Case Studies of Historical Epoch-Shifts: Impacts on Space Systems and their Responses

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Massachusetts Institute of Technology

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Introduction and Motivation

Operating in space offers unique advantages, but systems…

- Come with high costs
  - Time, Resources, R&D
  - Political factors, red tape, regulations
- Must do more, for longer lifecycles, with less cost
- Often have limited accessibility once in orbit
- Must provide value in unfriendly, dynamic environments
  - Physically
  - Operationally

Need to design and operate systems for longevity, affordability, and value sustainment

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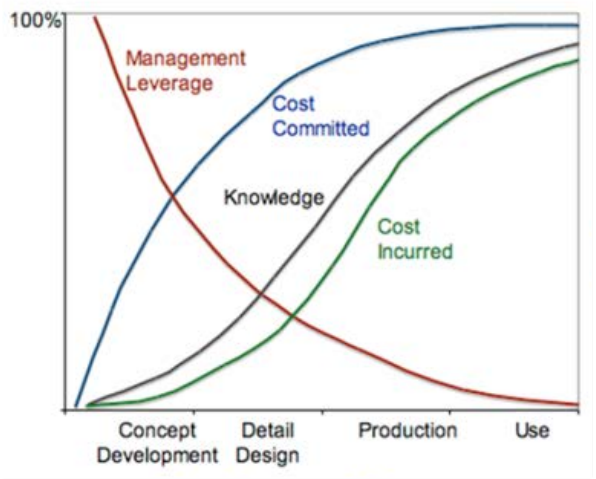
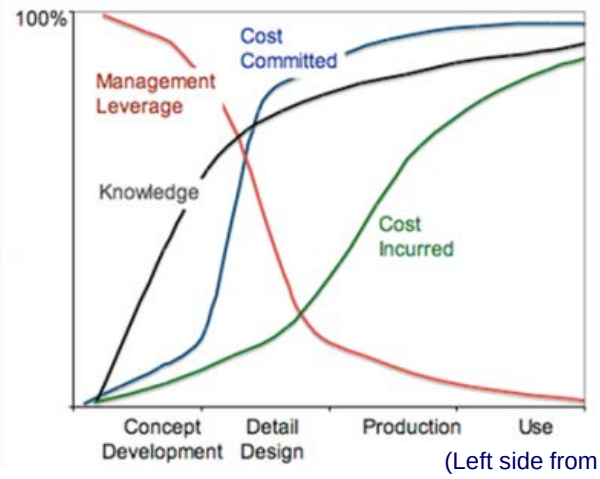
Motivation cont'd



Classic paradigm



New paradigm

(Left side from Blanchard and Fabrycky (1998))

- High leverage early decisions usually made with
  - Incomplete system knowledge
  - High upfront committed costs
- Advancements in SE aim to change these curves
  - Extending managerial leverage
  - Delaying committed costs
  - Increasing knowledge earlier in design

There is a need to alter these curves, enabled by finding designs that display improved performance throughout their lifecycles

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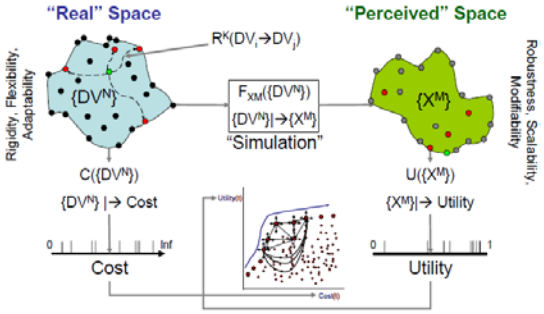
Design to Value

