The Final Frontier: Spacecraft Go Modular

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A bit about your speaker…

- Dual faculty member in Aero/Astro and ESD. Teach non-SDM version of System Architecture course (ESD.34).
- Ph.D. in ESD from MIT. Worked in government space systems architecture; Wall Street.
- Broad research area
  - Problems at the intersection of aerospace policy and system design
- Specific interests
  - Dynamics of complex systems architecture change and innovation in aerospace systems
  - Role of government in fostering aerospace innovation and change
  - Decision processes driving the policy and technical aspects of aerospace systems

What you should be hearing…

- **During this two day conference, Systems Thinking for Contemporary Challenges, MIT professors and industry experts will each share on the following:**
  - **Case for action -- the imperative for adopting systems thinking - what it is and how to apply it**
  - **How the experts use system design, system architecture, and system engineering to integrate technology, management, and social sciences to support their organization's overall strategic goals**
  - **A mini-case study to illustrate**
  - **Lessons learned and how attendees can apply them when they return to the office on Monday.**

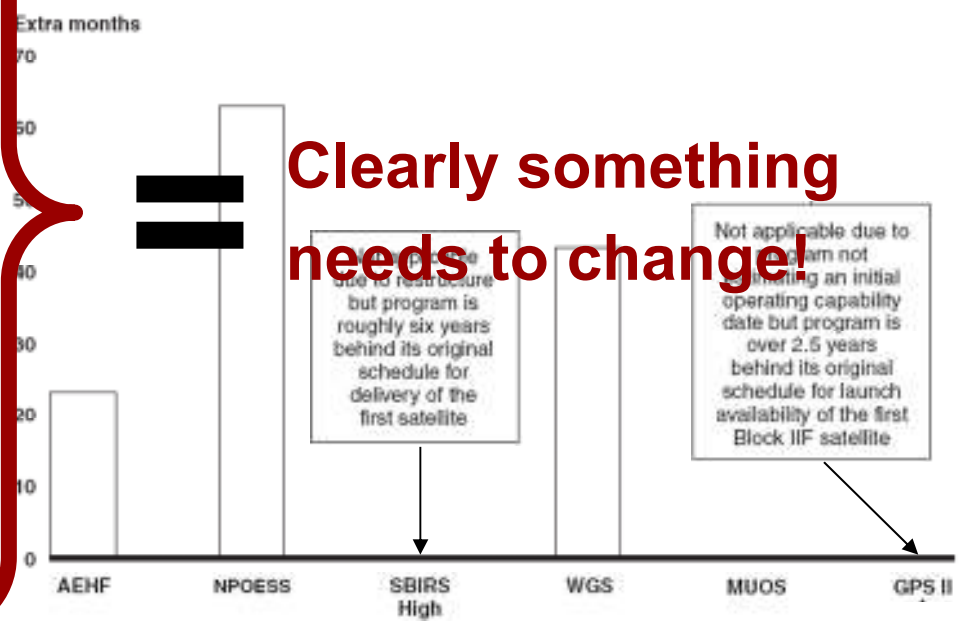
Product Design and Sustainability

Source: SDM Conference 2008 materials

Motivation: Current problems

- Growing costs of spacecraft programs
- Schedules keep moving to the right
- Dominant design has emerged
- Minimal performance gains

Schedule Slips



Clearly something needs to change!

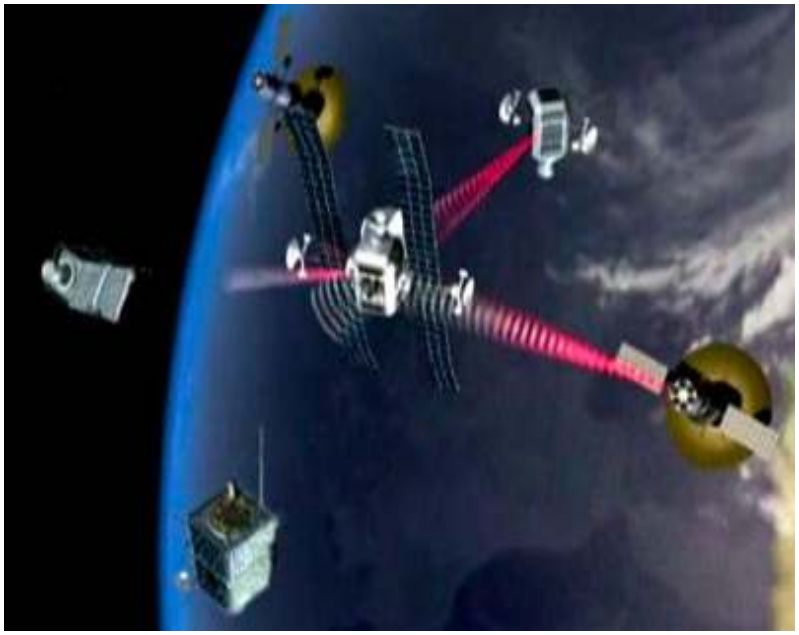
Q: If this were your industry, what would you think?

Source: GAO

Wanted: Flexible and Sustainable Space System Architectures

Current Traditional Spacecraft		New Distributed Spacecraft Concepts
• Monolithic architectures	→	Heterogeneous on-orbit clusters
• Highly integrated	→	Modular and physically separated
• One of a kind	→	Standardized
• Large non-recurring costs	→	Distributed non-recurring costs
• Limited flexibility	→	Greater flexibility

Source: ESA

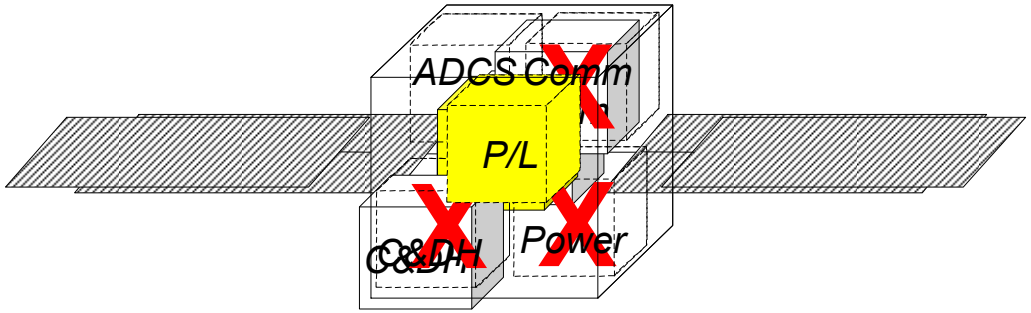


Source: DARPA

For Discussion…

- **Why are spacecraft built the way they are today – i.e. large, monolithic, highly integrated, unique?**

From Current Traditional Spacecraft…



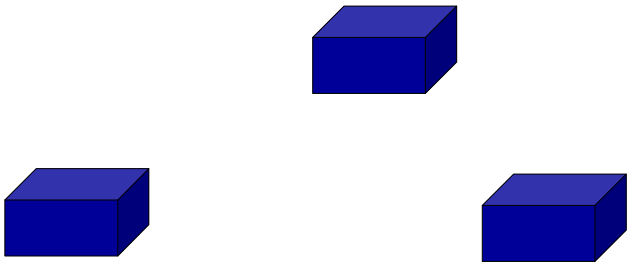
Payload

Bus Subsystems

…to New Distributed Spacecraft (called fractionated spacecraft)

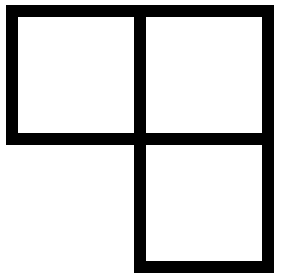
Payload Module

Infrastructure Modules

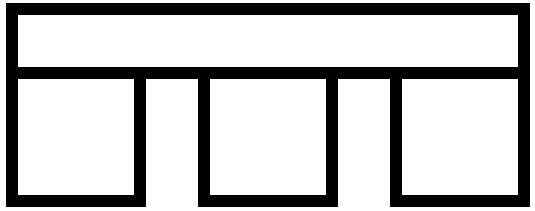


Flashback to System Architecture Class: Interfaces and Styles

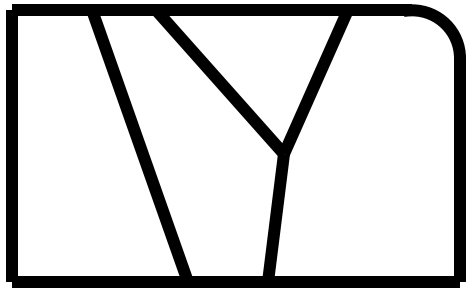
- **The way in which modules interface defines a module style.**
  - **With any other directly, according to a standard: modular-sectional**



  - **With a specialized element, according to a standard: modular-bus**



  - **With another, according to no standard: modular-slot**



For Discussion…

- **Why might customers not like this kind of new fractionated distributed spacecraft design?**

Evaluating the Common Wisdom

- **Some prevailing beliefs**
  - Distributed spacecraft would be more massive and costly
  - Distributed spacecraft would offer more flexibility
  - Uncertainty about whether benefits would outweigh costs

- **Research questions**
  - Under what conditions might fractionated distributed spacecraft architectures be worthwhile alternatives to traditional architectures?
  - What impacts might fractionated distributed spacecraft have on industry and market structure, and what policy actions would help facilitate architecture change?

