How Start-up Firms Innovate: Technology Strategy, Commercialization Strategy, and their Relationship

Edward J. Egan*

Job Market Paper

(Download Latest Version)

A successful start-up firm makes two important strategic innovation choices during its early life. It must decide upon a 'technology strategy' – whether to specialize or generalize in the allocation of its research and development efforts – and a 'commercialization strategy' – whether to cooperate or compete with incumbents to secure the investment it will need to commercialize its inventions. In this paper, I advance a 'system vs. components' theory of innovation, which supposes that technological products are based on systems of complementary components. A pattern of specialize-and-cooperate and generalize-and-compete then occurs naturally as entrepreneurs maximize their expected profits given both the available technological opportunity and the state of technology in their industry. I derive measures of technology strategy for patent-holding start-up firms, and use the choice to sell the firm in an acquisition or to raise investment through an initial public offering (IPO) as prototypical examples of cooperate versus compete commercialization strategies. I then show that measures of technology strategy Granger-cause commercialization strategies in cross sectional analyses. I also address the endogeneity issue that arises because forward-looking start-up firms chose their technology strategy in anticipation of their commercialization strategy by using the introduction of the 2002 Sarbanes-Oxley Act (SOX) as a shock to the relative costs of an IPO. I provide evidence that successful start-up firms altered their technology strategies to favor component specialization following the introduction of SOX.

Keywords: Start-up Firm, Patent, System vs. Components, Complement, Substitute, Initial Public Offering, Acquisition, Sarbanes-Oxley, Venture Capital

*Innovation Policy Fellow, National Bureau of Economic Research (NBER). I would like to thank Jim Brander, Bronwyn Hall, Thomas Hellmann, Michael Katz, David Mowery, Suzanne Scotchmer, Scott Stern, Toby Stuart, Steve Tadelis, David Teece, and Ralph Winter for their input and guidance. I gratefully acknowledge funding from the Ewing Marion Kauffman Foundation's Doctoral Dissertation Fellowship, the Canadian Graduate Scholarship program (Social Science and Humanities Research Council of Canada award #752-2008-1770), and a Post-Doctoral Research Fellowship in the Strategy and Business Economics group at the Sauder School of Business, U.B.C. All correspondence should be addressed to: ed_egan@haas.berkeley.edu.

1 Introduction

Many successful, innovative start-up firms appear to follow a pattern: if they specialize in creating a better version of a component technology that is already used by incumbents, they tend to commercialize their technology through cooperation with an incumbent; whereas if they generalize and create versions of all of the component technologies needed to produce a stand-alone product, they often later raise independent commercialization investment, enter the market as a rival, and compete with incumbents.[1]

Cisco Systems, Inc., a network device manufacturer founded in 1984, provides an example of an incumbent who routinely cooperates with successful start-up firms that specialize in developing component technologies. Aside from its own corporate venture capital fund, which fosters promising start-up firms, and its extensive list of partnerships and joint-ventures, Cisco has cooperated in the commercialization of component technologies by making more than 150 acquisitions of start-up firms in the last 20 years.[2] Cisco claims that it makes acquisitions in order to integrate new high-quality component technologies into its product offerings. It even classifies its acquisitions by the type of components they provide, for example, firewall solutions, routing and switching, and wireless chipsets. However, Cisco generally doesn't buy potential rivals. Successful network device start-up firms that developed complete 'systems' of complementary components, like D-Link Corporation and Netgear, Inc., have instead raised commercialization investment through an initial public offering (IPO) and entered the market as a competitor to Cisco.

This pattern of specialize-and-cooperate versus generalize-and-compete raises a number of important questions: Why do some successful start-up firms specialize and others generalize in their research and development (R&D) stage? Why do start-up firms that specialize not use public domain technologies to produce products and compete in the marketplace? And why do incumbents often elect not to cooperate with start-up firms that generalized and produced rival products? In this paper, I advance a 'system vs. components' theory of start-up firm innovation that explains this pattern.

Let's begin with the nature of business innovation. Business *innovation* is normally taken to have two steps: coming up with an *invention* and then *commercializing* it. Accordingly,

[1] Through-out this paper, I will use 'generalize' or 'pursue a general strategy' interchangeably to denote a technology strategy where a start-up firm distributes its research and development efforts over the complete set, or 'system', of component technologies needed to produce a stand-alone product.

[2] Venture capitalists are financial intermediaries that specialize in investing in the equity of privately-held high-technology firms with the intention of making a substantial return at either an IPO or an acquisition. Corporate venture capitalists manage funds for an industry incumbent. Intel, Cisco, Microsoft, Qualcomm, Xerox, Dow Jones, and Eli Lilly, all have large, well-known corporate venture capital funds. For details of Cisco's acquisitions see: http://www.cisco.com/web/about/doing_business/corporate_development/

successful innovative start-up firms face two important strategic choices during their early life: 1) a *technology strategy* choice of how to allocate their R&D efforts – in effect deciding which inventions to pursue; and 2) a *commercialization strategy* choice of whether to cooperate or compete with incumbents to raise the investment finance needed to commercialize their inventions. Understanding how start-up firms innovate therefore means understanding these two choices and the relationship between them.

I suppose that the relationship between these two choices is driven by the structure of production when it is based on technological innovation. In information technology (I.T.) products are generally assumed to be complex (see Cohen et al. 2000) – a firm must assemble many complementary components together to create a product. In the life sciences sector, including biotechnology, products typically rely upon cumulative innovation (see Scotchmer 1991) so that one generation of a product is a complementary input into the next. And in other high-technology sectors, products typically require many different proprietary complementary processes for their manufacture.

Aside from direct technological components, successful commercialization of an innovative technological product can also require tacit knowledge, distribution channels, established brands, and many other difficult to imitate complementary components. Moreover, even when a technologically innovative product might be described as a stand-alone component, there are often complementarities between products, whether in development, regulatory approval, manufacture, or distribution, so that they naturally form a coherent product line. As Teece (1986) puts it, "Even when an innovation is autonomous, as with plug compatible components, certain complementary capabilities or assets will be needed for successful commercialization." Outside of sectors characterized by technological innovation, new products can often stand alone. But within sectors characterized by technological innovation, products are almost always made using systems of complementary components.

Complementarities between components imply that product value is a multiplicative, not an additive, function of component quality. Complementarities therefore imply that components of like quality should be assembled together to maximize independent firm value. Public domain components are usually of lower quality than the components used by incumbents in a sector – this is especially true for patented technology components as renewing patents is costly and there is no point in maintaining intellectual property rights on a component that is inferior to that available in the public domain. A start-up firm that uses public domain components to complete its system of complementary components would therefore not be maximizing its value as a stand-alone firm. Such a start-up firm might, however, maximize its value by cooperating with an incumbent. A start-up could choose to specialize all of its R&D resources into creating a single high-quality technology component that replaces an incumbent's weakest technology component and so benefit from the complementarities it has with an incumbent's strongest components.

An incumbent can also benefit from cooperation with a start-up firm. An incumbent could use a start-up firm's high-quality technology component to replace its weakest technology component and so be better off. Put another way, choosing a technology strategy of specialization can lead to what Teece (1986) calls 'cospecialized assets'; the start-up firm's high-quality technology component is most valuable when used in conjunction with the incumbent's complementary components, and vice versa. When this happens, cooperation can be profit-maximizing for both the start-up and the incumbent in question.

Of course, a start-up that follows a specialist technology strategy might have specialized assets, rather than cospecialized assets – that is, there may be unilateral gains from cooperation to the start-up firm but not to an incumbent. Many such start-up firms will fail. If they can't contract with an incumbent, their only source of complementary assets will be from the public domain and their value as a competitor in the marketplace will be low. On the other hand, a start-up firm that follows a general strategy of distributing its R&D efforts to create an entire system of technology components, internalizes the complementarities between technology components. Such start-up firms may then be able to compete with incumbents using solely their own technology.

The systems vs. components theory advanced in this paper is therefore a theory of innovation. The relationship between invention and commercialization is characterized by the choice to specialize-and-cooperate or generalize-and-compete, and this relationship is driven by the nature of technological innovation. Cospecialized assets provide the foundation for cooperation, and the absence of cospecialized assets makes competition a profit-maximizing commercialization strategy. Start-up firms choose their technology strategy in order to harness or avoid cospecialized assets by electing to specialize or generalize, given their technological opportunity.

In the theory section of this paper, I provide a detailed description of the system vs. components theory of innovation. A game-theoretic oligopoly model of the theory is provided in Egan (2013). However, the majority of this paper is concerned with tests of the theory. The theory is tested by considering patent-holding start-up firms that achieved either an IPO or acquisition from 1986-2004. The use of patent-holding start-up firms allows patent-based measures of technology strategy, and IPO versus acquisition is a prototypical example of a compete versus cooperate decision.

The amount of investment needed to commercialize a successful start-up firm's inventions can be very large, particularly in high-technology sectors. As a result, many start-up firms raise the investment needed to commercialize their inventions through either an initial public offering or by selling themselves to an incumbent in an acquisition. For venture capital backed firms, which account for around a quarter of my sample, essentially all successful start-up firms pursue one of these two options.[3] Some non-venture-capital-backed start-up firms do remain independent and raise finance from other sources, including bank debt and organic growth, or cooperate with incumbents, for example through partnerships, licensing arrangements, and joint-ventures. However, IPOs and acquisitions provide readily observable and largely unambiguous outcomes of cooperate or compete decisions.[4]

Patent applications are published by the patent office. We may therefore be able to learn something about a start-up firm's inventions that allows us to infer its research and development choices – its technology strategy. A start-up firm following a generalist technology strategy must protect more components with intellectual property rights. Accordingly, the number of patents filed, and perhaps claims made per patent, will be higher for a start-up firm that followed a generalist technology strategy. However, one insight of this paper is that patent citations – recordings of relevant prior-art to a patent – can be used to provide a better measure of a firm's technology strategy. Some patent citations may indicate economic substitution.[5] If systems are industry specific, the number of components covered by a start-up firm's patent portfolio might be inferred from the number of citations to active patents (i.e., patents that haven't expired or otherwise lapsed into the public domain) to and from incumbents in the same sector as the start-up firm.[6]

This paper tests the systems vs. component theory of innovation in two ways. First, it tests whether measures of technology strategy Granger-cause commercialization outcomes in cross-sectional analyses.[7] The effects of measures of technology strategy are consistent with the theory. Acquisitions and failure are associated with a specialization technology strategy whereas IPOs are associated with a general technology strategy. The measure of technology strategy derived from 'in-sector citations to active patents' explains approximately 20% of

[3] There have been a small number of recent venture-capital-backed start-up firms that have instead been sold on secondary private equity markets.

[4] Some firms secure an IPO only to (sometimes quite quickly) be acquired by an incumbent. Likewise, some firms are acquired only to later be 'spun-off' through an IPO. I exclude both types of firms from my data where possible.

[5] Patents cannot be technical substitutes for one another – the second patent would then not be novel. However, many different 'inventive steps' may achieve different qualities of the same economic functionality. Patent applicants have an incentive to cite these other inventive steps to establish novelty and provide themselves with legal protection against challenges of validity.

[6] This applies within sectors and not necessarily across sectors which might use different numbers of components in their systems.

[7] Granger-causality is not true causality. X Granger-causes Y when X occurs before Y and X and Y are correlated. In this paper technology strategy and commercialization strategy are both driven by a third, unobserved variable – technological opportunity. Nevertheless, technology strategy choices are made prior to commercialization strategy choices and the choices are related.

variation in commercialization outcomes.

Second, this paper addresses the endogeneity issue that arises because forward-looking start-up firms chose their technology strategy in anticipation of their commercialization strategy. A start-up firm chooses either specialize-and-cooperate or generalize-and-compete, and in effect makes a single *cooperate or compete* decision that unites its technology strategy and commercialization strategy.

The introduction of the 2002 Sarbanes-Oxley Act, commonly known as 'SOX', increased the regulatory costs of an IPO for start-up firms. It did not directly affect the costs of an acquisition. As such, the introduction of SOX was an exogenous shock to the commercialization strategy of start-up firms. Increased costs of pursuing a competitive commercialization strategy incentivize cooperation, which in turn is paired with component specialization. This paper presents results from a panel analysis, considering only changes within a successful start-up firm, which suggests that start-up firms changed their technology strategies to favor specialization in response to SOX.

The Sarbanes-Oxley Act was designed to increase the quantity and quality of information disclosure from publicly-traded firms. High-technology firms have large information asymmetries between themselves and their investor, whereas non-high-technology firms do not (see Brander and Egan 2008). SOX may, therefore, have been more burdensome for high-technology firms than for their non-high-technology counterparts. Evidence from the accounting and legal costs of filing for an initial public offering suggest that high-technology firms experienced a large increase in regulatory costs, whereas non-high-technology firms faced only a mild increase in regulatory costs, as a result of Sarbanes-Oxley. Accordingly, a difference-in-differences analysis is used to provide evidence that SOX, and not some other event in 2002, is driving the results. Overall, the results suggest that SOX had the unintended consequence of altering the balance of the innovation ecosystem towards greater component-based invention and cooperation, and away from the creation of rival systems and competition in product markets.

2 Literature Review

The driving assumption underlying this paper is that a firm needs an entire system of complementary components to produce an innovative technological product. The economic literature on systems of complementary components has its roots in Milgrom and Roberts (1990, 1995), who suggest that complementarities in production are a primary determinant of organizational performance and so a major factor for strategic optimization within a firm. Cohen et al. (2000), Fleming and Sorenson (2001), Hall (2004), and others characterize innovative technological products as being 'complex' and made up of (or produced using) many complementary components.

