Understanding Technology Development Processes
Theory & Practice

by

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Abstract

Technology development is hard for management to understand and hard for practitioners
to explain, however it is an essential component of innovation. While there are standard
and predictable processes for product development, many of these techniques don’t apply
well to technology development. Are there common processes for technology development
that can make it predictable, or is it unpredictable like basic research and invention?

In this thesis, after building a foundation by looking at product development processes,
I survey some of the literature on technology development processes and compare them to a
handful of case studies from a variety of industries. I then summarize the observations from
the cases and build a generic model for technology development that can be used to provide
insights into how to monitor and manage technology projects.

One of the observations from the product development literature is that looping and
iteration is problematic for establishing accurate schedules which becomes one of the
fundamental disconnects between management and engineering. Technologists rely heavily
on iteration as a tool for gaining knowledge and combined with other risks, technology
development may appear “out of control”. To mitigate these risks, technologists have
developed a variety of approaches including: building a series of prototypes of increasing
fidelity and using them as a form of communication, simultaneously developing multiple
technologies as a hedge against failure or predicting and developing technologies they think
will be needed outside of formal channels.

Finally, I use my model to provide some insights as to how management can understand
technology development projects. This gives technologists and non-technical managers a
common ground for communication.

Thesis Supervisor: Steven D. Eppinger
Title: Professor of Management Science and Innovation
Co-Director, MIT System Design and Management Program
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Chapter 1

Introduction

Figure 1-1: Three Components of Technical Innovation

Innovation, *taking an idea and developing to an impact which creates value*\(^1\), is essential to any technology business. It is typically thought of having the following components: basic research or invention; technology development and product development with each feeding the next in turn. Innovation implies change, either in developing new products that operate in new ways, or changes in the way the company performs its processes. These changes are often dependent on the development of new technologies within the organization.

Much research has gone into product development processes, resulting in product development being reasonably predictable and manageable – i.e. for a given amount of time and cost, generally it is possible to develop a product. Basic research is considered to be less predictable – there are too many unknowns and it is hard to know when a good idea will occur.

Technology development is at the heart of innovation. New technologies enable these new products, or processes. But, how does technology development occur? Can it be managed in a similar way to product development? Is it fundamentally a predictable process like product development, or unpredictable, like idea generation? *How can a non-technical manager gain insight into the activities and progress of a technology development effort?*

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\(^1\) Luis Perez-Breva used this description during an Innovation Workshop series taught the summer of 2012 at MIT for the Skolkovo Technical Institute.
To answer these questions I looked at some of the literature on technology development processes and then interviewed an assortment of people who are developing technologies in different industries to compare the similarities and differences.

1.1 Motivation

Working in product development in a variety of industries at a plethora of companies, I wanted to understand some of the challenges that I observed at company after company:

- Why is there a fundamental disconnect between management and those developing technologies?

- What are the elements that allow companies to be innovative – specifically, what the challenges are for companies adopting new technologies to make new products.

During my time in the System Design and Management (SDM) program at MIT, many of the classes were focused on theories for system thinking, strategy, technology, management, and product development. Each theory would give me a little insight as to what was right or wrong in companies I worked at and projects I worked on over the years. The analysis and theories were world-class, each giving me little glimpses of how innovation might be done.

For example, we had several courses that looked at product development from several points of view. While the companies I had worked with had less formal processes, it was still valuable to see a systemic treatment from start to finish. I also learned a few tools and techniques that would have been valuable to get past some of the “rough spots” I had encountered in the past. In looking at these approaches, I now have a clearer “mental map”; I could navigate through the product development process before, but a map gives you a much better idea of how the world works, and might even allow you to find a few shortcuts along the way.

The business course aspects of SDM gave me a much better idea of where some of the fundamental disconnects are between the business world and the engineering world. It allowed me to see where both sides were making mistakes, often real mistakes – engineering misunderstanding the needs of the business, business misunderstanding what is needed to build products. Sometimes, the problems arise from poor communications, misunderstandings or incorrect “mental models” of how the other side does things.

The problem with theory is that it can sometimes be hard to map to practice. One of my goals the SDM program is to connect the two; this thesis is a part of that effort.

For this paper, I survey some of the literature on technology development processes and then talked to a variety of companies to try to understand how they do technology development. Specifically a few questions to be understood are:
• How do technology development processes relate to product development processes?

• What are the implications for the management of technology development?

Through multiple conversations with my advisor, professor Eppinger, I began to wonder:

• Do generic model(s) of a technology development process exist? What do they look like?

If there are some generalizations that can be made, then this could offer some interesting insights into understanding of the technology development and how to approach its management.

In essence, much of this paper is about mapping processes from theory and practice to understand the similarities and differences. Through this effort, neither theory nor practice seemed to be complete, but patterns did emerge. By generalizing these patterns, we can gain some insight into how technology development occurs.

1.2 Additional Difficulties

While technology development may be confusing to non-technical management, there is also confusion on the technical side.

One challenge in explaining the differences between product development processes and technology development processes is with terminology. Some terms are vaguely defined (i.e. Technology Development) and others may lead the reader to develop a mental picture of the theory that is inaccurate. It became necessary to define some terms such that there was a common basis to compare the cases and literature and to limit the scope of the problem. Some terms will be defined that have similar meanings to conventional terms, but are intentionally separate to reduce these prejudices.

1.2.1 Perspective and Preconceived Notions

When looking for companies to interview, I asked a classmate who worked as a product designer at a high-end medical device design consulting firm if I could interview their research and development team about their technology development processes. Initially, as a product designer she was offended: “I do technology development as part of my job!”.

I suggested that talking to someone closer to the research end was more of what I was looking for – because at first thought, technology development must come before product development. On reflection I became less sure that what she was doing wasn’t technology development. She wrote back, “I thought about it, and maybe what I do is more product development.”
development, but I'd be happy to talk to you anyways.” This kind of confusion was pervasive throughout the research until I realized that everyone I interviewed had different definitions of technology development.

Her story of “product development” of medical devices was nearly identical to the technology development processes that I found at all of the other companies I interviewed. If anything, the main differences in her descriptions were because of her industry. Her processes were very thorough – medical device development requires meticulous documentation of every decision and the test results of every step in order to certify a new device.

1.2.2 Epistemological Concerns

While it may concern the reader that a relatively few interviews were conducted, one consideration is that this thesis essentially is a mapping and a proposal for a theory of how technology is developed and how management could think about that development process. While statistical methods have become popular and the norm, they are more effective at theory verification, but a case approach can be more effective at theory formation [Hög11, pp 30-37]. In *Case Studies and Theory Development in the Social Sciences* George and Bennett say that both methods can “…develop logically consistent models or theories, they derive observable implications from these theories, they test these implications against empirical observations, and use inferences to modify the theories.”[GB05, pg 6] In essence, George and Bennett argue that for full theory development a combination of methods can be used in a complementary fashion.

1.3 Some exclusions...

For the most part, I have intentionally limited the discussion to companies that are building some sort of physical product. I have excluded software only companies, as their development practices are somewhat different from physical product companies, and startups. Because this paper is focused on processes for technology development, many of the common business concerns such as market size, cost, etc. are not addressed directly by these processes. Instead, these factors serve as inputs or requirements for the technology being developed – but they are outside of the technology development process itself. However, as we will see in section 2.4 most of these aspects are covered by the product development process. For the purposes of this paper, the technology development process may be constrained by business aspects and may interact with business aspects at regular intervals (through waypoints, reviews, etc), but the business issues are not part of the day to day development.

Since I suspected their processes may be more intermingled with the development of the business, and thus harder to distill.

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1.4 A System Engineering Approach...

In Edward Crawley’s System Architecture\textsuperscript{3} class at MIT, he talks about a system engineering analysis approach which he calls “two down, one up”. The methodology of this paper invokes this philosophy. Crawley would say to understand a system, you should look at it from multiple levels to gain a better understanding. For example, for a given system you should:

- **Level One (Starting Problem)**– This is the system you are trying to define. This could include descriptions, specifications, etc.

- **Level Zero (One up)** – What is the higher level purpose, structure, and function of the system? This description can be more abstract.

- **Level Two (One Down)** – A more detailed, description of the system. For example, this could be a block diagram of the level one description.

- **Level Three (Two Down)** – What does the implementation of those blocks look like?

In each level he states you should describe the form, function and operands. For example, data in a computer would be the operand, the algorithms operating on that data would be the function, and the form would be the computer itself.

For someone implementing the system and trying to explicitly architect their blocks at level two or three, they can use the same technique, in which case these blocks would be their level one. Crawley says that any system is a system of systems and the two down, one up approach can be applied at any level of detail to determine the architecture.

1.4.1 ...Applied to This Paper

In this paper, we are trying to gain insight into how technology development occurs so that we can have better insights into how to understand and manage it in relation to the rest of the company. To answer this question we will apply an approach similar to the above:

\textsuperscript{3}This discussion is based off of the sections of his 2011 class taught in January and the fall. This theory will be included in the forthcoming book [Cam14].
Level One (1) Problem – How do we understand and manage Technology Development Processes?

One Down (4) Current Literature – What does the literature say about technology development processes? What are the basic structures and characteristics? To understand them more fully, we will first look at product development processes, which are better understood and considered more predictable.

Two Down (44) Company Cases – Stories about how companies developed a specific technology. The reader will be spared of many of the specific details, but most of the case interviews were stories of how a company developed a specific technology. The companies that were interviewed span a variety of industries and the positions ranged from design engineer to product manager to vice president of research.

One Down (4) What is their process? – The stories were then simplified into diagrams of the processes that actually occurred. These are summarized in appendix B. For example, they show the order in which a series of prototypes were made, and why. At this level, specifics of what was being made are factored out.

One Up (1) Generalization of Technology Development Processes – Patterns appeared in level zero, which suggest there are common attributes to how technology development occurs across a wide variety industries and scales.

Return to Level One: What can we apply? – Based on the observations above, what are some of the considerations when trying to understand and manage technology development in an organization?

This decomposition/analysis approach is very powerful. By adding and removing layers of detail of a system, the architecture emerges– adding detail forces understanding of the actual complexity and implementation, while removing layers leaves behind the architecture and a greater understanding of the system itself. In our case, this allows to gain some

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4For companies that had well-established processes, the conversations were more about the process than a specific technology implementation.
general insights into technology development that might be lost with only looking at case studies of specific implementations.

1.5 Structure

As background and context, this chapter provided an overview and describes many of the problems encountered with thinking about technology development.

Chapter 2 reviews the pieces of innovation: basic research, simple product development processes and technology. I will form some definitions for technology and technology development and look at a system used by NASA for evaluating the stages of technology.

Chapter 3 reviews more complex product development processes—those that are commonly found in complex products and software. Part of this complexity comes from the loops that arise from rework and iteration. This will point to a fundamental disconnect between the questions that management and engineering use to approach a project.

Chapter 4 reviews some of the literature on technology development—pointing out the differences the authors see between technology development approaches and product development approaches.

Chapter 5 discusses the case studies and how technology is developed in practice.

Chapter 6 combines both the theory and the observations gleaned from the processes to develop a general process—a look at how technology is actually developed. My hope is that this model will give managers insights into the complexities of technology development and some ideas of how to understand the process.

Chapter 7 concludes with some of the key takeaways from this research.

The appendices contain more detail a symbol “key” to the diagrams and more information on the specific cases.

In the next chapter we will look at the three basic components of innovation, and develop some definitions so that we have a context to compare technology development processes with product development processes.
Chapter 2

The Components of Innovation

This chapter builds a basic understanding of the components of innovation to set a context for some of the issues we will encounter. It will provide an overview of the main components of innovation, define technology development and provide a basic description of product development processes, which will be used as a basis for understanding technology development processes. Finally, it will introduce a system used by NASA to evaluate technologies and tie all of these ideas into a single framework.

In initial discussions of this topic with professor Eppinger, I was introduced to the following sketch:

Let's go into more detail of the innovation components I introduced earlier.

The basic research, or invention stage, is sometimes described as the "fuzzy front end" [Rei99] of development and the work is described as "Experimental, often chaotic. Difficult to plan... [involving] Eureka moments." [Koe+01, pg 47] Both authors go on to say that it is hard to predict when an idea will appear that can be commercialized and what the revenue will be.

The product development process is considered to be more predictable. While the processes may differ from industry to industry, knowing the basic structure allows for a basis of discussion to understand of how product development is done and progresses. Authors like Ulrich and Eppinger [UE08] wrote books about product development and have generated
generic product development processes.

