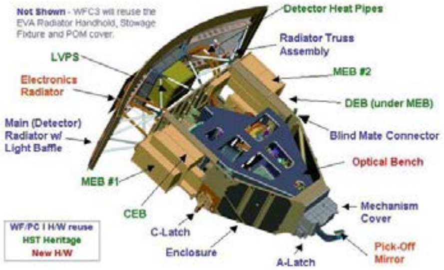

Patterns of Innovation in Technology-Intensive Government Organizations: Insights from NASA

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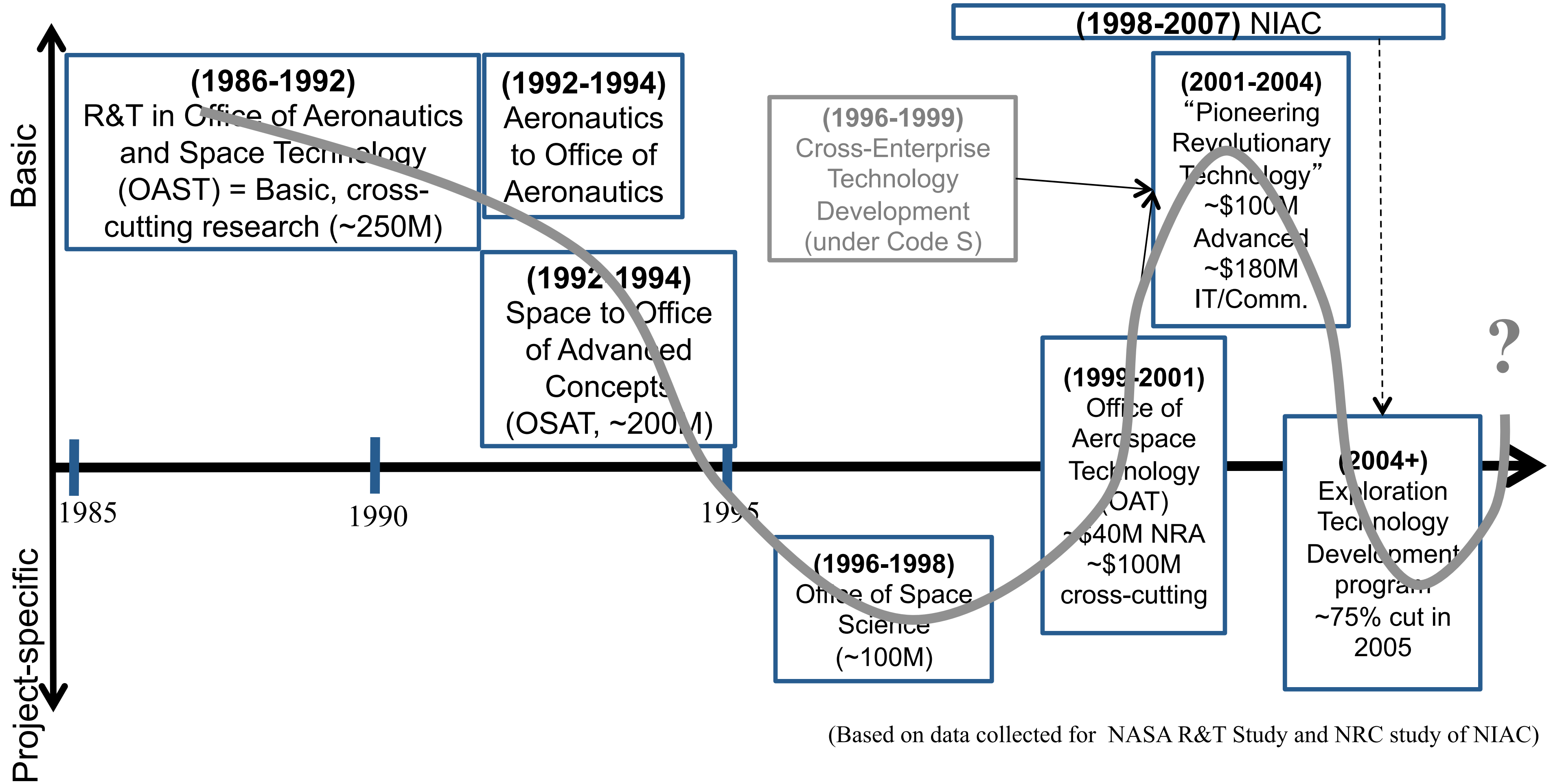
Engineering Management and Systems Engineering

The George Washington University

Goddard Space Flight Center: February 7th 2012

Context:

Changes in NASA Strategic R&D Orientation over time



(1998-2007) NIAC

(1986-1992) R&T in Office of Aeronautics and Space Technology (OAST) = Basic, cross-cutting research (~250M)

(1992-1994) Aeronautics to Office of Aeronautics

(1992-1994) Space to Office of Advanced Concepts (OSAT, ~200M)

(1996-1999) Cross-Enterprise Technology Development (under Code S)

(1996-1998) Office of Space Science (~100M)

(2001-2004) "Pioneering Revolutionary Technology" ~$100M Advanced ~$180M IT/Comm.

(1999-2001) Office of Aerospace Technology (OAT) ~$40M NRA ~$100M cross-cutting

(2004+) Exploration Technology Development program ~75% cut in 2005

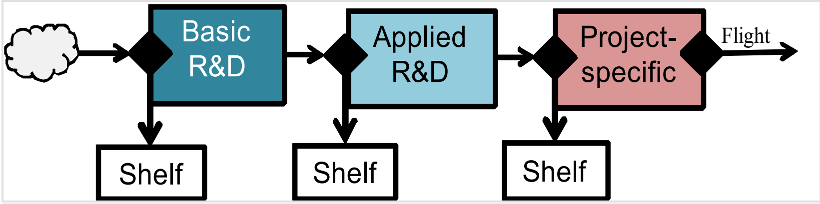
(Based on data collected for NASA R&T Study and NRC study of NIAC)

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

Project Overview

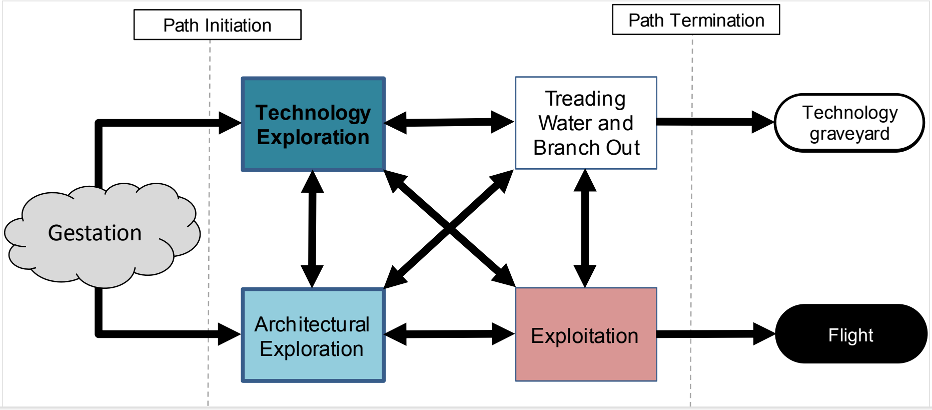
Research Questions:

1. How do new capabilities traverse the innovation system as they are matured and infused into flight projects?
2. To what extent can the observed *innovation pathways* be improved through feasible management interventions?

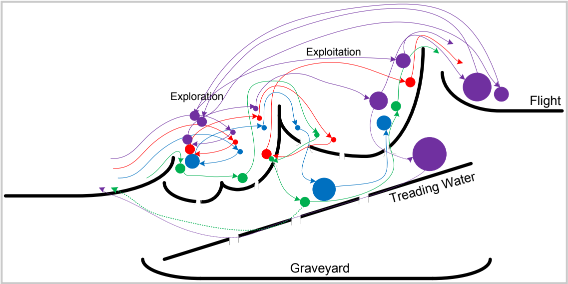

Basic R&D
Applied R&D
Project-specific
Flight
Shelf
Shelf
Shelf

Stage-Gate conceptualization is not just coarse; it's wrong.

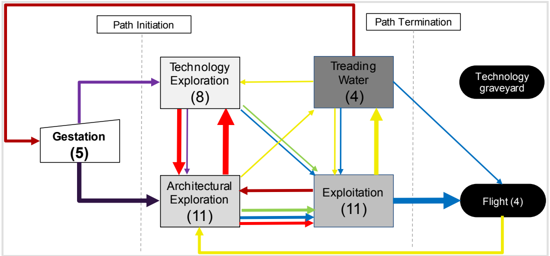
vs.


