - from source to sink



Heat Energy is transferred from system 1 to system 2

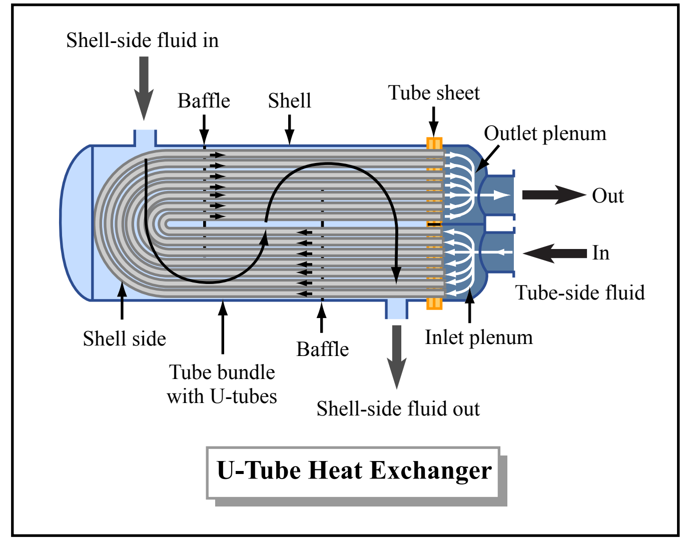
Important Note: typically we first map the desired interactions, later as we know more also the undesired ones (e.g. waste heat flux)

Mass Flow

- Mass Flow implies that matter is being exchanged between two elements (or subsystems)
  - mass flow = dM/dt [kg/sec]
  - Fluids
    - cooling liquid (refrigerant), fuel, water, …
  - Gases
    - air, exhaust gas, …
  - Solids
    - toner, paper (media in general),…
  - Typically implies an underlying physical connection
- Mass flow is typically directed
  - from source to sink
  - can form a continuous loop

Mass Flow (cont.)

Examples



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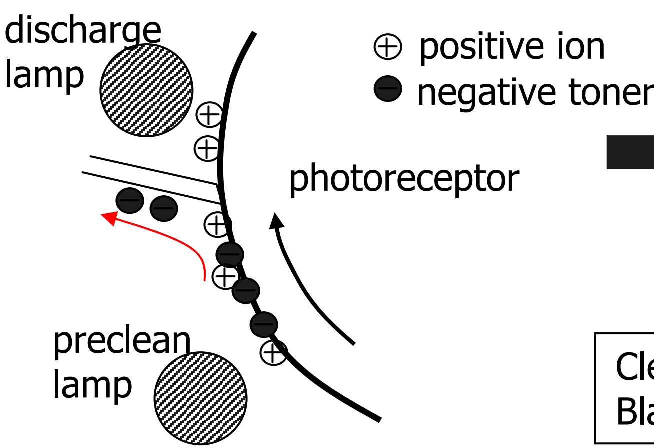
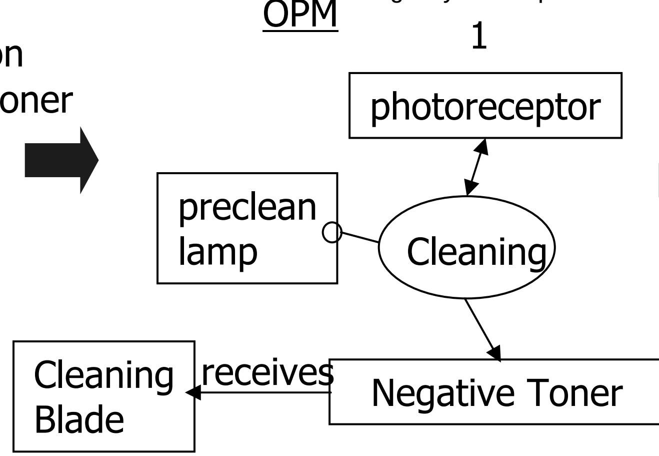
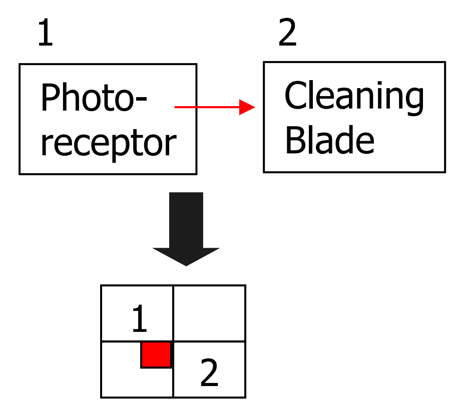


OPM



DSM



(Mainly Marking & Media Paths)