Analysis in Two Complementary Parts

- **Part I - Architectural analysis**
  - Investigate different fractionated architectures and compare them to traditional ones in terms of utility and cost
- **Part II - Industrial and policy analysis**
  - Investigate the fractionated spacecraft industrial paradigm and examine its potential effects on industry and market structure
  - Suggest policies to enable the implementation of the fractionated spacecraft concept

Part I -
Architectural Analysis

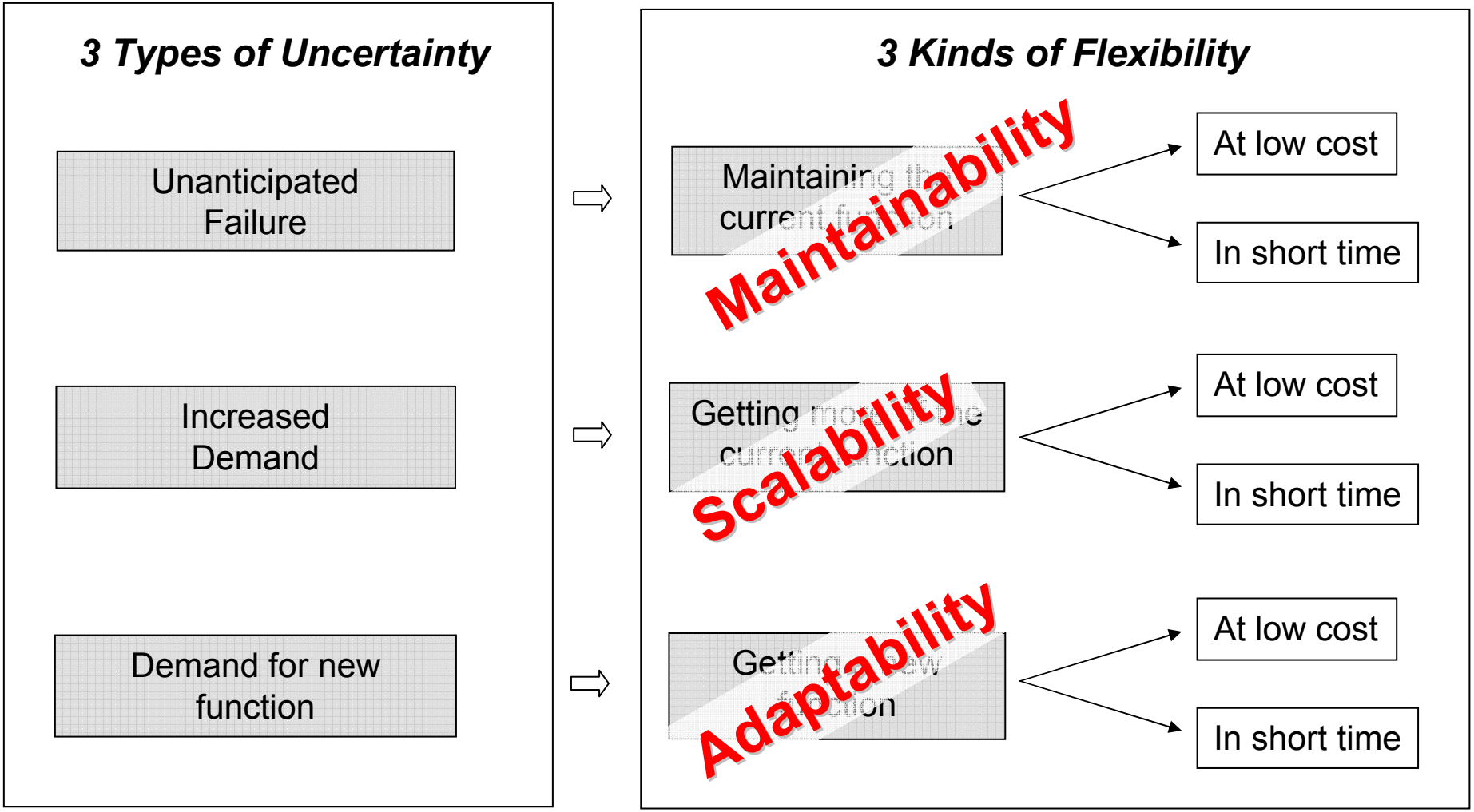
Under what conditions might fractionated distributed spacecraft architectures be worthwhile alternatives to traditional architectures?

Architectures Assessment Criteria

Fractionated and traditional architectures are assessed at iso-performance and iso-lifetime in terms of:

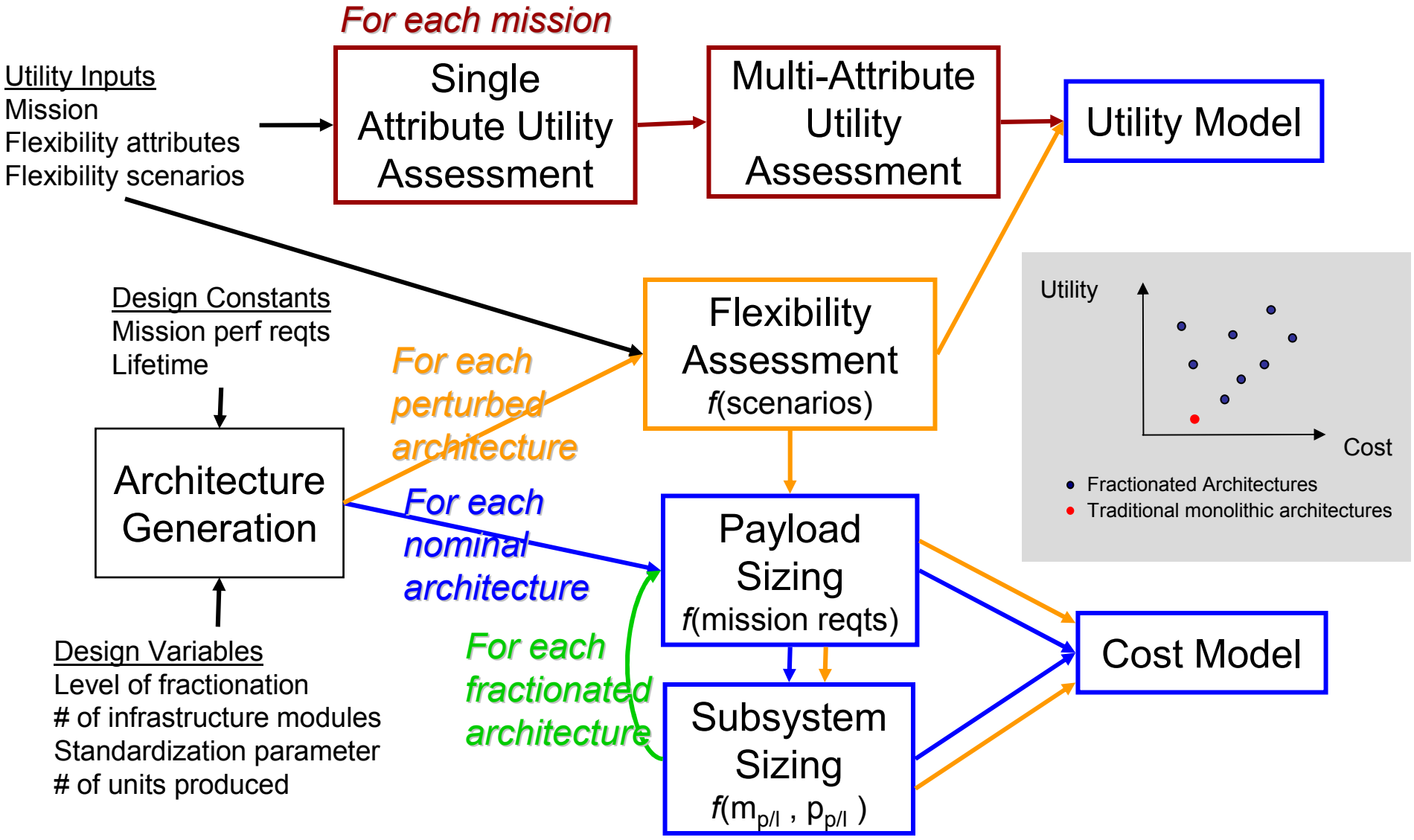
- **Traditional attributes**
  - **Mass**
  - **Cost**
- **Utility (Non-traditional attributes)**
  - **3 different kinds of flexibility**