Path Initiation
Path Termination
Technology Exploration
Treading Water and Branch Out
Technology graveyard
Gestation
Architectural Exploration
Exploitation
Flight

Introduce empirically grounded model; better captures observed dynamics

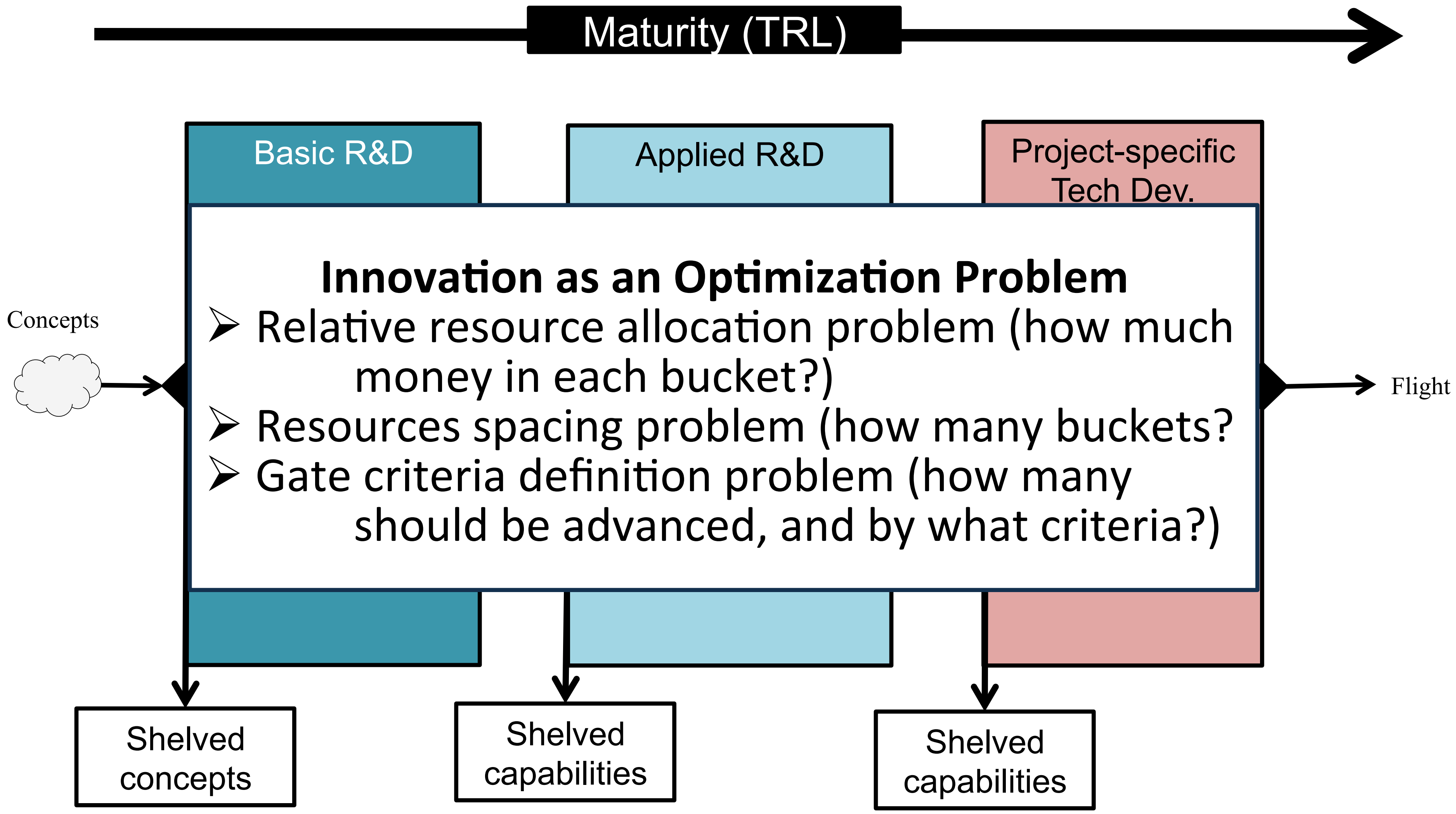


New theoretical insights that can inform future strategic decisions



Problem Formulation

Current Conceptualization: Stage-Gates

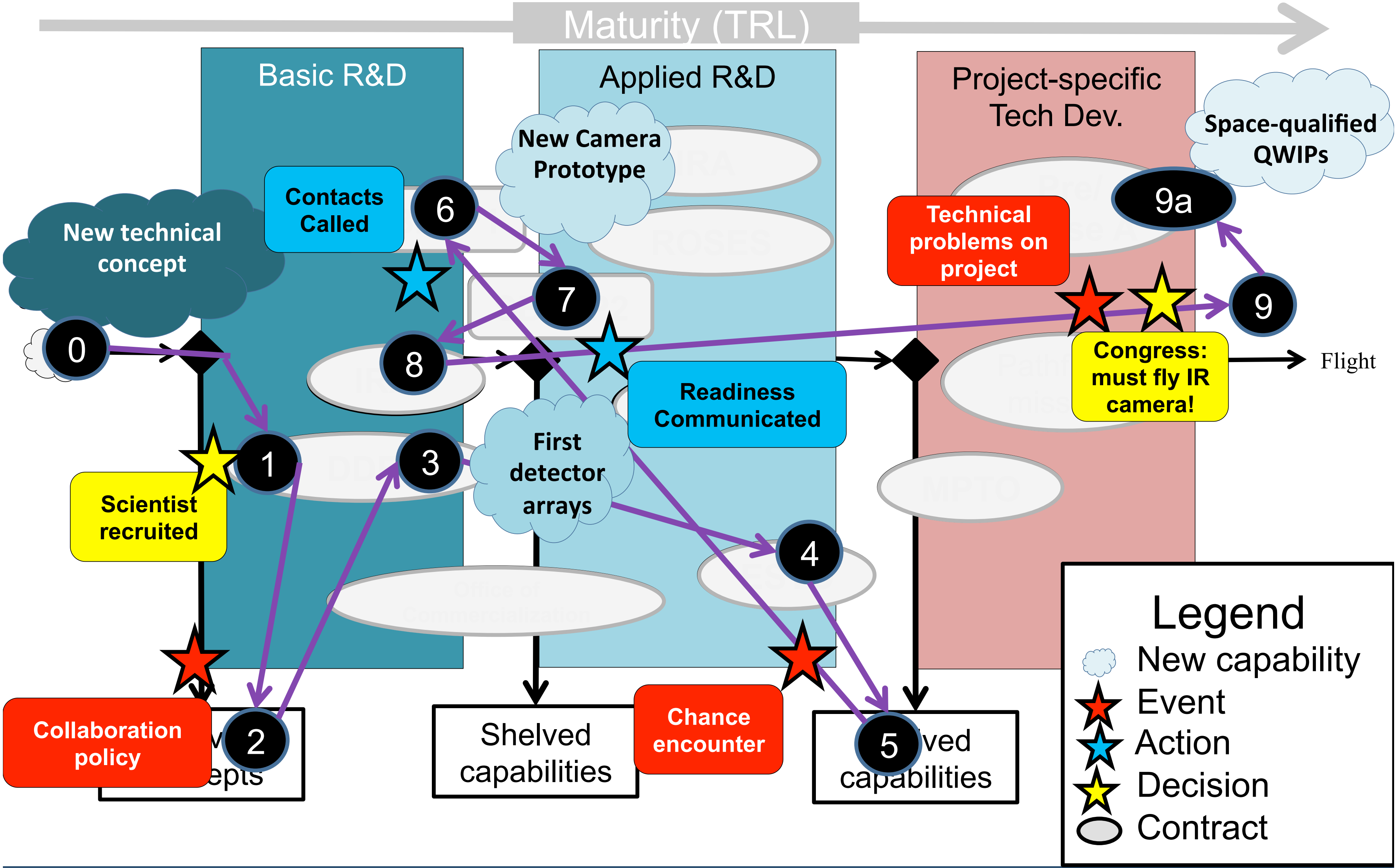


Innovation as an Optimization Problem

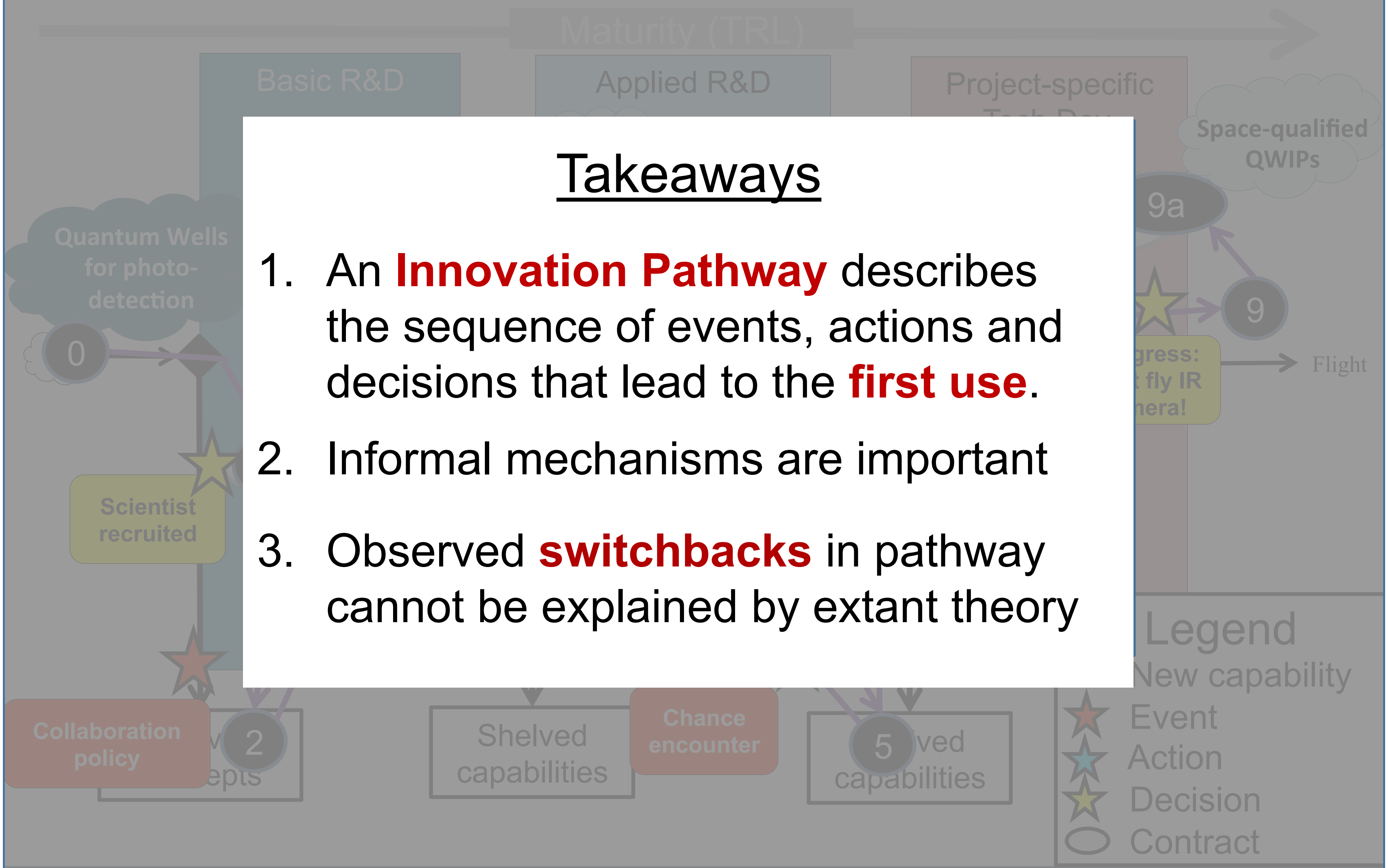
- Relative resource allocation problem (how much money in each bucket?)
- Resources spacing problem (how many buckets?
- Gate criteria definition problem (how many should be advanced, and by what criteria?)