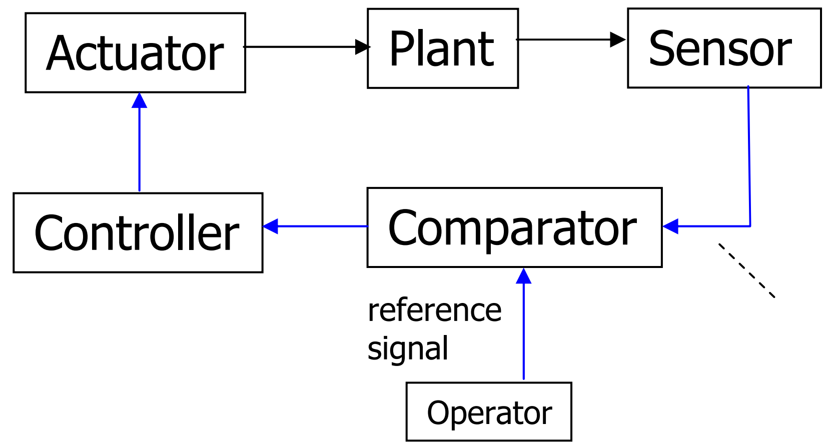
Mass is transferred
from system 1 to system 2

Information Flow

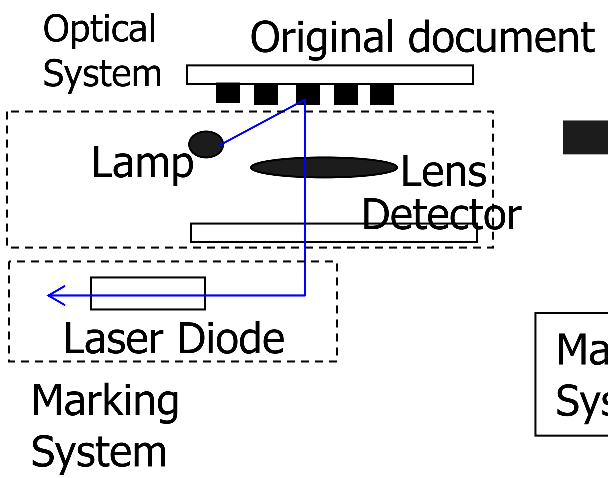
- Many modern electro-mechanical systems have replaced functions previously implemented with mechanical elements in software
- Required for Interactions with the user/operator
  - GUI, I/O
- Required for interactions with other devices
  - Analog (ADC, DAC), Digital (DIO), Wireless (e.g. IEEE 802.11)
- Required for internal device controls
  - Sensors
  - Actuators
  - Controllers
  - Filters, Amplifiers, …
- Information flow is always directed
  - Telemetry (sensor data) … how is my system doing?
  - Command data …this is what I want my system to do

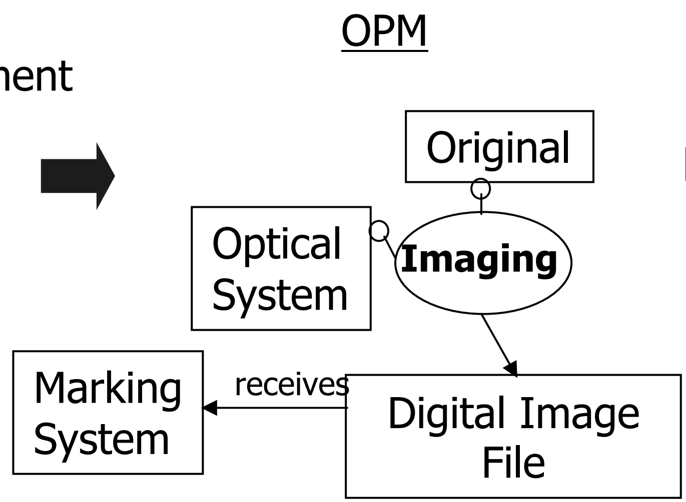
Information Flow (cont.)

