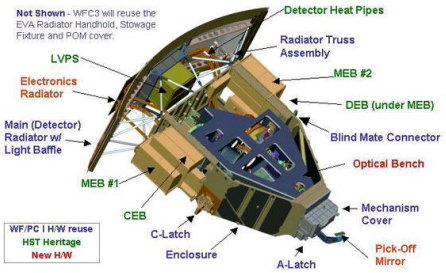

Beyond TRL: A Revised Model of Technology Development and Considerations for Programmatic Analysis

Prof. Zoe Szajnfarber

Assistant Professor of Engineering Management & Systems Engineering and Space Policy, The George Washington University

Research Affiliate, MIT Engineering Systems Division

NASA Cost Symposium

NASA Langley – August 14, 2014

On Technology Cost Estimating

- Technology development– or the focused long term development of – is a major part of R&D at NASA.
- Technology Cost Estimating is a relatively unexamined field in the academic literature on cost estimating
- NASAs recent efforts to fund technology cost estimating research have been helpful in understanding how technology develops (Cole et al 2013, 2014)
- Our focus is not on technology cost estimating: we study the process of technology development itself
  - However, we hope our research can provide insight for the cost and scheduling community

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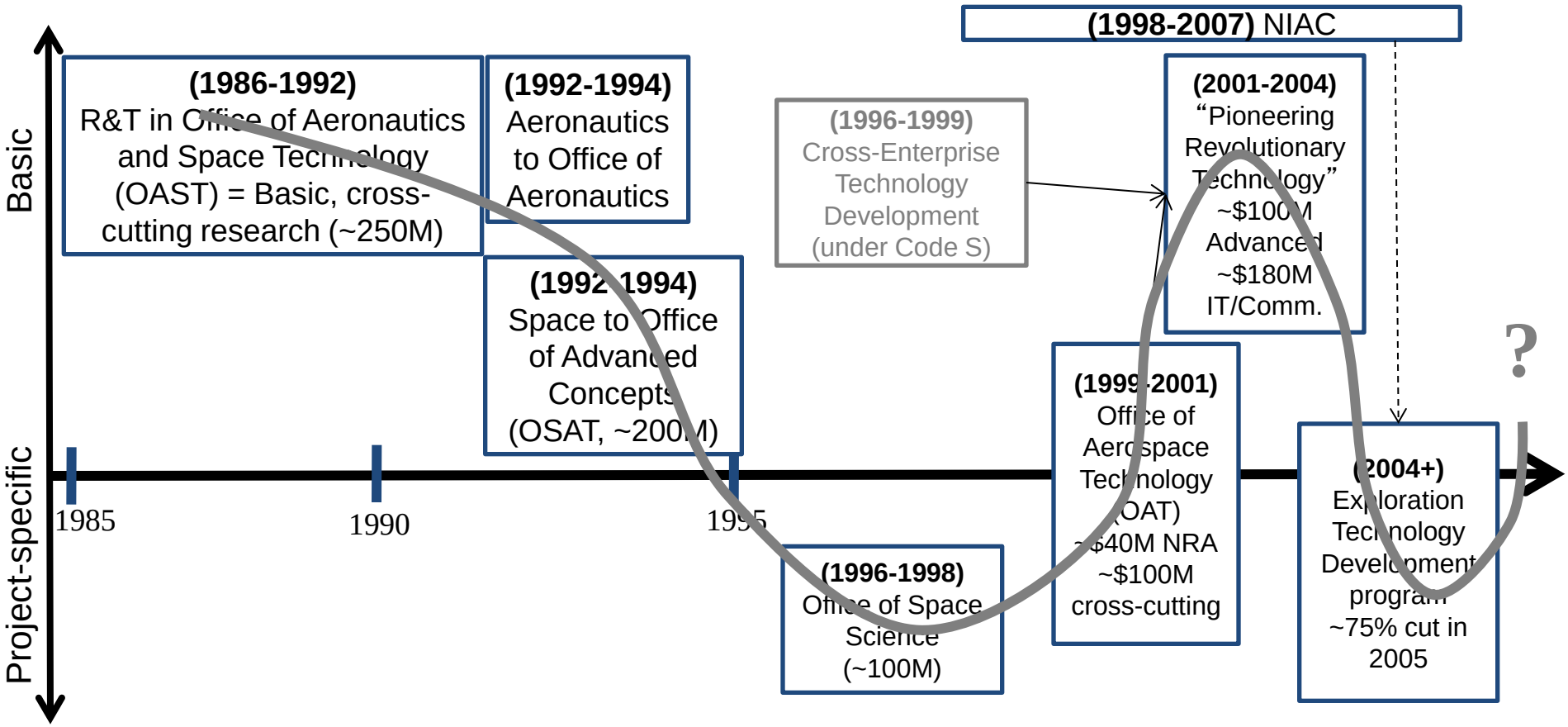
History of Shifts in R&D Strategy



(Based on data collected for NASA R&T Study and NRC study of NIAC)

NEED: To control the system better, we need to understand it better.

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Guiding Research Questions

NEED: To control the system better, we need to understand it better.

1. How do new capabilities traverse the innovation system as they are matured and infused into flight projects?
   - Empirically grounded models of the innovation process
   - Considers technical, social and political factors
   - Can this process be predicted/estimated?

2. To what extent can the process be improved through feasible management interventions?
   - Exploring organization configuration as a design lever
   - Design for evolvability/tinkerability
   - Improved incentive systems, based on valid preference structures.
   - Balanced technology investment strategies that acknowledge key attributes of space innovation ecosystem