A small number of papers have previously imposed structure on the nature of invention. For example, Baldwin and Clark (1997), Schilling (2000), Ethiraj and Levinthal (2004) and others use 'synergistic specificity' to reflect the complementarity between components in a given arrangement in modular systems.[8] Henderson (1993) separates inventions into 'incremental vs. radical'. And Jones (2009) ties the creation of productive knowledge to the structure of an area of knowledge. However, these papers do not allow for choices regarding inventive effort. Instead, the compatibility of inventions, the type of invention, or the structure of knowledge is exogenously given.

The strategy literature suggests that inventive effort involves strategic choices. The seminal definition for technology strategy comes from Friar and Horwitch (1985), who define it as "that set of activities by which management chooses its technological activity [and] allocates the resources for its technological undertakings..." In this research, a start-up firm is assumed to face a choice in how it allocates its available technological opportunity. Specifically, a start-up firm can either specialize in producing a single high-quality component or pursue a general technology strategy and create an entire system of components.

In the economics literature on innovation (see Reinganum 1989, Scotchmer 2004, and others) firms often face a choice regarding the extent of their R&D efforts. But papers that have previously endogenized a choice for inventive effort that results in different types of inventive outcomes are rare. Henderson and Clark (1990) suggested that inventors face a choice between 'component vs. architectural' invention. As such, they originated the idea of component-based invention in component-based systems of production, but they did not integrate this choice with a choice of how to commercialize an invention.[9]

Teece (1986) provides the seminal work on commercialization strategy. Teece (1986) introduces the notions of cospecialized, specialized, and generic assets (like capital) and so describes the mechanisms underlying commercialization strategy choices in this paper. Gans and Stern (2000, 2003), Gans et al. (2002), and Cockburn and MacGarvie (2009, 2011) all either explicitly or implicitly build on the framework provided in Teece (1986).

Gans and Stern (2003) define commercialization strategy as a compete versus cooperate choice: "[C]ommercialization strategy for start-up innovators often presents a tradeoff between establishing a novel value chain and competing against established firms versus

[8] Mikkola (2003) suggests that modularity promotes component-based specialization and the inter-firm transfers of components.

[9] In a different approach, Fleming and Sorenson (2001) set aside issues of commercialization entirely and describe invention as a recombinant search process, so that invention depends not just on the volume of inventive activity but also its 'location'.

leveraging an existing value chain and earning returns through [cooperation]." Gans et al. (2002) and Gans and Stern (2003) suggest that firms are able to cooperate with incumbents when it is possible to protect against appropriation of cospecialized assets using patents, whereas without feasible intellectual property right protection firms must compete. Likewise, Gans and Stern (2000) provide a model where the possibility of licensing determines whether a start-up firm will cooperate with a monopolist or enter the product market and compete as a duopolist. However, appeals to variation in the appropriability regime as a driving mechanism for cooperation versus competition are not necessary in Teece (1986)'s framework. A lack of a cospecialized assets is sufficient to prevent cooperation and encourage competition.

Cockburn and MacGarvie (2009, 2011) hypothesize that 'thickets' of patent rights held by incumbents raise entry costs and so discourage competition. They argue that firms that have large exposures to patent thickets, and so need many diversely-held patented complementary inputs, have specialized assets. Following Teece (1986), they argue that these firms would benefit from cooperating with an incumbent with a large defensive patent portfolio.[10] However, with specialized assets, rather than cospecialized assets, the benefit from integration to the incumbent must come through market power.

This paper defines an industry as being characterized by a system of components, or at least having many components in common. Industries are therefore oligopolies and, as in the 'network devices' example given in the introduction, gains to market power should not be a primary determinant of cooperation. Instead, this paper draws directly from Teece (1986)'s cospecialized assets as a primary determinant of cooperation.

In summary, Gans et al. (2002), Gans and Stern (2003), and Cockburn and MacGarvie (2009, 2011) all take the existence of cospecialized/specialized assets and the state of the technology in a firm's industry as given and then advocate optimal strategy.[11] The foremost contribution of this paper is to endogenize both technology strategy and commercialization strategy, and to explain how one is related to the other.

In the empirical analysis, as in both Gans and Stern (2000) and Cockburn and MacGarvie (2009), the decision to cooperate or compete is operationalized as a choice between acquisition and IPO for start-up firms. In order to measure technology strategy, the empirical analysis will also focus exclusively on firms that use patents to protect their technology components. Although the measurement of technology strategy is new, the analysis of patent-holding firms as representative of other technologically innovative firms is usual in the

[10] Defensive patents are those that can be used to either force licensing or otherwise gain access on non-demanding terms to patented complementary inputs.

[11] Gans and Stern (2000) allows start-up firms a choice of R&D intensity, but not type, that influences commercialization strategy.

literature (see Jaffe and Trajtenberg 2002). This is especially true for research considering start-up firms, where patents are frequently the only observable measure of innovation.

Some of the empirical results presented in this paper have appeared in the literature before. Cockburn and MacGarvie (2009) report a positive correlation between the number of patents that a start-up firm held prior to its commercialization event and the likelihood that it will secure an IPO rather than an acquisition. And Mann and Sager (2007) report a positive correlation between patenting and success for venture-capital-backed start-up firms. However, in these papers inventive activity has no type. This research can therefore be used to reinterpret these results – the systems vs. components theory of innovation suggests that more patents are indicative of a general technology strategy, and so a different choice of allocation of inventive effort.

Other empirical results are essentially new. The effect of patent citations on the choice to IPO or be acquired was foreshadowed in a working paper version of Cockburn and MacGarvie (2009). However, without the focus on in-sector citations to active patents, and the understanding that this new citation measure captures economic substitution and so can be used to differentiate between technology strategies, these findings could not be explained.[12] Conversely, Shadab (2008) provided a theoretical justification for a decline in patenting for publicly-traded firms following the introduction of the Sarbanes-Oxley Act without empirical support.[13] Shadab (2008) argued that increased corporate governance costs for innovative activity would decrease innovative output. This may be true, but it cannot explain the changes in citations per invention, which suggest that the first-order effect comes instead from changes to the nature, rather than the volume, of inventive activity.

3 Theory and Hypotheses

In this section I describe the system vs. components theory of innovation and derive five testable hypotheses from it. The theory is formally modeled as a two-stage, complete information, economic game in Egan (2013). Egan (2013) embeds the theory in a heterogeneous-cost Cournot oligopoly market structure, adds considerations of the allocation of surplus through bargaining strength, and provides an analysis of the welfare consequences of entry and acquisition. Moreover, Egan (2013) frames the model in the context of the literature of incomplete contracting and discusses information asymmetries, moral hazard, and other aspects that are central to the relationships between entrepreneurs, incumbents, and finan-

[12] As an aside to its main thesis, this paper also provides insight into the meaning of patent citation measures that may be of broader interest to the literature. Griliches (1998) provides a formative discussion in this area.

[13] Anand (2008) provides an overview of the Sarbanes-Oxley Act.

cial intermediaries like venture capitalists. Comparative statics on the formal model can be used to derive the hypotheses in the main body of this paper, and provide foundations for the additional results included in footnotes.

3.1 The System vs. Component Theory of Innovation

Technological innovation is complex: A smart-phone contains thousands of patented components; a new life-saving medicine is typically the end result of a long sequence of cumulative patents; and an industrial chemical, material, instrument, or piece of equipment may require hundreds of process patents for its manufacture.[14] This complexity comes not just from the number of technological inputs that are required for a new innovation, but also from the relationship between them. Inputs to innovative products are complementary with one another. Complementarities imply that components of similar quality belong together.

Technological innovation also does not take place in a vacuum. A start-up firm should make its innovation decisions to maximize its expected profits in the context of three factors that characterize its innovation ecosystem. First, established firms already use technology components to produce their goods. The theory of system vs. components supposes that components are common to an industry – it isn't necessary that every firm uses exactly the same set of components, even allowing that component quality varies, just that certain technology components characterize some industries and not others. Industries are therefore fairly broad, perhaps like semiconductors, computer media, and high-technology instruments, and are best described as oligopolies. Second, public domain components are widely available in almost every industry.[15] There is no point in an incumbent maintaining intellectual property protection on technology components that are of lower quality than those available in public domain, so a range of qualities of components should exist in a start-up's innovation ecosystem. And third, start-up firms face different levels of technological opportunity, which can let them create more or fewer components at different levels of quality relative to the incumbents' components and public domain components.

The theory then supposes that a start-up firm faces two sequential decisions. Early in its life, a start-up firm must decide how to allocate its research efforts – in effect whether to specialize and concentrate all of its available technological opportunity into the creation of a single component; or to generalize and distribute its technological opportunity and

[14] Apple has filed 1,298 iPhone™ related patents (416 of which are on core smartphone technology, the rest of which are on cameras, user interfaces, batteries, antennas, and other components used in smartphones) since 2000. Estimates of the total number of patents needed to create a smartphone vary wildly.

[15] Public domain components might represent components covered by expired patents, components that are ineligible for patent protection (for reasons of obviousness or lack of novelty), or open-source or other non-proprietary and freely available technologies.

create an entire system of proprietary components. Later on, a start-up firm must decide how to commercialize its invention – whether cooperate or compete with incumbents to raise the investment needed for commercialization.[16] Because industries are assumed to be oligopolies, the theory also assumes that cooperation can only take place when there is cooperative surplus available.[17] Cooperative surplus is the value that the start-up firm and an incumbent can achieve together less the values of the firms as independent entities.

A numerical example of how complementarities give rise to cooperative surplus is instructive. Suppose that systems are made up of two components – let's call them A and B – with qualities on a scale that is relative to the amount of technological opportunity available to the start-up. As an example, suppose that an incumbent's component qualities are 6 and 8 (respectively), components with a quality of 1 are available in the public domain, and that the start-up has a technological opportunity of 10. This situation is depicted in figure 1 below.

Insert Figure 1 Here

If the start-up specializes, it will create a proprietary A component of quality 10 and have an independent value of 10 (using a public domain B component of quality 1). But it could use its A component with the incumbent's best component – its B component – and create a cooperative value of $10 \times 8 = 80$. This would create a cooperative surplus as $80 - (6 \times 8) - 10 = 22$. So, as this simple example shows, the start-up firm can use the complementarities between its best technology component and the incumbent's best technology component to create a cooperative value that is higher than the sum of values of the two firms as separate entities. Moreover, the start-up would optimally choose to do this – a general strategy would give the start-up firm a value of $5 \times 5 = 25$, which is less than it can get from specializing and cooperating with an incumbent where it can have a value (depending on how much of the surplus it can capture) as high as $10 + 22 = 32$.

It is important to note that surplus to cooperation arises because of cospecialized assets, and not out of any consideration of market power. The start-up's best component and the incumbent's best component are cospecialized through their complementarity. The full implications of the theory are apparent by considering three cases: when the available level of technological opportunity is low, moderate, or high, relative to the state of technologies available in the ecosystem. In order to stress the relativity of technological opportunity, I

[16] For venture-capital-backed firms around five to six years typically elapse between these decisions. Founding date information for non-venture-capital-backed firms is not systematically available. However, it appears that non-venture-capital-backed firms spend considerably longer in their research and development phase.

[17] In reality, cooperation might also take place for reasons of market power, and bargaining strength will dictate the allocation of surplus. Both of these considerations are addressed in Egan (2013).

will now change the qualities of the public domain technology to 2 and the qualities of the incumbent's A and B technological components to 3.8 and 4.2, respectively.

First suppose that the start-up firm has only a low level technological opportunity available. This is the situation depicted in figure 2 below.

INSERT FIGURE 2 HERE

The start-up firm can either spread its low level of technological opportunity across a system of components, or it can specialize and rely on public domain technologies for its remaining components. At low levels of technological opportunity specialization can yield the highest value for the start-up at an IPO; it can get the public domain technologies for free and does not have to waste its scarce technological opportunity on re-creating these technologies from scratch. Moreover, although it may be able to create some cooperative surplus by surpassing the quality of an incumbent's weakest technology, it is unlikely to match the value it could achieve as a competitor. Of course, many start-up firms that have only low levels of technological opportunity will fail. They would typically create independent firms with lower values than the lowest quality incumbents, who may already be making just enough from product markets to cover their fixed costs. A start-up firm that has lower value than pre-existing incumbents also does not make an attractive value proposition to public investors.

For the next case, suppose that the start-up firm has a moderate technological opportunity available to it. This is the situation depicted in figure 3.

INSERT FIGURE 3 HERE

Now if the start-up firm specializes it can best the incumbent's weakest component by a sizeable margin and create substantial cooperative surplus through its complementarities with the incumbent's strongest component. A general strategy is also feasible – the start-up can certainly surpass the qualities of all of the components available in the public domain – but a specialization strategy is likely to dominate.

For the third and final case, suppose that the start-up firm has high technological opportunity available to it. This is the situation depicted in figure 4. Now if the start-up firm generalizes it can best all of the incumbent's technologies. There is no point in specializing and relying on a complementarity with an incumbent's inferior component; the start-up would rather internalize the complementarities between its own high-quality components.