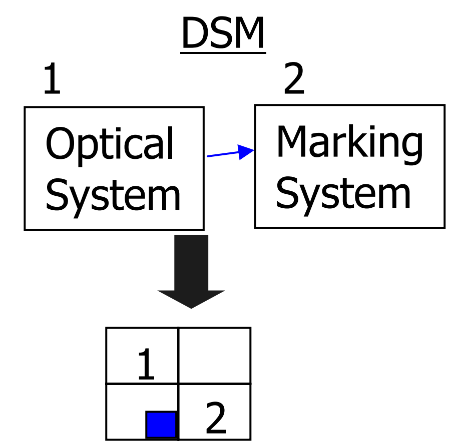
Control Loop



Xerography: Imaging



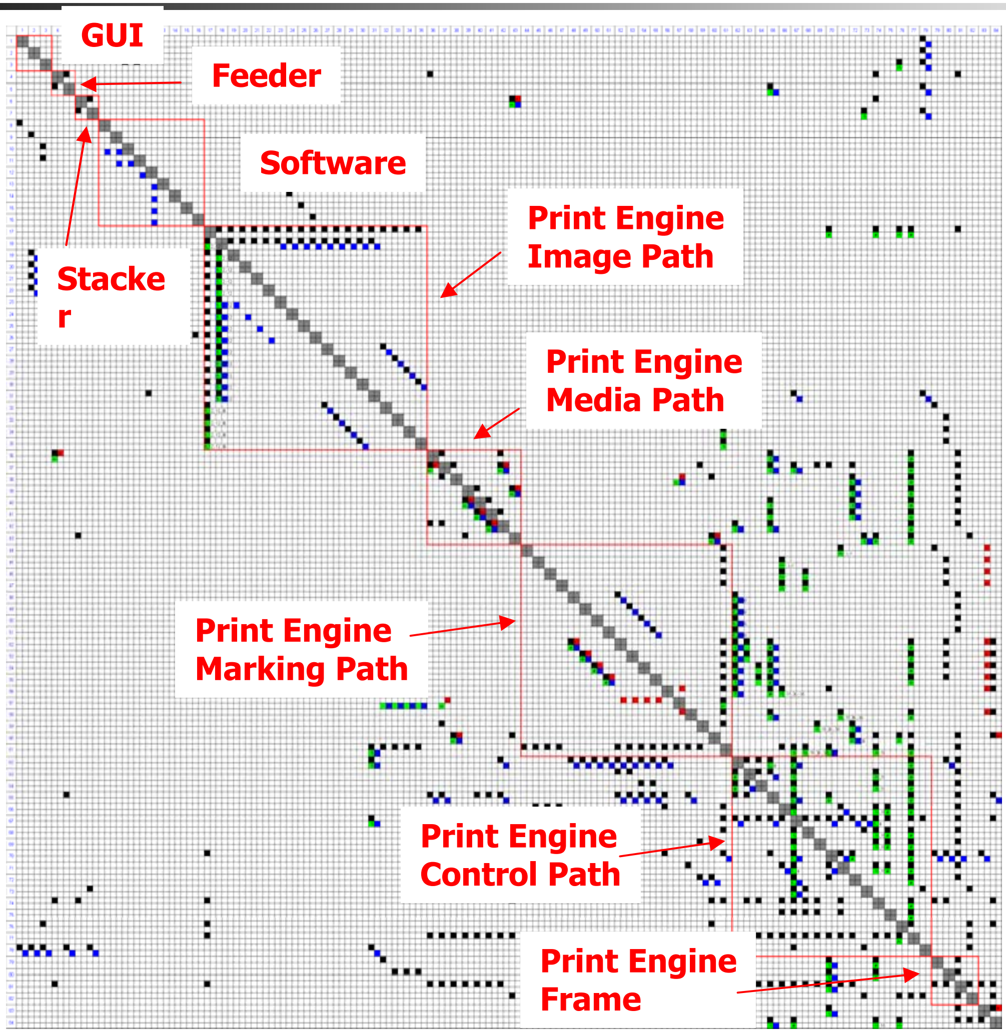




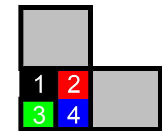
(Mainly Image Path & Device Controls)

Information is transferred from system 1 to system 2

Xerox iGen3 Baseline Design Structure Matrix (DSM)



Legend	
1	Physical connection
2	Mass flow
3	Energy flow
4	Information flow



Key

p	Paper
t	Toner
a	air (purified / ready for use)
o	Ozone
d	Dirt
HV	High Voltage
LV	Low Voltage
5, ...	DC Voltage
m	Mechanical energy (translation, rotation, etc…)
h	Heat energy (Fuser only)

Base iGen DSM

Total number of DSM Elements	84
Total number of physical connections	572
Total number of mass flow connections	45
Total number of energy flow connections	167
Total number of information flow connections	165
Number of Base DSM cells	27972
Number of non-empty cells	1033
Sparsity (Nonzero Fraction NZF)	0.037

Figure 17 on p. 201 in Suh, E. S., M. R. Furst, K. J. Mihalyov, and O. de Weck. "Technology Infusion for Complex Systems: A Framework and Case Study." *Systems Engineering* 13, no. 2 (Summer 2010): 186-203. © 2010 Wiley-Interscience. Reprinted with permission of John Wiley & Sons, Inc.