Between basic research and product development is technology development\(^1\) - some development that is needed before the “experiments from the lab” are reproducible and of high enough quality that they can be applied into a product\(^2\).

So the initial research question was:

\[
\text{Is technology development more like product development (i.e. predictable) or more like invention (i.e. unpredictable)?}
\]

In the next sections we will define some terms and describe these three parts of innovation: invention, technology development and product development.

### 2.1 Idea / Invention

The innovation process usually starts with an idea. For a simpler organization, such as a startup or small company, developing a simpler technology, this can be enough. For organizations with a research department, the innovation process can grow from an invention.

Invention is concerned with developing the idea for the technology. It may come from a university, research laboratory, or even an individual, building something to meet a need in their garage or basement.\(^3\)

Knowing how to proceed once you have invented something often isn’t obvious. In the summer of 2011 I interviewed two dozen researchers and scientists across MIT to survey how their inventions would impact the future of manufacturing\(^4\). The majority were working on inventing a variety of technologies: miniature thruster “engine” to enable satellites the size of a baseball; developing a complete, continuous, pharmaceutical factory that fit in a room; making miniature machine tools to move individual atoms. When I asked the majority of these researchers when they would be “done”, at best they would say “we hope to be testing something in a few years” but more often the answer was “we still have some things to work out.”

I also asked if they were to commercialize their projects what they would need and what would be the next steps. The answers almost always seemed fuzzy to them. They may have done some technology development, but the majority was enjoying their work on the invention. Few had access to equipment beyond the laboratory such as a production line, or

\(^1\) Although [Koe+01, pg 47] would say that technology development is the last step of the fuzzy front end before product development.

\(^2\) We’ll revise this to a more formal definition/description in section 2.2.

\(^3\) von Hippel suggests that a source for innovation is to look at what he calls “lead users”. For more information on lead users and user centered information, see von Hippel’s work [Hip05].

\(^4\) This was part of the Production in the Innovation Economy (PIE) project looking at the future of American manufacturing.
some other means to allow them to reproduce their invention at scale. Almost all cited that the next steps would be to acquire or gain access to the machinery and people to take their ideas to the next level.

It was clear that for most of the researchers, how to move their invention into being a product wasn't apparent. However, there were a few who could answer these questions about how to commercialize their research. They were extremely hard to find and even harder to interview because they were in the process of leaving MIT to found start-ups to commercialize their inventions!

2.2 What is Technology?

What is technology?

Professor: “What do we know about this new thing?”

Student: “Nothing?”

Professor: “Right! So, let’s give it a name so that we can start knowing something about it!” [Tay88]

An exact definition of technology development is difficult as it can vary, depending on industry, application or the level it is being applied. One of the first questions for each of the cases was “Give me an example of a technology that you have developed.” Each subject provided a different answer—not only in subject but also in scope. Furthermore, when asked if others were doing technology development, they would express strong opinions, usually opposite of their own view—if they were doing technology development, others in the company were not. The wildly different points of view may be due to where their position in the technology stream—how technology develops over time—its relation to product development. I will discuss the concept of a technology stream in more detail in section 4.4.

For the purposes of this paper, it is useful to have some understanding of what technology is, so that we can better understand what the goals of technology development are and so that we can separate it out from what technology development isn’t.

Starting off with an analysis of the dictionary definitions of the technology, there is an interesting progression over time. The Greek root technο- where it meant “art, craft, or skill”[13c][13a] and -ολογυ meaning “a combining form in the names of sciences or bodies of knowledge”[13b]. In a dictionary published in 1848, before the second industrial revolution5, and the invention of mass production and the assembly line, the definition was:

Lemma 2.2.1 Technology (1848 Dictionary) “1. A description of the arts, or a treatise on the arts. 2. An explanation of the terms of the arts.” [Ogi70]

5Considered to start with the steel purification process developed by Bessemer Steel in 1860.
...which gives an almost creative or applied feel to the definition. By 1914, a later edition of the same dictionary had revised the definition of technology to be:

**Lemma 2.2.2** Technology (1914 Dictionary) “That branch of knowledge which deals with the various industrial arts; the science or systematic knowledge of the industrial arts and crafts, as in textile manufacture, metallurgy, etc.” [Dwi14]

...still applied, but also has a systemic treatment and approach as applied to scientific or industrial contexts. Finally, a modern dictionary claims technology is:

**Lemma 2.2.3** Technology (2013 Dictionary)

1. The application of scientific knowledge for practical purposes, especially in industry: advances in computer technology, recycling technologies.

2. Machinery and equipment developed from the application of scientific knowledge.

3. The branch of knowledge dealing with engineering or applied sciences.

[13c]

Some authors will also assert that a product, arising from the product design process is technology. While this is valid, I will ask the reader to set this notion of technology aside until later in the paper to reduce confusion. Additionally, a company may consider some non-technical disciplines to have “technologies”, for example, a business model or marketing approach may be called a technology. These are beyond the scope of this paper.

For the purposes of this paper, the main definition of technology I will focus on is:

**Definition: Technology**

Technology: a systematic treatment of knowledge for practical purposes, often in the sciences and engineering.

Our discussion to this point suggests that technology development starts with an idea or invention. Through the case discussions an additional trigger of a technology development process could be a technical problem. To provide consistent terminology, I call all of these triggers a “challenge”:

**Definition: Challenge**

Challenge: a technical idea, invention or problem that triggers a technology development process.

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6 Högman’s interpretation of Burgelman. See [Hög11, pg 7] who is interpreting [BCW08].
7 Christensen says that “...This concept of technology extends beyond engineering and manufacturing to encompass a range of marketing, investment, and managerial processes...” [Chr06].
In the cases the reader will see that a challenge can come from inventions, new ideas, a product development process, or even a problem discovered in a technology development process itself. Which means, for the purposes of this paper, technology development is:

**Definition: Technology Development**

**Technology Development:** the systematic treatment of taking a technical challenge and building the knowledge and capability to implement it for practical application.

This definition implies a variety of tasks, from selecting and refining the challenge, to understanding and developing the approach to make it repeatable and suitable for integration into one or more larger products or systems.

**What forms does technology take?**

So, if the input is a problem, then what is the output? The output can take a variety of forms. Robert Cooper[Co06, pg. 23] suggests the results of technology development are:

- New Knowledge
- New Technology
- A Technical Capability
- A Technology Platform

Högman [Hög11] states that technology can take the following forms:

- Tools
- Capabilities
- Knowledge
- Product Prototype

I suggest that almost all of these forms of technology can be reduced to building *knowledge* and *capabilities*. The *knowledge* generated is stored in various ways such as people, documentation, and prototypes. *Capabilities* can include technical capabilities, processes, tools, teams, etc. If not codified (captured in documentation) or transferred by other means then often knowledge exists in people – their understanding and expertise of the problems.
This has an interesting implication for management. It can mean that if careful steps are not taken, then company events like layoffs, plant closures, disposal of little used tools, employees leaving, etc. can impact a company’s technology capabilities.

2.3 Overview of Product Development

2.3.1 What Happens During Product Development

Figure 2-2 shows Eppinger’s generic steps to product development which we will examine over the next few pages. The process is as follows:8

Planning: Sometimes called “phase zero” [Edm06] planning occurs before the product effort is launched. In phase zero the overall scope and understanding of the project is developed. A corporate strategy is determined along with target markets, possible technologies, and market understanding to create a mission statement outlining product, business goals, key assumptions, and constraints. The design firm IDEO calls it “understanding the world” so that they can find “new product opportunities”.9

Concept Development: Sometimes called the “front-end process” where “the needs for the target market are identified, alternative product concepts are generated and evaluated, and one or more concepts are selected... A concept is a description of the form, function, and features of a product and is usually accompanied by a set of specifications, an analysis of competitive products, and an economic justification...”[UE08, pp 13-15]

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8 Descriptions based on those in [UE08, pp 12-18] and others as noted.
9 IDEO is a well known product design firm. The case notes that this description was taken from a customer presentation booklet, “Project Bindle for Simmons, p. 8.” that IDEO prepared describing their research process and findings.
System Level Design: Defines the product architecture and decomposition of the product into subsystems and components. It may also describe the generic development phases of the product, specifications, manufacturing and assembly descriptions.

Detailed Design: Determines all of the internals of the product, including part selection, operation, final specifications, tooling, and fabrication. Extensive documentation is also generated and maintained on parts, design decisions, assembly, testing, and user/service manuals. Two of the major goals here are to generate a robust (reproducible) design and determine production costs.

Testing and Refinement: Multiple versions of the product are built and refined. Early (Alpha) prototypes determine that the design meets the customer needs and initial specifications. Later (Beta) prototypes are often built with the intended parts using the intended production processes. These are extensively tested internally and externally (by customers). Changes are fed back to engineering to improve function, manufacturability or reliability.

Production Ramp-up: The product is made with the production system. It is used to train manufacturing staff and work out any remaining problems in the production process.

Launch: The product is released to the market.

Note that much of what is done during planning and concept development are heavily focused on determining the business needs and understand the market. Then the product development effort is building the “right” product for the market.

We will see later, that many of the activities in Technology Development overlap with these steps. Concept development will often provide inputs to the technology development process. System level design also provides inputs or may lead to the development of a technology platform. Finally, the processes in detailed design, testing and refinement closely match those found in technology development.

This description is focused on new product development at the beginning of a product’s life-cycle. There are additional development stages and steps that occur once the product is released to maintain, reduce cost, and add new features to the product. Just because the product is released, doesn’t mean that design and engineering stop; products often continue to be improved requiring new technology development.
2.4 How Product Development Occurs

Twenty-five years ago, the major risk in creating a company (or in launching a new product...) was the feasibility of the technology. Managers believed: "If we can build it, they will come." Today, the product development cycle is more predictable... So the biggest risk for most companies has shifted from getting the product to work to getting it to market.[LH06, pg 4]

This section gives an overview of some of the product development processes that have enabled this shift. We will then compare these process maps to see how they interact with technology development.

Part of the breakthrough has been that the steps to product development have been generalized and there is a process that can be followed to produce predictable results when the product will be released, that the product that is built is what was intended, and suitable for the market. Predictability for business is important to manage risk, create stable cash flows, create a stable business model, and create stable returns for investors. While the predictions are not perfect and products are often late to market, having a process often prevents the situation where a product that was supposed to take six months to develop ends up taking multiple years.¹⁰

One such process description is Robert Cooper's Stage Gate approach (see figure 2-3). In Cooper's simple model, all of the steps that should be done before, during and after product development are laid out in sequential order which Cooper calls stages. By following the process and going through the steps in order, it reduces the chances of common problems, like making a product that there isn't a market for, or is too expensive.

**Definition: Stage**

**Stage:** A visible set of steps that represent a phase of development.

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¹⁰ A recent survey of developers show that 43% of their projects are completed on-time, 73% completed were within 15% of the scheduled completion date. 90% were completed within six months (+50%) of their due date.[Dav13]

¹¹ His method is outlined in [Coo11], and figure 2-3 is taken from [Coo06].
• Idea – The product starts with an idea. This could be a customer need, a suggestion from sales/marketing, a product based off of a new technology, etc.

• Scoping – Determining what the product will and won’t do. Specifications are created here. Limitations of the product/product architecture are often as important as capabilities.

• Business case – Research to determine market demand, pricing, competition, etc.

• Development – Figuring out how to build and manufacture the product.

• Testing – Confirming that the product meets the specifications and quality requirements. Can also include testing with users to verify fit with end-user’s needs.

• Launch – Build and release the product to market.

Between each stage Cooper has brought in the notion of gates.

**Definition: Gate**

**Gate:** A formal evaluation point in the process. Also often referred to as “tollgates”.

At each gate, progress on the project is evaluated by management and the engineering team and one of three actions can be taken:

1. **Go** – progress has been made to declare that this stage of development has been completed.

2. **Kill** – the project didn’t meet the goals of this gate, and the project should be terminated.

3. **Go-Back** – there was a problem meeting the goals of this gate, so there is more work to do before we try again.