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NASA Innovation Landscape

Political-level context

Agency-level planning

Project-level Development & Implementation

Technology-level Research & Development

Scientific and Technical State-of-the-art

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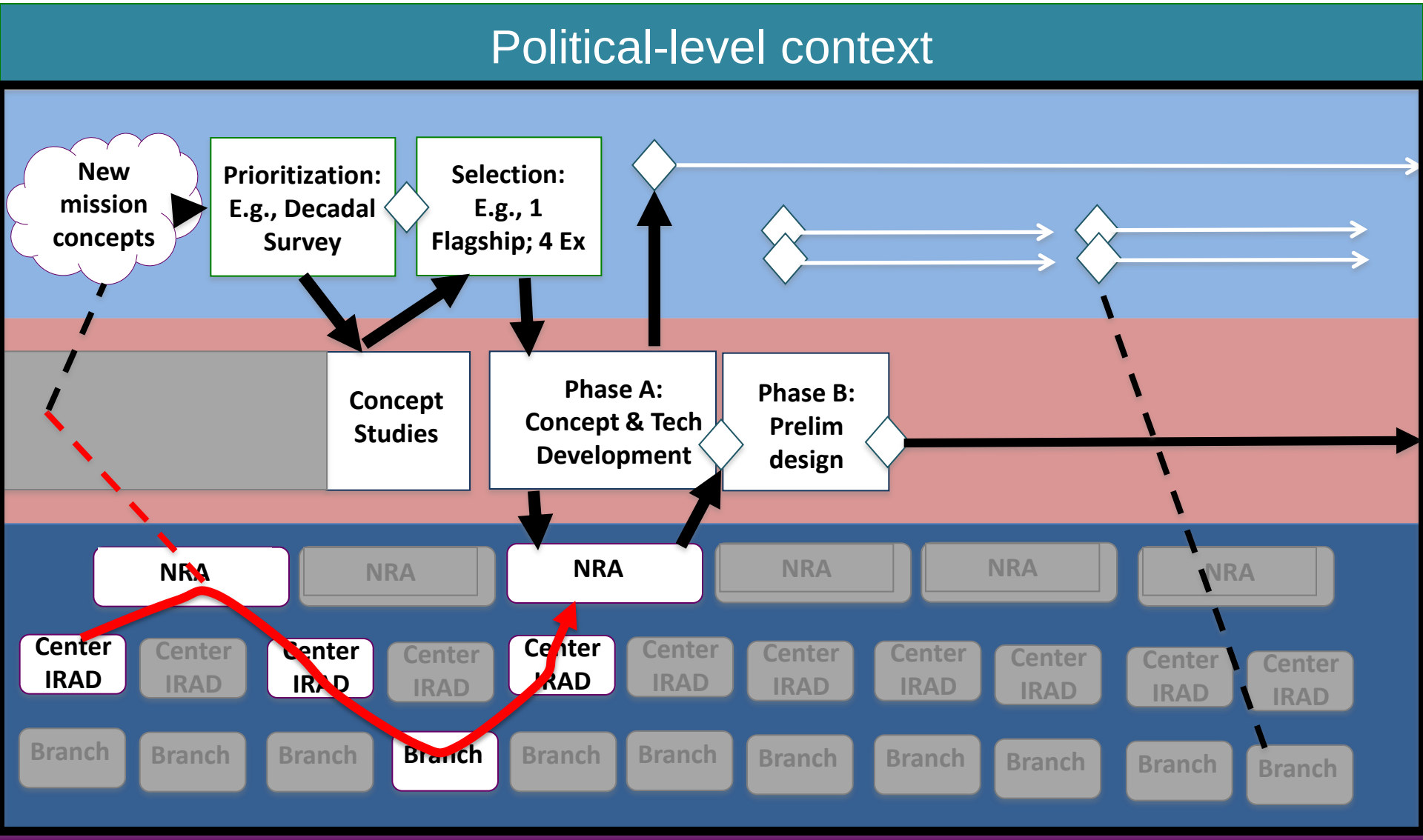
NASA (Space Science) Innovation Landscape



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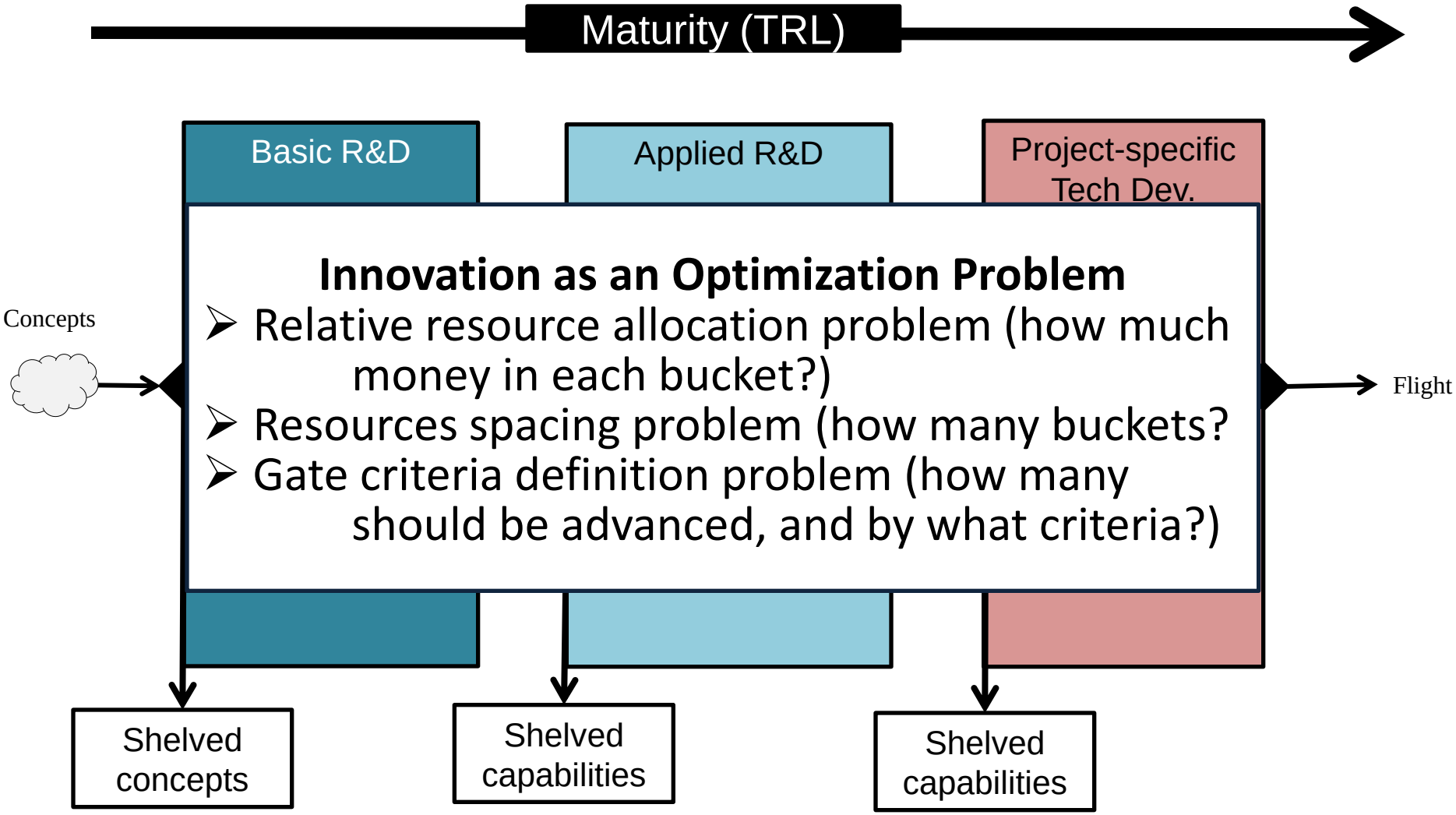
Current Conceptualization: Stage-Gates



Innovation as an Optimization Problem

- Relative resource allocation problem (how much money in each bucket?)
- Resources spacing problem (how many buckets?
- Gate criteria definition problem (how many should be advanced, and by what criteria?)

