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

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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

- NASA’s 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
NEED: To control the system better, we need to understand it better.
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
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

Political-level context

New mission concepts

Prioritization: E.g., Decadal Survey

Selection: E.g., 1 Flagship; 4 Ex

Concept Studies

Phase A: Concept & Tech Development

Phase B: Prelim design

Scientific and Technical State-of-the-art

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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*
Stage-Gate Assumptions

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.

*Synthesized from NASA strategic planning documents 1990-2006
Switchbacks in Maturity

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

Expectation: monotonic increase
vs. Observation: switchbacks

Time

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# Switchbacks in Maturity

## Table:

<table>
<thead>
<tr>
<th>Case</th>
<th>Time spent in &gt;1 Stage</th>
<th># of “Concept” grants after 1st “Proof”</th>
<th># of “Proof” grants after 1st “Flight”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech A</td>
<td>90 (%)</td>
<td>2(out of 4 total)</td>
<td>0(3)</td>
</tr>
<tr>
<td>Tech B</td>
<td>60 (%)</td>
<td>4(4)</td>
<td>4(6)</td>
</tr>
<tr>
<td>Tech C</td>
<td>33 (%)</td>
<td>5(8)</td>
<td>1(2)</td>
</tr>
<tr>
<td>Tech D</td>
<td>33 (%)</td>
<td>9(12)</td>
<td>2(5)</td>
</tr>
<tr>
<td>Tech E</td>
<td>20 (%)</td>
<td>9(10)</td>
<td>12(13)</td>
</tr>
<tr>
<td>Tech F*</td>
<td>10 (%)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

## Diagram:

*switchbacks in maturity*
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 /1yrs</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
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)
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

<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>
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)
Implications:
Stage-Gate-based management strategies suppress important dynamics. The Epoch-Shock view provides a basis for feasible, productive intervention.
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).
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
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 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
Thanks for your attention. Comments welcome.

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