*Synthesized from NASA strategic planning documents 1990-2006

Actual Complexity of Process



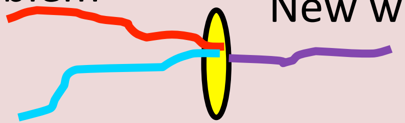
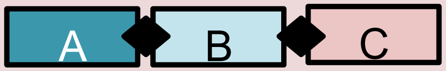
Actual Complexity of Process



Takeaways

1. An **Innovation Pathway** describes the sequence of events, actions and decisions that lead to the **first use**.
2. Informal mechanisms are important
3. Observed **switchbacks** in pathway cannot be explained by extant theory

Some Partial Explanations

PoliSci **(Windows of opportunity)**	**Project** **(Stage-gate)**	**Org. Design** **(Exploration vs. Exploitation)**
 Problem New way Solution (Kingdon; Stone) Studies: Sapolsky, Posen, Rosen, Logsdon	 A B C (NASA Systems Engineering Handbook; Cooper 1990+) Practice oriented	**Explore** + **Exploit**  Quantum Wells for photo-detection Space-qualified QWIPs (c.f. March 1991; Tushman et al.; Gupta et al 2006;)
Focus: How do you create a window? How do you recognize one?	Focus: What are the right gate criteria? Relative investment in stages?	Focus: What's the right balance? How can they be coupled?
Limitation: Policy solutions may generally exist, and continue to exist until useful, but technology needs to be actively matured.	Limitation: Innovation cannot be cleanly scheduled or sequenced, but the model still has practical value. Why?	Limitation: Key questions remain unresolved. Theoretical propositions require further empirical test, NASA provides potential platform.

Study Design

Pathway Selection

- Theoretical sampling: Selected for expected variation in path taken, based on several indicators(Eisenhardt 2009)

New Capability	Impact of Change	Period	Level	Priority
Continuous ADR **(CADR)**	Solves key limitation of incumbent technology (no hold time). Improvement on traditional performance measures too.	Late 90s to present	New concept	Flagship/ Explorer
CdZnTe detector **(CZT)**	First detector in its class (room temp gamma-ray). Achieved significant position resolution improvement.	Late 80s to early 2000s	Detector physics – fabrication	Explorer
Semiconducting Microcalorimeter **(Si)**	Two order of magnitude resolution improvement (non-dispersive x-ray spectroscopy) – fundamentally new approach.	Early 80s to ~2012	New concept, components materials	Flagship/ MoO
Superconducting Microcalorimeter **(TES)**	Improved resolution (Si thermometers), enables scalability of array (where Si doesn't)	Mid 90s to present	New detector physics/ architecture	Flagship
X-ray Polarimeter **(Pol)**	First practical X-ray polarimeter (two orders of magnitude resolution improvement)	2001 to present	New concept	Explorer

Analysis Approach

Process Data

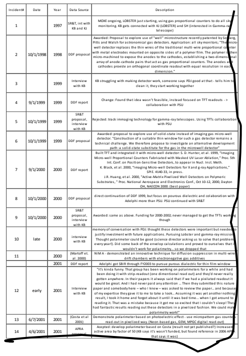
~100 hrs interviews

~150 archival documents

~2 months informal observation

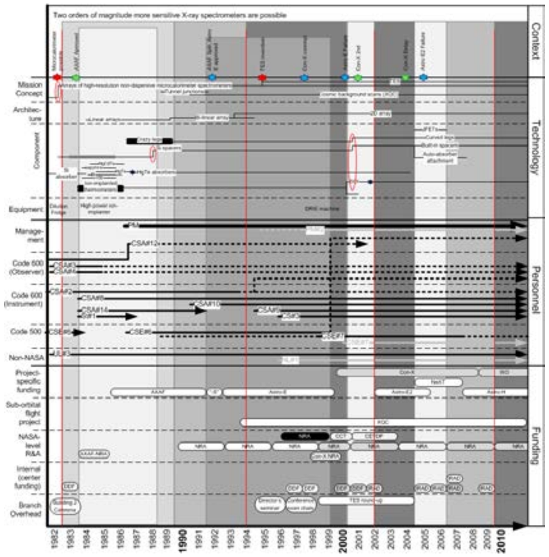
Within-case "sense-making"

Analytical Chronologies (Pettigrew 1990)



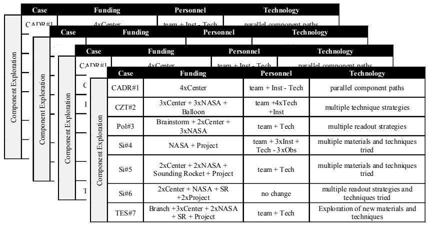
Event Database (Van de Ven et al 1990; 2000)

Structured Visual Map (per Langley 1999)



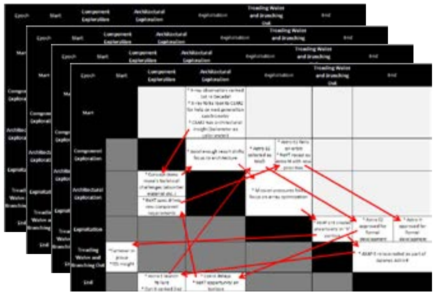
Cross-case theory building

Characteristic Epochs

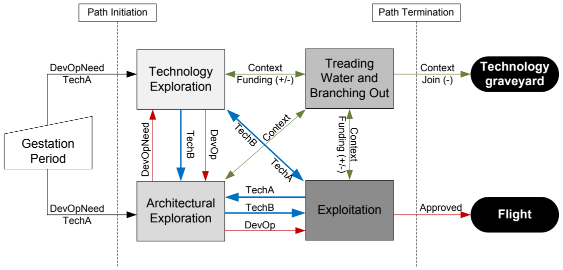


	Case	Funding	Personnel	Technology
Component Exploration	CADR#1	4xCenter	team + Inst - Tech	parallel component paths
	CZT#2	3xCenter + 3xNASA + Balloon	team +4xTech +Inst	multiple technique strategies
	Pol#3	Brainstorm + 2xCenter + 3xNASA	team + Tech	multiple readout strategies
	Si#4	NASA + Project	team + 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

Transition inducing Shocks



Epoch-Shock Model

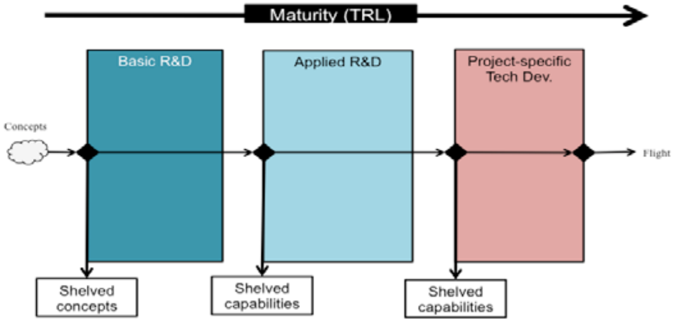


Limitations of the Stage-Gate View:
Is the model coarse or meaningfully inaccurate?