*Synthesized from NASA strategic planning documents 1990-2006

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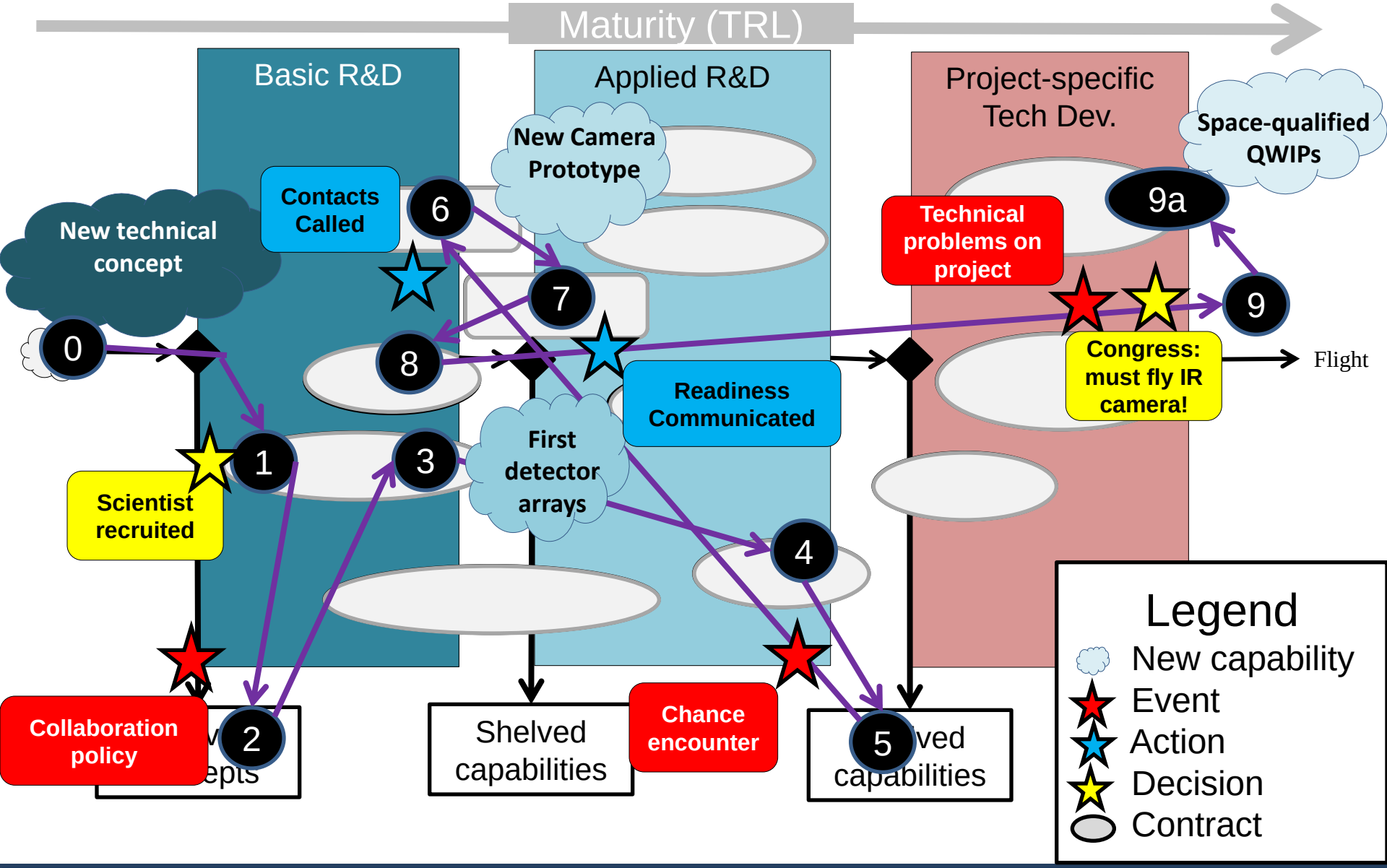
Actual Complexity of Process



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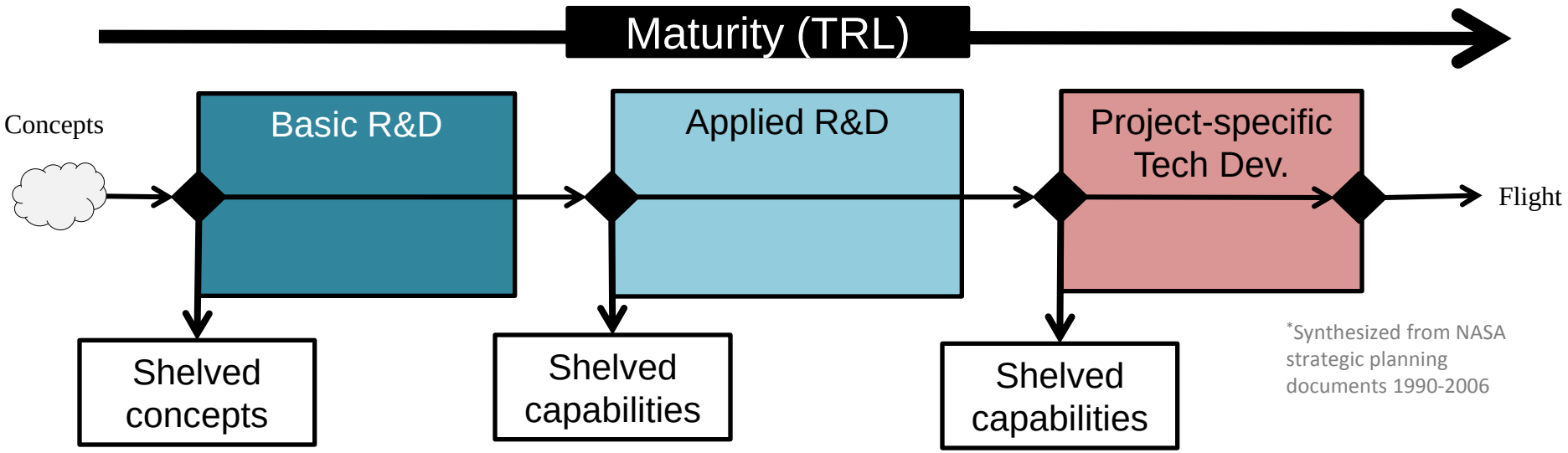
Stage-Gate Assumptions



Underlying assumptions:

(1) Technologies **mature** from <u>left to right</u> over time;
(2) **Stages** are <u>mutually exclusive</u> (at a given time);
(3) **Shelving** is an <u>active process</u>, controlled by decision makers;
(4) **Shelf life** is <u>passive</u> and a function of technical obsolescence.