INSERT FIGURE 4 HERE

The relationship between technology strategy and commercialization strategy is causal in the sense that the technology strategy choice comes first and the commercialization strategy choice depends solely on whether or not the start-up firm has cospecialized assets created through specialization or not. As such, technology strategy Granger-causes commercialization strategy. However, forward looking start-up firms should view the relationship between commercialization strategy and technology strategy as two facets of a single cooperate or compete decision that varies according to the available technological opportunity. Start-up firms make their technology strategy choice in anticipation of their commercialization strategy choice. Put another way, commercialization strategy is endogenous to technology strategy – I will later address this issue in the empirics by exogenously shocking commercialization strategy and examining the effect on technology strategy. Figure 5 summarizes the system vs. components theory of innovation.

INSERT FIGURE 5 HERE

3.2 Patents and Citations as Measures of Technology Strategy

Although the systems vs. components theory of innovation is applicable to non-technology components and more broad cospecialized asset based relationships, like those envisioned in Teece (1986), the focus in this paper is on technology components. A technology component needs some form of protection to prevent appropriation. If a start-up firm or an incumbent cannot protect a technology component, they can't exclude others from using it, and it will naturally fall into the public domain.

The three most common forms of protection for technology components are trade secrets, copyright, and patents. Trade secrets are secrets and so are not observable to econometricians. Copyrighted technology can be observed but the characteristics of a copyrighted piece of technology, for example a piece of software, are very difficult to measure. Therefore, in this paper, as is common in the innovation literature, I will consider patented technology components. Only certain inventions are eligible for patent protection. In particular, patent applications require an 'inventive step' that can be codified. Therefore patented technology components may not be representative of all technology components. Nevertheless, considering patented technology components allows us to consider whether the relationship between technology strategy and commercialization strategy predicted by the theory holds for a large and important group of start-up firms.[18]

[18] Around 5% of all start-up firms that secured an IPO or an acquisition between 1986 and 2006 had one or more patents prior to their commercialization event.

In order to see why and how patent-based variables provide natural measures of the technology strategy followed by a start-up firm, it is important to understand the economic nature of patents, their claims, and their citations.

Patents are made up of claims. Each claim should embody a useful, novel, and non-obvious inventive step. Novelty requires that patent claims are not technical substitutes for one another – a technology is not novel if it has been patented before. However, patent claims may still be economic substitutes for one another as many different technologies may accomplish the same economic ends.[19] When different technologies can be used to create the same component, it is natural that the quality of the components will vary.

When a start-up firm creates a system of components, it is logical to assume that it will file more patents, or patents with more claims, compared with when it creates a single proprietary component. In the two component example used in the diagrams above, a general strategy should be associated with patents and claims for both A and B, where as a specialization strategy of should be associated with patent claims to cover just A.

Patents usually cite other patents. Applicants have a "duty to disclose information material to patentability" to the patent office.[20] This duty is fulfilled by recording citations to relevant prior art in the patent application.[21] If a patent application is granted, there is a presumption of validity against the cited prior art. Patent applicants therefore have an incentive to provide citations to pre-existing patented economic substitutes. Such a citation would serve the duty to disclose information material to patentability by showing that, although other technologies can achieve approximately the same economic end, their patent's claims have different and novel inventive steps. It would also protect the applicant against future litigation; a patent examiner has reviewed the alternative technology and concluded that its inventive step is different and non-infringing. Hence a patent which covers an A component should cite other patents that also cover A components, and likewise for B components. In other words, patents citations should contain information about component-based substitution.[22]

[19] There is a common misconception, particularly among non-economists, that patents confer monopolies. They do not. They confer exclusionary rights over the usage of the codified inventive step(s).

[20] This is sometimes called 'Rule 56' as it appears in section 1.56 (Appendix R: Consolidated Patent Rules) of title 37 (the U.S. patent code).

[21] Patent examiners should review all disclosed prior art, and frequently add additional citations to other prior art to the patent application. Alcácer and Gittelman (2006) estimate that almost $\frac{2}{3}^{\text{rds}}$ of patent citations are added by examiners.

[22] Citation counts should be irrespective of the relative qualities of the start-up's and incumbents' components. The start-up firm's component might be a superior substitute, a perfect substitute, or an inferior substitute to an incumbent's component. In every case the incumbent's component is relevant prior art. Citations therefore do not form a quality ladder, with higher quality components citing only lower quality components. Instead, more citations-made will indicate that a start-up firm's patent has substituted for a greater number of pre-existing components and more citations-received will indicate that subsequent substi-

Start-up firms that create systems of proprietary components might then cite more patents than start-up firms that specialize in creating a single proprietary component: start-up firms with systems need to differentiate themselves, and protect themselves, against multiple different sets of prior art; whereas start-up firms that specialized in creating a single component only need to do so against one set of prior art. Likewise, with invention occurring in the start-up firm's industry between the time that it files its patents and the time that it secures its commercialization investment, a start-up firm that builds a system might also receive more citations than a start-up firm that specializes.

However, citations appear to be made for many reasons. Some citations might convey information about component-based substitution and others might not. Systems of technology components are specific to industries and only active patents provide protection for components.[23] A novel potential measure of technology strategy is therefore the count of citations between active patents held firms in the same sector as the start-up. These citations are much more likely to indicate component-based substition. Moreover, if we look at the variation in the counts of these citations within an industry, we might find bifurication: high counts might occur when the start-up's system has similar numbers of components to its incumbents' systems, and low counts might indicate specialization. This is illustrated in figure 6, below

Insert Figure 5 Here

3.3 IPOs and Acquisitions as Commercialization Outcomes

There are many ways that a start-up firm can raise commercialization investment and compete or cooperate with incumbents. Initial public offerings and acquisitions are generally large, complicated, and hard-to-reverse events – but they are the prototypical example of a compete-vs-cooperate decision. IPOs and acquisitions are commonly used for five reasons: they are clearly observable; they are reasonably unambiguous compete vs. cooperate decisions, at least providing that one takes care to use a sample that does not contain acqusitions after IPOs or spin-offs after acquisitions; they are tractable – commercialization investment is raised in a single event, and firm values and other characteristics are generally disclosed; they are comparable – there is a sense, with appropriate controls, that a firm that

tution by rival firms has taken place. As such, the theory predicts that citations-received will be negatively correlated with firm value.

[23]Patents expire at the end of their statutory term. This is 20 years from application after 8$^{\text{th}}$ June 1995 and 17 years from granting prior to this date. They also expire if patent holders opt not to pay their renewal fees. Renewal fees, introduced on December 12$^{\text{th}}$, 1980, are due at $3\frac{1}{2}$, $7\frac{1}{2}$, and $11\frac{1}{2}$ years after granting. Terminal disclaimers and declarations of invalidity (either by the court or the patent office at a post-grant opposition) also result in the expiration of patents.

experienced an IPO had a hazard of being acquired, and vice versa; and they are important group to consider in their own right. Almost 80,000 U.S. privately-held start-up firms were acquired and around 10,000 U.S. privately-held start-up firms secured an IPO from 1986 to 2004.

In addition, both IPOs and acquisitions are subject to regulation. In this paper, I will use the introduction of the Sarbanes-Oxley Act (SOX) in 2002 as an exogenous shock to a start-up firm's commercialization strategy. Sarbanes-Oxley may have increased the average regulatory costs for publicly-traded firms by US$5m.[24] This would provide start-up firms with an incentive to choose a cooperative commercialization strategy over a competitive one.

Firms with high-levels of information asymmetry between themselves and their investors are likely to have faced the greatest increase in costs following the introduction of SOX. Sarbanes-Oxley is "An Act [t]o protect investors by improving the accuracy and reliability of corporate disclosures..."[25] Brander and Egan (2008) demonstrate that information technology and biotechnology firms consistently rank as having the highest levels of information asymmetry across a variety of measures of information asymmetry that are commonly used in the literature. High-technology firms are characterized by complex development and production processes based upon technical information that is difficult to share, quantify, and validate. Non-high-technology firms may still use patents, but are generally less complex and so face lower levels of information asymmetry with their investors. Their increase in regulatory costs as a consequence of SOX should therefore probably have been more modest.

Figure 7, below, provides an analysis of the legal and accounting costs of compliance with SOX for both high-technology and non-high-technology start-up firms filing for an IPO. These costs may proxy for other regulatory costs imposed by SOX. The graph shows linear predictions of costs, after controlling for firm size, both pre- and post-SOX. The change in costs is dramatically (and statistically significantly) larger for high-technology firms than their non-high-technology counterparts. High-technology firms faced increases in accounting and legal costs of filing an S-1 of around US$0.5m as a consequence of SOX.

Insert Figure 7 Here

[24] An industry study by Korn/Ferry (2004), cited in a speech to the U.S. House of Representatives, puts average SOX compliance costs for Fortune 500 firms at $5m. Zhang (2007) uses data from A.R.C. Morgan on the direct costs of compliance with Section 404 of SOX to estimate costs between $1.56m and $10m per firm, depending on firm size, in a sample of 280 publicly-traded firms. Leuz (2007) suggests that these cost estimates may be high.

[25] From the title page of the Sarbanes-Oxley Act, 107th Congress Public Law 204.

3.4 Hypotheses

In the theory of system vs. components, specialize-and-cooperate and generalize-and-compete are paired together. In the real world, there are many other factors at play, including chance. As a consequence, the predictions of the theory should be interpreted as an increased likelihood of observing these relationships. Furthermore, some measures of technology strategy are likely better than others. Accordingly, the theory yields three immediate hypotheses concerning the relationship between measures of a successful start-up firm's technology strategy and its likelihood of pursuing a particular commercialization strategy:

Hypothesis 1 *The correlation between counts of patents and claims and* $\frac{p(IPO)}{p(Acq)}$ *will be positive for successful start-up firms.*

Hypothesis 2 *The explanatory power of citations made and received in-sector to active patents in predicting the commercialization strategy of start-up firms should be higher than that for aggregate citation counts.*

Hypothesis 3 *The correlation between counts of both citations made and received to active patents held by firms in the same sector as the start-up firm and* $\frac{p(IPO)}{p(Acq)}$ *will be positive for successful start-up firms.*

Start-up firms that have only a low technological opportunity are those that are likely to fail. The best course of action for these firms is to specialize and concentrate their efforts into creating at least one strong component. Therefore, failed firms should follow the same technology strategy as firms that cooperate. This yields another hypothesis that can be tested using data on venture-capital-backed firms, where failed start-up firms are observable.

Hypothesis 4 *Counts of patents, claims, and citations in-sector to active patents should be uncorrelated with* $\frac{p(Acq \cap Success)}{p(Fail)}$ ***and*** *positively correlated with* $\frac{p(IPO \cap Success)}{p(Fail)}$ *for venture-capital-backed firms.*

Finally, the introduction of the 2002 Sarbanes-Oxley Act raised the cost of an IPO but did not directly affect the cost of an acquisition. The introduction of SOX would be a truly exogenous shock to a start-up firm's commercialization strategy and so technology strategy, providing two assumptions are met: the induction of the Act must not have been a response to start-up firms' future technology strategy plans, which seems very unlikely; and the introduction of the Act must have come as a surprise to start-up firms (so they could not adjust their technology strategies in advance), which seems very likely. Some start-up firms presumably had technological opportunities that put them just on the compete side of the compete-cooperate boundary proir to SOX. If such a start-up firm had not already fully implemented its technology strategy (and was still yet to reach its commercialization choice) when SOX was introducted, it should have changed its technology strategy to favor greater component specialization.

Hypothesis 5 *Taking a start-up's patenting activity as a panel and considering only variation within a start-up firm, the introduction of the 2002 Sarbanes-Oxley Act should be associated with a decreased propensity to patent, patents with fewer claims, and patents that make and receive fewer citations in-sector to active patents.*

4 Data and Measures

4.1 Data Sources

Data were drawn from the NBER patent data (see Hall et al. 2001), the U.S. Patent and Trademark Office (USPTO) Maintenance Fee data (distributed by Google), the Global New Issues (GNI) database (owned by Thomson-Reuters), the SDC Mergers and Acquisitions database (owned by Thomson-Reuters), VentureXpert (owned by Thomson-Reuters), COMPUSTAT and CRSP (through Wharton Research Data Services at the University of Pennsylvania) and Orbis (owned by Bureau Van Dijk). In each case, all available data meeting some basic criteria, discussed in the appendix, were drawn. Data were joined using patent numbers and firm names to create a dataset containing the near-population of privately-held U.S. start-up firms with one or more patents prior to their commercialization events (i.e., IPO or acquisition), which must have occurred between 1986-2004.[26] An additional dataset of failed venture-capital-backed start-up firms with one or more patents was also created for use in the analysis of failure vs. success.

4.2 Sample Descriptions

This paper uses four data samples: 1) a main sample consisting of a near-population of successful start-up firms (i.e., those that achieved either an IPO or an acquisition) that held

[26]Custom-built matching software, available from the author's website, provided normalization-based and algorithm-based firm name matches, which were validated using state of incorporation and event-date information. In the U.S., companies are incorporated in a U.S. state, rather than federally. As a result, it is possible (though unlikely, as trademarks are federal), that two firms can have the same name but be incorporated in separate locations. Likewise, in very rare cases, I found firms with identical names in the same state, but operating in different time periods. Every effort was made to ensure correct matches, but it is possible that a small number of errors persist in my data. I do not believe that these have any material effect on my analysis.

at least one patent prior to their commercialization event, which must have occurred between 1986 and 2004; 2) a venture-capital-backed subsample consisting of only successful venture-capital-backed patent-holding start-up firms; 3) a subsample consisting of only successful patent-holding start-up firms with a disclosed firm value at their commercialization event; and 4) a 'failed' sample consisting of failed patent-holding venture-capital-backed firms.

