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14. ABSTRACT
Science and technology policy continues to be limited by how little is known about the drivers of innovation. One barrier in conducting systematic studies is the lack of an objective measure for innovation. Patents continue to be an attractive measurement tool, but many questions remain about their comprehensiveness, relevance in different domains, and accuracy given the highly skew med distributions seen in different estimates of patent value. This study develops a new approach to measuring research and innovation performance using patents by examining the trends in patent filings over time within organizations and within technology classes. Within any single organization?s patent portfolio, the sequence of patent filings over time in any given class tends to follow one of four patterns. These within-organization, withinclass patterns are potentially signatures of specific research and commercialization approaches which have innovative connotations. This study develops several hypotheses regarding the organizational drivers of these patenting patterns and, using data from the DOD laboratories demonstrates how these patenting patterns can be used to study the relationships between the rate and type of innovation and various quantitative and qualitative organizational characteristics.

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Kay Sullivan Faith

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RAND PARDEE RAND GRADUATE SCHOOL

Abstract

Science and technology policy continues to be limited by how little is known about the drivers of innovation. One barrier in conducting systematic studies is the lack of an objective measure for innovation. Patents continue to be an attractive measurement tool, but many questions remain about their comprehensiveness, relevance in different domains, and accuracy given the highly skew med distributions seen in different estimates of patent value. This study develops a new approach to measuring research and innovation performance using patents by examining the trends in patent filings over time within organizations and within technology classes. Within any single organization's patent portfolio, the sequence of patent filings over time in any given class tends to follow one of four patterns. These within-organization, within-class patterns are potentially signatures of specific research and commercialization approaches which have innovative connotations. This study develops several hypotheses regarding the organizational drivers of these patenting patterns and, using data from the DOD laboratories, demonstrates how these patenting patterns can be used to study the relationships between the rate and type of innovation and various quantitative and qualitative organizational characteristics.

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Dedicated to Patrick E. Sullivan (1920 – 2003)
– the original Sullivan engineer –
who always believed I could and should do this

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Abbreviations

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Lab
AFRL RB	Air Force Research Laboratory Air Vehicles Directorate
AFRL RD	Air Force Research Lab Directed Energy Directorate
AFRL RI	Air Force Research Lab Information Directorate
AFRL RV	Air Force Research Lab Space Vehicles Directorate
AFRL RW	Air Force Research Lab Munitions Directorate
AFRL RX	Air Force Research Lab Materials and Manufacturing Directorate
AFRL RY	Air Force Research Lab Sensors Directorate
AFRL RZ	Air Force Research Lab Propulsion Directorate
AMC	Army Materiel Command
AMRDEC	Aviation and Missile Research Development and Engineering Center
AMSAA	Army Materiel Systems Analysis Activity
ARDEC	Armaments Research Development and Engineering Center
ARI	Army Research Institute
ARL	Army Research Lab
ARO	Army Research Office
ASD(R&D)	Assistant Secretary of Defense for Research & Engineering
CB	Chemical and Biological
CERDEC	Communications-Electronics Research Development and Engineering Center
COTS	Commercial Off-The-Shelf
CRADA	Cooperative Research and Development Agreement
CT	Computed Tomography
DARPA	Defense Advanced Research Projects Agency
DASA(R&T)	Deputy Assistant Secretary of the Army for Research and Technology
DDR&E	Director of Defense Research and Engineering
DNA	Deoxyribonucleic acid
DOD	Department of Defense
DOE	Department of Energy
DSB	Defense Science Board
ECBC	Edgewood Chemical Biological Center
EM	Electromagnetic
ERDC	Engineer Research and Development Center
FY	Fiscal Year
GPS	Global Positioning System

HHS	Department of Health and Human Services
HQ	Headquarters
HR	House Resolution
ILIR	Independent Laboratory Innovation Research
IR	Infrared
IRI	Industrial Research Institute
MIT	Massachusetts Institute of Technology
MWW	Mann-Whitney-Wilcoxon
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NAWC	Naval Air Warfare Center
NHRC	Naval Health Research Center
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NMRC	Naval Medical Research Center
NRC	National Research Council
NRL	Naval Research Lab
NSF	National Science Foundation
NSRDEC	Natick Soldier Research Development and Engineering Center
NSWC	Naval Surface Warfare Center
NUWC	Naval Undersea Warfare Center
NVESD	Night Vision and Electronic Systems Directorate
OECD	Organization for Economic Co-operation and Development
ONR	Office of Naval Research
ORTA	Office of Research and Technology Applications
PCR	Polymerase Chain Reaction
R&D	Research and Development
RDEC	Army Research Development and Engineering Center
RDT&E	Research, Development, Test and Evaluation
RIETI	Research Institute of Economy, Trade and Industry
S&T	Science and Technology
SBIR	Small Business Innovation Research
SIR	Statutory Invention Registrations
SMAW	Shoulder-Launched Multipurpose Assault Weapon
SMDTC	Space and Missile Defense Technical Center
SPAWAR	Space and Naval Warfare Systems Command
STTC	Simulation and Training Technology Center
STTR	Small Business Technology Transfer

TARDEC	Tank Automotive Research Development and Engineering Center
TVP	Technology Value Pyramid
U.S.	United States
USAMRMC	United States Army Medical Research and Materiel Command
USC	United States Code
USPTO	United States Patent and Trademark Office

Chapter 1 Introduction

> *"...we [need] to reach a level of research and development we haven't seen since the height of the Space Race… We'll invest in biomedical research, information technology, and especially clean energy technology -- an investment that will strengthen our security, protect our planet, and create countless new jobs for our people." President Barack Obama (2011), State of the Union Address*

1.1 Background

Improving the performance of the national innovation system has been and continues to be an active area of public policy.[1] While one of the prototypical examples of a national innovation program is the 1960s Apollo Program,[2] the Space Race was not necessarily the height of U.S. research and development (R&D) investment. Federal support for R&D-driven innovation has remained high throughout the last half of the 20th century and the beginning of the 21st. Since the Apollo Program's peak, total federal R&D funding has grown by 50%, from about $87 billion in fiscal year 1966 to $130 billion in fiscal year 2011 (in constant 2012 dollars).[3] This funding has supported several high-profile Big Science programs,[4] such as the War on Cancer and the Human Genome Project that focus resources on particular scientific and technological challenges, as well as national laboratories and individual research grants that aim to support national defense, protect the environment, and accelerate the economy in general.[5]

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[1] A national innovation system is the set of actors within a nation who produce or influence the production of new technologies, including private companies, universities, and government institutions, and the relationships among them (see summary in OECD (1997, pp. 9–10)).

[2] A second prototypical example is the Manhattan Project.

[3] Based on analysis of American Association for the Advancement of Science (AAAS) data table "Federal R&D Funding by Performer, FY 1955-2011", available at http://www.aaas.org/spp/rd/guihist.shtml (accessed 2/9/2013).

[4] Big Science refers to "projects that [require] large-scale organization, massive commitments of funds, and complex technological systems," (Capshew & Rader, 1992, p. 4). The origin of the term is generally attributed to Weinberg (1961) and de Solla Price (1963), although the phrase appears at least once in the 1950s as well (Capshew & Rader, 1992; Mack, 1998). The Big Science concept has been used to describe unitary crash technology programs like the Apollo Program or the Human Genome Project (e.g. Lambright (2002)), investments in large and expensive scientific instruments like the Superconducting Super Collider or the Large Hadron Collider (e.g. Office of Technology Assessment (1991)), as well as the growth in the scale of the global scientific enterprise since the 1600s (de Solla Price, 1963).

[5] The term national laboratory, as used in this sentence, covers all in-house government research facilities including those run by the Department of Energy (DOE), the Department of Defense (DOD), the Department of Agriculture, the National Aeronautics and Space Administration (NASA), and the Department of Health and Human Services (HHS). The term individual research grants refers to funding sent to university and other private-sector researchers by government agencies including the National Science Foundation (NSF), the National Institutes of Health (NIH), and those listed in the previous sentence.

Today, there is a particular focus on using federal R&D policy to speed the development of renewable energy technologies and advance the competitiveness of American industries. Ten different bills calling for a Manhattan Project or Apollo Program for green energy have been introduced in Congress since 2005,[6] and the need for more research-driven innovation to support the environment or the economy has been a theme in seven of the last eight Presidential State of the Union addresses.[7]

However, these policy problems – the need for renewable energy and competitive industries – require Big Innovation, not necessarily Big Science.[8] If Big Science is the large-scale applications of resources to obtain new knowledge,[9] then Big Innovation is the large-scale application of resources to obtain inventions which are used to solve large-scale problems. Policies that enable one do not necessarily advance the other.

Most science and innovation policy-making assumes that if more resources are provided to science, particularly university- and laboratory-based basic science, more economically and socially significant innovations inevitably result (Averch, 1985; Jensen, Johnson, Lorenz, & Lundvall, 2007; Stokes, 1997).[10] Yet a number of unanswered questions remain about how this chain from laboratory research to implemented innovation actually works. For example, how much basic research is sufficient to supply the rest of the research and development pipeline with fundamental knowledge?[11] How can the rate at which knowledge is implemented in inventions be increased? What is the relationship between the goals of a national innovation program and the most effective organizational format for the program?[12] Furthermore, must all research organizations endeavor to be radical innovators or should some focus on incremental advances of the state-of-the-art?

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[6] Relevant bills identified by reading summaries of bills returned by a search for the terms "Manhattan Project" or "Apollo Program" in the Congressional Record at the Library of Congress. See for example (U.S. House of Representatives, 2007a, 2007b, 2008a, 2008b, 2008c, 2008d, 2009, 2011; U.S. Senate, 2005, 2009)

[7] Based on keyword-in-context analyses of the terms "innovation" or "innovative" in the C-SPAN State of the Union transcript archive

[8] Mack (1998) notes that "the confusion between science and technology starts not in the minds of historians writing about the projects but in the minds of the policymakers and scientists who shaped and advised these projects."

[9] See footnote 4.

[10] The cited books provide evidence of this trend in policy-making; they do not necessarily agree that it is the best approach.

[11] As former director of the White House Office of Science and Technology Policy, John Marburger, noted, "Perhaps the U.S. is spending as much on federal R&D as it needs to, perhaps more, perhaps less. Undoubtedly it could be spending it more wisely," (Marburger, 2007, p. 29).

[12] Nor is there even consensus on how well past national innovation programs have performed. For example, some argue that the War on Cancer has delivered over a trillion dollars in value to cancer patients through higher survival rates (Sun et al., 2009), while others point out that those gains have been restricted to only a few types of cancer, resulting in no overall gains for the population (Faguet, 2005). A recent line of criticism argues that an overly conservative proposal review process at NIH has blocked revolutionary research proposals that could have delivered larger breakthroughs (Begley, 2008; Faguet, 2005; Leaf, 2007; Ness, 2010).

Despite a vast scientific literature that discusses innovation,[13] the understanding of innovation remains, as John Kao put it, in a pre-Copernican state:

> *"It's as if we don't yet know which heavenly bodies revolve around which others. We don't even know where all the planets are located, nor do we have a viable theory of planetary motion. We rely on metaphors and images to express an as yet imprecise and unsystematic understanding." (Kao, 2007, pp. 16–17)*

Alternately, the current understanding of research and innovation could be called pre-Newtonian. Thomas Kuhn wrote of pre-Newtonian physics,

> *"Being able to take no common body of belief for granted, each writer… felt forced to build his field anew from its foundations. In doing so, his choice of supporting observation and experiment was relatively free, for there was no standard set of methods or of phenomena that every… writer felt forced to employ and explain." (Kuhn, 1962, p. 13)*

Applying either metaphor, the challenge for those who would make innovation policy a more deliberate tool is to identify the key variables, and the relationships among them, that govern the innovation process. A logical place to start is to define innovation and determine a way to measure it. With no common definition of innovations, researchers are currently relatively free to choose their own supporting observation and experiment.[14] A standard measurement for innovation would enable researchers to compare different organizations along this measure and isolate factors that seem to be correlated with higher or lower levels of innovation. With repeated testing, these approaches could become the standard set of methods that lead to a systematic understanding of the innovation process.

1.2 Approach

> *"In this desert of data, patent statistics loom up as a mirage of wonderful plentitude and objectivity. They are available; they are by definition related to inventiveness, and they are based on what appears to be an objective and only slowly changing standard. No wonder that the idea that something interesting might be learned from such data tends to be rediscovered in each generation." (Griliches, 1990)*

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[13] For a sense of scale, consider that a google scholar search for the keyword "innovation" on 10/29/2012 returned "About 2,360,000" hits.

[14] For example, NSF's 2008 Science of Science Policy Roadmap recommends measuring innovation as an outcome of scientific research, but it neither defines innovation nor states how such a measurement could be done (Valdez & Lane, 2008). The Oslo Manual, the Organization for Economic Co-operation and Development's (OECD) guide to surveying firms about innovation, defines a technological product innovation as a product that is new (to the firm) and has been offered for sale. The innovation may be new because it uses a completely new technology or because it combines existing technologies in a new way to achieve new functionality. However, innovation measurement techniques descried in the Oslo Manual are, perforce, focused on surveying firms directly about their innovative activities.

To move forward the development of a standard measure of innovation, this dissertation develops several new patent-based tools for monitoring the performance of research organizations and identifying potential innovations among their outputs. The patent-based measures discussed in this dissertation can be used to identify specific innovations produced by research groups within a laboratory, to monitor the fit between the laboratory's outputs (both innovative and non-innovative) and policy guidance provided by the parent agency, and to study the impact of organizational mission, culture, and practices on the production of innovations. The results of this research are a first step towards developing a consistent, quantitative, and innovation-relevant measure of research laboratory performance.

Departing from the citation-count approach to valuing patents, this study instead builds on an emerging line of work that examines relationships between the accumulation of patents within specific technology classes over time and the innovativeness of the filing organizations.[15] In particular, this study is indebted to the conceptual foundations established in the largely unpublished work of Chris Eusebi. Eusebi (2011) analyzes the rate and sequence of patenting in technology classes and subclasses to determine which organizations were leading patentees early in the life of an emerging technology. This study builds on Eusebi's idea that the trends in patent filings within technology classes and subclasses over time contain information about the innovativeness of the inventors. However, rather than examining trends in the entire patent record, this study focuses on trends by technology class within the patent portfolios of individual organizations.

Not including the absence of patents, this study finds four distinct patterns of patenting that occur within single organizations' patent portfolios when those portfolios are examined by technology class and application year. At least two of these patterns can be logically associated with the emergence of an innovation. Using the Department of Defense (DOD) in-house laboratories as case studies, this dissertation pursues three hypotheses about the relationships between these patenting patterns, innovation, and evaluating government research laboratories.

The first hypothesis driving this work is that an organization's patenting patterns reflect its research and commercialization strategies. Each of the basic patenting patterns is therefore an indicator of a particular behavior on the part of the research organization. For example, when an organization produces a discovery that they believe is novel and has the potential to be widely used there is a corresponding spike in their patenting behavior reflecting the lab's attempt to protect the core invention and as many associated technologies as possible. Examining in detail the technologies in which these patterns occur provides insight into the organization's research strategy and identifies the technology areas in which the organization thinks it can be influential.

However, an organization's belief in the innovative usefulness of their technology will not necessarily be realized. There are a number of reasons why a technology may not live up to its

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[15] The terms technology classes and subclasses refer to the USPTO's technology classification system. This system is explained in Chapter 2 and Appendix C.

inventor's expectations. The second hypothesis underlying this work is that, regardless of a laboratory's own evaluation of their work, the relative timing of an organization's patent filings compared with the activity of other inventors in the same field can be an independent indicator of innovativeness. A number of authors have observed that the cumulative number of patents issued in a technology area often follows an s-curve (e.g. see Eusebi & Silberglitt (N.d.), Ernst (1997)). Eusebi (2011) hypothesizes that organizations that have patents in the early part of the curve are innovators in the sense that they were leaders in a technology that eventually became widely pursued. Building on Eusebi's approach to identifying innovators in the patent record, this dissertation will explore the ways in which the relative timing between an organization's patenting pattern and the technology class's overall patent s-curve may be an indicator of innovativeness on the part of that organization.

The rate at which an organization employs certain patenting patterns and the rate at which those patents lead or lag the rest of the field may be limited by the organization's mission and research practices. The third hypothesis of this study is that the distribution of each type of patenting pattern in an organization's patent portfolio, the technology areas in which they occur, and whether that pattern occurs early or late in the overall s-curve are all related to the organization's mission, research and commercialization practices, and culture. Statistical analyses of patenting patterns within and across organizations can therefore relate organizational mission and culture with types and rates of innovation.

1.3 Document structure

The next chapter of this dissertation, supported by Appendix A and B, continues the introduction by providing a general background. Chapter two describes in more detail the difficulties in measuring public-sector research innovativeness and explains the emerging approaches to analyzing patent trends by technology class, which is the foundation for the methods used later in this study. Chapter three defines the common patent patterns and describes the data sources and methods used to identify these patterns in organizations' patent portfolios. Chapter four develops a theory of the research activities that produce each pattern, using example cases from the DOD laboratories to illustrate the points, and explains how the patenting patterns can be indicators of innovation. Chapter five presents a qualitative and quantitative example of using the overall frequency of patenting patterns in an organization's portfolio to study the missions, cultures, and practices that contribute to research innovation. Chapter six summarizes this study.

1.4 Note on sources

Many individuals throughout the DOD laboratory system contributed interviews, background documents, and written comments for this study. To preserve their anonymity, all information obtained from these sources will be referenced as "Personal Interview, 2012".

Chapter 2 Background

In order to advance the study of factors that affect the production of innovations, this dissertation develops several new patent-based tools that are suitable for monitoring the production of innovations by public research organizations. Following the broad definition of innovation used in the Oslo Manual (OECD, 2005) and early patent studies (e.g. Schmookler (1966)), this study defines an innovation as any novel, non-obvious, and used product. This study focuses on use in the definition of innovation because the transfer and use of research products is a key part of the mission of government research organizations[16] and because current research evaluation approaches have difficulty measuring the actual utility of research products.

Patents, which are often viewed in the same framework as journal articles as a count of knowledge outputs, can also be interpreted as indicators of inventions that are released to the market and, hopefully, used. The main difficulty in interpreting patents in this manner is confirming actual use. While there are a variety of approaches for estimating a patent's value (summarized in Appendix B, note that value is not necessarily synonymous with use), this study draws from an emerging line of research that analyzes patents based on their positions along technology maturation s-curves.

This background chapter discusses the gaps in existing research evaluation measures (as applied to the production of innovations by public research organizations), why use is a key aspect of innovations, and how location along the technology maturation s-curve can be a proxy for patent value and use. Section 2.1 reviews the many approaches that have been used to evaluate research organization performance and the challenges of finding measures that are relevant to military R&D outcomes. Section 2.2 defines innovation as used products as employed in this study. Section 2.3 explains the occurrence of s-curves in the patent record and the potential usefulness of patents as an indicator of innovation. These sections are supplemented by additional literature reviews in Appendix A and Appendix B.

2.1 Overview of current research performance measures

When evaluating the performance of a research organization, there are at least a dozen possible approaches an analyst can choose. While the most appropriate approach will logically depend on the research question, the type of organization being examined, and the data available, those who study and evaluate research organizations are relatively free to select their own measures "for there [is] no standard set of methods or phenomena that every… writer [feels] forced to employ and explain," (Kuhn, 1962, p. 13).

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[16] The mission of the DOD laboratories to "discover new phenomena that may have military value" (Coffey, Lackie, & Marshall, 2003), implies that the laboratories' outputs must be transferred to and used by the military.

The list of possible approaches could be considerably longer than a dozen if the question is sufficiently broad. For example, while considering metrics to include in the Technology Value Pyramid (TVP) approach to R&D management, Industrial Research Institute (IRI) researchers uncovered over 1,000 different R&D metrics in a range of texts going back 400 years to when the "princes of Europe were sponsoring R&D… [and] asking the question: Are we getting our money's worth?" (Parish, 1998).

Focusing on more recent applications, Ruegg & Jordan (2007) identify 13 general approaches to R&D evaluation "that have proven useful to R&D program managers in [U.S.] Federal agencies," (Ruegg & Jordan, 2007, p. ii). These methods can be used independently or in combination.

1. Peer Review/Expert Judgment – evaluating research programs or projects based on feedback from individuals who are experts in that area of study
2. Monitoring, Data Compilation, and Use of "Indicators" – on-going tracking of inputs, outputs, and outcomes; a primarily quantitative variant of benchmarking (#5)
3. Bibliometric Methods: Counts and Citation Analysis – analyzing numbers of publications, patents, citations they receive, and networks among them
4. Bibliometric Methods: Data Mining – analyzing information, beyond counts or networks, contained in various documents
5. Benchmarking – comparing research programs/projects to each other or to a common standard
6. Technology Commercialization Tracking Method – linking commercialized products to contributing research
7. Benefit-Cost Case Study – comparing programs/projects based on cost and quantified outcomes
8. Spillover Analysis – estimating the public and private value of program/project outcomes
9. Network Analysis – analyzing relationships among researchers based on a variety of records
10. Historical Tracing Method – tracking the historical antecedents to or the ultimate impacts of a research discovery
11. Econometric Methods – using mathematical models to explore potential causal relationships between programs/projects, their characteristics, and their outcomes
12. General Case Study Methods – using narratives supported by other data to explore program/project processes and impacts
13. General Survey Methods – collecting data on research projects/programs directly from participants or other stakeholders

These evaluation approaches, their uses, and their limitations are summarized in Appendix A. A good metric should be relevant to the mission of the organization, credible, "tolerably easy to calculate," and understandable (Parish, 1998). While each approach is best suited to certain types of questions, and no one approach is likely to be appropriate in all situations, these common approaches are not well suited to analyzing the performance, particularly the innovative performance, of DOD laboratories.

Consider, for example, four challenges with using two of the most common science-evaluation tools, bibliometric measures and peer review, to evaluate the innovativeness of public research organizations such as the DOD laboratories. First, bibliometric measures, when interpreted as measures of knowledge generation, are not necessarily relevant to the missions of the DOD labs, particularly their mission to transfer discoveries and inventions to users. Second, using bibliometric outputs as part of a monitoring scheme for knowledge and invention transition results in an incomplete picture because many transfers occur through unobserved interpersonal contacts. Third, current approaches to valuing patent and publication counts based on their utility are better for measuring average performance than detecting innovative performance. Fourth, peer reviews of organizational process or outputs, which may be better at capturing factors relevant to a variety of missions, are inherently subjective and different sets of experts can and have produced contradictory results when evaluating the same organization. The following subsections expand on these four issues.

2.1.1 Relevance of bibliometrics to DOD research goals

Bibliometric measures such as publication and citation counts are good performance measures for universities whose primary mission is research excellence. However, publication and citation counts say very little about the performance of industrial or government research labs whose primary mission is to be relevant to their customers. Consider the missions for DOD research labs spelled out by the Director of Defense Research and Engineering (DDR&E) in 1961 (Coffey et al., 2003):

1. discover new phenomena that may have military value
2. communicate the needs of the military to the broader scientific and technical community
3. provide objective scientific and technical advice to the managers of research, development, test, and engineering, (RDT&E) contracts
4. educate military planners on the technical art of the possible
5. enhance the technical training of military officers by providing laboratory research experience

An evaluation of a DOD laboratory that uses academic publication counts and impact factors is comparing the lab's ability to generate standard science outputs to that of other organizations that focus on academic publication outputs (e.g. research intensive universities). But do publication counts fully evaluate Brown's first mission for DOD labs: discover new phenomena that may have *military value*? One could argue that high quality science will naturally yield military-relevant discoveries, but this assumption should be explicitly developed in any assessment that relies on academic bibliometric measures.[17]

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[17] Furthermore, what measure tracks whether military planners have been sufficiently educated on the art of the possible?

2.1.2 Inputs, outputs, and unobserved knowledge transition

An additional challenge for evaluating transition-focused programs based on their inputs or their bibliometric outputs is that important transition activities occur without a written record. The issue was explored in detail in the 1975 National Institute of Standards and Technology (NIST) research productivity experiment and has been observed in several historical tracing studies of significant innovations.

In 1975, NIST (then called the National Bureau of Standards) conducted an experiment to determine which R&D productivity measures were appropriate for the type of work performed at NIST (J. T. Hall & Dixon, 1975). The study made a critical distinction between *performance* measures and *productivity* measures. Publication counts had become standard individual and institutional performance measures, the study report noted, but had little to say about productivity if productivity was defined as progress toward organizational goals. NIST's primary research goal was impact through the transfer of knowledge to those who could use it. The NIST experiment was searching for a tolerably easy way to evaluate programs based on knowledge-transfer impacts and potentially improve their performance.

The NIST experiment tracked human capital and financial inputs, conducted detailed observations of work processes, and tallied outputs including publications, devices, and software generated, but they found that the research process was so idiosyncratic that input levels were poor predictors of output levels. Furthermore, the actual rate of knowledge transfer, the outcome of interest, was unrelated even to the volume of outputs (J. T. Hall & Dixon, 1975).

A major measurement challenge for NIST was that knowledge transfer could occur without physical outputs. Other studies have reported similar phenomena. In DOD's Project Hindsight, 45% of science knowledge transfers were the results of informal personal contacts. In engineering fields, more than two-thirds of knowledge transfers tend to occur through personal contact ("Technological Forecasting Lessons from Project Hindsight" cited in Hall & Dixon (1975)). Allen (1984) observed similar results in his study of communication patterns in government research contracts. In NSF's TRACES study, informal knowledge transfer mechanisms were important to the successful development of 9 out of 10 societally important technologies (IIT Research Institute, 1968).

2.1.3 Measuring average versus innovative performance

Furthermore, many outputs have little impact. Both patents and publications have highly skewed distributions when their value is measured as either citations or, in the case of patents, commercial value, meaning that most patents are found in the low-value end of the scale (B. H. Hall, Jaffe, & Trajtenberg, 2005; Harhoff, Narin, Scherer, & Vopel, 1999; Scherer & Harhoff, 2000; Trajtenberg, 1990). The value distributions are so skewed that value-weighted bibliometric

statistics are more likely to measure a lab's ability to produce average-value outputs than its ability to produce high-value outputs (Scherer, 1965).[18]

2.1.4 Consistency of peer reviews in evaluating research processes

Most studies of government labs do not even attempt to track quantitative performance measures, instead relying on expert reviews of project inputs, processes, and outcomes. Indeed, expert reviews are the standard approach to evaluating public research programs. In a review of evaluation literature for the Department of Energy, Jordan & Malone (2001) note that the consensus in the literature is that "peer review is the most effective method for evaluating the quality and value of fundamental research," (p 11). COSEPUP (1999) states, "The most effective means of evaluating federally funded research programs is expert review," (p 5). In addition, Harvey A. Averch (2004) argues that expert reviews are the best way to assess programs that face high degrees of uncertainty, particularly when

- "A public agency has been operating a "program" for a number of years, and it cannot be certain about the effective quantity or quality of inputs it has bought during those years, and there is no clear way to measure these;"
- "The expected "benefits" or "outcomes" of the program are highly uncertain in the present or must occur in the future."
- "The agency does not know with precision whether decision-relevant outcomes can be attributed to the inputs and the design of the program." (p 293)

However, if, as found in the 1975 NIST study, there are no demonstrable links among research inputs, processes, outputs, and mission-relevant outcomes, then when reviewers draw conclusions about an organization's performance based on the organization's inputs or processes, rather than by considering the actual outcomes, they are basing those conclusions on their own preferences rather than on evidence.[19] Not only can such reviews produce contradictory results, but there is also no guarantee that any recommended changes to the organization will actually be effective.

Most studies of the DOD labs ask panels of experts to judge whether descriptions of the labs' processes and inputs match the experts' expectations for a high-quality government research laboratory. While these studies are staffed by individuals with extensive experience managing research programs, the bases for their conclusions can be unclear and different panels of experts sometimes report contradictory findings.[20] For example, the 2009 JASONs study of National

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[18] Scherer (1965) actually estimates that the distribution of patent values does not have a finite mean or variance. This means standard statistical inference techniques will produce biased estimates of patent values. Taleb's Black Swan theory provides another view of this long-tailed distribution problem with an emphasis on the unpredictability of such extreme outliers (Taleb, 2010).

[19] For example, G. B. Jordan, Streit, & Binkley (2000) find that researchers employed in different types of work (e.g. more basic or more applied) prefer different types of work environments.

[20] Recent expert studies of the DOD labs include the Defense Science Board study of DOD Basic Research (Defense Science Board, 2012), the JASONs study of the same (JASONs, 2009), the National Defense University

Security S&T (JASONs, 2009) found that DOD basic research was becoming too tied to short-term applications. However, the 2012 Defense Science Board (DSB) study of Defense Basic Research (Defense Science Board, 2012) disagreed, finding that DOD basic research was appropriately targeted and in good health.[21] Neither study directly addresses whether the defense basic research program is helping to meet warfighter needs.

2.2 A DOD-relevant definition of innovation as use

In order to focus this review on laboratory outputs and outcomes that are relevant to warfighter needs, this study employs a definition of innovation based on use. After all, the DOD laboratory mission to "discover new phenomena that may have military value" (Coffey et al., 2003), implies that the laboratories' outputs are transferred to and used by the military.

Borrowing from Schmookler (1966), this study defines an innovation as a concrete product that is widely used, novel, and non-obvious. This definition provides guidelines to separate the non-innovative - an unimplemented idea, a product with promise but few users (e.g. the flying car) - from the innovative - the iPhone and its user interface, stealth fighter/bombers.

General inventions, as opposed to innovations, fail one of the three criteria; they are either not widely used, not novel, or are obvious. For example, Microsoft developed and sold the Tablet PC in the early 2000s (Fontana, 2010), but it has not become as widely used as the Apple iPad. Android tablets have captured significant market share,[22] but patent infringement lawsuits (e.g. Apple v. Samsung (Lowensohn, 2012)) have held that they are derivatives of the iPad (i.e. Android tablets are less novel and therefore less innovative than the iPad).

Some may object that this definition of innovation conflates research and development, manufacturing, marketing, and the fickleness of the market. That is actually the point. The most innovative organizations, according to this definition, are those that understand what their customers need and want and execute their research, development, and manufacturing functions to deliver it.[23]

In the context of the DOD labs, this study's definition of innovation focuses on the labs' ability to both discover new phenomena that may have military value and also their ability to

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series by former laboratory executives (Chait, 2009; Lyons, 2012; Lyons & Chait, 2009; Lyons, Chait, & Willcox, 2009; Lyons et al., 2005), and the 2010 Decker panel on improving Army Basic Research (Decker et al., 2010).

[21] Other analysts have identified issues of reviewer bias in other settings. G. Jordan & Malone (2001) observe that reviewers may display favoritism to certain researchers or lines of research or respond negatively to research that contradicts their own work. Bias can also arise from the information a program's staff chooses to reveal. Averch (2004) emphasizes that reviewers should carefully judge the credibility of an organization's claims and be particularly skeptical when failures are blamed on shortages of money or personnel.

[22] For market shares of Android, Apple (iOS), and Microsoft devices see IDC (2013).

[23] As Peter Drucker wrote, inventions without a focus on need and users are like Da Vinci's drawings – brilliant ideas that are never adopted; inventors who do not systematically consider customer requirements miss opportunities or misinterpret the need (Drucker, 1985).

connect with program officers and contractors who can bring these innovations to the field. However, identifying use can be particularly challenging for the products of defense research since the idea must pass through many different organizations on its way from bench to field,[24] and the ultimate use may be classified.

2.3 Patent trends as an indicator of innovation

Admittedly, deciding when an invention crosses over into innovative territory, as defined above, is a subjective judgment. In theory, patent data can help make this decision more objective.[25] To receive a patent, according to U.S. patent law, an invention must be new, non-obvious, and potentially useful. The definitions of these terms are laid out in the law, answering the question of how new, useful, and non-obvious an invention must be to qualify as an innovation. Specifically, an invention must not be known in the public domain more than a year before the filing date, must be implementable, and must be not obvious "to one of ordinary skill in the art."[26] However, there are certainly trivial patents that do not meet the connotation of innovation. The distribution of patent values is highly skewed (Scherer, 1965); most patents are commercially worthless, some are even 'wacky' (Czarnitzki, Hussinger, & Schneider, 2011), and only a few provide significant returns to their owners.

As described in Appendix B, several approaches have been developed to measure the value (for different definitions of value) of any given patent and distinguish the significant patents from the trivial. For example, the number of citations received by a patent from other later patents (i.e. forward citations) has been used as a proxy for a patent's commercial value (which is concept similar to degree of use) or as a proxy for a patent's originality (i.e. novelty). Like the research evaluation methods described in Appendix A, these measures of patent value have their uses and their limitations. However, thinking about patents in terms of a series of actions rather than as discrete and independent points can yield additional insights into their relative value and the organizational processes that led to their creation.

The measures developed in this study start from Eusebi's insight that the accumulation of patents in specific technology classes over time is the result of many organizations making bets on the importance of future technologies (Eusebi & Silberglitt, n.d.).[27] Collectively, these bets and the response of the patent office to a technology's popularity result in an s-curve-like growth

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[24] as opposed to an industrial research lab which may be more closely connected to its related manufacturing and marketing departments

[25] Patenting is not the only way in which DOD labs transfer technologies to users. It may not even be their primary method of technology transfer, but patents may be representative of a lab's general research focus. This issue of patents and representativeness is discussed in section 3.3 and in section 3.7.

[26] The patent examiner being the person whose skill in the art matters the most. For more information on patent law, see the Bitlaw website which provides non-technical summaries with links to official sources.

[27] See Appendix C for an overview of the USPTO technology class system.

of patents that corresponds with the maturation of that technology over time. As the following sections explain, patents that are filed near the take-off inflection point of a technology s-curve are thought to have a larger commercial potential, and to generally be more "innovative", than those filed later (Eusebi, 2011). This study expands this line of work by developing hypotheses about the meaning of analogous patterns within single organization patent portfolios, and comparing those single-organization curves to the s-curve trends in the field as a whole.

2.3.1 S-curves in the cumulative growth of patents per technology class

The cumulative number of patents assigned to a technology class over time often follows an s-shaped curve. Technology class here referrers to the U.S. Patent Classification System codes. The U.S. Patent Classification System is a hierarchical system of classes and subclasses (usually designated using numeric codes separated by a slash in the form "class number/subclass number") used by the U.S. Patent Office to identify similar patents and patent applications. Every patent is assigned to one primary and any number of additional (called cross reference) class/subclasses. Together, these assigned class/subclasses fully describe the technology and applications areas covered by the patent's claims (see Appendix C for more details). [28] The cumulative number of patents assigned to a given class/subclass often begins to resemble an s-curve over time.

"S-curve" is the generic term for any of several of functions (e.g. the logistic function, Gompertz function, or many cumulative probability distribution functions) that, when graphed, look like tilted S'es (Figure 2.1). The curve starts flat, and then at some point – the point of "take off" – the slope of the curve begins increasing at an increasing rate (positive second derivative). Next, at the inflection point, the slope begins to decline at an increasing rate (negative second derivative) until it becomes flat again as it approaches the curve's maximum value.

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[28] "[A patent's] claims state, in technical and precise terms, the subject matter of the invention (or discovery), as well as its purpose, principal properties, how it operates and the methods it employs," (Strumsky et al., 2012, p. 4).

Figure 2.1 Generic s-curve
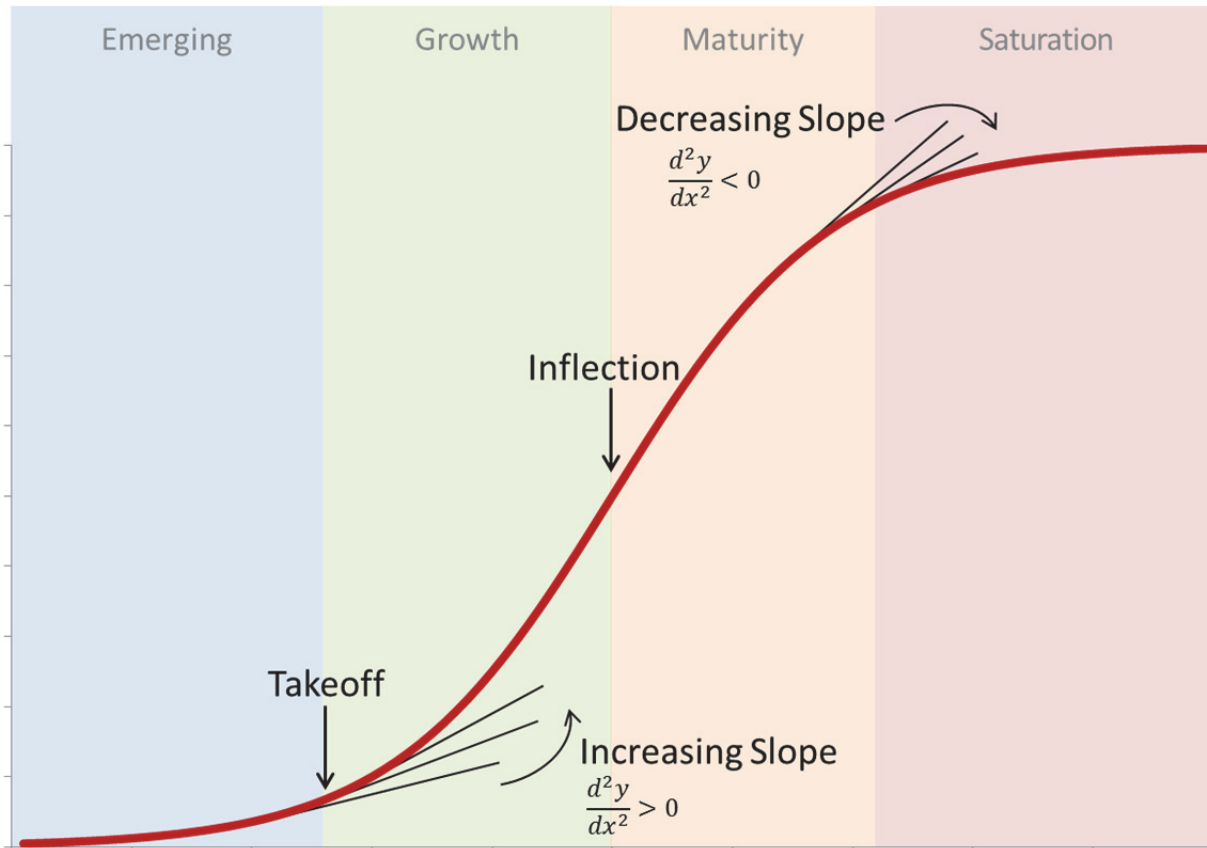
This pattern can be described in terms of regions. Different authors use different names for the various regions. Some authors identify six regions, including birth (at the far left) and death (at the far right). This study borrows a four-region terminology from Chen, Chen, & Lee (2010) and Ernst (1997). The first region, prior to takeoff, is called the Emerging region. The period of increasing growth (positive second derivative) is the Growth region. The period of decreasing growth (negative second derivative) is the Maturity region. The final period, as the curve flattens toward its maximum value, is called the Saturation region.