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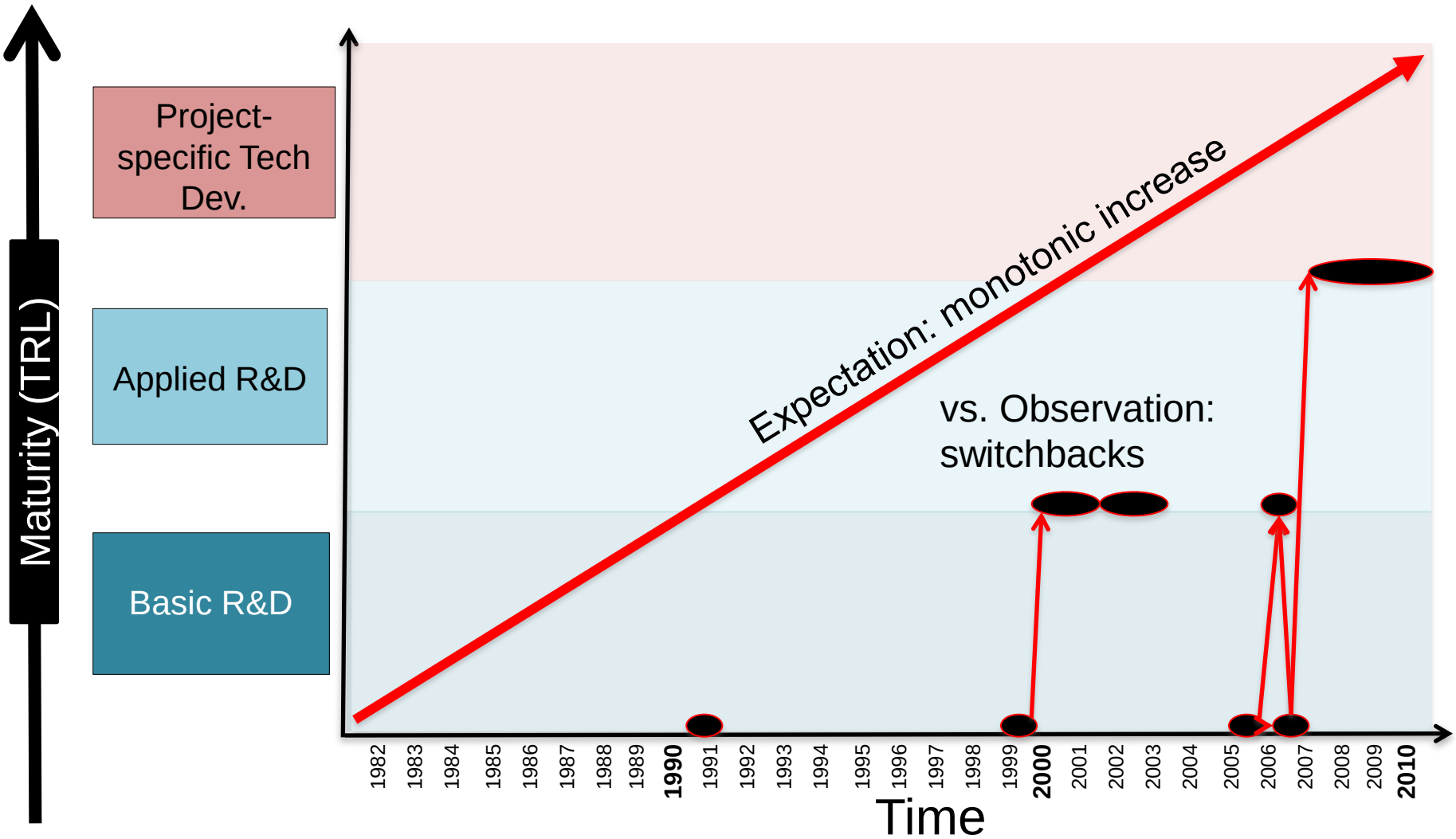
Switchbacks in Maturity



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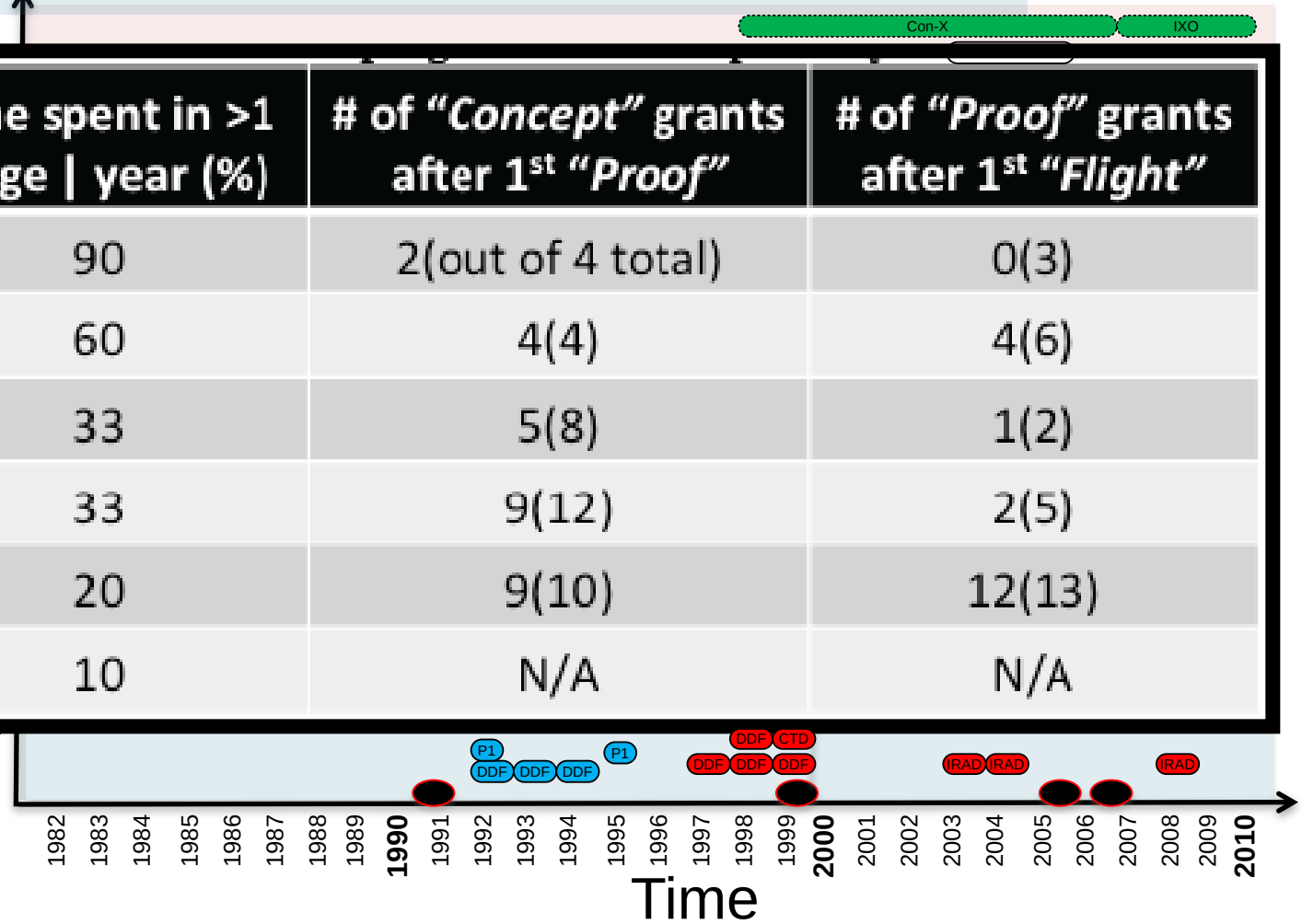
Switchbacks in Maturity