For management, these gates are commonly thought of has hard evaluation events, which occur at specific times in the schedule. When the gate occurs, a decision is made and usually the project continues or is killed. “Going back” is typically avoided as it is a form of looping, i.e. repeating work, and may be less favorable for reasons we will see in section 3.3. Most commonly, the decision may be delayed until the requirements of the gate have been met. From a project management point of view, this becomes “schedule slip”, which ideally we want to be minimized.
<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic Principles Observed/Reported</td>
<td>Very Low</td>
</tr>
<tr>
<td>2</td>
<td>Concept or Application Formulated</td>
<td>Very Low</td>
</tr>
<tr>
<td>3</td>
<td>Analytical and experimental function and/or proof of concept</td>
<td>Low</td>
</tr>
<tr>
<td>4</td>
<td>Component/breadboard verified in lab</td>
<td>Low to Moderate</td>
</tr>
<tr>
<td>5</td>
<td>Component/breadboard verified in relevant environment</td>
<td>Moderate</td>
</tr>
<tr>
<td>6</td>
<td>System/subsystem model/prototype in relevant environment</td>
<td>A fraction up to the cost of level 7</td>
</tr>
<tr>
<td>7</td>
<td>System prototype demo in space</td>
<td>Significant fraction of cost of level 8</td>
</tr>
<tr>
<td>8</td>
<td>System flight demo qualification through test/demo</td>
<td>Highest cost</td>
</tr>
<tr>
<td>9</td>
<td>Flight proof through mission</td>
<td>Mission specific, but less than level 8</td>
</tr>
</tbody>
</table>

Figure 2-4: Description of NASA’s Technology Readiness Levels

2.5 Technology Readiness Levels

Technology development is critical to innovation and the long term viability of many businesses. Unfortunately, there have been few metrics to evaluate the risk and maturity of a given technology. One such metric is the notion of technology readiness levels (TRL) which was developed by NASA to evaluate technologies for space missions. While the initial white paper is space focused, the levels can be applied to product development. For NASA, a flight is their product and having their technology being used on “missions” is equivalent to their product being released to the market. A summary of the levels are shown in table 2.5.

In general, as the TRL level rises, so does the cost, however the risk is reduced. As a technology is taken through the TRL levels, it becomes more mature (better understood – we become more knowledgeable) and more stable – hence the reduction in risk. It is important to remember that just because a technology is mature, that doesn’t mean that it is suitable for a desired application. [BHL09, pp. 3-159]

2.5.1 SBIR Funding

Figure 2.5.1[Nas13] shows how the technology development levels relate to NASA’s system of Small Business Innovation and Research (SBIR) grants. Many government departments use this system to fund technology development projects, with the largest being the Department of Defense, and the Department of Energy. Note that the “technology research and development” and the “technology development and demonstration” are the classic gap between basic

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12[BHL09, pg 3-161] also mentions this similarity.
The SBIR grants are available to businesses of 500 employees or less, are used for “product development”. For a technology NASA wants investigated, they issue a series of grants. The first grant issued is $125,000 is for a six month research project to investigate feasibility of an idea. Stage two awards are $750,000 and the next a prototype is expected to take 2 years. The third stage is privately funded and is intended to take the project to commercialization. Each stage is executed in turn and if the technology doesn’t look promising, then they don’t fund the next stage. In the scientific instrument company case, the challenge was based off of a SBIR grant from the National Institute for Science and Technology (NIST).

2.5.2 Extending the TRL Metrics

In [BHL09] the authors extend NASA’s technology readiness levels model to a wider range of technology stages beyond the initial bringing an invention to impact. They point out that this is necessary, because of a few limitations in the NASA TRL process:

- It does not consider multiple technologies—i.e. how do the individual parts affect the whole?

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14 NASA’s “products” are complex, containing multiple technologies that are integrated together into one or more “systems”.

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31
• A lack of consideration of **criticality** of each technology, i.e. which parts can be safely substituted?

• An inability to access the **applicability**, i.e. how does the technology under development suit its intended application context?

• A lack of consideration of **life-cycle** aspects, i.e. what happens with the readiness as the product is modified or competing technologies become more mature? Do we downgrade the TRL, and for what reasons?

• NASA’s TRL is focused on the initial R+D and does not capture later technology development that is found once a product is released.\(^{15}\)

In the next section, we will look at product development processes and then relate the TRL levels to the stages of product development processes.

### 2.6 Connecting the Components Together

Figure 2-6 integrates all of these ideas together into a single diagram. Invention or idea generation is described by TRL level 1, TRL levels 2-6 correspond to technology development, TRL levels 6-9 correspond to the product development process and the product launch. The added TRL 10 addresses product enhancements after the product launch. There is not necessarily a "crisp" mapping between TRL levels and the boundaries between invention, technology development and product development. Often these boundaries are a little fuzzy and may have some overlap.

In the next section we will look at some more complicated aspects of various technology development processes. Some of this complexity will be similar to the complexity we will encounter in the technology development processes presented later in this paper.

\(^{15}\)For example, improvements, new applications, variants, etc. that are later incorporated into products.
Figure 2-6: Relationships Between TRLs, Innovation, and Product Development
Chapter 3

Complex Product Development Processes

In this chapter we will look at more complex product development processes that mirror some of the characteristics of technology development processes. We will also discuss the difficulties with iteration and rework and how they cause headaches for management.

3.1 More Complex Product Development Processes

With Cooper, we talked about the simple case of a general product development process with five steps. We can outgrow this simple model quickly when looking at complex products or software development. In their book “Product Design and Development” Eppinger and Ulrich give examples of more complex general product development processes shown in figure 3-1[UE08].

The “generic product development process” shown in figure 3-1 is more elaborate than Cooper’s. The front end stages include taking time to plan, develop the concept and a system level design before the detailed design. Eppinger and Ulrich also add stages to account for testing of the product and ramp-up to production.

Each of these stages can contain a process as well. For example, figure 3-2 shows the general steps that make up concept development. By going through all of the stages and steps, this technique insures that nothing is missed and promotes proper planning without taking shortcuts. Each step is small enough that the approximate time can be estimated to create an accurate project schedule.
Figure 3-1: Examples of Three More Complex Product Development Processes

The bottom process in figure 3-1 shows a more complex process, where there are multiple components being developed in parallel. Each development subprocess has a design, (implied) build and test steps:

```
Design -> Build -> Test
```

Each of the parallel subprocess could be a little process itself— a design, build, test group which can be found in the detailed design and testing stages of the first product design process.

Again, it is a linear process (no loops) so the development stage is predictable. Sometimes,
these linear processes are described incorrectly as a “waterfall” after the paper by Royce [Roy70]. Royce’s paper points out that the progression from stage to stage is idealistic and that there is often looping and backtracking.¹

Figure 3-3: Ideal Waterfall

Figure 3-4: Waterfall with Large Loops

The middle process of figure 3-1 is labeled as a spiral process. This is based on the notion of spiral development used in computer science which will be described in the next section. The distinguishing characteristic is that there are loops – in this case, when the development stage does not meet the testing requirements, we go back to the design. This will typically be repeated multiple times until the development is successful, or until the project is canceled.

3.2 Spiral Development

Spiral development was proposed by Bohem while developing software in the 1980’s, and has become part of agile software development²—which is now one of the dominant models for software development processes. Bohem argued that one of the problems with linear development processes, sometimes called “waterfall” development, was that for some applications it was impossible to know the full specifications of the system at the beginning. He says that “It is also based on the often-unrealistic assumption that the ... system will be flexible enough to accommodate unplanned paths.”³ Specifically, in cases where the product requires lots of customer interaction, such as the development of a user interface, integration with other systems, or will require gradual phase in, it is difficult to know ahead of time a complete specification.

Bohem’s solution was to develop software in a series of cycles of:

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¹ Fig 3-3, shows the idealistic waterfall with no loops. Figure 3-4 shows large unplanned iterations spanning multiple stages.
² See [BA04] for more on agile software development.
³ Boe88, pg 63.
These cycles are shown in figure 3-5. With each successive cycle more knowledge is gained about the problem and solution, risks are understood and mitigated, and the system eventually converges on the final product.

The problem is that it may not be possible to predict how cycles through the loop are required. If each cycle through the loop takes a long time, then the process can take a long time to complete. However, even this can be accounted for in a linear schedule if the number of loops and their duration are known. In computer science, this is called “unrolling the loops” – imagine unrolling the spiral and using it as a time-line for a linear schedule. This is sometimes called planned iteration.[IKE00] However, if the number of loops isn’t known, then this approach won’t work.

For example, at one company I worked for, an electrical engineer would develop a circuit design, layout, build a circuit board, and then test it. He claimed on a good week, the circuit would be working and optimal by the third try, but for a complex circuit it might take him as many as eight. With each revision the results would get better, and the revisions would get faster, but eight revisions would take considerably longer than three. Even the best engineers would go through a “few spins” of a circuit board design before they were satisfied.

### 3.3 Minimizing the Effects of Loops

The biggest problem is when a mistake is discovered in a later stage, requiring a jump back to rework an earlier stage. For example, it is very undesirable to get to the testing stage of a product and discover that the market for the product doesn’t exist, which could mean that the specifications for the product need to be changed and the product needs to be re-developed. This is called unplanned iteration. These cases end up adding large multipliers onto the time needed to complete the project, which greatly increases cost and risk.4

It is unrealistic to think that mistakes will not happen, therefore will always be some looping and rework. One way to combat these large schedule slips is to verify often that the work done is correct and complete. If a problem is found, then it should be corrected as quickly as possible to make the loops as small as possible. This localizes the effects of rework.

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4A survey of embedded developers showed that as much time is spent testing and debugging as is spent of the initial design.[Dav13] System dynamics is a modeling tool that can also deliver some striking insights. Similar insights arose from a simple dynamics homework problem showed that a project where 80% of the work was correct and complete (20% defect) rate, resulted in rework that doubled the time to complete the project.[Lyn12]
and minimizes the time spent looping by making the loops smaller.\textsuperscript{5}

In the design\textsuperscript{6} and software worlds, the approach of “make your assumptions explicit, build frameworks and hypotheses, and then review, test, learn, and adapt”\textsuperscript{7} is common place. We will see that the scientists and engineers interviewed in the cases use iteration extensively as a method to build knowledge and understand problems.

\textsuperscript{5}Steve Spear’s work (see: (Spe09) and (SB99)) documents how these approaches are done in lean manufacturing.

\textsuperscript{6}The phrase “Design Thinking” has become popular. This movement takes many of the ideas and techniques used in the design world and applies them to business.

\textsuperscript{7}McC08.
3.4 Loops – Disconnect Between Business and Engineering

In looking at the goals of business and engineering, there is a fundamental difference. For business, many of the questions around development are asking “when?”. When will the product be ready? When can we go to market? From when management can estimate costs (time is money) and develop strategies for the market. For engineers and scientists developing technology, many of the questions are focused on “how?” How can we develop something to do this? How can we work around this problem?

In the book *The Back of the Napkin* Dan Roam explains a variety of ways to “solve problems and sell ideas” by using pictures. In a chapter on frameworks for presenting information he uses the diagram shown in figure 3.4.

Now, consider the process diagrams in the previous sections. As soon as looping is added to the process it changes from a timeline to a flowchart—a description of how instead of when.

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8 “Flowchart” from the comic XKCD[Mun13]. There is no route that doesn’t end up in perpetual repetition.
9 Roa09.
I believe that this is what makes it hard for management to apply their techniques to technology development. Management wants a logical sequence of events that lead to a desired outcome, while developers want an iterative process. [Hög11, pg. 67] Developers recognize that they may not know enough information at the start of the project and that the actual details will evolve as they work through the development. As a consequence, there will be some rework. How much can be hard to predict. This is a fundamental disconnect in their respective approaches.

Attempts are then made to either ignore the iterations, or integrate the looping into a linear time-line. There are three techniques that typically occur:

1. **Small and Hidden-Loops**—Loops are small, exist within individual stages of the process and are not shown/considered on the schedule.

2. **Planned Looping**—A certain number of iterations are planned for in the schedule. The loops are “unrolled”. (i.e. each iteration is added in sequence to the schedule, back to back)

3. **Unplanned Loops**—Large loops are not considered in the schedule and extensive backtracking in the schedule is required to accommodate the rework of these unplanned loops. This type of iteration is most detrimental to the accuracy of a schedule.\(^{10}\)

We will see that iteration (looping) is a common technique in technology development processes.

### 3.5 Summary

Complex product development shares many of the same stages and subprocesses as simple product development. One of the principle differences is the more complex structures built from the stages and subprocesses. Looping and iteration often occur and management often tries to hide or convert these structures into linear time-lines so they can answer *when* questions. For engineers, looping and iteration are essential tools in determining *how* to solve a problem. Many of these themes will also arise in technology development.