Figure 2.2 shows the cumulative number of patents filed (top line) in Vehicle Navigation Using Global Positioning Systems (GPS) (class 701/213) between 1985 and 2010. Class 701/213 was selected for this illustration because it is a particularly clean case of an s-curve in the patent record. This example first appeared in Eusebi (2011).

The filled series in the lower portion of Figure 2.2 shows the number of new applications (which ultimately resulted in issued patents) each calendar year. The top series, showing the cumulative number of patents, has an s-curve shape. Emerging, Growth, Maturity, and Saturation regions are also approximately labeled in Figure 2.2. The number of patents filed each year begins increasing around 1994, the year that GPS code was released to the general public. Presumably as a result of this newly available technology, the cumulative number of patents filed

"takes off"; its slope begins increasing at an increasing rate. By the mid-2000s, this technology area reaches its inflection point, and fewer new patents are granted. The cumulative sum line begins to flatten, and by about 2006 has leveled off at a maximum of almost 2000 patents total filed in this technology area.

Figure 2.2 Illustrating patent s-curves in a sample technology class/subclass
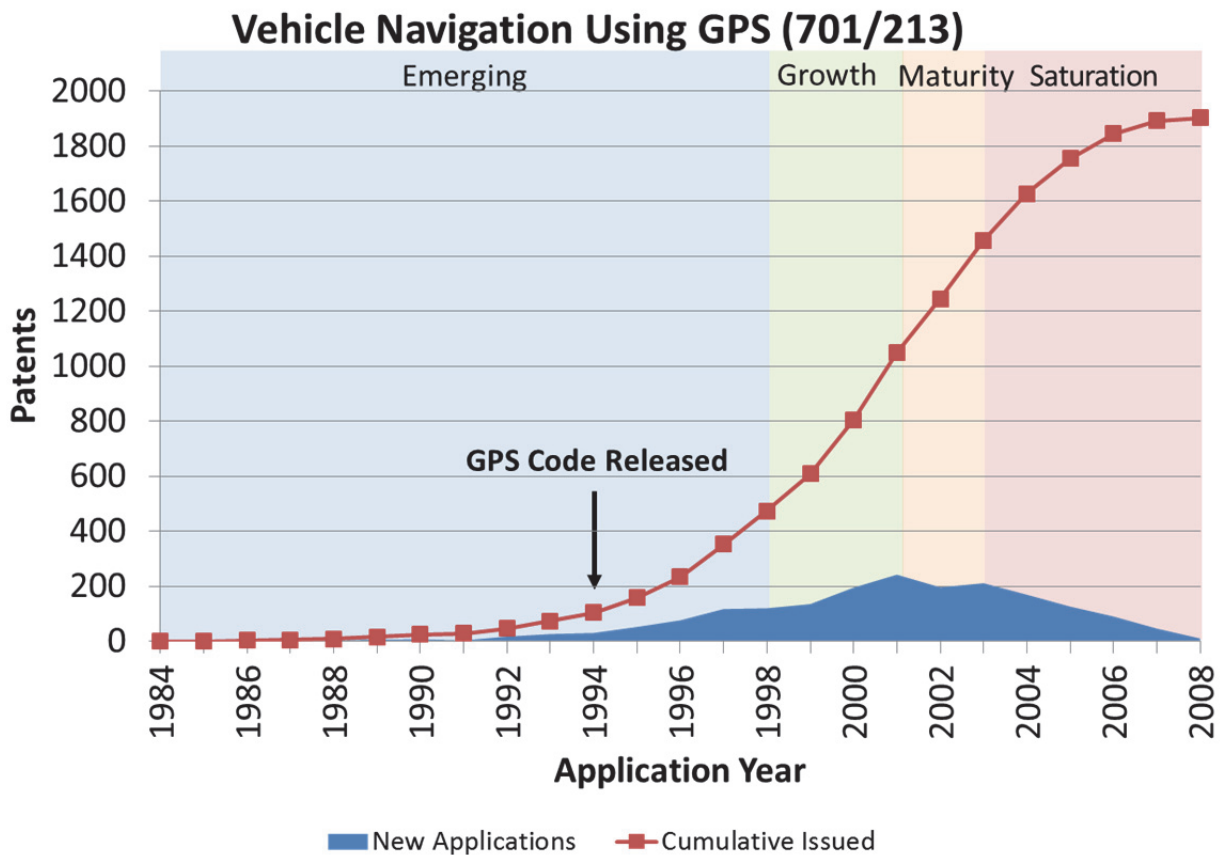
Source: Analysis of U.S. Patent and Trademark Office (USPTO) 2009 patent grant bibliographic data file

Analyzing the cumulative number of patents granted in each class/subclass in the USPTO system shows that this s-curve-like growth is common, although there are exceptions.[29] Some classes seem to have multiple growth phases resulting in cumulative sum curves that look like

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[29] Early exploratory work for this study used statistical analysis software to fit a logistic equation to every class/subclass cumulative sum series in the USPTO 2009 patent grant bibliographic data file. Of the 152,128 class/subclasses that appeared at least once in the data file, this method obtained parameter estimates for 106,903 class/subclass trends (70%); 45,225 class/subclass cumulative sum curves had a shape too different from the logistic curve or had too few observations to obtain parameter estimates using R's "nls" package. This exercise should not be taken to mean that the cumulative number of patents in a technology class necessarily follows a simple logistic curve. There are a number of other possible functional forms. See Modis (2007) for cautions regarding attempting to fit s-curve-like data to a logistic function.

multiple "loglet" curves (Meyer, Yung, & Ausubel, 1999). For example, multiple wavelength laser arrays (see left side of Figure 2.3) seem to have grown in two phases. The first burst of work occurred in the mid-1980s; in the 1990s, there was very little activity in this field; and in the 2000s patenting in the class took off again. Other classes have either yet to take off or reached maturity before the start of the data file[30] and therefore have flat cumulative sum curves (see right side of Figure 2.3). In the second example, there was some activity in solar-pumped lasers in the 1970s, at the very beginning of the dataset, but only three patents have been filed in the class since 1980.

Figure 2.3 Non-s-curve technology class examples: multiple "loglets" (left) and flat (right)
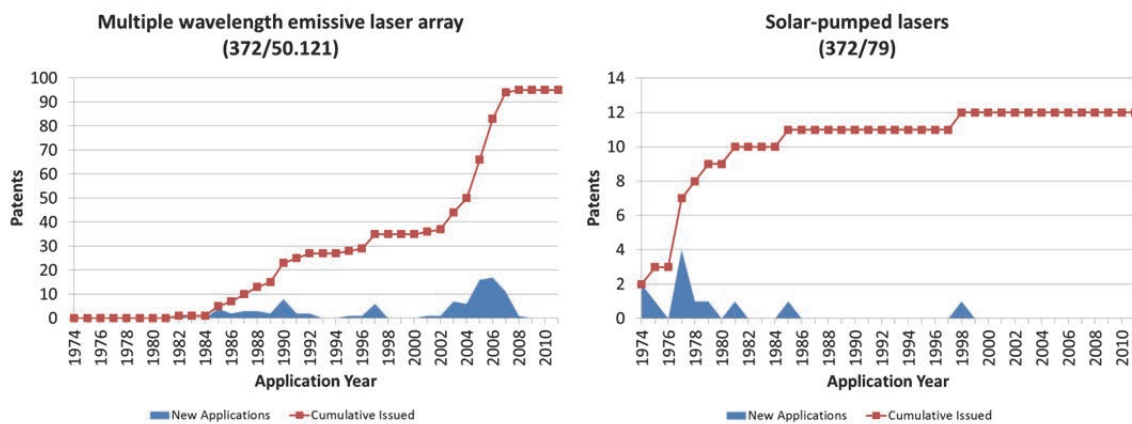
Source: Analysis of USPTO 2009 patent grant bibliographic data file

Why does the growth in patents per class follow an s-curve?

S-curves describe growth in a self-limiting population (Kucharavy & De Guio, 2007; Modis, 2007). The population of a species competing for resources, either with another species (e.g. predatory-prey) or with its environment, follows an s-curve (Modis, 2003, 2011). The market shares of competing technologies can be modeled using these s-curve population dynamic models (Dattee, 2007; Meyer et al., 1999; Pistorius & Utterback, 1997). The diffusion of ideas or the spread of disease from the early adopters to the rest of the susceptible population also follows an s-curve (Bettencourt, Cintrón-Arias, Kaiser, & Castillo-Chávez, 2006; Rogers, 1995), as do improvements in the performance of a class of technologies (Asthana, 1995; Christensen, 1997; Foster, 1986).

The population of patents in a technology class is limited by two factors: inventors' collective productivity in the field and patent examiners' collective willingness to accept the novelty of a new claim. At first inventors produce few patentable discoveries in the field and few patents exist in the class. At some point a technology area begins to "take off" and increasing

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[30] The USPTO 2009 patent grant bibliographic data file which contains patents granted since 1976.

numbers of patents are applied for and awarded in that class. As the technology area becomes mature, three complementary forces slow the rate of growth in patents: one, additional patent applications contain fewer and fewer things that are sufficiently novel to merit a patent, and examiners accept fewer patent applications in that class (Eusebi, 2012); two, diminishing returns to research reduce the number of patentable discoveries in that field that can be easily produced;[31] and three, less successful firms exit the market (see cases studies in Foster (1986) and Christensen (1997)) reducing the number of inventors still searching for additional breakthroughs.

2.3.2 Location on the S-curve as an indicator of innovativeness

The business strategy literature suggests that organizations inventing in the growth part of the technology s-curve are more innovative than others in the sense that they are creating novel technologies that are likely to be used in the marketplace. More specifically, one stream of the business literature recommends a company carefully analyze the rate at which a technology is improving (whether it is in the growth or maturity phase) when deciding whether to invest in incremental improvements, invest in a totally new technology direction, or acquire a possible competitor. If the technology is still growing, the company may want to invest in improvements itself or acquire a competitor that is threatening to introduce an incremental improvement. If the technology is mature, then it is better to invest in new directions and watch out for disruptive competitors that are operating on the growth part of a new s-curve. This kind of tracing can be done by carefully examining the performance characteristics of technologies, as in Christensen (1997), Asthana (1995), or Foster (1986), or by tracking the accumulation of patents within technology classes as demonstrated in Eusebi & Silberglitt (N.d.), Chen et al. (2010), Andersen (1999), or Ernst (1997).

Turning this recommendation around, because they represent the work of someone who moved on a profitable technology area before it was obviously "hot", patents that are filed before the technology takes off are more innovative than ones that are filed when the technology area is mature. Early patentees are leaders in a field that many other inventors later recognized as an important area for investment. Those early patents were novel and, in a general sense, were eventually widely used as others built on or imitated them.

However, it is possible to be too early as well as too late.[32] Patents filed in the far left tail of the curve may just be "wacky" – trivial or useless combinations of distantly related technologies (Czarnitzki et al., 2011). Even if they represent useful combinations of technologies, early patents may be "before their time." For example, the patent may include technologies that cannot

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[31] Foster (1986) describes several cases in which an industry was reaching the physical limits of a technology (e.g. the theoretical maximum chemical yield or the maximum strength of a material) yet continued to spend significant sums on research with very little resulting improvements in performance.

[32] "It's always about timing. If it's too soon, no one understands. If it's too late, everyone's forgotten." – Anna Wintour (Cordero, 2011).

yet be manufactured at an affordable rate. Alternately, the early market for the technology may be small compared to its later size limiting the early technology's adoption and other inventors' awareness of it.

Therefore the most innovative patents in a technology class are probably among those that are filed near the point of takeoff in the late-emerging or early-growth parts of the s-curve.[33] These patents represent research done around the time inventors figured out how to make the field a success and before the technology became mature and diminishing returns to research resulted in only incremental discoveries. Following this argument, the most innovative research organizations are those that tend to have patents in the late-emerging and early-growth parts of technology classes with s-curves.

S-curve example in military technology

This theory seems to be valid for military as well as commercial technologies. For example, patent data show an increase in stealth technology activity in the early 1980s. Figure 2.4 shows the rate of patenting in a stealth technology-related class (342/2 Radio Wave Absorber for Aircraft or Missiles). The bottom, blue series shows the number of patents filed (and ultimately issued) in this class by application year while the top, red series shows the cumulative number of patents in the class by application year. While it is unclear if this class has reached maturity (patents filed in the late 2000s are probably still being processed and do not appear in the dataset), the rate of patenting in this class increased around 1984. Black lines show the approximate slope of the cumulative sum series before and after 1984. Given that it takes some time to progress from the start of a research project to a patent application, research that contributed to this increase in patenting likely occurred sometime in the late-1970s or early-1980s.[34]

A patent representing a significant innovation in stealth technology appears approximately where one would expect if the hypothesis that big innovations appear just before the takeoff point is correct. Stealth technology was revolutionized in the mid-1970s when defense contractors Lockheed and Northrop independently developed methods to reduce the radar cross section[35] of aircraft by several orders of magnitude (Aronstein & Piccirillo, 1997). Lockheed patented their approach in 1979 (U.S. patent 5,250,950),[36] and went on to build the F-117A, the

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[33] Independent co-discoveries and delays between conducting research and filing a patent may lead to some innovative patents appearing just after the point of takeoff.

[34] While one could trace the conceptual ancestors of any particular invention arbitrarily far back in time, studies of private-sector projects find that patents tend to be filed early in the R&D process (Griliches, 1990, p. 1674).

[35] Radar cross-section is a measure of how visible an object is to radar sensors. Objects with smaller cross-sections are harder to detect. A number of factors can affect radar cross-section including the shape of the object, the surface material of the object, and the angle between the sensor and the object.

[36] Northrop seems not to have filed a utility patent on their stealth technology, although they have several design patents for military aircraft. This may have something to do with the different contract terms Lockheed negotiated during the stealth fighter demonstration project. Lockheed entered the stealth design contest on a non-standard

world's first stealth fighter, which became operational, but still classified, in 1983 (Rich & Janos, 1996).[37]

Figure 2.4 Illustrating the location of innovative patents in the s-curve
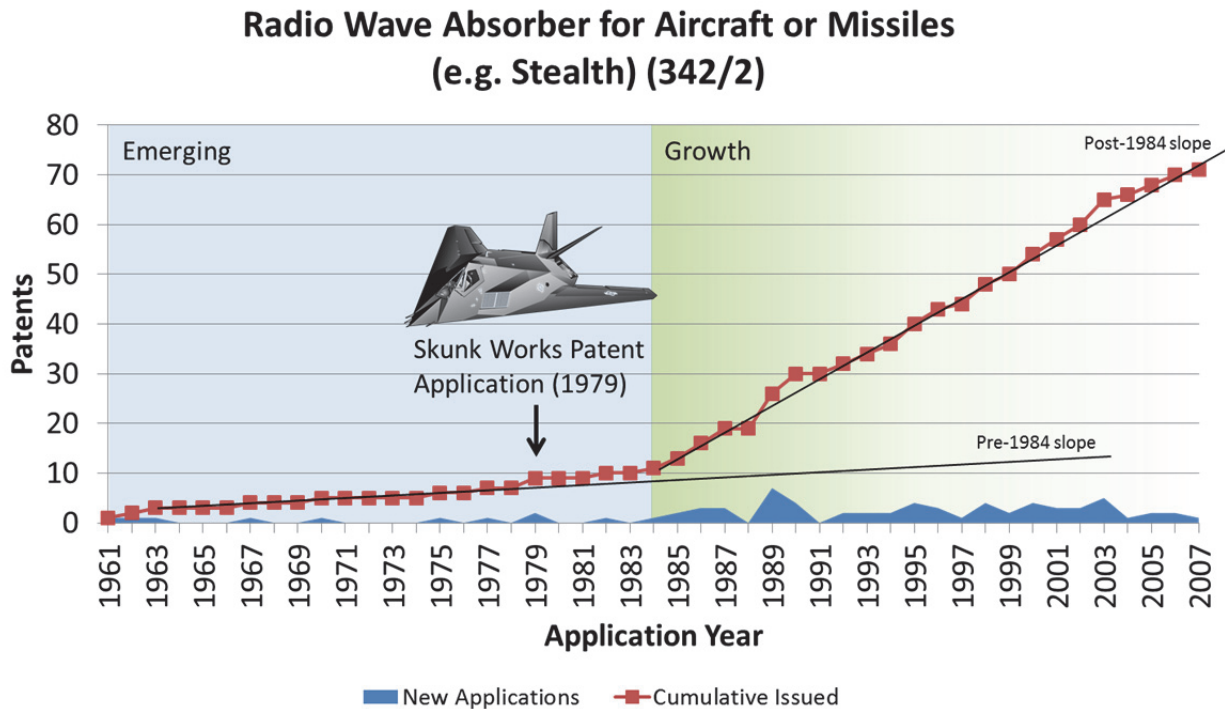
Source: Analysis of USPTO 2009 patent grant bibliographic data file

It is difficult to say whether Lockheed's work on the F-117A was the breakthrough that made later work possible, or if this type of stealth was being simultaneously pursued by many inventors and Lockheed was just the first of many to make it work. The challenge of responding to increasingly sophisticated air defense systems had been an issue throughout the Cold War. For example, in the late-1950s Lockheed developed radar absorbing coatings for the SR-71 in response to President Eisenhower's request for the lowest possible radar cross section (Rich & Janos, 1996, pp. 197–199). The expansion in stealth-related work in the 1980s could simply have been due to increasing concerns on the part of military planners. However, before Lockheed and Northrop's work in 1975, no one knew how to actually calculate the radar cross section of a new aircraft design (Aronstein & Piccirillo, 1997), and in the 1980s, with that problem solved, coincidentally or not, stealth went from being a niche business to an expanding one. Either way,

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contract that allowed the company to keep all of their intellectual property (Rich & Janos, 1996). Northrop developed their equivalent technology under contract to the Air Force (Aronstein & Piccirillo, 1997).

[37] Lockheed's stealth vehicle patent was not issued until 1993. The 14-year delay probably reflects a secrecy order on the patent since the existence of the F-117A was not officially acknowledged until 1988 (Morrocco, 1988).

based on the location of their stealth patents in the class s-curve, Lockheed should be called an innovator in stealth technology.

2.4 From cumulative s-curves to within-organization patenting patterns

The region – emerging, growth, maturity, or saturation – in which a given patent appears can be an indicator of the innovativeness and usefulness of the underlying idea. As demonstrated with the Lockheed stealth example above, patents that appear in the late-emerging or early-growth phase of the cumulative patent s-curve can be indicators of this type of innovative leadership.[38] In studies of drivers of innovation, the number of leading patents an organization has could be used as the objective measure of innovativeness (i.e. the dependent variable) and compared with various factors (i.e. independent variables) such as the qualifications of research staff or organizational mission and culture.

However, there is additional information in organizations' patterns of patenting that may help focus the study of innovation. Just as the cumulative behaviors of organizations result in the accumulation of patents along an s-curve, the cumulative behavior of inventors *within* a single organization creates a coherent patenting trend. Sometimes this within-organization patenting trend resembles an s-curve, but other times it is more irregular and spikey. Furthermore, just as patent s-curves occur because many organizations are betting that the technology will be profitable (Eusebi & Silberglitt, n.d.), patentees within an organization are responding to some signal about the importance of their research areas. Which signals correspond with which within-organization patenting patterns is the subject of the next two chapters. Understanding the drivers of these within-organization patenting patterns may lead to a better understanding of how different organizations pursue invention and innovation. Section 4.2 will return the discussion to innovation and the cumulative field s-curve by comparing the within-organization patenting patterns with contemporaneous trends in the field as a whole.

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[38] A second example, IBM in nanotechnology, is discussed in 4.2.

Chapter 3 Within-Organization Patent Patterns: identification and data sources

Just as patents filed over time by multiple inventors and organizations can produce an s-curve in the full patent database, the sequences of patents filed over time by inventors employed by any single organization can form distinct patterns. As discussed in Section 2.3, s-curves in the full patent record have been interpreted as indicators of technology diffusion (Ernst, 1997) and as indicators for the occurrence of (Eusebi, 2011) or remaining potential for (Y. H. Chen et al., 2010) innovation in a field of technology. There is as yet no equivalent set of theories explaining how within-organization patenting patterns occur, what the specific patterns signify, or why different patterns occur with different rates in different organizations. This dissertation aims to fill this gap.

This study has three hypothesis regarding the causes and implications of within-organization patenting patterns. First, an organization's pattern of patenting in a technology class over time reflects the research and commercialization approach the organization has applied to that technology. Second, certain patterns themselves as well as the location of that pattern on the broader technology class s-curve can be indicators of innovation. This study hypothesizes that organizations produce distinctly different patenting patterns when they believe a line of work is highly valuable and potentially innovative than when they believe a line of work is of average value. In addition, since an organization's individual patenting pattern is part of the larger technology class patenting trend, within-organization patenting patterns that occur early in the larger technology class s-curve can be an indicator of actual innovation as described in section 2.3.2. Third, the distribution of patenting patterns across various technologies in an organization's portfolio is related to the organization's research mission, culture, and procedures. Research organizations with different missions, cultures, and procedures will therefore have different distributions of patterns in their patent portfolios.

This study explores these hypotheses in three steps. First, this chapter describes the patterns that occur within laboratory patent portfolios and demonstrates their occurrence within a set of test cases: the DOD laboratories. Second, chapter 4 addresses the second hypothesis by developing the theoretical argument for the link between innovation (as defined as a concrete product that is widely used, novel, and non-obvious) and these patenting patterns, again drawing on results from the DOD laboratories for supporting or contradictory evidence. Third, chapter 5 demonstrates approaches for analyzing relationships between patenting patterns within the DOD laboratory portfolios and characteristics of the laboratories such as technological focus area, budget, and character of work (e.g. more basic or more applied, more investigator-directed or more service-directed).

3.1 Identifying within-organization patent patterns: methodology overview

This study finds that histograms of a single organization's patents constructed along technology class and application year (e.g. a bar graph of the number of patents per application year filed by a given organization in a given technology class) can be classified into four pattern types. The frequency with which each pattern appears in an organization's portfolio may be related to the organization's research mission, culture, procedures, and innovativeness. If the definitions of these patterns and the behaviors behind them proposed in this study hold, then these patterns can be used to both evaluate the alignment between a research organization's stated mission and its actual performance as well as to identify specific innovative outputs.

This chapter explains this study's methodology for identifying within-organization patenting patterns in 5 steps. First, section 3.2 describes the organizations – the DOD laboratories – whose data have been used to develop the methods in this dissertation. Second, section 3.3 describes the sources of DOD patent data used in this study. Third, section 3.4 provides summary statistics for this data set and describes the limitations of the data sources. Fourth, section 3.5 presents the visualization techniques this study uses to summarize organization patenting by technology classes. Fifth, section 3.6 presents the visual signature of each of the four patenting patterns identified in this study and defines the rules this study uses to classify patent histograms by pattern type. Chapters 4 and 5 addresses the possible organizational drivers of and evaluative applications for these patenting patterns.

3.2 Organizations of interest

This study focuses on the patent portfolios of the DOD in-house research laboratories. The DOD research laboratories are a set of organizations, run by the military services, which conduct and fund research across the social, physical, engineering, and medical sciences. Depending on how one draws the organizational boundaries and the type of work one includes, there can be some discrepancies as to the identities of the DOD research "labs". For example, some sources list the Army Corps of Engineers' seven component research laboratories separately while other sources group them all into the single Engineer Research and Development Center (ERDC).

This study identifies "laboratories" based on the level at which patent data is reported (described below) and the availability of budget data in the DOD In-House S&T Activities Report series. The DOD laboratories relevant to this study are those that reported in-house S&T budgets (DOD budget category 6.1 through 6.3) between 1990 and 2010 (the period for which patent data is available) and which have received at least six patents in at least one technology class (the reason for this patenting threshold will be discussed in section 3.6).[39]

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[39] This definition excludes organizations that only issue extramural research grants such as the Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA), contractor-operated Federally Funded Research and Development Centers (FFRDCs), University Affiliated Research Centers (UARCs), and

Based on the DOD In-House S&T Activities Report series, there are 36 separate DOD research "labs" with significant amounts of in-house S&T work during the study period including the [40]

- Naval Research Lab (NRL),
- Army Research Lab (ARL),
- ten Air Force Research Lab (AFRL) directorates,
- five Army Research Development and Engineering Centers (RDECs),
- Army Medical Research and Materiel Command (USAMRMC) laboratories,
- Edgewood Chemical Biological Center (ECBC),
- Army Corp of Engineering Research and Development Center (ERDC) (as one unit),
- Naval Health Research Center (NHRC),
- Naval Medical Research Center (NMRC), and
- four Naval Warfare Centers.

However, because the level at which patent data are reported and the level at which budget data are reported do not always agree, some "laboratories" may be aggregated or disaggregated for specific analyses. This issue primarily affects AFRL, USAMRMC, and the Naval Warfare Centers. While the terms lab or laboratory are used throughout this dissertation, the more appropriate term may be research organization. Patent data are available by research organization, and while all labs are research organizations, not all research organizations are labs.[41] Summaries of each DOD laboratory's technology focus areas and budgets by activity type (e.g. basic research, applied research, technology development) are provided in Appendix D.

3.3 Data sources

The primary challenge when analyzing DOD laboratory patents is matching patents to the specific originating facility as opposed to the owning service.[42] Patents derived from work performed at a government laboratory (as opposed to at another organization which received funding from the laboratory) will usually be assigned to the lab's parent agency [43] In the case of patents generated in-house at DOD labs, the assignee is the service (e.g. United States as

organizations like the Marine Warfighting Lab that conduct research and experimentation into doctrine and use of technology.

[40] For comparison note that the Office of the Assistant Secretary of Defense for Research & Engineering (ASD(R&E)) listed 67 Service Laboratories in the on-line Defense Laboratory Enterprise Directory as of November 2011 (ASD(R & E), 2012; Defense Science Board, 2012). The In-House S&T Activities Reports aggregate many of these 67 laboratories and report data only for the parent organizations.

[41] Credit to Susan Marquis for pointing out this distinction.

[42] This is a challenge for research on patents from any U.S. government organization. See, for example, the number of assumptions made in Jaffe & Lerner (2001) to reduce DOE patents to DOE FFRDC patents.

[43] The assignee is, essentially, the entity that owns the patent and all the associated rights. If the lab declines to file a patent, the inventor may pursue a patent on his or her own, in which case the patent will be assigned to the individual inventor or a company of the inventor's choosing.

Represented by the Secretary of the Army). In theory, the originating facility could be inferred by finding the DOD laboratory closest to the inventors' home addresses, which are listed on the front page of a patent. However, in areas where there are several DOD facilities, it can become difficult to identify the most plausible home facility for an inventor, and the error rate of this indirect facility identification method could be high.[44] Therefore, some external source is desired that links the inventor or the patent itself with a specific research facility. This study relies on the list of patents by facility at the DOD TechMatch website.

3.3.1 DOD TechMatch

In the case of DOD labs, a list of laboratory-related patents is available through one of the partnership intermediary organizations established to support the transition of DOD technologies to the commercial sector. Partnership intermediaries are state, local, or non-profit entities that facilitate cooperative or joint ventures between federal laboratories and small businesses or educational institutions (see 15 USC § 3715). Federal laboratories were given the authority to contract with partnership intermediaries in the Defense Authorization Bill of 1991.

DOD TechMatch is a partnership intermediary founded in 2005 to improve the data available for match-making between DOD labs and commercial users of their technologies (Morrison, 2007). TechMatch maintains an on-line information center for DOD patents, licenses, Small Business Innovation Research (SBIR) grants, and contracting opportunities (West Virginia Technology Consortium Foundation, 2010). In order to direct interested private-sector parties to the correct contact, TechMatch employs a liaison who works directly with the DOD laboratories to link patent licensing opportunities to specific DOD facilities (West Virginia Technology Consortium Foundation, 2012).

DOD TechMatch lists patents by number, title, and originating facility for 58 DOD "labs".[45] In addition to the labs identified in the previous section, TechMatch also lists patents for organizations that are not S&T performers according to the In-House S&T Activities Reports. For example, TechMatch lists patents for the Naval Postgraduate School and for both the Naval Air Systems Command as well as its subordinate Warfare Center labs at China Lake, Point

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[44] If the inventor of an Army-assigned patent lives anywhere in North Alabama or Southern Tennessee, it is likely that the inventor works for the Army's Aviation and Missile Research and Development Center (AMRDEC) at Redstone Arsenal in Huntsville, AL. This is the only Army facility in the region with significant in-house research activities, although there are a few others with minor research expenditures. However, a Navy inventor who lives in Northern Virginia could plausibly work for one of several Navy research labs including the Naval Research Lab (NRL), the Naval Surface Warfare Center (NSWC) at Carderock, or NSWC Dahlgren.

[45] As discussed above, what counts as a lab can vary by source. DOD TechMatch generally lists "labs" at a level one might expect from organizational charts, e.g. the Office of Naval Research (ONR) and NRL are listed separately while the Army Research Office (ARO) is not listed as a separate entity from the ARL; each AFRL directorate is a separate lab, but all of the USAMRMC organizations are grouped together as one lab (see Appendix D for organizational charts).

Mugu, and Patuxent River. DOD TechMatch also includes a "TechMatch Patent Lab" entry for each of the services to indicate patents for which they could not identify a specific laboratory.

As of January 2012, the DOD TechMatch website lists the patent number, title, and related laboratory for 6,905 patents. Note that TechMatch lists only patents issued since 1990. The vast majority of these patents are assigned to the Army, Navy, or Air Force and most likely represent in-house work. Two-hundred fifty-three, or about 4% of the patents, are assigned to other entities. A plurality of these otherwise-assigned patents, 109, are assigned to individuals. The remainder are assigned to various other entities, including large U.S. government contractor organizations like General Dynamics, other government agencies such as NASA and the Department of Energy (DOE), and some foreign entities such as Toyota and the United Kingdom's Ministry of Defense. These patents could be the result of CRADAs or individual assignment after the service declined to patent. All of these patents are kept in the dataset regardless of assignee under the assumption that, given TechMatch's mission to connect private-sector organizations with in-house developed government technologies, the patents not assigned to a military service were still created in close collaboration with the lab (see discussion of CRADAs below).

The TechMatch dataset also includes 243 statutory invention registrations (SIR). These are not patents, but are rather published patent applications for which the applicant has waived the right to a patent. SIRs place an invention in the public domain and prevent others from patenting similar material. SIRs are included in the USPTO database with an 'h' at the beginning of their patent number (see 35 U.S.C. 157). All SIRs are also retained in the dataset since they represent inventions that could qualify for patents if not for some prior disclosure (such as a conference presentation) or the desire of the Service to place the technology in the public domain.

3.3.2 Note on identifying patents resulting from extramural or cooperative research[46]

While this study focuses on in-house generated patents, the majority of the DOD laboratories' budgets go to extramural research (see Appendix D). Patents resulting from extramural defense research are not listed in TechMatch, and identifying them would require additional analyses of various patent and research contract databases. If extramural research results in a patent, following the Bayh-Dole Act of 1980, the patent will usually be assigned to the contractor, university, or individual who performed the work. In such cases, it may be possible to link the assignee to their funder through a contract number listed in the required statement of government funding at the beginning of the patent text. Since contractors and grantees are required to disclose to the funding agency any patents derived through government funded research, it may also be possible to ask the funding agency for a list of external patents.

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[46] Background information on patent regulations was obtained from the Federal Laboratory Consortium's (FLC) guide to Federal Technology Transfer Legislation and Policy (aka the Green Book) (Federal Laboratory Consortium, 2009), interviews with technology transfer and patent professionals, and summaries of legislation in Jaffe & Lerner (2001) and Hughes et al. (2011).

It is not clear how successful either approach would be in practice. While several databases exist that contain both patent bibliographic data and government research grant information, attempts to link patents to their related grants generally rely on matching inventor names to the grantee names. For example, Zucker et al have developed an extensive database of U.S. patents, highly-cited articles, and NIH, NSF, Small Business Innovation Research (SBIR), and Small Business Technology Transfer (STTR) grants, but while they have linked organizations and individuals across these records, they do not appear to have extracted and linked grant numbers from relevant patent or grant texts (Zucker, Darby, & Fong, 2011).

Parents generated during Cooperative Research and Development Agreements (CRADAs) can also be relevant to this study if some new research was actually performed at the lab. If a patent is generated during a CRADA, then the assignee will depend on the specifics of the CRADA. Licensing of existing intellectual property and the disposition of future intellectual property are part of CRADA negotiations. There have been cases in which both the contractor and the laboratory were assignees for patents generated during CRADA work. For example, patent 5,989,194 for a "Method and apparatus for detecting ocular disease and abnormalities," was part of a CRADA between the U.S. Army's Aviation and Missile Research Development and Engineering Center (AMRDEC) and Vision Partners, L.P. It is assigned to both the commercial partner and to the U.S. Army.[47] Identifying the specific government facility involved in the CRADA faces the same challenges as identifying the originating facility of in-house-research generated patents.

3.3.3 Patent class and bibliographic data

Although the TechMatch dataset identifies DOD laboratory patents by number, title, and facility, this analysis also requires more detailed information for each patent, particularly a complete list of technology classes and the application year. To add this information, the TechMatch patent list is merged by patent number with the USPTO's 2009 patent grant bibliographic data file and the Jan. 6, 2012 USPTO master classification file. These were the most current files available at the beginning of this study.

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[47] This CRADA was the result of a fortunate coincidence of geography and hobby. One of the co-founders of Vision Partners, L.P. wanted to improve the early diagnosis of lazy eye in children. Existing detection methods took pictures of young children's eyes and sent them to an expert for analysis. The co-founder thought there might be a way to automate the screening process and had heard that AMRDEC, which was only a few hours away, may have relevant expertise. At a Huntsville, AL Chamber of Commerce meeting (local to AMRDEC), the co-founder struck up a conversation with an Army researcher on the basis of a shared home town. The researcher was from Memphis, TN where Vision Partners, L.P. was based. The Army researcher, it turned out, happened to be a professional photographer, was familiar with the optics of the eye from his work as a laser safety officer, and had experience in image processing from automatic target recognition research. The Army researcher thought there might be a way to exploit the phenomena that created red eye in photographs to automatically evaluate the likelihood that a subject in the photo had lazy eye. After a prior art search, they initiated a CRADA that was ultimately successful in producing a prototype and a patent (Personal Interview, 2012).

The annual USPTO patent grant bibliographic data file provides the patent title, inventors' names and state, assignee name, primary technology class, application date, and issue date for patents issued since 1976.[48] The USPTO master classification data file lists the associated class, subclass, and patent number for all patents ever issued. The classification file is updated quarterly to include new patents and changes to the classification system. Merging the master classification file with the bibliographic data file results in a complete list of patents issued since 1976, information about their inventors and owners, and a complete list of primary and cross-reference classes (for a review of the USPTO technology class system see Appendix C).[49]

3.4 Data summary and limitations

The 2009 USPTO bibliographic data file lists 11,444 patents issued to the U.S. military services between 1990 and 2009. After merging the TechMatch and USPTO datafiles, 6,725 patents remain in this study's dataset. Around three percent of the original 6,905 TechMatch records could not be matched to a USPTO bibliographic entry. These 180 patents are all dropped from the data set.[50] Of the remaining patents, in 92% of cases (6,179 patents), TechMatch and the USPTO records agree on the associated Service, i.e. the patents are assigned to the Service that owns the TechMatch-identified lab. Assignees associated with the mismatched cases include both different services and private entities. Table 3.1 summarizes these statistics.

Table 3.1 Summary of overlap between TechMatch and USPTO records

Category	Patents
Issued to U.S. Military Services 1990-2009	11,440
Listed on TechMatch website as of Jan 2012	6,905
Active with issue date 1990-2009	6,725
Assigned to TechMatch ID'ed Service	6,179
Other assignee	546

TechMatch therefore lists a little more than half (58%) of the patents issued to the U.S. Military Services between 1990 and 2009. The exact fraction varies by grant (or application) year and Service. Table 3.2 shows the percentage of patents assigned to each Service that are included in the TechMatch data set by application year blocks. Overall TechMatch includes 71% of all Army patents, 68% of all Air Force patents, and only 44% of all Navy patents issued

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[48] The bibliographic data file also comes with a table listing all citations between patents, although this information was not used in this study.

[49] It also results in a *very big* file. The fully merged text file is over 1.3 GB in size.

[50] One-hundred seventy-seven patents in the TechMatch database were issued in 2010 or later and therefore did not appear in the 2009 USPTO bibliographic data file. Three patents had been withdrawn.

between 1990 and 2005. Navy patent coverage improves over time, while Air Force patent coverage declines over time. TechMatch contains only around one-fifth of Navy patents with application dates between 1990 and 1997, but it has 70% of Navy patents with application dates between 1998 and 2005. TechMatch includes 84% of Air Force patents with application dates between 1990 and 1997 but only 48% of Air Force patents with application dates between 1998 and 2005. Army coverage is between 70 and 80% in both time periods with no consistent trend over the two decades of interest.

Table 3.2 Percent of service-assigned patents in TechMatch dataset by application year range

Application Year	Army	Air Force	Navy
1990-1997	70%	84%	22%
1998-2005	79%	48%	69%
1990-2005	74%	70%	44%

Figure 3.1, figure 3.2, and figure 3.3 compare USPTO and TechMatch coverage for the Navy, Army, and Air Force respectively by application year. The solid red area in the background shows the number of patents for that service in the 2009 USPTO bibliographic data file, the solid green area in the foreground shows the number of TechMatch patents for that service, the blue line shows the percent of USPTO patents included in TechMatch (right axis).