3 Kinds of Flexibility Investigated

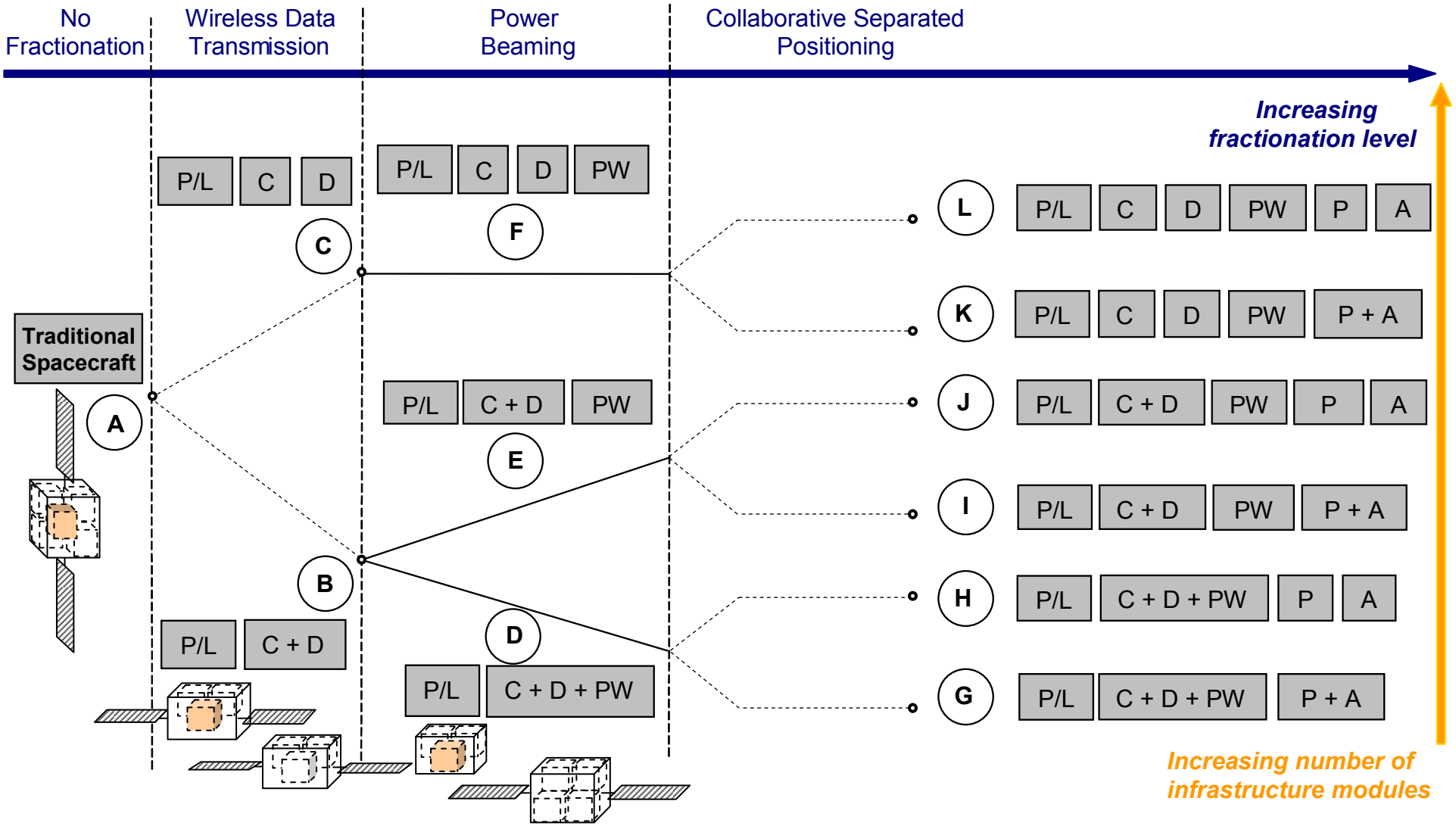


Σ (3 kinds of flexibility) = Utility

Modeling Approach

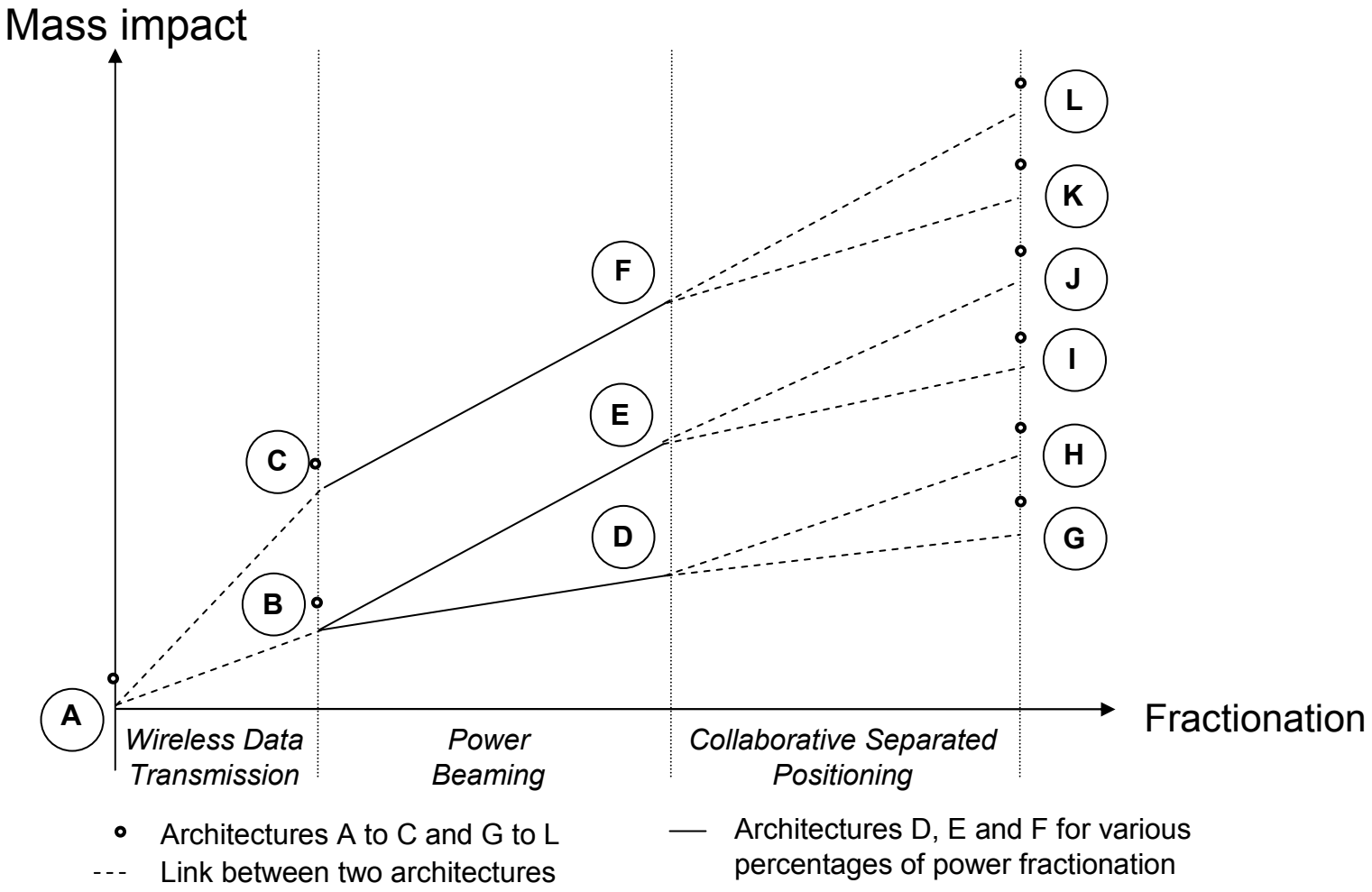


Architectures Investigated



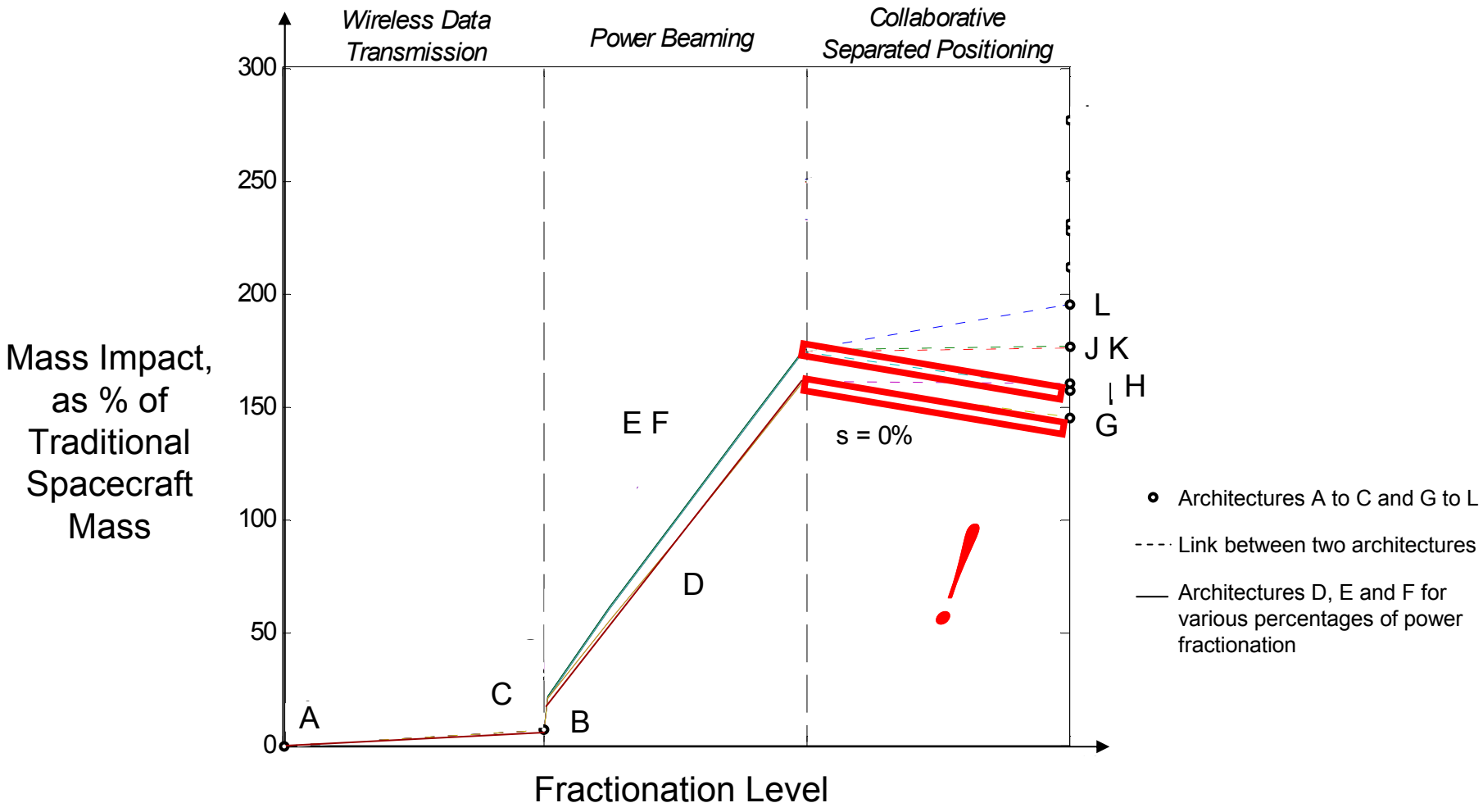
Notional Impact of Fractionation on Space Segment Mass