Infused Technology – ΔDSM captures Changes

Impact of Technology Infusion on Current System

Technolog
y

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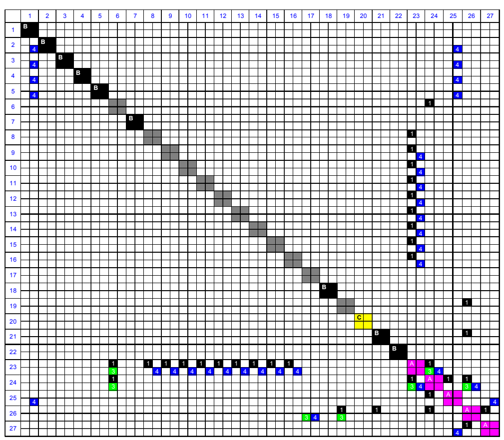
ΔDSM



Technology Invasiveness Index	Count	Subtotal	Base DSM	TI
New component/subsystem	5			
Eliminated component/subsystem	1			
Component redesign	9	15	84	**17.86%**
New physical connection	20			
Eliminated physical connection	0			
Modified physical connection	13	33	572	**5.77%**
New mass flow connection	0			
Eliminated mass flow connection	0			
Modified mass flow connection	0	0	45	**0.00%**
New energy flow connection	3			
Eliminated energy flow connection	0			
Modified energy flow connection	4	7	167	**4.19%**
New information flow connection	17			
Eliminated information flow connection	0			
Modified information flow connection	15	32	165	**19.39%**
Total	**87**	**87**		
Technology Invasiveness Index			**Total TII**	**8.42%**

TI is the unweighted ratio of actual changes over possible changes

$$TI = \frac{\sum_{i=1}^{N2}\sum_{j=1}^{N2} \Delta DSM_{ij}}{\sum_{i=1}^{N1}\sum_{j=1}^{N1} DSM_{ij}}$$

TI (Technology) ~= 8.5%

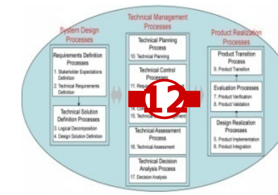
Complete ΔDSM for Auto Density Correction Technology
- captures all changes made to basic system to infuse the technology
- count number of cells in baseline DSM affected by technology
- compute technology invasiveness index (between 0 and 100%)
- also estimate non-recurring effort (engineering hours)

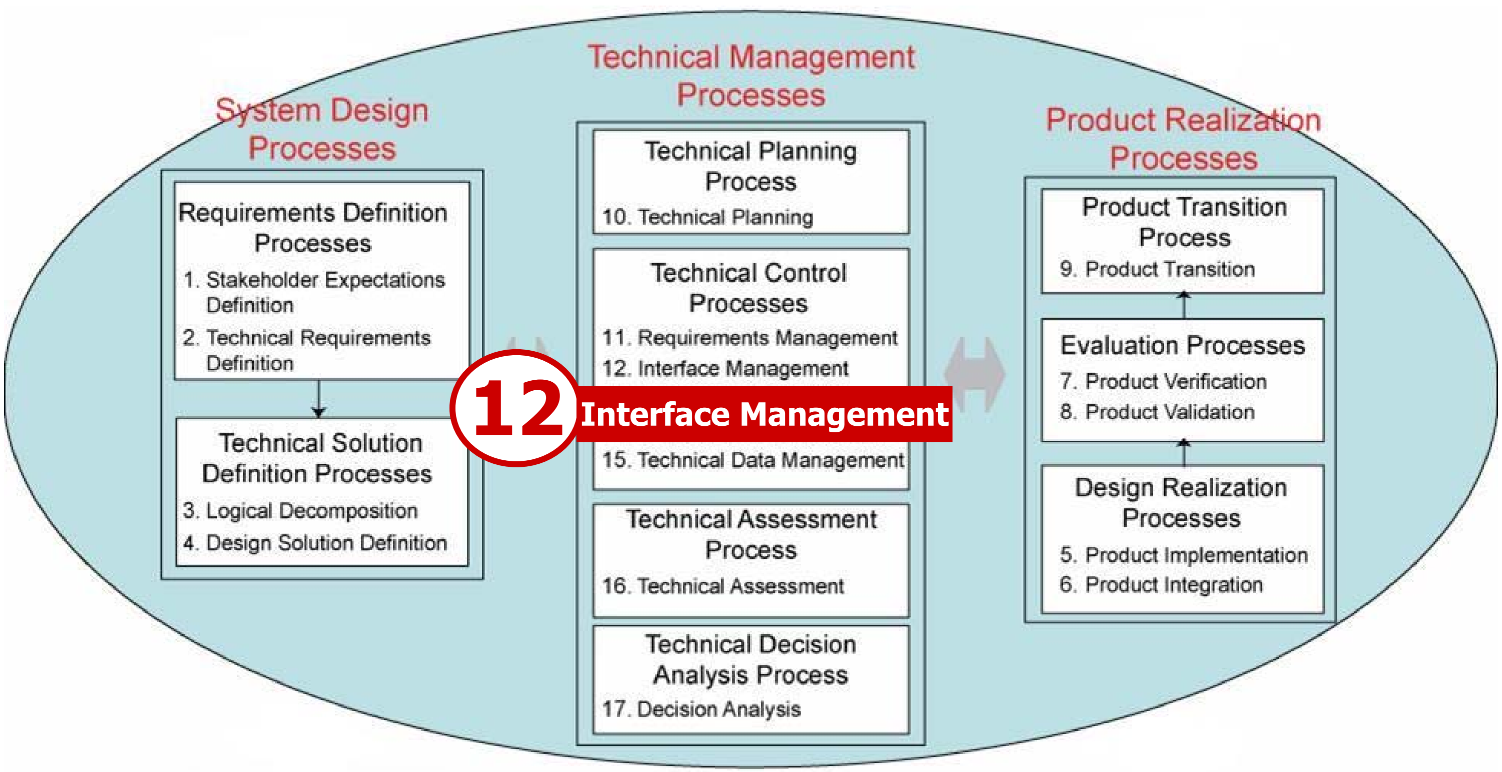
Figure 13 on p. 197 in Suh, E. S., M. R. Furst, K. J. Mihalyov, and O. de Weck. "Technology Infusion for Complex Systems: A Framework and Case Study." Systems Engineering 13, no. 2 (Summer 2010): 186-203.