The next section is a survey of some of the literature on technology development processes and the differences and similarities to product development processes.

\(^{10}\)Note that management has learned that this can happen and now builds in some buffer of time into the schedule. This is referred to as the "management reserve" in the critical path.
Chapter 4

Technology Development from Literature

This chapter examines some of the literature on technology development. Cooper will modify his stage-gate process, suggesting that gates should be “soft”, especially in the early stages. Creveling emphasizes that an important part of technology development is to thoroughly characterize the new technology before it is released. Clausing proposes that technology development should be separated from product development to reduce risk. Högman suggests that an increasing series of prototypes resembling the TRL levels is the way that technology development is actually done.

4.1 Technology Development Management Challenges

Fundamentally, Cooper asserts that “…basic research or fundamental knowledge … projects are often mismanaged because companies employ the wrong process to manage them or apply inappropriate financial criteria for project selection.” [Coo06, pg 23] He later asserts that these mistakes are due to several reasons:

- For new technologies, it may not be possible to generate an accurate business case and financial model, especially if the technology is enabling new products for the business or the market.

- Technology development processes take a longer time-frame than management works with. Technology development may take several years, while much of management is focused on quarterly results.

- Product development processes may not fit in the early stages before the project is fully formed, resulting in distractions and extra work for the technology development
Additionally, there are situations where:

- Technology development projects are fragile. At a minimum, the initial stages of technology development are closer to a creative process than a manufacturing process. Early and constant evaluation may cause ideas to be rejected before they are fully developed.

- Financial models tend to be biased against long term projects, or those with large uncertainty. Often based partially on *net present value* (NPV), where returns in the future are discounted back to today's dollars. There are two flaws. First, it is difficult to estimate the value of a "disruptive technology" since there is no historical data. Similarly, innovations that have explosive growth are also hard to predict, as there is no data to come up with believable numbers. Second, since the future returns are discounted and the discount rate is often larger than market to account for risk, even a high-return project that takes longer than several years will look like it has poorer returns than the stock market.

4.2 Cooper's approach to Technology Development

In [Coo06] Cooper applies a modified version of the stage gate approach to technology development. He focuses on the "increasingly rare" technology development, which is before or part of the front end of a product development effort.

4.2.1 Anatomy of Cooper’s Approach

His approach is shown in figure 4-1. His process consists of three stages and four gates, and feeds the front end of the product development process. These stages and gates are as follows (gates are in **bold** and stages are in *italics***):

- **Discovery** – Where "quality" ideas are brought to the process. These ideas can come from: strategic planning, technology mapping/forecasting, brainstorming, customers, etc.[Coo06, pg 25]

- **Initial Screen** – asks the question: "Does the idea merit expending any effort at all?"

- **Project Scoping** – review technical literature, patent searches, etc.

- **Go to Technical Assessment** – "Does the idea merit some experimental work?"
Cooper argues that at the beginning of his process the gates should be "soft" instead of the kill/go gates he proposes for his product development processes. This is to accommodate the "fragile" aspect of new technology development. As the process progresses, the commitment of time and resource increases, and the gates get progressively stricter.

To select projects, Cooper recommends a scorecard approach, where each technology development project is rated and then ranked.

The results of the technology development process can be integrated into the product development process at one of several points. Cooper would say that typically it is inserted before the business case, but the technology development may be used to establish the scope.
Alternatively, the products of technology development may be inserted into the product development process after the business case, but before the development—a full business case is a driver for the technology development efforts.

### 4.3 Six Sigma Technology Development

In *Design for Six Sigma* [CSA03] Creveling et al. also propose a process for technology development they call $I^2DOV$. It is a stage-gate based process, with enhancements for “six-sigma” to measure critical parameters. These parameters are tracked by the use of “checklists” and evaluated by the use of “scorecards”. Checklists are tools and best practices that should be applied to a project. Scorecards are a summary of deliverables. His process is shown in figure 4-2. It is relatively high level, as multiple tasks and techniques reside in each stage.

![Figure 4-2: Creveling's Six-Sigma Technology Development Process.](image)

His process is as follows:

- **Market, Business or Customer Need**: This is our technical challenge.

- **Invention and Innovation**: This includes everything from technology roadmaps, to business and market forecasting, to concept generation to system architecture.

- **Gate 1: Readiness**: Do we have the science, customer needs, and candidate concepts?

- **Develop**: This includes concept selection, modeling, prototyping, characterization and developing of metrics to be used in later stages.

- **Gate 2: Readiness**: The product at this gate should be as correct as possible.

- **Optimize**: The technology should be optimized for robustness, actual tolerances and adjustment ranges should be established. These should then be tested for variation due to noise, deterioration, or unit-to-unit differences.

- **Gate 3: Readiness**: Is the technology safe, stable, robust and immune to variation?

- **Verify**: Significant testing occurs, including stress testing.

- **Gate 4: Readiness**: Patents, costs, reliability, and risk should all be established.
• **Transfer**: The technology is now ready for transfer.

Their process is very focused on metrics and he suggests a long\(^1\) list of techniques for evaluating each step of each stage of a single technology development effort. His technique also highlights that an important part of technology development is characterization. For a technology to be mature, it needs to be well understood and reproducible, so that when it is integrated into a product, there is as little risk from the technology itself as possible.

### 4.4 Fishing for Technology Development

In *Total Quality Development* Clausing introduces the concept of a *technology stream* and uses the metaphor that technology development is much like fishing. His basic technology development process is shown in figure 4-3[Cla94, pg 322].

For Clausing, his technology development process starts off with *strategy*, where technologies to be developed are selected by capabilities, technology and market trends. Next there is a *creative work* stage, where the needs are defined, invention and a technology is selected for development. During invention, the goal is to build an initial mental model of how an approach may be taken and some breadboard prototypes are developed to assist with determining which technology to select and carry forward. After the creative work stage, there is a *robustness optimization* stage where the technology is characterized by a variety of metrics in both ideal and realistic, non-ideal situations. Clausing suggests that this would be done with hardware that is “convenient” to obtain. This hardware could either be a general purpose PC, or a “mule” – a production product that can be modified to show the functionality of interest.[Cla94, pg 326] Finally, there is a *select* stage, where the technology is either: “fished” out of the technology stream and pulled into the concept stage of the product development process; requires additional work to make it more robust; or is rejected as not an improvement over the existing solution (typically due to cost or functionality).

There are a couple of aspects of the above description that are distinctive. One is that technology is often “hacked” from other products or devices\(^2\) to test/prove theories and improve understanding. Another is this notion of a *technology stream*, suggesting that technology should be separate from product development. Clausing recommends that technology be developed outside of the product development process, so that the uncertainties involved don’t destabilize the product development efforts.

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\(^1\)and useful!

\(^2\)i.e. PC’s in the above example.
4.5 Höganäs’s Technology Development Process

Höganäs’s thesis [Hög11] has the closest parallels to what was found in the cases. Unlike the other literature, his thesis is tied to his experience as Volvo Aerospace, which will explain the close parallels to my findings in the next several chapters.

Höganäs worked closely with Volvo Aerospace to come up with a technology process.
that would have some appeal to management and technology developers. The process he comes up with is reflected in figure 4-4. It closely resembles the NASA TRL levels that were discussed in section 2.5. Högman notes two characteristics:

1. The activity flow on each stage is largely the same, with each stage producing a “higher level of detail and concretization” [Hög11, pg 67].

2. The process can call itself in a recursive manner. As the technology is developed, new problems can arise that were not anticipated. To solve these problems, sub-technologies may have to be developed.  

He goes on to say that due to the high degrees of uncertainty the technology developer continuously uses iteration to develop company/user needs and potential solutions/technologies to address the challenge. This may result in what Högman calls a “technology tree” or hierarchy of technologies that are developed to solve the technical challenge.

Högman notes a few advantages and disadvantages of having such a structure:

- “Achieved results and challenges are expressed explicitly, and adjustments ... can be made pro-actively.”

- “Clear structure makes it possible to better link to overall strategies and adapt...”

- TRL 6 becomes a “rule of thumb” for when a technology is mature enough to integrate into a product.

- “There is the risk of burdening projects with too much administration.”

- “Management has to show restraint and find a reasonable balance.”

While he doesn’t go into detail on the gates, he does say that the process mirrors Cooper, only with more steps, and more closely matched to the TRL levels two through six. His description only seems to address technology development before the product development process, as technology isn’t ready until it reaches level six.

### 4.6 Technology Platforms

While a technology may be developed for a single, specific purpose, a technology can also enable multiple products. A technology platform is a technique where a company is developing a technology that can target a variety of applications – possibly resulting in a variety of products.

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3 Högman mentions several ways that a company can combine their technology development processes. I will call these structures in section 6.1.3.
One problem with developing technologies, is that the details of the eventual application may not be known. In the case of Volvo aerospace engine development [Hög11], they may develop an engine platform that is flexible enough that portions can be reused in developing multiple technologies. If the product development architecture is designed in such a way that it is compatible with the technology platform, then integration into future new products becomes straightforward. New technologies developed on the platform can then be quickly integrated into the existing product lines, either as new products, or product enhancements.

The development of a technology platform can be an effective way to provide continuity in technology development. It can also shape the technology road map, product direction and longer term company goals, even if the details are not fully known at the beginning of the technology development effort.

4.7 Summary of Key Ideas from Literature

Technology development is different from product development and needs to be managed differently. It is often developed on a different time scale than product development, the challenges may not be well defined or understood. First, the gates need to be soft and flexible to accommodate the uncertainty and creativity required to make progress. Second, it is important to fully characterize the technology before it is transferred to reduce surprises in the eventual applications. This is accomplished by multiple levels of experimentation and prototyping, each with increasing in detail and understanding of the technology. The goal becomes not only to develop a solution, but to prepare a complete solution that can be readily transferred to the desired application.

Because of the uncertainty, Clausing recommends that technology be developed separate from product development, both to shield product development from the unpredictability of technology development and to protect the fragile technology development from the hard schedule pressures of product development. Technologies may then be “pulled in” to the product development process as they become mature. One way to do this is to develop technology platforms that can be developed independently of any specific product design process.

Finally, Högman found that having a defined process for helped both the team and management have a better understanding of achievements and problems during technology development. Technology platforms provide long term direction over multiple technology development projects.

The next chapter summarizes the insights taken from the cases, which will be used to create a general model for technology development.
Chapter 5

Technology Development Case Studies

This chapter will summarize the findings in the case studies and comment on various interesting aspects. The next chapter will synthesize these examples, along with ideas from the literature in the previous sections into a generic process, common characteristics and structures that were found in my survey of technology development processes.

The cases include a petrochemical company, a semiconductor company, a consumer company (Polaroid), a medical device design firm, a test equipment company and a scientific instrument company. All of the cases are from active companies, with the exception of Polaroid, which has gone through extensive changes since the project described was developed. The cases were selected across a variety of industries, however all of the stories are told from the technical professional’s point of view. The questions in appendix A served as a starting point, but in many cases the conversations drifted to examples of a variety of technology development examples. Descriptions and process diagrams of the individual cases are in appendix B.

In the following sections, I will discuss the major common themes from the cases.

5.1 Management of Technology Development

Given the definitions in section 2.2, the primary distinction between the technology and product development processes was that the market, users and management aspects of process were not part of the processes. Most of the technologists were given a challenge, but did not have direct, or regular contact with the end user. Some mentioned that they thought this hampered development efforts (i.e. are we building the developing the right technology?).
Most of the cases described management as being hands-off, although for projects in trouble, some managers resorted to very active (micro) management style with little success. It was not clear if management's silence was due to trust in the technologists, or a quiet fear and lack of understanding. Yet, a survey of managers reports that 25-30% said their biggest concern was integrating new technology and new tools [Dav13].

Hard gates were rare—most often associated with large funding commitments and imposed by management. As one product manager said: "There are supposed to be hard evaluation points in the process, but most companies don't have them." Projects would tend to not be canceled for technical reasons, but more often due to a business strategy or market shift and this could be announced at a project gate.

5.2 Two Types of Technology Development

In discussing the cases, two categories of technology development emerged. The first was characterizing and developing the technology itself. The second was how to produce it reliably, at scale. This was especially apparent in the chemical industry\(^1\) related processes, but was also mentioned in the scientific instrument and medical product design firm. Many, if not all of the cases were concerned about how to manufacture the technology and in some cases there could be sizable technology development challenges in building parts of the manufacturing process.