Stage-Gate Assumptions

Innovation as an Optimization Problem

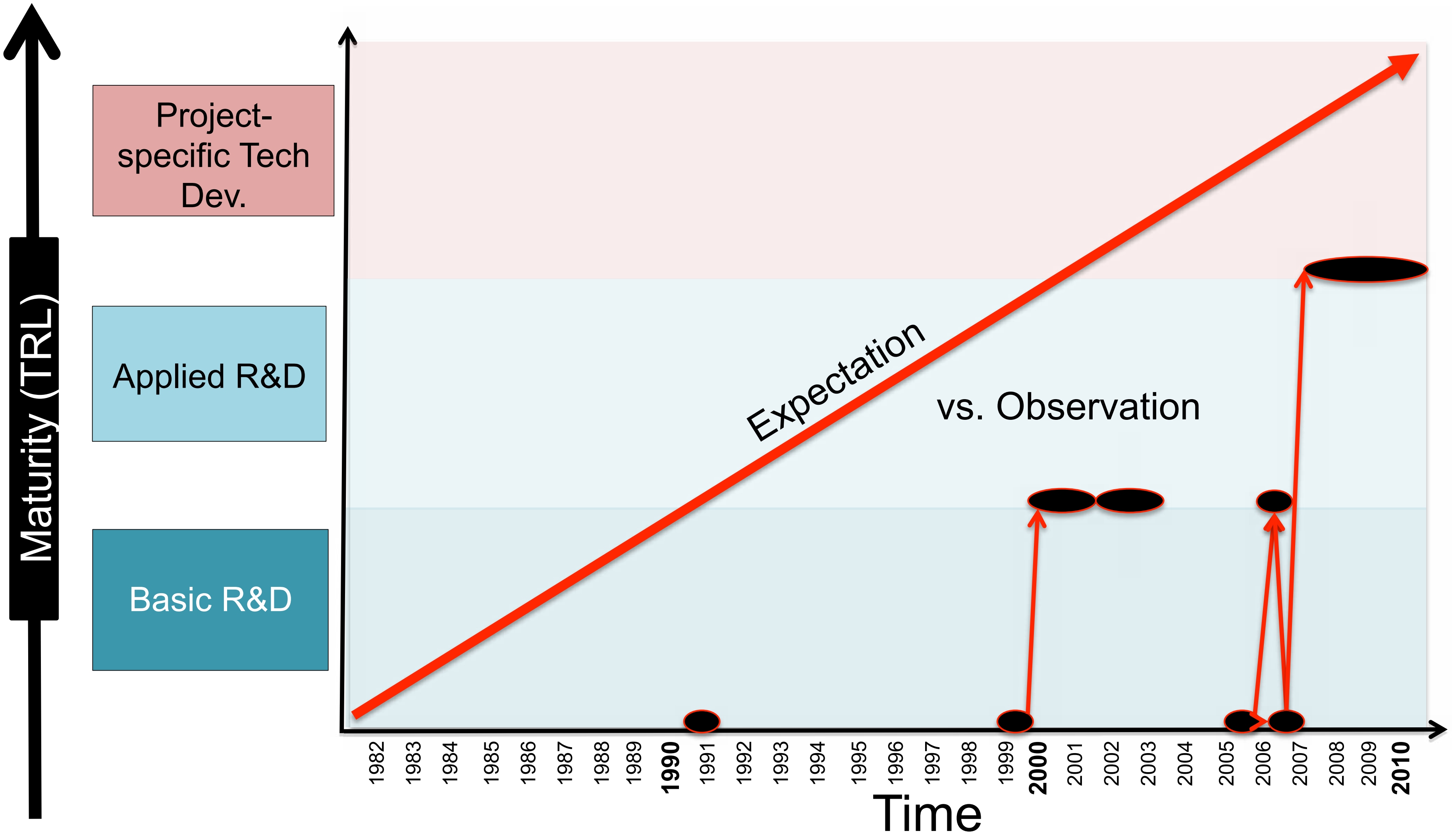
- Relative resource allocation problem (how much money in each bucket?)
- Resources spacing problem (how many buckets?
- Gate criteria definition problem (how many should be advanced, and by what criteria?)



Underlying assumptions:

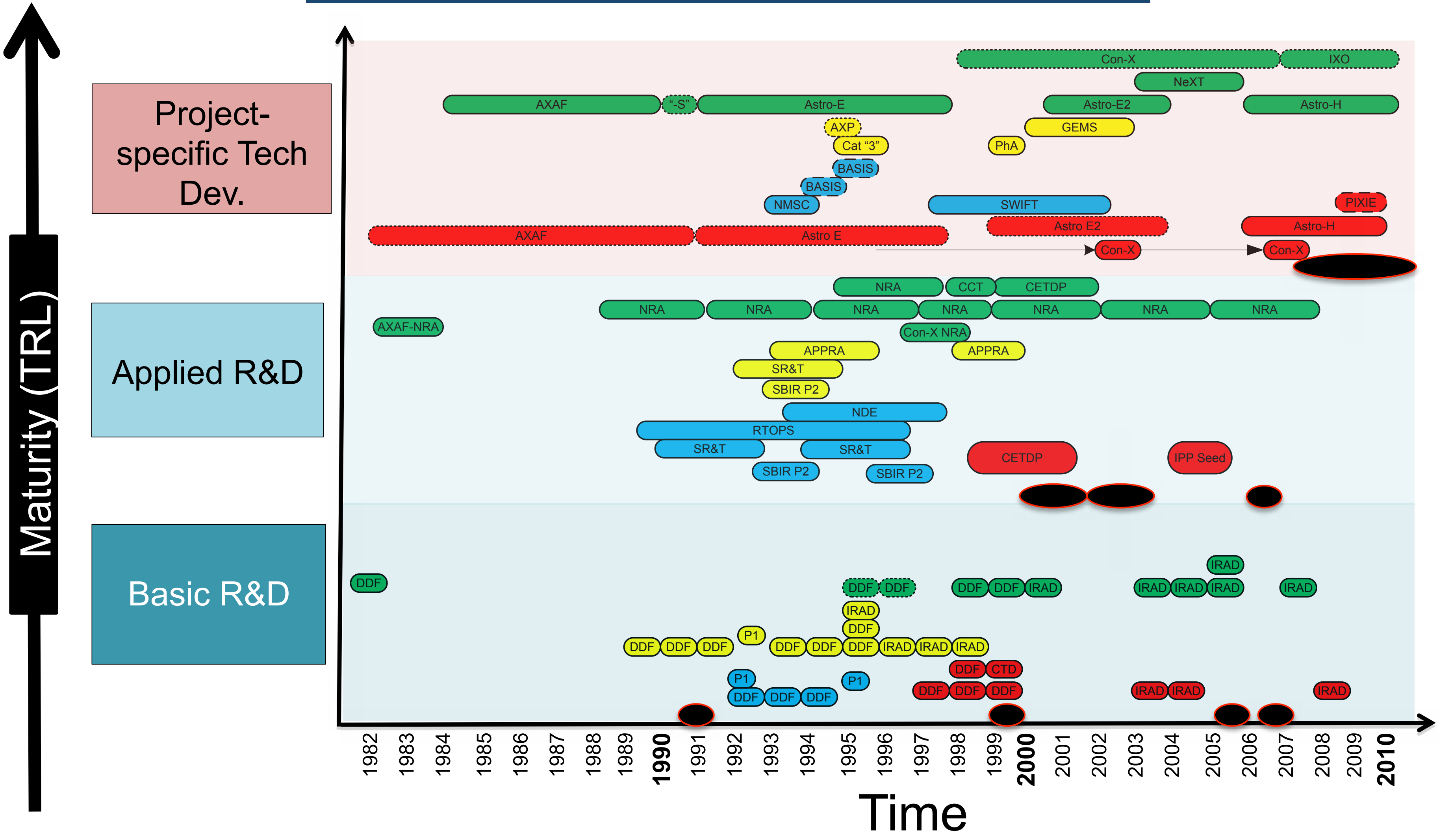
(1) Technologies **mature** from left to right over time;
(2) **Stages** are mutually exclusive (at a given time);
(3) **Shelving** is an active process, controlled by decision- makers;
(4) **Shelf life** is passive and a function of technical obsolescence.

Switchbacks in Maturity



Switchbacks in Maturity

Assumptions #1 and #2 not respected



Passive Gates, Active Shelves

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

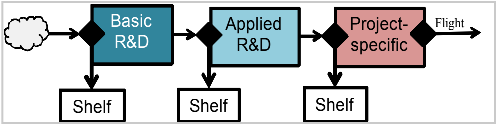
Case	Rejected + Shelf	Rejected + !Shelf	!Rejected + Shelf	Duration on Shelf
Tech A	1	1	1	8 /1yrs
Tech B	0	2	1	5 yrs
Tech C	0	3	0	N/A
Tech D	0	2	1	2 yrs
Tech E	1	Multiple	1	2 / 5 yrs
Tech F	0	multiple	0	N/A

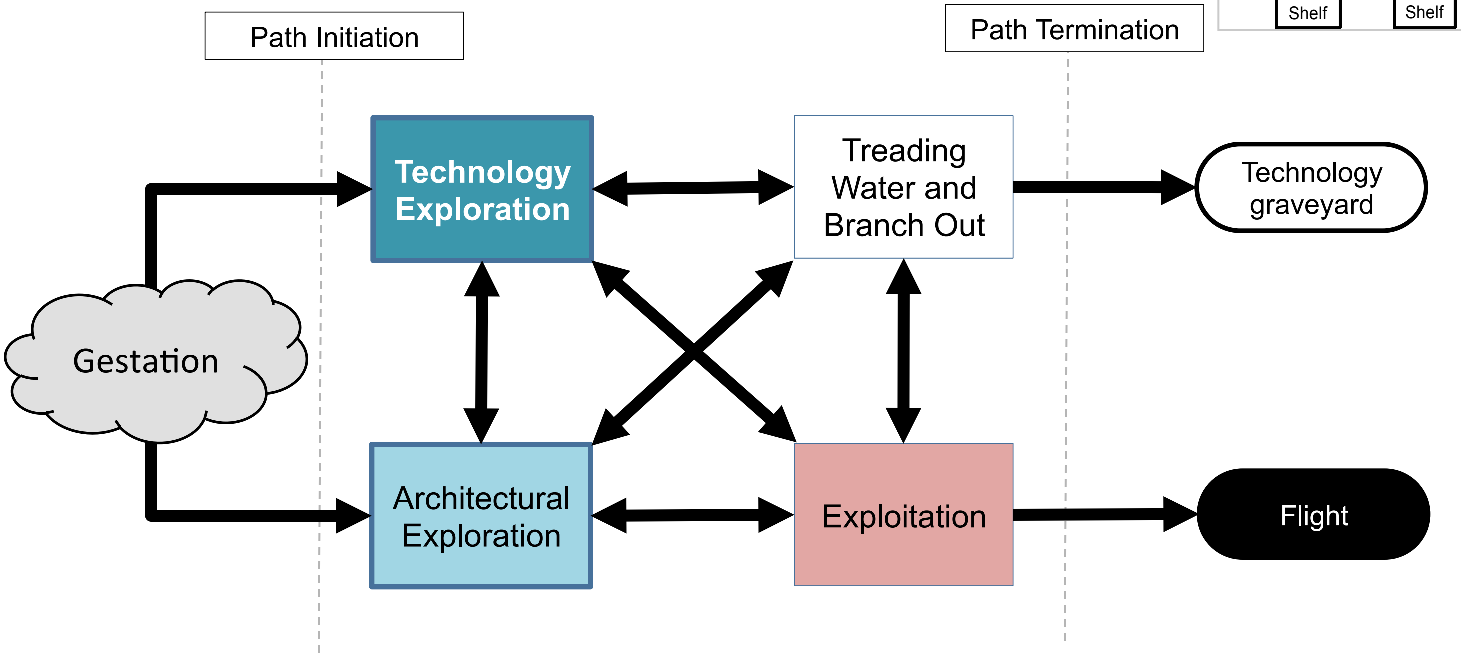
Need: More nuanced understanding of underlying processes