Figure 3.1 Total reported Navy patents USPTO versus TechMatch
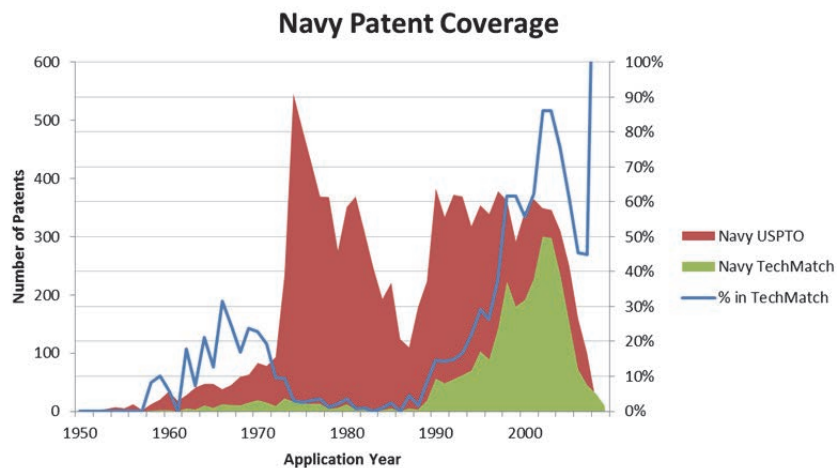
Figure 3.2 Total reported Army patents USPTO versus TechMatch
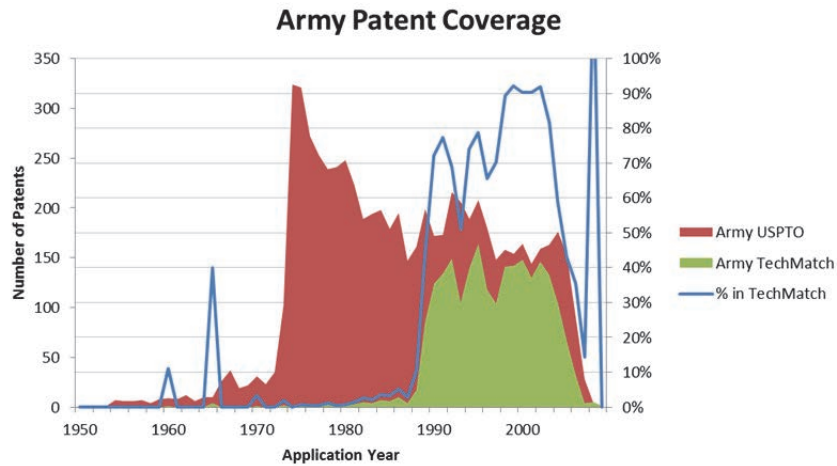
Figure 3.3 Total reported Air Force patents USPTO versus TechMatch
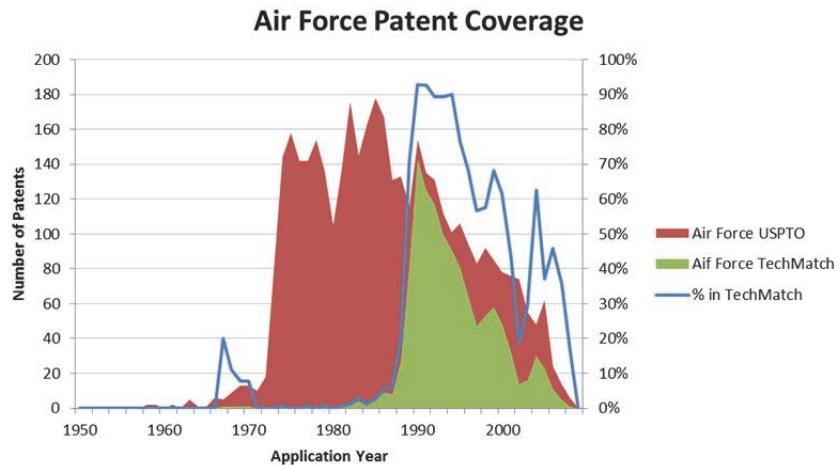
While it is possible that the remaining Service patents were filed by individuals outside the DOD laboratory system, and therefore are outside the mission of TechMatch, it is also possible that most of the missing patents were filed by the labs and TechMatch's data collection is incomplete. None of the current employees of the West Virginia Technology Consortium Foundation, the consortium that ran TechMatch until 2011, are familiar with the patent data collection effort, making it difficult to determine where and why gaps might exist in TechMatch's data base (West Virginia Technology Consortium Foundation, 2012).

This evidence of missing data suggests that the TechMatch-based data set is not a census of DOD in-house laboratory patents (issued 1990-2009), but is instead a sample of DOD laboratory patents with unknown biases. This introduces an additional source of uncertainty in interpreting the laboratory patenting trends. Where appropriate, statistical tests are used by this study to

characterize this uncertainty. Whether due to low propensities to patent or due to missing data, some targeted laboratories had to be dropped from this study or aggregated with a higher organizational unit because they were associated with too few patents to analyze individually. Fortunately, for laboratories with sufficient patents in the TechMatch data set there is some evidence that the data available for each laboratory is at least consistent with their full range of research areas.

3.4.1 Summary of data set by laboratory

Figure 3.4 shows the number of patents in the final merged dataset by lab and service (see color key) after dropping unmatched patents and cleaning the lab names. The laboratories are arranged in order of total patents. Note that the AFRL directorates are combined together in figure 3.4 because several of the directorates are associated with fewer than 20 patents each. Also note that several organizations shown in figure 3.4, particularly the Naval Facilities Engineering Service Center and all "labs" with fewer than 20 patents, are not included in this study. They are excluded either because they are not in-house S&T performers according to the DOD In-House S&T Activities Report series or because there is no single technology class in which they have at least 6 patents.

Figure 3.4 Number of patents in the DOD TechMatch database by organization and service
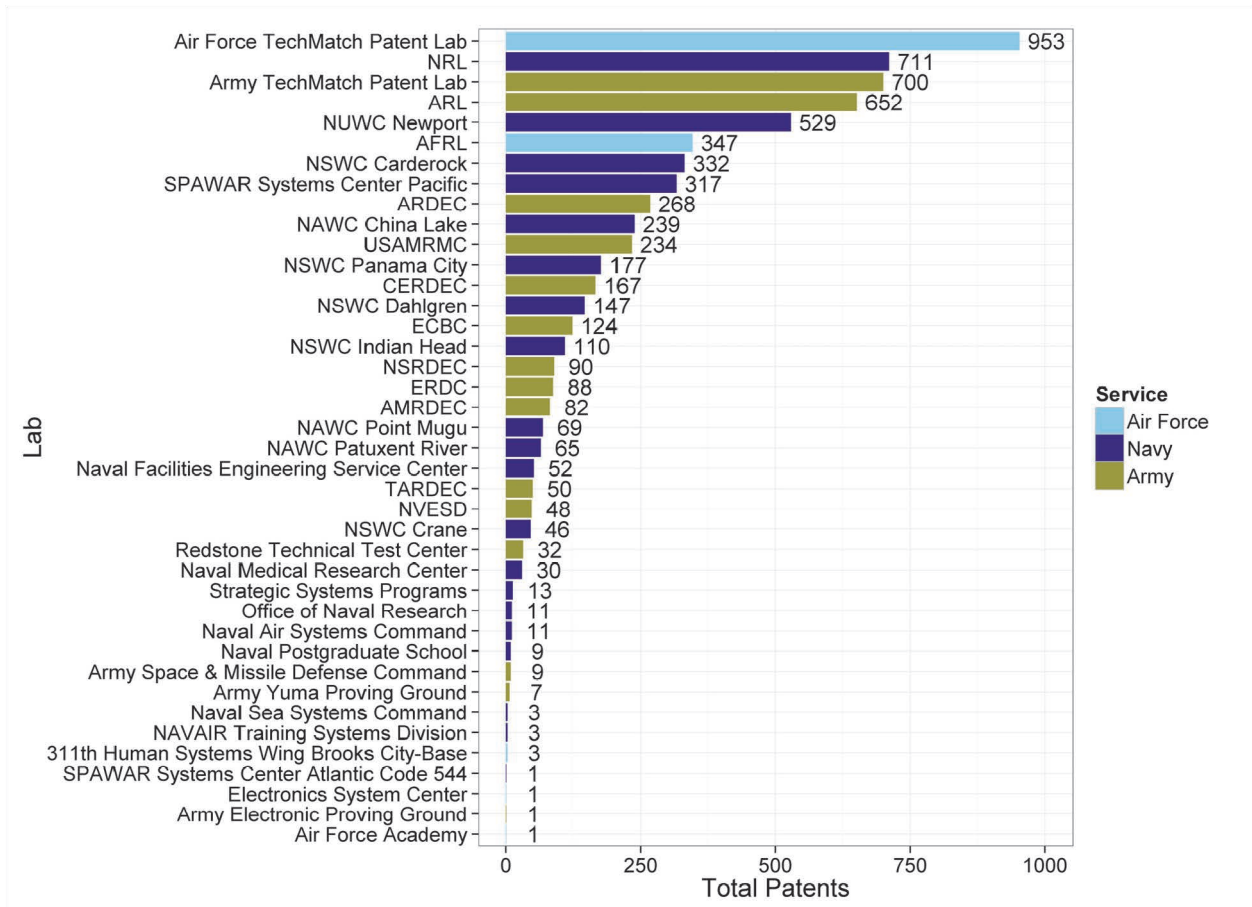
Note: Seven patents assigned to two laboratories. NUWC = Naval Undersea Warfare Center; NSWC = Naval Surface Warfare Center; NAWC = Naval Air Warfare Center; SPAWAR = Space and Naval Warfare Systems Command; ARDEC = Armaments Research Development and Engineering Center; CERDEC = Communications-Electronics Research Development and Engineering Center; NSRDEC = Natick Soldier Research Development and Engineering Center; AMRDEC = Aviation and Missile Research Development and Engineering Center; TARDEC = Tank Automotive Research Development and Engineering Center; NVESD = Night Vision and Electronic Systems Directorate. All other acronyms defined earlier in this chapter.

Despite the apparent missing data, there is evidence that suggests the patents included in TechMatch may be representative, in terms of classes covered, of the labs' complete patent portfolios. A simple comparison of each lab's most frequent patent classes, based on the TechMatch patent list, and that lab's mission shows an alignment between the two. For example, the Armaments Research Development and Engineering Center (ARDEC), which "[develops] advanced weapons, ammunition and fire control systems for the U.S. Army", ("ARDEC Home Page," n.d.) patents primarily in the following areas (specific patent topics in parenthesis for illustration).

- Ammunition & Weapons (self-explanatory),
- Measuring & Testing (weapon sights and testing weapon quality),
- Aero/Astro (for ballistics),

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- Optical Systems (targeting),
- Communications & Electromagnetic (EM) devices (fuses, targeting, and countermeasures), and
- Buildings (ammunition cases - containers are a subclass within the buildings subject group).

In contrast the Natick Soldier Research Development and Engineering Center (NSRDEC), which is responsible for the soldiers' "survivability, sustainability, mobility, combat effectiveness and quality of life," ("About Natick Soldier RD&E Center (NSRDEC)," n.d.) patents primarily in

- Resins and Rubbers (polymers and solvents),
- Organic Compounds (also polymers and solvents),
- Life and Agricultural Sciences (shelf-stable foods and more polymers),
- Aero/Astro (parachutes), and
- Apparel and Textiles (self-explanatory).

While in theory the labs could patent only spin-off technologies that are unrelated to their defense missions, prima facie, it would be strange if the technology classes covered by a lab's patents and the lab's stated mission did not align. That this dataset includes a representative range of technology classes for each laboratory, given their stated missions, increases the confidence that any missing data is not systematically biased by technology class. The representativeness of the technology classes covered in this data set will be revisited in section 3.7.2.

3.4.2 Impact of a restricted issue-year range on the data set

In addition to uncertainties introduced due to overall missing data, there is uncertainty with respect to trends in the most recent patent filings. Because of the different date ranges covered by the various source files, the data set used in this study contains only patents issued between 1990 and 2009. Since it takes an average of 3 years for a patent to move from application to issuance,[51] this dataset should contain few patents with application dates prior to 1988 or after 2005.

Figure 3.5 shows the number of patents in TechMatch by issue year (line) and application year (area). The left side of the graph shows the expected pattern: a steep drop in the by-application-year line from 1990 to 1988 and very few patents with application years of 1987 or earlier (around 5% of the total data set have application years prior to 1988). On the right side of the graph, the overall number of patents in this dataset actually begins to decline after an issue year of 2006 and an application year of 2004. Many patent applications submitted between 2005

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[51] Traditional Total Pendency as of August 2012 was 32.7 months according to the USPTO statistics dashboard, http://www.uspto.gov/dashboards/patents/main.dashxml, accessed Oct. 8, 2012.

and the present were therefore likely still pending at the time of TechMatch's last data collection and therefore do not appear in TechMatch's database of issued DOD patents.

While the decline in available patent data begins earlier than expected, this truncation has no effect on the results other than to make them less current. Figures throughout this document will shade regions from 2005 to the present to indicate that the visible trends in these regions are likely incomplete.

Figure 3.5 Total TechMatch patents by application and issue year
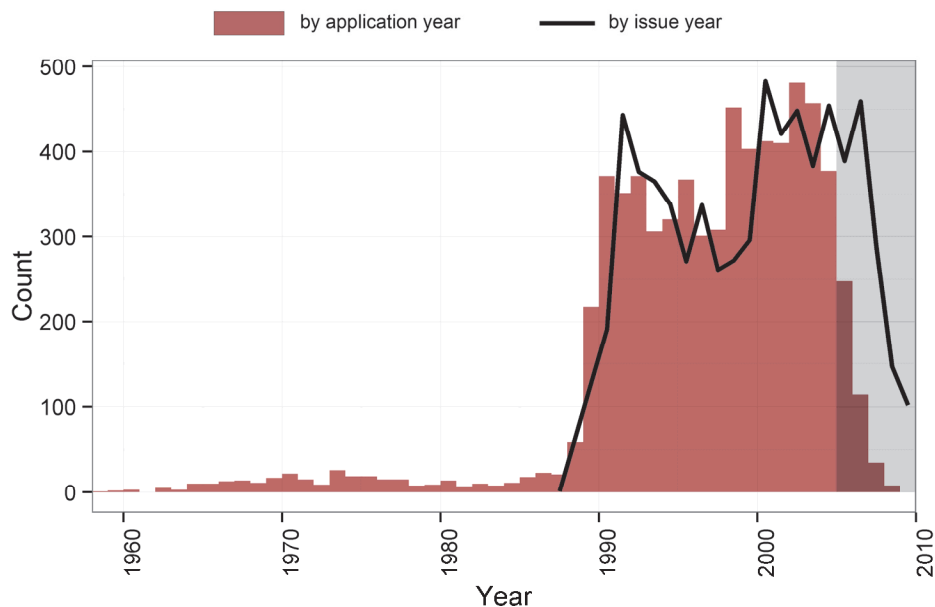
3.5 Visualization: creating and organizing histograms

Once the data has been collected and cleaned, the next step in this methodology is constructing the patent histograms. The theories and measures proposed in this study are based on analyzing collections of histograms, such as figure 3.6, which show the number of patents received by an organization per technology class and application year. The bars in figure 3.6 indicate the number of (ultimately issued) patents filed by this sample organization in a given year in the sample technology class. The class code and a brief description of the technology class are given in the bar at the top of figure 3.6. Note the shaded area on the right side of the figure indicating that the trend from 2005 through the present is likely incomplete as explained in subsection 3.4.2.

Any data analysis system can produce these types of histograms. This study used, and recommends using, the ggplot2 graphical package (Wickham, 2009) in the R statistical computing environment.

Figure 3.6 Sample within-organization histogram
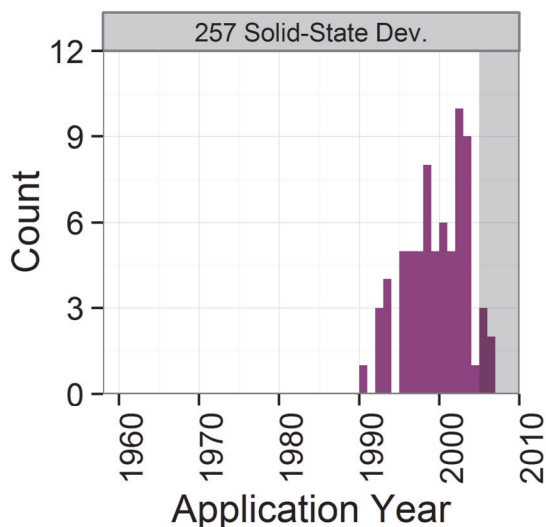
3.5.1 Patent Maps

When all of a lab's patents are plotted this way together on one page, such visualizations provide an overview of a laboratory's patenting activities. This image is like a map identifying the lab's major research areas. Therefore this study calls figures such as figure 3.7 Patent Maps. This example Patent Map covers all of the technology classes in which NRL has at least six patents. Each cell in figure 3.7 contains the same features described above for figure 3.6. Each cell has the same count (vertical axis) and time (horizontal axis) scale, making comparisons between the timing and level of patenting between classes easier.

In addition, the color of the bars in each cell groups the technology classes into broader subject areas. These subject area groups are based on the USPTO's "Classes Within the U.S. Classification System (Arranged by Related Subjects)" document which groups the roughly 500 technology classes into approximately 30 subject groups.[52] The subject groups are ordered and colored such that similar subjects have similar colors and are plotted near each other.

Note that not all subject groups will show up in the Patent Map for any given lab. Being a large and diverse lab, NRL has patents in many subject areas, but it does not patent significantly in ships, aeronautics and astronautics, building materials, and several other categories. As a result, figure 3.7 includes only 13 of the 27 total subject groups.

The icons in the top left corner of each cell mark in figure 3.7 the type of pattern each histogram represents. The rest of this chapter explains those patterns.

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[52] Available at the USPTO website as of Nov. 2012

Figure 3.7 Patent trend diagrams for all active NRL classes

Figure 3.7 Patent trend diagrams for all active NRL classes
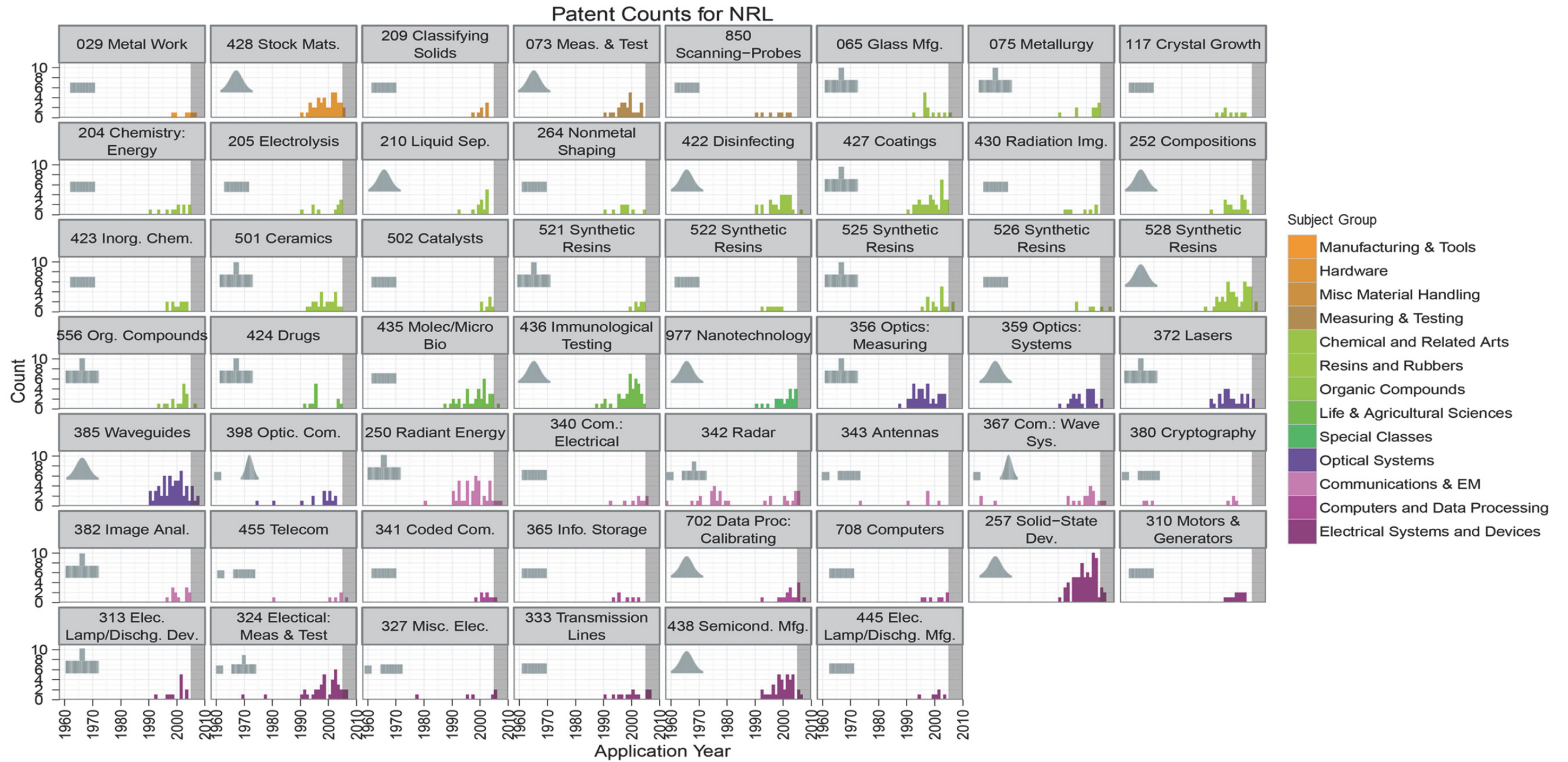
3.6 Classify histograms by pattern type

By examining the patent maps for the DOD laboratories, this study has identified four basic patterns of patenting that are common across research organizations. Together with the zero-patents case,[53] these patterns form a collectively exhaustive and mutually exclusive set of within-organization patent trend descriptors. Each cell in NRL's patent map (figure 3.7), or any other patent map, can be identified as one of these four types of patterns. Figure 3.8 shows an example of each pattern.[54] A short description of the technology class used in each example is along the right side of the diagram. Icons on the left indicate the type of pattern.

Figure 3.8 Patent Trend type examples

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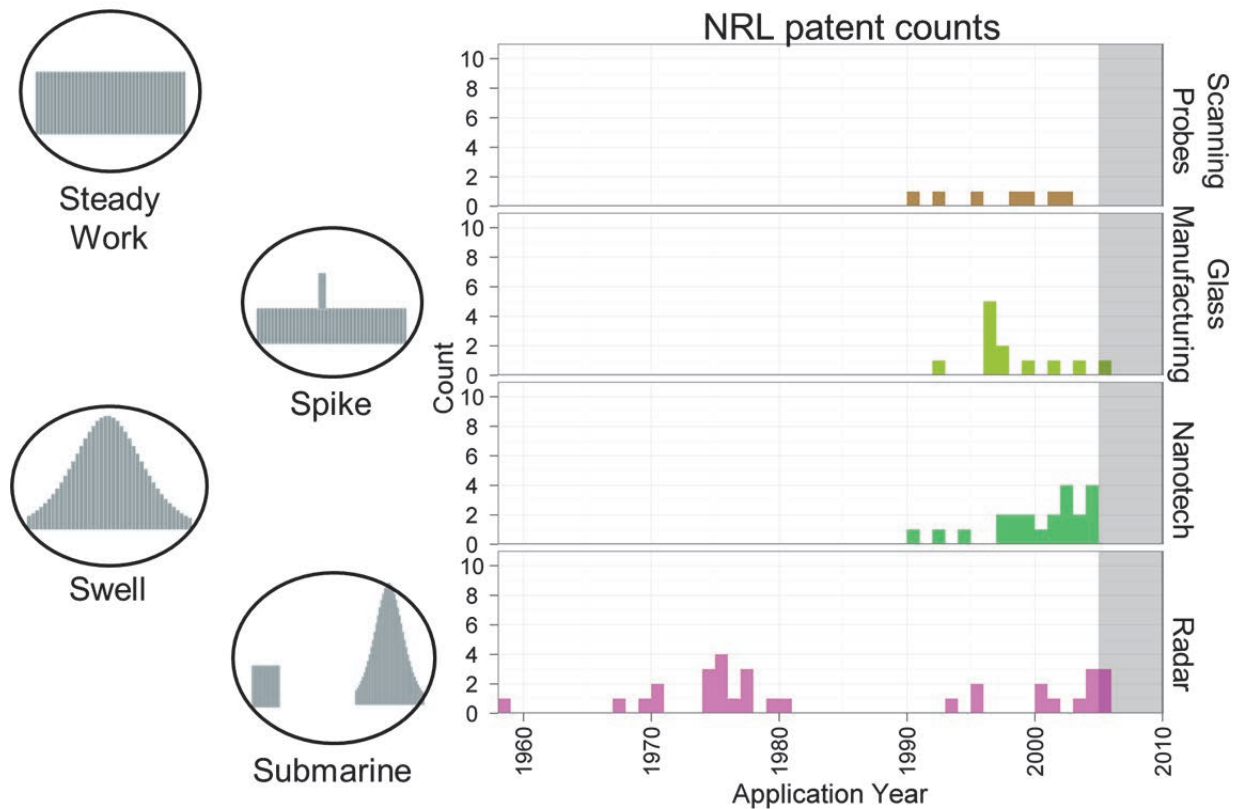
[53] The zero patent case is not discussed in this dissertation for two reasons. First, given that there are around 500 top-level patent technology classes, the number of possible zero-patent cases for any given organization is overwhelmingly large. See section 3.7.1 for more on the rate of few or zero patent class cases in the DOD patent portfolios. Second, the question of why an organization did not produce patents in a given class is a different question than why it produced this particular pattern given that it produced any patents in this technology class. This dissertation focuses on the latter question.

[54] Histograms in Figure 3.8 are drawn from the Naval Research Lab's portfolio.

This study selected the names for each pattern primarily to reflect the visual shape of the patent trend. The first pattern, called steady-work, shows a steady and generally low level of patenting that remains unchanged over the years in the dataset. The second pattern, called a spike, shows an isolated burst of patenting. In contrast, the third pattern, called a swell, shows a gradual increase in the rate of patenting over time. The fourth pattern, called a submarine, shows two clusters of patents separated by several years or even decades. As will be explained in section 3.6.4, the fourth trend is called a submarine because the early cluster of patents were unpublished and hidden from view ("underwater") for many years.

The remainder of this section describes the features that distinguish each pattern and the rules this study uses to classify patent histograms as specific patterns. This study classifies the DOD lab histograms manually, but the information in this section could be used to develop an automated classification system. Later chapters will discuss the possible research activities that generate each pattern and how some patterns point to innovative outputs.

This study uses three steps to classify a patent trend histogram as one of the four patterns. The first step in all cases is to visually inspect the shape of the patent trend to identify the most likely categorization. Second, in order to clearly distinguish spikes from steady-work and swell cases, this methodology analyzes the distinct networks of inventors that contribute to the sequence of patenting under consideration. Spikes, as defined in this study, involve a single inventor group while the other patterns may involve multiple groups. Third, this method employs an additional statistical test, the CUSUM test, in order to estimate the likelihood that an apparent swell trend is actually not due to random variations in the observable data alone. The following subsections walk through the descriptions and classification rules for each pattern individually.

3.6.1 Steady-Work

The steady-work pattern is effectively the baseline; the majority of cases (57%) observed in this study fall into this category. Steady-work histograms with higher total numbers of patents appear as described above: a consistent one or two patents per year, every few years, throughout the data set. As the total number of patents filed by the organization in the class decreases, steady-work histograms begin to look more random with each individual patent filing separated by several years from the next. Figure 3.9 shows an example of a high-count and a low-count steady-work case drawn from NRL's portfolio.

Figure 3.9 Steady-work examples: high-count (left – 14 patents), low-count (right – 6 patents)
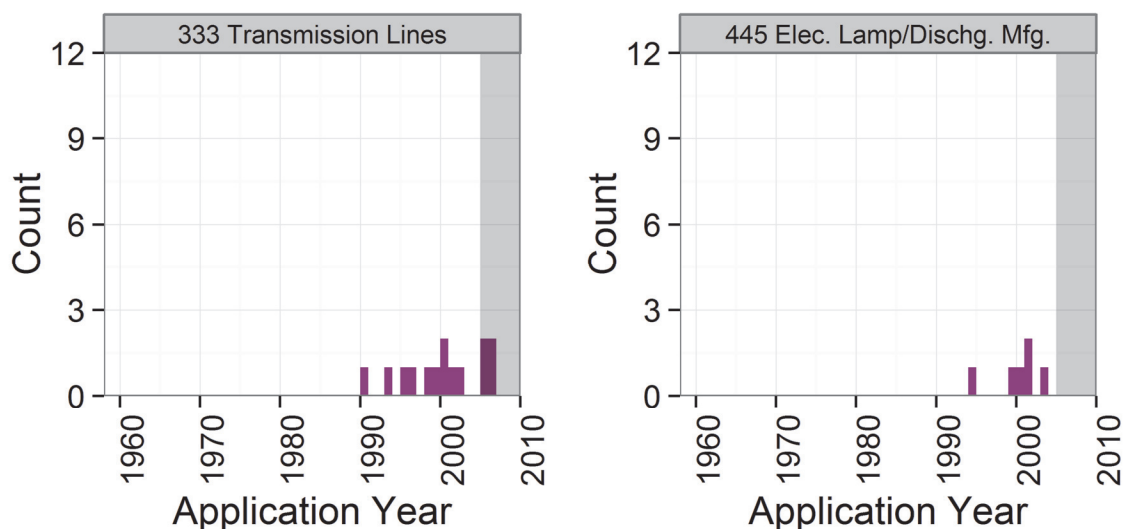
3.6.2 Spikes

The introduction to this section describes a patent spike as an isolated burst of patenting. The burst of patenting is isolated in the sense that it is not part of a larger increasing trend of patenting such as the swell described in the next section. Furthermore, the burst of patenting is also isolated in the sense that it is primarily attributable to a single inventor group.

An inventor group is defined as the network of all inventors from the same organization that appear together on a patent (i.e. the network of patent co-inventors). Each distinct network is designated as a separate group. One might expect that all researchers within a lab would be linked together by at least one person in a "six degrees of separation in the research lab" effect. However, while there are sometimes one or two large groups of inventors within a lab who span a wide range of research areas, there are also many smaller groups of three to five inventors who work in a narrow range of technologies and never patent with people outside their group.[55]

Understanding the range of inventor groups involved in producing a given patent trend is an important step in separating spikes from steady-work or swells. Whereas in steady-work and swell cases the organization tends to have multiple inventor groups who are filing patents in similar but not directly-related areas, in spike cases the organization has one inventor group that has filed several closely-related patents and few others who are working in the same technology area.

Figure 3.10 shows the differences in inventor-group activity between a spike case (left) and a swell case (right). The bars are colored by inventor groups (note that some colors are used to

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[55] This behavior is an interesting area for future work, and may already be more fully explored in the literature on scientific collaboration networks.

represent several groups). In the spike case, all of the patents in the burst, and all but one of the patents filed by this organization in this class, are filed by the same group of inventors. In the swell case, there is an apparent burst of patenting in 1999, but it is made up of patents from several different inventor groups. Furthermore, an inspection of the patent titles and abstracts would show that the patents in the spike case (except the first from the other group) are all related to the same invention (a particular type of fiber optic, discussed further below) while those in the swell case cover a range of topics within the Measuring and Testing subject area.

Figure 3.10 Sample spike (left) and swell (right) patent patterns by inventor group
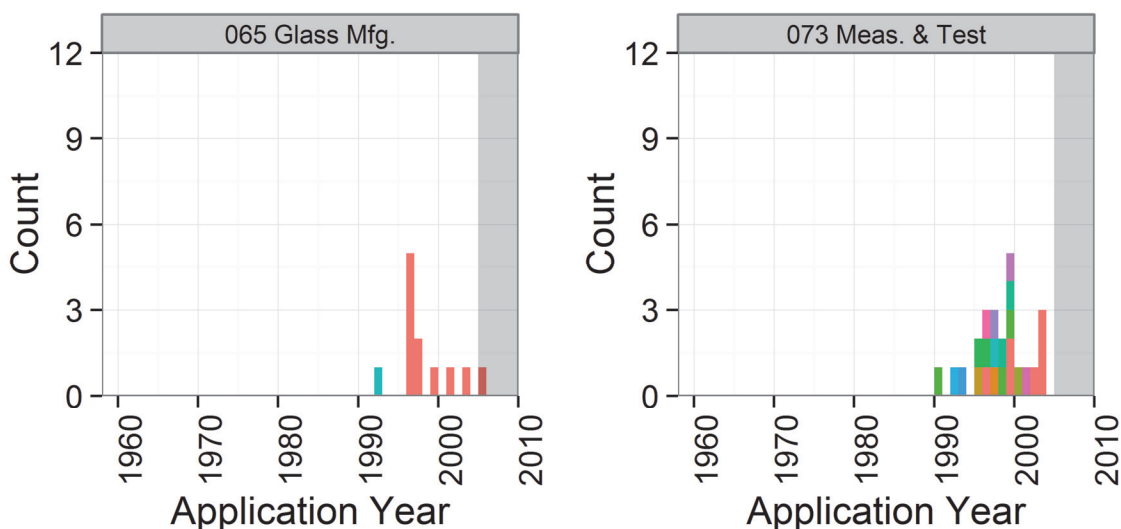
Since the visual signature of a patent spike – a burst of patenting in one or two years that sticks out above the rate of patenting in the rest of the class – can occur by chance in a noisy steady-work case, this study requires at least three related patents filed by the same inventor group within two years in order to classify the visible patent trend as a spike rather than as another pattern. If the visible spike is attributable to multiple inventors, and the rate of patenting in the class otherwise is flat, the trend is classified as steady-work.[56]

Distinguishing spikes from other patterns therefore requires an additional data preparation step beyond what is required to generate the basic histograms: labeling patents based on the group of inventors to which they belongs. To perform this step, this study has implemented an automated, name-matching, network-tracing algorithm that labels each patent in the data set by

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[56] Note that visible spikes that are part of an overall increasing trend are classified as swells regardless of the number of inventor groups active in the apparent spike because the overall increasing trend is considered dominant to the work of any particular inventor group. This phenomena is discussed further section 3.6.3.

its inventor group (a number between 1 and X).[57] In addition, because the inventor names have not been cleaned,[58] for any Patent Trend Diagram in which there may be a spike, the methodology also involves manually scanning the inventor names to check for errors in group assignment.

Spike cases must not only come from the same inventor group, they must also cover closely related subject matter. Confirming that the patents in the spike case are indeed closely related follows a similar, but less strictly objective process: reading the titles of patents in a potential spike, which on several occasions have been nearly identical, or reading the patent abstracts if the titles are not sufficiently clear.[59] While inventor groups are unambiguously defined – specific inventors either do or do not patent with each other – the degree of similarity in title or abstract that is sufficient for a spike is left to the judgment of the researcher.

For example, all of the patents in the spike example in figure 3.8, except the first in 1995, were filed by Ishwar D. Aggarwal, Jasbinder S. Sanghera, and one or two co-inventors drawn from a pool of 10 recurring individuals.[60] As shown in Table 3.3, the patents in the spike also have similar titles. Many of the titles share words and phrases such as "producing" or "making" "core/clad glass optical fiber". This degree of similarity is sufficient to call this set of 11 patents a spike.

Table 3.3 Patents application year, number, and title for spike example

Application year	Patent number	Patent title
1996	5735927	Method for producing core/clad glass optical fiber preforms using hot isostatic pressing
	5779757	Process for removing hydrogen and carbon impurities from glasses by adding a tellurium halide
	5879426	Process for making optical fibers from core and cladding glass rods
	5900036	Multi-cylinder apparatus for making optical fibers, process and product
	6195483	Fiber Bragg gratings in chalcogenide or chalcohalide based infrared optical fibers

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[57] Inventor names are provided in the USPTO patent grant bibliographic data release, although they are in a separate file from the main bibliographic information.

[58] For example, an inventor may include his or her middle initial on one patent application but not on another.

[59] Patent abstracts are available at the USPTO website or through Google Patents

[60] Interestingly, the effects of mentoring may be visible at the end of this trend. The first listed inventor of the final patent in this group is one of Aggarwal and Sanghera's early co-inventors, Brian Cole. Cole's patent for an application of chalcogenide fibers is filed with a co-inventor who had not previously appeared in this group.

Application year	Patent number	Patent title
1997	5846889	Infrared transparent selenide glasses
	5949935	Infrared optical fiber coupler
1999	6021649	Apparatus for making optical fibers from core and cladding glass rods with two coaxial molten glass flows
2001	6526782	Multi heating zone apparatus and process for making core/clad glass fibers
2003	7197899	Multi heating zone apparatus and process for making core/clad glass fibers
2005	7245424	Amplification device utilizing thulium doped modified silicate optical fiber

Impact of missing data on the detection of spikes

Note that missing data may cause some actual spikes to be unobserved. If the data include two closely-related patents from an inventor group, and a third patent exists but was missing from the TechMatch data, then the laboratory will not get credit for that spike in this study. This method therefore produces a lower estimate for the number of spikes in a lab's portfolio.

3.6.3 Swells

Classifying a particular patent trend as a swell involves all three classification steps mentioned in the introduction to section 3.6: visually identifying a likely candidate, examining the inventor groups, and testing for the likelihood that the observed trend is not due to missing data or noise. First, swells involve a gradual increase in patenting, rather than concentrated burst seen in swells. Second, in swells the increase in patenting is usually attributable to the actions of many different inventor groups rather than just one. Third, the increase in patenting should be sufficiently large as to be statistically different from the result of random fluctuations in the year-by-year rate of patenting. The following subsections expand on each of these points.

Visually identifying swells

The third pattern is called a swell because of the sustained rise in patenting rates shown in the histogram. Also note that the cumulative sum line for these cases bears a resemblance to a full or partial s-curve. Figure 3.11 shows a swell with a more complete s-curve-like cumulative sum. The histogram shows the number of ultimately issued patents growing at an increasing rate from 1987 through 1999 and then decreasing through the end of the data set. The cumulative sum line has a corresponding s-curve-like shape. Note that any observed drops in the rate of patenting that

begin around 2005 may be the result of delays in the processing of patent applications rather than an actual decline in the rate of patenting at the organization.

Figure 3.11 Swell example with cumulative sum line
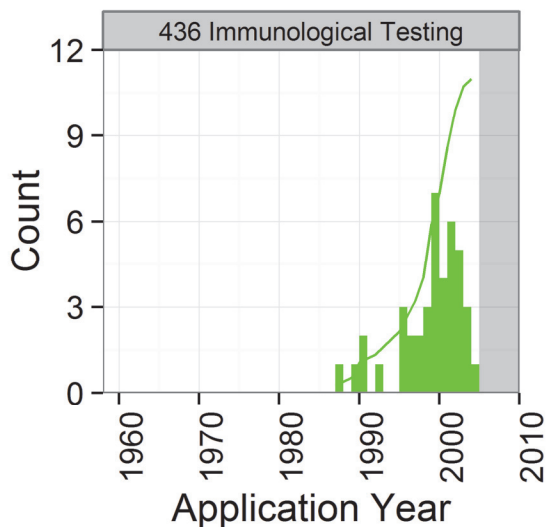
Examining inventor groups in swells

Swells, as observed in this study, tend to be the result of multiple inventor groups. Occasionally one large and highly productive inventor group is responsible for the majority of patents in a swell, but in these cases the patents tend to cover a wider range of subjects than would be the case in a spike. Swells can also include small spikes within the larger trend, but for classification purposes the swell trend is considered to be dominant pattern. Swells therefore have the connotation of a sustained program in contrast to the spike's more project-like profile.