Only patents that were filed prior to the start-up firm's commercialization event were included in the construction of the start-up firm's patent portfolios for any of the samples. Likewise, only citations received before the commercialization event (including failure) were considered.[27,28] Furthermore, original patent assignment records were used to determine patent ownership. Patents assigned to firms that failed or were acquired are recorded as being assigned to the start-up and not an acquirer.

4.3 Measures

Patents accrue to firms over time, and the likelihood of filing a patent, as well as the typical counts of citations made and received by a patent, varies by year.[29] It is therefore important to address time-based variation within the firms' patent portfolios in the cross-sectional analyses. Year-fixed effects using the commercialization event date are not sufficient on their own as firms that achieve IPOs typically patent closer to their event date than firms that achieve an acquisition (see table 1, below). I therefore use the mean 'portfolio time distance' as a control measure in conjunction with year fixed-effects in all cross-section analyses. The mean portfolio time distance computes the average time elapsed between patent application dates and the start-up firm's commercialization event for each start-up firm.

Patenting and citation activity also varies by sector. North American Industry Classification System (NAICS) codes are available for all start-up firms in the main sample, as well as for almost all U.S. corporate assignees that might cite or be cited by these start-up

[27] All citations-made were considered. In actuality, citations can be added to patent applications at any point in the application process, either by the applicant (or their legal representatives) or the patent examiner. However, I am unable to discern when citations were added to an application in the data.

[28] Patenting and citation behavior appear to undergo different, systematic, and dramatic changes after a commercialization event depending on the type of event the firm experienced. For firms that are acquired or fail patenting drops precipitously because the start-up firm generally ceases to legally exist. The patents that belong to acquired firms are also cited less after an acquisition. It is unclear why this happens and future research is needed to understand this puzzle. However, for the purposes of this paper, including citations beyond the commercialization event would then introduce an omitted variable bias: greater numbers of citations-received would be correlated with an initial public offering as compared with an acquisition for reasons other than the chosen technology strategy of the firm.

[29] So called 'citation inflation' is dramatic. Patents in the mid-2000's made and receive materially more citations than patents in the mid-1980's. This may be due to the increased complexity of technology, decreased search costs, or other factors.

firms.[30] However, NAICS codes suffer from a well-known problem: they do not aggregate into meaningful industries very well.[31] Hence NAICS codes must be grouped into suitable industries for an empirical analysis centered on product markets, such as semiconductors, software, biotechnology, and so forth. The method for the assignment of NAICS codes into sectors used in this paper is detailed in the appendix.[32]

Initial public offerings and acquisitions both come in waves that vary by sector (see, for example, Rau and Stouraitis 2011). To control for this, the empirical analysis uses *sector* $\times$ *year* fixed effects in all specifications.[33] Within the main sample of successful start-up firms, approximately 35% of firms were in I.T., $18\frac{1}{2}$% were in biotechnology, 20% were in high-technology industrials, and the remaining $26\frac{1}{2}$% were non-high-technology firms.[34] Almost 10% of successful firms achieved their commercialization event in 2000 – the end of the dot-com boom – and the overall trend was one of a steady rise in commercialization events throughout the 1990's, followed by a drop back to 1990 levels in 2001. However, I.T. peaked in 1999 (with 25% of commercialization events occurring in 1999 and 2000 combined), and biotechnology had its greatest peak in 1996 (with 11% of commercialization events) followed by a secondary peak in 2000 (with 10% of commercialization events).

Firm value is a potentially endogenous regressor in the analysis of the relationship between technology strategy and commercialization strategy. Firm value is directly related to technology opportunity, which is an unobserved and omitted variable.[35] Nevertheless, firm value controls are included in some specifications to make it apparent to readers that

[30] The sample of failed start-up firms was drawn from VentureXpert, which uses a proprietary industry classification rather than NAICS codes. VentureXpert's industry classification is based on product markets and it was straight-forward to construct a concordance with the sector definitions used in this paper.

[31] Although the NAICS system is hierarchical, the hierarchy reflects the "similarity in processes used to produce goods or services" and not the proximity of product markets. See the FAQ on www.census.gov/naics.

[32] Firms with patents naturally tend to be concentrated in high-technology sectors (see Levin et al. 1987). My industry classification reflects this. However, the algorithm used to assign NAICS codes to sectors relied on there being sufficient numbers of firms within a 3, 4, 5, or 6 digit NAICS code. As a result, I was left with an 'other' group, made up of firms scattered over a huge number of NAICS codes. Inspection of the codes in this 'other' group, lead me to name this the 'non-high-technology' sector. It consists of firms from mining, utilities, construction, textile mills, apparel manufacturing, transportation, and many other non-high-technology NAICS codes. This non-high-technology sector is useful in the identification of the Sarbanes-Oxley shock.

[33] Every analysis also uses modal patent category fixed effects, where the patent category aggregation of patent classes was performed using the classification provided by Hall et al. (2001). These have no effect on any analysis and are included solely to reassure readers. Patent classes are extremely noisy measures of the nature of the technology embodied within a patent application, let alone of the product market in which the patent will be used.

[34] Failed firms followed a similar pattern, but with a higher proportion in I.T., and lower proportions in high-tech industrials and non-high-technology firms.

[35] Start-up firms with higher level of technological opportunity are more likely to create systems of components and are more likely to compete.

citation-based measures do not simply proxy for firm value.[36,37] Likewise, some analyses restrict attention to successful start-up firms that had values in excess of US$100m at their commercialization events. This makes it clear that start-up firms that get acquired follow a specialization strategy even if they are not 'fire-sale' acquisitions.[38] Overall, although it is the case that more valuable firms undertake initial public offerings, technology strategy strongly predicts commercialization strategy even when firm value effects are taken into account.

The cross-sectional analyses explore whether technology strategy Granger-causes commercialization strategy. Accordingly, the explanatory variables are patent-based measures of technology strategy. These include the number of patents in a start-up firm's portfolio prior to its commercialization event (including failure), the average number of claims made within these patents, and measures of the average number of citations made and received (prior to the commercialization event) by these patents. Aggregate counts of citations made and received are used solely to demonstrate that they are not good measures. Counts of citations made and received (either separately or combined) to and from firms in the same sector as the start-up and to prior-art covered by active patents are the primary measure of technology strategy. High-values on these measures will indicate a general strategy and low values will indicate a strategy of specialization.

4.4 Descriptive Statistics

Table 1, below, shows descriptive statistics for the main sample of 4,176 patent-holding successful start-up firms, made up of 2,998 firms that got acquired and 1,178 firms that achieved an IPO.[39] It also shows the descriptive statistics for the failed sample of 1,025 failed venture-capital-backed start-up firms. Successful venture-capital-backed start-up firms were more likely to achieve an IPO than successful non-venture capital backed start-up firms. The sample of successful venture-capital-backed start-up firms consists of 454 firms that achieved an IPO (44% of the total) and 561 that achieved an acquisition (19% of the total). 2,149 of the successful start-up firms had disclosed firm values at their commercialization event.

Insert Table 1 Here

[36] Quadratic log firm value controls are in the analyses. Other firm value controls, including linear controls, higher-order polynomial controls, and decile-based firm value fixed effects yield very similar results.

[37] Patent citations are related to firm value: citations-made are positively correlated with firm value and citations-received are negatively correlated with firm value. These findings are a second-order effect and are consistent with the findings of Shane and Stuart (2002). These effects are explained by citations representing component-based substitution. See footnote 47 for further information.

[38] A 'fire-sale' acquisition is one where the target is bought, usually very cheaply, for its assets and not for continued operation.

[39] Note that in the analyses some observations will be omitted because they are perfectly predicted by the fixed effects.

There are four important observations concerning the descriptive statistics in table 1. First, all of the measures demonstrate considerable skewness. The medians are invariably well below the means. To address this, I will adopt the convention of using the log of one plus the variable in the analyses. Second, counts of patents, claims, and citations made and received, all appear comparable across IPOs and acquisitions. They are a little different between failed firms and successful firms. However, the decomposition of citations made and received into citations made and received in-sector to active patents is striking. Start-up firms that cooperate with an incumbent in an acquistion typically make and receive a single citation to active patents in-sector, whereas start-up firms that compete with incumbents by securing commercialization investment through an IPO typically make and receive around 8 such citations. This suggests that this decomposition is uncovering important, meaningful variation. Third, as previously cautioned, portfolio time distance – the measure of how much time elapsed between patent filings and the commercialization event, is dramatically different for acquisitions as compared with IPOs. Firms that get acquired appear to stop patenting some time previous to their commercialization event. And fourth, unsurprisingly and consistent with the theory presented earlier, firm values at IPO tend to be much larger than firm values at acquisition.

5 Empirical Analysis

5.1 The Relationship between Technology and Commercialization Strategies

I begin the empirical analyses with a simple univariate analysis. Table 2 asks the questions: Without controlling for other factors, are firms that pursued a general strategy (i.e., have higher patent-based technology strategy measures) more likely to have opted to compete (i.e., secure an IPO) as compared with cooperate (i.e., pursue an acquisition)? And do firms that fail have the same measures of technology strategy as firms that cooperate?

Insert Table 2 Here

The results are compelling providing that other uncontrolled factors do not have first-order effects. Patenting, claims per patent, and in-sector citations to active patents are all higher, indicating a greater likelihood of a general strategy, for firms that IPO as compared with firms that get acquired. This is true for both the full sample and for the subsample of successful firms that had commercialization values greater than US$100m. Start-up firms that get acquired appear to have followed the same technology strategy as firms that failed.

The table also reports results of a comparison of failed firms against firms that were acquired for more than US$100m. For these firms only the number of claims per patent is significant. The negative sign on the coefficient suggests that claims are not a good measure of technology strategy.[40] In unreported t-tests, a comparison of failed firms against all acquired firms yielded no significant differences on any technology strategy measure.

Table 3 tests whether measures of technology strategy Granger-cause commercialization outcomes in multivariate analyses, where it is possible to control for a large number of other factors including time, industry, and firm value effects. Time controls are important as all measures of technology strategy increase over time, and industry controls are important because systems are assumed to be industry-specific. Firm value controls are necessary to rule out the possibility that everything is simply driven by firm value.

The theory suggests that more patents and more claims per patent (hypothesis 1), and more citations in-sector to active patents (hypothesis 3), should indicate a greater likelihood of a system-based technology strategy, which in turn should be associated with an increased propensity to secure an initial public offering and compete. The theory also suggests that aggregate citation-based measures may reflect many things besides the technology strategy of a start-up firm, and that counts of citations made and received in-sector to active patents should more accurately reflect technology strategy (hypothesis 2).

Table 3, below, reports the results of logit regressions. The dependent variable takes the value 1 if a successful start-up firm achieved an IPO and 0 if it achieved an acquisition. Columns 1, 2, and 3 report results using the main sample. Column 4 reports results restricting the sample to successful start-up firms with commercialization values greater than US$100m, and column 5 includes firm value controls using the disclosed value sample. Column 6 reports results for the venture-capital-backed subsample, again with firm value controls.

Insert Table 3 Here

The results are broadly consistent with hypothesis 1: More patenting, indicative of a general technology strategy of creating an entire system of components, is highly statistically significantly positively correlated with the likelihood of an IPO in every specification except specification 5.[41] Including firm value controls in an analysis using the main sample renders

[40] The number of claims per patent is related to firm value in a non-linear fashion, but overall more claims are generally associated with lower firms values.

[41] Logit regressions report log odds and the explanatory variable is the log number of patents. Therefore, a coefficient of 0.5 translates to a 0.6 increase in the odds of an IPO relative to an acquisition for each additional patent in the start-up firm's portfolio: $\frac{e^{0.5}}{e^{1}} \approx 0.6$.

the coefficient on the number of patents insignificant. However, within the venture-capital-backed subsample, patenting activity continues to predict commercialization strategy even with the inclusion of firm value controls. Claims-based measures of the technology strategy of the firm are generally insignificant – the inclusion of measures of citation activity in-sector to active patents eliminates their effects. Absent the inclusion of these measures, counts of claims made were statistically significantly positively correlated with the likelihood of an IPO, even after controlling for firm value.

Column 1 of table 3 reports the estimation of the effects of aggregate counts of citations-made and citations-received on the commercialization strategy of start-up firms. Citations-made are weakly positively correlated with the likelihood of an IPO and citations-received are very weakly negatively correlated with the likelihood of an IPO. The poor statistical significance of these measures, as well as their inconsistent signs, suggests that they capture something besides the technology strategy of start-up firms. The effect of counts of citations made and received in-sector to active patents, shown in column 2, is entirely consistent with these new citation-based measures reflecting the technology strategy of start-up firms. The coefficients are both positive and very highly statistically significant. Therefore the results support hypothesis 2 – citation activity between a start-up firm's active patents and active patents held by incumbents in the same sector as the start-up firm is what truly matters in the measurement of technology strategy.

Hypothesis 2 is also supported by the observation that using citation activity in-sector to active patents dramatically increases the explanatory power of the analyses. Although pseudo-R^2 measures cannot be relied upon to accurately represent the 'goodness-of-fit' of a logit in the same that an R^2 measure can in an OLS regression, McKelvey & Zavoina's pseudo-R^2's (reported in the table) increased from around 0.47 to around 0.67 with the inclusion of the decomposed patent citation measures.[42] Moreover, Wald ($\chi^2 = 341.26^{***}$) and Likelihood Ratio ($\chi^2 = 688.47^{***}$) statistics, which measure the extent to which a variable or variables add information to the model, reveal an impressive amount of new information content.[43] Accordingly, from this point on in the paper, I will use the terms 'citations-made', 'citations-received', and 'total citations' (or just 'total cites') to refer to citations in-sector to active patents. All other citations will be discarded from citation counts.