Empirically Grounded Process Model

Epoch-Shock Model: Track View

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

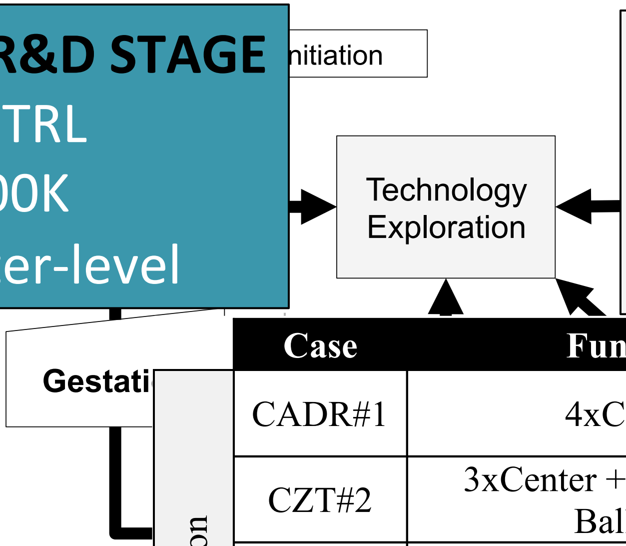




  - **Epochs** are illustrated as boxes, and roughly map to stages
  - **Shocks** induce transitions following arrows from one box to another

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

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

	Case	Funding	Personnel	Technology
Technology Exploration	CADR#1	4xCenter	team + Inst - Tech	parallel component paths
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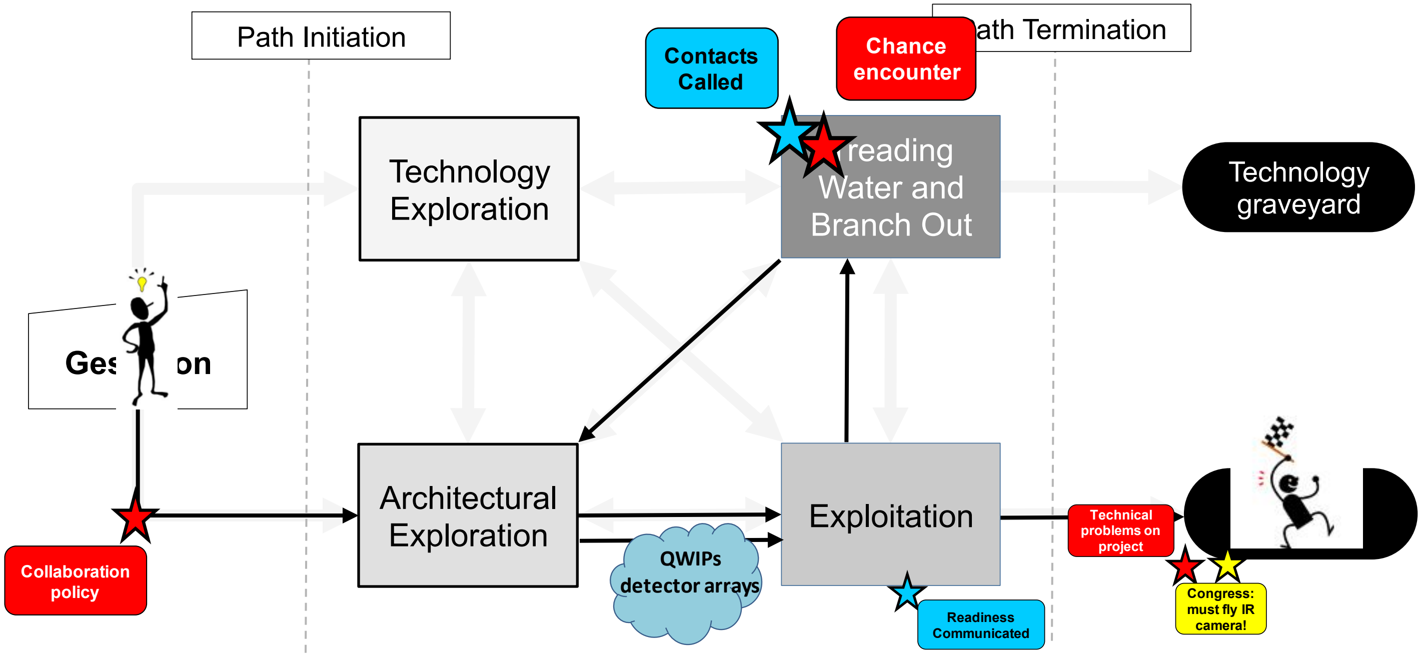
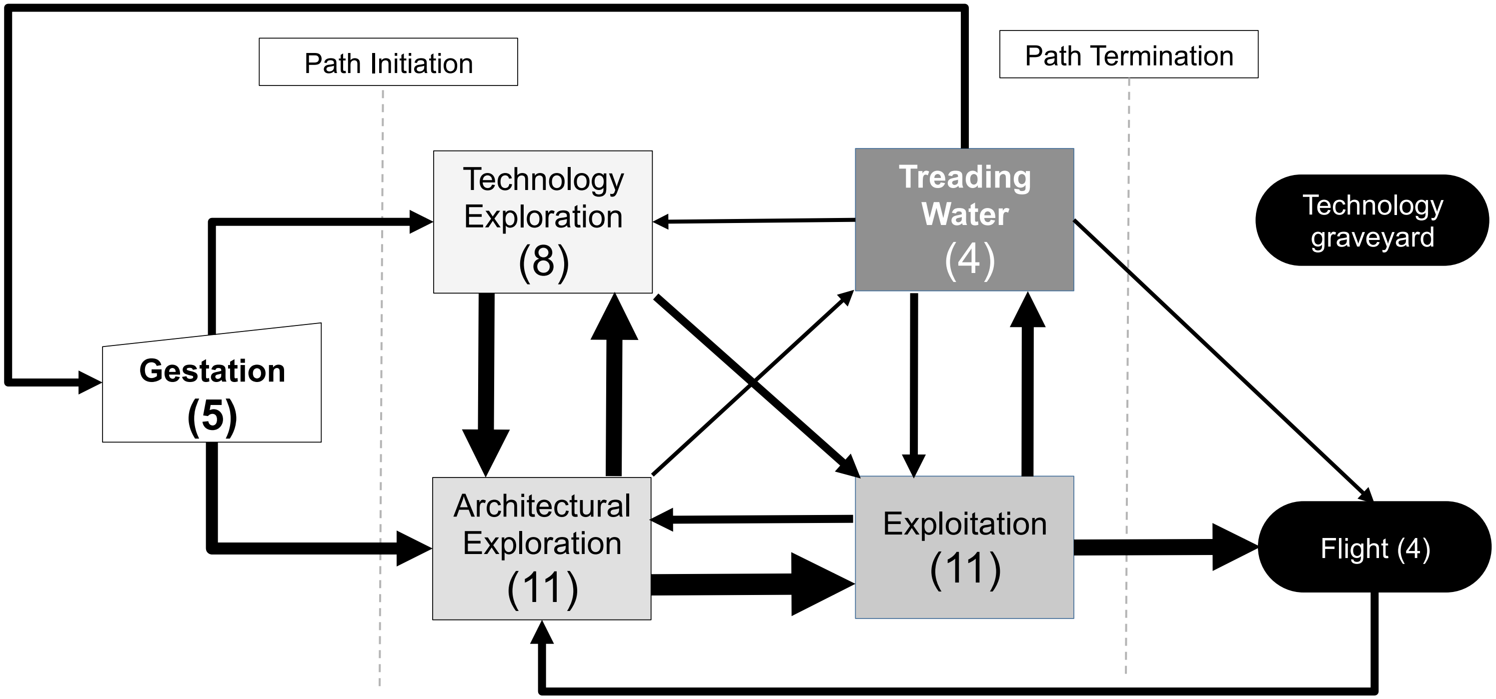


  - **Epochs** are illustrated as boxes, and roughly map to stages
  - **Shocks** induce transitions following arrows from one box to another
  - **Innovation pathways** start in gestation and move through the system.