Examining the inventor groups in swells involves the same process as examining the inventor groups in spikes. Using the inventor group labels described above, by-inventor-group visualizations such as figure 3.10 will quickly show whether a potential swell involves few or many different inventor groups. A manual scan of the inventor names will quickly confirm whether this is the case. If one inventor group appears to be dominant, then the person performing the classification will have to judge whether the patents are sufficiently related to classify the pattern as a spike rather than a swell.

Using change-point detection to classify swell patterns

Determining whether the rate of patent filings is trending upwards to a sufficient extent to be classified as a swell as opposed to noisy steady-work depends primarily on the researcher's judgment. The limited number of data points in each histogram and the lack of a known underlying distribution limits the types of statistical methods that can applied to this situation.

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However, there are some trend detection methods that can assist researchers in pattern identification. This study uses a version of the bootstrapped CUSUM change-point detection method (Taylor, 2000) to estimate the likelihood that the mean rate of patenting shown in a patent trend histogram is changing over time. Swell patenting patterns should show an increase in the mean rate of patenting over time, possibly followed by a decline in the mean rate.

The CUSUM method monitors the cumulative sum of the distance between each observation and the sample mean in a sequence of observations (Page, 1954). The first step is to calculate the series of CUSUM points using the equation

$$S_0 = 0; S_i = S_{i-1} + X_i - \bar{X}, \text{ for } i = 1,2, \dots, \#years$$

where $\bar{X}$ is the mean observed annual patenting rates, X_i is the number of patents received by the organization in year i, and S_i is the value of the CUSUM line in year i. If the observed patenting rate consistently trends below the mean for a period, the CUSUM line will trend negative. If the observations consistently trend above the mean, the CUSUM line will trend positive. If the observations are randomly distributed around the mean, the CUSUM line will tend to be flat.

If the characteristics of the underlying distribution are known, then the likelihood of observing a trend in the CUSUM statistic of a certain size under the null hypothesis of a constant generating distribution can be calculated (Page, 1954). If the underlying distribution is not known, as is the case here, bootstrapping can be used to estimate the likelihood of a given CUSUM trend. This study uses the bootstrapping method described in Taylor (2000).

Taylor's approach uses as the test statistic the difference, S_d, between the maximum and minimum value of the CUSUM line S_i. To estimate the likelihood of observing an S_d as extreme as calculated for the observed sequence, the method randomly reorders (i.e. bootstraps) the observed data points to create a new sample drawn from the same underlying distribution. A CUSUM line and S_d are calculated for each new sample. This procedure is repeated multiple times, Taylor (2000) recommends 1000 iterations, to produce an approximation of the cumulative distribution function for S_d. The likelihood of observing a test statistic smaller than the original S_d^0 if all of the observed data points are randomly drawn from the same distribution is the fraction of resampled S_ds that are smaller than the original, i.e.

$$P(S_d < S_d^0) = \frac{number\ of\ resampled\ S_d < S_d^0}{numer\ of\ resampling\ iterations}$$

A $P(S_d < S_d^0)$ above a certain threshold (e.g. 0.90, 0.95, or 0.99)[61] indicates that the observed trend in the CUMSUM line is unlikely to occur if there is actually no change in the mean rate of patenting over time. Therefore, the null hypothesis of a constant mean should be rejected. This study investigates all histograms with a $P(S_d < S_d^0)$ above 0.80 as possible swells. Note that the CUSUM is calculated using only patents with application dates between 1990 and

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[61] Note that $P(S_d < S_d^0)$ is defined here and in Taylor (2000) in the opposite direction of the traditional p-value. P-values usually test the liklihood that of a test statistic greater than or equal to some threshold instead of less than.

2004 in order to avoid a false positive caused by the drop-off in data at the edges of the data sources' date windows.

The CUSUM test is not an automatic detector of swells. Very large spikes followed by low-count steady-work can trigger a positive result as can low-count steady-work with long blocks of zero patents followed by long blocks of a few patents. Figure 3.12 shows the patent histogram, CUSUM line, and $P(S_d < S_d^0)$ for two steady-work cases and a swell case. In the first steady-work case, the CUSUM line is flat and $P(S_d < S_d^0)$ is near zero. In the second steady-work example, the few patents in the case occur in clusters that trigger the detection threshold. In contrast, the third example shows the extent of trend in the CUSUM that is seen in a large swell.

Figure 3.12 Sample CUSUM results for a true negative (steady work), false positive (steady work) and true positive (swell) case
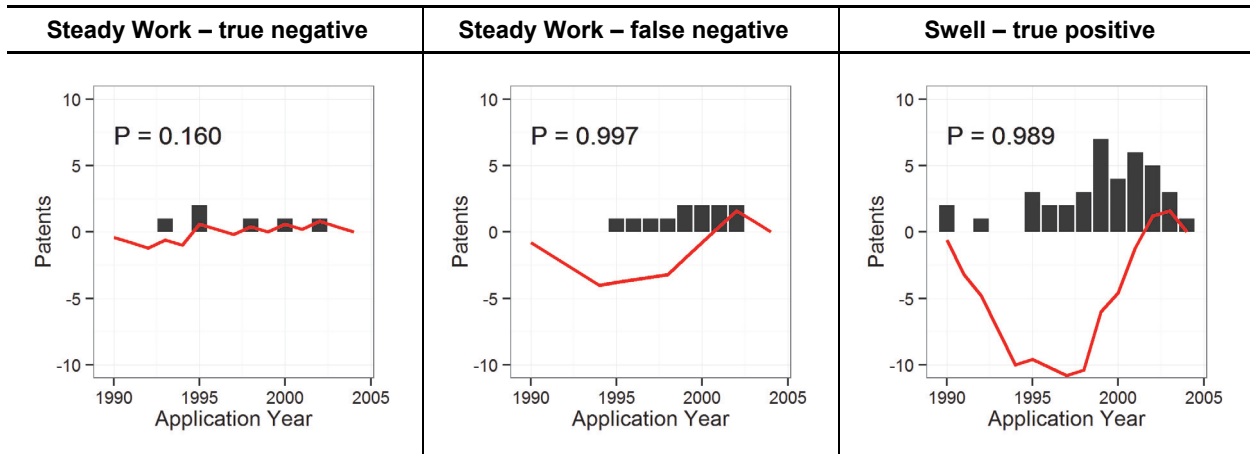
Note: CUSUM line shown in red over the patent histogram (black bars). CUSUM probability of trend shown on graph. Middle case is classified as steady work because maximum rate of patenting remains below 2 patents per year.

Because of false positives like the one shown in the middle cell of figure 3.12, the CUSUM test should be used in combination with a visual inspection of the histogram and a scan of contributing inventor groups and patent titles. This study uses the following two rules to determine whether a sequence of patents flagged by the CUSUM algorithm is a swell or is better classified as another pattern.

1. In order to be classified as a swell, the number of patents per year must reach three or more in at least one year. Given the volume of possible missing data, it seems unreasonable to call a trend of one or two patents per year growth even if this low-rate of patenting is an increase from zero in the early years of the data set.
2. If a spike (as determined from a scan of inventor groups and patent titles) exists in the class and is large relative to the number of non-spike patents, recalculate the CUSUM without the spike. If the trend remains significant, then the sequence of patents is likely better classified as a swell. If the trend disappears when the spike is excluded, then the sequence is better classified as a spike.

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Subject to these two conditions, all trends with a $P(S_d < S_d^0)$ above 0.80 are classified as swells. These rules will classify as swells patent trends that increase from zero to three patents per year near the end of the date range and patent trends that include of one or more spikes within an overall increasing rate of patenting.

3.6.4 Submarines

The fourth and final patent trend identified by this study is the submarine. The submarine trend is visible in the Patent Trend Diagrams because of the difference between filing (or application) dates and issue (or grant) dates. The filing date is the date the organization submitted the patent to the patent office. The issue or grant date is the date the patent office officially approves the patent. This dataset only contains patents that were *issued* in 1990 or later. Therefore, excepting special circumstances, it should include no patents that were filed earlier than around 1980 because they should have been already issued prior to 1990.[62] The submarine trend highlights when one of those special circumstances has occurred. In the DOD context, one likely special circumstance is the patent secrecy order.

In the submarine example in figure 3.8, there is a cluster of patents *filed* in the 1970s, then no patents, and then another cluster of patents filed in the mid-1990s and early 2000s. However, this does not mean NRL was performing no work in this technology class in the 1980s. The lab may have other patents that were filed in the 1980s that were also issued in the 1980s and therefore do not show up in this dataset.[63] The early cluster of patents in figure 3.8 were filed in the 1970s but were not issued until sometime after 1990, a delay of 20 to 30 years. One patent in figure 3.8 was filed in 1958 but not issued until 2003. One possible cause of this 45 year delay is secrecy.[64]

At the request of a defense agency, patent applications may be held under a secrecy order. "A secrecy order withholds the grant of a patent, orders that the invention be kept in secrecy and restricts filing of foreign patent applications," (Federation of American Scientists, 1991). When a patent application is under a secrecy order, the USPTO will continue to process the application and determine whether it is to be accepted or rejected, but they will not publish the application or actually issue the patent until the secrecy order is lifted (see 37 C.F.R. § 5.3). Secrecy orders expire after one year unless renewed by a request from a government agency, although additional

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[62] Recall it takes on average about 3 years and sometimes more than 5 years to approve and issue a patent

[63] Also, these may not be the only patents the lab filed in the 1960s and 1970s. Deducing the explanation for this statement is left as an exercise to the reader.

[64] In the private sector, it was possible, until 2001, to create a similar effect by constantly revising a patent application. Using this technique, private companies could maintain a trade secret but also establish priority in the event that a competitor independently discovered and attempted to patent a similar technology. In 2001, the patent office began publishing all applications (except secret applications per above) 18 months after they were filed, removing the ability to keep such applications secret. Because these patents with long delays between filing and granting would stay unpublished and hidden, or "underwater" for so long, these types of patents were called "submarine patents" (Graham & Mowrey, 2004, p. 447). This study borrows this terminology to label the pattern that shows these types of patents.

laws may still prevent the disclosure of certain information, particularly technical data that has been classified by the DOD (USPTO, 2012a).

Note that patent secrecy orders are not the same thing as Confidential/Secret/Top Secret classification by the U.S. government, although a patent for a technology that has been classified as Secret will likely receive a patent secrecy order. There are three types of secrecy orders. The first, and least restrictive, identifies patents that include export controlled technologies. Owners of patents covered by these "Type 1" secrecy orders may disclose the content of their patents for "legitimate business purposes" as long as they comply with applicable export control laws (Federation of American Scientists, 1991). The second, Type 2, secrecy order specifies procedures for handling classified material at the USPTO. Type 3 secrecy orders instruct the USPTO to withhold the disclosure of patent applications that are not officially classified but do contain information that could be detrimental to national security if published (see Federation of American Scientists (1991), USPTO (2012a) chapter 0100 section 120, and 25 USC § 181).

The early patents in the submarine example are likely patents that the government filed in the 50s, 60s, and 70s, but were covered by a Type 2 or 3 secrecy order until sometime in 1990s. All are in subject areas that were conceivably classified. The earliest patent in the example, filed in 1958, is for a concept related to stealth technology. The patents in the main group are related to the analysis and filtering of radar side-lobes, a technique that was related to several radar improvements being developed or improved in the 1960s and 1970s including over-the-horizon radars and phased array radars (Chapman, n.d.; Howard, n.d.).

If the government does not excessively and trivially request patent secrecy orders, then submarine patents are significant inventions.[65] However, they will not be a major focus of this study, primarily because submarines are a secondary effect. Submarines exist within technology-class histograms in addition to the steady-work, spike, or swell trend. For example, the more recently filed patents in the submarine case in figure 3.8 form a low-volume steady-work pattern. Therefore, this study will focus on explaining and using the three primary patterns: steady-work, spikes, and swells.

3.7 Constraints and Limitations

As mentioned in section 3.4, the data set used in this study does not contain a complete list of patents for all DOD labs. This missing data plus natural variations in patent activities in a lab each year introduces some uncertainty to the pattern classification process described above. The rule that spikes include at least three related patents filed within two years by the same inventor group and the CUSUM test for swell-related shifts in the mean annual patenting rate are designed to address this uncertainty. However, there are two additional limitations that should be

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[65] 5321 secrecy orders were in effect during fiscal year 2012 (Aftergood, n.d.) compared with 253,155 patents granted in 2012 (USPTO, n.d.).

noted. First, this analysis is performed at the primary class level rather than at the technology subclass level. This has the effect of aggregating a laboratory's work in different but related technologies into one trend. Second, by focusing only on active classes (those in which a lab has at least 6 patents), this study implicitly suggests that a lab's patents in just their active classes are representative of their primary research focus areas.

3.7.1 A note on level of technology aggregation

Note that the pattern analysis in this study is conducted at the class level because there is generally too little data in any given lab's *subclass* portfolio to identify any pattern other than steady-work. The USPTO defines around 500 technology classes, with around 150,000 subclasses defined in a hierarchical system beneath those classes.[66] Organizations observed in this study typically have fewer than 5 patents in any one class, and only in the largest laboratories did the number of patents in any one class reach the low-triple digits. (Figure 3.13 shows the distribution of patents per class in each laboratory's portfolio.) Therefore, since there may be hundreds of subclasses beneath any one class, most organizations will have few to no patents in any given subclass.

Low numbers of patents per subclass mean that most subclass portfolios will appear to be low-count steady work cases. Even at the class level, the dominant pattern for most laboratories is low-count steady-work. However, in theory, all of the patterns described here from the class-level data may also exist within subclasses, providing a more detailed view of an organization's work by showing trends within more narrowly defined technologies. Since the subclass structure is hierarchical, there may be some intermediate subclass level that still provides interesting insights. Examining the relationship between the hierarchical structure of subclasses and patenting patterns remains an area for future work.

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[66] Based on an analysis of classes and subclasses listed in the Jan. 6, 2012 USPTO master classification file.

Figure 3.13 Distribution of patents per technology class for DOD TechMatch dataset (by lab)
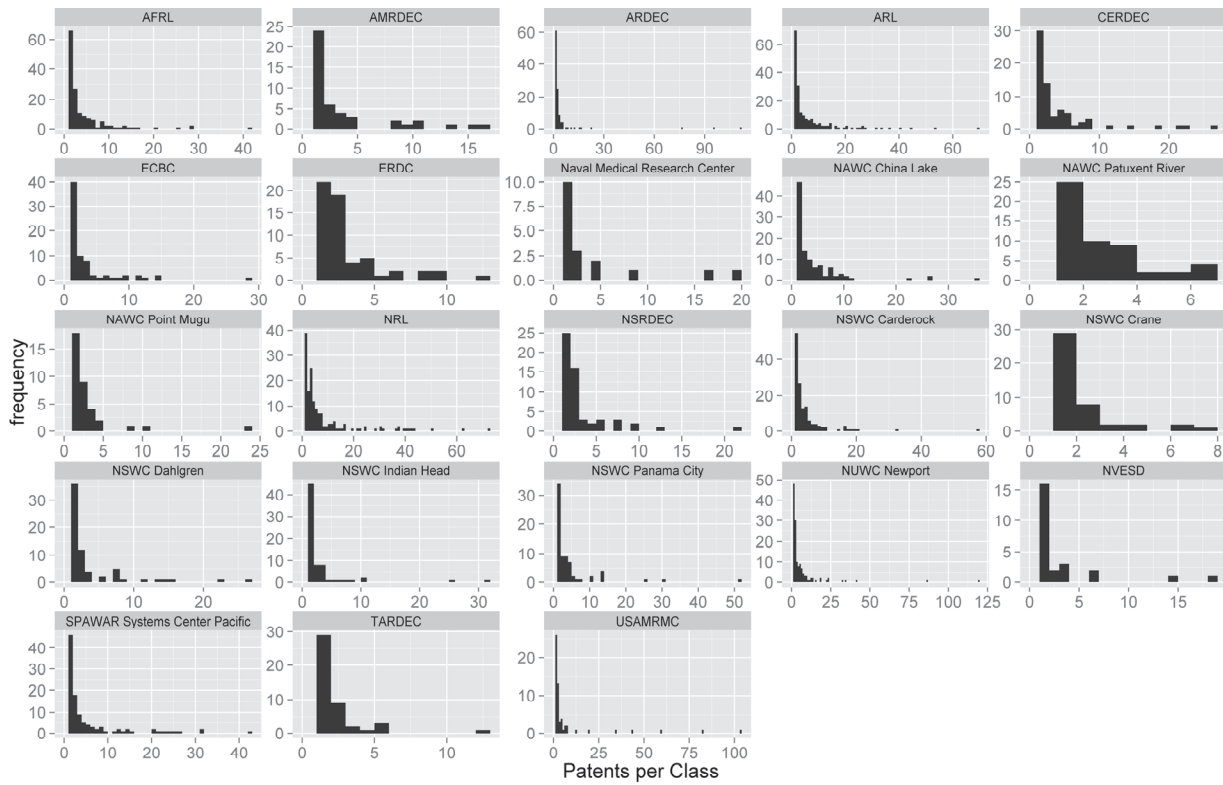
Note: Horizontal and vertical scales vary by lab.

Notice that in Figure 3.13 there is a break in the distribution around 5 patents per class in many cases, and in all cases the tail of the distribution is reached by 10 patents per class. In order to focus this study on the technology areas with the highest volume of patenting, this study only examines technology classes in which the lab has at least 6 patents. These are the lab's "active" technology areas. The term "active" is used to distinguish these higher-patent-population classes from those that are referenced only few times within the lab's patent portfolio and therefore may be tangential to rather than a core part of the lab's research efforts. While there can still be a lot of noise in lab-class combinations with fewer than 10 patents, indicated by frequent jumps in the numbers of patents per year or long gaps between the appearance of patents in the portfolio, a threshold of 6 patents per class strikes a balance between a more complete view of lab activities and having sufficient data to draw inferences by class.

Limiting the analysis to only classes in which a lab has at least 6 patents can delay the detection of current spikes if they are emerging in a class for which the lab has little or no prior work. This is less of an issue if the spike occurs in a class for which the lab already has an amount of steady work since the steady work patents may be sufficient to register the class as active. However, a three-patent spike in a class with no other prior work will go undetected. The detection of currently rising swells would be delayed even without this restriction since the

pattern is unlikely to trigger the swell detection methods described above until the total volume of patenting in the class exceeds six patents total.

3.7.2 Validity of patent trends as an indicator of research activity

Patent data may not capture all or even most of the research activities that occur at a DOD laboratory. Section 3.4 notes that the data set appears to include a range of patent technology classes for each lab that is plausibly representative of the full range of technology focus areas assigned in the lab's mission. This establishes some confidence that a patent-based analysis can encompass a representative set of research activities for the labs. A further check on the validity of interpreting patent trends in active classes as indicators of the primary research focus areas of the laboratory is to examine the fit between the variety of *active* classes in a portfolio and the stated mission of the lab.

The DOD laboratories are not necessarily free to pursue any technology they wish. Many of the labs, arguably all of the labs except ARL and NRL, have fairly limited missions.[67] If the patent trends are good indicators of a lab's primary research activities – as opposed to, for example, being linked to spinoff technologies that are unrelated to the lab's core research mission – then the patent portfolios of labs with broader technology missions should include more active technology classes than those of labs with narrower missions. However, this analysis must first control for the relationship between portfolio size and the number of active classes.

Figure 3.14 plots the laboratories by two measures of portfolio size: total patents in the dataset (horizontal axis) and the total active classes amongst those patents (vertical axis). The circles in figure 3.14 mark clusters identified with the k-nearest-neighbor algorithm.[68] The line shows the best linear fit, using simple linear regression, for the relationship between total patents and total active classes. The gray area shows the 95% confidence interval for the fit. The fit equation and R-squared value are shown as well.

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[67] The technology focus areas of each of the DOD labs are listed in Appendix D.

[68] The k-nearest-neighbor algorithm minimizes the sum of square distance between the cluster's center and each of its members. The user specifies the number of clusters to attempt. See documentation for the R package cluster or Hastie, Tibshirani, Friedman, & Franklin (2005) for more details.

Figure 3.14 Lab clusters by portfolio size and class variety

$$y = -0.64 + 0.076 \cdot x, \ r^2 = 0.953$$

1 - NRL
2 - ARL
3 - NAVSEA Newport
4 - AFRL
5 - SPAWAR Systems Center, Pacific
6 - NAVSEA Carderock
7 - NAVAIR China Lake
8 - NAVSEA Dahlgren
9 - ECBC
10 - CERDEC
11 - USAMRMC
12 - NAVSEA Panama City
13 - ARDEC
14 - AMRDEC
15 - ERDC
16 - NSRDEC
17 - NAVSEA Indian Head
18 - NAVAIR Patuxent River
19 - NVESD
20 - Naval Medical Research Center
21 - NAVAIR Point Mugu
22 - Redstone Technical Test Center
23 - NAVSEA Crane
24 - TARDEC

Given that the relationship shown between total patents and number of active classes is linear, one could argue that the main driver of portfolio class variety is just portfolio size: labs that tend to patent more will tend to have patents that touch on more technology classes and will therefore have more active classes in their portfolios. However, this study's data set includes fewer active classes for any given lab than expected given the number of patents in the lab's portfolio, the mean number of technology class assignments per patent, and the number of technology classes that exist. Consider the following example.

While any single patent could be assigned to any number of classes, in practice the average number of classes per patent is 4.4 (Strumsky, Lobo, & van der Leeuw, 2012, p. 8). If every patent in a lab's portfolio had the average number of class references and each reference was different, a smaller patent portfolio, such as the one observed for TARDEC which includes only 50 patents, would at most cover 220 classes. A larger portfolio, such as NRL's with over 700 patents, could in theory touch on the entire range of patent technology classes (around 500).[69] Yet, something seems to have a strong constraining effect on the actual variety of classes

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[69] Note that this argument could, in theory, go in either direction. While including more patents increases the possible number of classes related to the portfolio, a lab that wanted to have a portfolio that touched on more technology classes would, by the same logic of constrained numbers of classes per patent, need more patents to do it.

observed in a portfolio despite the total number of patents. TARDEC's automotive-focused patent portfolio actually includes only 1 active (and 44 other) classes. NRL's portfolio covers only 54 active (and 101 other) classes rather than the full 500.

A lab's technology mission may be, and arguably should be, a strong constraint on the variety of classes in the lab's patent portfolio. Mission-based constraints can plausibly explain the clustering in figure 3.14. The clusters in figure 3.14 can be described in terms of the level of class variety. NRL, ARL, and NAVSEA Newport are in the "high variety" group with 54, 53, and 34 active classes respectively; AFRL and several Navy Warfare Centers make up a "mid variety" group with 20 to 30 active classes;[70] and the Army RDECs and the rest of the labs fall in the "low variety" group with fewer than 12 active classes each.

The clustering of labs into high and low variety groups can be interpreted as a clustering of wide and narrow mission labs. In the high-variety group, NRL and ARL both have broad missions that, through their basic research portfolios, can touch on nearly any area of technology. The Navy Warfare Centers, which fall in the mid and high variety groups, have missions that are focused on types of Navy systems (air, sea, space & cyber), but within those domains they work on a range of technologies including computer systems, electrical systems, and munitions. In contrast, the Army RDECs, which form the majority of the low-variety group, could plausibly be described as having responsibility for more specific technologies in a narrower set of classes such as electronics and sensors (CERDEC), food and clothing (NSRDEC), which could be considered narrower than the other mission descriptions.

Given these clusters, the number of active classes in each DOD laboratory's patent portfolio seems plausibly representative of the number of technologies included in the lab's mission. This finding increases the confidence that patents in the lab's active classes can be interpreted as representative of a lab's primary research areas. It also increases the confidence that this data set includes a representatively complete range of technologies for each lab – with the possible exception of AFRL, which perhaps should be in the high variety group since it encompasses all of the Air Force's S&T research.

3.8 Final Steps – from patterns to innovations

Visualizing an organization's patent portfolio as technology class histograms, and classifying those histograms by patenting pattern, can clarify the type of work a research organization performs, the organization's relative emphasis on work across fields, and how their work has changed over time. This is useful for understanding and monitoring the focus, or technological

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[70] USAMRMC and ARDEC are outliers in this group. Both USAMRMC and ARDEC have over 200 patents, which suggests they should be mid-variety labs like China Lake, but their total number of active classes, 11 and 10 respectively, are closer to the low-variety labs. With approximately 10 fewer active classes, perhaps USAMRMC's medical research and ARDEC's armaments research are related to fewer patent classes than China Lake's aviation and missile research.

competencies, of a research organization. However, the primary goal of this study is to produce an indicator of innovative research.

Technology-class histograms can be indicators of innovative research in two ways. First, some of the behaviors that may produce spikes and swells suggest that the organization believes certain research products will become widely used, one of the criteria for an innovation. Second, independent of the organization's hopes for their work, where an organization's patenting pattern falls relative to the trend in the field as a whole (i.e. relative to the pattern made by all patents filed in that technology class), early or late, can be an indicator of innovation. This second method builds on the concept of technology s-curves in the patent record as a signal of innovation by comparing an organization's entire trend to the field s-curve rather than comparing the timing of individual patents as done in Eusebi (2011). Chapter 4 develops these ideas and explains how to estimate the relative locations in time of two patenting patterns.

However, in addition to being an indicator of innovation, an organization's patenting patterns could also be used as a tool to identify and monitor the organization's research and commercialization processes. If certain research approaches are more likely to produce spikes than swells or steady work, then a lab that predominantly employs that approach should have a portfolio with a preponderance of spikes. By this reasoning the fraction of spikes, swells, steady work, and submarines in a lab's patent portfolio can be used as an indicator of its particular approach to conducting research. If some approaches are more desirable to managers than others – for example using a near-term versus a long-term research focus – and those approaches have distinct patenting signatures, then the pattern fraction can be used as a monitoring tool to assess the fit between the lab's actual practices and the desired performance. Chapter 5 demonstrates approaches for using patenting patterns as either organizational classification tools or as output measures in the study of research practices.

Chapter 4 Patenting Patterns as Indicators of Innovation

As discussed in the first and second chapters of this dissertation, measuring innovative research performance continues to be a challenge in the study and implementation of science, technology, and innovation policy. Given the difficulty of observing outcomes, most studies and evaluations of government research organizations rely on expert evaluations (aka expert or peer review) to determine the health and performance of the research enterprise (see chapter 2). To the extent that patents are used to evaluate government research organizations, they are used as bibliometric indicators of knowledge production in a manner similar to academic journal articles.

This study proposes an alternate approach to analyzing the patenting trends of research organizations which more directly relates to an organization's ability to produce used innovations. Chapter three introduced four patterns that can be observed in the by-technology-class patent portfolios of research organizations. This study hypothesizes that these patterns are not the results of random chance but are instead the signatures of specific research and commercialization activities within organizations. More specifically, organizations, this study hypothesizes, employ the activities that generate patent spikes and swells when they are pursuing technologies they believe will be highly useful. If innovations are defined as novel and widely-used inventions, then under this hypothesis patent spikes and swells are indicators of potential innovations.

Determining whether the inventions embodied in spike or swell patents were actually used, and therefore represent actual innovations, requires additional information beyond observing the existence of a pattern. Tracing the eventual disposition of patented inventions through interviews or other general case study methods would perhaps be the most certain way of confirming use, but such methods are quite resource intensive (Ruegg & Jordan, 2007). A faster but less direct approach is to locate an invention along the technology maturation curve (aka s-curve). Inventions that emerge near the take-off inflection point of their technology s-curves are innovative in the sense that they were early and possibly foundational contributions to a field that became widely used (see section 2.3 and Eusebi (2011)). However, organizations that have early patents and continue to increase their rate of patenting during the technology's growth stage have likely recognized the importance of the technology and are attempting to improve their competitive position in the field (see comparison of German and Japanese machine tool patents in Ernst (1997)). Therefore, the relative location of an organization's patenting pattern along the technology class patent s-curve can be an indicator of the actual, rather than hoped-for, innovativeness of its underlying inventions.

This chapter develops these ideas in two phases. Section 4.1 presents a theory linking research and commercialization activities to specific patenting patterns and uses examples from the DOD laboratories to illustrate the extent to which spike and swell research activities indicate

the pursuit of innovation. Section 4.2 demonstrates how to compare an organization's patenting pattern to the full-field's technology s-curve in order to produce a measure of actual innovativeness.

4.1 A theory of patenting behavior

4.1.1 What activities generate steady-work?

As an introduction to thinking about the activities that yield different patenting patterns, consider the case of steady-work patenting. This study hypothesizes that the steady-work patenting pattern is the result of most organizations' default research and commercialization activities. Within the DOD laboratories, the majority of technology class histograms (57%) are steady-work cases, suggesting that steady-work patenting is indeed what happens most of the time. The theoretical argument for this hypothesis is as follows.

Research organizations have certain technology areas in which they have established lines of work and certain established rules for patenting the outputs of that research. If neither the subject of the research, the intensity of the research, the productivity of the research (including sudden serendipitous breakthroughs), nor the intensity of patenting changes, then there should be no change in the rate of patenting from year to year. In other words, if

- $D_{t,o}$ is the amount of resources (e.g. dollars and people) organization o puts into researching technology area t,
- $R_{t,o}$ is the rate (per year) at which the organization can turn those inputs into patentable discoveries,
- $P_{t,o}$ is the rate (per year) at which the organization converts research discoveries into patent applications in class t, and
- $A_{t,o}$ is the rate at which the patent office accepts and grants patents to organization o in class t,

then the number of patents organization o receives in class t per year, $N_{t,o}$, is a function of these terms.

$$N_{t,o} = f\left(D_{t,o}; R_{t,o}; P_{t,o}; A_{t,o}\right)$$

A change in any one term will change the rate of patenting from that point forward.[71] A brief increase in the rate of patenting, which then returns to the previous rate, produces a spike pattern. A consistent compounding increase in the rate of patenting, followed by a leveling off at the final higher rate, produces the swell pattern.[72]

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[71] Recall that this study includes only issued patents, therefore the patent office's rate of acceptance is a factor in the rate of patenting visible in the histograms.

[72] Note that submarine patterns are the result of a different process. As explained in section 3.6.4, in submarines the patent office delays the issuance of a patent for many years. This could be modeled as a temporary decrease in $A_{t,o}$, the rate at which the patent office accepts patents from the organization. However, the analogy does not quite fit

Spikes and swells could be the result of a change in any of the parameters above. For example, if an organization increases the dollars and people employed in one technology area for several years (increase in parameter $D_{t,o}$), the amount of patentable knowledge generated in that technology area should increase each year, and a swell would appear. Hiring one new researcher who is interested in pursuing a particular idea could temporarily increase an organization's research productivity ($R_{t,o}$) in a given technology area while that idea is played out.[73] However, after a few years, that researcher may return to some lower baseline level of productivity while searching for his or her next big idea. In this case, a spike would appear in the organization's patent portfolio.

The rest of this section uses brief case studies of DOD research projects and programs to illustrate more specifically how changes in these parameters lead to spikes and swells. The case studies use data collected via interviews with patent attorneys and technology transfer personnel at the laboratories, interviews with research managers or the inventors themselves when possible, and reviews of archive material including the patent itself, the inventors' CVs and online bios, papers and books written by the inventors, and any articles that talked about the work, for example on the occasion of the inventors receiving an award.

4.1.2 What activities generate spikes?

Recall that patent spikes are clusters of three or more patents issued within two years to the same group of inventors on closely related material. Single inventions may be protected by several patents because of actions initiated by the patent office or by the inventing organization. Using the framework presented above, changes in any of four rates can yield a spike. However, because spikes are an isolated and short-term burst in patenting, those changes are only temporary and all parameters return to their previous levels.

For example, if the laboratory thinks it has found an idea with large commercial potential, they may apply more resources to research in that field, experience a burst of productivity as researchers become more focused and inspired, and they may selectively apply for patents related to that technology over others. However, once that project is completed, the level of work in that technology area returns to its former level.

Alternately, decisions made by the USPTO itself may create a spike. The patent office may decide that what the organization sees as a single invention is actually several different patentable inventions according to patent law and instruct the lab to file separate patents for each piece. This can occur, for example, in biological research in which each of several chemical compounds is a separate patent even though they are being used together for a common effect. The organization may be trying to patent the use of the chemicals in aggregate, but the patent

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because the delay applies only to certain patents and not to all of the patents the organization filed in that class that year.

[73] Research resources, ($D_{t,o}$), would increase slightly as well in this scenario.

office requires a separate patent for each compound in addition to the combined application (Personal Interview, 2012).[74]

Regardless of whether the driving factor was internal or external to the lab, patent spikes represent inventions which cost the lab more money than usual to protect. Office of Research and Technology Applications (ORTA) personnel interviewed for this study estimated that each patent application cost the lab between $5,000 and $10,000.[75] An invention covered by a 3-patent spike (the smallest possible spike) therefore cost the lab between $15,000 and $30,000 in intellectual property protection. Even if multiple patents filings were requested by the USPTO, it is reasonable to believe that the lab would only follow-through with a $30,000 cluster of patents if it believed that it would get a higher return (financial or otherwise) from the cluster than from a single $10,000 patent. Based on this reasoning, this study hypothesizes that patent spikes represent inventions that the lab itself believes will have a higher military or commercial impact than the average invention.

Consider two patent spike examples identified during this study, one from NRL and one from NAVSEA Dahlgren. In both cases, research related to military requirements led to discoveries with sales potential, in one case commercial and in the other case foreign military. The ORTAs worked with the researchers to create a cluster of patents protecting this work and to license these patents to other companies. These actions can be described in terms of the variables used above: researchers increased their productivity in a narrow area as they focused on particular breakthroughs ($R_{t,o}$) and the laboratory patent office focused their applications on these particularly promising technologies ($P_{t,o}$).

Spike Case 1: NRL Optical Fibers

This case was already briefly described in the discussion about inventor groups in section 3.6.2. Aggarwal and Sanghera were pursuing the application of fiber optics in several Navy systems. However, to meet their performance needs they required a material that transmitted at higher wavelengths than traditional silica fibers. Fibers made of chalcogen elements (sulfur, selenium, or tellurium) had good theoretical properties, but their manufacture had yet to be perfected (Higby, Aggarwal, & Friebele, 1994; Sanghera, Pureza, Aggarwal, & Miklos, 1998). Aggarwal and Sanghera developed a more reliable manufacturing approach, prototyped it at NRL, and then, since fiber optic manufacturing was not a core NRL mission, licensed the technology to industry and moved on to other projects (Personal Interview, 2012; University of

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[74] The intellectual property literature discusses multiple patent strategies (i.e. patent fences) in terms of their ability to increase the difficulty a competitor faces when trying to invent around a primary patent (see, for example, Gilardoni (2007) page 425). The story told here about the patent office requesting multiple patents to cover what the lab thought of as one invention suggests another, less strategic, reason why firms end up with multiple patents covering closely related inventions.

[75] The ORTA is the office within a federal research organization responsible for coordinating technology transfer activities including the filing and licensing of patents. For authorizing language see 15 USC § 3710 and the Technology Transfer Act of 1986 (Public Law 99-502, 1986).

North Carolina at Charlotte, n.d.). In 2012, Aggarwal and Sanghera received the Dr. Arthur E. Bisson Prize for Naval Technology Achievement which recognizes "individuals who have successfully translated research findings into substantive fleet programs that meet critical Navy requirements," for their fiber optic and transparent ceramics work (NRL, 2012). Their work in chalcogen fiber-optics forms an 11 patent spike for NRL in class 065 Glass Manufacturing (Figure 3.10 left).

The Aggarwal and Sanghera fiber optic work is an example of a coherent project, driven by service needs, that required a deep understanding of fundamental scientific principles, and which, once completed, had significant commercial or military impacts. The second spike case study tells a similar story at a different lab, although the results were less widely used.

Spike Case 2: NAVSEA Dahlgren Firearms

Between 1988 and 1992, two engineers at the Dahlgren Naval Surface Warfare Center, Michael M. Canaday and Fred Watson Jr., were studying several design problems in the Mk 153 Mod 0 Shoulder-Launched Multipurpose Assault Weapon (SMAW) (Delguidice, Monolo, & Bechtel, 1997). The SMAW was originally developed by McDonnell Douglas in the 1980s, with Dahlgren assistance, using as many commercial off-the-shelf (COTS) parts as possible (Delguidice et al., 1997). The Mk 153 Mod 0 combines a British spotting rifle with an Israeli rocket launcher. The spotting rifle allows the user to test the aim of the weapon before firing the rocket. The SMAW is capable of firing several different types of anti-structure and anti-armor warheads. Problems with the Mk 153 Mod 0 include bubbled launch tubes, sand jamming the triggers, and loss of alignment between the spotting rifle and the rocket launcher (Delano, 2003). Rather than tweaking the Mk 153 Mod 0 design to address each issue separately, Canaday called the original design "kludged together" (Delano, 2003), the Dahlgren engineers decided to create an entirely new design, the Mk 153 Mod 1.

This redesign effort resulted in one prototype and 15 patents (Delguidice et al., 1997). All 15 patents do not appear in the TechMatch data set, but four of these patents form a visible spike for Dahlgren in class 042 (Firearms) in 1995. Because they were classified in both class 042 (firearms) and class 089 (ordnance), some of the Mk 153 Mod 1 patents also show up as a three patent spike in Dahlgren's class 089 trend diagram (Figure 4.1).

