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

Zoe Szajnfarber, PhD
Assistant Professor
Engineering Management and Systems Engineering
The George Washington University

Goddard Space Flight Center: February 7th 2012
Changes in NASA Strategic R&D Orientation over time

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

Aeronautics to Office of Aeronautics

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

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

(1996-1999)
Office of Space Science (~100M)

(1998-2007) NIAC

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

(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?

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

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?)

- Basic R&D
- Applied R&D
- Project-specific Tech Dev.

- Shelved concepts
- Shelved capabilities
- Shelved capabilities

*Synthesized from NASA strategic planning documents 1990-2006*
Actual Complexity of Process

Maturity (TRL)

Basic R&D
- Contacts Called 6
- New technical concept
- Scientist recruited 0

Applied R&D
- First detector arrays 7
- New Camera Prototype
- Readiness Communicated

Project-specific Tech Dev.
- Technical problems on project 9
- Congress: must fly IR camera!

Legend
- New capability
- Event
- Action
- Decision
- Contract

Office of Commercialization

New Camera Prototype

Pathfinder missions

Space-qualified QWIPs

Flight
**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

<table>
<thead>
<tr>
<th>PoliSci</th>
<th>Project</th>
<th>Org. Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Windows of opportunity)</td>
<td>(Stage-gate)</td>
<td>(Exploration vs. Exploitation)</td>
</tr>
<tr>
<td>Problem</td>
<td>New way</td>
<td>Explore + Exploit</td>
</tr>
<tr>
<td>Solution</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Practice oriented</td>
<td></td>
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## Focus:
- How do you create a window? How do you recognize one?
- What are the right gate criteria? Relative investment in stages?
- 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.
- Innovation cannot be cleanly scheduled or sequenced, but the model still has practical value. Why?
- 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)

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

**Process Data**

- ~100 hrs interviews
- ~150 archival documents
- ~2 months informal observation

**Within-case “sense-making”**

- Analytical Chronologies (Pettigrew 1990)
- Structured Visual Map (per Langley 1999)

**Cross-case theory building**

- Characteristic Epochs
- Transition inducing Shocks
- Epoch-Shock Model

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

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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

- Project-specific Tech Dev.
- Applied R&D
- Basic R&D

Expectation vs. Observation

Time

Maturity (TRL)

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Switchbacks in Maturity

Assumptions #1 and #2 not respected

- Project-specific Tech Dev.
- Applied R&D
- Basic R&D

Maturity (TRL)

Time

- Assumptions #1 and #2 not respected
- Switchbacks in Maturity

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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:

<table>
<thead>
<tr>
<th>Case</th>
<th>Rejected + Shelf</th>
<th>Rejected + !Shelf</th>
<th>!Rejected + Shelf</th>
<th>Duration on Shelf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech A</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>8 /1 yrs</td>
</tr>
<tr>
<td>Tech B</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>5 yrs</td>
</tr>
<tr>
<td>Tech C</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Tech D</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>2 yrs</td>
</tr>
<tr>
<td>Tech E</td>
<td>1</td>
<td>Multiple</td>
<td>1</td>
<td>2 / 5 yrs</td>
</tr>
<tr>
<td>Tech F</td>
<td>0</td>
<td>multiple</td>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Need: More nuanced understanding of underlying processes
Empirically Grounded Process Model
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

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

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• 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.
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)
• 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

- Epochs are stable equilibria, with potential differences between them
- Shocks induce transitions from one Epoch to another
- Goal is to climb the mountain, from gestation to flight, without slipping
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:
  - Architectural complexity creates “option” for switchbacks.
  - Switchback “option” is exercised as a common survival strategy.
Explanation 1: Architectural Complexity

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

(Old) ADR

Architectural idea

Revealed component need

System prototype

CADR (Concept)

C/multi-ADR applications

Alternative components

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**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...

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**Component Architecture Research**

### Development

- **Exploit the option by:**
  1. focus on maturing a key component...
  2. find a new system application to research

### The “Option”

- **C/multi-ADR applications**
- **Alternative components**
Explaination

(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

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

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

Replicate study in comparable context

1

>> Do the observed dynamics hold?

2

Identify feasible interventions at lower institutional levels

3

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

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

>> How can mismatches in technology cycles and context shocks be mitigated by architecture
Questions, Comments?

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