Process for Generating Object-DSM

- Bottom-Up
  - Select system/product to be modeled
  - Perform product dissection
  - Carefully document the following:
    - Parts List/Bill of Materials
    - Liaison Diagram (shows physical connections)
  - Infer other connections based on reverse engineering/knowledge of functions:
    - mass flow, energy flow, info flow
  - Manipulate DSM
    - clustering
- Top Down
  - Generate System OPM
  - Hide attributes and states
  - Collapse all processes into “tagged” structural links
  - Generate DSM

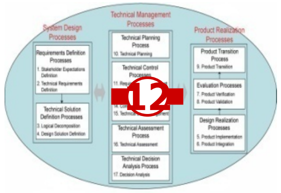
Interface Management Process





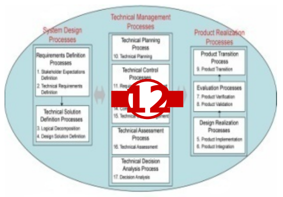
NASA Systems Engineering Handbook

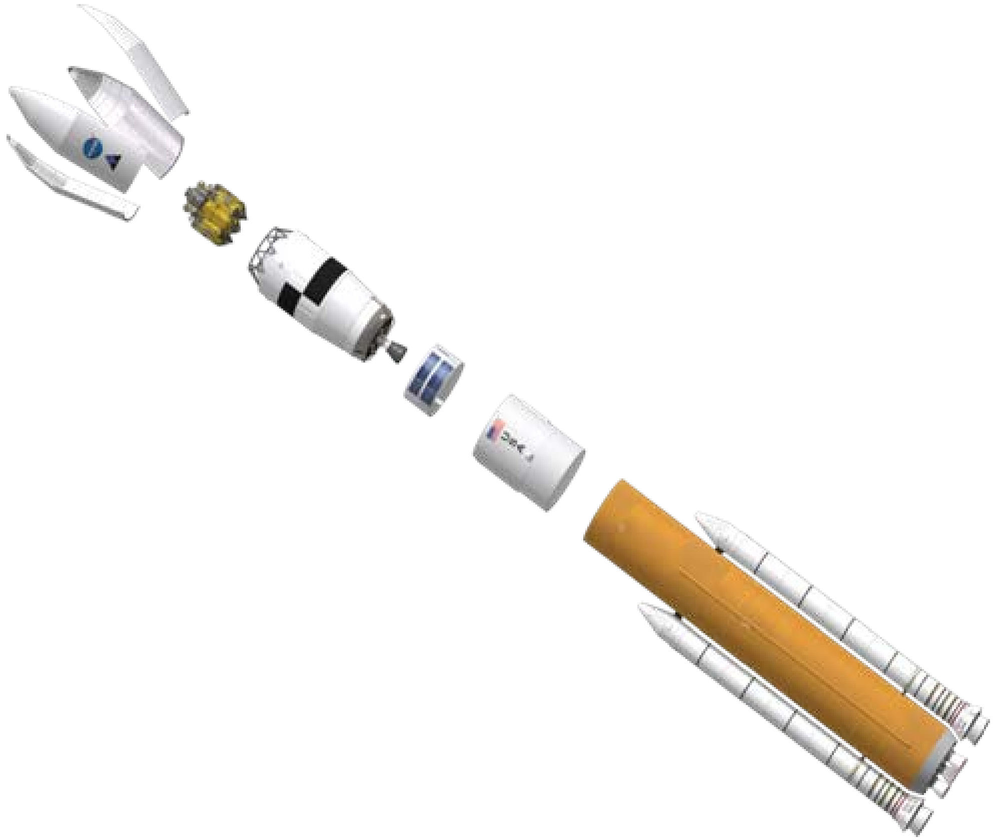
Interface Management Process Purpose



- The Interface Management Process is used to:
  - Establish and use formal interface management to assist in controlling system product development efforts especially when the efforts are divided between Government programs, contractors, and/or geographically diverse technical teams within the same program or project and
  - Maintain interface definition and compliance among the end products and enabling products that compose the system as well as with other systems with which the end products and enabling products must interoperate.