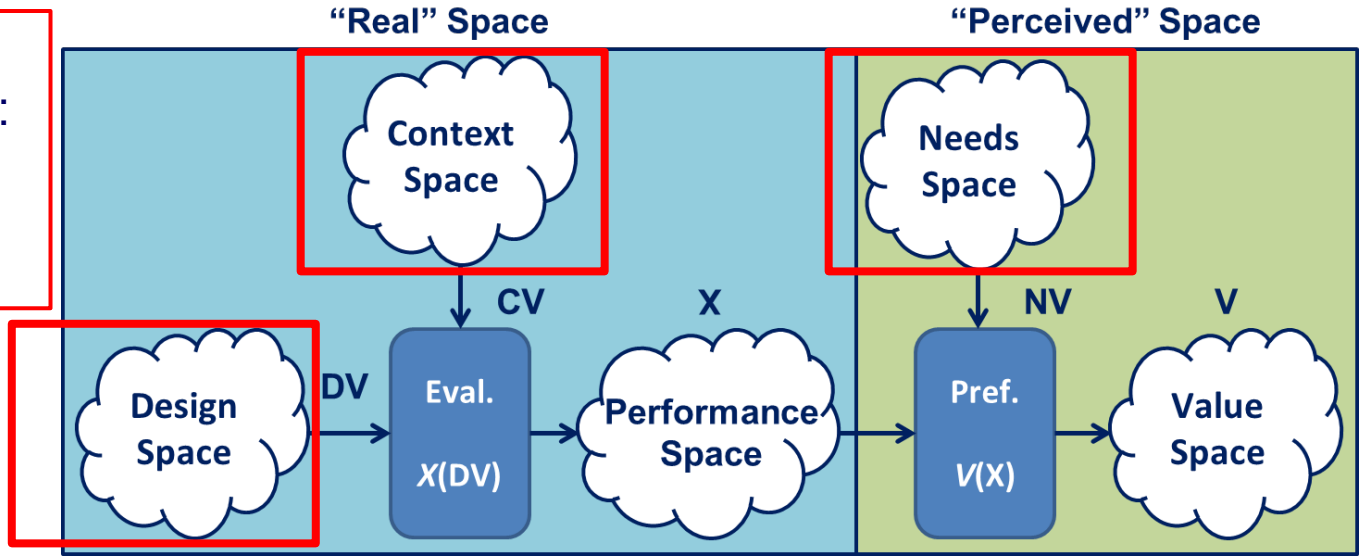


(Ross 2006)

- Engineering design is a means for creating stakeholder value by fulfilling some needs
- The "design" reflects factors within the control of the designer in an effort to meet needs
- But success is determined by more than design

Success depends on balancing three factors:

1. Design,
2. Context, and
3. Needs



Success over time requires the ability to anticipate or respond to changes in these factors

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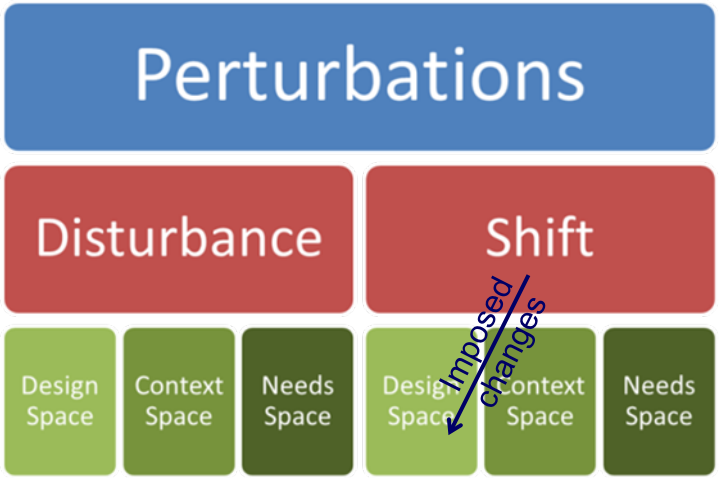
Value Sustainment

A system may face imposed (or threats of imposed) changes in design, context, or needs during its lifetime



- Perturbations
  - any "imposed state change in a system's form, operations, or context which could jeopardize value delivery" (Mekdeci 2012)
  - can include changes in needs as well
- Two types of perturbations
  - **Shift**: Long-lasting changes in design (i.e. form and operations), context, or needs [that could affect value delivery] (Ross, Rhodes, and Hastings 2008)
  - **Disturbance**: Finite-(short) duration changes of a system's design, context, or needs [that could affect value delivery] (Richards 2009; Mekdeci 2012)

Ultimate Goal: Continue to deliver value despite perturbations in design, context, or needs

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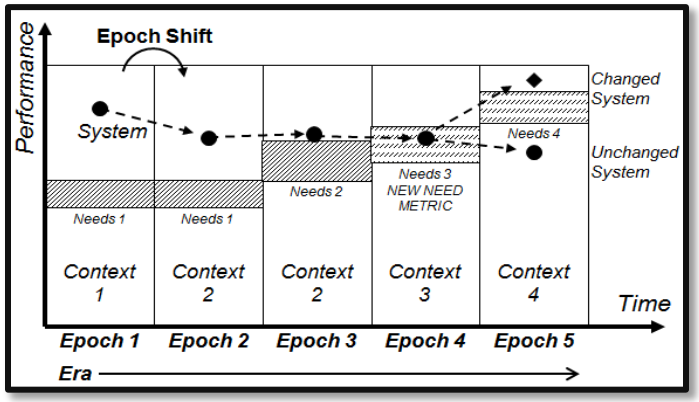
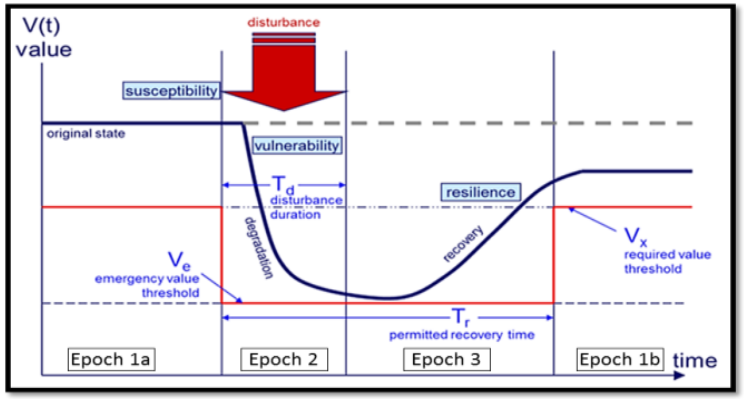
Dynamic Environments