5.3 Aspects of the Technology Process

This section discusses some of the common process components of the technology development in the case studies.

5.3.1 Sources of Challenges (Front End)

The technical challenges that started the technology development process originated from a few sources:

- Grants – One company was asked by NIST to develop a chip scale version of their core technology. Other government departments use this system to investigate technologies.

- Research – Development of a patent or other laboratory research. This type of technology development was rare, as most was triggered due to existing needs instead of new developments.

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\(^1\)Specifically the petrochemical company and Polaroid.
• Other Technology Development Efforts – In the process of developing one technology, the technologists realize that they need to develop other technologies to support the first.

• New Products – A new product line would often reuse some of the company’s old technology, and develop new.

• Product Enhancements – Technical development to improve product performance, lower cost, or replace obsolete technology.

In the Polaroid case, the challenge was to develop an earlier patent of one of the founders. He also mentioned that they may ask other teams to develop supporting technologies, triggering the start of another technology development process. The petrochemical case, mentioned that they may focus on developing a technology from previous internal research, work that was published in a journal, or from a university research group. In the test equipment case, the next generation product triggered a variety of technical challenges.

5.3.2 Selecting an Approach (Front End)

Once given a problem, the technologists would scan for suitable approaches or even solutions to solve the challenge. Was it necessary to build everything from scratch, could something be reused or bought? Very often, technologies used in past projects would be used directly, or modified to meet the new application. One industry survey showed that reuse was as high as 70% [Dav13]. In the test instrument case, many of the subsystems were borrowed directly from other products and enhanced later. Others were borrowed and modified to be suitable for the new application.

Since most projects involved substantial amounts of risk and multiple technological development efforts, not building everything is one way to reduce the amount of risk and time in development. But betting on a single technology could also be foolish. “Management needs to understand that sometimes it just won’t work.” was frustration from one technology development veteran. To hedge against a single approach failing, often multiple technologies would be pursued. A quicker, more expensive technology may be used in the short term to test or release an initial version of a product, while the slower, cheaper, ground-up design may percolate in development to be used as a backup, or introduced into a later version of a product as a “product enhancement”. Sometimes, time to market considerations may trump using the “right” technology.
5.3.3 Early Results (Front End)

Not all of the benefits of technology development occur when the technology is complete and ready for transfer. Several of the companies reported that patents\(^2\) are generated, especially at the beginning when ideas for the approach are generated. One company published papers to improve their reputation as a thought leader in their industry.

5.3.4 Prototypes to Build Knowledge and Understanding

All of the cases reported building a series of prototypes of increasing detail and sophistication as a fundamental mechanism of building knowledge and understanding. Like Högman and the TRL metric suggests, prototypes progress from abstract mock-ups and bench breadboards, to more sophisticated examples that closely approximate the actual implementation. These prototypes also allowed them to start to characterize the technology. Typically, the first prototypes may be labor intensive. For example, Polaroid described making the first film samples in the lab by hand. Later prototypes are made with simplified or actual production processes.

The prototypes could take a variety of forms. For feasibility studies, anything that was quick could be used, such as a "mule pc" (Clausing) to an evaluation board from a manufacturer. For semiconductor development, early prototypes were computer models that would be extensively analyzed. In the test instrument case, the main prototype evolved from a rough (pile of junk) form to close to the actual configuration (See B.5.1). Similarly, for production, the prototype may evolve to becoming the actual production equipment.

5.3.5 Iteration and Looping

Building prototypes reduces risk and can quickly increase understanding. The goal is to find out the problems as quickly and as early as possible to reduce risk. The quicker these experiments can be performed, the smaller the loops and the quicker the development. Polaroid mentioned that they were developing new film samples daily for evaluation. This is impressive for a physical product, but this "agile" approach with tight development cycles is common in software development.

It was also common for an approach to fail, or more information to be needed, so they would jump back to an earlier prototype or experiment to run more experiments, which then could often be quickly carried forward to the current prototype.

\(^2\)In addition to protecting a idea, creating "patent thicket" can be a defensive move: making the company appear willing and able to defend its IP. Often other companies will enter into cross-licensing agreements and the patent holder will never actually have to defend their patents in court. [Niv]
5.3.6 Gates

In all of the cases interviewed, there was little concern for gates. None of the technical professionals was concerned about their project being canceled at a gate. Rarely would a technical project be killed due to poor performance unless the budget was exceeded. The medical device designer said simply that they make sure that we are not in a position where they are presenting something that is so far from expectations that the client would cancel the project. The semiconductor company case said more often a project would be killed due to a market or business strategy shift.

Hard gates didn’t exist, except in cases where more funding needed to be allocated. As one product manager said: “Most milestones are internal to the technical teams.” He went on to say “There are supposed to be hard evaluation points in the process, but most companies don’t have them.”

What did occur were reviews of prototypes or technologies that were selected. Sometimes these would be in a meeting format, but they also could be a less formal “gathering in the lab” to discuss or “show off” progress on a prototype.

While hard gates are generally absent, it suggests that Cooper’s fuzzy gates are occurring as internal milestones to the technical team such as the development of successive prototypes, or technical accomplishments integrated into those prototypes.

5.3.7 Prototypes as a Communications Medium

Frequent prototyping served as the most important way for his company to communicate with clients, marketers, experts, and end users. Prototypes ensured everyone was imagining the same design during discussions about a product. [TAN07, pg 4]

One of the most interesting insights from the cases is that these prototypes served as the main form of communications. I expected that technologists would be passing reports of results or designs to each other. On the contrary, as was the case at Polaroid, the technology teams were communicating by passing the prototypes back and forth for evaluation. In the test equipment case, development was slow until a prototype was erected in a very public place within the company. Suddenly everyone could see the progress, how their pieces fit together and what still needed to be done. Tom Allen’s book confirms this technique where he describes how the BMW design center uses centrally located prototypes to increase communications between teams.[AH12].

Instead of Cooper’s hard-gates, these meetings to discuss the prototypes were softer, usually some formal or informal presentation – often referred to as reviews. While they

\[^3\text{See B.5.1.}\]
would usually be internal to the technical team, the medical device firm shows them to the client to show progress, build understanding of the issues and get feedback. The BMW and test equipment cases illustrate how they may convey information at the company level.

5.4 Putting Technology Development in Context

5.4.1 Product Lifecycle

![Figure 5-1: Phases of Development Through the Life of a Product Line.](image)

Much of the literature (and this paper) have been focused on the initial product that is based on original research. This may be an oversimplification. Not only was technology development found before product development, but also during and after product development. The cases were taken from a variety of points of view: products based on new research, new products, or product enhancements. The primary difference was the scale of the technologies being developed – a disruptive technology involving higher risk, such as the work being done at Polaroid, would be hard to predict, whereas the core being developed as part of a microchip was smaller in scope and reasonably predictable.

Larsson et al. [BHL09] specifically adds another stage to the TRL metric which talks about technologies that may be developed post product release. Cooper suggests [Coo06, pg 30] a company’s “portfolio” of projects typically includes the following types:

- Technology Development (New Technology Based Products) – Front end technology development that bridges ideas/inventions to the product development process.
- New Products – May require some new technologies, but also may reuse some technologies from previous products, or other company expertise.
- Modifications/Improvements – Upgrades to existing products.
- Marketing/Sales Requests – Sometimes referred to as “specials”. These are versions of an existing product that are requested by a specific customer and are typically “one-offs”.

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New Products  In practice, new products are leveraged from technologies that a company might already have. For example, in one test instrument company, large parts of a new product development effort were based off of technologies that they had already developed. This reduced risk – much of the design and integration risks were removed, since they already had extensive knowledge of the older technologies. Key technologies would be developed internally, a modified version of an internal technology\(^4\) or “purchased” from external sources.\(^5\)

Modifications/Improvements  Technologies development efforts from new products may carry over to later versions of that product, or to other products:

- For example, in the Polaroid case, it was mentioned that two solutions might be perused to solve a problem. The first solution, may be quicker to market because it works “well enough” although it may also be more expensive. The second solution may take longer to develop, but has better quality and is cheaper. In this case, the company goes with the first solution to get to market faster, continues to develop the second solution, and when it is perfected it is integrated into the product. The product is then marketed as “new and improved” and the technology development cycle is complete, even though it was developed before, during and after the product was released.

- In the test instrument case, a new control architecture designed for a new product was so successful, that it was then modified and integrated as an upgrade to an older product. The older product became the “special edition” version and used as a way to “freshen” the older product with a “new” model. In this case, customers could also buy the new control architecture as an “expensive” field upgrade, breathing new life into their older machine.

In these cases, the changes are often well contained – they may be a single module of the development that is replaced or upgraded.

Specials  In most of the cases the product enhancements were small and did not involve much technology development, although some of these requests would be fed back or integrated into new products as additional features in “the next version”.

\(^4\)For example, in one large test system they adapted a specialty power-supply from a hand-held product.  
\(^5\)I.e. an external module is purchased, or the sub-design is contracted out to be integrated later, in-house.
Product Development as Integration of Technologies

Integration would also be an important aspect of product development – bringing the appropriate technologies together into one integrated product. It is extremely hard to separate all technology development from product development. Inevitably in the product development process there would be little pieces of technology missing that need to be developed to make the complete product. Technology development adds risk and complexity to product development. The prudent product developer on a tight time-line should try to avoid developing too many new technologies on a single time-line. An anecdote from one designer summarizes the balance between the two: “I try not to do too many new things in a single product. Even changing a compiler (tool) can be a technical challenge that should be taken as seriously as developing a module.”

5.4.2 Technology Development Independent of a “Project”

Many of the cases described technology development occurring independent of a specific product development effort. In the test equipment case, the early stages of technology development started based on a conversation around the coffee machine. Only later was the official start declared by management. There were numerous examples of engineers toying with technologies. Tinkering is a part of learning.

There were examples of technologies that would eventually be integrated into existing products at “improvements”. Sometimes these came from engineers “playing around” developing technologies and sometimes they managed to perfect a technology that was developed for, but wasn’t ready for integration into the product when it was released.

These observations confirm Clausing’s technology stream theory – that often technologies are developed separate from product development. But the cases also suggested that there was an evolution of a company’s technology portfolio of capabilities. Development of one technology would lead to an evolution of technical competence in that area.

For example, in the test equipment case, one of the engineers became interested in an older, simpler product that used relays instead of a complex electromechanical system. He wondered if he could scale the system up, while maintaining physical size requirements. With this approach, he was able to shrink a machine that was the size of a small car to the size of a washing machine (machine #1). The next product he designed quadrupled the capabilities by shrinking the approach even smaller which wouldn’t have been possible without developing the technology for machine #1. Customers were shocked when the tiny machine completed two months of testing in two hours. The new machines became leaders in their market. This wouldn’t have been possible if the development evolution hadn’t occurred in-house.
5.5 Technology Portfolio Evolution

Technology strategy will often talk about a company's technology portfolio – those technologies that a company has developed. This is broader than a technology platform, as a company may have multiple platforms in their portfolio.

Each technology development effort adds to a company's portfolio – Polaroid perfecting instant film adds instant film to their portfolio, as well as any supporting technologies that were developed. The test instrument case shows that certain in-house technology development isn't possible without knowledge and capability already in-house from prior developments. This evolution of the technology portfolio was only possible because certain technologies were developed in-house.

This adds an additional consideration during the "technology selection" stage: while it may make sense to go outside and buy or hire consultants to save time and cost during development, there is a hidden cost. By going outside to purchase technology, or hiring a temporary consultant to solve the problem can result in limited knowledge and capabilities are developed in the company. For technologies that may only be integrated into one product in one way, this may be fine. But as a long term strategy, this shortcut will hamper to develop that technology further. However, the design firm mentioned that this was an excellent source of repeat customers – since they had not built their expertise in house, they would need to come back for the next design.

For example, one startup did not have product design expertise in house, so they hired an outside industrial design firm to design and build the entire product. Because there was minimal expertise in house, they had no way to judge the quality of the work of the design firm. After a year and a half development effort, the firm delivered a product that appeared to work, but had a "few bugs". I was hired to look at some of these bugs and found some architectural flaws in one of the core technologies. To correct them required re-developing that piece of technology, almost from the ground up. Rebuilding this expertise and knowledge in house took another year and a half.