a priori hypothesis

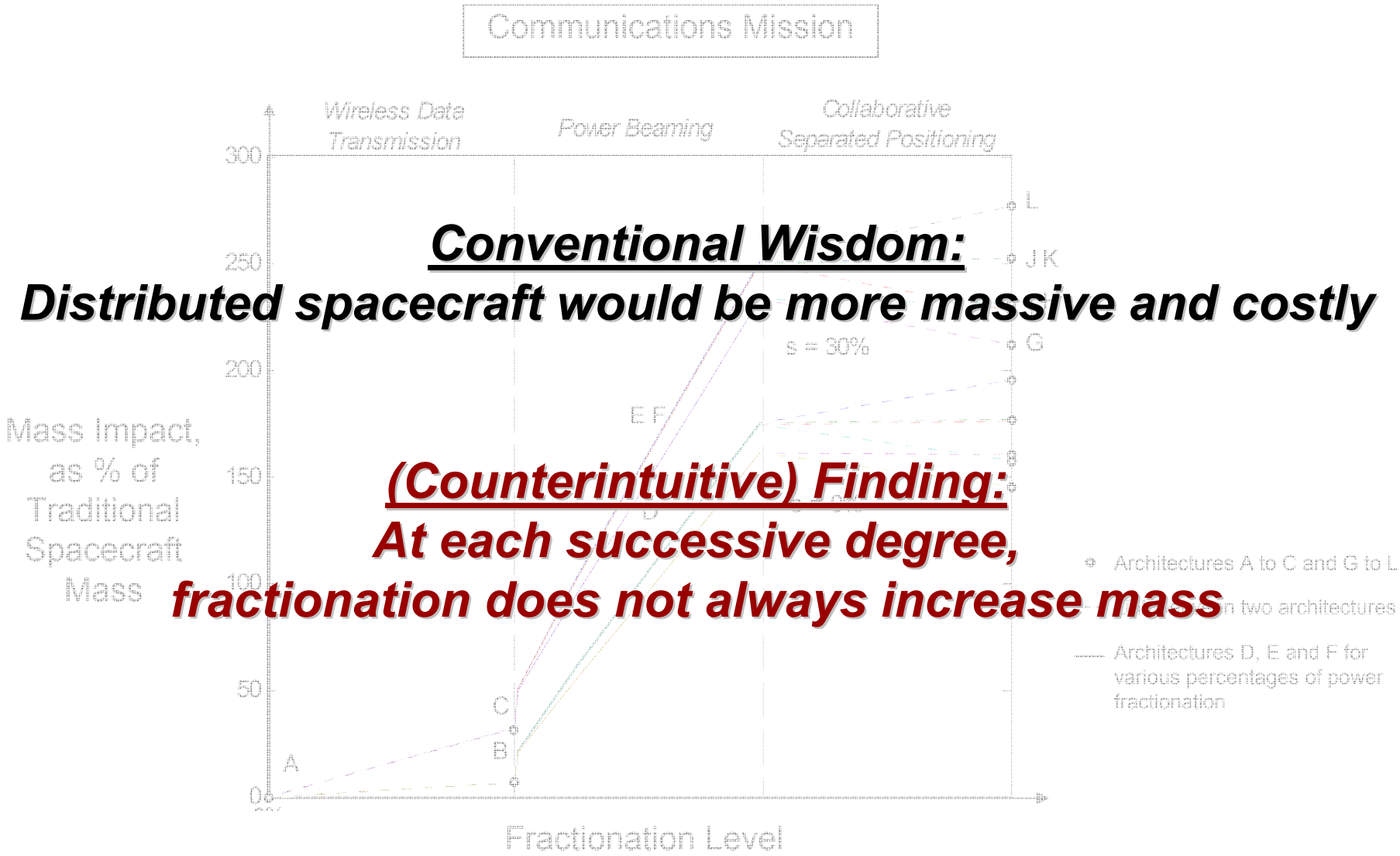


Modeled Impact of Fractionation on Space Segment Mass

Communications Mission



Modeled Impact of Fractionation on Space Segment Mass



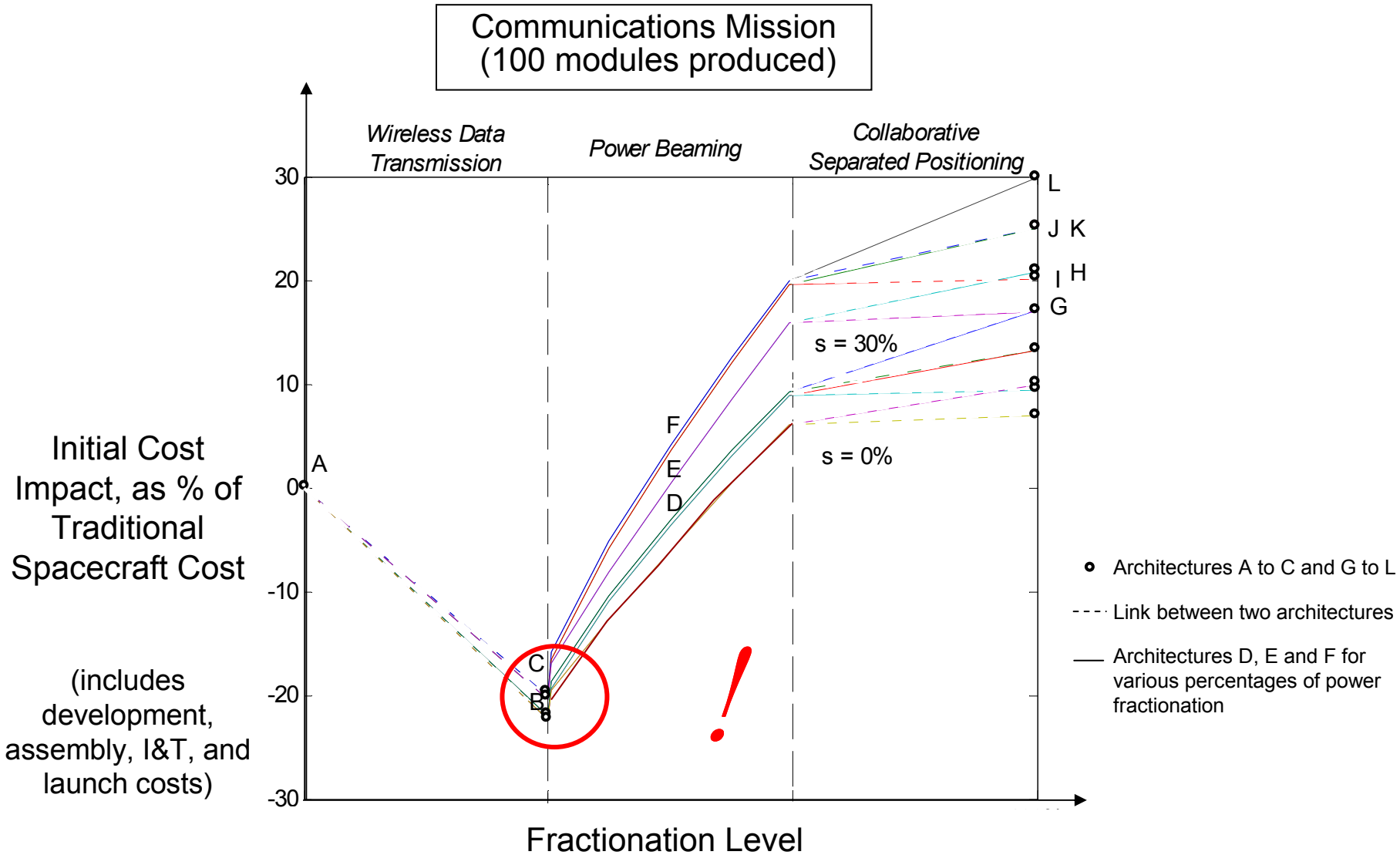
Conventional Wisdom:

Distributed spacecraft would be more massive and costly

(Counterintuitive) Finding:

At each successive degree, fractionation does not always increase mass

Modeled Impact of Fractionation on Space Segment Cost



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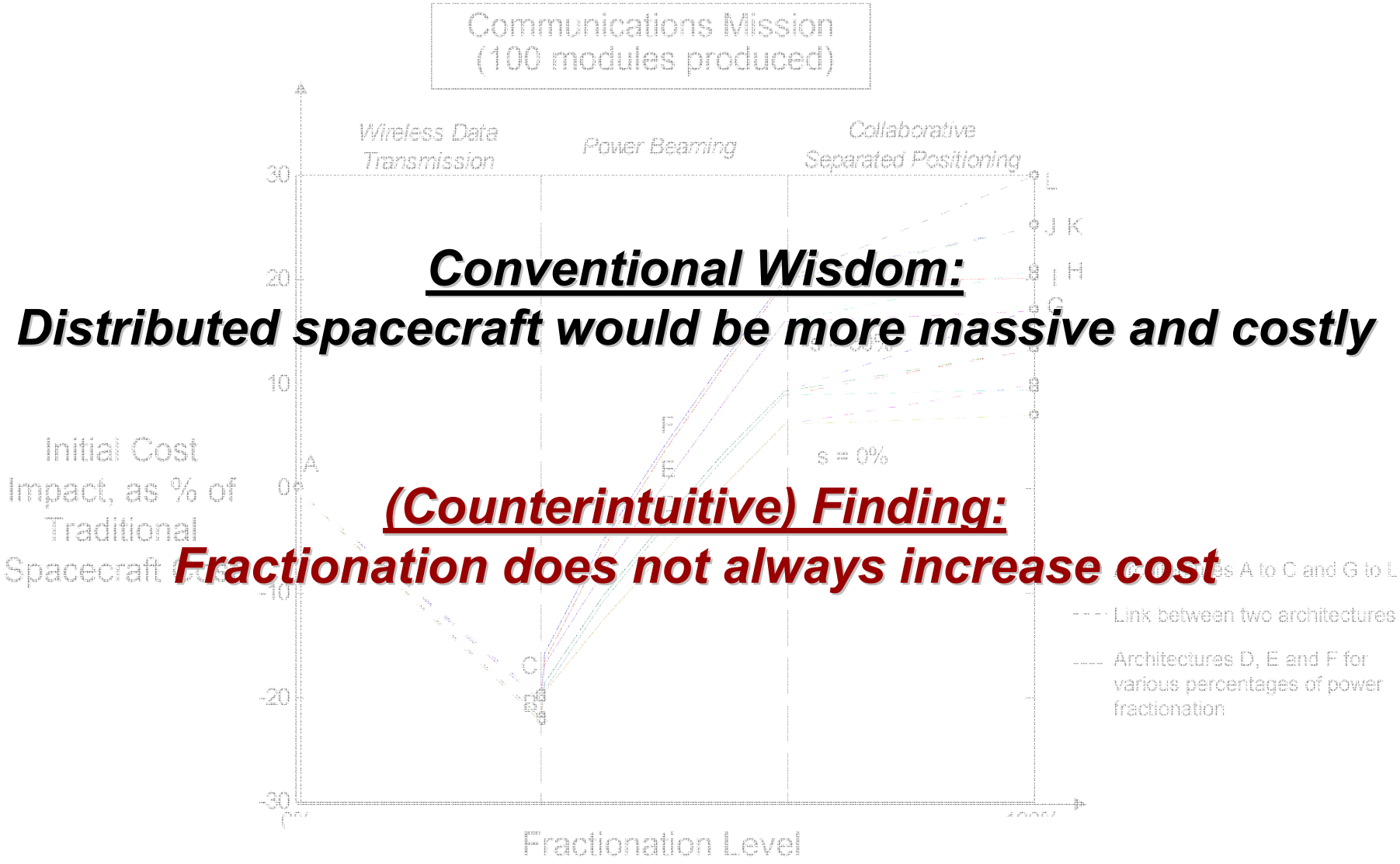

Conventional Wisdom:

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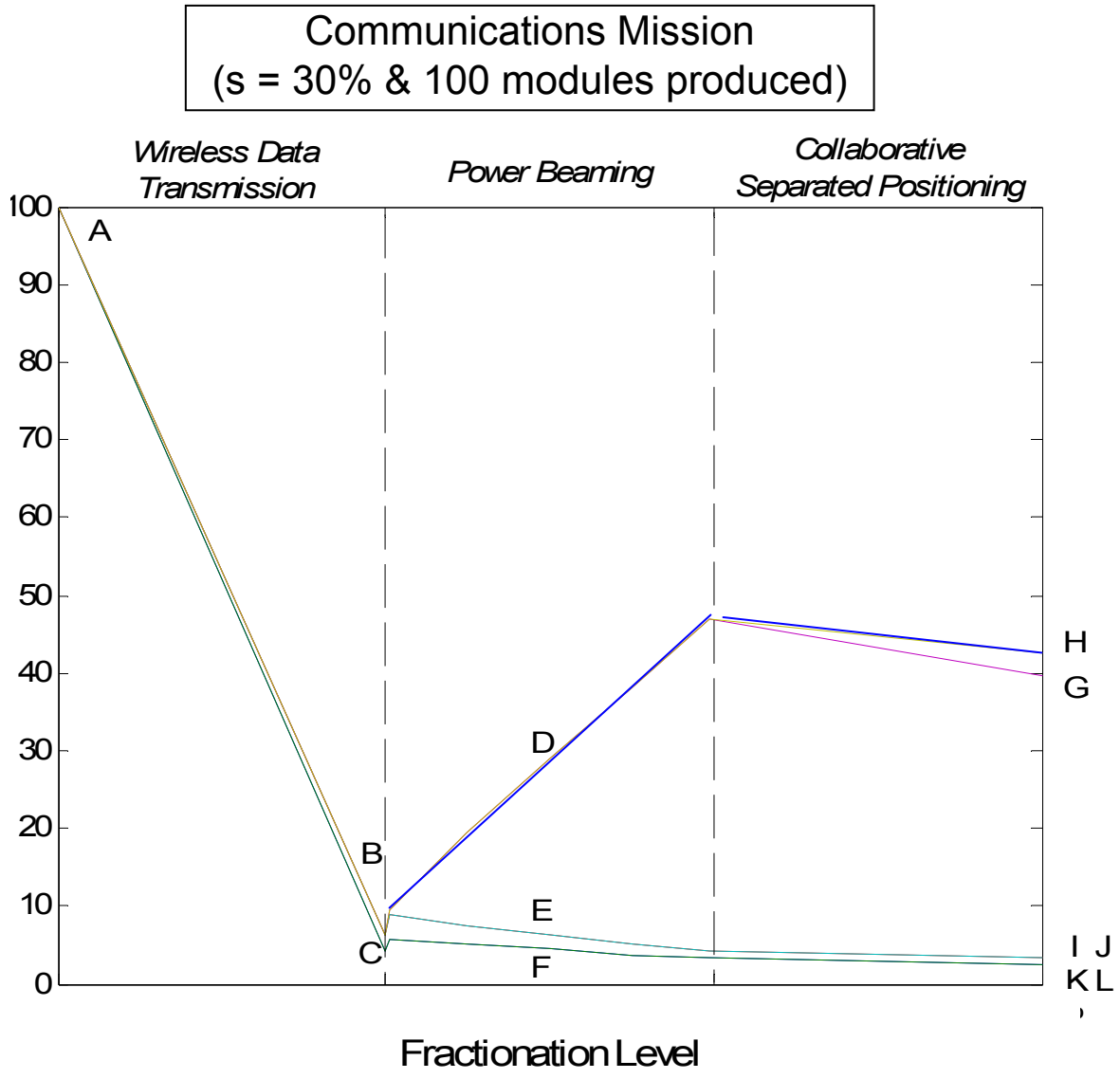
(Counterintuitive) Finding:

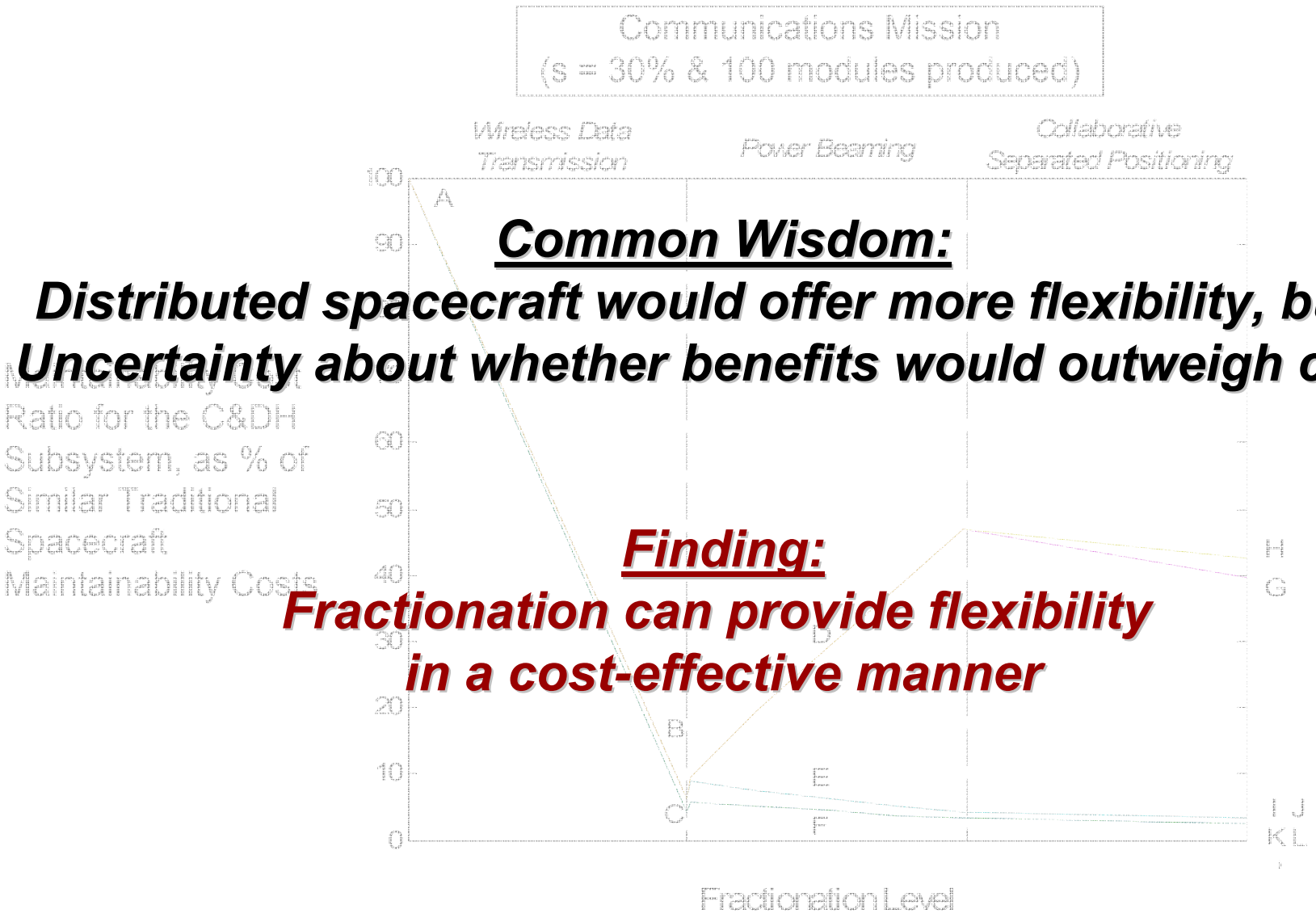
Fractionation does not always increase cost

Cost of Flexibility in Fractionated Architectures

Maintainability Cost Ratio for the C&DH Subsystem, as % of Similar Traditional Spacecraft Maintainability Costs