- Systems are exposed to perturbations throughout their lifecycles (epoch shifts and disturbances)
- Two main strategies for dealing with these dynamic environments:
  - Remain ***robust*** ("weathering the storm")
  - ***Change*** in response ("if can't beat them, join them")

Focus of this paper

Space systems can implement both strategies to achieve value sustainment

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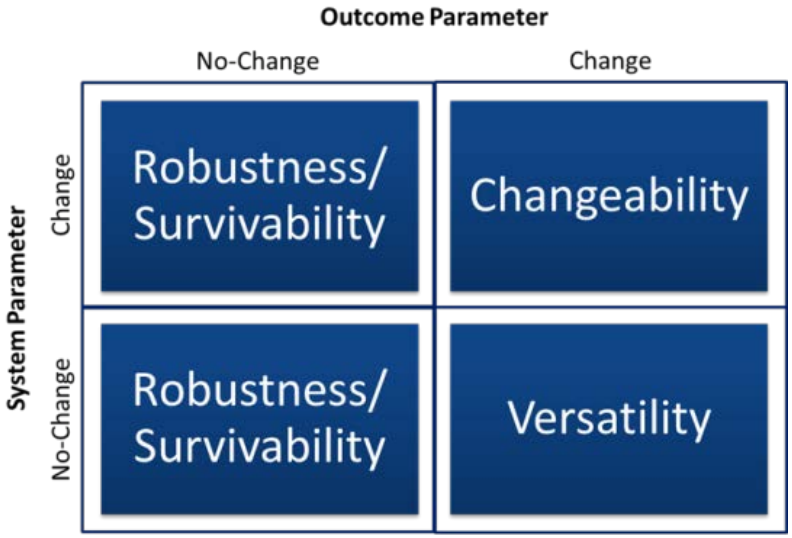
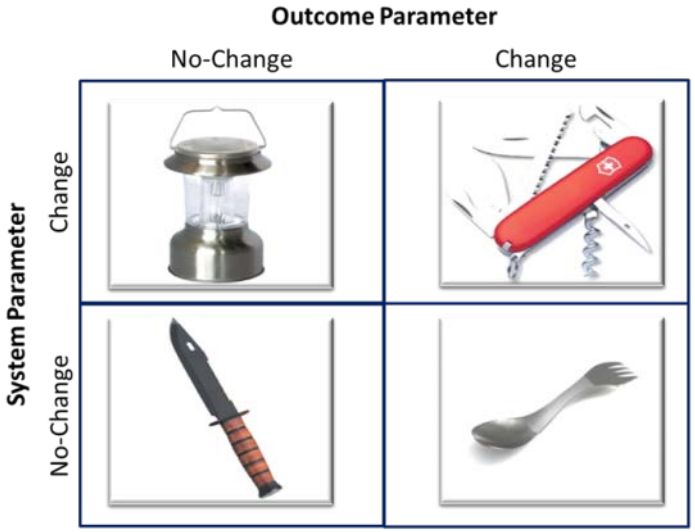
To change or not to change?





Implement response with a “change” or “no-change” strategy?

- Depends on the parameter in question
  - System parameter (Aspect of form, function, or operations, i.e. design space)
  - Outcome parameter (Either another system aspect or an outcome attribute, i.e. performance or utility)
- Different response strategies relate to different lifecycle properties: “ilities”

There may not be one “correct” response;
studying historical examples of system responses could provide insights

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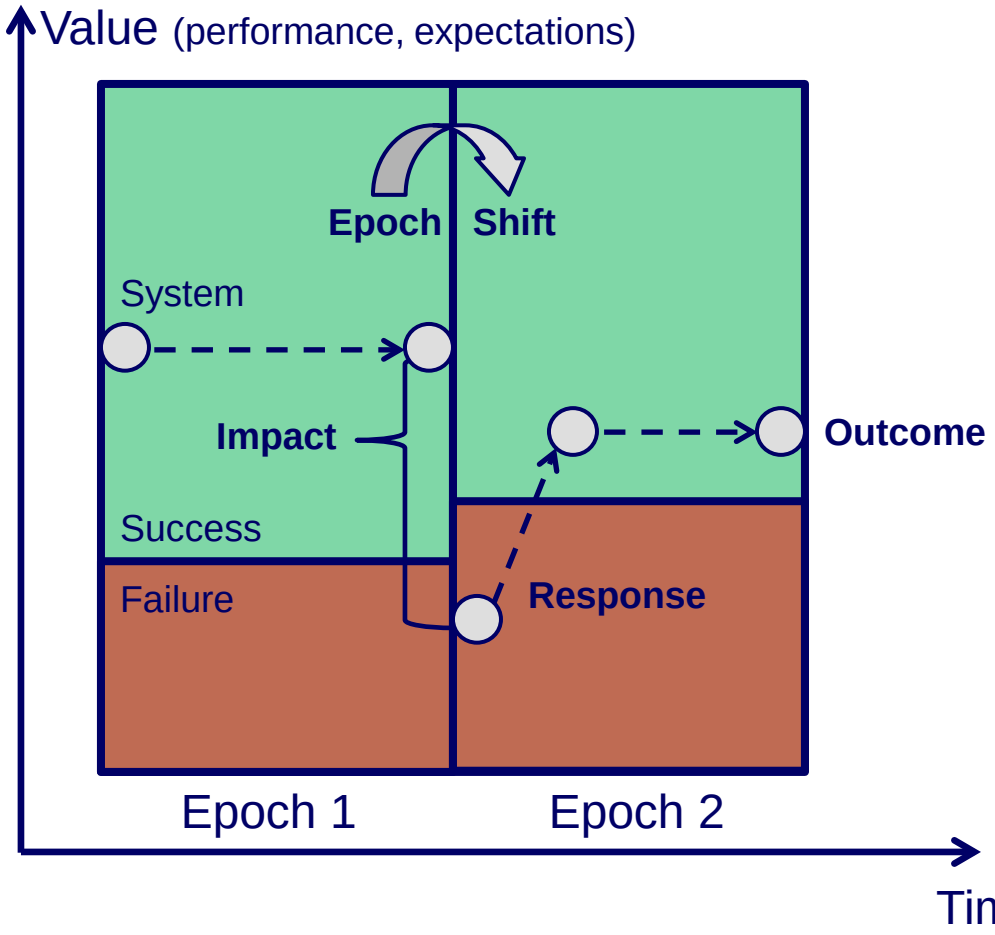
Epoch Shift – Impact – Response – Outcome