Case	Time spent in >1 Stage | year (%)	# of "*Concept*" grants after 1st "*Proof*"	# of "*Proof*" grants after 1st "*Flight*"
Tech A	90	2(out of 4 total)	0(3)
Tech B	60	4(4)	4(6)
Tech C	33	5(8)	1(2)
Tech D	33	9(12)	2(5)
Tech E	20	9(10)	12(13)
Tech F*	10	N/A	N/A



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Passive Gates, Active Shelves

- Expectation (assumptions #3 and 4):
  3. Rejection at Gate => Shelving
  4. Similar shelf lives for similar technologies
- Observation:

Case	Rejected + Shelf	Rejected + !Shelf	!Rejected + Shelf	Duration on Shelf
Tech A	1	1	1	8 /1yrs
Tech B	0	2	1	5 yrs
Tech C	0	3	0	N/A
Tech D	0	2	1	2 yrs
Tech E	1	Multiple	1	2 / 5 yrs
Tech F	0	multiple	0	N/A

Szajnfarber, Z., and Weigel, A. L. (2012). "Managing Complex Technology Innovation: the need to move beyond stages and gates" International Journal of Space Technology Management and Innovation, 2(1), 30-48

Need: More nuanced understanding of underlying processes

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Building Theory from Case Studies

Process Data

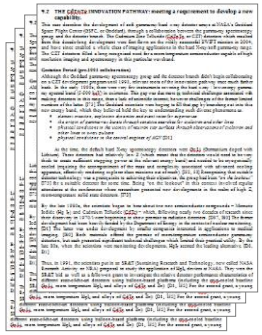
Within-case

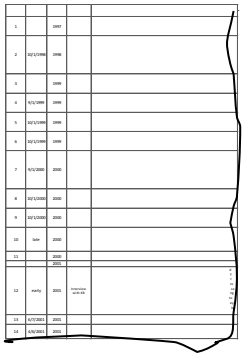
Analytical Chronologies (Pettigrew 1990)

~100 hrs interviews

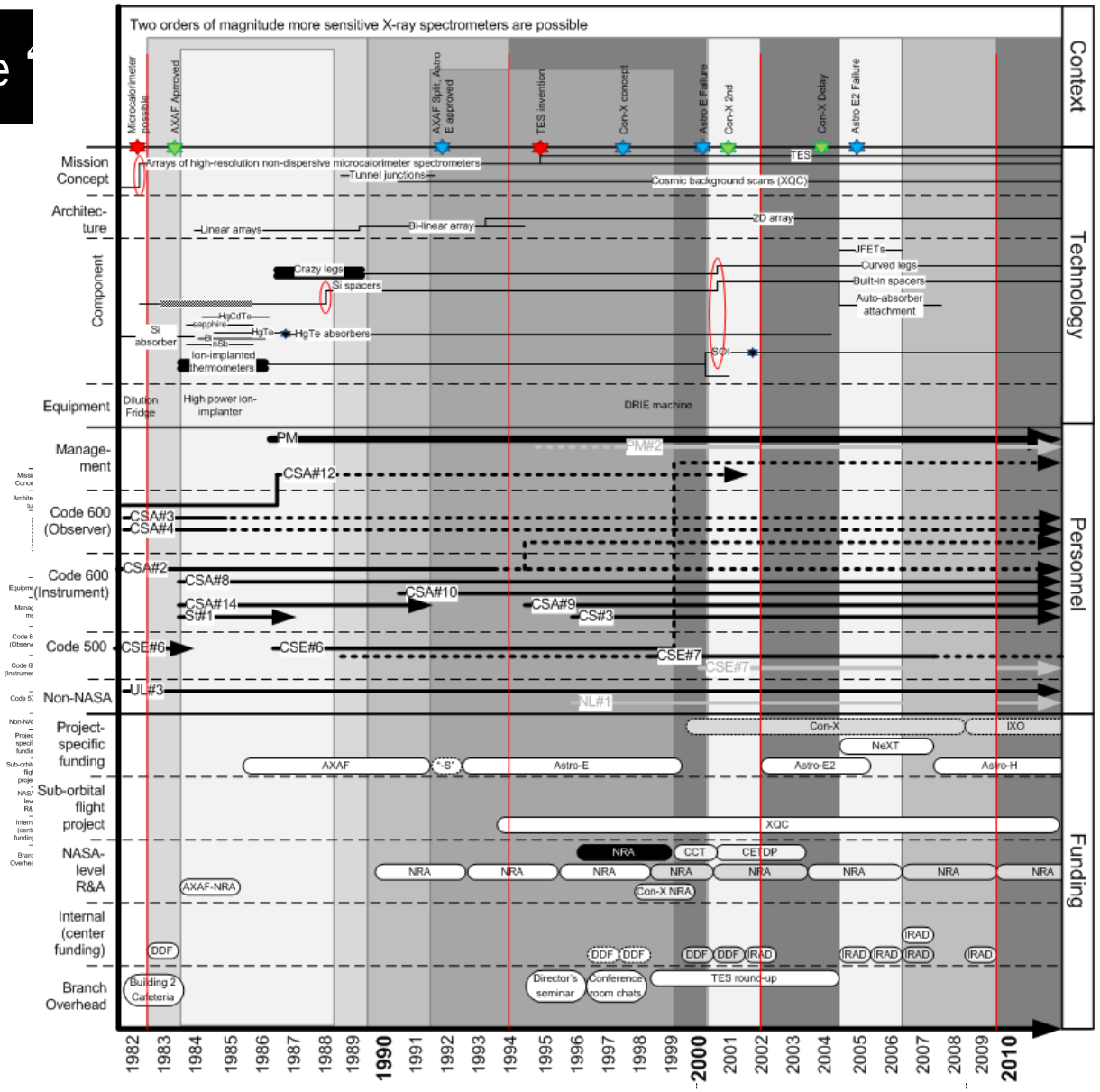
~150 archival documents

~2 months informal observation





Event Database (Van de Ven et al 1990; 2000)