Figure 4.1 Dahlgren SMAW Patents in the patent trend (colors represent inventor groups)
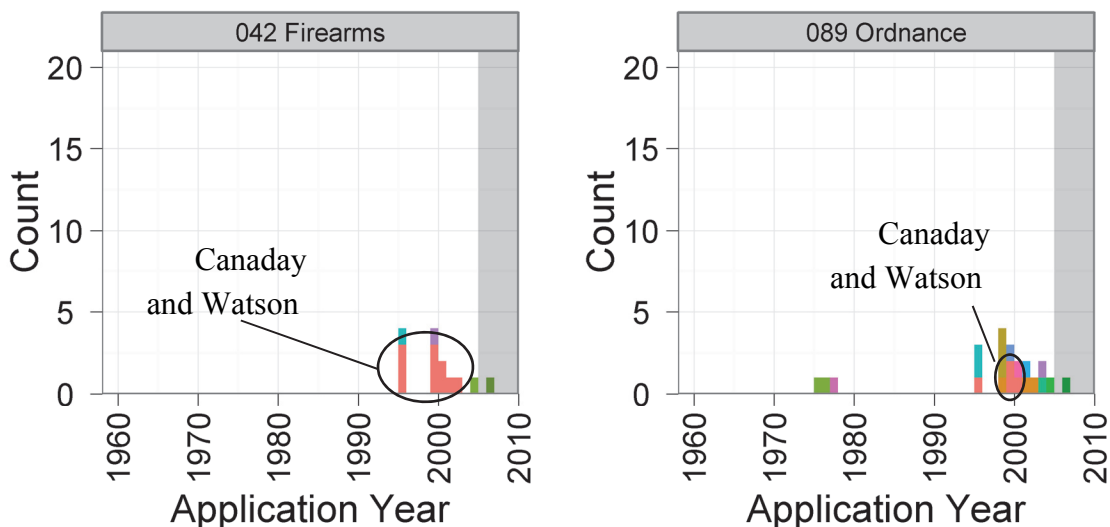
Supporting the idea that inventions that are covered by patent spikes are more commercially valuable than inventions covered by only a single patent, a case study of this invention published by Dahlgren states that the lab pursued a "more is better" patenting approach under the philosophy that "a strong, complete patent portfolio protects a product... by claiming as many new features as possible," (Delguidice et al., 1997). This strategy is sometimes called fencing or surrounding. In patent fencing, a firm files patents for the core invention as well as for related lines of research in order to make it more difficult for competitors to infringe on the main patent by submitting an application for a closely related invention or use (Gilardoni, 2007). However, Dahlgren may not have been as strategic in its use of patent fencing as some commercial firms since the Dahlgren study also notes that "an awful lot of creativity was involved" in deciding which specific aspects of the invention should be protected with a patent (Delguidice et al., 1997).

While the U.S. Marine Corps decided not to pursue the Mk 153 Mod 1 (Delano, 2003), CMS Inc., a subsidiary of Deutsche Aerospace, approached Dahlgren about licensing the Mod 1 patents and forming a CRADA (Delguidice et al., 1997). With Marine Corp approval, Dahlgren partnered with CMS to build a second prototype and further improve the Mod 1 design (Delguidice et al., 1997). Three additional patents related to the Mod 1 were filed in 1999, presumably as a result of this follow-on work. These additional patents are visible as second spikes in Dahlgren 's class 042 (firearms) and class 089 (ordnance) trend diagrams (see Figure 4.1). CMS eventually sold 28 Mod 1s to Taiwan (Delano, 2003).

4.1.3 Spikes as potential innovations

Both of the examples above support the hypothesis that patent spikes are the output of highly successful projects. Both of these cases are examples of projects in which some improvement in performance was needed to meet military needs. Not only did the laboratory's research succeeded in meeting that need, but the results were also sufficiently promising that the lab pursued marketing the results outside the service. In the NRL fiber optic case the need was more basic – a new material with certain optical properties. In the Dahlgren firearm case the need was more applied – improvements to an existing weapon system. In both cases, the projects succeeded in their aims, and the resulting knowledge was used, although use was more extensive in the NRL case than in the Dahlgren case.

It is not a given, however, that all spikes indicate technologies that are actually used. The laboratory expects patent spikes to have a higher than usual chance of generating revenue, but there are several factors that might defeat that expectation. For example, the laboratory could be wrong in its evaluation of the market opportunity; a technical hurdle could be discovered during later-stage development or manufacturing that reduces the profitability of the invention; or the laboratory, which is not in the business of producing and selling products itself, could do a poor job advertising the invention to potential licensees.

Therefore, while it is tempting to say that spikes are examples of innovations because the laboratory expects the inventions to be widely used, additional work would be necessary to confirm actual use of these inventions. Still, patent spikes represent promising technology transition candidates. Performing case studies of patent spikes, such as the ones described above, could be a more focused way of evaluating a laboratory's success in transition discoveries to users.

4.1.4 What activities generate swells?

This study hypothesizes that swells are the result of long-term increases in the rate of research or patent production. One can think of this increase as being directed or undirected. Directed growth, as defined here, is the result of the organization's leadership determining that a particular new technology will be important and purposefully focusing more of the lab's resources on that technology. Undirected growth occurs when researchers independently begin pursuing a new technology without specific and explicit leadership guidance and without directly coordinating with other researchers. For example, directed growth may occur when Service S&T leaders decide that the Service's research should focus more on computer networking-related technologies. Undirected growth may occur, for example, as researchers search for ways to apply nanotechnology to their research under the anticipation that funding agencies will increasing provide resources to projects that involve that particular concept.

The two swell cases described below contain elements of both directed and undirected growth. The ARL swell in solid-state devices has a more directed character as the laboratory

used its director's discretionary funding stream to support early exploratory research in a potentially important field. The NRL swell in nanotechnology seems to have begun in a more undirected fashion as several researchers independently decided to pursue experiments in nanotechnology. However, NRL's work in nanotechnology may be becoming more tied to customer-driven work with the establishment of the Institute for Nanoscience within the lab.

Swell Case 1: ARL 257 Solid-state devices

ARL's work in solid-state devices class 257 (shown in figure 4.2) is diverse, but mostly related to the creation and application of quantum wells.[76] While it is unclear if technology foresight at the laboratory specifically identified quantum wells as an important future technology, several of ARL's solid-state device research lines began as Director's Research Initiatives ("Army Investment in Sensors Research Leads to Advances in Soldier Protection," 2010) or other internally-funded exploratory projects (Barrick, 1990).[77] At least one of these lines of research found its way into fielded Army systems. Dr. K.K. Choi's work on quantum well-based infrared (IR) detection systems, which accounts for 7 of the 53 patents in this trend, matured over 20 years to provide significant cost reductions in IR-detection systems. In 2010 Dr. Choi received the Presidential Rank Award for dramatically improving the performance and reducing the cost of IR systems in the Army (Spatchek, 2010). Choi filed his first patent for quantum well-based infrared (IR) detection systems in 1990.

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[76] Quantum wells are subatomic features that confine electrons such that they can only respond to certain energy levels or wavelengths of light. Sandwiching different semiconductor materials together can produce quantum wells. These features can be used to produce efficient lasers at certain wavelengths or sensors that are sensitive to a narrow range of wavelengths. For a technical summary see Levine (1993).

[77] Since this swell starts around the time ARL was established, much of the foundational work in this swell was probably actually done in the Army laboratories that were consolidated to form ARL in 1991.

Figure 4.2 ARL Swell in Solid-State Devices
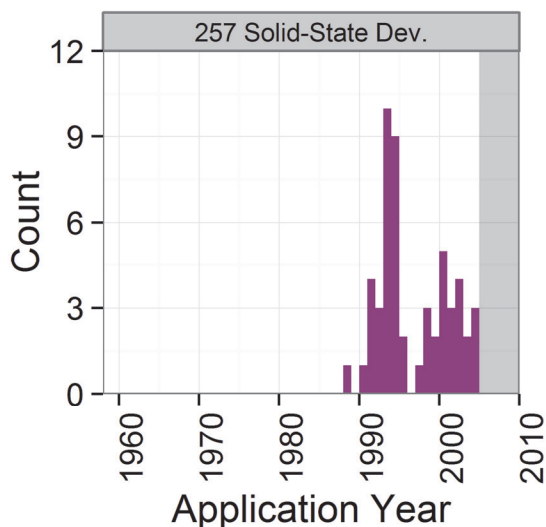
Swell Case 2: NRL 977 Nanotechnology

NRL's small swell in Nanotechnology is an example of a swell generated organically by the uncoordinated and not-necessarily-product-driven work of many researchers. Figure 4.3 shows NRL's patent trend histogram in this class. While the total number of patents in this class in this dataset is small, the rate of patenting at NRL in class 977 has clearly been accelerating since 1990, placing class 977 at NRL solidly in the swell category. Feedback from research managers at NRL suggests that the growth of nanotechnology research and patents at the lab happened organically as researchers independently pursued various academic funding streams.[78] Based on the TechMatch data, nine different, non-overlapping inventor groups are active in class 977 at NRL. Their work ranges from fundamental research into the production of nanotubes and nanoparticles, to nano-scale measurement work, to medical devices.

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[78] Interviewees thought the work represented by the patents tended to be on the more basic side of NRL's portfolio and was therefore sensitive to trends in science funding.

Figure 4.3 NRL swell in nanotechnology
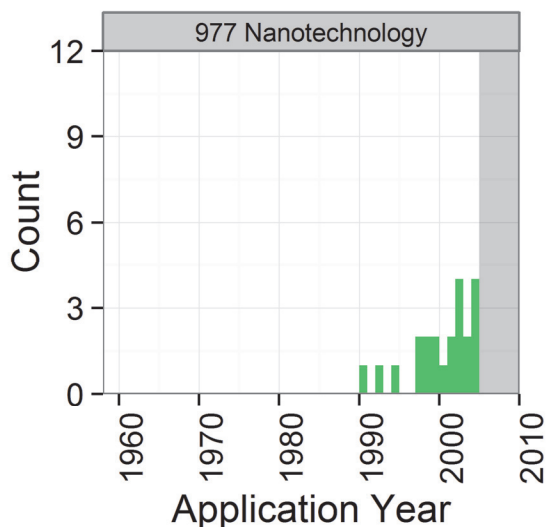
While this swell initially seems to have grown as the result of independent researcher activities, nanotechnology research at NRL may be becoming more directed toward specific customer-driven products, and this swell may continue to grow as an area that is supported by the lab's own internal funds and technology foresight. In 2001, NRL established the Institute for Nanoscience in order to better support interdisciplinary, nano-related research at the lab. The institute receives a portion of its funding from the "core" funds NRL receives each year from the Office of Naval Research (ONR).[79] This money helps support the sophisticated facilities required to investigate, fabricate, and manipulate nano-scale materials. These facilities are open to any and all of NRL's research staff, providing a way for similarly-interested researchers to connect with each other as well as providing a common, already-paid-for, high-tech facility to researchers who wish to apply nanotechnology-related techniques to their projects for other customers.

Saturated Productivity

The rate of patenting in patent swells may eventually level off or begin declining. An analogy with s-curves may be appropriate in these cases. S-curves have two inflection points: one that marks the switch to increasing growth and a second that marks the switch to decreasing growth (recall the discussion in section 2.3.2). The rate of patenting in a swell class within an organization may level off because that laboratory has reached its maximum capacity. For example, to continue expanding work in the class may require a discontinuous increase in resources such as constructing a new building. Alternately, the laboratory's managers may just

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[79] NRL also receives transfers through the Navy's Working Capital account to perform research for Navy and other government clients.

feel they have reached a sufficient level of activity given their goals. Shifting priorities at the laboratory may also move resources from a mature trend to a new area. The USPTO may also signal that work in the area is saturated by decreasing the rate at which they accept patents in that class (again, see discussion in section 2.3.2). Because the number of patents in this dataset begins declining in 2005 (due to the delay between application and issuance, see section 3.4.2), it can be difficult to determine if many of the swell cases have actually reached saturation.

4.1.5 Swells as potential innovations

Within-organization swells are conceptually similar to the s-curves observed in the full patent database in that they reflect the accumulation of increasing amounts of inventive effort. In the two swell cases described above, the within-organization swells were driven by increasing numbers of researchers pursuing emerging technologies: quantum wells at ARL and nanotechnology generally at NRL. At ARL, at least some of this research resulted in improved military devices. At NRL, existing expertise in nanotechnology is being harnessed to support NRL's broader research portfolio through the Institute for Nanoscience. Note that within-organization swells could also, in theory, be the result of shifting service direction which shifts resources from an old to a new technology such as the increasing relative emphasis on network technologies in the Army in the 1990s.

Continuing the analogy between swells and s-curves, if patents in the early part of the field s-curve are potential innovations because they represent ideas that helped trigger the rapid expansion of interest in the field, then early patents in the within-organization swell are also potential innovations because they are the foundations on which the rest of the trend are built. Patents that both start a within-organization swell and lead the field s-curve are doubly interesting as potential innovations because they are potentially used both within the lab and in the wider industry. Section 4.2 continues this discussion by describing how to visually and mathematically compare the timing of a within-organization swell with the timing of a field s-curve.

4.2 Identifying Leadership in Patent Trends

Thus far, this chapter has described how patent trends can identify what a lab is doing but has not measured the value of those activities. One way to approximate the value or impact of a lab's patented research, other than performing multiple case studies, would be to look at the relative number of citations received by each patent in a trend. However, as discussed in Appendix B, several uncertainties remain about the validity of forward citations as a measure of patent impact. For example, citation rates vary across technology areas (B. H. Hall, Jaffe, & Trajtenberg, 2001), interactions occur between the length and breadth of a patent's claims and the number of citations it receives (Eusebi, 2012), and the actual correlation between citation rates and commercial impact is still under study. An alternative approach could be to compare the timing

of a single patent application, or the entire trend, with the evolution of patent filings in the field as a whole (i.e. against all patents in that class).

Several authors have suggested using the evolution of s-curves in the patent record as a tool for identifying emerging and potentially disruptive technologies (Eusebi, 2011) and as a tool for aligning technology development strategies to emerging market conditions (Andersen, 1999; Ernst, 1997). These suggestions are based on the theory that the rate of patent filings within a technology class does not accelerate unless the earlier ideas in the class are used and diffused (Andersen, 1999, p. 5). When the cumulative number of patent applications in a technology class enters the growth phase (i.e. begins to "take off"), it reflects a sudden increase in the number of parties betting that the technology will be valuable (Eusebi & Silberglitt, n.d.). Presumably this expectation is rational and, for at least some of the patentees, is realized.

Under this theory, individual early patents may be more innovative than later patents in the sense that their inventors were early movers into an area that became popular, widely used, and profitable. Applying this theory to the patent patterns suggests that patent spikes that lead the field s-curve (occur relatively near the field's take-off inflection point – a more specific definition leadership is provided below) are cases in which an organization developed a prescient and potentially innovative invention that contributed to the growth of the technology class.

Yet, if an organization had an early breakthrough (represented by an early spike or steady-work trend) in a field that later strongly took-off, why did the organization not accelerate their research investment along with everyone else? Did the lab underestimate the value of their discovery? Did the lab's mission constrain their follow-on work?[80]

In contrast, when an organization has a patent swell that leads the field s-curve, this suggests that the organization was not only an early mover but also recognized the potential of the field early and continued to expand their investment in the field. Because of this extra connotation of innovativeness, this section focuses on methods that identify leading and lagging swells in an organization's portfolio as an indicator of innovative behavior.

4.2.1 Visualizing swell leadership

Identifying when an organization's patent swell leads the development of an s-curve in the field as a whole requires some method to compare the relative timing of patents in these two different distributions. In his ongoing research, Eusebi uses a disease-outbreak CUSUM-based model to estimate when the s-curve in a technology subclass begins to take-off and compares this date to the filing date of an organization's patents in that subclass. The more patents an

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[80] Many reviewers have suggested that spikes could be characterized as "swells that didn't take", but there may be alternate explanations for the appearance of spikes versus swells in a given part of an organization's portfolio that have little relationship to pursuing the field trend. However, regardless of whether the lab "should have" pursued the s-curve trend in that class, patent spikes, as defined in section 4.1.2 are still inventions that the laboratory believes have the potential to make a commercial impact. While the lab may or may not be correct, patent spikes could be a good place to look for performance "nuggets" – stories of specific high-impact inventions used to illustrate a lab's contributions during performance reviews.

organization has before the take-off date, the bigger a leader and innovator it is considered to be.[81] This method works to compare the relative innovativeness of two (or more) organizations, but this study attempts to develop a measure that can determine leadership and innovativeness in a more absolute sense. Therefore, this study compares the relative timing of an organization's entire patent trend, not just the leading edge, to the entire trend in the technology class.

A first diagnosis can be done visually, although this comparison is difficult to do with the patent trend histograms because any one organization has many fewer patents in a single class than have been filed in the field as a whole. Fortunately, a slight transformation of the data can enable a direct comparison of the timing of patent filings.

To illustrate how a transformation of data can make easier the comparison of patent trends between differently sized organizations over time, consider the case of IBM's patenting in nanotechnology. IBM has the reputation of being a pioneer in nanotechnology. IBM researchers were responsible for some of the enabling discoveries and inventions in nanotechnology including the Scanning Tunneling Microscope (at IBM Zurich in 1981) (Binnig & Rohrer, 2000), the first precise positioning of individual atoms (to spell out IBM at IBM Almaden in 1989) (Shankland, 2009), and the independent co-discovery of single-walled carbon nanotubes (at IBM Almaden in 1993) (D. Bethune et al., 1993; D. S. Bethune, 2002). These early discoveries were patented (e.g. U.S. Patent 4,343,993 for "Scanning Tunneling Microscope" and U.S. Patent 5,424,054 for "Carbon Fibers and Method for their Production"). Today, IBM is the largest holder of U.S. nanotechnology patents. Yet its patent holdings are dwarfed by the global expansion of nanotechnology patenting over the last 20 years.

The left side of figure 4.4 shows the histogram of IBM's patents in nanotechnology and the right side of figure 4.4 shows the histogram for the entire field in nanotechnology (class 977). Note the very different vertical scales in each figure. Up to 1200 patents have been submitted per year to the USPTO in nanotechnology (right half of figure 4.4) while the maximum filed per year by IBM in the same class (left side) is only 20. If both curves were shown on the same graph with the same scale, IBM's curve would barely be visible.

Figure 4.4 IBM (left) and all USPTO (right) patents in class 977 Nanotechnology

IBM Nanotechnology Histogram   USPTO Nanotechnology Histogram

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[81] Eusebi and Silberglitt's work comparing the leadership rates of various organizations has not yet been published. That work is currently the subject of a RAND project. This author's understanding of that work is derived from several interim briefings by Eusebi and Silberglitt given under the auspices of that project.
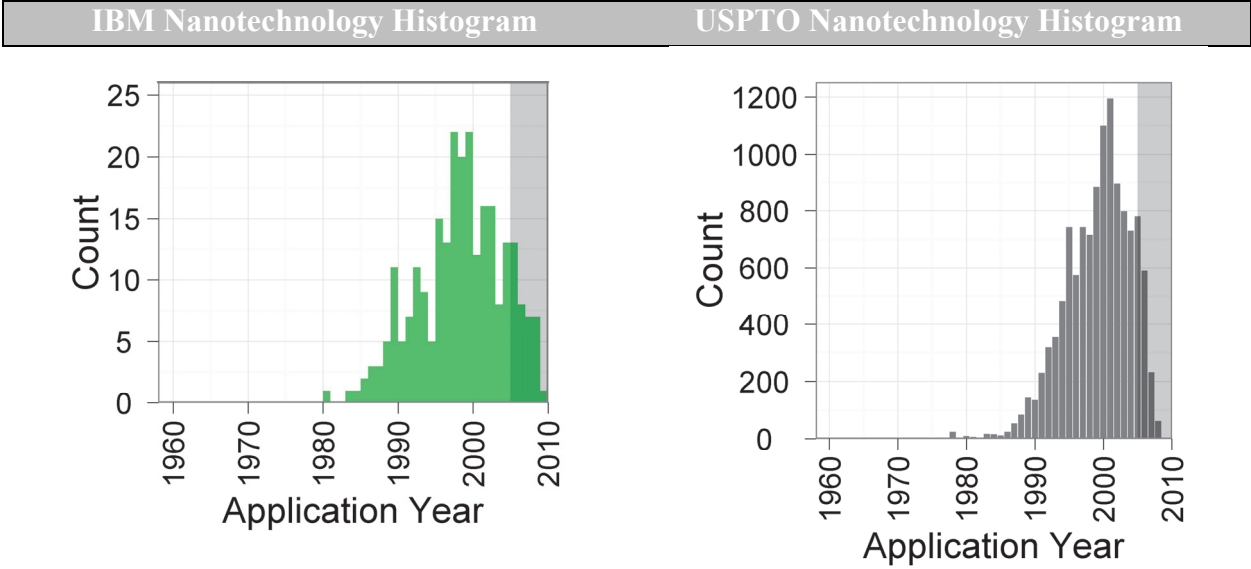
Transforming the histograms into density plots can enable a direct comparisons between very differently sized patent portfolios. A density plot normalizes the number of patents filed per year in a histogram such that the total area under the curve equals one. The gray background area in figure 4.5 shows the fraction of total U.S. nanotechnology patents filed in a given year (excluding IBM's patents). The green transparent foreground area in figure 4.5 shows the fraction of IBM's total nanotechnology patents filed each year. These areas are equivalent to areas from figure 4.4, only scaled.

Figure 4.5 Density plot comparing IBM and all USPTO patent rates in nanotechnology (class 977)
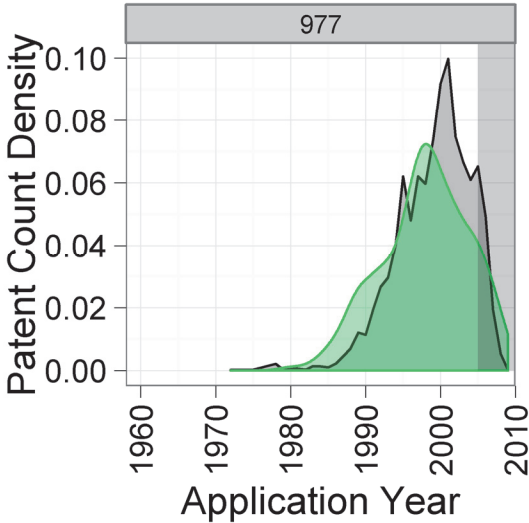
The relative location of IBM's (green transparent foreground) curve in Figure 4.5 suggests that their patenting activities led the rest of the field by several years, as one would expect given

their role in early nanotechnology research and invention. While the patent density curves can be used to compare a lab's trend to the field s-curve in this manner, relying on the visualization alone is both imprecise and time consuming. It is imprecise because of both the limitations of visual acuity and the potential errors introduced by missing data. A faster and more precise classification approach is to use the Mann-Whitney-Wilcoxon (MWW) Rank Sum Test to determine the likelihood that the organization's density curve lies above and to the left of the field density curve.

4.2.2 MWW statistical test for leadership

The Mann-Whitney-Wilcoxon (MWW) Rank Sum Test first combines all observations from the groups of interest, places each observation in order along some parameter of interest, and assigns each observation a number from 1 to N, called its rank order, where N is the total number of observations. In this case, the patents issued to all organizations are ordered by application year. For example, suppose there are two organizations, each with four patents as shown in Table 4.1. Placing the patents in order of application year results in the rank numbers in the right-most column. Notice that patents with the same application year are assigned their average rank.[82]

Table 4.1 Example data for the Mann-Whitney-Wilcoxon Rank Sum Test

Patent Number	Application Year	Organization	Rank
X00001	1990	A	1
X00002	1991	A	2
X00003	1992	B	3
X00004	1993	B	4.5
X00005	1993	A	4.5
X00006	1994	B	6
X00007	1995	A	7
X00008	1997	B	8

Next, the test adds together the total rank for each organization. In this example, the "rank sum" for A is $W_A = 1+2+4.5+7 = 14.5$ and the rank sum for B is $W_B = 3+4.5+6+8 = 21.5$. The rank sum of one group, say group A, is the test statistic. Note that the rank sum for the comparison group, W_B, is fully determined by the number of observations N and the rank sum for the group of interest, W_A. The null hypothesis for this test is that observations from both groups are drawn from the same distribution, and therefore W_A should equal W_B. Under this null hypothesis, the distribution of the rank sum test statistic is known even with very few observations (Mann & Whitney, 1947).[83]

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[82] This explanation of the Mann-Whitney-Wilcoxon Rank Sum Test is based on several textbooks and online resources but is particularly indebted to Wild & Seber (1999).

[83] With many observations, a normal distribution is a good approximation for the distribution of Wa (Wild & Seber, 1999).

Since the distribution of W_A under the null hypothesis is known, one can calculate the likelihood of observing a rank sum as or more extreme than W_A if the null hypothesis of $W_A = W_B$ is true. This likelihood, or probability, is known as the p-value. As used here, the MWW p-value gives the probability of observing this particular distribution of patents for a lab if the lab was actually filing patents at the same time as the rest of the field. Errors in the dataset or random fluctuations in when, exactly, the lab's patent attorney submitted the paperwork could cause minor shifts in the reported application year of patents. These small, random shifts could make one organization appear to have slightly earlier or later patent applications than everyone else. If the result of the test, the p-value, is a very small number, then it would be highly unlikely that the observed timing is due to these random errors alone. Therefore, small p-values increase the confidence that the observed difference in timing is real. The traditional thresholds for small p-values in the social science literature are 0.1, 0.05, or 0.01. This study uses a less conservative threshold of 0.2, which is sufficiently large to consistently identify cases that have a large visual separation in the density diagrams, although this threshold still yields a variety of results for visually closer cases.

Both one-sided and two-sided tests are possible. In a one-sided test, one can compare specifically whether the lab's patent distribution is shifted *either* to the left (early) *or* the right (late) of the comparison (i.e. field) distribution. Formally, in a one-sided tests the alternate hypothesis is that *either* $W_A < W_B$ *or* $W_A > W_B$, and the p-value is the area under the left *or* right tail of the distribution respectively (i.e. from W_A through +/- infinity). In the two-sided test, one is comparing simply whether there is any difference in the timing of the two distributions. Formally, in the two-sided test the alternate hypothesis is $W_A \neq W_B$, and the p-value is the area under both tails of the distribution.

MWW test example: nanotechnology innovators

In the IBM case above (figure 4.5), the two-sided p-value for IBM's rank sum compared with the rest of the field is 4.7×10^{-6}. For the one-sided test with alternate hypothesis $W_{IBM} < W_{USPTO}$, the p-value is 2.4×10^{-6}. Therefore, it is highly unlikely that one would see this degree of left-ward (early) shift in IBM's patent trend due to chance alone.

IBM's leadership is even more pronounced when compared with the density diagrams of other top nanotechnology patentees. The Navy and the Massachusetts Institute of Technology (MIT) are also among the top 4 holders of nanotechnology patents in the U.S. (H. Chen, Roco, Li, & Lin, 2008). Their density curves versus the field in nanotechnology class 977 are shown below in figure 4.6. In the density diagram, the Navy's nanotechnology trend seems to have the same timing as the field's curve.[84] Except for a 2-patent bump in the 1980s,[85] MIT's nanotechnology trend appears to lag the rest of field.

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[84] Note that NRL accounts for the majority of Navy nanotechnology patents (Snow, n.d.). As explained in section 4.1.4, NRL has a small swell in nanotechnology as a result of a combination of basic research grants and discretionary funding supporting more applied projects. This example uses all patents assigned to the Navy rather

For the Navy's nanotechnology patent portfolio, the p-value for the 2-sided Rank Sum Test (alternate hypothesis is that the Navy's patent portfolio is shifted either left or right from the rest of the USPTO portfolio) is 0.96. Therefore, under the null hypothesis (Navy's nanotechnology portfolio has the same timing as the rest of the field), it would be quite likely to observe this particular portfolio of Navy patents. MIT's nanotechnology patent portfolio shows the opposite trend. The p-value for the two-sided Rank Sum Test for MIT versus the rest of the field is 0.17, indicating that it is somewhat likely that MIT's patent distribution is shifted from the rest of the field. The one-sided Rank Sum Test with alternate hypothesis of MIT > USPTO (i.e. MIT's patents are later) has a p-value of 0.085, meaning it would be highly unlikely to see this distribution of patents if MIT's portfolio actually had similar timing to the rest of the field.

Figure 4.6 Navy (left) and MIT (right) nanotechnology density diagrams versus USPTO (grey)
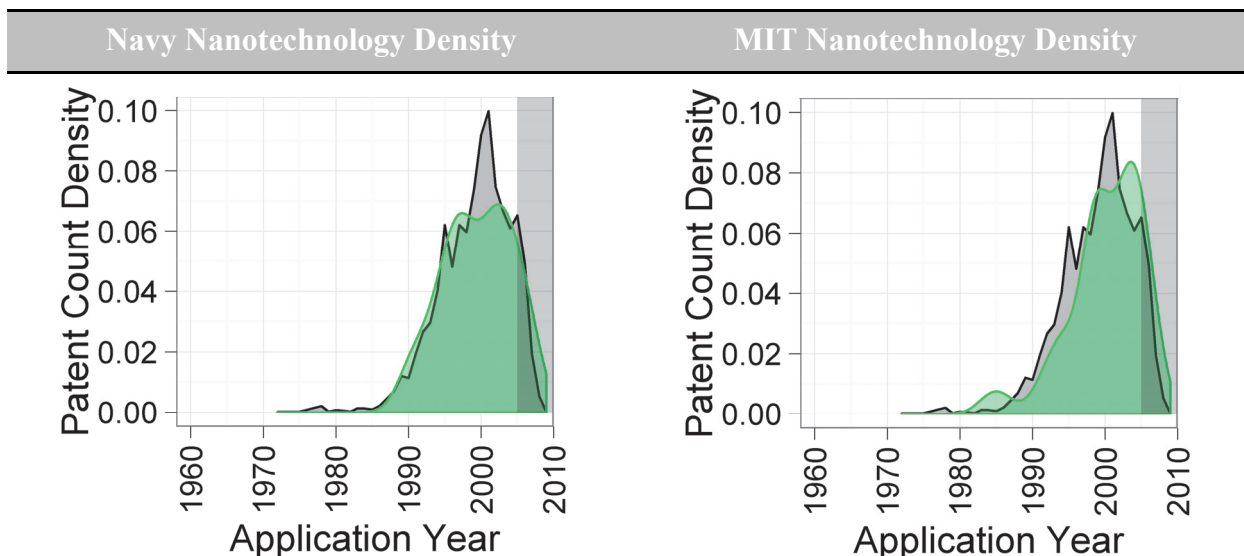
Summary of the MWW method for identifying leadership

The MWW Rank Sum Test, as applied here, identifies the likelihood that one organization's patent pattern is shifted earlier or later than the pattern of patenting in the field as a whole. This relative timing can also be seen by comparing an organization's patent density curve to the density curve produced by all patents in a class. Organizations with early swells are innovators in

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than the NRL patents identified in TechMatch in order to make a more consistent comparison with IBM and MIT's patent portfolios, which are based on all patents (in the relevant class) assigned to those organizations in the USPTO 2009 patent grant bibliographic data file.

[85] These two patents (US patent 4,721,601 "Molecule-based microelectronic devices," filed in 1984; and US patent 4,850,707 "Optical pulse particle size analyzer," filed in 1986) seem unrelated to both each other and to MIT's work after the take-off point based on a review of the relevant patent texts.

the sense that they were among the first to produce discoveries and accelerate their investment in an important technology.

Note that while the MWW test can identify spike and steady-work trends that begin before the field s-curve takes off, this discussion only compares an organization's swell trend to the field s-curve trend. This restriction simplifies the analysis of organizational drivers of innovation-via-leadership which follows in the next chapter. Understanding the relationship between spike or steady-work trends at an organization and the rate of work being done in the rest of the field remains an area for future studies.

Nor is this method intended to provide a comprehensive indicator of innovation. As with all of the methods suggested in this dissertation, it should be used as part of a suite of evaluation tools. Specific innovations – individual inventions that are novel and widely used – may also exist within spike, steady-work, or lagging swell trends and may be identified using other methods.

The remainder of this chapter summarizes the frequency of leading swells in the DOD laboratory portfolios and develops hypotheses to explain the range of observed results.

4.2.3 Summary of leadership results for DOD labs

Figure 4.8 (at the end of this chapter) summarizes the DOD labs' patent portfolios by pattern type and, for swells, whether that trend leads, lags, or is in-synch with the rest of the field. Each row in figure 4.8 corresponds with the data for one DOD lab. The labs are grouped by Service. Each row has colored boxes indicating classes in which the lab has at least 6 patents (i.e. marking an active class for that lab). The color of the box indicates whether that lab's dominant pattern in that class is a swell, a spike, or steady-work.

The "+/-" symbols within some boxes mark swells that are leading or lagging the field in that class.[86] Swells *lead* the field if the p-value in the *left*-hand-sided MWW Rank Sum Test (lab has a smaller rank sum and is shifted to the left) is less than 0.2. Swells *lag* the field if the p-value in the *right*-hand-sided MWW Rank Sum Test (lab has a larger rank sum and is shifted to the right) is less than 0.2. If neither condition holds, i.e. the p-value is greater than 0.2 in both tests, then the swell is considered in-synch and is not marked with a "+/-" symbol.[87] Within each Service group, the rows are ordered such that labs with the most leading swells are at the top, labs with the most lagging swells are in the middle, and labs with no swells are at the bottom.

This being a new theory and method, there is, as yet, no expected rate of leadership for a high-performing laboratory. However, leading swells are rare among the DOD research labs. Of

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[86] The MWW Rank Sum Test can also identify spikes and steady-work trends that lead the field. However, results for spikes and steady-work trends are not shown in Figure 4.8 because of the questions raised in the introduction to section 4.2.

[87] Note that for these comparisons the field dataset only includes patents with issue dates in 1990 or later in order to provide a fair comparison with the TechMatch dataset. Recall the TechMatch dataset includes patents issued in 1990 or later while the USPTO dataset includes patents issued in 1975 or later.

the 74 different lab-class trends with swells, only 16 (22%) lead the rest of the field. Only 7 (28%) of the 24 laboratories in this study have at least one leading swell. Table 4.2 shows the frequency of swells and leading swells relative to the size of a lab's portfolio for those labs with at least one swell. Leading swells make up less than one quarter of any single DOD lab's portfolio, and the upper end of this range is only reached in a lab with few active classes, the Night Vision and Electronic Sensors Directorate (NVESD).

Table 4.2 Frequency of leading swells in DOD patent portfolios

lab	active classes	swells	leading swells	leading swells / active classes	leading swells / swell classes
NVESD	4	1	1	25%	100%
NAWC China Lake	20	1	1	5%	100%
ARL	53	7	5	9%	71%
CERDEC	12	3	2	17%	67%
NRL	54	15	4	7%	27%
NSWC Panama City	11	4	1	9%	25%
SPAWAR Systems Center Pacific	27	8	2	7%	25%

This rarity, perhaps, should be expected. Three conditions must align in order for a lab to have a leading swell in a patent class in this study. First, the field s-curve must develop in the range of data available to this study: between 1990 and 2010. Second, the laboratory itself must have a swell. Third, the laboratory must actually be ahead of the field, which one might expect to be difficult given how little is known about predicting emerging technologies.

The timing of the development of the field s-curve is the first constraint on these results. If the class matured prior to 1990, then the lab's own work will appear to be lagging, or at best, in-synch because the TechMatch dataset does not go back far enough to reveal what was going on at the lab at the time of the field's first inflection point.[88] If the class has yet to mature, then the lab's curve will also seem to be in-synch or lagging because the proportion of field patents in the left tail is relatively high. See, for example, ARDEC's work in Ammunition and Weapon classes in Figure 4.7. While ARDEC has a swell in three of its four Ammunition and Weapon portfolios

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[88] It may be quite difficult to compare DOD work to fields that matured prior to 1990 because several of the DOD laboratories did not exist in their current form prior to the mid-1990s (e.g. see ARL (2003), Duffner (2000), Hazell (2008), Moye (1997)). Finding patent data for those precursor organizations could be very challenging (see discussion in section 3.3).

(089, 102, and 149), because the rest of the field is flat, the MWW Rank Sum Test finds that ARDEC is lagging (102, 149) or in synch (089).

Figure 4.7 Lab swells versus flat field curves
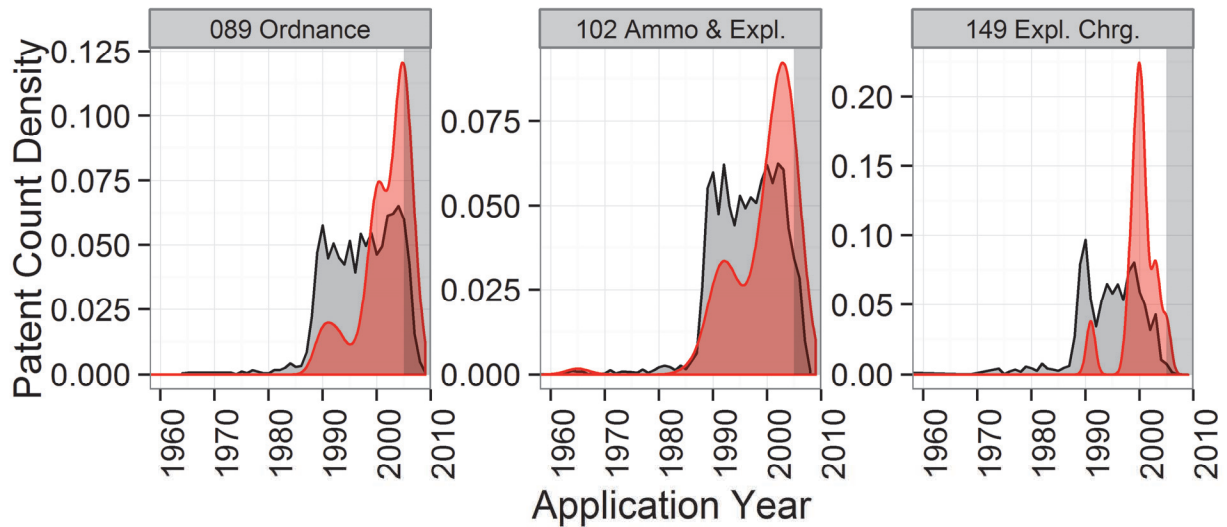
It is plausible that many fields of interest to this study would have peaked long before 1990. Mission constrains the DOD laboratories to work in certain technology areas, and those technology areas may tend to be old and already mature. For example, this was a concern expressed at NVESD which conducts research into optical sensor technologies including night vision and laser designation. The U.S. military may have a reputation as a pioneer in night vision and infrared sensing, but Army research in that field dates back at least to the 1950s (NVESD, n.d.). It may therefore be difficult to detect leadership in NVESD's recent patents. However, note that this study did detect one leading swell in NVESD's patent portfolio.

In addition, note that Eusebi (2011) and Eusebi & Silberglitt (N.d.) explored s-curves in the patent record primarily at the subclass level because competing trends within the larger primary classes can obscure any signal. If thousands of patents are being filed in any one primary class each year, then a ten patent uptick in one subclass would be drowned out by the overall activity. Alternately, declining activity in one subclass or natural fluctuations in a particularly large subclass can cancel out any increases in patenting in another subclass. Given these caveats, it is remarkable that this study found s-curves at the primary class-level at all, perhaps indicating how important some of these broad technology areas have become to modern society.