- Using Epoch-Era Analysis as a framework to dig deeper into historical cases
- Epoch Shift – Impact – Response – Outcome as construct for evaluation
- To remain viable, some systems may need to respond by changing to ensure desirable outcomes

Key: epochs are defined by factors *outside of the designer's control*

An ***epoch*** is a period of fixed context and needs;
an ***epoch shift*** is a change in one or more of these factors

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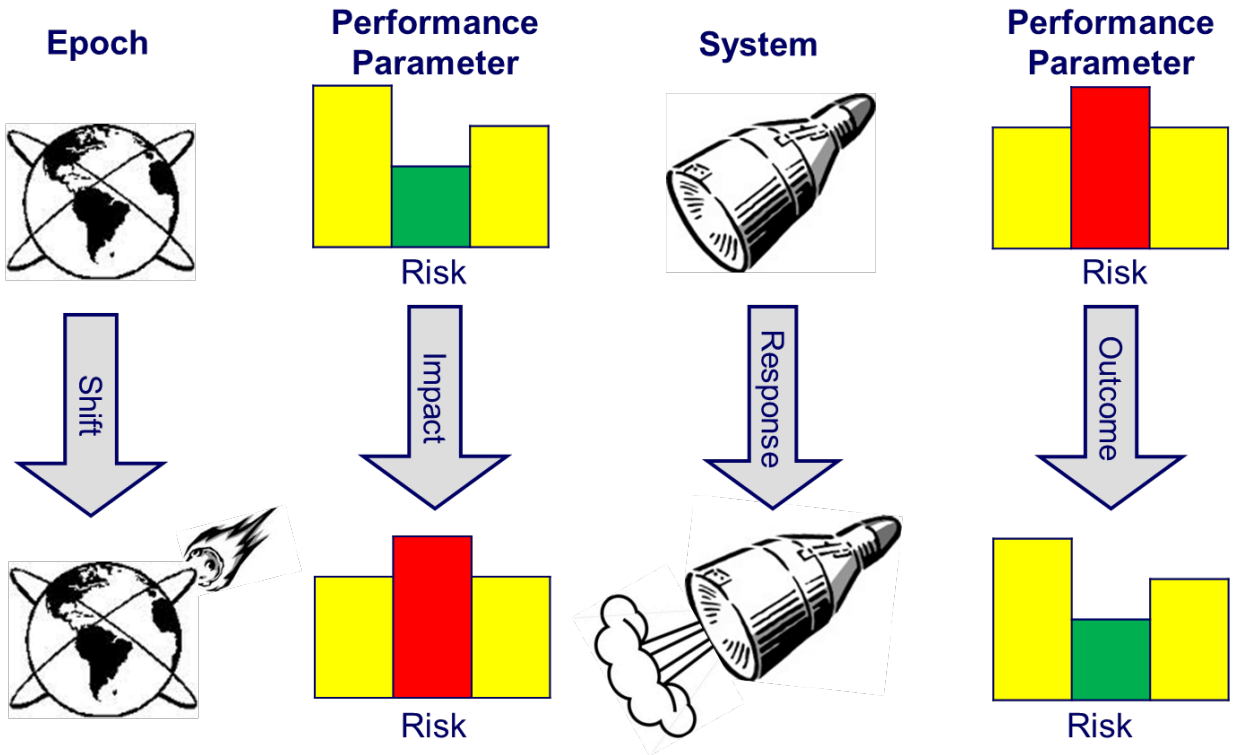
Epoch Shift – Impact – Response – Outcome

May look to past systems for examples of changing to meet new needs or succumbing to the environment and failing.