[42] Veall and Zimmermann (1996) demonstrate that McKelvey & Zavoina's pseudo-R^2 has the closest relationship to an OLS R^2. The Count Pseudo-R^2, Adjusted Count Pseudo-R^2, and many other commonly used measures of the accuracy of predictions of a logit regression, all increased by around 0.2.

[43] Note that a Wald test is preferred, as a Likelihood Ratio test can only compare estimates made without heteroscedasticity-consistent standard errors.

Technology strategy, as measured by total citations, is an excellent predictor of commercialization outcomes. According to citation measures, start-up firms that generalize overwhelming follow a competitive commercialization strategy and secure initial public offerings – hypothesis 3, is supported with high-levels of statistical significance for citations-made (column 2), citations-received (column 2), and total cites (columns 3 through 6). One problem with the analysis in column 2 is that counts of citations-made and citations-received are positively correlated in the data.[44] This is addressed by using the combined count of citations-made and citations-received in columns 3 through 6.

Overall, the analyses in table 3 provides compelling empirical evidence consistent with notion that technology strategy Granger-causes commercialization strategy. With low values of technology strategy measures indicating specialization and high values indicating a general strategy, the pattern of specialize-and-cooperate or generalize-and-compete emerges clearly. Column 6 shows that these results hold when considering just venture-capital-backed start-up firms. Similar results are found when considering only patents that occur before the first round of venture capital investment in the sample of venture-capital-backed start-up firms. This suggests that patent citations can be used to uncover the optimal commercialization strategy for a venture-capital-backed firm prior to its receipt of venture capital. Moreover, the analyses suggest that the considerations in the model are of strong material importance. Technology strategy, as measured by patent citations, predicts around 20% of the variation in start-up firm's commercialization outcomes.[45] A single citation (made or received in-sector to an active patent) increases the odds of an IPO relative to an acquisition by around 1.25.[46,47]

5.2 Predicting Failure vs. Success

The theory of systems vs. components also makes a prediction concerning failure: firms that fail should adopt a specialist technology strategy and so be indistinguishable, in terms of measures of their technology strategy, from firms that secure an acquisition (hypothesis 4).

[44] The raw correlation between log measures of aggregate citation counts is about 17% and highly statistically significant. Once time effects are taken into account, the correlation between log citations made and log citations received is 8%, but this is still highly statistically significant.

[45] Time and sector effects predict around another 20%.

[46] The base odds of an IPO relative to an acquisition in the estimation are reported in the constant. In columns 1 through 3, the base odds are around 4 to 10. Including firm value controls then reduces the base odds.

[47] In unreported regressions, I considered the effects of citations made and received on firm value controlling for the commercialization outcome of a start-up firm. Consistent with the hypothesis that citations should reflect component-based substitution, citations-made were positively correlated with value, and citations-received were (very strongly) negatively correlated with value. An additional citation-received in-sector to an active patent was associated with an average $44m decline in firm value for successful start-up firms.

Table 4, below, shows the results of logit regressions between failure-and-acquisition and failure-and-IPO, using the venture-capital-backed subsample (where failure is observable) to test this hypothesis.

Insert Table 4 Here

In column 1, the log number of patents, the log number of claims, and the log of total cites all have an effect that is not statistically significantly different from zero when testing failure vs. acquisition. This result is consistent with the same technology strategy being followed by both firms that fail and firms that get acquired. In column 2, the two best measures of technology strategy – the number of patents and the total citations – are both highly statistically significantly positively correlated with the likelihood of an IPO as compared with failure. This result is consistent with firms that fail following a specialization technology strategy and firms that secure IPOs following a generalist technology strategy. Taken together, the results from columns 1 and 2 provide strong evidence in support of hypothesis 4.

5.3 Sarbanes-Oxley as a Shock to Commercialization Strategy

I now turn to time-series analyses to address the endogeneity concern that arises because forward-looking start-up firm chose their technology strategy in anticipation of their commercialization strategy. The thought experiment here is that some start-up firms had technological opportunities that, absent SOX, put them just on the compete side of the compete-cooperate threshold. If the Sarbanes-Oxley Act was introduced during the period that such a firm was implementing its technology strategy choice, then SOX's increased costs of competing as an independent entity should have provided the firm with an incentive to switch from a generalize-and-compete strategy to a specialize-and-cooperate strategy.

Accordingly, tables 5 and 6 report the results of time series analyses that estimate the effect of SOX on a start-up firm's technology strategy. The unit of analysis is always a start-up firm's patent application year and the data is set up as a panel of a start-up firm's patent application flows. Each analysis uses firm fixed effects, so only variation with a firm is considered. Standard errors are clustered at the firm level.

In table 5, below, four different measures of technology strategy are used as dependent variables. Three of these measures, the number of patents, the number of claims, and the log total citations, have all been used previously.[48] The fourth measure is the log number of normalized total citations. As mentioned previously, citation counts are subject to 'inflation'

[48]The number of claims and the number of citations are totals, rather than averages, in these analyses.

over time. To prevent this problem from confounding the analysis, this new measure normalizes citation counts by their sector-year averages for all patent applicants (i.e., not just start-up firms). Through-out table 5, the explanatory variable is a binary measure that takes the value 1 if the patent application occurs after the introduction of the Sarbanes-Oxley Act (i.e., if the application year is greater than or equal to 2003).

The results in table 5 are consistent with hypothesis 5: Every measure, aside from claims made, shows a material, statistically highly-significant, decline from 2003 forward. As such, the results suggest that start-up firms changed their technology strategies to favor increased specialization after the introduction of the Sarbanes-Oxley Act in 2002.

Insert Table 5 Here

However, the results in table 5 could be caused by something else besides the introduction of the Sarbanes-Oxley Act. To mitigate this concern, table 6 provides further analyses that together provide prima-facie identification that the technology strategy change was caused by Sarbanes-Oxley and not something else. Each analysis in table 6 uses un-normalized total citations as the dependent variable, as the results for this measure are easier to interpret. Very similar results were obtained using the normalized measure from table 5, and an identical pattern (albeit with different coefficients) emerges if the log number of patent applications is used instead.

Insert Table 6 Here

The first two columns of table 6 use placebo measures instead of the post-SOX indicator variable. They ask the question: What would the effect be if we looked at a previous year, or three years previous just after the dot-com crash?[49] The results indicate that start-up firms did not change their technology strategies as a result of the dot-com crash, as the coefficient on the 'year $\geq$ 2000' indicator (column 1) is not statistically significantly different from zero. The coefficient on the 'year $\geq$ 2002' indicator (column 2) is statistically significantly less than zero, but with a coefficient that is just a little less than half of the coefficient for the post-SOX (year $\geq$ 2003) indicator (column 3). The Sarbanes-Oxley Act was enacted on July 30$^{\text{th}}$ 2002, so this effect is entirely consistent with the introduction of SOX.

Finally, column 4 of table 6 presents the results of a difference-in-difference test between high-technology and non-high-technology firms regarding their technology strategy changes following the introduction of Sarbanes-Oxley. The analysis is consistent with the change in technology strategy of start-up firms that occurred in 2002 being caused by the introduction

[49] March 10$^{\text{th}}$ 2000 is usually taken as the date of the start of the dot-com crash.

of the Sarbanes-Oxley Act. High-technology start-up firms that had the greatest exposure to SOX changed their technology strategy to favor specialization relative to non-high-technology start-up firms.

6 Discussion and Conclusion

This paper joins a small literature that 'opens the black box' and looks inside a start-up firm. Outside of the world of start-up firms, complementarities have a twenty year history as a key driving force for decisions both within and across the firm boundary. This paper shows that a simple consideration of complementarities between technological components can influence two of a start-up firm's most fundamental innovation choices: which technologies to invest in and how to commercialize them.

The 'system vs. components' theory of invention advanced in this paper has a wealth of close antecedents in the literature, but provides a surprising depth of new implications. Most importantly, it emphasizes that invention and commercialization are intertwined – a theory of invention is therefore a theory of innovation – and that a start-up firm's innovation choices are made in the context of its surrounding ecosystem.[50]

A start-up firm must make a technology strategy choice concerning the allocation of its research and development efforts. An optimal technology strategy can often involve harnessing the power of high-quality components available in the public domain, so that a start-up firm can focus its own resources on developing just a small number of proprietary components. When there is not enough technological opportunity available to best incumbents on all fronts, a start-up firm should always pit its strengths against its incumbents' weaknesses.

Moreover, optimal commercialization strategy – whether a start-up firm should compete or cooperate with incumbents – is essentially determined by a firm's earlier technology strategy choice. A forward looking start-up firm actually faces a single cooperate or competition decision: it can specialize in developing a small number of high-quality components, benefit from creating complementarities with an incumbent's best technologies, and use its cospecialized assets to cooperate with an incumbent; or it can create an entire rival system, internalize the complementarities between components, and raise commercialization investment to compete with incumbents in the product market.

The public policy consideration given primary focus in this paper concerns the impact of the 2002 Sarbanes-Oxley Act (SOX) on the commercialization strategy and so technology strategy of start-up firms. SOX was explicitly designed to increase the quantity and quality

[50] From an industrial organization perspective, the theory also makes explicit the intuition that complements belong together and substitutes belong apart.

of information disclosure from publicly-traded firms. A well-known adverse effect of SOX is that the demand for additional and better disclosure increased regulatory costs for firms that raise investment from public markets. This research suggests another, more indirect, adverse effect of SOX: The Sarbanes-Oxley Act appears to have altered the innovation ecosystem by encouraging start-up firms to forgo competition with incumbents and instead engage in a cooperative strategy based upon component specialization.

However, this paper's policy implications are not limited to just the effects of Sarbanes-Oxley. Any policy initiative that affects the technology strategy of start-up firms is likely to affect their commercialization strategy. This includes changes to patent policy, changes to requirements for tax credits for research and development, the imposition of eligibility rules for the receipt of funding from government-sponsored venture capital firms, and so forth. And any policy initiative that affects the commercialization strategy of start-up firms is likely to affect their technology strategy. This includes changes to listing requirements on stock exchanges, amendments to SOX, the enactment of policy concerning the transfer of intellectual property between firms, et cetera.[51] Policy makers, like firm strategists, should be aware of the relationship between technology strategy and commercialization strategy that is fundamental to the system vs. components theory of innovation.

[51] Recent amendments to the Sarbanes-Oxley act include the 2010 Dodd-Frank Wall Street Reform and Consumer Protection Act, H.R. 4173, as well as the 2010 SEC issue of rule 33-9142 excepting small firms from some disclosure requirements.

7 References

Alcácer, J. and Gittelman, M. (2006). Patent citations as a measure of knowledge flows: The influence of examiner citations. The Review of Economics and Statistics, vol. 88 (4), pp. 774–779.

Anand, Sanjay (2008). The Sarbanes-Oxley Act: An Introduction. Van Haren Publishing.

Baldwin, CY and Clark, KB (1997). Managing in an age of modularity. Harvard Business Review, vol. 75 (5), p. 84.

Brander, James A. and Egan, Edward J. (2008). Investor expectations and the role of venture capitalists in acquisitions. University of British Columbia, Working Paper.

Cockburn, I.M. and MacGarvie, M.J. (2009). Patents, thickets and the financing of early-stage firms: Evidence from the software industry. Journal of Economics & Management Strategy, vol. 18 (3), pp. 729–773.

Cockburn, I.M. and MacGarvie, M.J. (2011). Entry and patenting in the software industry. Management science, vol. 57 (5), pp. 915–933.

Cohen, Wesley M, Nelson, Richard R, and Walsh, John P (2000). Protecting their intellectual assets: Appropriability conditions and why us manufacturing firms patent (or not). Tech. rep., National Bureau of Economic Research.

Egan, Edward J (2013). Venture capitalists as vendors of complementary components. Job Market Companion Paper.

Ethiraj, Sendil K and Levinthal, Daniel (2004). Modularity and innovation in complex systems. Management Science, vol. 50 (2), pp. 159–173.

Fleming, Lee and Sorenson, Olav (2001). Technology as a complex adaptive system: evidence from patent data. Research Policy, vol. 30 (7), pp. 1019–1039.

Friar, John and Horwitch, Mel (1985). The emergence of technology strategy: A new dimension of strategic management. Technology in Society, vol. 7 (2), pp. 143–178.

Gans, Joshua S, Hsu, David H, and Stern, Scott (2002). When does start-up innovation spur the gale of creative destruction? RAND Journal of Economics, vol. 33 (4), pp. 571–586.

Gans, Joshua S and Stern, Scott (2000). Incumbency and R&D incentives: Licensing the gale of creative destruction. Journal of Economics & Management Strategy, vol. 9 (4), pp. 485–511.

Gans, J.S. and Stern, S. (2003). The product market and the market for ideas: Commercialization strategies for technology entrepreneurs. Research Policy, vol. 32 (2), pp. 333–350.

Greenberg, G. (2010). Small firms, big patents? Estimating patent value using data on Israeli start-up firms' financing rounds. Unpublished Working Paper.

Griliches, Zvi (1998). Patent statistics as economic indicators: a survey. In R&D and Productivity: The Econometric Evidence. University of Chicago Press, pp. 287–343.