Cost of Flexibility in Fractionated Architectures



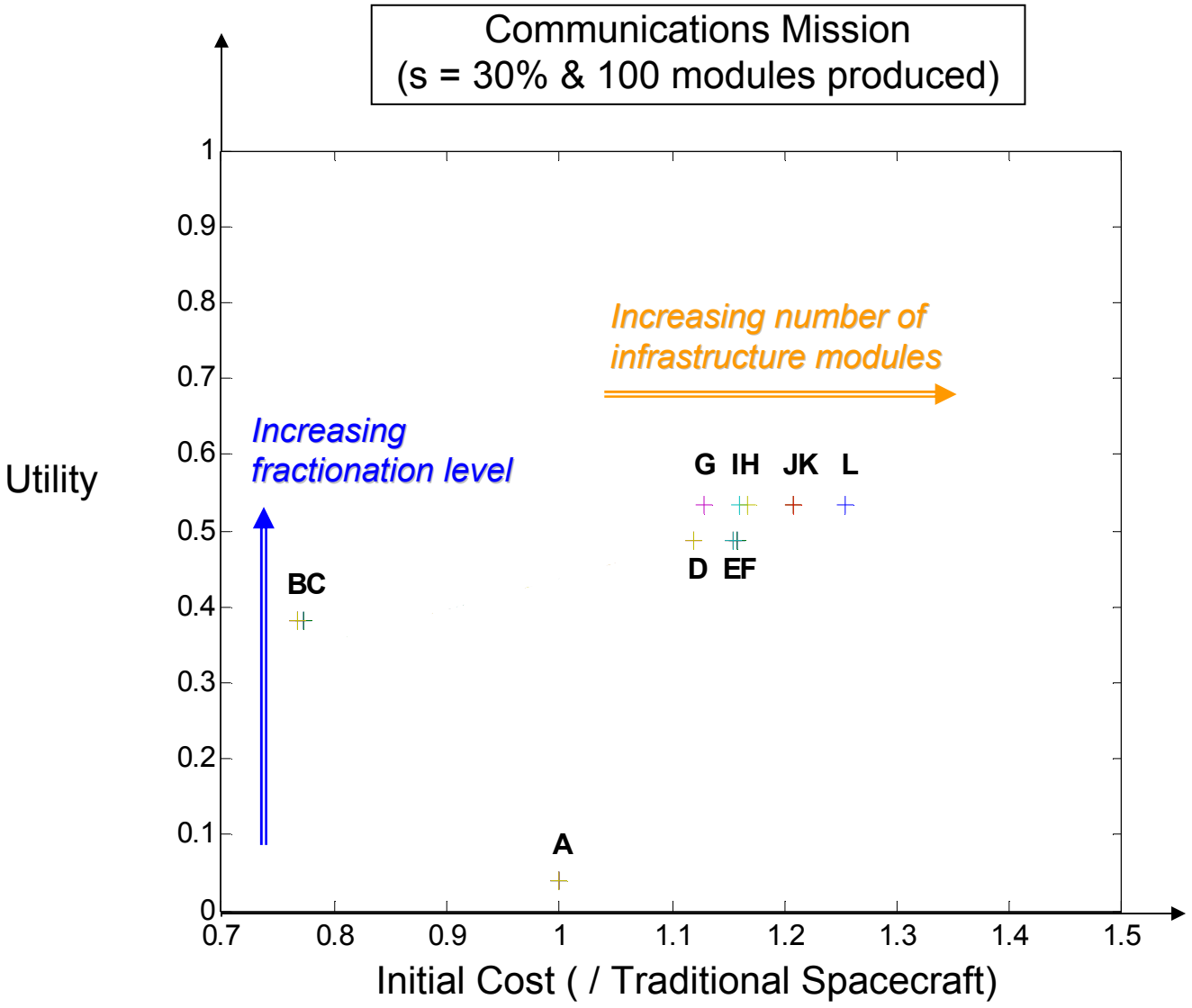
Common Wisdom:

Distributed spacecraft would offer more flexibility, but…
Uncertainty about whether benefits would outweigh costs

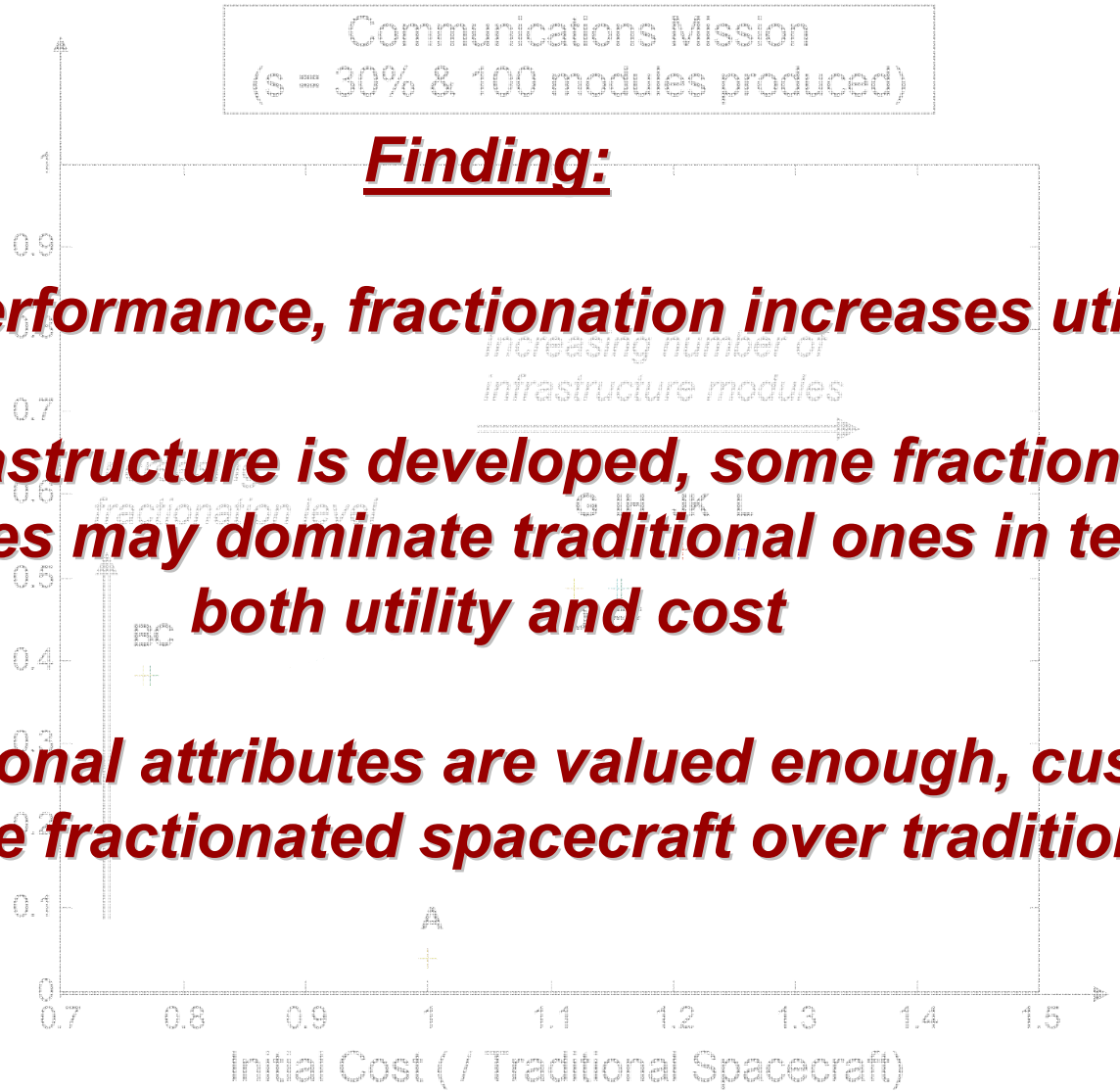
Finding:

Fractionation can provide flexibility in a cost-effective manner

Utility versus Initial Cost



Utility versus Initial Cost



Finding:

At isoperformance, fractionation increases utility

If an infrastructure is developed, some fractionated architectures may dominate traditional ones in terms of both utility and cost

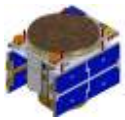
If non-traditional attributes are valued enough, customers would choose fractionated spacecraft over traditional ones

Part II-
Industrial and Policy Analysis

What impacts might fractionated distributed spacecraft have on industry and market structure, and what policy actions would help facilitate architecture change?

A New Industrial Paradigm?