Illustrative example for applying ESIRO:

- an epoch shift (incoming debris)
- impacts a risk parameter,
- requiring a response (burn onboard fuel)
- to mitigate risk to an acceptable outcome level

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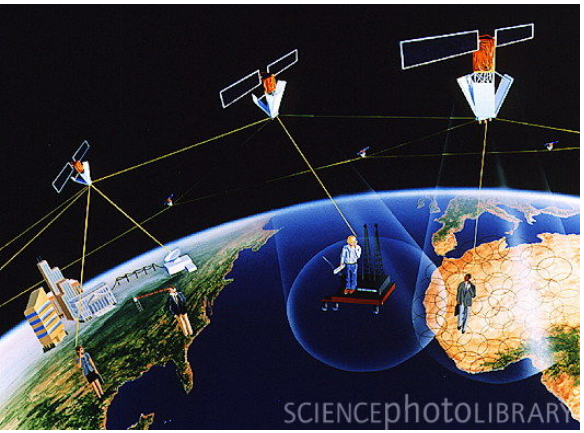
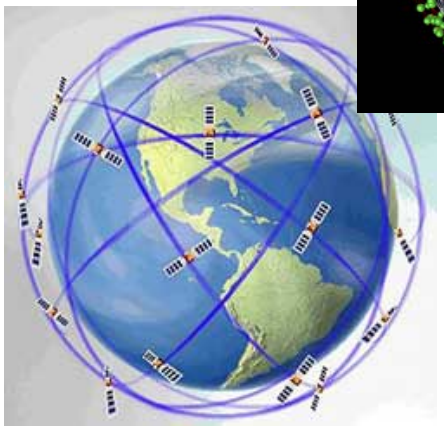
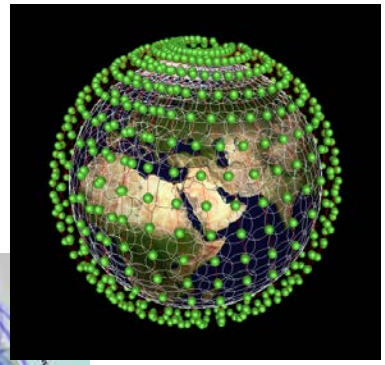
Historical Cases

- Four historical cases were examined using Epoch Shift – Impact – Response – Outcome construct
  - Iridium, Globalstar, Teledesic, Galileo
- Systems chosen for their varying responses and outcomes to illustrate approach







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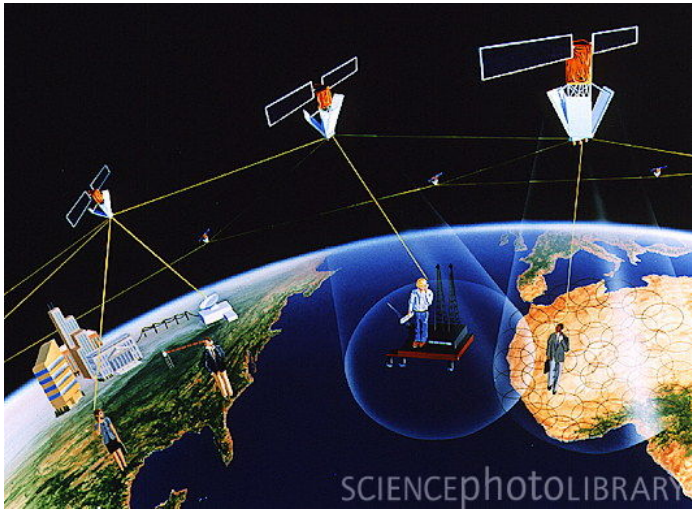
Iridium

- 66 cross-linked LEO satellites (plus 6 in-orbit spares) at 778 km altitude
- 6 polar planes w/ 11 satellites in each
- Included inter-sat links, earth gateways to interconnect w/ telephone networks
- 11 years concept-to-development
- $6 Billion to build and maintain in 1998
- Significant expertise (1,000+ patents)
- Very strong top leadership and engineering teams
- $3,000 handset cost with $3-$8 per minute calls



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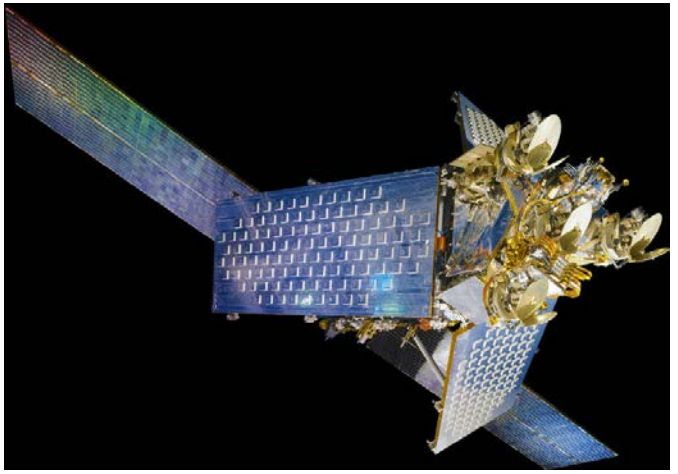
Iridium Epoch Shift