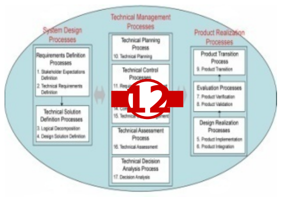
Interface Management Importance





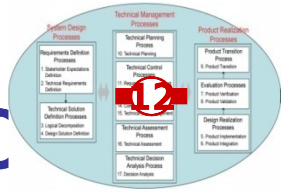
- Complex systems have many interfaces
  - Common interfaces reduce complexity
  - System architecture drives the types of interfaces to be utilized in the design process
  - Clear interface identification and definition reduces risk
  - Most of the problems in systems are at the interfaces.
  - Verification of all interfaces is critical for ensuring compatibility and operation

Interface Definition



- An Interface is the functional and physical characteristics required to exist at a common boundary between two or more systems, end products, enabling products or subsystems
  - These functional and physical characteristics can include physical, electrical, electronic, mechanical, hydraulic, pneumatic, optical, software, or human aspects
- Two interfaces of concern:
  - **Internal interfaces** are those boundaries between products that are controlled by a developer or NASA technical effort
  - **External interfaces** are the boundaries between a system end product and another external system end product or a human and the operating environment in which the system products will be used or operated

Key Interface Documentatic



- Interface Control Document or Interface Control Drawing (ICD) - Details the physical interface between two system elements, including the number and types of connectors, electrical parameters, mechanical properties, and environmental constraints.
  - The ICD identifies the design solution to the interface requirement.
  - ICDs are useful when separate organizations are developing design solutions to be adhered to at a particular interface.
- Interface Definition Document (IDD) - A unilateral document controlled by the end item provider, and provides the details of the interface for a design solution that is already established.
  - This document is sometimes referred to as a "one-sided ICD."
  - The user must then design the interface of the system to be compatible with the already existing design interface.
- Interface Requirements Document (IRD) - Defines the functional, performance, electrical, environmental, human, and physical requirements and constraints that exist at a common boundary between two or more functions, system elements, configuration items, or systems.
  - Interface requirements include both logical and physical interfaces.

Interface Management Example

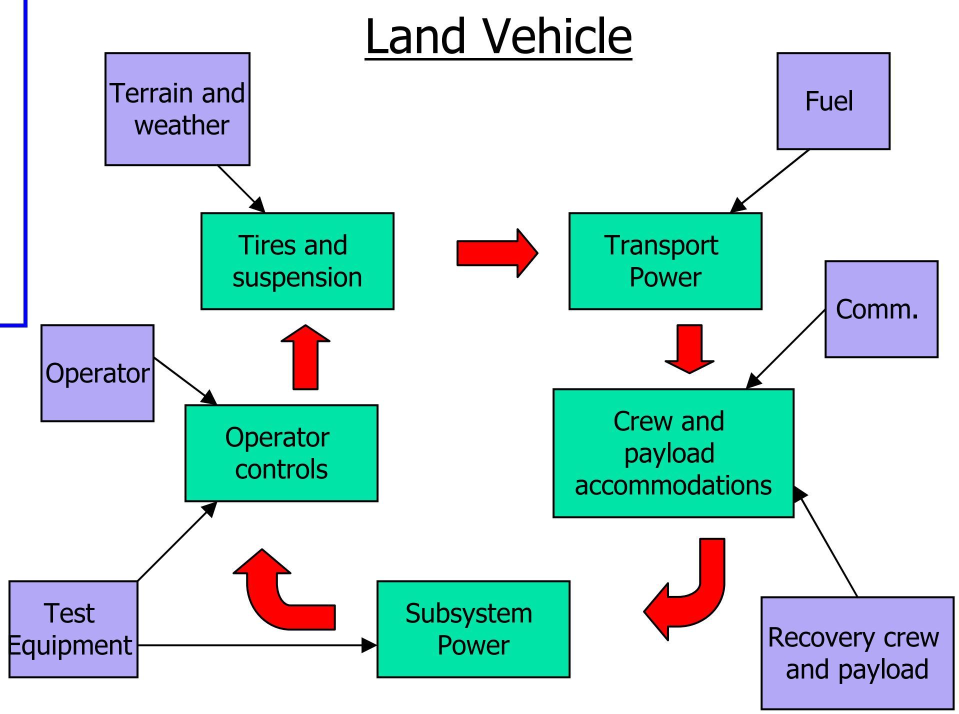
- A Mobile Transportation System must be developed that is able transport a recovery crew in squad level units over a distance of 50 km from the expected landing site.