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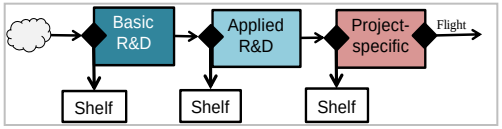
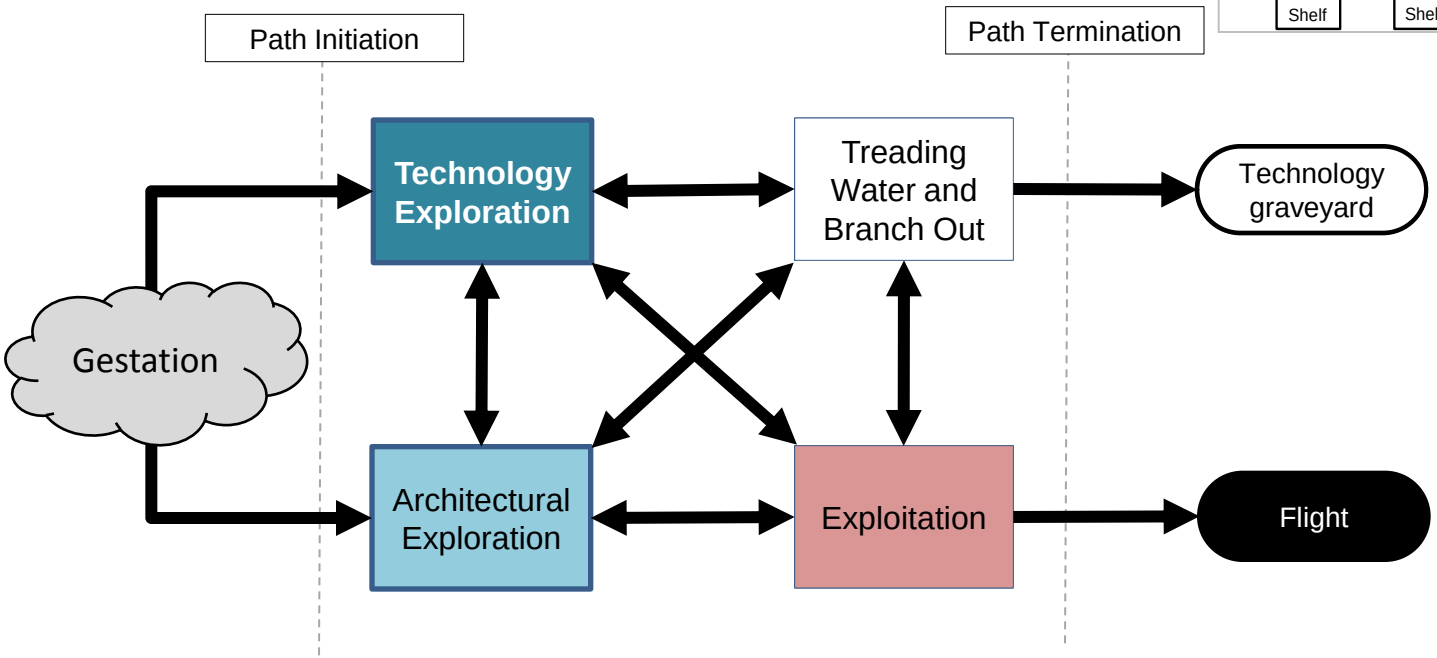
Epoch-Shock Model: Track View

- System exhibits **epochs** of persistent stable (and identifiable) behaviors punctuated by transition inducing **shocks**





  - **Epochs** are illustrated as boxes, and roughly map to stages
  - **Shocks** induce transitions following arrows from one box to another

Szajnfarber, Z., and Weigel, A. L. (2013). "A process model of technology innovation in governmental agencies: insights from NASA's science directorate" Acta Astronautica, 84(3-4), 56-68

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Epoch-Shock Model: Track View

- System exhibits **epochs** of persistent stable (and identifiable) behaviors punctuated by transition inducing **shocks**

Basic R&D STAGE
- Low TRL
- <$100K
- Center-level

nitiation

Technology Exploration

Technology Exploration EPOCH
- Patchwork of funding sources
- Small core team; *ad hoc* collaborations
- Multiple parallel technology paths

Gesta

Technology Exploration

Case	Funding	Personnel	Technology
CADR#1	4xCenter	team + Inst - Tech	parallel component paths
CZT#2	3xCenter + 3xNASA + Balloon	team +4xTech +Inst	multiple technique strategies
Pol#3	Brainstorm + 2xCenter + 3xNASA	team + Tech	multiple readout strategies
Si#4	NASA + Project	team + 3xInst + Tech - 3xObs	multiple materials and techniques tried
Si#5	2xCenter + 2xNASA + Sounding Rocket + Project	team + Tech	multiple materials and techniques tried
Si#6	2xCenter + NASA + SR +2xProject	no change	multiple readout strategies and techniques tried
TES#7	Branch +3xCenter + 2xNASA + SR + Project	team + Tech	Exploration of new materials and techniques

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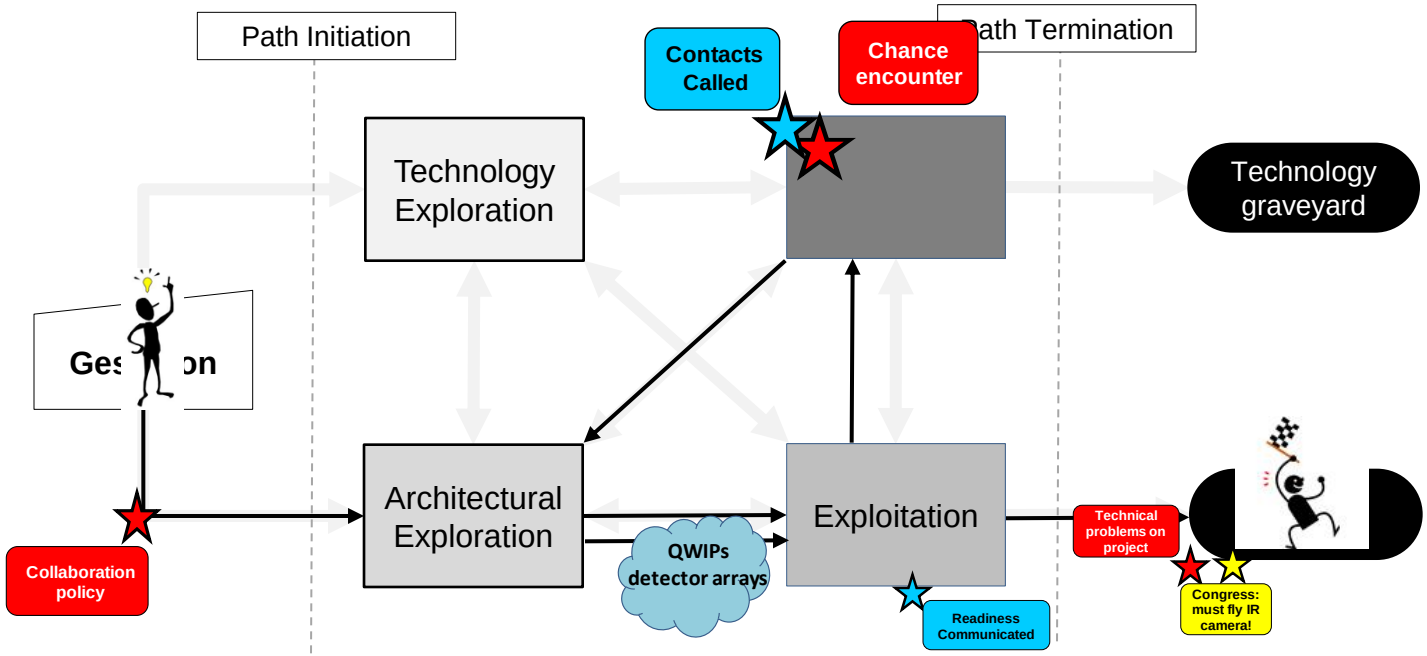
Epoch-Shock Model: Track View