Hall, B.H., Jaffe, A.B., and Trajtenberg, M. (2001). The NBER patent citation data file: Lessons, insights and methodological tools. NBER Working Paper, No. 8498.

Hall, Bronwyn H (2004). Exploring the patent explosion. The Journal of Technology Transfer, vol. 30 (1-2), pp. 35–48.

Henderson, Rebecca (1993). Underinvestment and incompetence as responses to radical innovation: Evidence from the photolithographic alignment equipment industry. The RAND Journal of Economics, vol. 24 (2), pp. pp. 248–270.

Henderson, R.M. and Clark, K.B. (1990). Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. Administrative Science Quarterly, pp. 9–30.

Jaffe, Adam B and Trajtenberg, Manuel (2002). Patents, citations, and innovations: A window on the knowledge economy. MIT press.

Jones, Benjamin F (2009). The burden of knowledge and the death of the renaissance man: is innovation getting harder? The Review of Economic Studies, vol. 76 (1), pp. 283–317.

Kaplan, Steven, Stromberg, Per, and Sensoy, Berk (2002). How well do venture capital databases reflect actual investments? Available at SSRN 939073.

Korn/Ferry (2004). 31st Annual Board of Directors Study. PeopleMetrics, on behalf of Korn/Ferry International.

Lemley, Mark A and Sampat, Bhaven (2008). Is the patent office a rubber stamp? Emory LJ, vol. 58, pp. 181–1305.

Leuz, Christian (2007). Was the Sarbanes–Oxley Act of 2002 really this costly? a discussion of evidence from event returns and going-private decisions. Journal of Accounting and Economics, vol. 44 (1), pp. 146–165.

Levin, R.C., Klevorick, A.K., Nelson, R.R., Winter, S.G., Gilbert, R., and Griliches, Z. (1987). Appropriating the returns from industrial research and development. Brookings Papers on Economic Activity, vol. 1987 (3), pp. 783–831.

Mann, Ronald J and Sager, Thomas W (2007). Patents, venture capital, and software start-ups. Research Policy, vol. 36 (2), pp. 193–208.

Mikkola, Juliana Hsuan (2003). Modularity, component outsourcing, and inter-firm learning. R&D Management, vol. 33 (4), pp. 439–454.

Milgrom, Paul and Roberts, John (1990). The economics of modern manufacturing: Technology, strategy, and organization. The American Economic Review, pp. 511–528.

Milgrom, Paul and Roberts, John (1995). Complementarities and fit strategy, structure, and organizational change in manufacturing. Journal of Accounting and Economics, vol. 19 (2), pp. 179–208.

Rau, P Raghavendra and Stouraitis, Aris (2011). Patterns in the timing of corporate event waves. Journal of Financial and Quantitative Analysis, vol. 46 (01), pp. 209–246.

Reinganum, Jennifer F (1989). The timing of innovation: Research, development, and diffusion. Handbook of industrial organization, vol. 1, pp. 849–908.

Schilling, Melissa A (2000). Toward a general modular systems theory and its application to interfirm product modularity. Academy of Management Review, vol. 25 (2), pp. 312–334.

Scotchmer, Suzanne (1991). Standing on the shoulders of giants: cumulative research and the patent law. The Journal of Economic Perspectives, vol. 5 (1), pp. 29–41.

Scotchmer, Suzanne (2004). Innovation and incentives. The MIT Press.

Shadab, Houman (2008). Innovation and corporate governance: The impact of Sarbanes-Oxley. University of Pennsylvania Journal of Business and Employment Law, vol. 10 (4).

Shane, S. and Stuart, T. (2002). Organizational endowments and the performance of university start-ups. Management Science, pp. 154–170.

Teece, D.J. (1986). Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. Research Policy, vol. 15 (6), pp. 285–305.

Veall, M.R. and Zimmermann, K.F. (1996). Pseudo-R^2 measures for some common limited dependent variable models. Journal of Economic Surveys, vol. 10 (3), pp. 241–259.

Zhang, Ivy Xiying (2007). Economic consequences of the Sarbanes–Oxley Act of 2002. Journal of Accounting and Economics, vol. 44 (1), pp. 74–115.

8 Appendix

8.1 Data Criteria

The NBER patent data contains data on every utility patent application in the United States at the USPTO from 1963-2004.[52] USPTO Renewals information (i.e., the payment of maintenance fees) is also complete. This paper uses patent applications. In the U.S. almost all patent applications are granted (see Lemley and Sampat 2008).[53] The NBER patent data records all citations made subsequent to 1975, when citations were first stored in an electronically readable format, and has almost all assignment records even prior to this period. In total the data contains records on a little over 3.2m patents assigned to 4.86m entities.[54]

Acquisitions data were taken from the SDC Mergers and Acquisitions database from 1980 to 2010. Only completed acquisitions for 100% of the shares of the target firm, where the target was a U.S. private company, that had never been publicly-traded or spun-off from a publicly-traded firm, and that was acquired by either a public or private U.S. firm, were considered. The dataset very closely approximates the population of acquisitions by U.S. public firms for amounts above the mandatory disclosure limit. Privately-held firms are sometimes required to disclose material acquisitions under applicable Security Exchange Commission regulations, but not always. However, SDC collects data from surveys and press releases as well as from securities filings, and acquisitions above a certain threshold are very likely to be included. Coverage of low value acquisitions is likely sparse, but in robustness checks I found that my main results are essentially unchanged by their inclusion. A material proportion of the acquisitions do not disclose the transaction value or other measures of the target firm value. Again in robustness checks I found that this had no material effect on the analyses.

The data on initial public offerings come from GNI. As these data are extracted from offering prospectuses and other mandatory security filings, these data represent the entire population. I consider data from 1986 to 2010; prior to 1986 GNI's data collection was

[52]The original NBER patent data, detailed in Hall et al. (2001), covered 1963-1999. Updates to this data were released for 2002, 2004, and 2006. The 2006 data has incomplete assignee information and so was not used.

[53]The granting of a patent does convey additional information for start-up firms; Greenberg (2010) documents a value premium to start-up firm patent grants. Likewise, the granting of a patent will likely influence its citations-received. However, I have no reason to believe that the failure to achieve a grant introduces any systematic bias into my analyses.

[54]A small minority of patents are assigned to multiple entities. The analyses in this paper use the first declared assignee. However, the results presented are robust to the exclusion of multiply assigned patents or to the inclusion of indicator variables denoting multiple assignment.

not automated. To be included in my dataset, IPOs must have completed listings on any U.S. exchange, but must not be a leveraged buyout (LBO) or a spin-off. The firm must be have been privately-held and never have been publicly-listed or acquired before its initial (i.e., first) public offering. The market capitalization of the firm on the day following its completed listing was used as the firm value at IPO.[55]

Data on venture-capital-backed firms were taken from Thomson VentureXpert from between 1980 and 2010; the coverage of this dataset is regarded as unbiased and approaching the population of venture-capital-backed firms (see Kaplan et al. 2002). I checked that my sample of successful start-up firms included all successful VC-backed firms, and constructed a VC-backed indicator variable accordingly. In addition, I constructed a sample of 'failed' venture-capital-backed start-up firms, where I defined a start-up firm as failed if it did not secure either an acquisition, an IPO, or a subsequent round of financing for a period of four years after its last recorded round of financing.

COMPUSTAT and CRSP were used to provide North American Industry Code System (NAICS) codings to publicly-traded U.S. assignees. This was supplemented with data on privately-held U.S. assignees from Orbis. Based on 'COD' assignee-type codes from the USPTO, industry codings were made for slightly in excess of 90% of all U.S. corporate assignees.

8.2 Industry Classification

The NAICS codes of start-up firms with one or more patents that achieved success (i.e., an IPO or an acquisition) were grouped into 14 sectors, each belonging to one of 4 high-level industries: information technology, biotechnology, industrial, and 'other'. This classification is provided in table A1.

This industry classification is based upon that of Brander and Egan (2008), who created an assignment of 2002 NAICS codes to the information technology and life sciences sectors. This paper updates their classification to include codes added in the 2007 NAICS listing, and decomposes information technology into computer hardware, telecoms, computer media, Internet, and software, and life sciences into biotechnology and general life sciences. This decomposition was guided by VentureXpert's almost identical decomposition and a matching of NAICS codes to VentureXpert's classification for the sample of venture-capital-backed successful start-up firms, as well as by the counts of the observations in each sector in the data.

[55] Alternative firm value measures, including the net and gross proceeds, and market capitalization according to the prospectus, were also tried. The choice of firm value measure does not materially affect any of the results.

The remaining unclassified firms were sorted by their NAICS codes, and an algorithm was used to identify additional coherent industries. The algorithm was as follows: 1) If an entire 5-digit NAIC codes had over 40 observations, none of which were previously classified, and such that together it formed a coherent industry of operation, then extract it; 2) Repeat this for 4-digit then 3-digit NAIC codes; 3) Aggregate any 3, 4 or 5-digit NAICS which together form a coherent industry of operation; 4) Add any 6-digit industry codes that could be unambiguously assigned to a pre-existing coherent industry of operation; And 5) check a randomly-drawn sample of firms' classifications against a description of their business taken from Thomson-Reuters.[56]

The exception to this classification system was the instruments sector. It was not possible to aggregated the entire of NAICS 33451 - "Navigational, Measuring, Electromedical, and Control Instruments Manufacturing" into the instrument sector, as code 334515 was already assigned to semiconductors, and codes 334510, and 334516, 334517, 334519, were already assigned to biotechnology. A careful review of the firms holding these codes indicated that these assignments were correct, and so the remainder was used to create the instruments sector, which was then supplemented with two 6 digit codes: 333314 - "Optical Instrument and Lens Manufacturing" and 335314 - "Relay and Industrial Control Manufacturing".

Approximately $\frac{1}{4}^{\text{th}}$ of patent-holding start-up firms that later achieved success were left unclassified by the algorithm. These start-up firms were spread over a large number of NAICS codes (each of which had less than 40 observations) associated with non-high-technology sectors. Accordingly, they were grouped together into an 'other' industry and a 'non-high-technology' sector.

[56] 40 observations is a reasonable estimate of the threshold at which a t-distribution assumption becomes valid without strong symmetry, unimodality, and with outliers.

9 Figures and Tables

Figure 1: Cospecialized assets and cooperative surplus

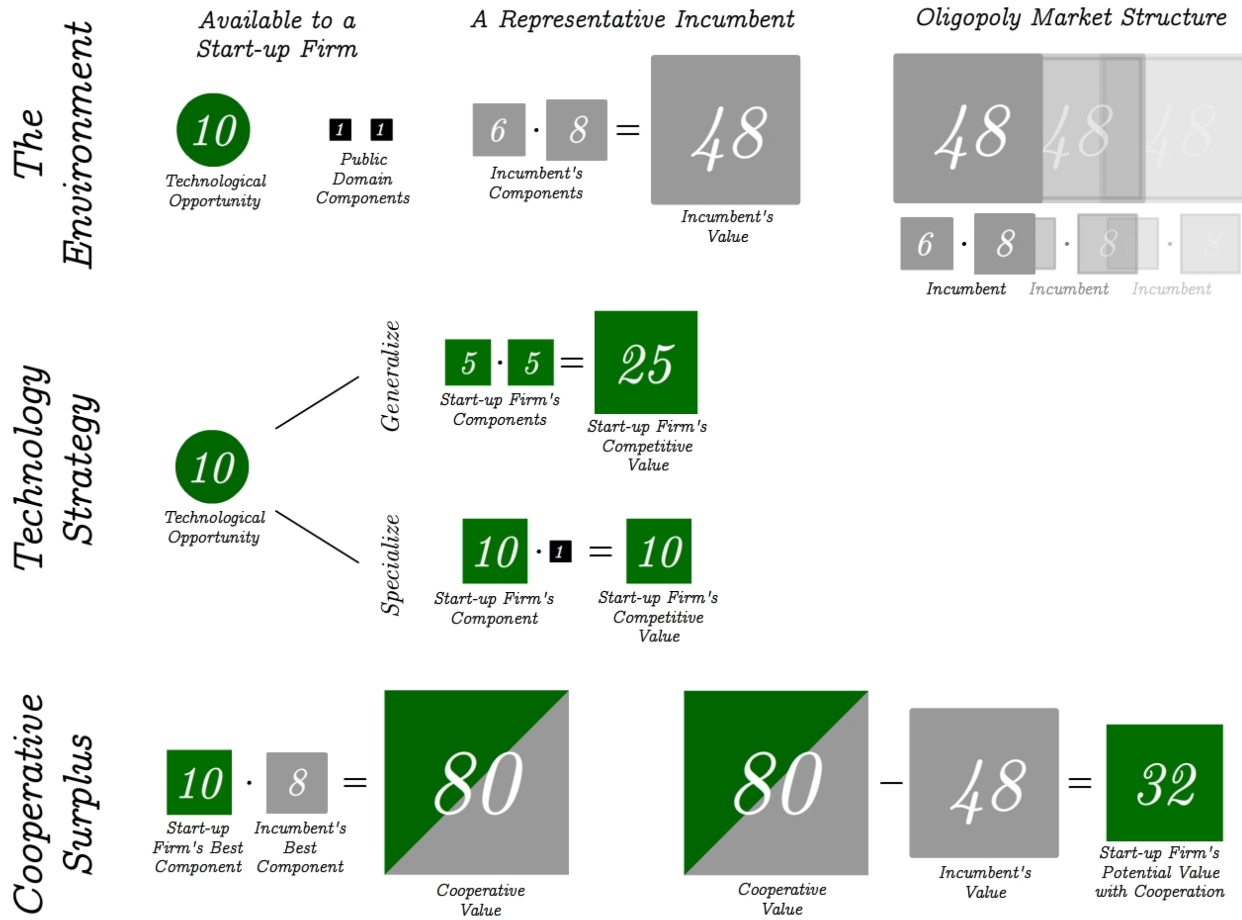

Figure 2: Low technological opportunity: technology & commercialization strategies