Epoch-Shock Model: Paths Traveled

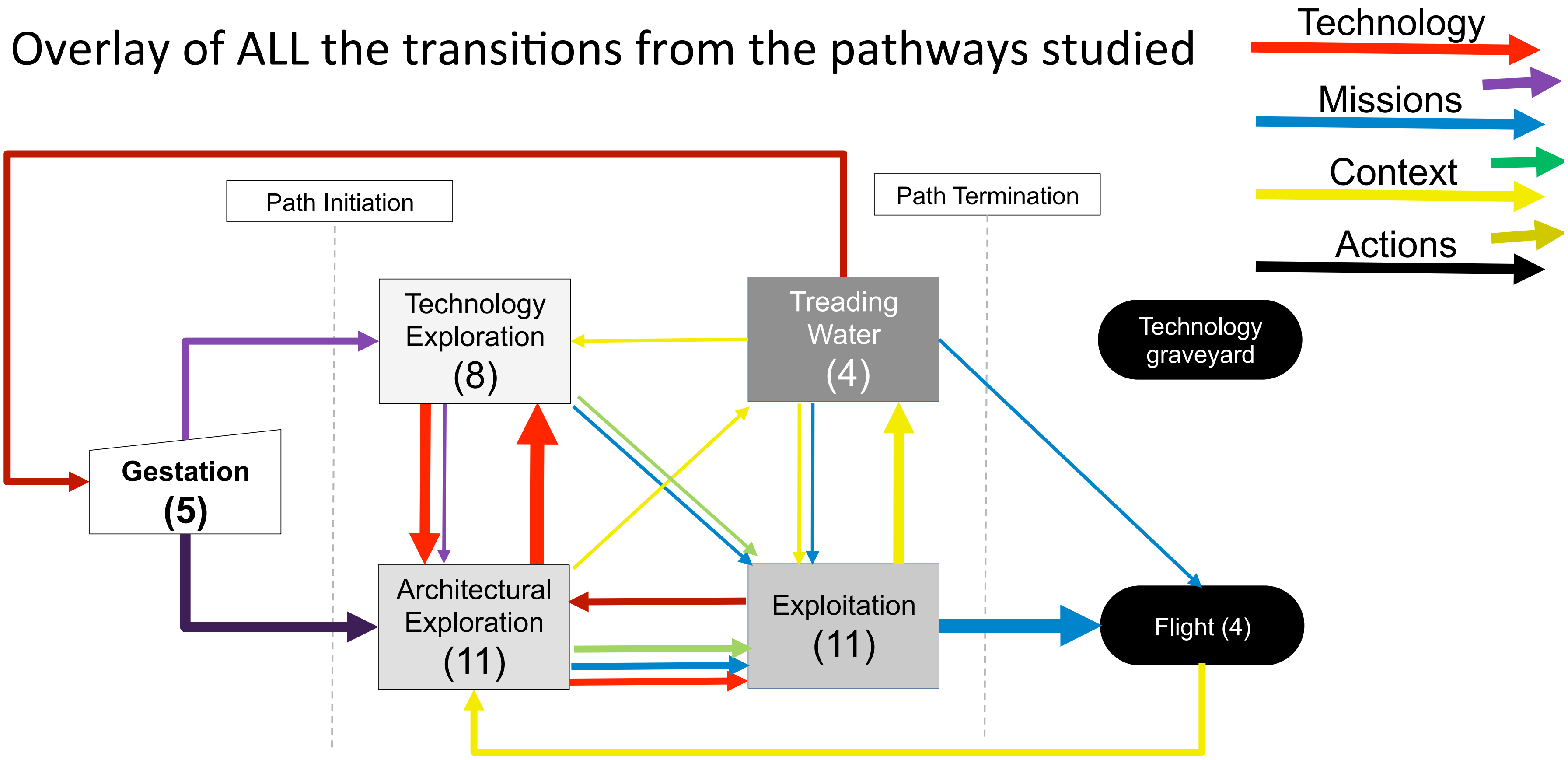
- Overlay of ALL the transitions from the pathways studied



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

Epoch-Shock Model: Paths Traveled

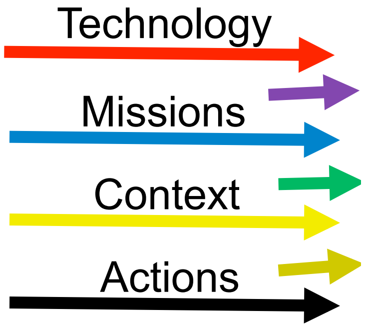
- Overlay of ALL the transitions from the pathways studied

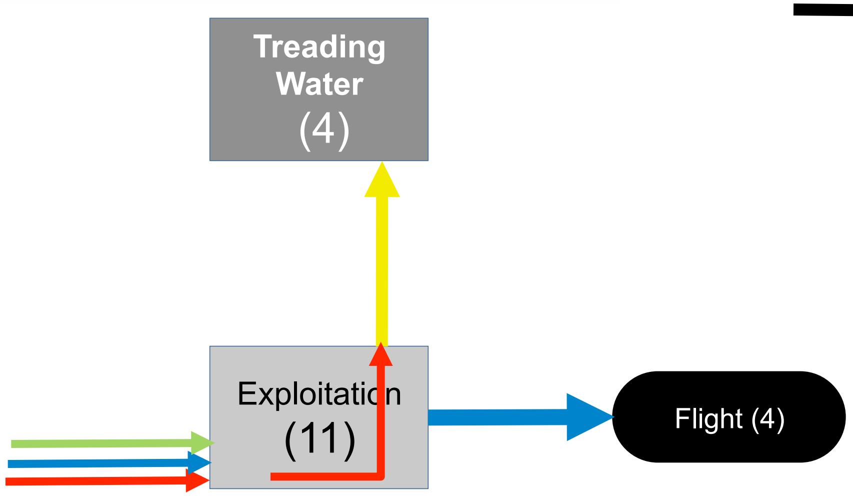


  - Colors differentiate different types of shocks, some of which are more controllable by management interventions
  - Combined shocks are possible (e.g., red + blue = purple)

Zooming in on Illustrative Pattern

- **The Breakthrough-Window Lag**
  - IF a technology shock initiates transition to *exploitation*, AND there is a delay before the next mission opportunity, OR there is any negative context, THEN *treading water*.

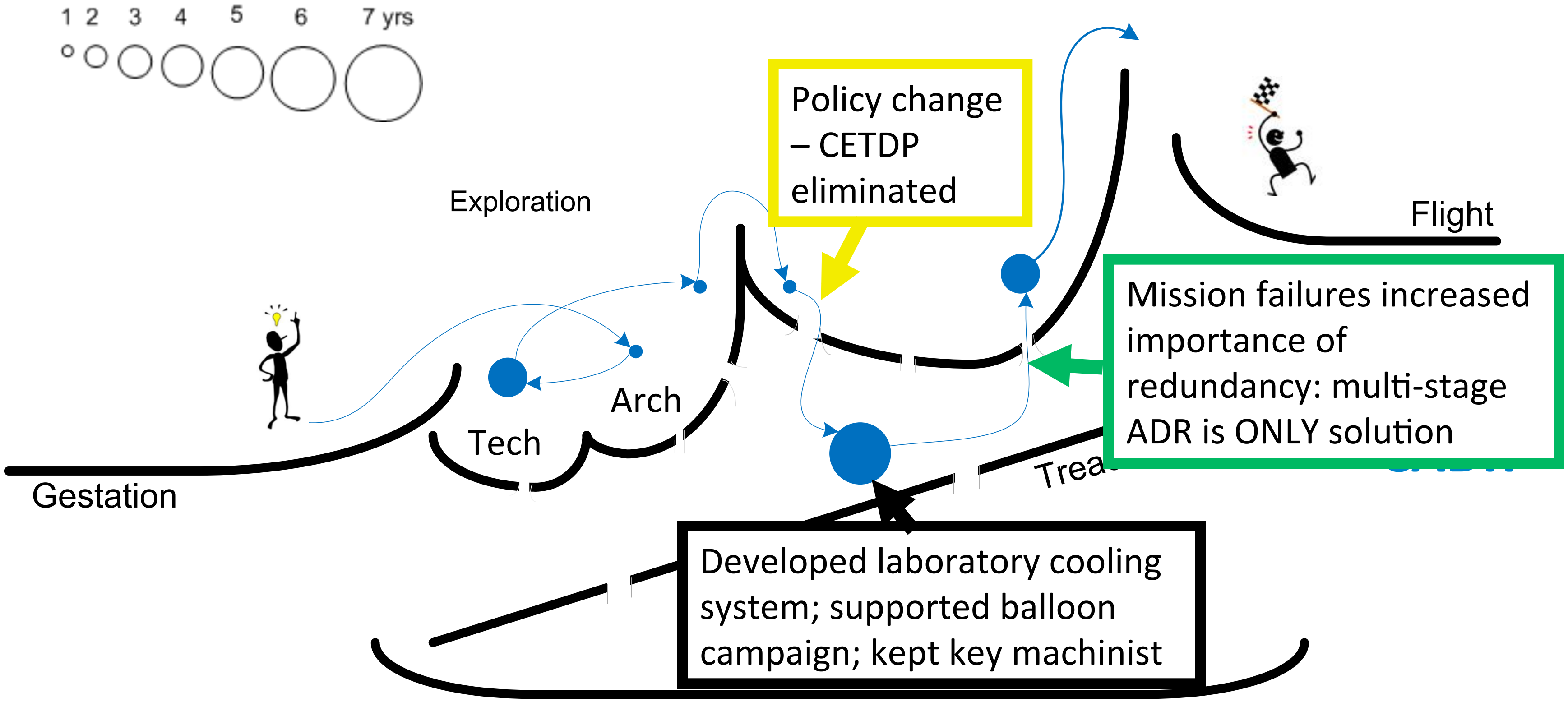




  - **Exploitation:** Expensive activities and fewer qualifying resources
    => Time limit
  - **Treading Water and Branching Out** is how teams survive the lag
    - Re-scoping to qualify for "early stage" resources
    - New application for existing technology

Epoch-Shock Model: Dynamic View

- Epochs are stable equilibria, with differences in “potential” among them
- Shocks induce transitions from one Epoch to another
- Goal is to climb the mountain, from gestation to flight, without slipping



Policy change – CETDP eliminated

Mission failures increased importance of redundancy: multi-stage ADR is ONLY solution

Developed laboratory cooling system; supported balloon campaign; kept key machinist