The second condition that must hold if a laboratory is to have a leading swell is that not only must there be an s-curve in the field, the lab must also have a swell pattern in the same class. While in theory one could compare the timing of a lab's spike or steady-work trend to the takeoff point of the field's s-curve, the interpretation of such a comparison is more complex (see

discussion in introduction to section 4.2). One must therefore be careful when comparing the leadership rates of laboratories with few or no swells, like ARL, to laboratories with many swells, like NRL. Because ARL has few swells, leading swells can only make up a small fraction of its total active class trends. The fraction of swells a lab has that are leading (right-most column in table 4.2) may be a more appropriate comparison measure.

Third, if there is an s-curve in the field and a swell at the lab, the lab must actually be ahead of the field, naturally, if it is to have a leading swell in the patent record. This leadership could be by design or by chance. However, historically, predicting the next big technology has not had a high success rate.[89] For example, a review of the Army's early-1990s STAR 21 technology foresight project found that about one-quarter of the predictions were accurate as of 2008 and the study missed a number of key trends in the spread of the internet and wireless communication (Chait, Valdes, & Lyons, 2009).

It may be that labs that encourage exploratory research have more leading swells out of sheer volume. By frequently establishing competencies in early-stage technologies such labs could be in a better position than less-exploratory labs to capitalize on a technology when it takes off. Such labs may have a relatively high number of leading swells but also a relatively high number of in-synch swells – reflecting occasions in which they became interested in an early-stage technology at the same time as many other players – resulting in a relatively small fraction of leadership among their swell patterns. Chapter 5 demonstrates how the distribution of patterns within organizations' patent portfolios can be used to test hypotheses such as this one on the practices that enhance the rate of innovation in research organizations.

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[89] Arthur C. Clark wrote, "It is impossible to predict the future, and all attempts to do so in any detail appear ludicrous within a very few years," and furthermore, "When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong," (Clarke, 2000, pp. 5, 1).

Figure 4.8 Summary of patent patterns in DOD labs

Chapter 5 Using Patenting Patterns in the Study of Research and Innovation Processes

The introduction to this dissertation noted that two major barriers in science policy are a limited of understanding of the research and innovation processes and the lack of standard measures with which to study these processes. Patenting patterns can be used as measures in the study of research and innovation in at least three ways: as a dependent variable in project-level analyses, as a classification tool, and as a dependent variable in organization-level analyses.

First, the type of pattern associated with patents from a research project, and whether that pattern leads or lags the field, could be used as an indicator of research output quality. Comparing and contrasting the characteristics of research projects that are associated with similar patenting patterns can help isolate project-level factors that drive the quality and nature of project outputs.

Second, the relative fractions of each pattern in a laboratory's patent portfolio may be a classification tool. Laboratories with certain research approaches or missions or cultures may tend to have relatively more spikes or relatively more swells. If relationships between pattern fraction and certain research missions or cultures can be established, then the relative number of spikes or swells in a lab's patent portfolio can then be used as a proxy for or indicator of those characteristics when detailed information about the lab's character is not available.

Third, the fractions of spikes, swells, or leading swells in a lab's portfolio could be used as measures of the laboratory's outputs. Comparing across laboratories and controlling for factors such as research mission, the fraction of each pattern in laboratory portfolios could be used as the independent variable in an analysis of factors that affect the generation of that type of output. A number of existing hypotheses about the research an innovation process might be reframed in terms of quantifiable laboratory characteristics such as pattern fraction, funding levels, staff demographic characteristics, etc. Econometric models could then be created to test the hypothesized relationships between these factors.

Chapter 4 discussed the first application. This chapter describes the second and third uses of patenting patterns and sets up initial examples of analyses using the DOD laboratories. Section 5.1 explains the basis for linking pattern fractions with laboratory missions, practices, and cultures, and demonstrates one way to classify laboratories based on pattern fractions. Section 5.2 demonstrates the use of pattern fraction as the independent output variable using a simplified hypothesis about the role of basic research in establishing new lines of research.

5.1 Pattern fraction as a classification tool

As discussed in section 4.1, this study proposes that the patenting patterns described in the previous chapters are not random but are the result of specific behaviors at both the research group and the organizational level. More specifically, steady-work patterns, this study hypothesizes, are an output of steady-work research: a mode of work in which the lab devotes a steady amount of resources (e.g. money, people, and attention) to a particular field of study. Spikes and swells represent departures from this baseline. Spikes are instances in which the laboratory has focused more resources than usual on producing and patenting a specific invention. Swells are instances in which the lab has steadily grown its investments in a field of research. The logical framework for this set of hypotheses is presented in section 4.1.

If the pattern of patenting a lab produces within a single technology is not random, then the rate at which spikes and swells appear in their overall portfolio may not be random either. Rather, the fraction of spikes, swells, and other patent patterns in a lab's portfolio may be directly related to characteristics of the organization. Given the characterizations of the individual patent patterns above, labs with higher fractions of swells in their portfolios could be said to have a tendency to build new programs out of their initial results, while labs with higher fractions of spikes are inventive but tend to move on to new research areas rather than continuing to build directly on past discoveries.

These tendencies could be a direct result of the instructions they receive from their parent organization, i.e. their mission, or it could be an outcome of the general culture of the organization. For example, laboratories with a mission to create specific inventions to meet the near-term needs of a parent organization (e.g. a military service or a commercial parent) may be more likely to have many spikes. Meanwhile, laboratories with more general missions of scientific discovery may be more likely to have many swells. However, a laboratory with an invention-oriented mission but a culture of scientific excellence and discovery may very well have many swells as it tries to increase its rate of innovation by building on past breakthroughs.

This characterization of laboratories as creation/discovery types is similar to the Pasteur's Quadrant paradigm established by Stokes (1997). Rather than thinking of basic research and applied research as opposites, Stokes (1997) suggests a two-dimensional model in which valuing advancing the boundaries of knowledge (i.e. discovery) is one axis and valuing the utilization of your work is the other axis (i.e. creation). Scientists and engineers can and do value both simultaneously. Stokes describes researchers in terms of the quadrant in which they place most value. Researchers who place a high value on discovery and a low value on creation are said to be in Bohr's quadrant. Researchers who place a high value on creation and a low value on discovery are said to be in Edison's quadrant. Researchers who highly value both are said to be in Pasteur's quadrant. Returning to the hypotheses above, labs with many swells may be in Bohr's quadrant, while labs with many spikes are in Edison's quadrant, and labs with equal numbers of spikes and swells are in Pasteur's quadrant.

If it holds that spikes and swells are indicators of certain types of research behaviors, then the fraction of these patterns in laboratories' portfolios can be used to classify laboratories into sets with like behaviors. Furthermore, the pattern fraction can also be used as a diagnostic tool to identify best practices for a desired research outcome or as a monitoring tool to assess the fit between a lab's desired and actual performance. Consider, for example, how the DOD labs cluster in terms of fraction of spikes and swells in their overall patent portfolios.

Figure 5.1 compares the fraction of steady work, swells, and spikes in each DOD lab's portfolio. While a number of clusters are possible, the labs are grouped together (black outlines in figure 5.1) based on whether their portfolios include more swells than spikes (ARDEC, USAMRMC, SPAWAR, and NUWC Newport), an equal number of swells and spikes (NSWC Panama City, NSWC Indian Head, NSRDEC, NRL, and CERDEC), or more spikes than swells (NSWC Dahlgren through NAWC Point Mugu). Within each group, the labs are listed by increasing fraction of steady work.[90]

The bottom five labs in figure 5.1 are not included in a cluster because of their low numbers of patents. The five labs each have 65 or fewer patents and are the labs with the smallest patent portfolios in this study. Most trends at these labs may look like steady work because the labs rarely patent at a rate high enough to produce a spike or swell.

If the hypothesis stated in the opening of this chapter is roughly correct – that labs with an emphasis on creating inventions for customers produce more spikes while labs with a focus on general scientific discovery produce more swells – then one would expect the labs in the top group (more swells) to have a relatively stronger discovery focus, the labs in the second (even spikes and swells) group to perhaps have some emphasis on both creation and discovery , and the labs in the third group (more spikes) to have a relatively dominant creation focus.

While this study does not possess sufficiently detailed information about the characteristics of each DOD lab to fully evaluate this statement, and the superficially heterogeneity of the laboratories in each group in figure 5.1 may seem to cast doubt on this hypothesis, there is some reason to hope that additional information on the character of the DOD labs will clarify the extent to which labs do or do not fall into groups along the creation/discovery paradigm. NRL and ARL do appear in the groups one would expect based on published critiques of their activities. NRL, in the second, equal spike and swell group, could be described as a Pasteur's quadrant, mixed creation and discovery lab. ARL, in the third, more spikes group, could be described as an Edison's quadrant, creation-oriented lab.

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[90] In figure 5.1, NAWC Point Mugu is out of order within its group. With only 69 patents and 3 active classes, NAWC Point Mugu may be better placed in the bottom "no patent" group than with the "more spikes than swells" group.

Figure 5.1 Distribution of patent patterns in DOD patent portfolios
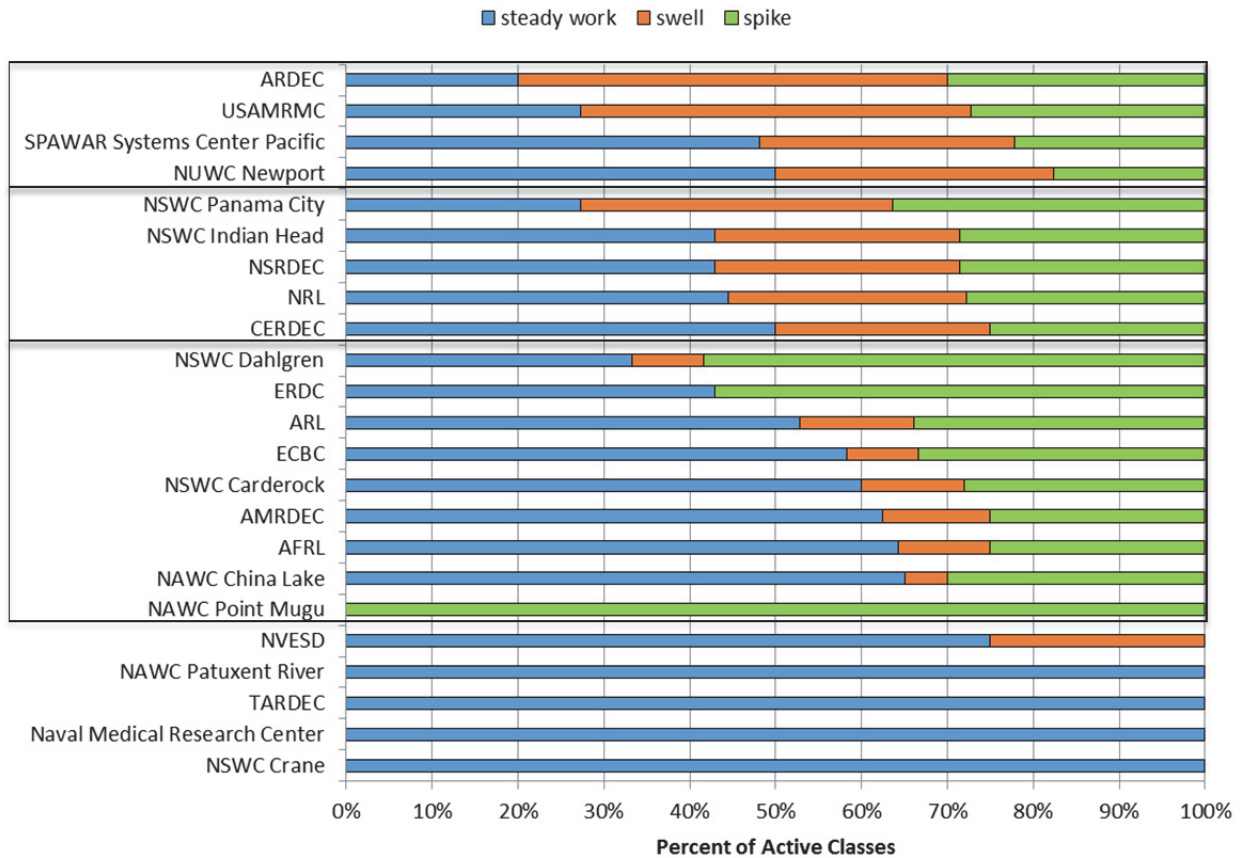
NRL has characteristics of both a creation-focused and a discovery-focused laboratory. On the creation side, Researchers at NRL talk about being "entrepreneurial" (Personal Interview, 2012), and NRL's funding process encourages researchers to find projects that are useful to customers. Around 80% of NRL's research activities are customer-funded, and individual researchers are responsible for finding customers and research grants. Even in the 20% of non-customer work, which tends to be more basic and exploratory, an internal review process rates proposals based on both scientific merit and the likelihood that the results will transition to a customer (Cozzens, 2001, pp. 29–31). Research groups that consistently fail to bring in work that is relevant to the lab's mission and its customers, a situation known at NRL as "taking in laundry", are terminated (Cozzens, 2001, p. 31).

On the discovery side, NRL is considered by some to be the DOD's top basic research laboratory (Decker et al., 2010, p. 62). Basic research, in this context, is research that is directed at expanding the frontiers of knowledge rather than research that is directed toward a specific application (DOD regulation 7000.14-R, Volume 2B, Chapter 5 (Office of the Comptroller, 2008)). Furthermore, Timothy Coffee, who was NRL's Director from 1982 through 2001

(overlapping in time with the first half of this data set), emphasized connections with the broader scientific and technical community as a core competency of NRL's research staff (Chait, 2009).

In contrast, ARL has been described as more near-term applications (i.e. creation) oriented than desired given its role as the Army's corporate research lab (Decker et al., 2010). Researchers at ARL talk about being "mission-oriented," and less interested in exploratory research. When asked about how they conduct exploratory research at ARL, one interviewee responded that "sandboxing is discouraged" (Personal Interview, 2012).[91] At ARL, most work is tied to Army Technology Objectives (ATOs) approved through a high-level review process within the Army S&T system. While ARL has a basic research portfolio, most of its in-house funding is applied (see section B.2), and half of ARL's applied work is tied to Army needs through the ATOs (DASA(R&T), 2010, p. I, 9–11).

The relative fraction of spikes and swells at NRL and ARL may be reflections of these different operational orientations. NRL's entrepreneurial creation orientation may provide an incentive to produce spikes in many technology areas. Meanwhile, the internal emphasis on continuing excellence in basic research discovery along with a desire to build unique competencies that enhance the lab's competitiveness with customers may lead to a high frequency of swells. However, few of NRL's swells are leading (4 of 15), perhaps reflecting the difficulty any one individual has in predicting the next important research area and in convincing a customer to invest in an unproven field.[92]

At ARL, an interest in producing many discrete inventions that are transferred to the warfighter could result in a high frequency of patent spikes. However, if the goal of ARL's research staff is to create high-quality inventions in the technology areas identified by Army planners, then they have little reason to search out work in emerging and un-prioritized technology areas. ARL would therefore have few swells. However, given the high-rate of leadership among ARL's few swells (5 of 7 are leading), when they do pursue more exploratory projects, ARL and Army S&T leadership may be good at focusing work on early-stage technologies that are highly likely to be important to the Army in the future. This success in technology foresight may be unrelated to the factors that drive ARL's overall focus on spikes/discrete inventions.

A number of other explanations are possible for the relative fraction of spikes and swells at the various DOD labs. For example, medical research, which is the focus of USAMRMC (group 1), may be more conducive to long programmatic research arcs than missile research, which is

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[91] Also note that most of ARL's researchers have historically been civil servants with low turn-over, who cannot be removed for "taking in laundry" as at NRL, but the lab has recently grown beyond its official personnel allocation and has brought on more scientists who are 100% funded through contracts with customers (Personal Interview, 2012).

[92] Recall from chapter 4 that this study considers spikes to be indicators of potentially high-value inventions while swells are indicators of growing research programs. However, in addition, swells that lead a field s-curve are considered to be indicators of technology leadership on the part of the lab. This leadership may coincidental or the result of a deliberate bet on the part of the laboratory personnel.

the focus of AMRDEC and NAWC China Lake (group 3). Although, under this alternate technology-type-based explanation it remains a mystery why ARDEC appears to behave more similarly to a medical lab, in terms of patent outputs, than to other ordnance labs (such as NSWC Dahlgren).[93]

More detailed analyses could help isolate those factors that do consistently explain why laboratories have distinctly different patenting pattern outputs. Furthermore, if such analyses compared laboratories based on the rate at which they produce leading swells, then such analyses may be successful in isolating significant factors affecting innovative research performance. While such studies could be qualitative, along the lines of the theory-based discussion above, the following section provides a more quantitative example of this type of analysis.

5.2 Pattern fraction as an output measure

In addition to its utility as a classification tool, the fraction of each pattern in an organization's patent portfolio could be used as measure of laboratory outputs. Controlling for mission and other characteristics (per the above discussion not all laboratories will place the same emphasis on e.g. spike-generating research), the fraction of certain pattern types in laboratory patent portfolios could be used as the dependent variable in the study of drivers of certain research outputs.

Given the breadth of the science and innovation management literature, there may be a number of existing hypotheses regarding drivers of research performance that could be interpreted in terms of pattern fraction. Patent patterns may prove an easier approach to measure these types of outputs than surveys or other current methods. To illustrate this approach to studying research processes, this section demonstrates a simplified analysis comparing two hypotheses regarding the role of basic research in establishing new lines of work in the ostensibly application-oriented DOD laboratories.

5.2.1 Sample hypotheses

Basic research is thought to be important for mission-focused laboratories because it provides a way to engage top scientists and engineers (e.g. see JASONs (2009, p. 11)), promotes a fundamental approach to engineering problem solving (see Lyons (2012)), and enables the lab to develop or maintain new competencies not currently covered by applied, mission-oriented work (e.g. see interview comments by Lyons and Russo in Chait (2009)). In terms of increasing the number of swell patenting patterns generated by a lab, basic research could provide the base of

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[93] Some reviewers have asked whether the number of active classes explains the fraction of spikes or swells in a lab's portfolio. Labs with fewer active classes and narrower technology missions (see section 3.7.2) could, in theory, have more swells because they have fewer areas in which to invest new resources. With the exception of those labs that have so few patents that they appear at the bottom of figure 5.1, this seems unlikely to be the case. Preliminary analyses conducted for the work reported in section 5.2 found no relationship between the number of active classes and the fraction of swells or spikes in a DOD lab's portfolio using a variety of correlation tests.

exploratory work that starts new patent swells. Alternately, an active basic research program could impact a lab's patenting rates by improving the efficiency of a lab's applied problem solving. In this case, larger amounts of basic research may be related to more patenting swells only in as much as that basic research is tied to patent-generating applied programs.

The remainder of this section (section 5.2.1) expands on these two possible connections between basic research funding and patent swells. Section 5.2.2 constructs measures relevant to each of the two hypotheses using data from the 1997-2007 DOD In-House S&T Activities reports. Section 5.2.3 discusses the results of a simple correlation analysis of these. Section 5.3.4 closes this part of Chapter 5 by summarizing the possible utility of patenting patterns in studying the drivers of research performance.

Hypothesis 1: Basic research budgets are an important source of discretionary exploratory research funding that increases the number of patenting swells

Larger amounts of basic research could increase the rate at which DOD laboratories identify, advance, and promote promising emerging technologies. For example, ARL's first director, Dr. Lyons, noted that he would use his discretionary funding to support promising early-stage research, such as quantum computing in the late-1990s, which was not yet within the technological horizons of the Army. As the line of research proved itself, it could be transitioned to an Army mission-supported funding stream (Lyons, 2012, pp. 4, 16). If basic research funding is important for developing research programs in emerging technologies, then DOD research laboratories with larger portions of their funding portfolios designated for basic research may generate more swells.[94]

Hypothesis 2: In-house connections across the basic-applied-development spectrum are an important source of synergies that increase the number of patenting swells

Alternately, expanding on the role of basic research funding in enabling fundamental approaches to applied problem solving, basic research may be important in generating swell patenting patterns only in as much as that basic research is part of a balanced portfolio of basic, applied, and technology development work. Large amounts of basic research alone may not lead to increasing rates of invention and patenting because, by definition, basic research is not directed at any particular application. Some amount of applied funding may be necessary to combine a basic research discovery with an application idea such that the concept is patentable. The productivity of an applied research portfolio, however, may be enhanced – perhaps resulting in more patent swell patterns – if it is paired with a sufficient amount of basic research from

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[94] They may also generate more leading or in-synch swells since they are more able to target early-stage technologies, but because of there are few leading swells among the labs in this study, the relationship between basic research and swell leadership will not be tested here.

which it can draw solutions.[95] The funding measure of interest in this second hypothesis, therefore, is one that captures the relative balance in a laboratory's funding among basic, applied, and development work.

5.2.2 Constructing funding measures

By combining funding information from the DOD In-House RDT&E reports with the patent pattern results presented in earlier chapters, this study can explore whether there is evidence of relationships between basic research funding or funding balance and swell generation.

The average fraction of basic research in the labs' 1997-2007 in-house S&T budgets is used as a proxy for the labs' relative emphases on basic research. Unfortunately, budgets for the entire range of patent data are not available. Laboratory reorganizations and changes in the format of the DOD In-House RDT&E funding reports make it very difficult to identify the amount of in-house basic research funding provided to the labs in this study prior to 1997. Fraction of in-house funding dedicated to basic research is used instead of the total dollar amount to account for the variation in the absolute size of budgets across labs. Figure 5.2 compares for each DOD lab in this study the fraction of active classes that are classified as swells against the average fraction of each lab's in-house S&T budget (1997-2007) designated for basic research.

Again using the average funding levels between 1997 and 2007, funding balance is measured by examining the variance among basic, applied, and development research funding proportions within a lab's in-house research budget. Labs with more evenly-divided research budgets will have smaller funding variances and hence smaller funding balance numbers. For example, NRL's in-house research funding is split 38% basic, 38% applied, and 23% development. NRL's funding balance measure is 0.085, which is the standard deviation (square root of the variance) among 0.38, 0.38, and 0.23. ARL's in-house research funding is 21% basic, 78% applied, and less than 1% development. ARL's funding balance measure is 0.40.[96] Figure 5.3 plots the fraction of swells in each lab's portfolio against a measure of funding balance.

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[95] The histories of research groups are replete with anecdotes about the importance of collaborations across the basic-applied-development spectrum for generating innovations. For example, the history of Bell Labs in Gertner (2012) tells of several occasions in which applied engineers found themselves at an impasse that was solved when the top basic research scientists in the organization drew on their expertise in mathematics and subatomic physics to suggest design changes. Stokes (1997) describes a similar synergy between practical application and an understanding of principles of biology and chemistry in Louis Pasteur's research into and discovery of bacteria during his applied attempt to standardize beer production.

A balanced research portfolio could also synergistically enhance productivity by increasing the organization's ability to use a wide range of externally-generated ideas. Called, absorptive capacity, it is thought that some level of internal competence in a field is necessary before an organization can utilized ideas generated elsewhere (Cohen & Levinthal, 1990). Such synergies have been observed in industrial R&D organizations. For example, Cassiman & Valentini (2009) note that, while technology firms have increased their R&D outsourcing, they have also simultaneously increased the fraction of their in-house research portfolios devoted to basic research.

[96] Credit to G. Ryan Faith for suggesting this summary measure of funding balance

Because laboratory mission or type may mediate any relationship between basic research funding and generating swells, the shape of the points in figures 5.2 and 5.3 indicate the pattern group to which the lab belongs. While a number of proxies for research mission may be possible, for consistency with section 5.1, pattern group as defined in figure 5.1 is employed as an indicator or mission or lab type in this example. Labs with more swells than spikes are in the first cluster (circle); labs with equal numbers of swells and spikes are in the second cluster (triangle); labs with more spikes than swells are in the third cluster (square); and labs with few patents are listed as a fourth cluster (plus).

Note that because of how data is reported in the In-House Activities reports, the Naval Warfare Center labs are aggregated into their parent Warfare Center (NAWC, NSWC, NUWC, or SPAWAR). When their patent pattern results are aggregated, the NAWC and NSWC laboratories fall into the more spikes than swells group; the individual labs appear in all but the first group in figure 5.1. With only one lab with sufficient patent data, the group assignment of NUWC and SPAWAR remains the same as in figure 5.1. Also note that funding data was not available for the Navy Medical Research Center.

Figure 5.2 Comparing basic research funding fraction and swell fractions of DOD laboratories
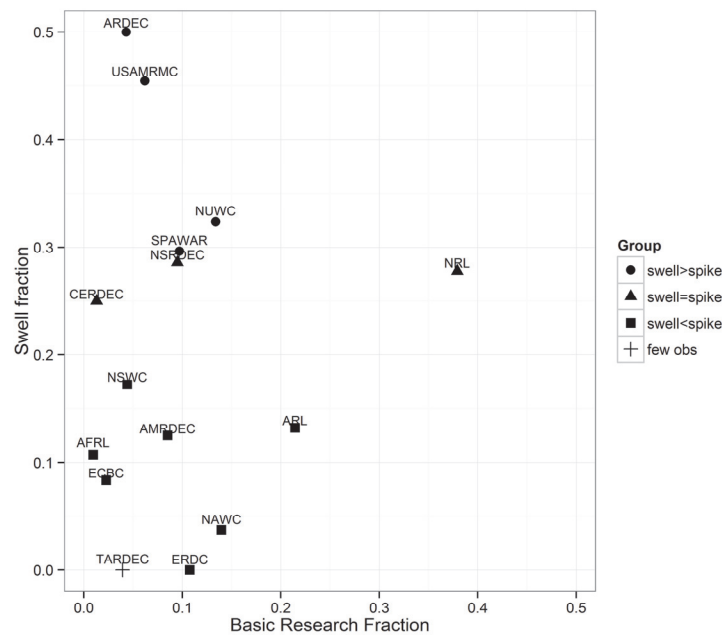
Most of the data points in figure 5.2 lie in a vertical band, suggesting that overall there is no direct relationship between the relative intensity of basic research and the tendency of a lab to generate swells. Examining the data by group, however, suggests that there may be an inverse relationship between basic research fraction and swell generation among labs with more swells than spikes (circles).

Figure 5.3 Comparing funding balance and swell fractions of DOD laboratories
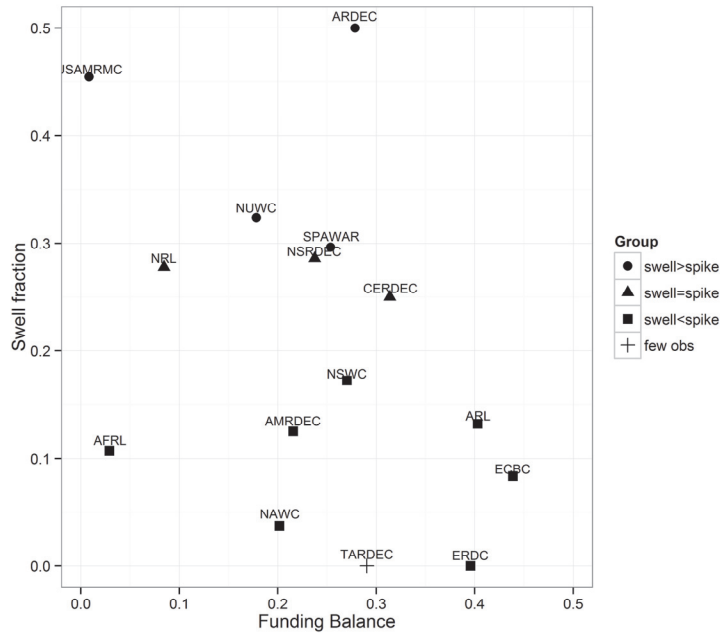
While the data points in figure 5.3 are still scattered, there does appear to be a moderate trend running from the top left to the bottom right of the displayed range. The fraction of swells in a lab's patent portfolio seems to be moderately inversely correlated with the funding balance measure (more evenly distributed portfolios are correlated with more swells). However, when each group is considered separately, the existence of any association between funding balance and swell generation becomes less clear.

5.2.3 Testing correlations

In order to estimate the likelihood that any observed trends (or lack of trend) between swell generation and the two funding variables exist given the small number of data points, table 5.1 reports the Kendall tau rank correlation coefficient and the p-value for the null hypothesis of no correlation (tau equals 0) for the data set as a whole and for each group separately.[97] Test results for the association between basic research funding fraction and swell fraction are given in the

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[97] Kendall's tau is a measure of correlation that examines the frequency with which repeated paired observations of two random variables result in similar rank orderings of the values across pairs (Kendall, 1938). A simplified explanation is that tau measures how often an observation with a relatively large value for variable A also has a large value for variable B. Negative values of tau indicate that large values of variable A tend to occur with small values of variable B or vice versa. It is a non-parametric test of association between two random variables, meaning that the likelihood of the observed association can be tested without making assumptions about the underlying distributions of the variables or the shape of the association (a reoccurring requirement in this dissertation). When there are few observations, the exact likelihood of the observed Kendall's tau can be calculated by enumerating all possible results (e.g. Valz & Thompson (1994)). This study uses the implementation in the R package Kendall version 2.2.

middle columns. Results for the association between funding balance and swell fraction are shown in the right-most columns. Values of tau closer to +/-1 indicate a stronger direct/inverse (respectively) association between two variables. The p-values in table 5.1 indicate the likelihood of observing a given tau if there is actually no association between the two variables (in which case tau should equal zero), i.e. smaller p-values increase the confidence that the observed tau is statistically significantly different from zero.

Table 5.1 Kendall's tau and significance test for relationships between laboratory funding variables and fraction of swells

Group	Obs.	basic v swell		balance v swell	
		tau	p-value	tau	p-value
All	15	0.1	0.8	-0.2	0.2
swell>spike	4	-0.7	0.3	0.0	1.0
swell==spike	3	0.3	1.0	-0.3	1.0
swell<spike	7	-0.0	1.0	0.0	1.0

The Kendall's tau tests reported in table 5.1 support the statement that there is no relationships between the fraction of basic research funding and the fraction of swells in a lab's patent portfolio overall in the data set or for the swell-equal-spikes or the swell-less-than-spike groups. The p-values are near one in these three cases. However, there may be a strong indirect relationship between basic research fraction and swell fraction in labs that have more swells than spikes (tau of -0.7), although with only four observations the p-value of the significance test (0.3) is outside the usually accepted upper bounds of 0.1, 0,05, of 0,01. In addition, the relationship implied by the location of the circle data points in figure 5.3 is in the opposite direction than expected based on the hypotheses stated above. Overall, the results comparing basic research budget fraction to swell generation fraction do not support the hypothesis that basic research is a key factor in starting exploratory research-driven swells. However, given the small number of labs in this preliminary analysis, it may be worth exploring a relationship between basic research and swell generation in a larger data set, particularly in set containing more swell-heavy labs.

In the correlation tests for funding balance versus swell fraction, none of the results are strictly statistically significant at traditional levels. In any individual group, the Kendall's tau coefficient between funding balance and swell fraction is indistinguishable from zero. However, the weakly inverse relationship (tau of -0.2) between funding balance and swells in the overall group results may be plausible enough (p-value of 0.2), given the limited number of data points, to warrant further investigation.

Keep in mind that the p-value gives the likelihood of a test statistic as or more extreme as the one observed if the null hypothesis of no relationship holds. While a 20% likelihood may not be a sufficient level of certainty for policy decisions, given the limited number of data points and the number of uncertainties involved in the pattern classification, it is not necessarily a

sufficiently level of doubt to strongly rule out the potential of further research to uncover some relationship.

Note that in the analysis of funding balance, ARDEC is an outlier, and as in the discussion of alternate cluster explanations, something of a mystery. ARDEC is an applied research lab with no appreciable basic research funding according to the DOD In-House S&T Activities Reports. As such, its funding balance measure falls in the middle-right of the observed range. Yet it has the highest fraction of swells in its portfolio out of the labs examined. It may be that there is in fact no relationship between funding balance and swell generation, and ARDEC's location in figure 5.3 is within the natural range of variation. Alternately, there may be some aspect of ARDEC's management or culture that results in more swells than expected based on the laboratory's funding characteristics and technology mission. ARDECs position as the lab with the highest fraction swell classes in this study alone makes it a priority target for future in depth research.

AFRL is also an outlier in that is has a more balanced funding portfolio but few swells. However, the AFRL data point is a consolidation of all of the AFRL research directorates because of the limited availability of Air Force patent data in the TechMatch dataset. Given their size and history as independent laboratories, each directorate could be considered a research lab equivalent to the Army RDECs. As such, it is difficult to make generalizations about AFRL's research behavior, and this study is less certain about AFRL's pattern classification result than in the results for laboratories with more complete data.

5.2.4 Summary of hypothesis tests

The simplicity of the model and the limited number of data points employed preclude drawing any generalizable conclusions from this test, but the results could be interpreted, at a minimum, to emphasize the importance of considering laboratory type when searching for drivers of research performance. Overall among the DOD laboratories, the relative focus on basic research at the lab seems unrelated to the fraction of swells in the lab's patent portfolio. However, basic research may have a negative role in swell generation in labs that have a particularly preferential orientation toward generating swells (i.e. the swell > spike labs). When looking at the DOD labs overall, balanced funding portfolios seem to have a positive association with generating swells (more balanced labs tend to have more swells), but this may be a result of the particular characteristics of labs with swell-generating research missions. When the association between funding balance and swells is analyzed within like-patenting groups (based on fraction of patterns) no statistically significant association is found.

There are a number of possible objections to this analysis. For example, the funding measures do not necessarily cover the correct time periods, and several of the laboratories are actually aggregations of different facilities (i.e. AFRL and the Naval Warfare Center labs). The intent, however, is to illustrate the potential utility of patenting patterns for operationalizing hypotheses about drivers of research behavior that have been difficult to test on a large scale.

Future work will, hopefully, be able to expand on this line of work with more organizations, more control variables, and more complete data sets.

5.3 Pattern Applications Summary

The patenting patterns identified in this dissertation have potential applications in understanding and categorizing the behaviors of research organizations, identifying the roles of different factors in the production of certain research outputs, and monitoring the performance of research organizations. If the explanations for the existence of patenting patterns presented in Chapter 4 hold, then the fractions of steady-work, spike, and swell patterns in an organization's patent portfolio provide a summary measure of the organization's research and commercialization activities. Research organizations can be clustered based on the frequency of these patterns in their patent portfolios (e.g. figure 5.1), and additional research may be able to identify common research missions, practices, or cultures shared by laboratories in these clusters.

Furthermore, it may be possible to identify specific organizational characteristics or research practices that tend to increase the production of certain patenting patterns by research organizations. Combined with an understanding of the type of work represented by each pattern – i.e. spikes as potentially high-value discrete inventions and leading swells as innovative research programs that lead the rest of the field – such analyses could help identify characteristics and practices that improve research productivity and innovativeness. For example, the analysis of relationships between funding variables and the production of swell patenting patterns in section 5.2 demonstrates ways in which existing theories about drivers of research performance can be operationalized and tested using patent and budget data.

Patenting patterns can also be used in a monitoring capacity in several ways. The following bulleted list provides a few examples.

- Once links between patenting patterns and types of research behaviors are established, the frequency of patent patterns can be used to compare an organization's actual research behaviors with the types of behaviors preferred by the organization's leadership.
- As mentioned in sections 3.4 and 3.7, a lab's specific active patent classes (those in which it has at least 6 patents) can be used as one proxy of the lab's research focus areas. These patent-based focus areas can be compared with the lab's stated technology mission areas to again evaluate the fit between expectations and actual performance.
- Program staff can also mine patent spikes and leading s-curves for innovative performance "nuggets" – examples of high-quality research outputs from the lab.
- The density and MWW Test-based patent pattern timing comparisons presented in section 4.1 can also be used to compare the relative timing of patent activities between organizations. Such comparisons may suggest areas in which technology transfers have occurred between laboratories, since labs with earlier patents are potential sources of knowledge for labs with later patents.

As additional research clarifies the relationships among patenting patterns, innovative and other research outputs, and research organization missions, cultures, and practices, the list of applications could grow in both specificity and breadth.

Chapter 6 Summary

Innovation, particularly government-driven, is an increasingly prominent topic in public policy. Innovation and its role in supporting the U.S. economy is now a regular feature in Presidential speeches and legislative proposals. Yet the drivers of innovation remain poorly understood. Studies of innovation tend to produce results that are "multiple, conflicting, and vague," [98] (see the review in van der Panne, van Beers, & Kleinknecht (2003)).

A major barrier to understanding innovation is the lack of good performance measures and benchmarks (Marburger, 2005). Crow & Bozeman (1998) identifies three improvements that are needed in the study of R&D laboratories:

- "better information;
- more powerful and useful concepts and classification tools; [and]
- a willingness to use information in analysis and evaluation." (p 6)

This dissertation address these gaps by developing

- indicators of laboratory inventiveness based on the patterns of an organization's patenting over time rather than on patent networks or citation rates;
- theories regarding the types of research activities that generate these patenting patterns and the circumstances in which the patterns denote innovation; and
- approaches for using the relative frequency of each patenting pattern in an organization's portfolio to analyze possible drivers of research organization performance and evaluate the fit between an organization's expected and actual research behaviors.

The following sections summarize each contribution.

6.1 Patenting Patterns

Patents have long been used as a performance measure for research programs and organizations. In addition to being indicators of general knowledge production, patents are also potential indicators of innovation. Patents are by definition related to inventions that are novel and potentially useful, key aspects of innovations. However, the actual innovativeness of a given patent can lie anywhere within a very large range of values, and existing estimates of patent value may not be appropriate for detecting innovative results of public research. While citation volume has been frequently used as a proxy for patent value, this study contributes to a line of research that is investigating whether relationships in the patent technology classification system provide better insights into the pursuit of innovations (e.g. Eusebi (2011; N.d.) and Strumsky et al. (2012)).

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[98] a la Widavsky (1987)

S-curves have been used to describe the rate of performance improvement of a technology, the diffusion of ideas, and the rise of substitute products in a market. S-curves also appear in the patent record as inventors collectively decide to bet on a new technology (Eusebi & Silberglitt, n.d.). These collective bets grow the number of patents in a technology area (as represented by the patent technology class/subclass) at an accelerating rate until both patent examiners' willingness to accept the novelty of new claims (Eusebi, 2012) and the marketplace for the technology become saturated. Inventors and organizations who tend to patent in the early parts of s-curves are more innovative than others in the sense that they have pioneered a new technology area that later became a popular subject for investment and research (Eusebi, 2011).

While an organization's position in the overall technology s-curve is one indicator of innovativeness, examining the organization's pattern of patenting over time can reveal more information about that organization's history of activity in a technology area. Histograms of an individual organization's patents by application date and technology class demonstrate four basic patterns of patenting at the organizational level (see figure 3.8):[99]

1. Steady-work: A single organization will generally have only a few patents in any given technology class. Even in an organization's larger classes, the most common filing pattern is a handful of patents every few years. This pattern of activity appears as a series of level data points in the organization's histogram of patents per year per class.