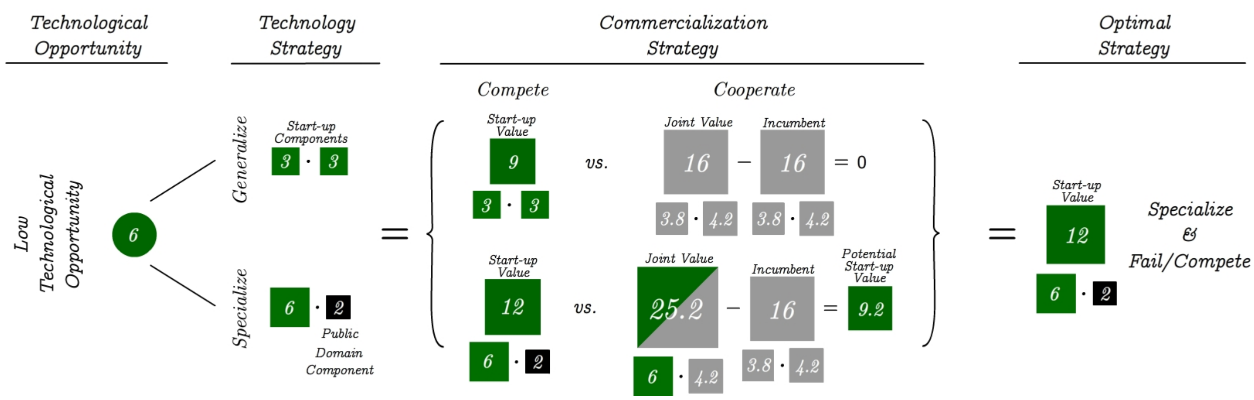

Figure 3: Moderate technological opportunity: technology & commercialization strategies

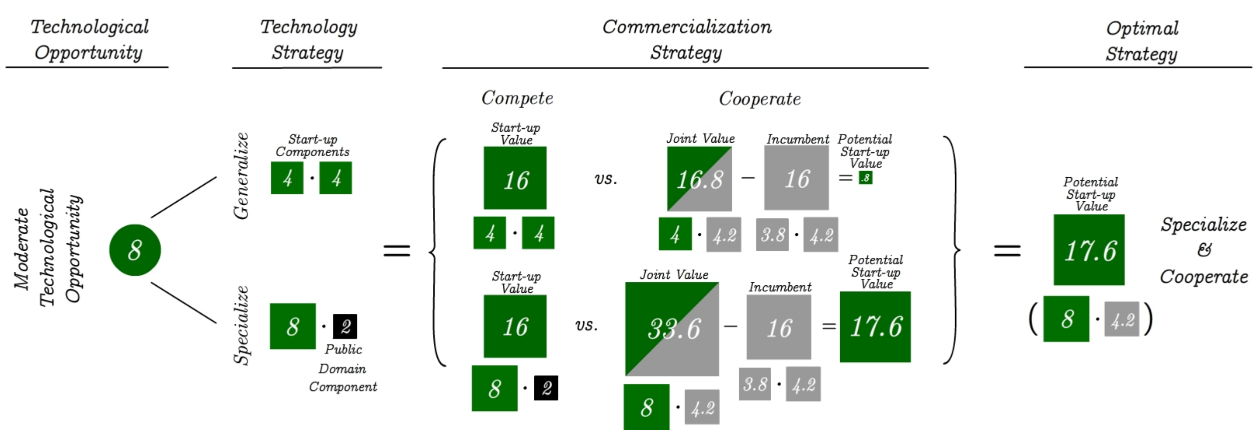

Figure 4: High technological opportunity: technology & commercialization strategies

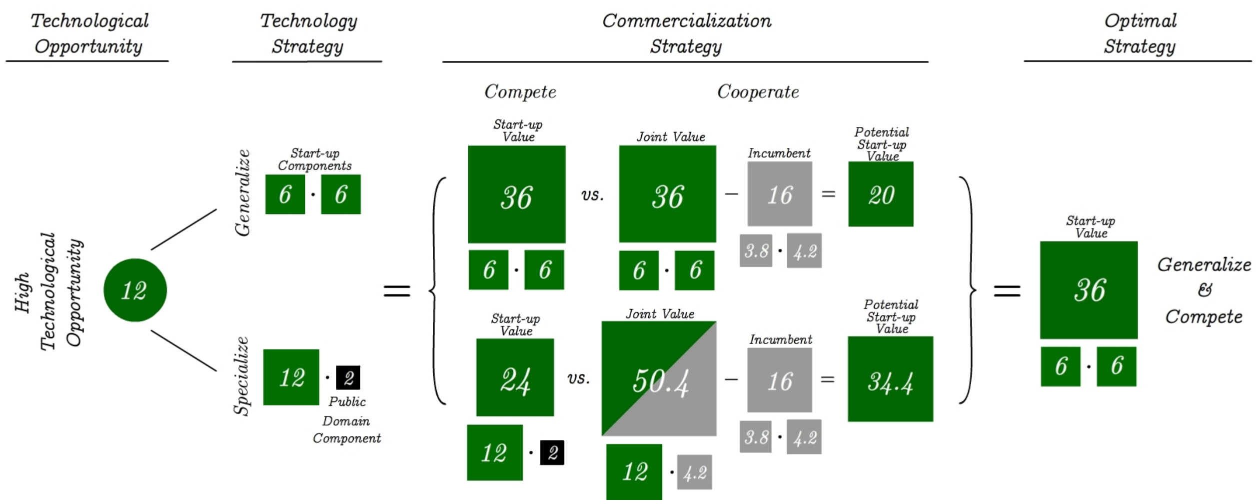

Figure 5: The system vs. components theory of innovation

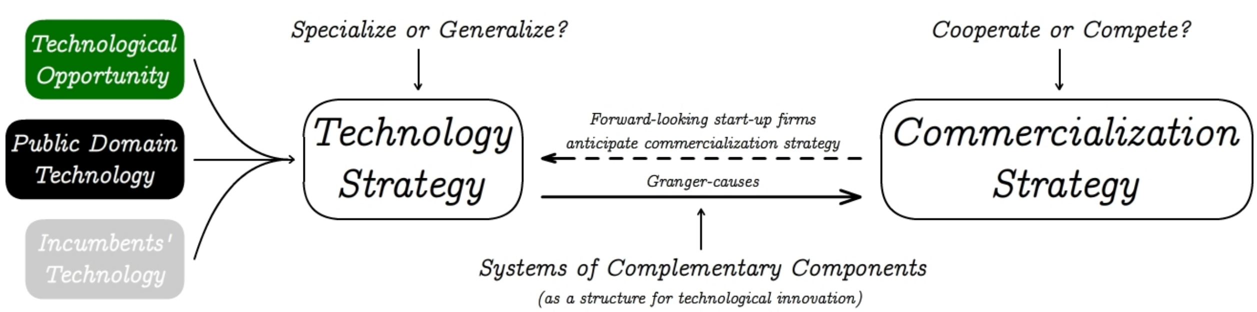

Figure 6: In-sector citations to active patents as measures of technology strategy

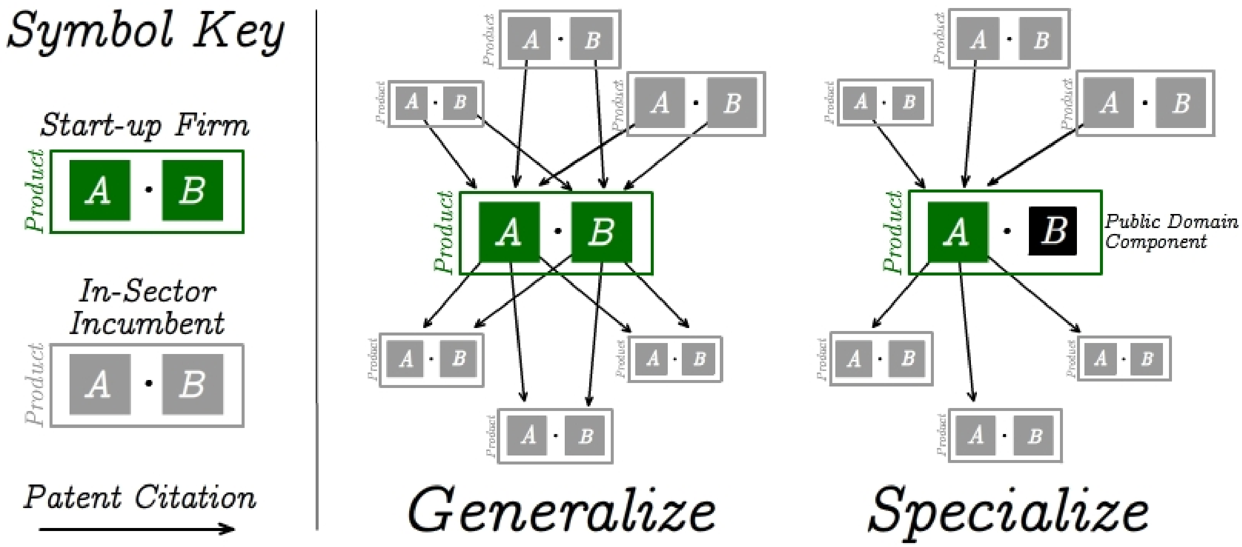

Figure 7: Changes in legal & accounting fees at IPO from SOX

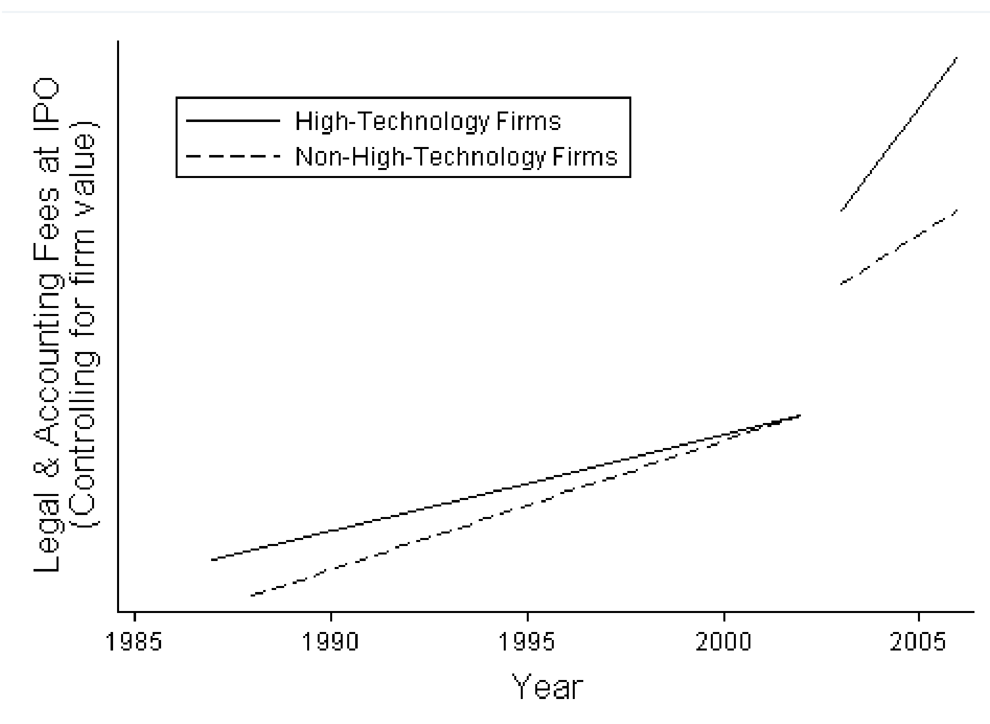

Table 1: Descriptive statistics

		Commercialization Outcomes					
		Failed ($N = 1025$)		Acquisition ($N = 2998$)		IPO ($N = 1025$)	
		Mean	$50^{\text{th}}\%$	Mean	$50^{\text{th}}\%$	Mean	$50^{\text{th}}\%$
Technology Strategy	No. Patents	5.6 (15)	2	12.7 (175.2)	2	13.7 (55.6)	4
	Avg. Claims	19.9 (12.7)	17.8	17.9 (13.4)	15	20.3 (13.7)	17.2
	Avg. Cites Made	10.4 (12.8)	7	9 (12.8)	6	11.5 (14.4)	7.2
	To Active, In Sector	0.6 (1.7)	0	0.7 (2.5)	0	5.5 (10.4)	1.9
	Avg. Cites Rec'd	9.8 (14.7)	5.5	6.8 (12.5)	4	5.5 (12.3)	2.9
	From active, In Sector	0.6 (3.1)	0	0.5 (1.7)	0	2.2 (4.3)	0.2
	Avg. Cites (Made & Rec'd)	20.2 (21.1)	14	15.7 (18.7)	11	17 (20.1)	11.6
	To/From Active, In Sector	1.1 (4)	0	1.2 (3.5)	0	7.7 (12.6)	3
	Firm Value	-	-	81.3 (200.7)	21.5	711.6 (4016.5)	109.6
	Avg. Portfolio Time Dist.	6.4 (4.3)	5.3	6.9 (5.5)	5.0	3.8 (2.5)	4.3

Table 2: t-tests of differences in technology strategy measures between commercialization outcomes

As technology strategy is implemented before commercialization outcomes occur, the table suggests that technology strategy Granger-causes commercialization strategy. The table provides t-tests of the difference in means of three measures of technology strategy between various commercialization outcomes. High values on the three measures should indicate a greater likelihood of a general, rather than specialized, technology strategy. The first set of columns tests the difference between all IPOs and acquisitions. The second set of columns tests the difference between IPOs and acquisitions where the start-up firm had a value of greater than \$100m at its commercialization event. The third set of columns tests the difference between failed firms and firms that were acquired for more than \$100m. *** and ** denote significance at the .01 and .05 levels, respectively. Significance tests are based on the two-sided alternative hypothesis that the means differ, allowing for unequal variances.