Epoch-Shock Model: Dynamic View

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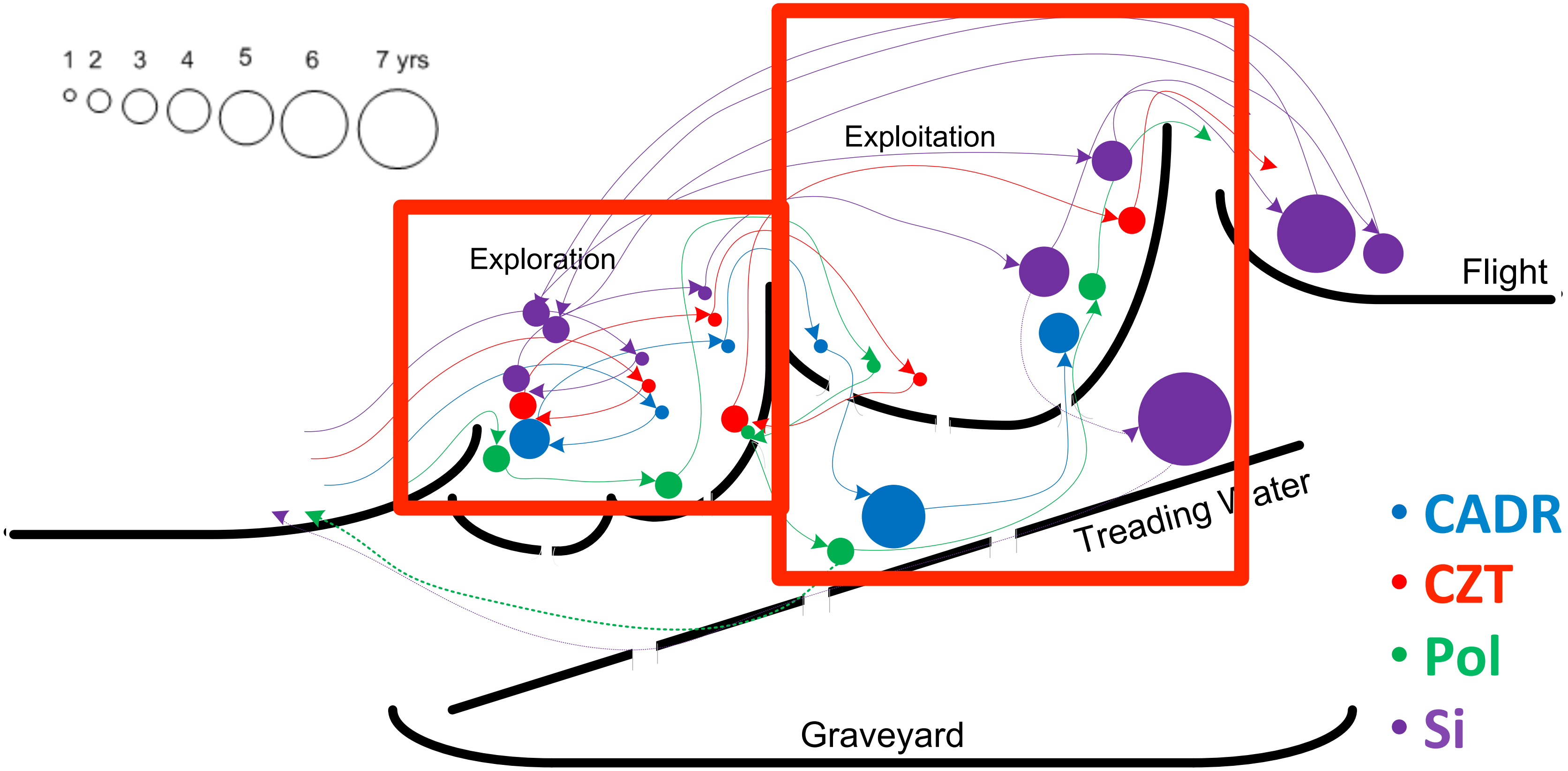


- CADR
- CZT
- Pol
- Si

Using this detailed understanding captured in the model to explain the observed behaviors

Explaining the Observed Behaviors

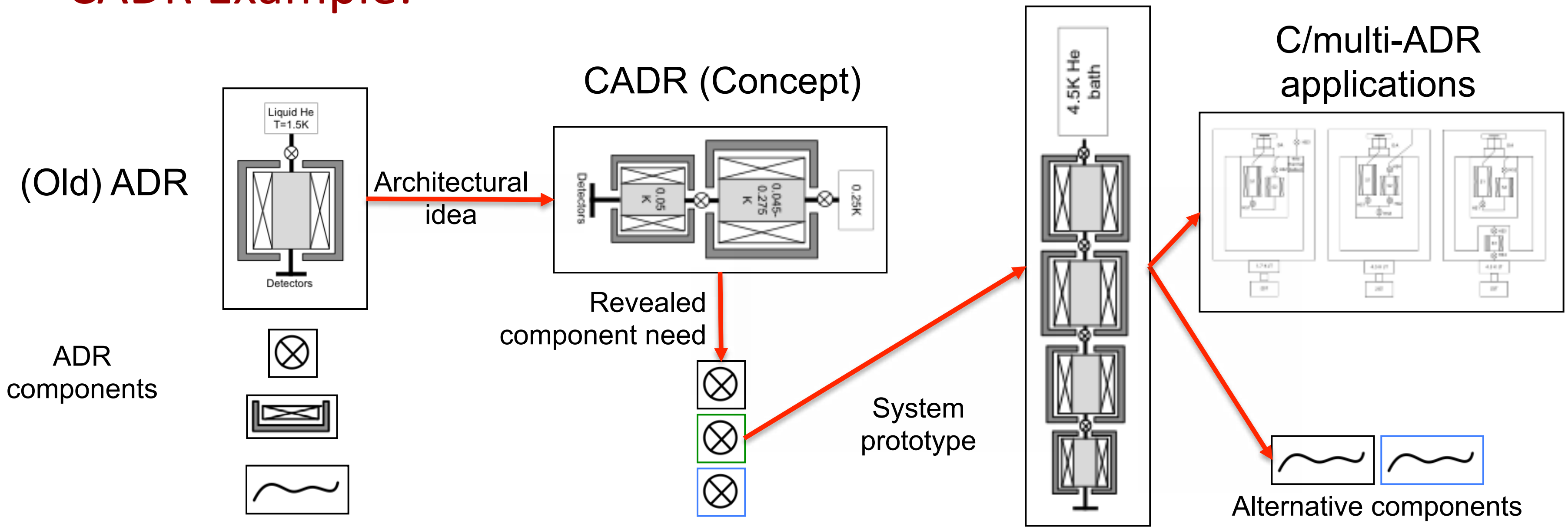
- Recall Conflicting Observations:
  - Innovation doesn't progress monotonically from left to right.
    - Resources are being drawn simultaneously from different stages
    - AND switchbacks to earlier stages were observed.
  - Shelving isn't an active administrative decision.
    - Some pathways persist despite being rejected at nominal gates,
    - while others wane due to external context changes
- Explanation in two parts:
  - <u>Architectural complexity</u> creates "option" for switchbacks.
  - Switchback "option" is exercised as a common <u>survival strategy</u>.

Explanation 1: Architectural Complexity

- Explanation 1:

In a complex integrated product, innovation can happen at different rates, in different sequences at different levels of the architecture. Thus, switchbacks are a natural corollary to complexity.

- CADR Example:



(Old) ADR

ADR components

Architectural idea

CADR (Concept)

Revealed component need

System prototype

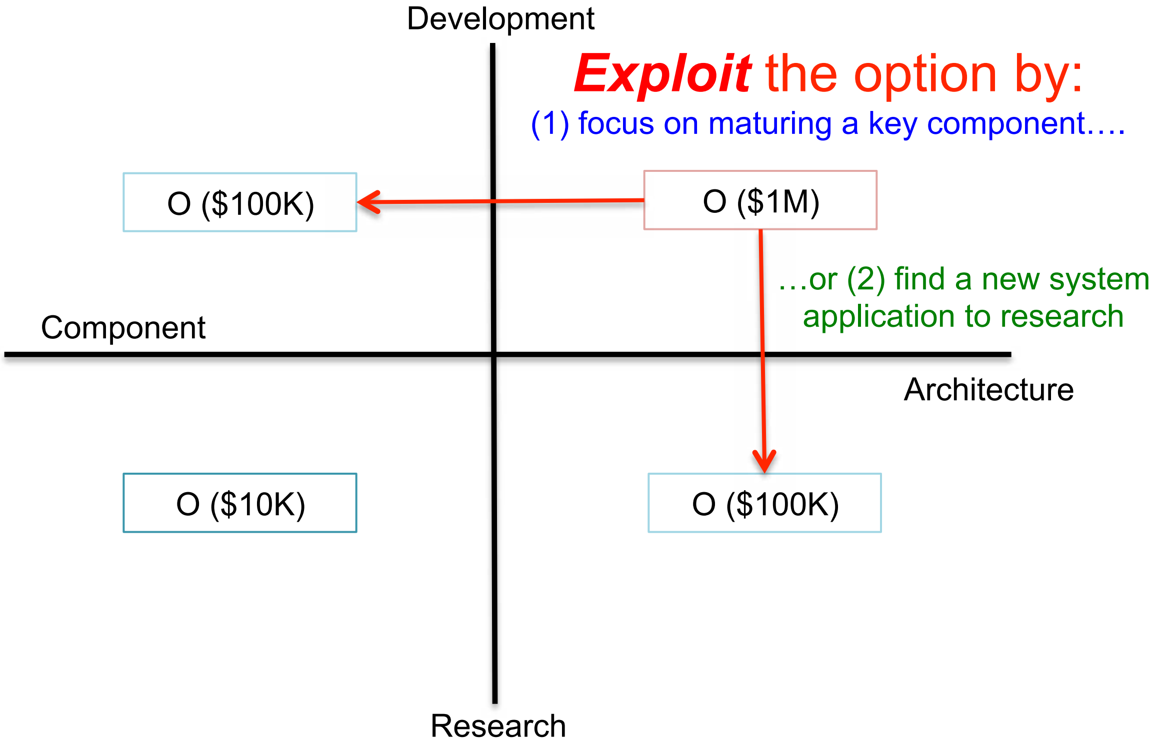
C/multi-ADR applications

Alternative components

Explanation 2: Survival Strategy

- Explanation 2:
  - Technologists can ***exploit*** the switchback "option" to *survive* funding droughts.