SPACECRAFT LIFECYCLE PHASES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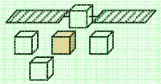
DEVELOPMENT | MANUFACTURING | INTEGRATION, ASSEMBLY, AND TEST | LAUNCH | OPERATIONS

TRADITIONAL SPACECRAFT 	Customized design Integral design	Prototype approach to manufacturing	Prototype approach to IAT	Large constraints and high risks	Less complex but unique operations
FRACTIONATED SPACECRAFT 	Modular design - Modules and interfaces standardization - Functional partitioning	Modular manufacturing Mass production approach	Modular IAT	Less constraints and lower risks	More complex operations

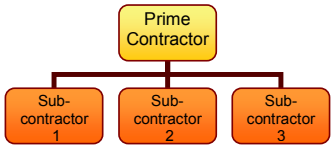
MISSION CHARACTERISTICS


RISK

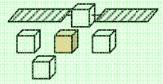

"FLEXIBILITY"


COST

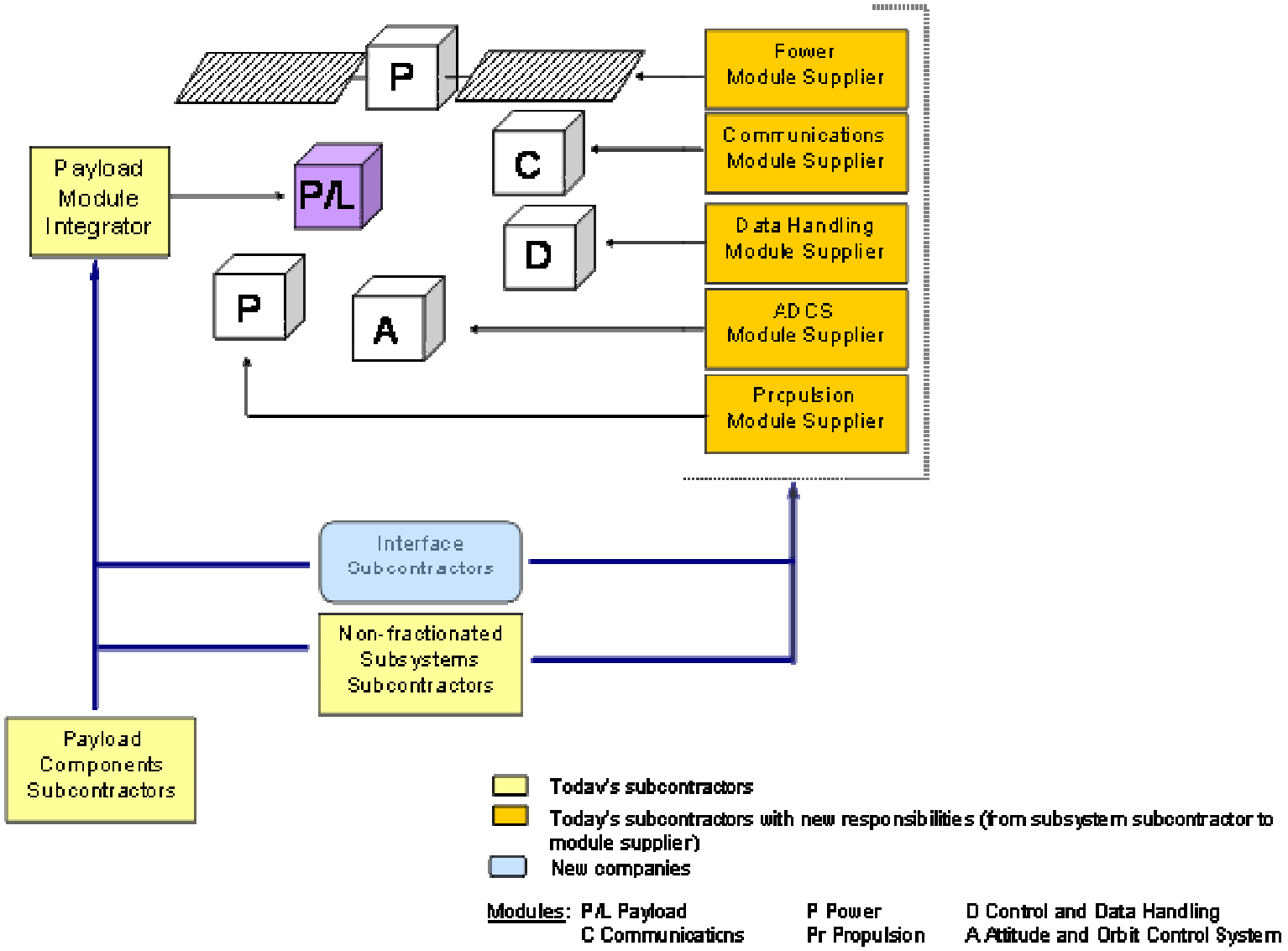

SCHEDULE



INDUSTRIAL ORGANIZATION

TRADITIONAL SPACECRAFT 	High financial risks	Limited flexibility	Large unique costs	Long cycles	Concentrated and stable industry
FRACTIONATED SPACECRAFT 	High technical risks Lower financial risks	Better accommodation of future uncertainty	Significant costs savings	Shorter cycles	Less concentrated and stable industry More competition

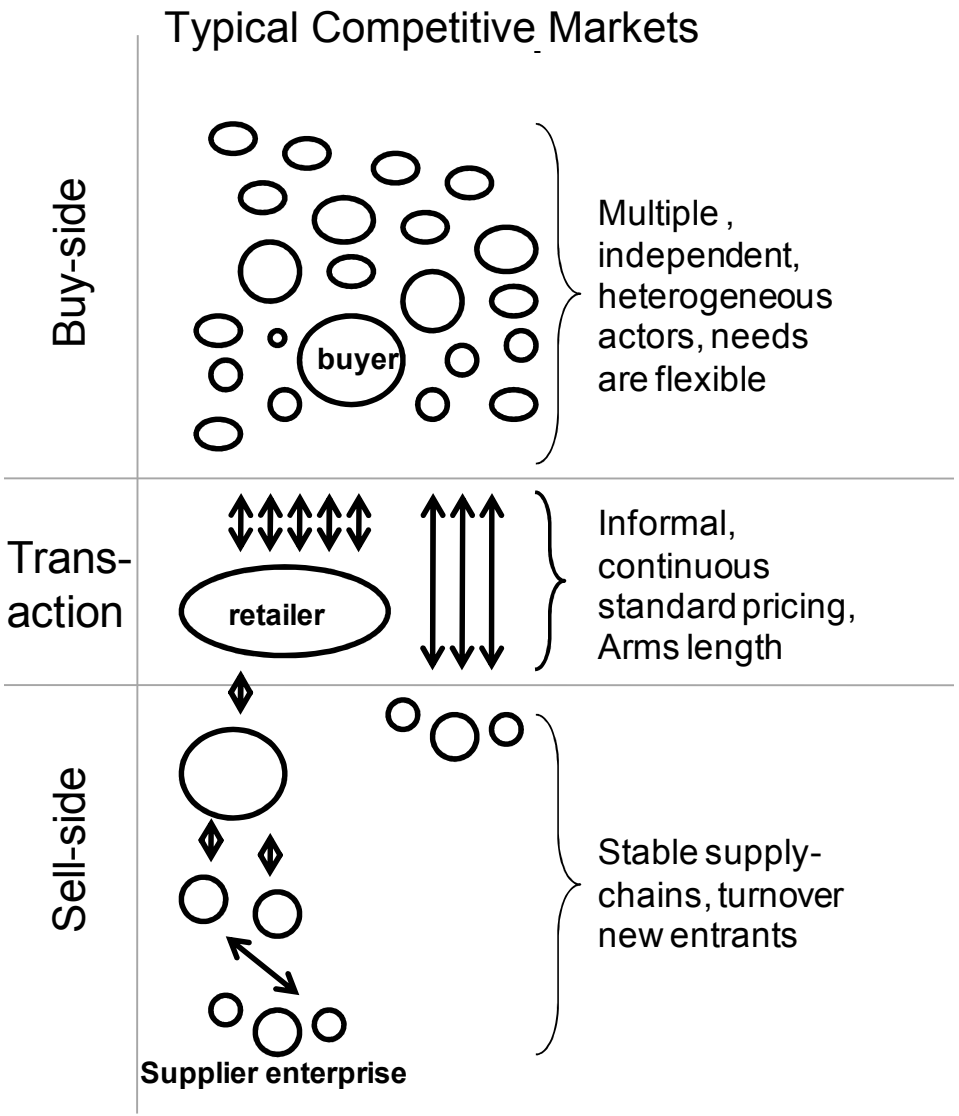
A New Industrial Organization?



Other organizational impacts of fractionation?

- **Integral vs. modular architecture**
  - **"modularity is a financial force that can change the structure of an industry" (Baldwin and Clark, 2004)**
  - **New dynamics**
  - **Much more competitive**
  - **Much shorter product cycles**
  - **Much less stable and concentrated**
- **Role of system integrator?**
  - **Standards and open architectures reduce need**
- **Protoflight (craft production) → mass production**