Additionally, it is very common that a technology will be reused from a previous product to a new product, even across divisions or companies. In one case, talking informally with a developer from the semiconductor test equipment company who was looking at reusing a technology used in a product from another division of their conglomerate. This technology sounded very similar to one developed at a local broadcast equipment company. On further investigation, a designer had left the broadcast equipment company to work for a division of the conglomerate and replicated the knowledge and capabilities he had developed at the broadcast company. The moral: technology can be carried by people as well as company processes.
Similarly, the portfolio will be negatively impacted if the people, teams, or capabilities are disposed of if the technology isn’t stored or transferred effectively elsewhere.

This chapter discussed many of the common themes that came from the case discussions. All of the technology development efforts exhibited remarkable similarity, despite the differences in scale and industry. In the next chapter, I will generalize many of these ideas into a generic, general model of technology development.
Chapter 6

Generalized Technology Development Model

6.1 Generalized Core Process of Technology Development

If a picture is worth a thousand words, a prototype is worth ten thousand. — IDEO innovation principle [TAN07, pg 4]

What was interesting is that all of the people that I interviewed described the same process, independent of where their projects were in the technology lifecycle. There was also a large similarity across industries for companies that were making physical products. What they all had in common were a few key points:

- The focus was on experimentation.
- All were building prototypes to gain knowledge and understanding.
- There was constant looping and rework, but their techniques were designed to cause this to converge.

Figure 6-1: Generalized Technology Development Core Process
• Typically, if there was risk, they would pursue multiple solutions at once, until the risk was mitigated.

• The solution might be to not develop.

• In addition to looping, the process was highly recursive.

**Definition: Technology Development Core Process**

**Technology Development Core Process**: A common process used in the activity of technology development. It includes taking a challenge, evaluating a variety of solutions, determining feasibility and building a series of prototypes of increasing sophistication to characterize a proposed solution. The result is the knowledge and capability to implement the technology in a practical manner.

The core process is shown in figure 6-1. As we will see, for a given project there may be multiple of these core processes applied to develop all of the technologies required for a specific project.

### 6.1.1 Stages

The generalized stages resembled the NASA technology readiness levels described in section 2.5 could best be described as the following:

**Problem Understanding and Survey of Technology** The process typically began with some problem. For the initial problem, this could be anything from “we want get into the bio-fuels business using organic waste.” to “we have a patent, and would like to develop it”. Typically, in this first stage, they would work to clarify the problem. If not already specified (say in the case of the patent) they would also scan for possible solution technologies that could be used. The Polaroid case was a typical example. This scan would include:

* External technologies (*Buy it!*). In the case of Polaroid, they needed a color dye for part of their film. They did a scan of what was available on the market, to see if there was something “off the shelf” that they could buy. This would allow them to continue quickly saving development time and costs, but may be more expensive. It also would lock them into a vendor for the dye, which would be a technology that they would need to develop later if this was a technology they would need to bring in house.

* “Leverage” an existing technology (*Reuse it!*). Since they have other products in this domain, there may be a product that uses a similar dye technology that could be
adapted to serve the new need. This has the advantage of shorter development time and most of the knowledge is in house and will stay in house.

- Develop in-house (Build it!) the technology is important, and it is important to have the knowledge in house, or the quality of the other solutions may not be good enough for the application. In this case, a full development effort as described in this section will be necessary. This is also the most expensive of the three in terms of development costs.

Typically, several technologies would be selected to mitigate the risks of development time, poor performance, or technical failure of a given approach. This effectively grants an “option” to change should the first choice technology prove unsuitable. They would be brought forward to the next steps until the risk was dispelled, they proved unsuitable or the cost of carrying the technology forward exceeded the cost of the risk. By carrying forward several solutions, the cost of changing the solution was lower - the project wouldn’t have to loop back to the beginning. Instead the project could continue forward. This is one of the ways that risk can be managed using options in the technology development process.

**Initial Evaluation:** Once the technology was selected, experiments would be run to try to evaluate the feasibility of the approach. This could take the form of a quick and dirty experiment, or in the electronic design industries the manufacturers of chips would provide evaluation boards that can be used to demonstrate functionality so that the designer can quickly become familiar with the chip. If the technology appeared feasible, then the project would move on to the next stage.

While in technology development you want to discover what-to-do, it is also (and sometimes as or more important) to discover what-not-to-do. In product development exploratory work can seem wasteful, but in technology development it is a necessary tool for knowledge building.

**Bench Prototype:** The goal of this prototype would be for the designer to get familiar with the technology and starting to develop intermediate functionality to increase knowledge about the technology and to characterize the technology. Physically, it may have little resemblance to the final, required technology, but the designer will be building out and testing basic functionality. Often the inputs and supporting environment may be “faked” with additional equipment, but the core functionality would be thoroughly tested. The goals of this stage are to build knowledge and characterize the technology.

**Working Prototype:** This prototype would be built so that the technology can be tested in the actual environment. This prototype would typically be built to size, but may be made
of different materials or with hand-built components. It would be integrated into a system for testing, or may be tested on its own in a real environment.

**Package and Transfer:** In this stage, the technology would be documented, packaged up and transferred to be integrated into its application. Documentation, test results, and often the prototype might be part of the transfer, along with some of the people on the team (designers) to transfer the knowledge accumulated during technology development.

There may be intermediate prototypes developed. Previous prototypes, as well as lab notebooks and bug reports from them, become tools that can be used to help diagnose problems later in the development process. Since a chain of prototypes have been developed, if there is a problem that requires rework or better understanding from a previous stage, then additional experiments can be run on the previous prototypes.

### 6.1.2 Waypoints

In our revised model, the “gates” in Cooper’s product development model don’t describe what goes on in technology development except in very extreme cases. For Cooper, in PD process ideal, these gates function as a Go, Kill, Go-Back decision points by management and the development team. One of their main functions is as a control mechanism and to evaluate progress. Often they are scheduled and compared to a master project schedule to make the decision—i.e. the project is too late, we should “kill” it. The reason for “killing” the project, tracking it closely on the schedule, etc. is because costs rise the longer a project runs, and often the next step will require additional investment. It is a way to answer the question *should we spend the money to take the product development effort to the next level?*

**Definition:** *Waypoint*

**Waypoint:** A recognized accomplishment within a technology development effort that is used to communicate understanding and show progress.

Within technology development, the fundamental purpose of the “gates” between stages is for communications and showing progress. In all of the cases the technologists described the “gates” more as “waypoints”¹ have the following characteristics:

¹Dictionary Definition: A *waypoint* is a reference point in physical space used for purposes of navigation.[13d] They could also be thought of as *milestones*, but hesitate to use that term as it implies linear progress and the technology development process may loop past this point/gate several times.
Waypoint Characteristic: Time

There was no mention of there being scheduled times when the waypoint would occur. This didn't mean that there wasn't predictability as to when they might occur. Depending on how constrained the development of the project is, it may be able to say reasonably accurately how long a task will take. At the beginning of the project we wouldn't be able to predict when a waypoint would be reached, but that it was likely that by a given time we would have reached the waypoint. For example, in the case of the semiconductor development, a full technology development project almost always took six to nine months.

Waypoint Characteristic: Progress

Similarly, what would be accomplished at these waypoints may not be precise. The previous stage would be considered finished when the problems were sufficiently understood such that they could be applied to the next stage—i.e., *this may not be perfect, but we understand it enough that we are confident that it won't be a problem to apply it to the next stage.*

Waypoint Characteristic: Redirection

There is always the risk that an approach that looked promising just won't work. The approach, may be changed, the project might need to loop back and reevaluate their approach to the challenge.

Waypoint Characteristic: Communication

Because of the above, the focus of the waypoint is understanding—knowledge and/or capability—and accomplishment. It becomes an opportunity to build a common understanding and share what has been understood and accomplished. For example a group may say “I've looked at the available technology approaches, and I think we should move ahead with approach X.” The feel might be more like an artist showing their work than a checkpoint at the border of a country deciding if they should allow you to pass.

Depending on the size and importance of the progress, these waypoints may be reviewed by only the technical team, or the findings may be shared with other stakeholders. This also provides a method of feedback and commentary about the solution. For example, when a technology is presented the cost of implementing that technology might be able to be estimated. The product team can then use that information for planning. Similarly, the product team might suggest characteristics they would like to see improved, which the TD team can try to address in future versions.

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2 It was mentioned in a few cases that multiple technologies would be brought forward to reduce risk.
Because the waypoints are the opportunity for input and feedback, it is common that a problem may come up in a review that requires looping back to previous steps. In practice, once the quick evaluation experiments, breadboards, and prototypes are built, these questions may be answered by running more experiments of the type that would be done in previous stages. Since the prototypes (capabilities) are already built, the time to evaluate and answer these questions can be quicker – effectively reducing the loop size of these iterations. Usually there would only be a group review on the first pass, unless there was an issue that required group presentation of a previous prototype.

**When Waypoints turn into Gates**

In the interviews, there were times when waypoints would turn into go/kill gates. Some of the cases mentioned that a budget was allocated for the project (or a portion of the project) and the project itself was treated as a black-box. This meant that the technology developers had a fair amount of autonomy, the gates functioned as waypoints instead of kill/go decision points.

**Funding:** However, a waypoint would turn in a hard gate when additional funding needed to be allocated. When additional funding was required to go to the next stage, management would need to actively show its support for the project and lobby for more funding. If they were not invested in the success of the project or if they could not get funding then the project may be killed or “shelved” 3.

**Results don’t meet expectations:** One interviewee mentioned a waypoint could turn into a gate if the results were too far from expectations. She mentioned, that if the technology being developed was wildly too expensive and no other options were given, then the external stakeholders may cancel the project. Alternatively, the stakeholders could ask for another technology to be developed to try to meet their needs. Högman calls this *redefining focus.* [Hög11, pg 72]

**External factors:** Finally and most common, the waypoints would turn into gates if there was some external reason to kill the project. One interviewee mentioned that the market could change, making the project no longer important and when they went to the review, the project was canceled. Another mentioned that a project was “shelved” when the resources of the project were needed for something else. This could happen due to a market shift, or a strategic change in the technology portfolio of the company.

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3 "Put on the shelf" for later and often never returned to – effectively canceled.
6.1.3 Structures

**Iteration (Small Cycles)** The biggest difference between technology development and product development is that iteration and looping are techniques that are used extensively and this looping often crosses multiple stages and gates. One reason for this is the domain of the challenges. Before we start we cannot know the complexity. We don’t have the knowledge to know all of the details, implications and tasks required; and we may not have the capabilities to implement everything we need to know how to develop the technology.

As a result, there is extensive looping and iteration to attack the unknowns. In the Polaroid example, they were constantly passing prototypes back and forth between teams to evaluate the performance, which made for small, tight loops.

**Looping (Larger Cycles)** Sometimes it can make more sense to loop back further in the process. Consider what happens when a gap in understanding is found in a later prototype? While it could be attacked on the current, more complex prototype, often it is easier to jump back to a simpler prototype (i.e. let’s run back to the lab and try this on the bench), run some experiments and then carry this information forward. In the product development process paradigm, this would be disastrous to the project, but for technology development the previous prototypes act as “tools” that can be used, representing capabilities that have been developed. For small gaps, this may be all that is required. For larger gaps, this may uncover more technology that needs to be developed.

**Recursion** As mentioned in 6.1.1 the trigger to start a technology development process is often a challenge. However what happens when a problem is encountered in the middle of a technology process where it requires a supporting technology that does not exist yet? When talking to Polaroid they mentioned that while they were developing coatings for their film, they discovered they needed a better way to apply those coatings to the sheet of plastic that would become the film. This triggered another technology development project, recursively. The input problem to this new product was “how do we apply coatings” and the output was a prototype machine and a process to apply those coatings.
Depending on the situation, this new technology development process could be parallel with the main technology development process, or the original technology development process may need to wait until the sub-process is done. The sub-process could also uncover additional technologies that need to be developed or could require looping as part of the development solution. Generally, these sub-processes will be smaller projects than the main project. All of these cases will impact the schedule, as typically none of this work was planned for at the beginning of the project.

**Figure 6-5: Relay Race – Sequential TD Process Example**

**Relay Race** At the high level and possibly at lower levels as described in the previous paragraph, technology development efforts may also be sequential. Högman refers to this as a “relay-race” [Hög11, pg 65] where each development project hands off knowledge and capabilities to the next. In the case studies we saw this basic structure used by the chemical company, Polaroid and the scientific instrument company – in order to bring a product to market, they will first experiment to determine feasibility and then develop a series of prototypes to improve the company’s ability to produce and manufacture the technology. In the case of the semiconductor equipment company, the prototyping stages occurred, but a single prototype evolved as the development progressed.