- Terrestrial cellular network development throughout Iridium's design and testing in the '90s
  - Customers begin to value small handsets, coverage indoors and in cars, and reasonable prices
- Iridium handset was costly, large/ heavy, didn't work well indoors/in cars
- Predicted 500,000 customers
  - Had 10,000 in first two quarters
  - Only 20,000 when it declared bankruptcy
  - Predicted 5M users by 2004

"We're a classic MBA case study in how not to introduce a product. First we created a marvelous technological achievement. Then we asked how to make money on it."
– Iridium Interim CEO John A. Richardson, August 1999



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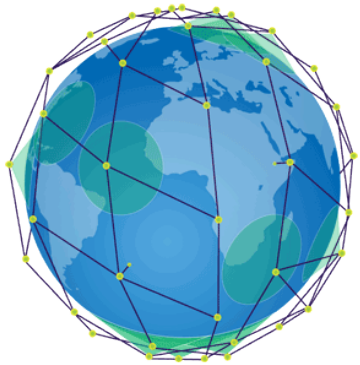
Iridium Response



- Filed for bankruptcy in ’99
  - One of the 20 largest bankruptcies
- Sold for $25 million in 2001
- Under new management (Iridium Communications Inc.) targeted wider customer groups
  - Business in remote locations (construction, oil rigs, foresting)
  - DoD (started with 2-yr $72 million contract) (23% 2010 revenue)
  - Emergency response workers
- Fast forward to today: Iridium continues to find new roles
  - FAA (guiding airliners over world’s oceans and poles)
  - FAA (collecting and storing ‘blackbox’ data for airliners)
  - Planning to launch new satellites (IridiumNEXT) in 2015
    - Enterprise data and voice
    - Asset tracking and other Machine-to-Machine applications
    - Higher data speeds and new services
  - 450,000 subscribers (March 2011)

Successful response?

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Iridium Snapshot

Epoch	1980s	1990s	2000s
	Need for global communications. Lack of cellular infrastructure.	Terrestrial cellular development (GSM). Increase in mobile communication demand.	Highly developed cellular networks. Increased globalization.
	Shift		Shift
Impact		Consumer demand shifts to lighter phones, cheap service, indoor use.	Higher data and connectivity demands
Response	Iridium Satellite constellation concept developed in order to allow for anywhere communications.	High costs ($6B) committed to development. Launched service in 1998 with heavy/expensive handset ($3K). $3-8 per minute calls	Iridium bought for $25M. Upgraded satellites and introduced new applications.
Outcome	Technically driven mgmt. Competitors in satellite based communications, as well as terrestrial cellular.	Lack of subscriptions due to better options/prices. Bankruptcy and possible decommissioning of satellites.	Wider user base including world businesses, DoD, rescue, maritime, FAA, agriculture, construction.

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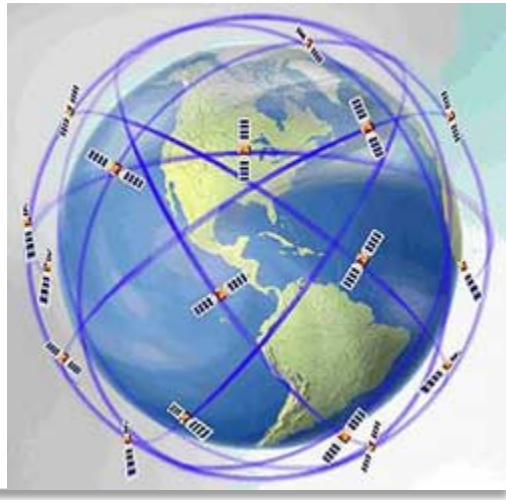
Globalstar

- 48 LEO satellites (4 spare) at 1414 km altitude
- 8 polar planes w/ 6 satellites in each
- Needs more earth gateways to interconnect w/ telephone networks
- Does not support on-board switching (ISL)
- Ground processing (not on satellite like Iridium)
- Meant for affordable voice and data communication
- $3.8 billion to build and maintain in 2000
- $1,000 handset cost with $1-$3 per minute calls
- Bankruptcy for $3.3B in 2002



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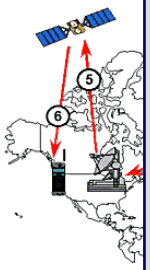
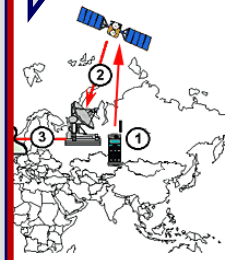
Globalstar Snapshot

Epoch	1980s	1990s	2000s
	Need for global communications. Complex Iridium concept. Lack of cellular infrastructure.	Cellular development (GSM). Consumer demand shifts to lighter phones, cheap service, indoor use. Iridium bankruptcy.	Highly developed cellular networks. Higher data demands. Increased globalization. Increased DoD usage (war)
Shift			
Impact		 Consumer demand shifts to lighter phones, cheap service, indoor use.	Higher data and connectivity demands
Response	Globalstar constellation concept to use higher, lighter sats, no ISL. Target developing nations.	High costs ($3.8B) committed to development. Launched service in 2000. Handset ($1K) heavy/expensive $1-3 per minute calls	Globalstar bought for $45M. Upgrading satellites, improving service Lower cost to $1 per minute w/ specials for calling home (US)
Outcome	Competitors in satellite based communications, as well as terrestrial cellular contending for market.	Lack of subscriptions due to better options/prices in cellular. Cheaper than Iridium but market cleared out following Iridium failure. Bankruptcy.	Wider user base including rural areas, DoD, travelers, maritime, developing nations.