- System exhibits **epochs** of persistent stable (and identifiable) behaviors punctuated by transition inducing **shocks**



  - **Epochs** are illustrated as boxes, and roughly map to stages
  - **Shocks** induce transitions following arrows from one box to another
  - **Innovation pathways** start in gestation and move through the system.

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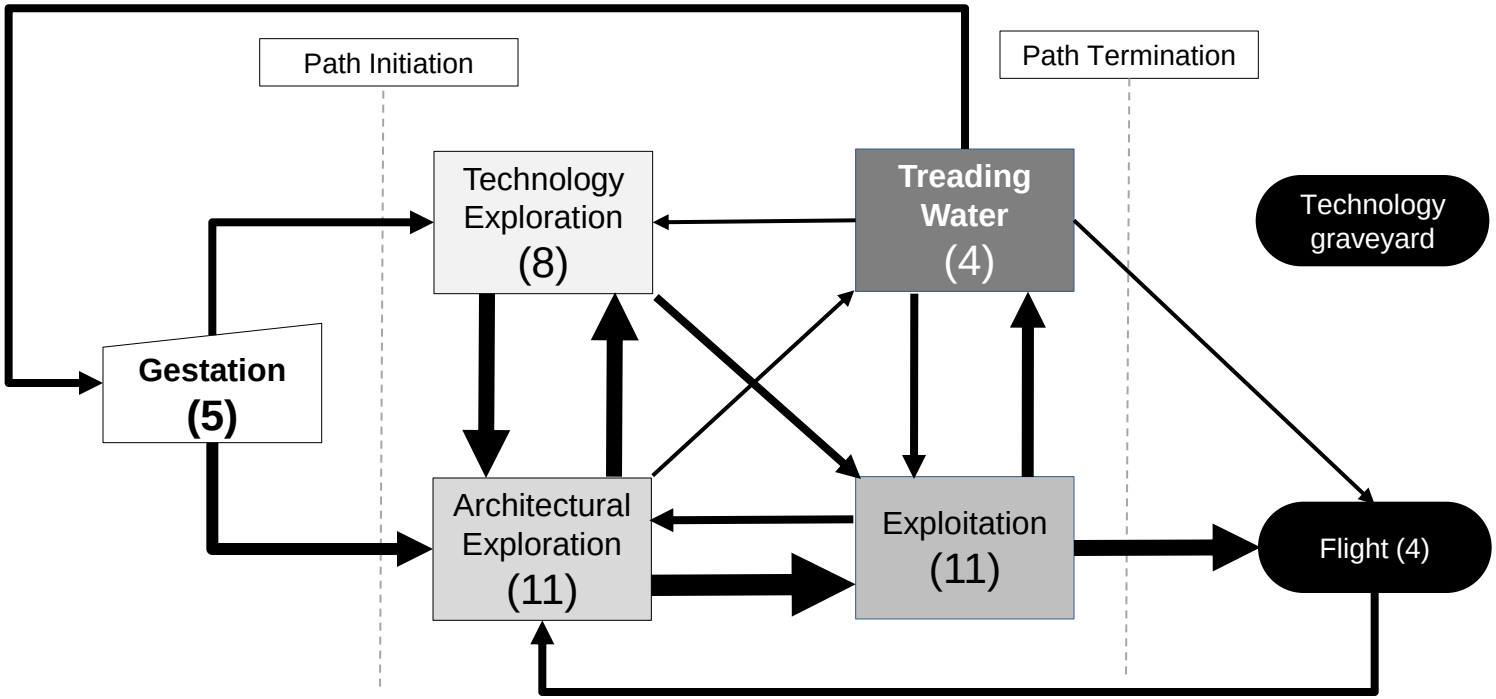
Epoch-Shock Model: Paths Traveled

- Overlay of ALL the transitions from the pathways studied



  - Bi-directional and heavy flow between Technology and Architectural exploration.
  - Flow through Exploitation forks between Treading Water and Flight

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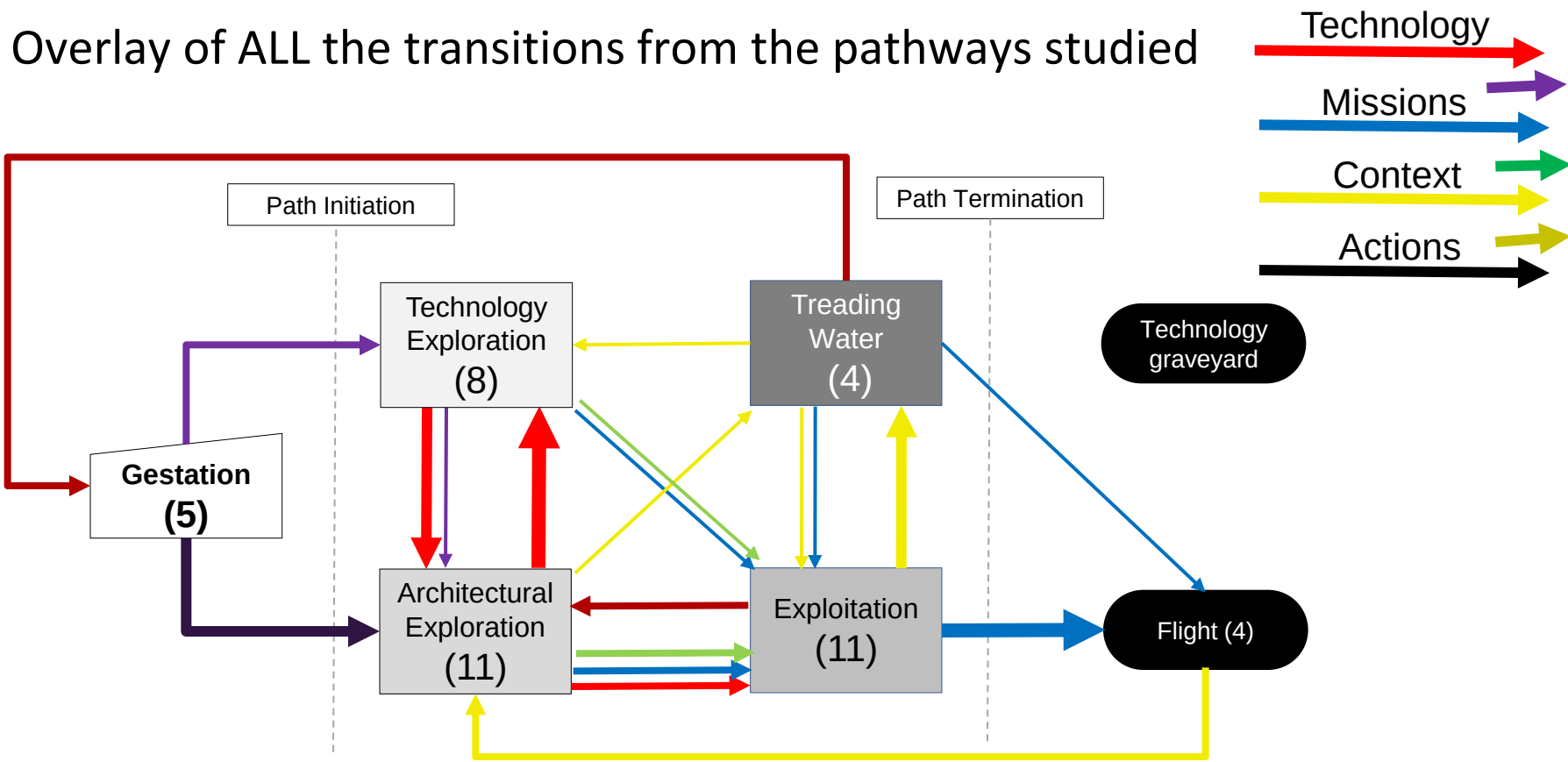
Epoch-Shock Model: Paths Traveled