2. Spikes: Occasionally an isolated burst of patents will appear above the level of steady work. A group of patents qualifies as a spike when three or more patents are filed within two years by the same group of inventors in closely related technology areas. Spike cases examined thus far have been the result of successful research projects that ultimately transferred technology to a military or commercial user.

3. Swells: Rather than one sudden burst of patenting, the third pattern appears as a gradual increase in the number of patents filed by an organization in a class each year. This trend can be thought of as a reflection of an organization's increased investment in or efficiency of research in this technology area.

4. Submarines: When there is a long delay between the filing and issuance of a patent, a cluster of patents may appear in an organization's portfolio far removed in time from the rest of their work. These patents are called submarines because of the long period of time during which they are unpublished and hidden from view. When a submarine surfaces, it can disrupt existing players in a technology by triggering negotiations between the patent owner and existing producers of the technology who were unaware of the hidden patent. Prior to changes in application rules in 2001, (patent applications are now published 18 months after they are submitted), some organizations used application revisions to

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[99] Excluding the case of no patents in a technology class

deliberately create submarines (Graham & Mowrey, 2004). Today similar patterns can still result from patent secrecy orders requested by the government.

6.2 Patenting Patterns as Indicators of Innovation

The presence of spikes and swells in a laboratory's patent portfolio can identify areas in which the laboratory has been potentially innovative. Furthermore, the relative timing of a laboratory's swell trend compared with a similar increase in patenting in the field as a whole can be an indicator of innovation via technology leadership.

Spikes signal a potentially innovative output from research organizations in the sense that they represent inventions which the organization expects to be highly valuable. This interpretation follows from two lines of reasoning. First, from a purely financial standpoint, patents cost the filing organization significant sums of money. Patent spikes represent clusters of related inventions in which the laboratory has made a relatively large investment in patent protection compared with inventions protected by only a single patent. Second, clusters of patents on related inventions (aka fencing or surrounding) are thought to be a more effective defensive strategy than single patents. Patent spikes, therefore, put an organization in a better position to defend their claims from potential competitors than would a single patent alone.

However, the methods presented in this dissertation alone do not provide direct evidence that the spikes are actually used. A number of factors could limit the actual use of what the lab thought was a promising invention. For example, the laboratory could misjudge the demand for its invention or the invention could prove more difficult to implement than originally thought. Therefore, while it is tempting to call spikes signals of innovations, additional work, such as a case study, is necessary to confirm actual use and actual innovation.

On their own, swells reflect capability building, but the relative timing of an organization's swell relative to the rest of the field may indicate innovation. Swells that lead the rest of the field denote occasions in which the organization has innovated by being among the first to do work in a popular technology area. Leadership can be detected visually by overlaying the organization and the field patent density curves on the same time axis, or it can be detected by applying the Mann-Whitney-Wilcoxon (MWW) Rank Sum Test to compare timing shifts between the respective patent series.

6.3 Studying Research Performance via Patenting Patterns

The overall distribution of patenting patterns in a lab's portfolio may be an indicator of the lab's overall research mission, culture, and practices. For example, labs with many spikes but few swells may be labs that focus on producing many discrete inventions but have relatively less interest in contributing to the advancement of scientific knowledge. Labs with more swells than spikes may place more emphasis on accumulating scientific knowledge and place less emphasis on transitioning inventions to users. Labs with similar rates of spikes and swells in their patent

portfolios may be operating in what Stokes (1997) called "Pasteur's quadrant" – a mode of research in which new scientific knowledge is pursued in order to create more innovative applied products.[100] While additional research is still needed to more fully explain how patenting patterns are related to research behaviors, comparing and contrasting the characteristics of research organizations with similar and different fractions of patterns in their portfolios can likely improve the understanding of drivers of research performance (for example see figure 5.1 for a classification of the DOD laboratories by patenting patterns).

In addition, more specific quantitative analyses of relationships between the distribution of patenting patterns and specific laboratory characteristics – such as the amount of basic or applied research funding or the percent of the staff with PhDs – can help evaluate the importance of these characteristics for producing particular types of research outputs. For example, if basic research is important for generating swells because it is a source of foundational ideas and exploratory funding, then, ceteris paribus, labs with larger emphases on basic research should also have relatively more swells in their patent portfolios. A preliminary analysis of the associations between research funding and patenting patterns (presented in section 5.2) is inconclusive but suggests that any relationships are likely mediated by the laboratory's mission or character, which in turn reemphasizes the importance of understanding the extent to which patenting patterns are indicators of labs' overall research missions, cultures, and practices.

6.4 Limitations and Future Research

The analyses presented in this dissertation employ a list of DOD laboratory-generated patents obtained from the DOD TechMatch website. The TechMatch list, as accessed in January 2012, includes an incomplete sample of DOD laboratory patents issued between 1990 and 2011. While several statistical techniques have been used to account for the uncertainties introduced by an incomplete data set, repeating the analyses presented in this dissertation over a longer and more complete data set would improve confidence in both the pattern classification rules used and the specific pattern classification results for the organizations examined in this study.

While expanding the range of data on which this study's findings are based would increase confidence in the pattern classification results, additional qualitative research would help refine the interpretation of these results. Comparing the histories and outcomes of swell (leading, lagging, and in-synch), spike, and steady-work projects would help refine understanding of the types of research activities for which these patenting patterns are signatures. A large-scale survey

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[100] Rather than thinking of basic research and applied research as opposites, Stokes (1997) suggests a two-dimensional model in which valuing advancing the boundaries of knowledge (i.e. discovery) is one axis and valuing the utilization of your work is the other axis (i.e. creation). Scientists and engineers can and do value both simultaneously. Stokes describes researchers in terms of the quadrant in which they place most value. Researchers who place a high value on discovery and a low value on creation are said to be in Bohr's quadrant. Researchers who place a high value on creation and a low value on discovery are said to be in Edison's quadrant. Researchers who highly value both are said to be in Pasteur's quadrant.

of inventors by pattern type, which obtained narratives of the project history and commercialization attempts, would provide a body of evidence for such research.

Even as this line of research moves forward, managers of government labs can use the patent patterns described in this study to evaluate and monitor their organization's performance. For example, patenting patterns can be used to

1. Answer "what have you done for me lately" by highlighting research projects that potentially transitioned to users (e.g. spikes and leading-swells)
2. Monitor laboratories' core competencies and shifts in those competencies over time by tracking changes in the rate of patenting in laboratories' active patent classes over time
3. Identify possible areas of supporting or duplicative overlap in research activities by comparing the timing of patenting activities in different laboratories within the same technology classes, and
4. Conduct open-source intelligence by applying these tools to the patent portfolios of other science and technology organizations foreign and domestic

Furthermore, while the research presented in this dissertation is exploratory, it is a step towards establishing an objective, relevant, and tolerably easy to use indicator of research quality. By comparing patenting patterns within and across organizations, future research will not only refine the interpretation of within-organization patenting patterns but can also refine the understanding of drivers of research performance. In particular, the spike and leading swell patterns are potentially indicators of innovative research programs. As such, future research that identifies drivers of spike and leading swell patenting patterns also, potentially, identifies drivers of innovation. Hopefully, an improved understanding of within-organization patenting patterns will lead to improved science and innovation policy making as well.

Chapter 7 References

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Appendix A Common Research Evaluation Methods

Program evaluation of government research is an evolving field (Ruegg & Jordan, 2007). Ruegg & Jordan (2007) lists 13 methods for measuring the performance of R&D programs, each tailored to a different question. Ruegg & Feller (2003) also provides an excellent summary of the pros and cons of using a variety of qualitative and quantitative evaluation methods on science and technology programs. Table A.1 summarizes common R&D program evaluation methods, their uses, and their limitations based on these sources.

Many of the methods listed in Table A.1 are targeted toward on-going, internal management of R&D programs rather than evaluation by outside researchers. For measuring the innovativeness of DOD labs, many fail either the relevance, ease of use, or credibility criteria from Parish (1998):

- Bibliometric indicators such as journal publication and citation counts are a standard measure of scientific output, but are not necessarily relevant to the production of military-relevant knowledge and hardware.
- Peer review is the standard approach to evaluating research organizations with difficult to observe outcomes, but by definition is potentially biased by the perceptions of the experts doing the review and the anecdotes provided by the program under review.
- Benchmarking compares the laboratory's inputs and process to those believed to be found in high-performing research organizations. However, many questions remain regarding which inputs and processes are really related to various outcomes. For example, the National Academies' Laboratory Assessment Board recommends monitoring the quality of the workforce on the theory that "Many organizations have determined that the quality of the workforce is the most reliable predictor of future R&D performance," (Laboratory Assessments Board, 2012, p. 4). However, this recommendation runs counter to the findings of J. T. Hall & Dixon (1975) which found that simple inputs, such as staff quantity and quality, were poor predictors of *outcomes* such as the transfer of knowledge to users.
- General indicators are similar to benchmarking but less explicitly tied to theories of "good" research environments.
- Technology commercialization studies, benefit-cost studies, and spillover studies are difficult to use in a military setting because the primary benefit, military performance, is difficult to monetize and because the path from laboratory to commercialization or deployment can be extremely difficult to trace.
- Network analysis could help trace those paths, and could be helpful in evaluating some of the training and communication goals of the DOD laboratories, but on its own it does not really address the impact of technological discoveries.
- Historical tracing methods do address that impact as well as knowledge flows, but they are extremely resource intensive. Project Hindsight, which traced the contributing research to 20 significant military inventions, consumed approximately 40 man-years of research time (Kreilkamp, 1971).

- Econometric studies could be very useful, but the appropriate data and models are not always clear.
- Similarly, the appropriateness of general case study methods and survey methods depends on the broader framework of the analysis. For example, this study uses case studies to provide additional context for patent data.

In addition, note that quantitative research impact measures may be collected by a laboratory but not reported due to fears about how that data will be used. Kostoff, Averch, & Chubin (1994) acknowledge that the results of a research impact assessment may result in the cancellation of a "pet" project or lead to budget cuts from disgruntled legislators. ARL reportedly collects a number of statistics about its research enterprise including papers and patents, percentage of doctoral level staff members, numbers of visiting scientists, overhead rates, and workforce turnover, but they are for internal use only (Cozzens, 2001).

Table A.1 Summary of laboratory evaluation methods

Method	Description	Typical Uses	Primary Challenges
Peer Review/Expert Judgment	Formal or informal review of programs and projects by individuals who are experts in that area of research. Usually involves presentations by researchers followed by discussion by the peer/expert panel	Project selection, In-progress review of quality, Assessment of portfolio balance and relevance	Subjective - variation among reviews, potential for reviewer bias
Monitoring, Data Compilation, and Use of "Indicators"	On-going tracking of inputs, outputs, and outcomes including money spent, publications, technological objectives achieved	In-progress review, Assessment of portfolio quality	Selecting appropriate metrics and obtaining data
Bibliometric Methods: Counts and Citation Analysis	Counting academic publications, academic citations, or patents	Provide evidence of knowledge creation and dissemination	Citation and publication rates vary across fields, Does not account for informal or non-academic knowledge dissemination
Bibliometric Methods: Data Mining	Text analysis to identify relationships within varied documents including technical reports, academic publications, resumes, and press releases	Provide evidence of knowledge creation and dissemination, Identify research gaps and opportunities	Large data gathering and cleaning burden (newer tools provide more automation), Development of visualization and interpretation tools is on-going
Benchmarking	Comparison with other programs	Determine relative quality of program, Identify best practices	Identifying relevant comparison programs and measures, Obtaining data

Method	Description	Typical Uses	Primary Challenges
Technology Commercialization Tracking Method	Tracking performance, cost, and market share data of products derived from the research program	Identify (applied) program impact, Support benefit-cost studies	Tracing & verifying technology or knowledge transfer, Separating effects of R&D program from technology transfer efforts
Benefit-Cost Case Study	Quantifying positive and negative impacts of a project or program and comparing them to the project or program costs	Evaluate (applied) program impact relative to costs, Estimate potential impact of proposed projects	Attributing impacts to the research project, quantifying qualitative or subjective impacts
Spillover Analysis Using a Combination of Methods	Estimating the public and private value of spillovers from research such as the spread of new knowledge or benefits of new technology that are not fully incorporated in the price of that technology	Provide a broader estimate of program impacts	Identifying and attributing spillovers, see Counts and Citation Analysis, Network Analysis, and Econometric Methods
Network Analysis	Visualize networks of researchers based on co-authorship, participation in research centers, email traffic, reported face-to-face contacts, etc.	Provide evidence of knowledge creation and dissemination, Evaluate impact of program on communication and collaboration networks, Identify relevant researchers	Large data gathering and cleaning burden, Accounting for impacts and changes over time increases difficulty
Historical Tracing Method	Working forward from a discovery or backward from an impact identify all subsequent/contributing (respectively) discoveries	Identify role of program in known innovations	Identifying all contributions can require a large number of interviews, a large amount of data mining, and skillful "detective work" (Ruegg & Jordan, 2007)
Econometric Methods	Using mathematical models and statistical tools to explore relationships between program goals and actual (quantifiable) impacts	Evaluate program impacts, provide support for cause-and-effect relationships, hypothesis testing	Availability of data and appropriate models, Large data gathering and cleaning burden, Applying and interpreting complex statistical methods
General Case Study Methods	Use narratives supported by other data to explore program processes and impacts	Explore or evaluate program processes, Provide illustrative examples	Generalizability, Access to sources
General Survey Methods	Ask program managers, participants, or other stakeholders questions about program processes, outputs, and outcomes	Determine participant or stakeholder satisfaction or needs, Gather data to support other methods e.g. identify outputs and outcomes not recorded elsewhere	Skillful survey design, Obtaining adequate response rates, Complying with the Federal Paperwork Reduction Act

Sources: (G. Jordan & Malone, 2001; Ruegg, 2007; Ruegg & Feller, 2003; Ruegg & Jordan, 2007)

Appendix B Review of Patent Value Studies

The main difficulty for using patents as a proxy for innovation lies in confirming use. Dernburg and Gharrity identify three components to patent use: "1) the patented invention is actually exploited commercially, 2) the patent is of value to its owner for purposes of building up a dominant market position or for bargaining for cross-licenses, etc., [and] 3) the patent is considered potentially useful because of the possibility that either the invention or the patent will be used in the future," (Dernburg & Gharrity, 1961, pp. 358–359). Dernburg and Gharrity's first aspect of use is most relevant to this study. However, direct evidence of a resulting product can be hard to find. Most studies fall back on some estimate of a patent's "value" which captures multiple connotations of "use".

There are two ways to approach patent valuation: directly and indirectly. Direct measures of patent value try to attribute a dollar value to individual patents or an entire patent portfolio. Direct measures are usually obtained through surveys, some of which ask about patent use explicitly, or through models that relate a firm's knowledge assets to its market value. Indirect measures rank patents based on some other characteristic that theoretically correlates with value, use, or some other concept of innovativeness. A patent's history of renewal payments is an indirect measure of value that has been in use since at least the 1930s. Perhaps the most common indirect measure in use today is the number of citations a patent receives from other later patents (a.k.a. forward citations). This section describes the results other researchers have obtained using direct and indirect methods, explains how well each method provides evidence of use or innovativeness, and states some of the challenges associated with using each method in a government setting.

B.1 Direct measures

Inventor surveys

Surveys that ask inventors whether their patent was used to produce a product that was sold are clearly direct measures of whether a patent was used to produce a product that was sold. A 1950s survey of 600 patent assignees found that over 50% of patents owned by corporations were used at some point in their lifetime (Sanders, Rossman, & Harris, 1958) (also see discussion of the Patent and Trademarks Foundation study in Schmookler (1966, pp. 48–50) and Griliches (1990)). Between 40 and 50 percent of inventor-owned patents were also eventually used (Schmookler, 1966, p. 52). Surveys that ask inventors to judge the value of their patents, however, measure something slightly different.

A patent's value and whether it was used should be correlated, although they are distinct concepts. On average, patents that are used to produce a commercial product should have a higher value than those that are not tied to a product, but patents that are not used will not necessarily have zero value. In addition to actual product revenues, the value an inventor assigns to their patent may be based on licensing revenues (which do not necessarily result in a marketed product)[101] or the perceived value of their technology portfolio for attracting investors or negotiating other deals.

Inventors and patent owners may also value patents because of their role in a larger business strategy. A patent represents a right to exclude others from making or using a technology (see the discussion of the decision to patent in Murphy, Orcutt, & Remus (2012)). If a patent holder declines to use the technology and also excludes others from using the technology, then the technology effectively does not exist. That exclusion, however, still has value to the patent owner.

Supporting this distinction between use and value, the survey by the Patent and Trademarks Foundation found that 11% of patents "though not used, have had or are expected to have other benefits," (Sanders et al., 1958). A further 7% of patents were licensed but not reported as "used" by their original assignee (Sanders et al., 1958).

More recent surveys have also found that around 50% of patents are used to support a commercial product. While, according to Griliches (1990), as of 1990 the Patent and Trademarks Foundation survey was the most extensive survey of patent use ever conducted, in the 2000s several large surveys were done of international patent holders. In addition, four smaller U.S. and European surveys were executed in the early 2000s to understand the relationship between patenting and scientific information sources in large corporations (Giuri et al. (2007) reviews these studies). The two recent large-scale and broadly-focused surveys are discussed below.

The Patval-EU survey, conducted in 2003 and 2004, received responses from the inventors of over nine-thousand patents granted by the European patent office between 1993 and 1997. The goal of the Patval-EU survey was to both continue to explore the validity of other indicators of patent value, particularly citation-based measures, and provide data on inventor characteristics and the research process on a larger-scale than had been done before. Patval-EU's measure of patent value was the amount for which inventors would have been willing to sell their patent immediately after it was granted given what they currently knew about the benefits to holding the patent. Patval-EU also asked inventors to indicate how their patent was used. In a result that is consistent with other studies, they found that slightly more than 50% of patents were used to protect a commercial product or were licensed to another firm. Almost 20% of patents in the study were held to block other firms (Giuri et al., 2007).

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[101] Licensed patents do not get used for many practical reasons. Several of these reasons boil down to: the invention isn't as profitable as expected. Maybe the market is smaller than expected. Maybe the invention is more difficult to manufacture and therefore costs more than expected. Federico (1937) has a larger discussion of this topic.

The Research Institute of Economy, Trade and Industry (RIETI)-Georgia Tech inventor survey, conducted in 2007, sampled over 5000 Japanese and triadic patents (patents that had been submitted to the European, U.S., and Japanese patent offices) filed in 1995 (Sadao & Walsh, 2009; Suzuki, 2011). The RIETI-Georgia Tech study borrowed from the Patval-EU study when designing its questionnaire. The main purpose of the survey was to understand how industrial research processes differed between Japan and the U.S., but the survey asked inventors to indicate the value of their patent in one of four bins and indicate whether the patent had been used within the company, licensed to another party, or used by a spin-off company (Suzuki, 2011). The RIETI-Georgia Tech study found that 60% of the patents in their sample had been used, although Japanese firms were more likely to use the patents to support products within the inventing firm than license the patents to another firm or use them for a spin-off company (Sadao & Walsh, 2009). Interestingly, among the surveyed triadic patents, those requiring no R&D or those which were generated from targeted research programs were the most likely to be in the highest value bin (as opposed to patents that resulted from a serendipitous discovery or general research) (Nagaoka & Walsh, 2009).

Patent valuation via stock price

Rather than ask a firm about the dollar value of their patent portfolio, some researchers will try to estimate patent value based on changes in a firm's stock market value. This approach is not applicable to government laboratories since they do not offer stock or otherwise have an overall monetary value like a private company. However, this stock-based valuation approach is reviewed below for completeness.

Estimating the change in stock price attributable to a company's patent portfolio is often done to compare the R&D-driven competitiveness of different companies. Figure 3 in Griliches (1990) illustrates the thought process. A company's overall profitability or stock market value is a function of both its physical assets and its non-physical knowledge and human capital assets. Patents are one proxy for unobservable research knowledge. Using the known value of the company, the known estimate of the replacement value of physical assets, and the known size of the company's patent portfolio,[102] researchers can use regression to estimate the fraction of a firm's value attributable to its patent portfolio. Since the size of the patent portfolio is a proxy for the firm's knowledge assets, researchers interpret this coefficient as a measure of the quality of the firm's R&D and other knowledge processes.

The main question here with respect to patents is whether they are a sufficiently good proxy for knowledge to be used in its place in equations describing productivity improvements. R&D expenditures seem to be a bigger factor in determining the stock price than the number of patents a firm has (Griliches, 1990). Pakes (1985) uses a more complex model to try to understand the

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[102] Sometimes the patent variables are time-lagged, depreciated, or weighted by technology area or by citation counts. B. H. Hall, Mairesse, & Mohnen (2010) review commonly used lag and depreciation coefficients.

relationships among a firm's R&D expenditures, the size and quality of its patent portfolio, and other events that change the way the market values a firm's knowledge assets. While Pakes is able to identify differences between short-term shocks that increase a firm's stock market value and the long-term market value due to the firm's general level of R&D activity, he seems uncertain about the direction of causality in the shocks. Did a new research discovery, with its associated patent, cause the market to reevaluate the firm's value or did some other event cause the market to place more weight on a firm's knowledge assets causing the firm's managers to increase their R&D and patenting activities? Balasubramanian & Sivadasan (2011) find that, at least for first time patentees, patents affect firm value primarily by increasing new product sales, although they too are unwilling to make a strong causal statement, noting that there are a number of external factors that could affect the decision to patent, new product sales, and firm value simultaneously.

Drawbacks to survey methods

There are two drawbacks to using survey methods to understand the use of patents for military technologies. The first and main drawback to survey-based methods of patent valuation is time. Each survey is a major investment in resources requiring determining the sample frame, gathering contact information, developing the survey instrument, and following up with target respondents. Furthermore, the process must be repeated for each new population (both in terms of laboratory and time frame) in the study. This makes surveys expensive to use as an on-going monitoring tool.

The second drawback is related to the different motivations and mechanisms for patenting in the DOD laboratories versus a private company. Because government laboratories have different motivations for patenting than private companies and inventors, asking inventors and technology transfer managers about the value of patents may have a different meaning than it does in the commercial sector. In addition, inventors and research managers may not be able to say whether a patent was used or what its approximate value is. Therefore, survey questions used in a commercial setting may not work well in a government laboratory.

Inventors, because they are bureaucratically separated from the technology transfer and acquisition organizations may not know if their patent has been used in a commercial license (although they should receive royalty payments if the license included a payment to the laboratory). Conversely, while inventors often are aware when their research was transferred to a military system, they may not know which particular patents were tied to that invention.[103] The laboratory's Office of Research Technology Applications (ORTA) does keep a record of all licenses from the lab's patents, but they are not always at liberty to say whether or not a particular patent has been licensed (Personal Interview, 2012).

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[103] This problem was encountered in several early interviews.

Furthermore, in a military setting, counting licensing revenue alone can undervalue patents that are used for military rather than commercial purposes. If a government researcher invents and patents something, and then that invention is used for government purposes, for example in a military system, then no money may change hands. Government technology transfer offices say that the government can negotiate more favorable purchase terms if the government owns the patent rather than the contractor. In theory, if the government has already developed a technology embodied in a patent, then they would be able to pay the contractor just for manufacturing and not for research and development. However, none of the technology transfer personnel interviewed could identify an example of this actually happening.[104] Even if it did occur, researchers outside the government would likely not have access to the information necessary to calculate the amount of money saved, i.e. the difference between the contract price with the patent and without the patent.

Overall, value in a government laboratory may be evaluated very differently than in a private company or in a university. While commercial value is considered because it generates income for the lab and for the inventor, potential licensing revenue is definitely not the only or primary concern for DOD technology transfer offices. DOD technology transfer and patent professionals generally listed defensive patenting (obtaining a favorable contract as described above) as the first motivation, although they acknowledged that actually defending their patent space was very difficult (Personal Interview, 2012).

Another DOD motivation for securing patents is encouraging the development of a key industry. By offering non-exclusive licenses to multiple suppliers, DOD labs can push technologies they believe to be better into the defense industrial base. One example of this mechanism was given to us by a Navy patent professional. A particular pipe coating was developed at a Navy lab and licensed to numerous ship-building subcontractors. The coating eventually became the new industry standard. The value of patents used for this mechanism would also be difficult to obtain from a simple survey of laboratory patent offices (Personal Interview, 2012).

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[104] One manager was actively derisive of the idea, noting that several different organizations, who rarely coordinate, would be involved in enforcing government patent rights. In the military, the laboratory Offices of Research and Technology Applications (ORTA) track government-owned patents, but they are mostly focused outward on technology transfer to non-military uses. The acquisition officers that manage government-purpose procurement are in an entirely different organization and have no knowledge of patents created at and owned by the laboratories. Even if the laboratory told the acquisition office about a specific patent, acquisition contracts for complex military systems are written in terms of performance specifications rather than technology specifications. Therefore the acquisition officer may not be able to tell the contractor to use the technology represented by the specific patent. Furthermore, if the military somehow later realized that they had paid extra money for technologies that they had created, they would have to go to the Justice Department to file a lawsuit (Personal Interview, 2012). One government patent attorney interviewed during this study mentioned that it is the job of the laboratory patent attorneys to help negotiate favorable terms for contracts including government intellectual property, but the patent attorneys' time can become oversubscribed with requests for new patent applications instead (Personal Interview, 2012).

B.2 Indirect measures

In contrast to survey methods described above, methods that value patents based on some recorded and archived piece of data may have a large initial investment, but once the algorithm is implemented, applying the code to a new dataset can be trivial (depending on the complexity of data cleaning required to make new raw data usable). There are two common indirect methods for estimating patent value, both of which take advantage of archival data: patent renewal payments and forward citation counts.

Patent renewal payments

In addition to the fees an inventor has to pay when they submit a patent, several patent systems require periodic payments to keep the patent active. Using renewal payments to estimate patent value is one of the oldest approaches. Early studies in this area were done on European patent systems (see for example Federico (1937) and Dernburg & Gharrity (1961)). The U.S. only started requiring renewal payments in 1980 (Griliches, 1990). The current USPTO renewal, or maintenance, fees are $1,130 after 3.5 years, $2,850 after 7.5 years, and $4,730 after 11.5 years.[105]

Patent renewal payments only approximate use for several reasons including because they are based on an inventor's perceived value of the patent and because the signal is truncated at the upper end. Being renewed may be a good indicator that a patent was used since inventors likely only renew patents from which they are deriving some commercial benefit. However, there are a number of reasons to suspect that renewal data tells us very little about actual use.

First, as discussed above, the benefit an inventor bases his renewal decision on may not be directly tied to an actual product. For example, if the inventor licensed the patent to someone who was unsuccessful in bringing the invention to market, or if the patent was part of some larger signaling strategy. Furthermore, inventors may make the first (or first few) renewal payments still with the hope of some future return.

Second, renewal payments are a coarse measure of value because they lump together patents that may have very dissimilar outcomes into a few bins. In the U.S. system there are only four possible bins: (1) never renewed, (2) renewed once, (3) renewed twice, and (4) renewed three times. Patents in the first category may include both trivial, "wacky" patents and "early bloomers", patents that generate substantial returns in the first few years but become obsolete in later renewal periods (Gambardella, Harhoff, & Verspagen, 2008). On the late end, Sanders argues that patents that survive all three renewal periods almost certainly saw some use (see attachment to Dernburg & Gharrity (1961)), but two different patents that both survive all three renewal periods may still generate very different commercial returns. Sanders also points out that

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[105] see the USPTO fee information website for updates to the fee schedule

returns generated by a patent associated with a commercial product are so much larger than the renewal fees that the renewal decision is "trivial".

Third, lapsed patents are not necessarily unused since, as Frederico puts it, lapsed patents become "part of the common fund of useful technology" and may be employed by anyone (Federico, 1937). Organizations whose primary interest in patenting is to prevent another organization from exerting monopoly control over the technology, like the DOD labs dealing with military contractors, may allow patents to lapse early in order to protect their interests with the minimum expenditure. However, in the current U.S. patent system, publishing the discovery in an academic journal or trade magazine would be a more cost effective way to place the invention in the public domain (Personal Interview, 2012).

Forward citations

Forward citations, the citations a patent receives from other later patents, are an attractive measure of patent value because they suggest relationships between foundational technologies and their children. In his study comparing patent forward citation rates with commercial product value, Trajtenberg cites as justification for his approach the description of forward citations made by the U.S. Patent Office's Office of Technology Assessment and Forecast:

> "During the examination process, the examiner searches the pertinent portion of the "classified" patent file. His purpose is to identify any prior disclosures of technology… which might anticipate the claimed invention and preclude the issuance of a patent; which might be similar to the claimed invention and limit the scope of patent protection…; or which, generally, reveal the state of the technology to which the invention is directed. If such documents are found they are made known to the inventor and are "cited" in any patent which matures from the application… Thus, the number of times a patent document is cited may be a measure of its technological significance," U.S. Patent Office's Office of Technology Assessment and Forecast Sixth Report cited in Trajtenberg (1990, pp. 173–174).

However, there are a number of factors that should obscure the relationship between forward citations and knowledge transfer or patent value.[106] First, forward citations occur for purely legal reasons that have no connection with actual use or knowledge transfer (Eusebi & Silberglitt, n.d.; Strumsky et al., 2012). Second, a patent may describe a concept that is fundamental to many other future technologies, but that specific patent may never have been implemented in a physical invention offered to the market. Third, patents that are written very broadly will intersect with more patents than those that are written modestly. Therefore, the number of forward citations is confounded by the language in the patent, which is independent of the

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[106] Patent forward citations are used in three different ways in the study of research outputs. One approach is to view the network of citations as a map that traces the lineage of patented technologies. A second and closely related approach is to view the network of citations as a network of collaboration or intellectual influence. The third approach estimates the significance or value of a patent based on the relative number of citations it has received. Only this last approach is relevant to this study.

usefulness of the patent (unless it turns out that more concise patents *are* more valuable patents) (Eusebi, 2012). Fourth, the number of forward citations are also a function of time. Older patents have had the opportunity to accumulate more citations from a larger pool of patents (Marco, 2007). Furthermore, while some studies have correlated forward citation counts with direct measures of patent value (summarized below), other studies have found that citation counts explain a very small fraction of the total variation in patent value (Gambardella et al., 2008).

Despite these drawbacks, there is some evidence that the number of forward citations, relative to other patents for similar technologies, correlates with the commercial value of the patent. Analyzing patents related to Computed Tomography (CT) scan devices, Trajtenberg (1990) correlated the number of forward citations a patent received with an estimate of the increment of consumer surplus gained by the underlying invention. Controlling for the age of the patent, more citations positively correlated with higher consumer surplus gains for the new invention. Trajtenberg also found that the largest consumer surplus gains occurred early in the life of the technology even though industry R&D spending peaked later.

B. H. Hall et al. (2005) found that while accumulated R&D stocks were the largest predictor of firm value,[107] firms that held highly-cited patents had market valuations 50% higher than they would have predicted based on R&D stocks or raw patent counts alone. Hall et al. say their work "confirms that the market values... 'high-quality' R&D output as measured by citation intensity," (B. H. Hall et al., 2005, p. 17). However, it seems unlikely that market analysts are literally examining a firm's patent citation intensity and modifying stock recommendations based on that analysis. It seems more likely that citation intensity correlates with some other firm characteristic into which market analysts have more visibility. Supporting this objection, Gu (2005) confirms that patent citations are useful predictors of a firm's future earnings, but finds that investors do not behave as if they include patent citations in their decision-making.[108]

Czarnitzki et al. (2011) further investigate the quality of patent citation metrics by seeing if they will distinguish "wacky" patents from other patents. "Wacky" patents are those identified by www.patentoftheweek.com as particularly futile, silly, obvious, or incremental. Indeed, wacky patents had significantly fewer forward citations. However, wacky patents had references to and from patents in a significantly broader array of technology classes. The authors say this diversity in technological antecedents occurs because wacky patents represent combinations of technologies "that should not be joined because the combination is trivial or useless," (Czarnitzki et al., 2011, p. 134).

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[107] B. H. Hall et al. (2005) use Tobin's Q as the measure of firm value. Tobin's Q is, basically, the ratio of a firm's market valuation to the replacement cost of the firm's physical assets. See section on Patent valuation via stock price.

[108] A key exception to this objection may be the pharmaceutical industry in which market analysts may very well pay close attention to patent characteristics, although such a model would also have to account for the drop in earnings after a drug patent expires and generics become available (see for example Hodgson, Falconi, & Spencer (2012)). Incidentally, B. H. Hall et al. (2005) do find that patent citations have the largest effect on firm value in the pharmaceutical industry.

Forward citations have also been used to evaluate the quality of federal laboratory patents. Jaffe & Lerner (2001) used forward citations to gauge changes in the quality of patents filed by DOE laboratories following legislation in the 1980s aimed at increasing transfer of technology from federal laboratories to the private sector. They find that patents awarded to DOE Federally Funded Research and Development Centers (FFRDCs) increased in the early 1990s despite falling research funding. While a similar increase in patenting occurred in universities following the Bayh-Dole act, universities appeared to be submitting lower quality patents as measured by the average number of forward citations received (Henderson, Jaffe, & Trajtenberg, 1998). In comparison, the quality of DOE patents, as measured by forward citations, remained nearly the same as the volume of patents increased (Jaffe & Lerner, 2001).

Jaffe, Fogarty, & Banks (1997) used similar methods to examine the quality of NASA patents from the 1970s through the 1980s. This time Jaffe et al found that NASA patent quality, as measured by forward citations, peaked in the late 1970s and declined over the following decade, although NASA patents remained more highly cited than the average federal patent. The authors also point out that citation-weighted patent counts should not be used as the only measure of a NASA lab's performance because NASA likely does not seek patents for much of its work and companies may not feel they need to cite NASA patents because NASA, like most federal agencies, is unlikely to sue for infringement. Both behaviors would cause citation-weighted patent counts to under estimate the innovativeness of a NASA facility.

Drawbacks to indirect methods

The main drawback to using renewal data to judge the innovativeness of DOD patents is the truncation problem described above. A second drawback is that the renewal rate may be determined more by the quality of the ORTA than the quality of the research since the decision to renew will be based on the ORTA's understanding of commercialization opportunities. A third drawback is that the DOD may have an incentive to let patents lapse quickly so the information is in the public domain. After all, commercial profit is not the primary motive for patenting in the DOD, and placing patented inventions in the public domain can support many of their other objectives including preventing contractors from claiming the invention and charging more for it and encouraging the use of new technologies in the defense industry (see the pipe coatings story in the "Drawbacks to survey methods" section). For all of these reasons, patent renewal rates are not a good measure of the quality, much less the innovativeness of government patents.

If forward citations correlate with commercial patent value, then forward citations could be a good approach to finding innovative government patents. Indeed, Jaffe et al. (1997) and Jaffe & Lerner (2001) explore this approach for NASA and DOE patents. Some controls would be needed for industry, technology area, and age of the patent, but these adjustments are feasible. In addition, relative citation rates may only be comparable with other government patents, rather than across the entire industry, because of the defensive issues described in Jaffe et al. (1997).

However, as mentioned in the second paragraph of this section, there are several reasons to be wary of forward citations as a measure of patent value. Gambardella et al. (2008) found that the number of forward citations accounted for less than 3% of the variation in patent values. Perhaps more importantly, the theoretical basis for using forward citations as a measure of patent value – that highly cited patents represent more fundamental technologies that are built upon by later patents – is in some conflict with the actual practice of patent law.

Patent citations occur for legal reasons that are unrelated to attribution including the responsibility of the patent examiner to skeptically test the novelty of the patent's claims (Alcacer, Gittelman, & Sampat, 2009; Eusebi & Silberglitt, n.d.; Jaffe et al., 1997; Strumsky et al., 2012). Studies that have attempted to assert a more literal connection between the citing and cited work have found a great deal of noise in the citation signal. Based on interviews with inventors, fewer than 50% of patent citations seem to reflect to an extension of the cited technology area or correspond with any known communication between inventors (Jaffe et al., 1997; Jaffe, Trajtenberg, & Fogarty, 2000; Packalen & Bhattacharya, 2012). This finding is unsurprising when one considers that the majority of citations on the average patent are added by the patent examiner (Alcacer et al., 2009).

B.3 Technology classification-based approaches to patent valuation

Recognizing the limitations of citation-based estimates of patent value, some authors are beginning to explore whether relationships within the network of USPTO patent technology classes are better descriptions of idea networks and, furthermore, whether some of these relationships can help identify innovations. Packalen & Bhattacharya (2012) use text analysis of patent claims and the USPTO technology classifications to identify early work in a technology area and to separate citations that indicate similar claims from citations that do indicate the building of ideas. Strumsky et al. (2012) recommend using the patent technology classification system to explore the evolution of the components of technologies. Strumsky et al. argue that patents actually represent bundles of "technological capabilities," each of which has its own history, and that citation-based studies therefore provide only a coarse look at the evolution of technologies. Eusebi & Silberglitt (N.d.) actually do trace the evolution of technologies through the co-occurrence of technology classes within patents. Eusebi and Silberglitt furthermore use the existence of s-curves in the accumulation of patents within technology subclasses to identify emerging technologies and their antecedents.

This study builds on Eusebi's technology class s-curve work to construct indicators of patent value that are based entirely within the technology classification signal. Additional discussion of the relationships between s-curves in the patent technology class system and patent value or innovativeness can be found in section 2.3.

Appendix C USPTO Classification System

Since 1900, the U.S. Patent and Trademark Office (USPTO) has maintained a classification system to organize and describe the subject matter of patent documents (USPTO, 2012b). This system evolved to help patent examiners group, search for, and more quickly identify other patents as they consider the validity of a new patent application (Eusebi, 2012), but this system can also be used by researchers to monitor the evolution of technologies.

Patent examiners assign each patent they process to one primary (aka original) and any number of additional (called cross reference) technology classes (Strumsky et al., 2012; USPTO, 2012c). This classification summarizes all of the distinct technologies and applications described in a patent's claims (Strumsky et al., 2012).[109] A technology class must be identified for each claim, although if more than one claim falls under the same class the assignment is only listed once (Strumsky et al., 2012; USPTO, 2012d). The rules for placing a patent claim in the appropriate class are described in detail in USPTO (2012d). Strumsky et al. (2012) provide several examples illustrating how a patent's many claims can be reduced to a few technology class assignments. Strumsky et al. note that there are many fewer class assignments on average, 4.4 per patent in 2005, than there are claims per patent, which they uses as evidence for the "descriptive efficiency of the technology codes," (Strumsky et al., 2012, p. 8).