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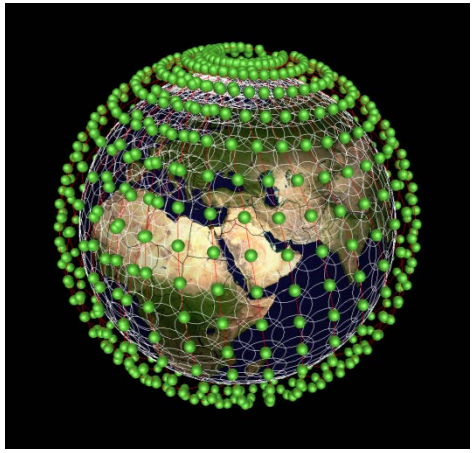
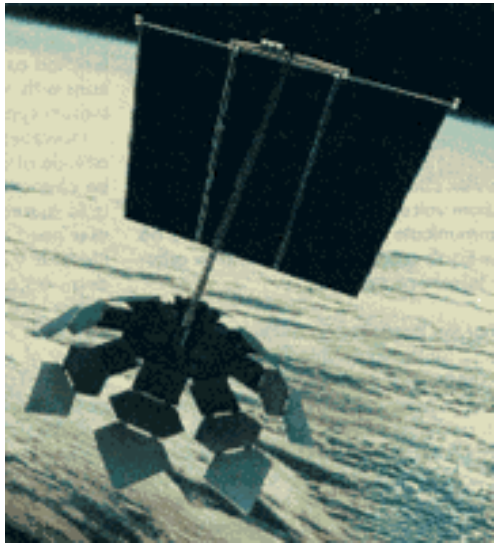
Teledesic

- $9 Billion internet satellite constellation
- 840 LEO satellites at 700km altitude (1995)
- Scaled to 288 sats at 1400km in 1997
  - 12 orbital planes with 24 sats in each
- Further scaled down to 30 sats as market demand continued to decrease
- Complex inter-satellite linking
- Launched one test satellite in 1998
- Raised $1B before Iridium failure showed signs of declining market
- Gave up frequencies and ceased work 2003





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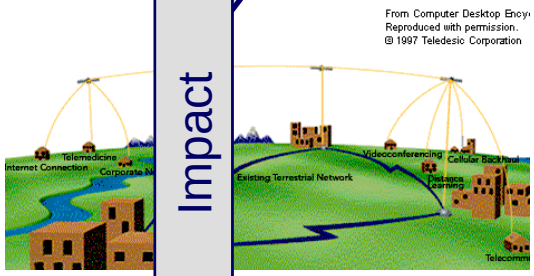
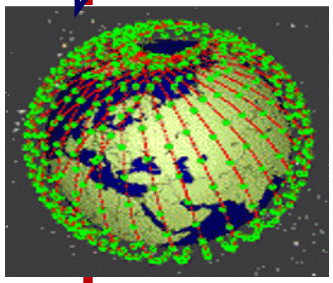
Teledesic Snapshot

Epoch	Early 1990s	Late 1990s	2000s
	Need for global broadband internet. Lack of cellular data infrastructure.	Cellular network development (GSM and data). Decreasing demand in space internet.	More cell data development. Iridium/globalstar bankruptcy. Ground to air internet services
	Shift		Shift
Impact		 Decreasing demand leads to decreased investment.	 Fear-induced decrease in investment/ interest
Response	Teledesic constellation concept developed. 840 LEO sats to deliver broadband speed internet.	Scaled down complexity and cost to 288 satellites. Launch test satellite in Feb 1998	Further scale # satellites to 30. Eventually release frequency license and cease work.
Outcome	Raised $1B in funding for ambitious $9B proposal. Competition in data delivery systems rises.	Decrease in demand followed by decrease in investors. Cellular networks evolving and meeting demands at lower costs.	Failed concept to development. Iridium failure showed weak market for LEO sat comm. Airliner internet through ground antennas wins out.

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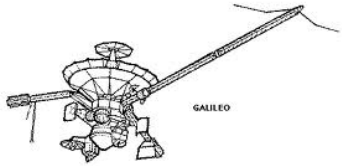
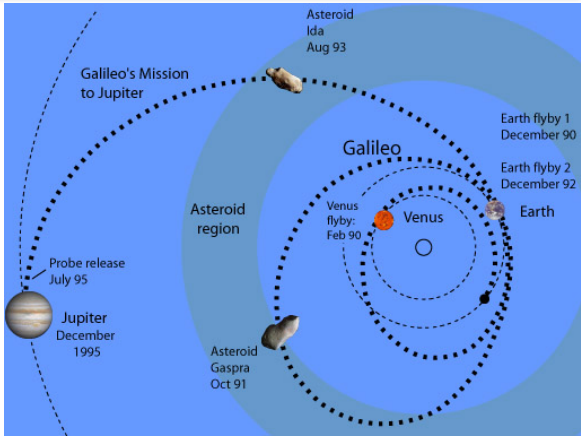
Galileo