		Three Pairs of Commercialization Outcomes								
		IPO vs. Acq. (n=4,176)			IPO vs. Acq. $> \$100m$ (n=2,705)			Fail vs. Acq.$> \$100m$ (n=4,176)		
		Δ(Mean)	Std. Err.	t-Stat	Δ(Mean)	Std. Err.	t-Stat	Δ(Mean)	Std. Err.	t-Stat
Tech. Strategy	Log No. Patents	0.35	0.03	10.12***	0.44	0.04	9.86***	0.03	0.03	1.05
	Log Avg. Claims (per patent)	0.14	0.02	6.82***	0.22	0.03	8.70***	-0.16	0.02	-6.90***
	Log Avg. In-Sector Cites To Active Patents	0.94	0.04	23.91***	1.03	0.05	20.81***	0.04	0.03	1.44

Table 3: The relationship between technology strategy and commercialization strategy

The table provides evidence that technology strategy Granger-causes commercialization strategy outcomes. Technology strategy measures, which have high values when a start-up firm adopts a general strategy, are down the left-hand side. Commercialization strategy is measured as the likelihood of competing versus cooperating, so that positive coefficients indicate both that a general strategy is associated with a greater likelihood of competition and that specialization is associated with a greater likelihood of cooperation. Specifically, the table shows the estimation of logit regressions with the dependent variable taking the value 1 if the start-up firm undergoes an IPO (competes) and 0 if it undergoes an acquisition (cooperates). The sample used is indicated at the bottom of each specification. Coefficients are reported with heteroscedasticity-consistent standard errors in parentheses. ***, **, and * denote statistical significance at the 0.01, 0.05, and 0.1 levels respectively. The *Portfolio Time Dist.* control measures the mean number of years between patent application(s) and the commercialization event, *Year* is the commercialization event year, *Sector* is detailed in the appendix, and *Modal Category* is the most common Hall-Jaffe-Trajtenberg category of patents in the start-up firm's portfolio. Quadratic firm value controls are used in some specifications. Alternative firm value controls yield very similar results. Column 4 uses only IPOs and acquisitions with values of more than US$100m to emphasize that results are not driven by low-value, 'fire-sale', acquisitions.

		Commercialization Outcomes: $\log(p(Compete)) - \log(p(Cooperate))$					
	Specification	(1)	(2)	(3)	(4)	(5)	(6)
Technology Strategy Measures (Higher values indicate a general strategy)	Log No. Patents	0.580***	0.397***	0.427***	0.495***	-0.011	1.147***
		(0.054)	(0.060)	(0.059)	(0.071)	(0.097)	(0.401)
	Log Avg. Claims	0.247***	0.063	0.064	0.073	-0.103	-0.805**
		(0.081)	(0.090)	(0.090)	(0.119)	(0.151)	(0.365)
	Log Avg. Cites Made	0.199**					
		(0.082)					
	To Active, In Sector		1.177***				
			(0.099)				
	Log Avg. Cites Received	-0.129*					
		(0.072)					
	To Active, In Sector		0.645***				
			(0.132)				
	Total Cites To Active, In-Sector			1.277***	1.352***	1.220***	2.563***
				(0.066)	(0.091)	(0.094)	(0.422)
	Constant	-0.740	-0.861*	-0.928*	-3.296***	-3.052***	-17.393***
		(0.451)	(0.501)	(0.501)	(0.810)	(0.929)	(3.532)
	Firm Value Controls	no	no	no	no	yes	yes
	Portfolio Time Dist.	yes	yes	yes	yes	yes	yes
	Sector x Year Fixed Effects	yes	yes	yes	yes	yes	yes
	Modal Category Fixed Effects	yes	yes	yes	yes	yes	yes
	Sample	full	full	full	$> 100m$	full	VC
	Observations	3,743	3,743	3,743	2,326	1,884	441
	Pseudo-R^2	0.47	0.631	0.618	0.666	0.748	0.944

Table 4: Failure and technology strategy for venture-capital-backed firms

The table provides evidence that firms that fail adopt the same technology strategy as firms that cooperate – as these firms both have low measures of technology strategy, it suggests that both groups of firms specialized. Specifically, the table shows the estimation of logit regressions using venture-capital-backed start-up firms that succeeded (i.e., achieved an IPO or an acquisition) or failed. Coefficients are reported with heteroscedasticity-consistent standard errors in parentheses. ***, **, and * denote statistical significance at the 0.01, 0.05, and 0.1 levels respectively. For *Fail vs. Acq* the dependent variable takes the value 1 if the start-up firm undergoes an acquisition and 0 if it fails. For *Fail vs. IPO* the dependent variable takes the value 1 if the start-up firm undergoes an IPO and 0 if it fails. Controls are as in table 3. Value controls cannot be included as they fully explain failure. However, essentially the same results are found if start-up firms that secured acquisitions and IPOs for more than $100m are used instead.

		Failure vs. Commercialization Outcome	
		Fail vs. Acq	Fail vs. IPO
Technology Strategy	Log No. Patents	0.002	0.873***
		(0.003)	(0.174)
	Log Avg. Claims	-0.077	0.015
		(0.116)	(0.207)
	Cites To/From Active, In Sector	-0.024	1.542***
		(0.114)	(0.160)
	Constant	1.228	0.634
		(1.312)	(1.488)
	No. Observations	1,376	1,074
	Portfolio Time Dist.	yes	yes
	Sector x Year Fixed Effects	yes	yes
	Modal Category F.E.	yes	yes
	Pseudo-R^2	0.256	0.821

Table 5: Sarbanes-Oxley (2002) and changes to technology strategy

The table addresses the endogeneity concern that arises as forward-looking start-up firms make their technology strategy choice in anticipation of their commercialization strategy choice. It uses the introduction of the Sarbanes-Oxley Act (SOX) in 2002 as an exogenous shock to commercialization strategy and so technology strategy. If the theory is correct, a start-up firm (with appropriate technological opportunity) should have altered its technology strategy to favor component specialization after SOX was introduced. This should appear as a reduction in the values of measures of technology strategy post-SOX. Accordingly, the table shows the estimation of panel regressions with technology strategy measures as dependent variables listed in the column headers. A panel is used so that only variation in technology strategy within a start-up firm can be considered. The main sample is assembled as a flow (not stock) of patent applications and their characteristics per firm per year. The explanatory variable is a binary variable taking the value 1 if the patent application year is greater than or equal to 2003 (i.e., post-SOX). Coefficients are reported with standard errors clustered at the firm (i.e., start-up) level in parentheses. ***, **, and * denote statistical significance at the 0.01, 0.05, and 0.1 levels respectively. Firm fixed effects (that remove all variation between firms) and patent class fixed effects are included as controls in all specifications.

	Four Measures of Technology Strategy			
			Log Cites To Active In Sector	
	Log No. Patents	Log Claims Made	Raw	Normalized
Year $\geq$ 2003	-0.449***	-0.113	-0.725***	-0.726***
	(0.096)	(0.117)	(0.192)	(0.150)
Constant	1.285***	2.649***	1.136***	0.747***
	(0.068)	(0.108)	(0.165)	(0.125)
Firm Fixed Effects	yes	yes	yes	yes
Patent Class F.E.	yes	yes	yes	yes
No. Start-up Firms	4,218	4,218	4,218	4,218
Observations	13,329	13,329	13,329	13,329
R^2	0.078	0.063	0.069	0.068

Table 6: Identifying the Effect of Sarbanes-Oxley

One concern with the previous analysis is that something besides the introduction of SOX could have driven the results. This table uses both placebo tests, that look for effects in other years, and a difference-in-difference analysis to identify the effects as being caused by SOX. The difference-in-difference analysis relies on the evidence provided in figure 7, which shows that high-technology firms should have experienced disproportionate effects of SOX relative to non-high-technology firms. It estimates the difference for high-technology versus non-high-technology start-up firms in the change to their technology strategies post-SOX. Technology strategy (the dependent variable) is measured using in-sector citations to active patents, as this is my best measure. Accordingly, the table shows the estimation of panel regressions using patent flows as in table 5. However, the explanatory variables are now binary variables taking the value 1 if the patent application year is greater than or equal to some threshold. For Post-SOX the threshold is 2003, as before. 'Post-SOX and High-tech' takes value one if the year is greater than or equal to 2003 and the firm is not categorized as non-high-technology, and zero otherwise. Coefficients are reported with standard errors clustered at the firm (i.e., start-up) level in parentheses. ***, **, and * denote statistical significance at the 0.01, 0.05, and 0.1 levels respectively. Firm fixed effects and patent class fixed effects are included as controls in all specifications.

	Placebos		Difference	Diff-in-Diff
Year $\geq$ 2000	-0.035			
	(0.038)			
Year $\geq$ 2002		-0.252***		
		(0.062)		
Post-SOX			-0.725***	
			(0.192)	
Post-SOX & High-tech				-0.740***
				(0.215)
Constant	1.103***	1.118***	1.136***	1.102***
	(0.170)	(0.165)	(0.165)	(0.170)
Firm Fixed Effects	yes	yes	yes	yes
Patent Class F.E.	yes	yes	yes	yes
No. Start-up Firms	4,218	4,218	4,218	4,218
Observations	13,329	13,329	13,329	13,329
R^2	0.066	0.068	0.069	0.069

Classification of sectors by NAICS codes

The official NAICS 2007 code definition is included verbatim for all two, three and four digit codes. NAICS code 516 is taken from the 2002 NAICS definition, this code was removed from use in the NAICS 2007 definition but remains in the data. Thompson-Reuters marks some Internet firms with a proprietary code of "BBBBBB". The instruments sector is defined solely by six digit codes, but most codes from NAICS 33451 'Navigational, Measuring, Electromedical, and Control Instruments Manufacturing' are included. The information technology and life sciences codes are updated from Brander and Egan (2008).

	Sector	**North American Industry Classification System (NAICS) Code(s)**
I.T.	Computer Hardware	3341 (Computer and Peripheral Equipment Manufacturing)
	Semiconductor	3344 (Semiconductor and Other Electronic Component Manufacturing); 42369; 333295; 333994; 334515; 335999
	Telecoms	517 (Telecommunications); 3342 (Communications Equipment Manufacturing); 33592; 561499;
	Computer Media	3346 (Manufacturing and Reproducing Magnetic and Optical Media)
	Internet	BBBBBB (Internet - Thomson Specific); 516 (Internet Publishing and Broadcasting); 518 (Data Processing, Hosting, and Related Services); 4541 (Electronic Shopping and Mail-Order Houses); 51913; 51919; 61142;
	Software	5112 (Software Publishers); 5415 (Computer Systems Design and Related Services);
L.S.	Life Sciences	3391 (Medical Equipment and Supplies Manufacturing); 42345; 42349; 42421; 62199; 446199; 541611; 541922
	Biotech	3254 (Pharmaceutical and Medicine Manufacturing); 5417 (Scientific Research and Development Services); 6215 (Medical and Diagnostic Laboratories); 54138; 236210; 325132; 334510; 334516; 334517; 334519; 541690;
Industrials	Chemical	326 (Plastics and Rubber Products Manufacturing); 3253 (Pesticide, Fertilizer, and Other Agricultural Chemical Manufacturing); 3255 (Paint, Coating, and Adhesive Manufacturing); 3256 (Soap, Cleaning Compound, and Toilet Preparation Manufacturing); 3259 (Other Chemical Product and Preparation Manufacturing); 32518; 32521; 32522; 33322; 42383; 42461; 42469; 325131; 325191; 325199
	Industrial	3334 (Ventilation, Heating, Air-Conditioning, and Commercial Refrigeration Equipment Manufacturing); 33312; 333298; 333313; 333319; 333911; 333912; 333913; 333921; 333922; 333923; 333924; 333991; 333992; 333993; 333995; 333996; 333997; 333999
	Metal	331 (Primary Metal Manufacturing); 332 (Fabricated Metal Product Manufacturing); 3335 (Metalworking Machinery Manufacturing);
	Instruments	333314; 334511; 334512; 334513; 334514; 334518; 335314;
	Paper & Printing	322 (Paper Manufacturing); 323 (Printing and Related Support Activities); 333291; 333293; 333315;
Other	Non-High-Technology	21 (Mining, Quarrying, and Oil and Gas Extraction); 22 (Utilities); 23 (Construction); 313 (Textile Mills); 315 (Apparel Manufacturing); 336 (Transportation Equipment Manufacturing); 48 (Transportation); and others.