Each technology class assignment is listed on the front page of a patent as a pair of numbers, e.g. 501/137. The number before the slash indicates the top-level technology class and the number after the slash identifies the technology subclass. The top-level technology classes, of which there are approximately 500, are broad descriptions of technologies like "Power Plants", "Ordnance", "Television", or "Organic Compounds"). These classes are also arranged into about 30 subject groups (USPTO, 2012e) which provide a good initial overview of the classification system (USPTO, 2012d).

Subclasses, of which there are around 150,000,[110] form a hierarchical system that gives more detail about the "processes, structural features, and functional features" (USPTO, 2012c, p. 1) of the technology described in the patent. For example, to find the description of class 501 (Compositions: Ceramic) subclass 137 the reader must trace a 6-level chain:

➢ Level I: Class 501: Compositions: Ceramic

   ➢ Level II: Subclass 1: Ceramic Compositions:

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[109] "[A patent's] claims state, in technical and precise terms, the subject matter of the invention (or discovery), as well as its purpose, principal properties, how it operates and the methods it employs," (Strumsky et al., 2012, p. 4).

[110] Based on an analysis of classes and subclasses listed in the Jan. 6, 2012 USPTO master classification file.

➢ Level III: Subclass 134: Titanate, zirconate, stannate, niobate, or tantalate or oxide of titanium, zirconium, tin, niobium, or tantalum containing (e.g., dielectrics, etc.):

  ➢ Level IV: Subclass 135: Alkaline earth or magnesium containing:

    ➢ Level V: Subclass 136: Titanate containing:

      ➢ Level VI: Subclass 137: Barium titanate:

Each entry on this chain is included in the list of subclasses. Because they are meant to be read hierarchically, any given subclass title may be difficult to comprehend out of context. The full class-to-subclass path, however, is too long to use frequently in a discussion or as a label on a chart. Therefore, this study has created more lay-person-friendly short description of classes and subclasses. Using the above example, this text refers to class 501/137 as Ceramics Containing Barium Titanate.

The patent office develops new classes as new areas of technology emerge. For example, class 977, nanotechnology, was created in 2004. When new technology classes are defined, patent examiners reclassify older patents into the new category and retire some older obsolete classes. Therefore, the first nanotechnology patent appears in 1986 (Strumsky et al., 2012). The USPTO issues monthly "Classification Orders", which are available at the USPTO website, detailing changes to the technology class system.

Appendix D Overview of the DOD laboratory system

This section provides an overview of the Army, Navy, and Air Force science and technology (S&T) systems. It provides a summary of each laboratory's budget and technological focus area. The relationship between funding and technology areas with patenting patterns is explored in chapter 5.

As stated in chapter 3, this study only covers the in-house S&T research laboratories. S&T is defined by budget activities 6.1 (basic research), 6.2 (applied research), and 6.3 (technology development research).[111] Contractor-operated research facilities and doctrine-focused "laboratories" like the Battlelabs are excluded. With this restriction in mind, each Service's laboratory system can be described as a combination of four types of organizations:

1. a "corporate" laboratory that performs basic and applied research in a wide variety of fields,
2. several applied research and technology development product centers focused on a few fields of technology each,
3. a medical research command with subordinate laboratories and hospitals, and
4. an extramural basic research office that primarily funds university researchers

In practice, each service apportions its research funds differently, with different organizational layers between the laboratory researchers and the Service Secretary, and with some research performing organizations also writing external grants to various government and private-sector research groups. Each of the following three sub-sections illustrates how each service organizes these four functions into different organizational units, lists the technological focus areas of each laboratory, and summarizes each laboratory's relative emphasis on basic, applied, or technology development research. Later sections of this chapter will show how technology focus area and the distribution of basic, applied, and technology development research correlate with a lab's patent trends.

Note that an organization is included in this study its budget and personnel numbers are reported separately in the 2007 DOD In-House S&T Activities Report. However, some "laboratories" are aggregated or disaggregated based on the availability of patent or budget data for that organizational unit (see chapter 4). As a result, some organizations that should more

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[111] The DOD allocates research and development money according to a sequence of categories that loosely represent a linear view of technology development. The entire category is called Research, Development, Test and Evaluation (RDT&E). The first three levels are collectively referred to as science and technology (S&T). S&T includes basic research, applied research, and technology development. DOD budget documents refer to these activities by the numbers 6.1 (basic), 6.2 (applied), and 6.3 (technology development), and discussions of DOD RDT&E often use the numbers rather than the words. The remainder of the RDT&E category consists of Advanced Component Development and Prototypes (ACD&P) (6.4), System Development and Demonstration (SDD) (6.5), RDT&E Management Support (6.6), and Operational System Development (6.7). See DOD regulation 7000.14-R, Volume 2B, Chapter 5 (Office of the Comptroller, 2008) for the formal definitions of each category.

properly be thought of as commands (i.e. large multi-function offices that include things like acquisition and logistics as well as the operation of one or more laboratories), particularly the medical research commands, are described here as one laboratory.

D.1 Air Force laboratory system

Among the Army, the Navy, and the Air Force, the Air Force has the most straightforward S&T funding system. Since 1997, all Air Force S&T funding has been directed through the Air Force Research Lab (AFRL) (Defense Science Board, 2012). AFRL contains nine research-performing directorates organized by technology area plus the grant-issuing Air Force Office of Scientific Research (AFOSR). This basic organizational structure is shown in Figure D.1. The directorates' focus areas are listed in table D.1.

AFRL is a relatively recent organizational construct that administratively groups many formerly independent Air Force research organizations. AFRL is headquartered at Wright-Patterson Air Force Base in Ohio, but some of the directorates are physically located in New Mexico, New York, Florida, or Virginia reflecting the physical dispersion of Air Force research prior to the consolidation of AFRL in the mid-1990s (see the AFRL organization chart available at the AFRL website and Duffner (2000)).

Figure D.2 shows the S&T funds spent in-house and directed out-of-house for each of the AFRL directorates as of fiscal year (FY) 2007, the most recent year available (all budget number from U.S. Department of the Air Force (2007)). Although Figure D.2 shows a small amount of in-house basic research at AFOSR, AFOSR is generally not considered to be a research performer. AFOSR manages all of the Air Force's basic research funding. Since most of this funding is issued for university research projects, AFOSR could be considered the Air Force's extramural research funding agency, but AFOSR also disperses a small amount of basic research funds to other AFRL directorates (Defense Science Board, 2012).

AFRL's research funding is primarily designated for applied research or technology development and primarily goes to external research contracts. External research contracts make up at least 50% of each of the directorate's S&T portfolio. In AFRL RD (directed energy) and AFRL RV (space vehicles), external research contracts make up over three-quarters of the total S&T funding managed by the directorate. Within their in-house portfolios, the AFRL directorates are primarily applied research laboratories. Between 50 and 90 percent of each directorate's in-house portfolio is applied research, technology development research accounts for 7 to 50 percent of in-house research, while basic research makes up between 1 and 10 percent.[112]

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[112] One commenter notes that AFRL pays for the lab's management activities out of its applied research account and that this is not necessarily the practice of the other service research labs.

Figure D.1 Major RDT&E organizations - Air Force
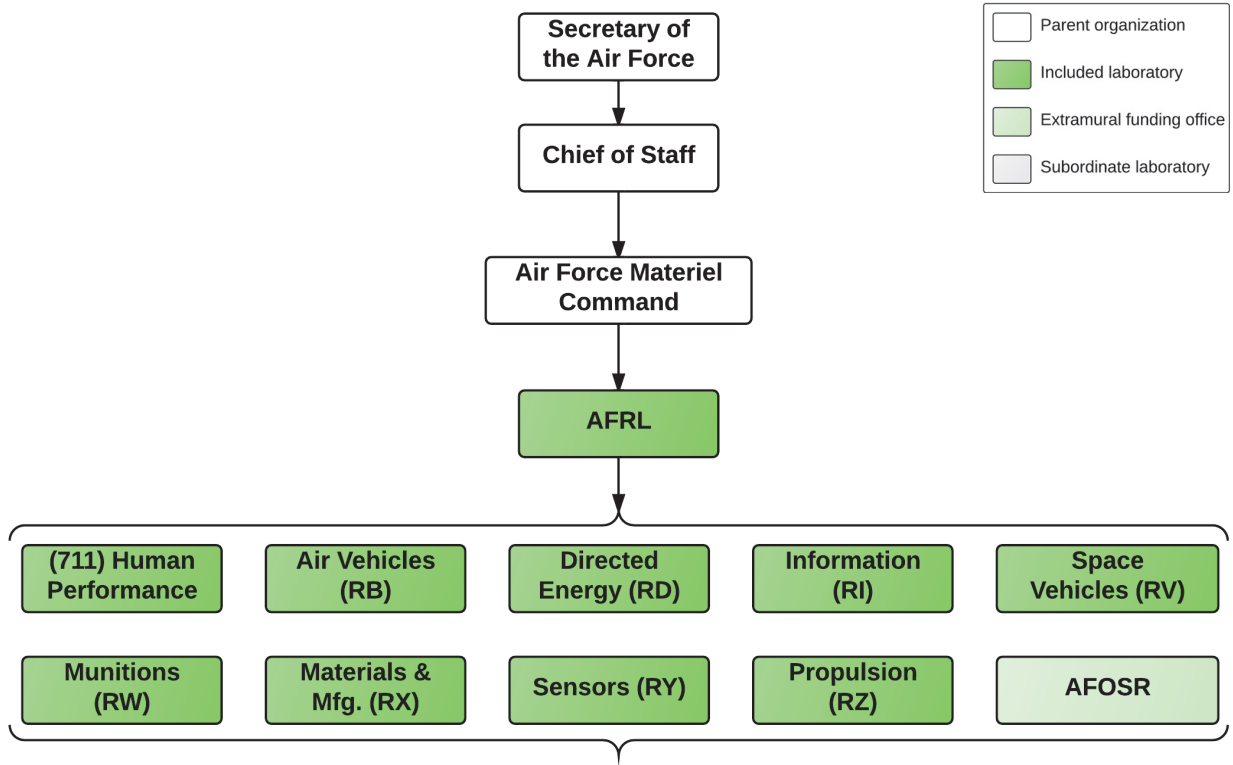
Sources: Carroll FedSearch (accessed 12/6/2012), U.S. Department of the Air Force (2007), AFRL website (accessed 6/2011)

Figure D.2 Air Force laboratory S&T funding FY2007
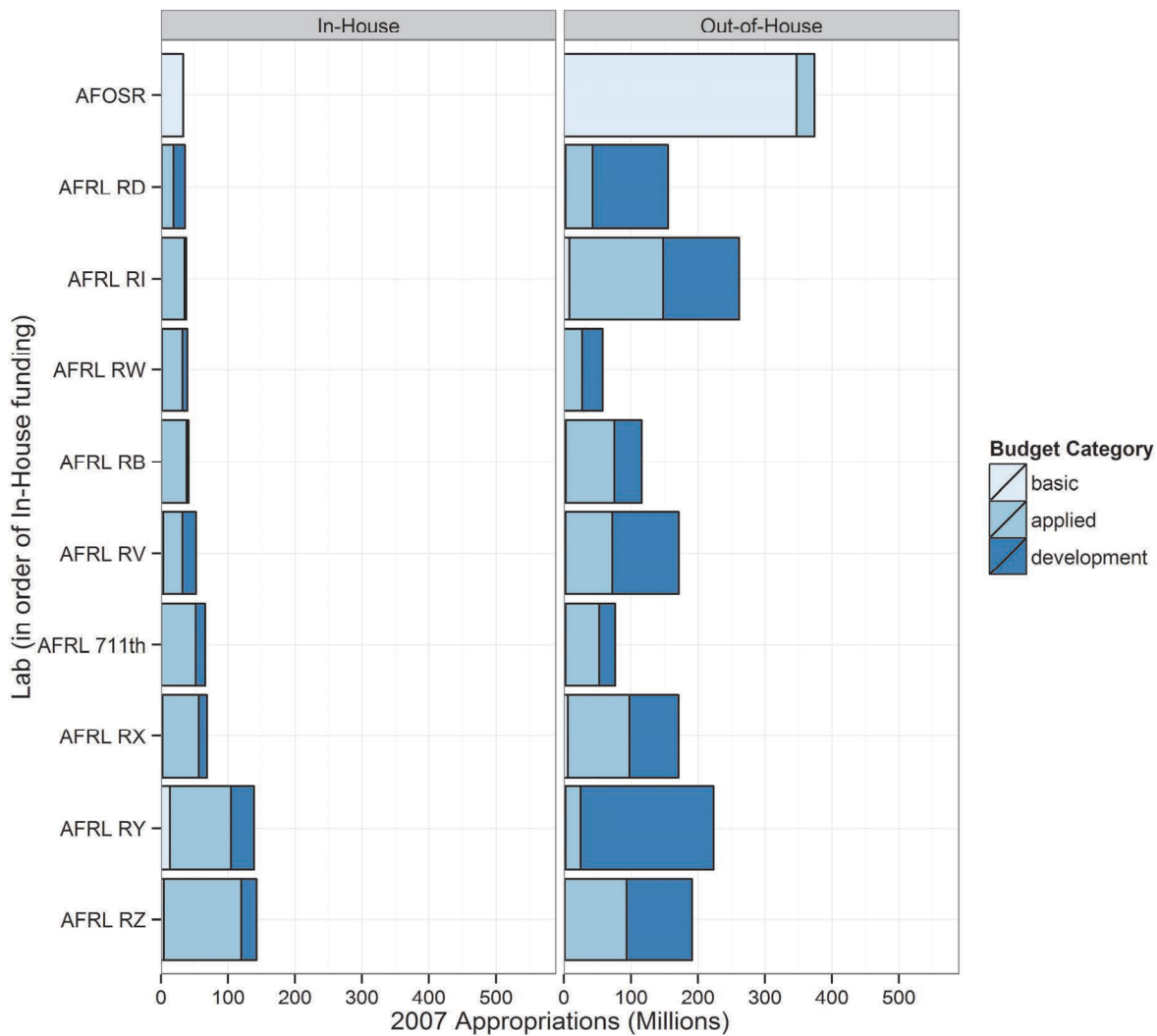
Source: DOD In-House S&T Activities Report FY2007 (U.S. Department of the Air Force, 2007)

Note: For definitions of laboratory acronyms see table D.1.
Does not include funding allocated to AFRL headquarters (HQ).

Table D.1 AFRL directorate descriptions

Acronym	Full Name	Focus Areas
AFOSR	Air Force Office of Scientific Research	Various, extramural
AFRL 711th	711th Human Performance Wing	Human factors, aerospace medicine
AFRL RB	Air vehicles	Aeronautics, control systems, structures, systems integration
AFRL RD	Directed Energy	Laser systems, high power electromagnetics, weapons modeling and simulation, directed energy, electro-optics
AFRL RI	Information	Communications and networking, modeling and simulation, information warfare, information fusion
AFRL RV	Space vehicles	Radiation-hardened electronics; space power, structures and control; in-space propulsion; space environment
AFRL RW	Munitions	Air-launched munitions
AFRL RX	Materials and Manufacturing	Material science, manufacturing processes
AFRL RY	Sensors	Radio frequency and electro-optic sensing, sensor fusion, network-enabled spectrum warfare
AFRL RZ	Propulsion	Aircraft and rocket engines, power sources

Source: Laboratory websites

D.2 Army laboratory system

The Army may have the most disaggregated laboratory system of the services. The Army splits S&T funding and program management between the Army Research Lab (ARL), five Research, Development, and Engineering Centers (RDECs), the Army Corps of Engineers' laboratory (ERDC), the U.S. Army Medical Research and Materiel Command (USAMRMC), and a few other miscellaneous centers (Defense Science Board, 2012). Figure D.3 shows the distribution of these research centers under various Army commands. Note that USAMRMC and ERDC have subordinate organizations that are sometimes listed as individual laboratories. TechMatch did not identify patents for those component laboratories individually. Also, while they are sometimes included in discussions of the Army's S&T system (e.g. in Miller (2010)) the Army Research Institute (ARI) for the Behavioral and Social Sciences, the Space and Missile Defense Technical Center (SMDTC), and the Simulation and Training Technology Center (STTC), have less than $12 million in S&T funding as of 2007. Because TechMatch includes no patent data for these labs, they are excluded in the following discussions.

Figure D.4 shows the S&T funds, as of fiscal year (FY) 2007, spent in-house and directed out-of-house for each Army laboratory included in this study (all budget data from (U.S. Department of the Army, 2007)). Around 75% of the Army's S&T funding flows through ARL and the five RDECs, ECBC, ERDC, and USAMRMC each account for about 6%.

ARL is the Army's "corporate laboratory" and the Army's primary performer of general basic research. USAMRMC has a larger amount of in-house basic research ($67M in 2007 versus ARL's $44M), but USAMRMC's mission is focused on medical R&D. Approximately one-fifth of ARL's in-house research budget is basic while the rest is applied. Note that while the major extramural basic research office is broken out separately in the Air Force and Navy budgets, the Army Research Office (ARO) sits within ARL and is not reported separately. Therefore, ARL's extramural budget is not directly comparable with the extramural research budget at NRL or the non-AFOSR AFRL directorates.

The S&T portfolios of the five RDECs (AMRDEC, ARDEC, CERDEC, TARDEC, and NSRDEC) focus on applied research and technology development, although they also have substantial budgets for technology demonstration through operational system development (i.e. 6.4 through 6.7, not shown in Figure D.4). The RDECs can be thought of as the direct customers of ARL's basic and applied research (Lyons, Mait, & Schmidt, 2005). While ARL is supposed to develop fundamental technologies, the RDECs are responsible for proving and developing those technologies for military applications (Wong, 2003). While the RDECs have small amount of basic research funding through the Independent Laboratory Innovation Research (ILIR) program (Decker et al., 2010; Lyons et al., 2005), the near monopoly of basic research funding at ARL reflects the intended division of labor.

In ARL and the Army RDECs, around 70 to 80 percent of S&T work is contracted out-of-house. USAMRMC executes very few extramural research contracts, and the Army Corps of Engineer's ERDC outsources slightly less than 50% of its S&T work. Overall, both the Army and the Air Force (including AFOSR) split their S&T funding 30% in-house, 70% out-of-house.

Figure D.3 Major RDT&E organizations - Army
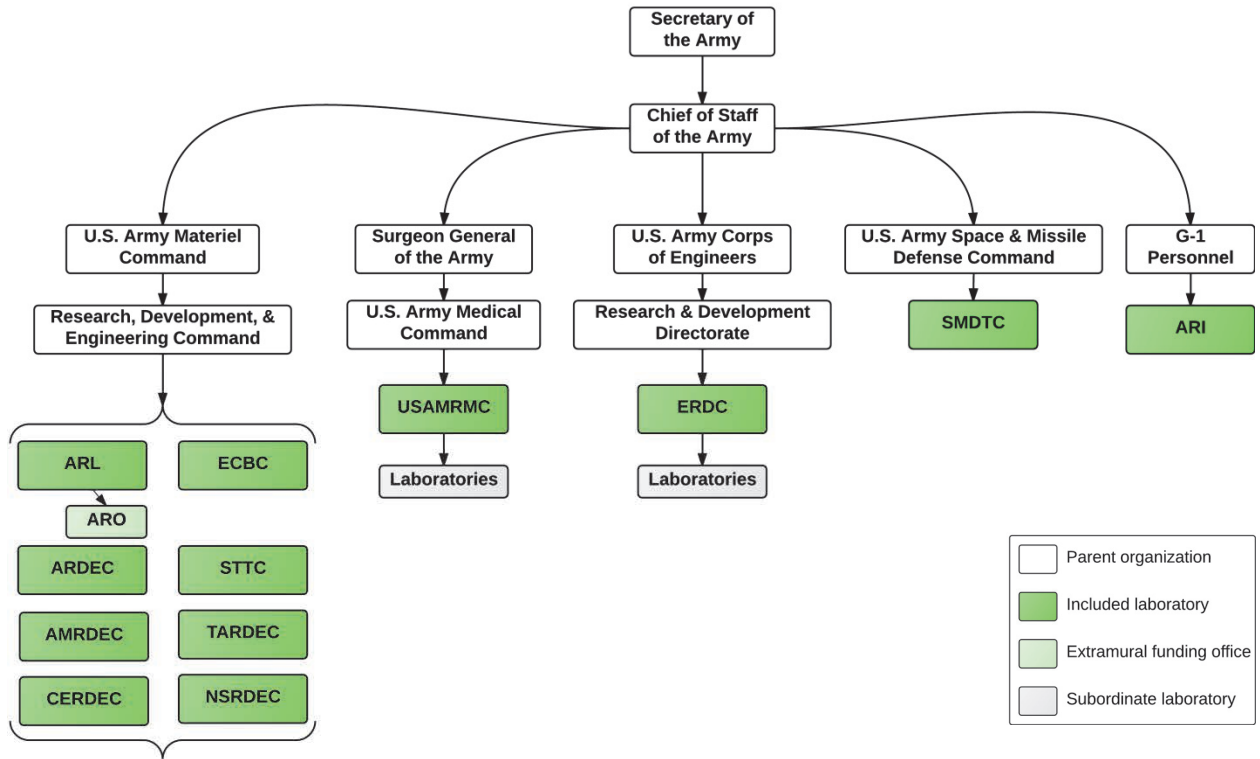
Sources: Carroll FedSearch (accessed 12/6/2012), U.S. Department of the Army (2007), Miller (2010)

Figure D.4 Army laboratory S&T funding FY2007
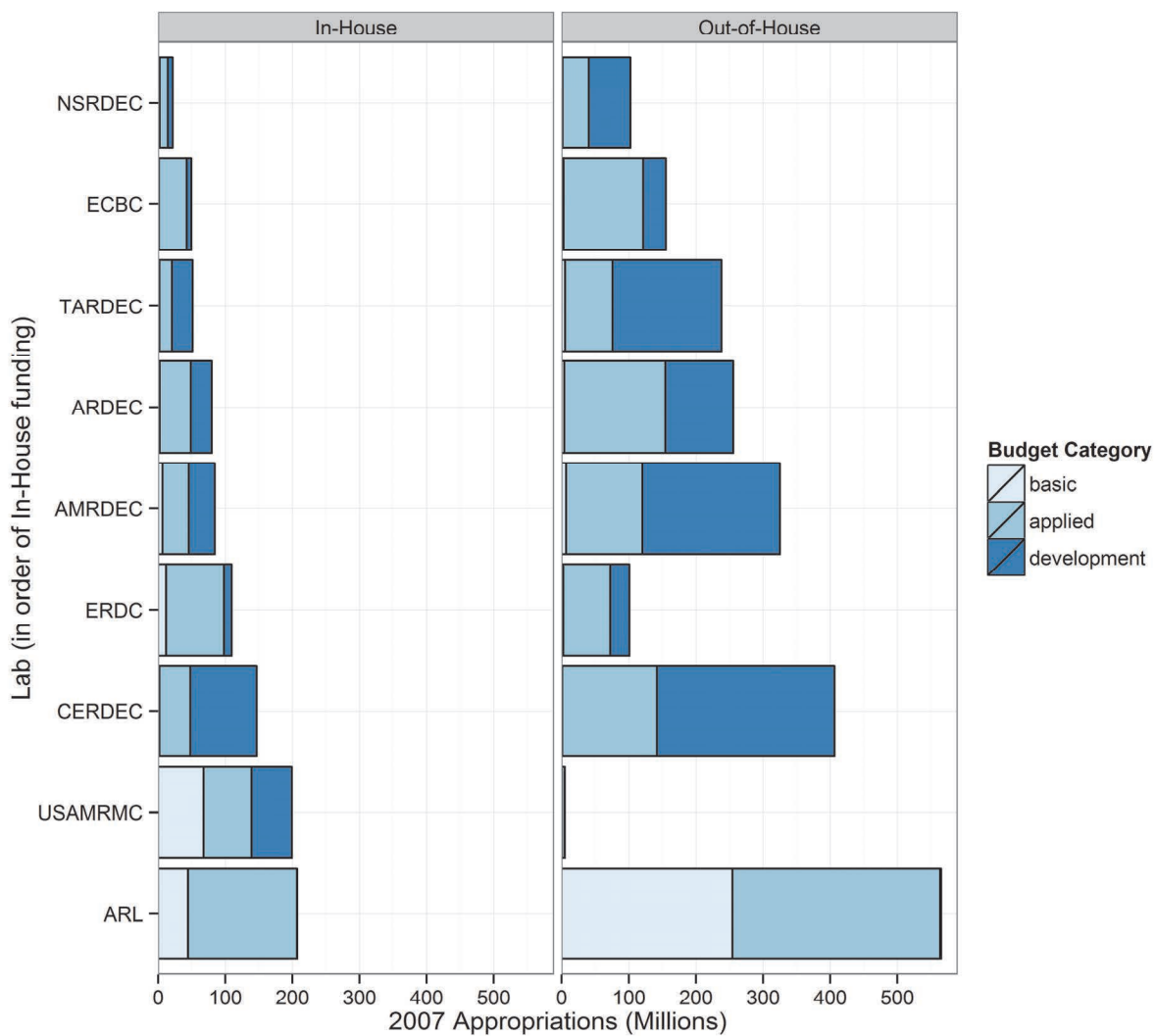
Source: DOD In-House S&T Activities Report FY2007 (U.S. Department of the Army, 2007)

Note: For definitions of laboratory acronyms see table D.2. Does not include four Army laboratories with less than $12 million of in-house S&T funding: U.S. Army Research Institute for the Behavioral and Social Sciences (ARI), Army Materiel Systems Analysis Activity (AMSAA), Space and Missile Defense Technical Center (SMDTC), and the Simulation and Training Technology Center (STTC).

Table D.2 Army laboratory descriptions

Acronym	Full Name	Focus Areas
AMRDEC	Aviation and Missile Research, Development and Engineering Center	Air vehicles, missiles
ARDEC	Armament Research, Development and Engineering Center	Armaments
ARL	Army Research Laboratory	Various
CERDEC	Communications-Electronics Research, Development and Engineering Center	C4ISR
ECBC	Edgewood Chemical Biological Center	Non-medical chemical and biological (CB) defense
ERDC	Engineer Research and Development Center	Army Corps of Engineers, structures, information technology, mapping, operating in various environments
NSRDEC	Natick Soldier Research, Development and Engineering Center	Food, clothing, human factors, biotech, materials, lasers, magnetic resonance imaging
TARDEC	Tank Automotive Research, Development and Engineering Center	Armor, tanks
USAMRMC	U.S. Army Medical Research and Materiel Command	Medical

Source: Laboratory websites

D.3 Navy laboratory system

Unlike in the Army and the Air Force, in the Navy the organization that manages extramural basic research grants sits outside the performing laboratories. The Navy's S&T system consists primarily of the Office of Naval Research (ONR), the Naval Research Laboratory (NRL), and laboratories within the four Navy Warfare Centers. ONR manages the Navy's extramural basic and applied research programs, including a basic research pass-through to NRL. NRL is the Navy's "corporate laboratory" and primarily conducts in-house basic, applied, and development research for Navy customers. NRL also contracts work out to other research entities and private companies in the course of achieving its mission. While NRL reports to the Office of Naval Research (ONR), the Navy Warfare Centers report to the System Commands (the Naval Sea Systems Command (NAVSEA), the Naval Air Systems Command (NAVAIR), and the Space and Naval Warfare Systems Command (SPAWAR)), which manage the Navy's acquisition programs. Consequently, the Warfare Centers tend to be more focused on the immediate needs of the fleet (see discussion of the evolution of the Warfare Centers in Hazell (2008)). Figure D.5 shows the position of each organization within the Navy's S&T system, and table D.3 describes the technological focus of each laboratory. Figure D.6 shows the distribution of S&T funding for NRL, the Warfare Centers, and the Navy Medical Research Command.

NRL, as the Navy's corporate research lab, has a portfolio that is nearly evenly balanced among basic, applied, and development research. Unlike the AFRL directorates and ARL, NRL

actually contracts out less work than it conducts in-house, although recall that ARL's extramural budget includes ARO which skews the comparison. The degree of out-of-house contracting at the Warfare Centers varies, but overall the Navy S&T budget is split about 50/50 in-house/out-of-house.

Like the Army RDECs, the Naval Warfare Centers have S&T budgets that heavily lean towards applied research and development in addition to large amounts of post-technology development (i.e. 6.4 through 6.7) funding (see Hazell (2008), the In-House S&T Activities report does not give post-S&T funding for the Warfare Centers). Research and development is actually in the minority of the Warfare Centers' overall activities, accounting for somewhere between 5 and 30 percent of their total business base (reports vary, see Hazell (2008) and Saunders et al. (1995)). While patents were reported for specific research laboratories operated by the Warfare Centers (see laboratories listed to the far right in Figure D.5), separate budgets were not. Note that patents are not available for all of the Warfare Center laboratories. Those Warfare Centers lacking patents are also those that arguably should not be defined as "in-house laboratories" because they focus primarily on training, testing, or servicing systems installed on ships rather than on technology development per se (see table D.3).

All of the Navy's in-house research and development work is primarily funded via contracts with customers. This system is called "Working Capital funding" because the exchanges of funds in these agreements are handled through the Navy's Working Capital account (see Department of the Navy (2012))This system evolved in the Navy because the various labs traditionally did work for many different commands and even other Services rather than being beholden to one superior headquarters organization. Paying for research services out of the Working Capital fund fairly distributed the total costs of supporting the laboratories to all customers (Hazell, 2008).

Figure D.5 Major RDT&E organizations – Navy
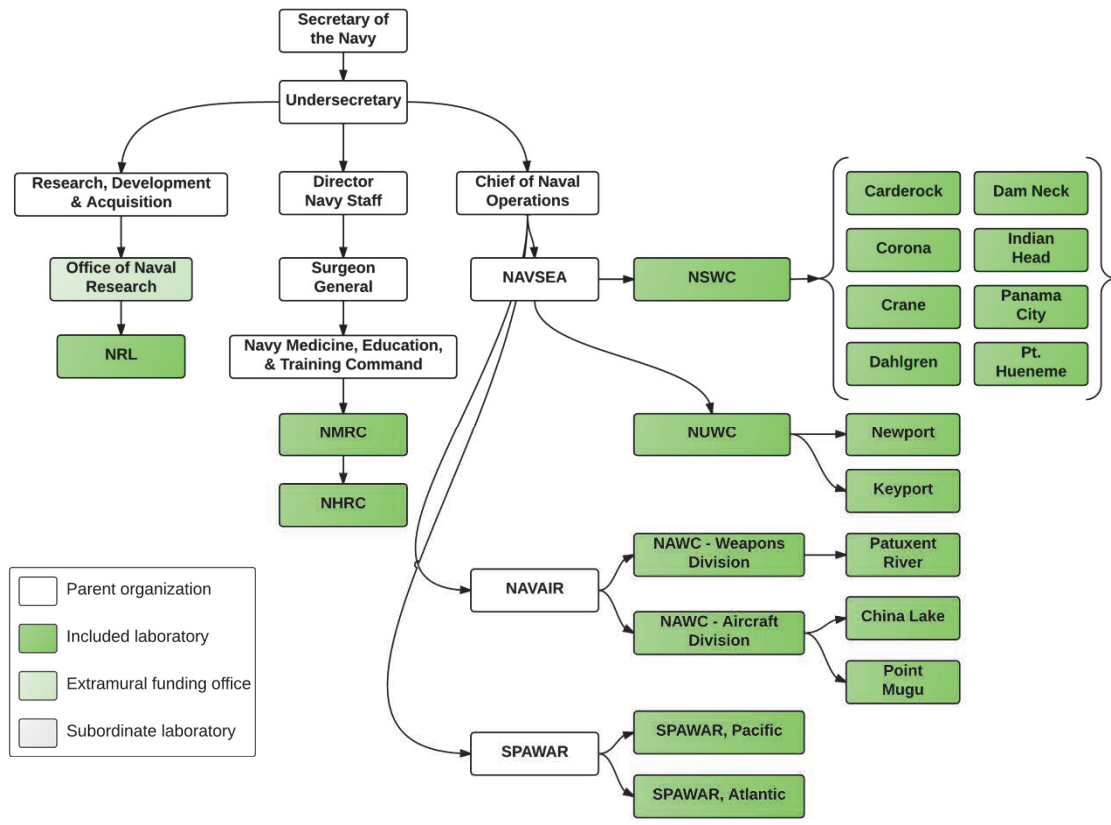
Sources: Carrol FedSearch (accessed 12/6/2012), U.S. Department of the Navy (2007), Warfare Center websites (accessed 12/6/2012)

Figure D.6 Navy laboratory S&T funding FY2007
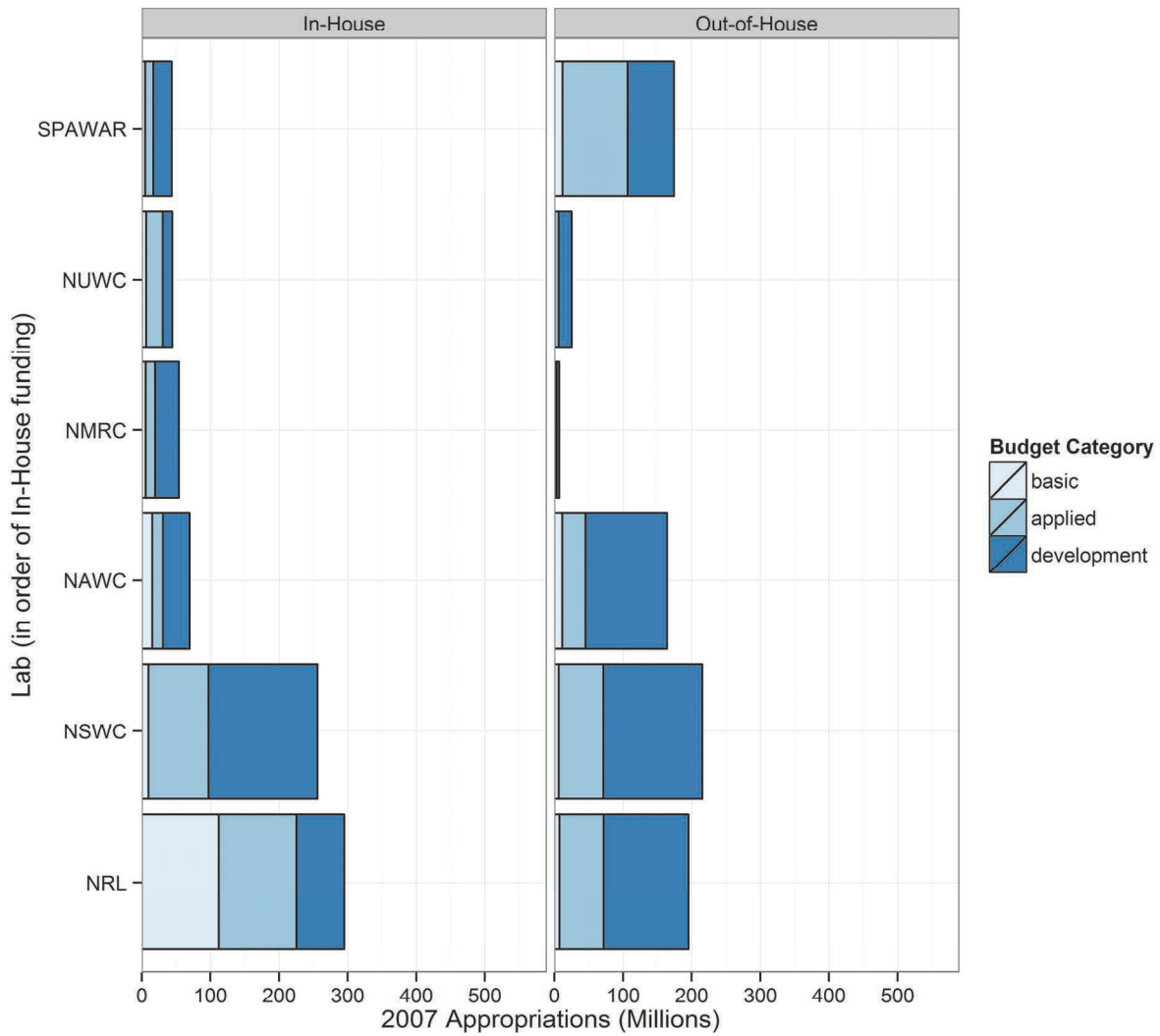
Source: DOD In-House S&T Activities Report FY2007 (U.S. Department of the Navy, 2007)

Note: SPAWAR = Space and Naval Warfare Systems Command, NUWC = Naval Undersea Warfare Center, NMRC = Naval Medical Research Center, NAWC = Naval Air Warfare Center, NSWC = Naval Surface Warfare Center, NRL = Naval Research Laboratory

Table D.3 Navy laboratory descriptions

Laboratory	Parent Organization	Patents	Focus Areas
NAWC Patuxent River	Naval Air Warfare Center	Yes	Life-cycle support of manned and unmanned aircraft and components
NAWC China Lake	Naval Air Warfare Center	Yes	Weapons Division's land range, missiles and bombs, avionics, basic and applied research, integration and testing
NAWC Point Mugu	Naval Air Warfare Center	Yes	Weapons Division's sea range, special weapons and projects, technology transfer, electronic warfare, integration and testing
Naval Medical Research Center (NMRC)		Yes	Medical
NSWC Carderock	Naval Surface Warfare Center	Yes	Ships and ship systems
NSWC Corona	Naval Surface Warfare Center	No	System test and assessment, measurement science and calibration standards
NSWC Crane	Naval Surface Warfare Center	No	Life-cycle support for sensors, electronics, electronic warfare, and special operations
NSWC Dahlgren	Naval Surface Warfare Center	Yes	Weapon system integration
NSWC Dam Neck	Naval Surface Warfare Center	No	Training, Integrated Combat Control Systems, Information Operations
NSWC Indian Head	Naval Surface Warfare Center	Yes	Explosives, propellants, pyrotechnics and their immediately related components
NSWC Panama City	Naval Surface Warfare Center	No	Mine warfare systems, mines, naval special warfare systems, diving and life support systems, amphibious and expeditionary maneuver warfare systems, other missions that occur primarily in coastal (littoral) regions
NSWC Pt. Hueneme	Naval Surface Warfare Center	No	Surface ship combat system engineering
NUWC Newport	Naval Undersea Warfare Center	Yes	Submarines, autonomous underwater systems, and offensive and defensive undersea weapon systems
NUWC Keyport	Naval Undersea Warfare Center	No	Fleet readiness support
NRL	Office of Naval Research	Yes	Various
SPAWAR Systems Center, Pacific	Space and Naval Warfare Systems Command (SPAWAR)	Yes	C4ISR
SPAWAR Systems Center, Atlantic	Space and Naval Warfare Systems Command (SPAWAR)	No	C4ISR

Source: Laboratory websites