> *… were never concerned that the technical capability would become obsolete…worried about losing one key technician… who was the kind of guy who would rather retire and work on his motorcycle than transition to another project while waiting for funding to be restored. And rebuilding that kind of expertise would have taken a very long time…*

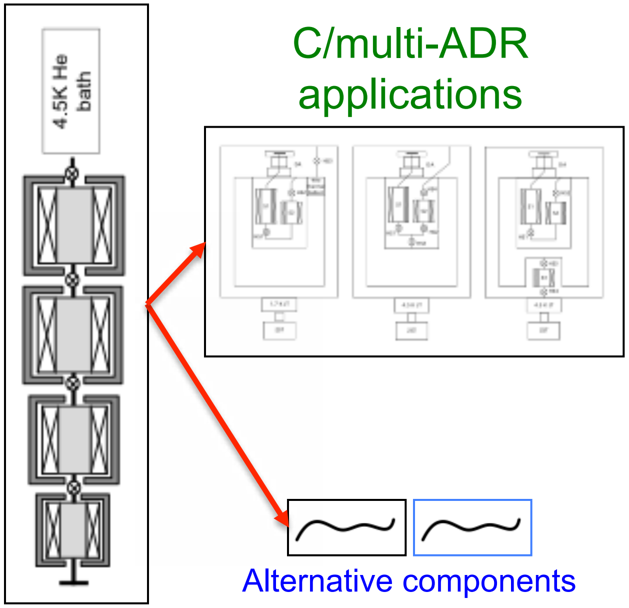


Exploit the option by:

(1) focus on maturing a key component….

…or (2) find a new system application to research

The "Option"



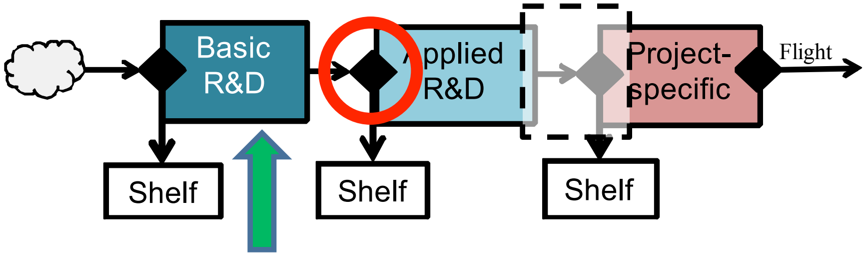
Explanation

(1) Switchbacks are a natural byproduct of complexity
AND
(2) Architectural complexity creates an “option” that can be exploited to tread water

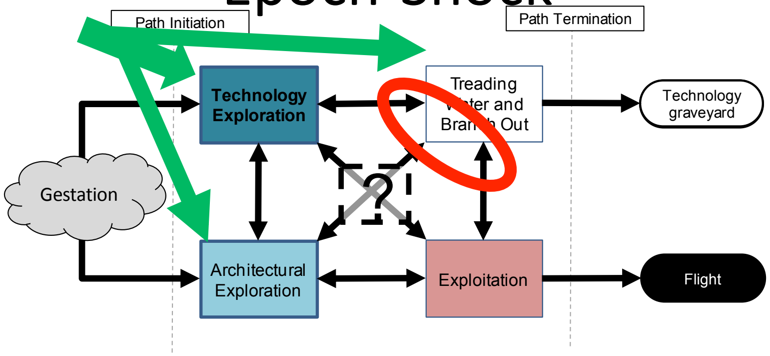
Implications

Stage-Gates vs. Epoch-Shocks

Stage-Gate



Epoch-Shock



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.

⬚ 3. Adding more stages to facilitate transitions

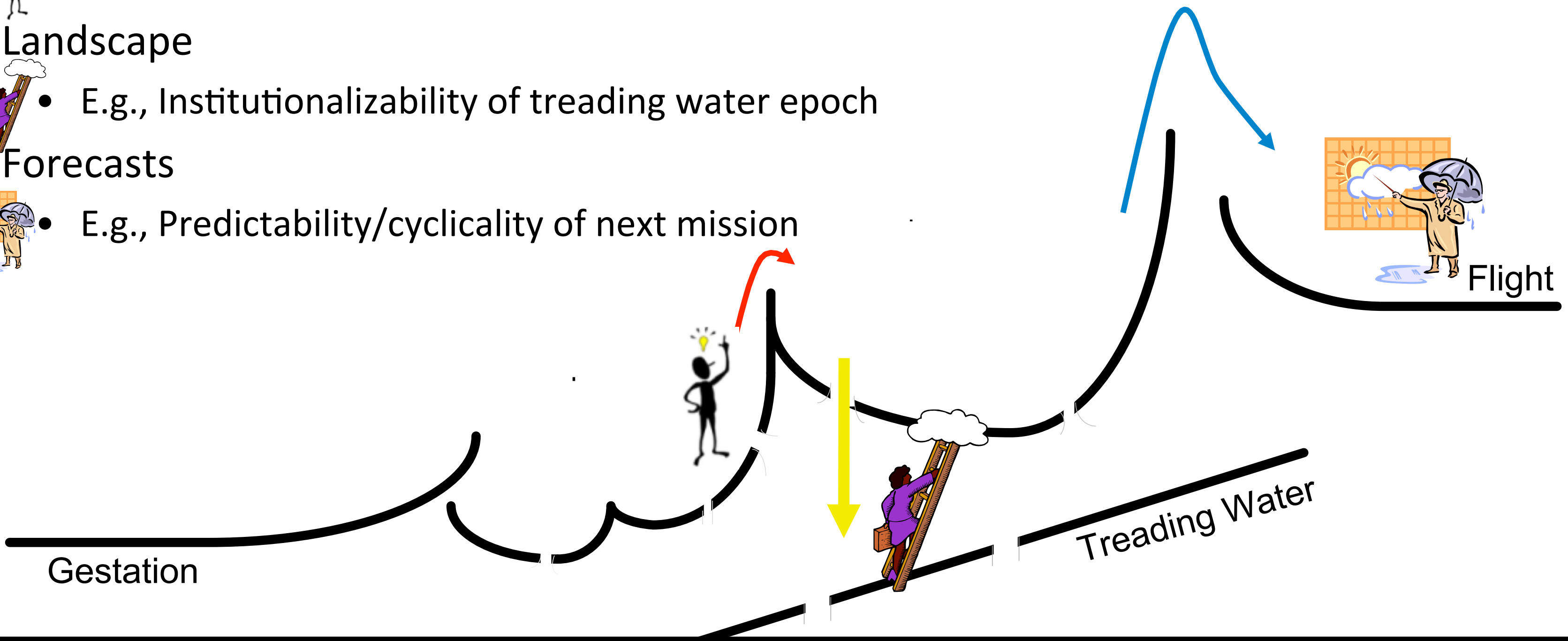
Assessment based on Epoch-Shock model

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).
3. The lack of linear progression invalidates the concept of bridging transitions. There is an important human component of the transition dynamics.

Re-Thinking the Policy Problem

Key Concept: Need to shift from centralized, flow control strategy to recognition of decentralized stochastic problem.

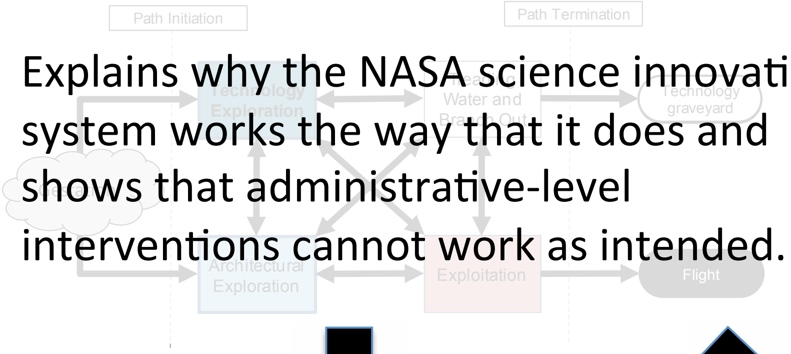
- Three levels of influence
  1. Decisions
     - E.g., Whether to enter exploitation w/o clear mission opportunity
  2. Landscape
     - E.g., Institutionalizability of treading water epoch
  3. Forecasts
     - E.g., Predictability/cyclicality of next mission



More than specific recommendations, the Epoch-Shock conceptualization captures the understanding required to make informed tradeoffs

Next Steps

Ongoing Research



Explains why the NASA science innovation system works the way that it does and shows that administrative-level interventions cannot work as intended.

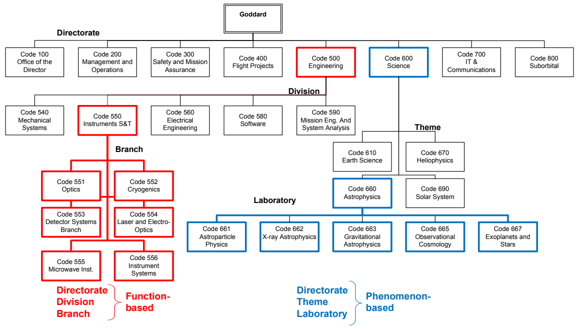
1

Replicate study in comparable context

>> Do the observed dynamics hold?

2

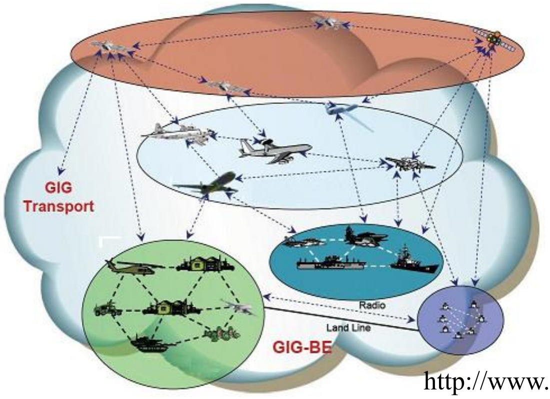
Identify feasible interventions at lower institutional levels



>> Can changes in org structure and/or funding strategies serve as levers

3

Extend the insights to examine relationship between technology complexity, architecture and sources of innovation



http://www.markjessing.com/

>> How can mismatches in technology cycles and context shocks be mitigated by architecture

Questions, Comments?

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