Examining the Space Market



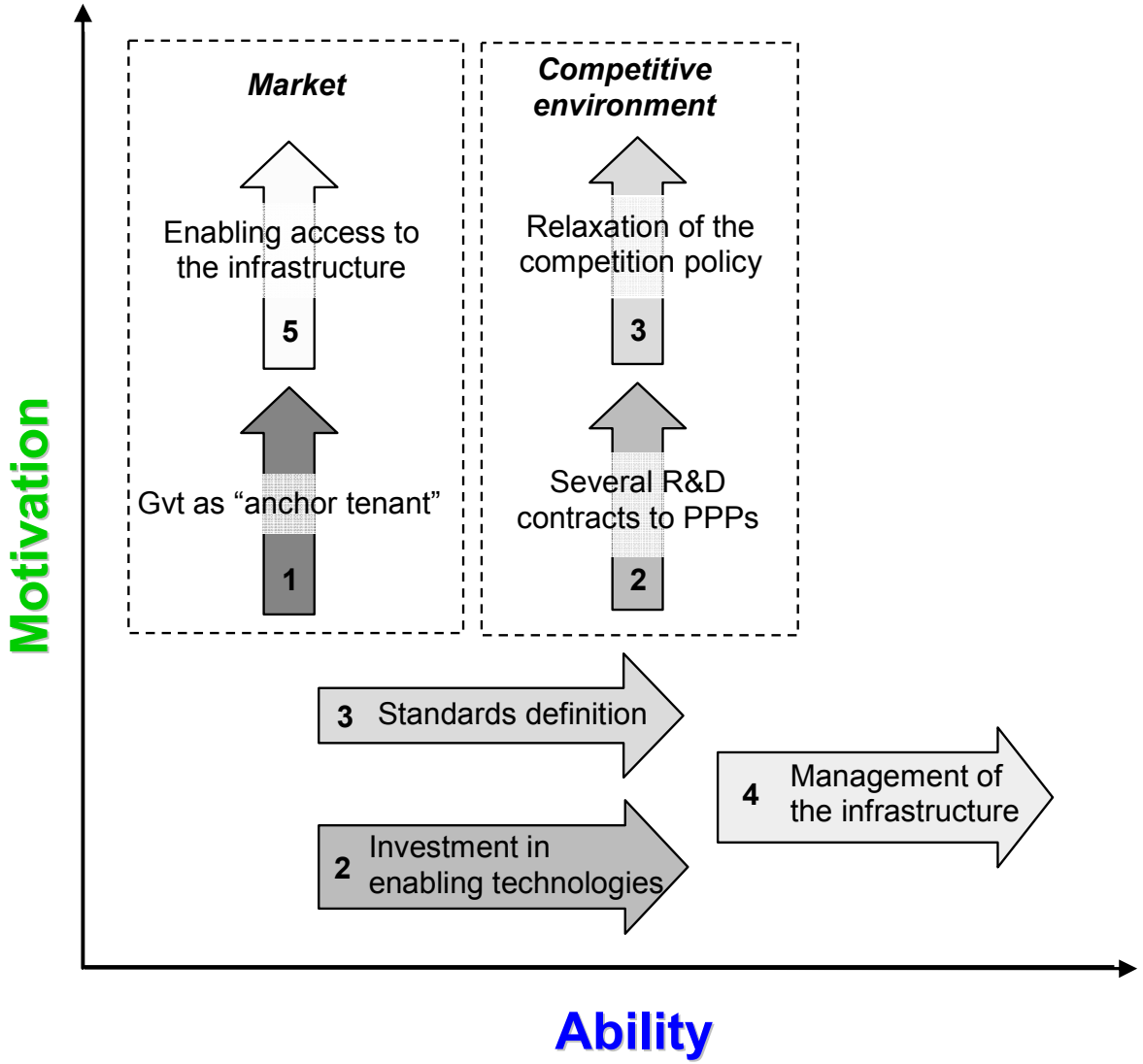
Policy Enablers to Affect Change

Motivation to Innovate
is generally determined by:

- Market size/growth
- Competitive dynamics
- Economics of opportunity
- Competitive forces

Ability to Innovate
is generally determined by:

- Resource availability
- Standards
- Market access
- Industry development



In Summary: Industrial & Policy Analysis

- **Fractionated architectures could have significant impact on:**
  - **Industrial paradigm (craft to mass)**
  - **Industry organization (integrator, prime, supplier, etc.)**
  - **Market structure**

- **Industrial organization changes likely in shift from craft to mass production**

- **Certain policies could facilitate successful proliferation of a fractionated spacecraft concept**

What Lessons to Take Away?

- **When you really dig into what the end user values, and focus on 'function' instead of 'form,' you can find surprising benefit in otherwise unlikely ideas.**

- **Product design change alone won't solve big problems. Organizations, industry and market structures usually need to change as well.**
  - ***But gosh, is that hard to do! And just when you thought the product design task was hard…***

Let's go back to see how well this discussion has illustrated all the conference speaker requirements…

What you should be hearing…

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Product Design and Sustainability

Source: SDM Conference 2008 materials

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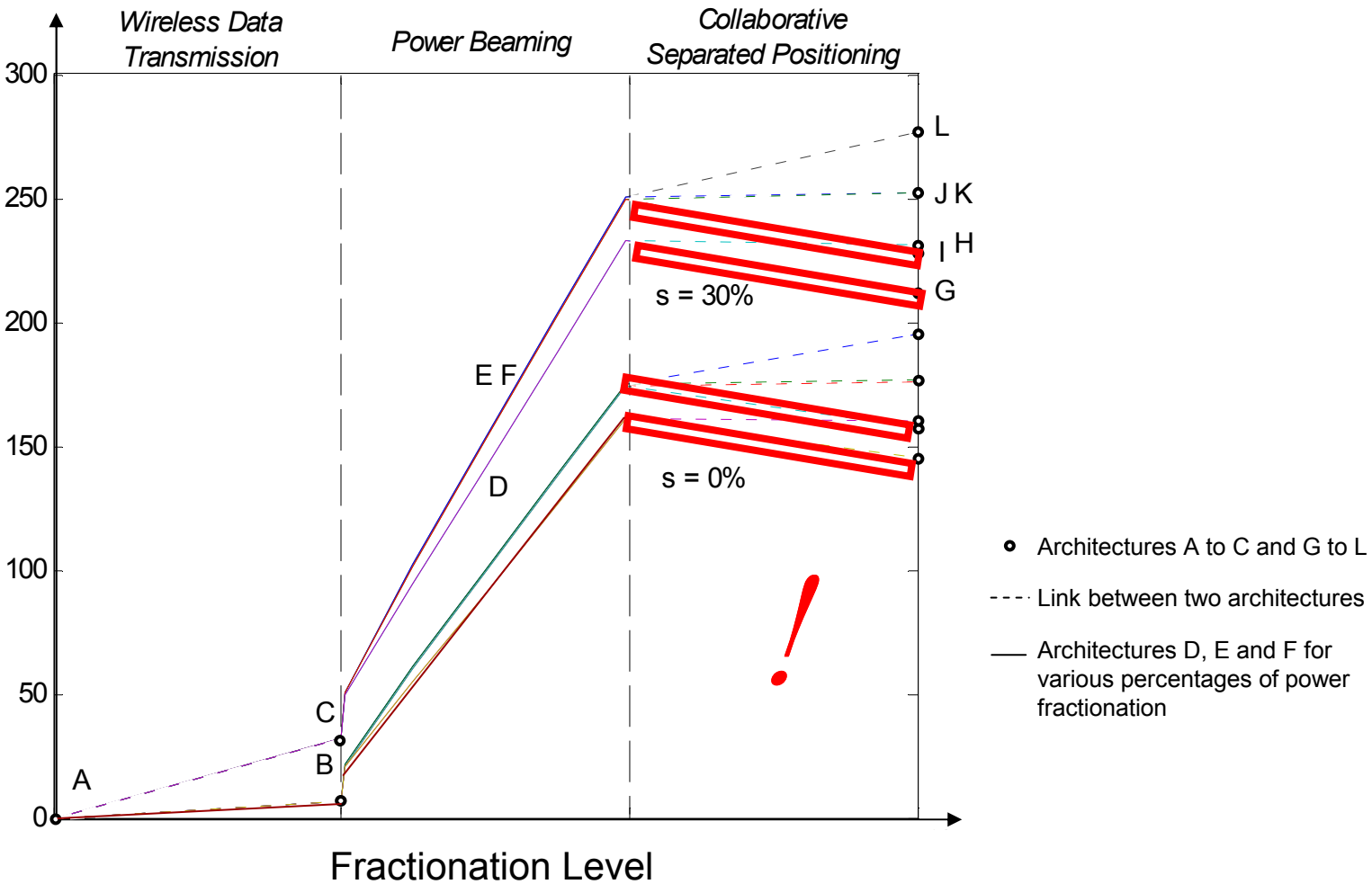
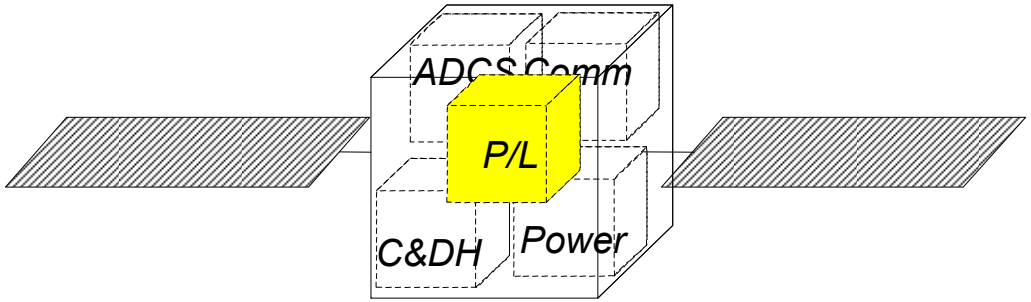
Backup slides

Modeled Impact of Fractionation on Space Segment Mass

Communications Mission



From Current Traditional Spacecraft…



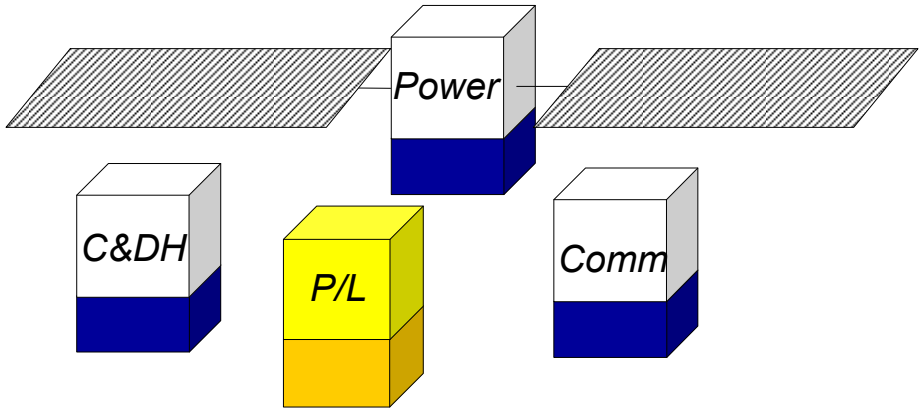
Payload

Bus Subsystems

…to New Distributed Spacecraft (called fractionated spacecraft)

Payload Module

Infrastructure Modules



Iridium Manufacturing

- Cycle time of 25 days vs. industry standard of 12-18 months
- Dock-to-Dock rate of 4.3 Days

Iridium Deployment

- 72 Satellites in 12 Months, 12 Days
- 14 Satellites on 3 Launch Vehicles, from 3 Countries, in 13 Days
- 22 Successful Consecutive Launches

Source: Ray Leopold, MIT Minta Martin Lecture, May 2004

Spacecraft Designs

Monolithic

Distributed

Homogeneous

Heterogeneous