Types of external interfaces include:

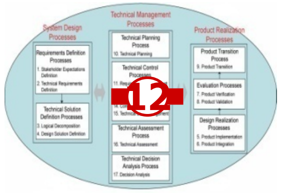
- Terrain and weather
- Fuel delivery system
- Operator
- Recovery crew
- Payload
- Test equipment
- Central command

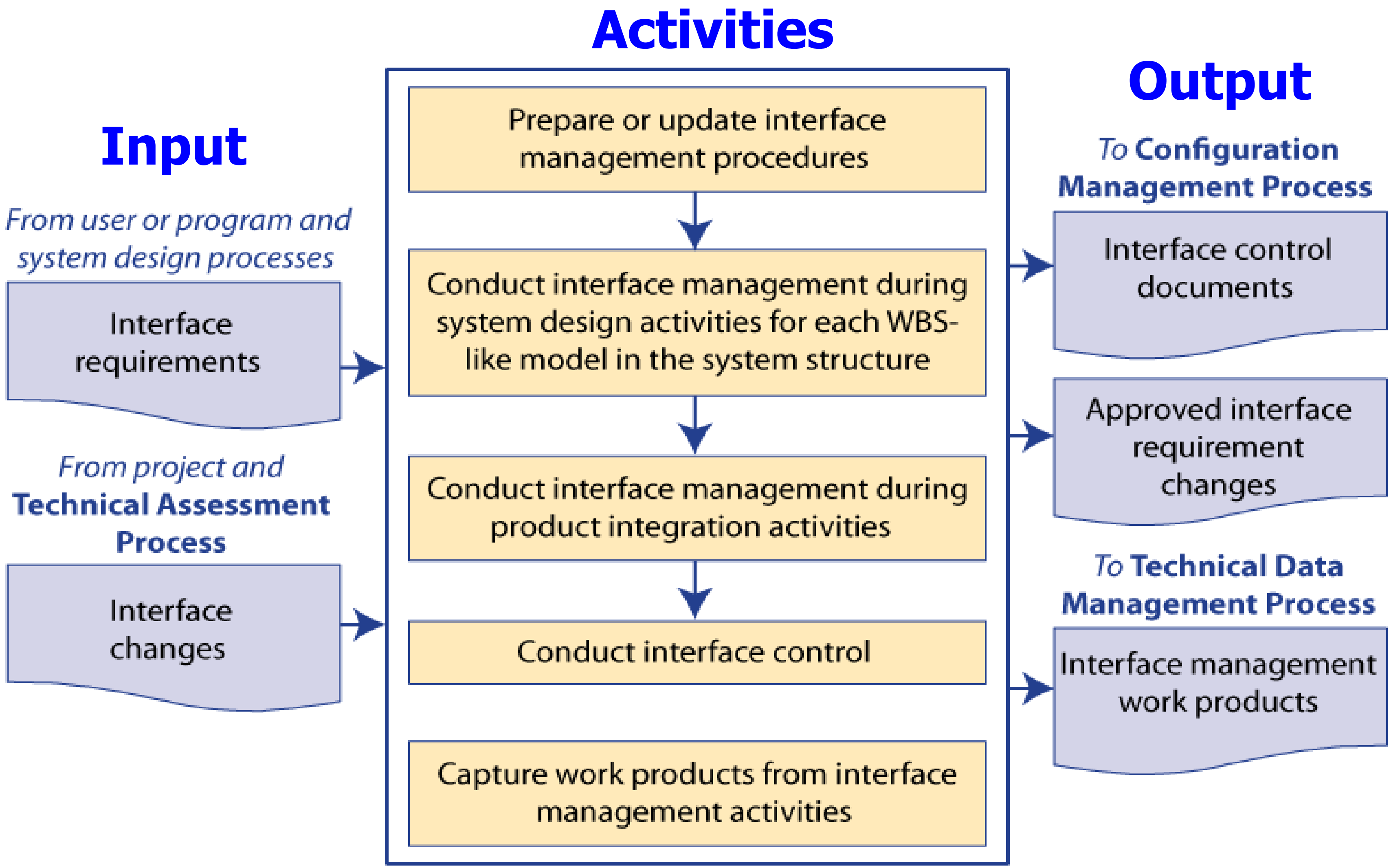
Assuming the system architecture is defined by a land vehicle, internal interfaces can be identified at the WBS level as follows:

- Surface interface – tires and suspension
- Control interface – operator controls
- Power for transport – engine and transmission
- Power for systems – electrical
- Crew and payload accommodations



Interface Management Process

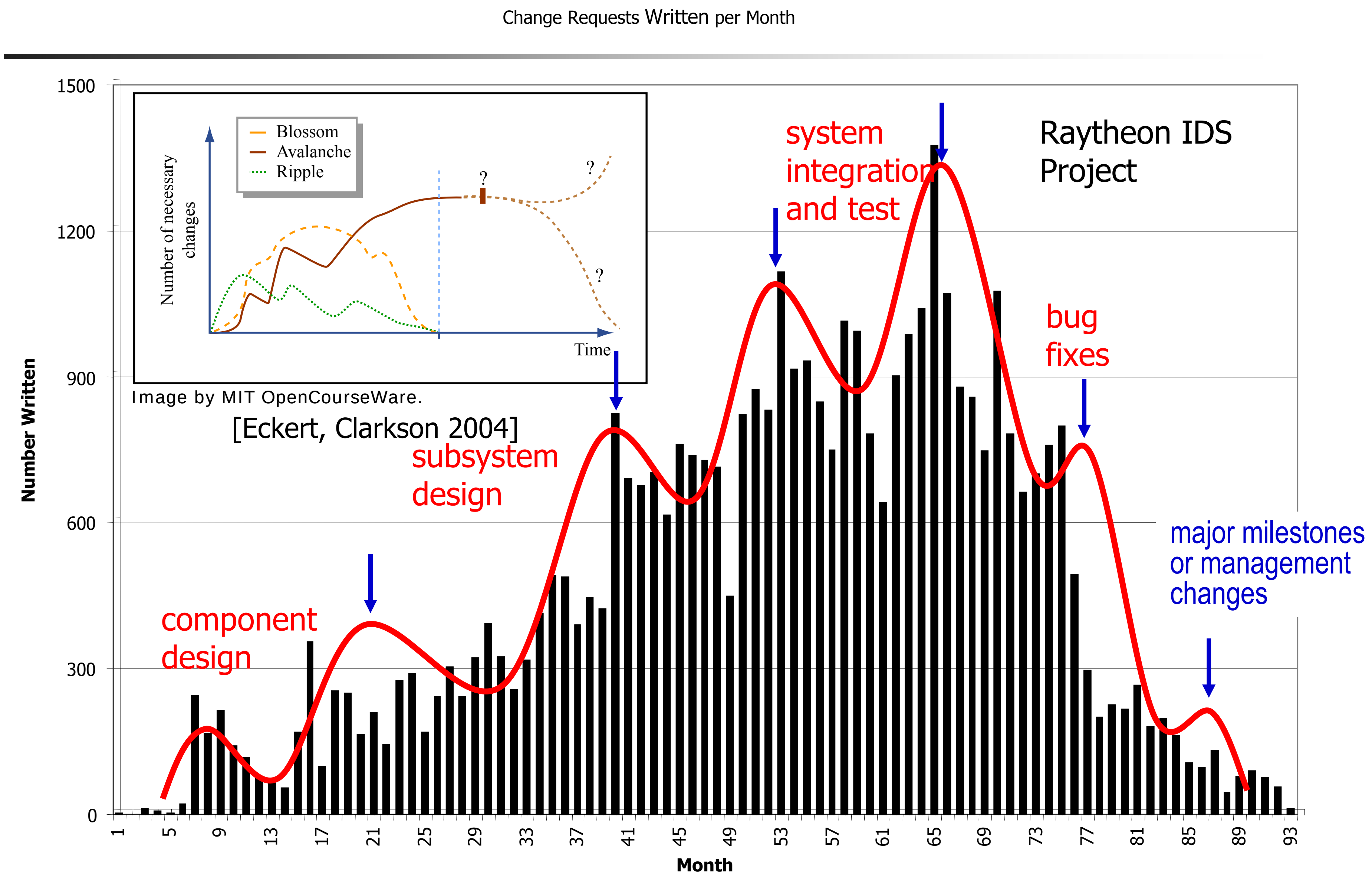




System Integration

- System integration is the process of deliberate assembly of the parts of the system into a functioning whole
  - Physical assembly of parts
  - Connecting different conduits, hoses
    - Filling in various kinds of consumables
  - Connecting electronics to power sources, avionics etc… (often with wire harnesses)
  - Uploading of test and flight software
  - Pre-condition for system testing
- The sequence in which integration occurs may be important (see paper in journal club)
- In complex systems many errors are only discovered during system integration and test

Change Request Generation



From the Earth to the Moon (HBO Mini-Series – Tom Hanks)

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Part 5: "Spider" - Design of the Lunar Module: 15 [min]