- Launched 1989 aboard shuttle Atlantis
- $1.39B space probe to study Jupiter
- Many delays lead to more probe development and lots of shelf time (possible cause of problem)
- Centaur-G stage became prohibited after Challenger disaster and forced mission to use gravity assists
  - Much longer and slower trip to Jupiter and its moons
- Primary payload, high gain antenna fails to deploy, severely limiting capabilities of data communications
- Reprogrammed software, Deep Space Network, and receiver upgrades allow for slow comm to save mission
- Radiation causes other components to malfunction over long mission life (recorder, camera, sensors)
- Reworks save mission and allow Galileo to meet and exceed most mission objectives



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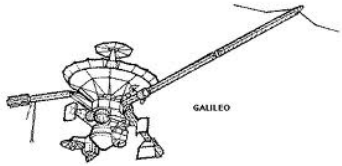
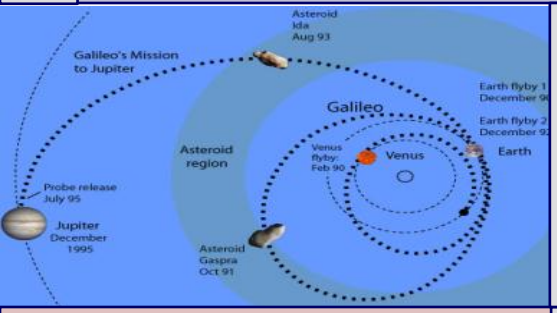
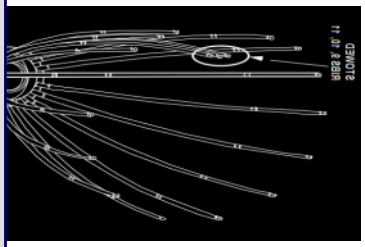
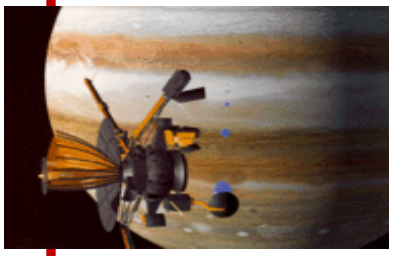
Galileo Snapshot



Epoch			
	1980s Delay in shuttle development early 1980s Hiatus in shuttle launches after Challenger disaster. CentaurG stage prohibited	Shift → 1991 After many years sitting in storage before launch and use, high gain antenna malfunctions, does not open, leaving only the low gain antenna.	Shift → 1990s Jupiter's harsh radiation environment plagued spacecraft. Tape recorder damage. Camera/sensor damage.
Impact		 Decreased communication bandwidth	 Decreased recording time
Response	Galileo planned launch for STS-23 in 1982 and STS-61 in 1986 – both delayed. Re-profiled w/ gravity assists around Venus and Earth.	Many exercises to open high gain: thermal cycling, power cycling, spinning sat and hammering. Re-program on-board computer to use low gain. Used DSN and many upgrades to receivers.	Salvaged tape recorder use. Changed mission CONOPS to deal with malfunctioned components. Developed new mission objectives
Outcome	Mission re-profiling (for weaker upper stage) for much slower Jupiter route. More time for development of probe.	Make-shift communications at much lower speed. Saved mission from failure using software, receiver upgrades and DSN	Survived long enough to reach most mission goals and more. Saved valuable tape recorder to store data for slow downlink.

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Summary Chart

System	Shift	Impact	Response	Outcome
Iridium	Cellular development	Low subscription	None	Failure
Iridium	Increased communications	More data demand	Bankruptcy/ Target niche markets	Success
Globalstar	Cellular development	Low subscription	Cheaper architecture	Failure
Globalstar	Increased communications	More data demand	Bankruptcy/ Target niche markets	Success
Teledesic	Terrestrial data development	Decreased demand	Scaled down	Failure/ Success
Teledesic	Iridium/ Globalstar bankruptcies	Decreased investment	Cease work	Failure/ Success
Galileo	High gain antenna failure	Decreased bandwidth	Tech/ Ops re-work	Success
Galileo	Component damage	Decreased performance	Ops/ objective re-work	Success

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Summary Chart

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Globalstar	Cellular development	Low subscription	Cheaper architecture	Failure
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Scalability?

Maximize profit
Minimize losses

Flexibility?

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Conclusion

- Often success stories for historical systems are attributed to system properties, or “ilities”
  - Flexibility, robustness, versatility, resilience…
- Specifying these ilities in a clear manner can help to reduce ambiguity in achieving these desirable characteristics
  - Some work has been done on clarifying these terms (e.g. semantic basis for ilities (Ross et al. 2011))
- But knowing which ilities generally lead to success, may not be straightforward
- ES-I-R-O as a framework may be a useful means for structured comparison of large numbers of systems to determine correlation between ility response and epoch shifts
- Patterns in response could provide insight into whether and when to intentionally design for particular ilities in systems

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QUESTIONS?

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