While the notion of a relay race provides a high level picture, in practice, often even sequential technology efforts overlap. If the technologists knew that they would need to evaluate reliability, or reduce costs, often they would start developing knowledge that could be useful to the these goals later. This could range from collecting information for the
technology scan" of later processes to a full understanding of the initial feasibility of an approach in a later technology development process.

6.1.4 Management and Waypoints

Managers often want to control a technology development process in the same way they are used to controlling a product development process. However there are a couple of problems with this approach. First, closer (active) management will add overhead to the technology developers. This will increase the loop time, and can slow the project down significantly, both due to the additional work, but also due to the task switching time/overhead, especially for times where there is much iteration.

\[ \text{design} \rightarrow \text{build} \rightarrow \text{test} \] is quicker than \[ \text{design} \rightarrow \text{build} \rightarrow \text{test} \rightarrow \text{manage} \]

Second, looking at the project on a day-to-day scale can lead to misinterpretation and poor decisions. What looks like a big hard problem one day, can disappear the next day.

What management wants/needs to do is have a way to monitor and evaluate the process, but this monitoring should be largely passive. That is, a process needs to be in place that everyone understands so that management can see what progress is being made and how things are progressing. By monitoring the waypoints is a way to get that insight. By understanding that they are "fuzzy" the can observe the trends and determine how the project is progressing.

This is hard to do. Högman mentions in his research that one of the hardest things for management to do is to take a "hands off" approach and not actively manage the project. As discussed in section 3.4, management wants a logical sequence of events to a desired outcome, while developers want an iterative process. [Hög11, pg.67]

All of these findings will be summarized in the next chapter.

\[^4\text{alla Cooper}\]
Chapter 7

Conclusion: Summary and Takeaways

7.1 Summary

I defined technology development as building knowledge and capabilities to bring a technical challenge to practical application. Technology projects are often longer term, scope is poorly understood resulting in extensive looping and risk. Often the solutions are fragile and take time to develop.

Management of technology development needs different approaches from product development. Cooper suggests that instead of hard gates, softer evaluations should be used. Creveling emphasizes that it is important to fully characterize a technology before it is ready to be transferred. Clausing recommends that to protect the fragile technology development from the pressures of product development, technology should be developed its own “stream” outside of product development. Högman found that an engineering team followed a process that closely corresponded to NASA’s technology readiness levels and that having a defined process helps with understanding.

From the cases it became clear that independent of industry, scale, or role, there were common approaches to technology development. These included: extensive looping and iteration; developing a system of prototypes of increasing fidelity to characterize technology and build knowledge; prototypes being used as tools and methods of communications; and a softer reviewing system for evaluating progress.

7.2 Key Takeaways:

Many of the key takeaways are as follows:
7.2.1 Technology Development is Different

Technology development requires developing knowledge and capabilities to take an idea or challenge and bringing it to the point of particle application. Almost by definition, it is impossible to know at the beginning of the tasks that will be required to make the technology, or if a given approach is even possible. It can occur on a large scale – taking a patent from the lab and creating a disruptive new product – to the implementation of a component or feature in a product.

There will be mistakes and rework, but they converge on a solution, because the mistakes and rework are building knowledge and understanding about the challenge.

7.2.2 How vs. When

I present that one fundamental disconnect is that management is concerned with knowing “when?” – driving a focus on timelines and schedules. Technology developers are focused on answering “how?” – focused on building knowledge and capabilities to ready a technology to be transferred and integrated into a product. To build knowledge and understanding, all of the technologists I talked to use extensive iteration and looping to learn more about their problem. This looping approach is useful for answering “how” questions, but is destabilizing to answers to “when” questions.

7.2.3 Core Process for Technology Development

The core technique used by technology developers was to experiment and iterate through a series of prototypes of increasing sophistication. These prototypes may be physical, or simulation models. The initial prototypes are very quick to build understanding and to test specific things. Later prototypes are approximations of how the technology will perform in the actual application. Each prototype becomes a tool – it may be faster to test an idea on an earlier, simpler prototype than a later one. Extensive looping and iteration is the norm. Each prototype is also a communication – developers will trade prototypes to share knowledge and prototypes can be a powerful tool to understand progress. Think art opening, instead of toll gate.

7.2.4 Evaluations Start Soft

Because ideas are unstable and prototypes are things instead of metrics, the evaluations should be “soft”. No-go conclusions should be used only in extreme cases, where it is clear that the approach will not work. The gates can get “harder” as the idea matures, but because of the complexity, unknowns and looping, management should try to avoid micromanaging techniques, as these can make the situation worse.
7.2.5 Risk

Given the unknowns, the looping and the risk of building capabilities for new technologies, how do developers take actions to mitigate these risks? Several approaches emerged from the cases:

- **Hedge bets by evaluating/developing multiple technologies simultaneously.** This gives the option to switch or drop with lower schedule cost if one technology fails, works better, develops faster, etc than another.

- **Consider buying or reusing technology, instead of building from scratch.** A team may buy first and build later to reduce costs. This may limit the future evolution of the technology portfolio.

- **Develop technology off of the critical path.** Technology development teams often evaluate technologies outside of the scope of a formal project. These technologies may become part of a technology platform (or portfolio) or may be integrated into later versions of a product.

- **Iterate quickly** If iteration must occur, learning can occur faster with many small experiments (and success or failure) than large experiments. Encourage quick experimentation.

7.2.6 When Possible Separate Product Development From Technology Development.

Given the risks and instabilities that can occur with technology development, minimize the amount of technology development that occurs in the product development schedule. Product development has enough challenges with building the correct product, managing a schedule, integrating technologies, testing the system and marketing the product. While some technology development will often be necessary, develop large technology projects separate from the product time-line. Then, “fish” the technologies for integration from your technology portfolio.

7.2.7 Technology Development May Occur Informally.

In many cases, teams will “play” with developing technologies outside of formal projects. This can build knowledge in the technical team that can expedite future technology development or be a source of product improvements.
7.2.8 Technology May Exist in People, Teams, or Physical Things.

Technological knowledge and capabilities often exist in people, teams, or in the physical artifacts of the company. Documentation is helpful, but often isn’t sufficient to retain or transfer the ability to produce a technology. Care should be taken in evaluating the impact of changing people, teams, factories, if the technological capabilities are to be preserved.

7.2.9 How the Technology Portfolio Evolves is Important.

Since technology knowledge and capabilities are tied to people and capabilities, choosing how to develop technology can have a significant impact on future technology development. While it may seem like a shortcut to buy or go to consultants for technology development, this may impair the future ability of the company to develop important technologies in-house. For supplemental technologies, it may not matter, but for technologies that will be core, this approach may impede the next generation.

7.2.10 Don’t Over/Under Manage

The very nature of technology development can be difficult to understand for management. As a consequence, management either tries of over manage the process by using tight controls borrowed from product development management techniques, or under manages – by treating the technology development as a black box. Neither are ideal.

So, how should management approach technology development? Understand that technology development is separate from product development and it will develop and evolve as your team’s knowledge and capability develops and your technology portfolio evolves. Ideally, you want to develop the technology before you need it. When starting a product development project take inventory of what new technology needs to be developed (there will almost always be some) and design your product development such that you don’t require too much high risk technology development on the critical path. Again, encourage technology development to evolve outside of product development projects. This will allow management to have much more certainty about when while allowing your technology development team to focus on the how.

Perhaps, most importantly, spend more time being a partner of your technology development team, not a judge. Observe and appreciate their prototyping victories. They will try multiple things and there will be failures and setbacks. It is all part of building knowledge.

Finally, be most weary of being told there is only one high risk approach to solve a challenge. Ask: Why? What if? What else? An expert will keep more than one option on the table while working to reduce the risk, while a gambler will bet the farm on a hunch.
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Appendix A

Interview Questions

For the interviews, I started off with the following questions:

- Give an example of a technology you developed. How did you go about it?
- What were the inputs you were given?
- What were the goals of the technology development?
- What were the outputs of the technology development?
- How did the technology development interact with the product development process?
- Was there a formal procedure?
- How were stages of the development evaluated? What actions could be taken?
- Did you have a formal method to evaluate technologies? (i.e. TRL)
- How did management oversee the process? (funding released, etc)
- What industry are you in?
- What is your role?

For the most part, the subjects would end up telling a story about their development of a technology, and I would draw out the process as a flowchart. They would then comment on what pieces I was missing, and interfaces to the product development process.

Not all subjects were asked all questions. Often they would answer most of the questions as we worked through their stories, or offer experiences from other projects they had worked on.
Appendix B

Case Summaries

This section has a summary of the case discussions. They are listed in the order they were conducted. For each case there is background information about the company, setting, project, etc; a diagram of the process and a description of the process stages.

As the interviews progressed it became clear that there was much similarity between the cases and different discussions focused on different aspects of their technology development processes. Thus, in the descriptions below, some of the descriptions are abbreviated if there was similarity to another, previous case. A few are focused on only a part of their technology development process.

The terminology used varied from case to case. To standardize, I've labeled some stages with a more consistent terminology in (). Stages or step titles are in italics, while gates or decision points are in bold.

The graphs were automatically generated for consistency by Graphviz[Ell+98] from a small language I wrote in M4[KR77]. A key to the symbols is shown in figure B-1. In most cases, only general information is provided to protect the companies and parties interviewed.

![Figure B-1: Key to Symbols used in Process Diagrams](image)

A higher level of discussion of the interesting takeaways is in chapter 5.
B.1 A National Petrochemical Company

B.1.1 Overview

The first company I interviewed was a national oil company in Asia. The person interviewed was a vice president of research and development. A typical project might be to develop a new bio-fuel product that is derived from animal waste. We discussed the general process of technology development at a high level.

A full project in this setting can take a decade or more to implement, and tens of millions of dollars in investment.

There are two different aspects of problems in the chemical industry that require technology development. First, knowledge and understanding needs to be developed about the formulation that will become the end product. Second, significant technology development is required to develop the processes (and eventually the chemical plants) to be able to make that formulation in volume.

The next section will discuss the process. A couple of themes to look for in the next section are:

- Building a series of experiments or prototypes to build capabilities and reduce risk.
- To management, technology development is treated as a black box. Management is relatively hands-off on the actual technology development process until the "gates" where more funding needs to be allocated to take the project to the next level of complexity.

B.1.2 Process

![Technology Development Process Diagram]

Figure B-2: Technology Development at a Petrochemical Company

We only discussed the high level process, which will have similarities to the process discussed in the consumer products company case. The process is as follows:

- **Problem**: For example: the company would like a new biofuel product. Officially there is a business case made, but in practice the scientists pull stock information on market size, etc, since most projects are similar – i.e. they know the market size for ethanol.
- **Ideation:** Literature, academia, and internal expertise or internal research may be evaluated as approaches.

- **Feasibility:** Initial experiments are run to determine if the selected approach has promise.

- **R+D Budget Allocation:** This is a softer gate. A group manager may approve a budget to buy equipment, and allocate people. If the budget is not approved, then they may look at a different approach, or focus on a different project.

- **R+D:** The researcher is given relative freedom to become familiar with the process, develop a few liters of prototype sample of the material being developed, and generate a report of its characteristics. This sample would be made by hand in the lab.

- **Pilot Budget Approval:** If the report in the R+D phase looks promising, then the resulting report is reviewed by upper management. If the project still looks promising, they will release the funding to build a pilot plant. If the budget is not approved, the project is killed.

- **Pilot Plant:** Equipment and processes are purchased and developed with the goal to make a few hundred liters of product. This plant serves as a prototype and model for what would be a full production plant. This may be a large room worth of equipment.

- **Plant Approval:** Higher levels of management decide to release funds to build a full petrochemical plant. This is a large investment, and the time scale may be years. If the project is not approved, then it is killed.

- **Production Plant:** The production plant is built. Once complete, the product will be produced in commercial quantities.

## B.2 A Semiconductor Company

### B.2.1 Overview

The second case interview was with a designer at a semiconductor company. In this case, the technology being developed would be a core subsystem in a larger microchip. In this case, the designer was given transistor geometries, and the problem is to build phase-locked-loops for data synchronization of digital video signals. This functionality would eventually be integrated into multiple products.
The technology development process is remarkably predictable—usually taking 6-9 months. Because the cost of manufacturing a production-like sample is so high, extensive testing and simulation is done to try to catch errors.