- Overlay of ALL the transitions from the pathways studied



  - Colors differentiate different types of shocks, some of which are more controllable by management interventions
  - Combined shocks are possible (e.g., red + blue = purple)

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Implications:

Stage-Gate-based management strategies suppress important dynamics. The Epoch-Shock view provides a basis for feasible, productive intervention.

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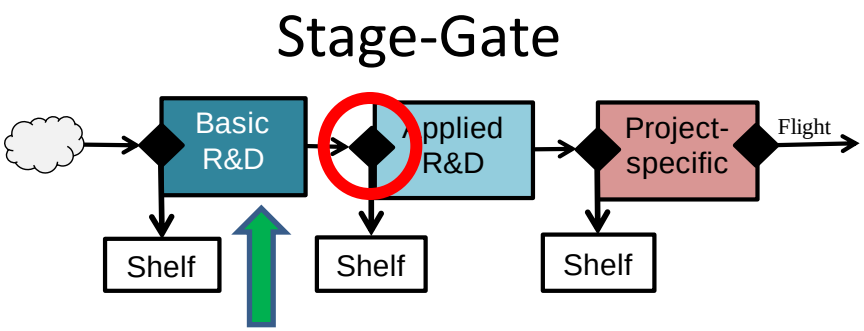
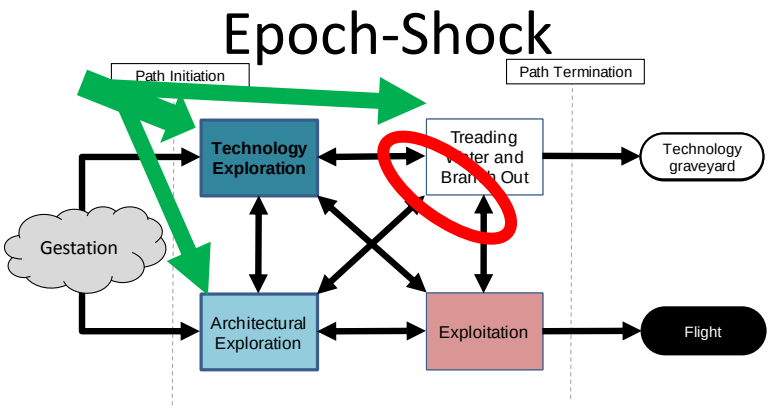
Why Stage-Gates Can't Work





Current control mechanisms

1. Proportionally more funding for basic R&D to increase pool of early-stage concepts.
2. Used gate decisions to control % progression to next stage.

Assessment based on Epoch-Shock model

1. Resources can't be earmarked for "early stage/basic." In practice that funding stream is split between basic concepts and others that are treading water and branching out.
2. Actively controllable gates don't exist. Winnowing happens based on the co-timing of a technical breakthrough (unpredictable) and the next relevant mission call (semi-cyclical).

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Rethinking the Management Problem

- Basic insight:
  - As long as innovation occurs at multiple technical levels simultaneously, and innovating teams can choose to draw resources from multiple institutional levels
  - Current management strategies can't work as intended!

- Epoch-Shock formulation provides a basis for rethinking the management problem:
  - Some shocks can be harnessed as management levers: exploring predictability and influenceability.
  - The work environment can be designed, to encourage desirable interactions and collaborations: exploring incentive systems and organizational/architectural interactions

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Implications for Cost & Schedule Analysts

- A key part of TRL analysis depends on the stage gate model of innovation
  - Thinking in terms of the epoch shock model may help point analysts to more complex nuances that they need to study and evaluate.
- A key part of estimating an individual technology depends on the depends on the broader tech ecosystem
  - Our cases showed that funding for these projects came from a variety of funding sources at multiple levels
- The process of technology development takes much longer than expected

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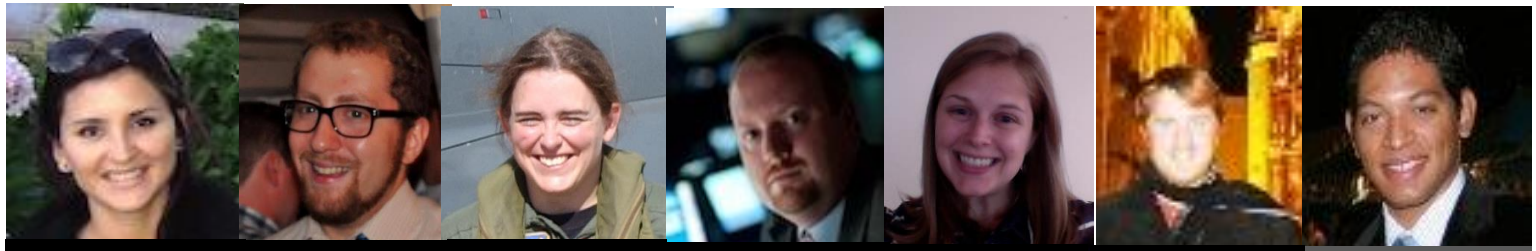
Thanks for your attention. Comments welcome.

SzajnLab@GW

Professor Zoe Szajnfarber
E-mail: zszajnfa@gwu.edu
Web: www.seas.gwu.edu/~zszajnfa



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