Funding is assigned to the project, but unless there is a market change/shift, it was unlikely that a project would be canceled. Management would usually be hands off once the project was started.

B.2.2 Process

Figure B-3 shows the process for this technology development project at a semiconductor company. The process in the product development box is not complete—only the steps that interact with the technology development process are shown. The steps and gates of the process are as follows:

- **Specification (Problem):** The initial problem would come from a product development team that needed some functionality for a product they were working on. This request would come to a technology development team and would be based on a product concept or need.

- **Refine Specification:** The technology development team would look for possible approaches to solve the problem. They may take technology from existing internal cores to modify, or take a core from a trade association to modify and/or integrate if that would solve the problem.

Simultaneously, they would work with the product development team to iterate ideas based on approaches to refine the specification to something that they thought could be built. This communications also creates mutual understanding of the problem. These discussions may result in modification of the product concept being developed by the product development team.
• **Innovation:** If the approach was a novel approach, they would file for a patent and the process would wait until the intellectual property was secured.

• **Design & Layout:** This step is where most of the layout and design of the core occurs. This would be a combination of layout/modeling tools, simulation. The result would be a "prototype" – a simulation model that could be used by the product development team, and a mask\(^1\) that could be used to manufacture the actual chip.

• **Characterize:** The core would be simulated to determine the actual operating characteristics of the chip. This information would be used to decide if more work needed to be done (returning to the design stage) or if the first samples could go through the manufacturing process. The prototype models are shared with the product team as a method to share the accumulated knowledge, and so that they can adapt the product as necessary to accommodate the predicted technological capabilities.

• **Manufacture & Test:** The mask is then used to manufacture a sample run of the chips. The setup costs are high and it takes time to complete the manufacturing step.

• **Recheck:** Once the sample chips are manufactured, they are tested to determine if the characteristics are as predicted. A small bug may be quickly fixable, and the expensive manufacture step can be repeated directly, otherwise the bugs are passed back to the design stage and the chip is redesigned.

• **Deliver Technology:** Once complete, the masks, sample chips and the models are delivered to the product team(s). For future products needing similar cores, they may be able to take this information and directly integrate it into future designs.

### B.3 A Consumer Product Company (Polaroid)

#### B.3.1 Overview

This case interviewed a former vice president of research at Polaroid, who was working on an instant film movie camera project that was parallel to the instant film still camera that became one of their most famous products. Edwin Land was one of the co-founders of Polaroid and was an inventor. His idea for this new type of film camera was the "problem" input for the technology development described in this section. At the time, Polaroid was an engineering/technology driven company. All projects were managed by Land directly, and all reviews and approval decisions were made by him.

\(^1\)A very detailed "stencil" used to manufacture a silicon wafer.
B.3.2 Process

Below in figure B-4 is the basic structure of the technology development process on this project at Polaroid. When we discussed the processes, there was additional complexity and technology development structures emerged from our discussions. For example, because of the complexity, there were multiple supporting technologies that needed to be developed to enable the technology in the patent.

The basic description and structure of the process is very similar to the petrochemical case, in that the basic structure was that of a chemical process. For that reason, I will place less emphasis on all of the steps, and only talk about the additional details.

Figure B-4: Core Technology Development Process for the Instant Film Movie Camera

- **Challenge**: The problem given was to develop the patent and determine if it was feasible.

- **Proof of Concept Prototype**: This was a quickly developed, simple prototype that would show understanding of the principles in the patent. It may not be of the quality level, or be reproducible, but it would add knowledge and understanding – providing confidence that the invention is possible. Samples (prototypes) would be sent daily to Land’s lab for evaluation and feedback.

- **Gates**: Controlled by Land. Approval to continue would be granted once he was satisfied with the quality.

- **Handmade Prototype**: Was made in the lab by a scientist. It may be very labor intensive, and typically the result would be small samples that would be taken nightly to Land for evaluation.

- **Pilot Scale-up**: Once the samples were approved, they would begin construction of a pilot scale production line that might make meters of product in a narrower form factor.
• **QA Testing:** The actual plant was built, and the results were tested for quality before full production was allowed to proceed.

• **Product Enhancements:** Once the product was released, promising technologies that would have taken too long to develop may continue. When they were complete, they could be integrated into the product line as product enhancements.

### B.4 A Medical Device Development Firm

#### B.4.1 Overview

This interview was conducted with a mechanical designer at a contract engineering design firm specializing in medical devices. While the projects would be product design in nature, the firm itself had a European branch that would develop new technologies for integration into customers' projects. The designer often needs to develop technologies that would later be integrated into the customer's products. In addition to the product design itself, they would also design many of the aspects of how the device would be manufactured, such as molds for injection molding the plastic parts. While they were often retained by customers for many years to design new products, the designs would be turned over to the client's own engineering teams once the product was released. Unlike Eppinger's product design process, they would have little direct access to end users, marketing information, etc.

Because of the high amounts of regulation and the expense of certification, every aspect of the design was documented (decisions, trade-offs, etc). The process described worked very well for them and problems only occurred when a piece of the process was skipped or missed.

In everything they do, they describe the basic process as: learn, design, and test.

#### B.4.2 Process

![Figure B-5: Product Design Process for a Medical Device Design Firm.](image)

Figure B-5 shows the process they use.

• **Challenge:** Design a medical product that will do XYZ.
- **Requirements**: Develop and refine a list of requirements and specifications for the proposed product.

- **Concepts**: Brainstorm ideas for approaches that could be used to solve the problem.

- **Evaluate**: Evaluate the concepts to determine pros/cons, risks and fit of each approach to solve the challenge. A scoring system is used. Multiple technologies may be selected to reduce risk by simultaneously developing alternative technologies until the risk can be dispelled.

- **Patents**: Patents would be generated for new approaches that seemed novel.

- **Concept Appraisal**: The concepts would be looked at in more detail and the level of risk would be accessed.

- **Concept Focus**: The narrowed concept is reviewed with the customer at this point.

- **Proof of Concept**: Quick prototypes would be developed to understand the risks as quickly as possible.

- **Customer Review**: This is a check-in with the customer to apprise them of risks and progress.

- **Detailed Design**: Design, how to manufacture, how to test and approximate cost determined here.

- **Verification Tests**: Functionality and reliability testing. Data is collected to characterize the system.

- **Design for Manufacture**: Similar to detailed design, but at higher volumes and with parts that are similar to the actual manufacturing parts. Life testing also is part of this stage.

- **Build Preproduction**: The real device is built using the actual parts and materials from the actual vendors.

- **Preclinical Approval**: The FDA reviews the device, test data and all documentation before the device can be tested on/in human subjects.

- **Human Testing**: Clinical trials of the device.

- **FDA Approval**: If passed, then the device is released. If the device fails, then it may go back for more clinical tests, manufacturing modifications, or even redesign.

- **Release**: The device is released to the public.
B.5  A Semiconductor Test Equipment Company

B.5.1  Overview

This case is about a struggling division of a large company that had an aging product line of semiconductor test equipment. An engineer had an idea to develop a new technology that would eventually drop testing times from two weeks to two hours. It became clear that the new product would need to be substantially redesigned and re-architected.

The technology design process started over a conversation near the coffee machine, sparking a conversation about what the next generation product could be like. Much of the technology investigation occurred before the project was “officially” endorsed by management. Even after the project was initially started, the development appeared to be stalled; although engineers were each developing technologies separately in their cubes. Management tried an assortment of approaches with little result.

One day, almost as a joke, one of the engineers took what their breadboards to a visible spot in the lab (within view of the coffee machine), stuck them in an old telecom rack and put a sign up with the product name on it. Everyone in the company laughed at the “pile of junk” as they got their coffee.

From this pile of junk, the development took off. Seeing that something was happening and not wanting to block progress other engineers brought out their breadboards and started characterizing performance and testing functionality. Soon the pile of junk was doing something. As each designer was ready, they would bring their newest prototypes for integration into the junk prototype. A few weeks later, literally overnight, the pile of junk disappeared and there was a tester. The mechanical designer had completed his chassis design and integrated the prototypes into the prototype of the case. In this case, the prototype communicated development progress and continued to evolve until the risk was low enough that they built the alpha, beta and manufacturing prototypes.

This case is described from the point of view of one of the designers. The core technologies described here became the basis for a line of product that became a leader in the industry.

B.5.2  Process

There were few formal gates obvious to the technical team. The transition between the later stages was largely dependent on progress and when parts arrived.

- *What should next generation product be?:* A conversation over coffee that turned into the technical challenge.

- *Evaluate Technologies:* Being curious, the designers started looking for and learning about approaches that could be used to solve problems in their domain of expertise.
- **Launch of Project**: Management decides we should develop a next generation tester and allocates people/resources.

- **Each engineer investigates technologies to develop.**: Each engineer further develops the approaches they have selected.

- **Bench Prototype 1-3**: Each engineer builds bench prototypes to gain knowledge about their challenge.

- **Lab Prototype Joke**: Engineer builds a “pile of junk” in the lab from his breadboard prototypes. Other engineers seeing progress and not wanting to be outdone also contribute their prototypes.

- **Lab Proto Alpha**: Mechanical designer integrates prototypes into the alpha chassis. The prototype now functionally and physically starts to resemble the end product.

- **Lab Proto Real**: The mature prototypes from all of the developers are now integrated into the lab prototype. Focus shifts from design and development to integration.

- **Manufacturing Full Prototype**: Eventually, several prototypes emerge. One is built by developers for their own use, one is built jointly by engineering and manufacturing. The third is built by manufacturing. This serves as training, knowledge transfer and verification of manufacturability between the design and manufacturing departments.

- **The Product is Released**: Becomes a leader in the market.

**B.6 A Scientific Instrument Company**

**B.6.1 Overview**

In this case I interviewed a product manager working for a company that makes specialized scientific equipment. We have worked together at several companies and he has led many
product development efforts. The company is considered a market leader and they are experts in their domain. The development team consists of conventional engineers and physicists that are providing the front-end research. They work directly with manufacturing to produce prototypes and eventually the products.

The latest project was triggered by a Small Business Innovation and Research (SBIR) grant from the National Institute of Standards and Technology (NIST). They requested a chip-scale version of their core technology. Other, larger companies were also given competing grants to develop the same technology, but they do not have the specific domain expertise to develop the miniaturized technology, but they do have the large volume manufacturing expertise.

As we have worked together on several projects at several companies in the past, much of the interview focused on the beginning of the process and some of the challenges that he has in managing management’s expectations of the technology and product development.

B.6.2 Process

Figure B-7: Development Process at a Scientific Instrument Company.

We talked about the front stage in some detail, but the later stage discussions were more general. Consequently, in the diagram the shaded section is of limited/minimal detail. The milestones listed functioned as information sharing reviews with the customer and served to obtain feedback.

- **NIST SBIR Request**: This is similar to the NASA SBIR description in section 2.5.1. Several competing grants for the same project were issued to companies with a range of differing expertise.

- **Bid/Proposal**: The company files a proposal for the SBIR project. If accepted, they are given funding to for feasibility research.

- **Research**: Initial research on the technology to determine feasible approaches. They also used this time to develop knowledge about miniaturization techniques.

- **Milestone**: An information sharing point of accomplishments to date. This would include that approaches selected and why. This is shared with the customer.
- **Scientific Paper (Output):** Since stage 1 is focused on research and this company wanted to be a "thought leader" part of the results of the initial stage were one or more scientific papers.

- **Build:** Designing and building various prototypes.

- **Milestone:** An information sharing point of accomplishments to date. This includes key learning to date, technical results, prototypes, etc. This is shared with the customer.

- **Characterize:** Understanding those prototypes. Performance, repeatability, etc.

- **Evaluate:** Were the results of the experiment good enough? If not, return to the build stage.

The following were also major stages of their process. They are shown in less detail. Each would have a design, build, test component similar to the other processes. While not discussed, typically there would be gates in between each stage.

While the bulk of the work for these stages is ordered, the initial work for later stages would overlap with earlier stages. As earlier stages were being implemented, knowledge and possible approaches for future challenges would be collected. Approaches may even be chosen before the stage is started on the schedule.

- **Reproducible:** A development process focused on making sure the results were reproducible from part to part.

- **Continuously Reliable:** A development process focused on making sure that the resulting part would operate in a consistent fashion.

- **Reduce Production Costs:** Development processes focused on reducing the cost to manufacture the parts.