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Technological Innovation, Intangible Capital, and Asset Prices

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Abstract

We review research on the asset pricing implications of models with innovation and intangible capital. In these models, technological innovation shocks propagate differently than standard total factor productivity shocks—and therefore have qualitatively distinct asset pricing implications. We discuss recent approaches to measuring intangible capital and innovation, many of which rely on the prices of financial securities. Last, we review models that explore the economic differences between intangible and innovation relative to other forms of investments—focusing on the role of human capital and cash-flow appropriability.

1. INTRODUCTION

We review the literature that examines the asset pricing implications of models with intangible capital and technological change. Since these concepts are somewhat fuzzy, it is helpful to first define them. We follow Corrado, Hulten & Sichel (2005) and define as capital investment any outlay that is intended to increase future, rather than current, consumption. This statement implicitly defines the capital stock as the accumulation—net of economic depreciation—of these investments.

We think of intangible capital as an accumulable factor of production that lacks a physical presence. Examples include brand value; intellectual property; the stock of knowledge, say, existing production methods; organization capital; and human capital. Just like physical capital, intangible capital can be increased through investment: advertising expenditures, spending on research and development (R&D), or employee training. To the extent that intangible capital is mismeasured, it obscures the difference between output and observable inputs. In a competitive market with no barriers to entry, firms will make no excess profits—thus, the stock intangible capital could be inferred from the level of excess firm profitability. However, intangible capital is more than poorly measured capital stock: Its somewhat fuzzy nature implies that it is hard to allocate ownership rights to the cash flows it generates. For instance, a talented division manager may enhance firm productivity, so she may be part of the firm's stock of intangible capital. However, either because her contribution cannot be clearly identified or because her knowledge is partly firm specific, she may not be able to appropriate the full value of her contribution; part of these rents is shared with firm owners.

Defining technological innovation in the context of economic models is somewhat harder. A dictionary definition of innovation (Merriam–Webster) is "the introduction of something new." In the context of economic models, innovation consists of the process of translating a new idea or invention into a production factor—tangible or intangible—that creates economic value. That is, we can think of technical change as a (possibly endogenous) event that shifts output given the existing inputs. However, since such a shift is likely to be permanent (examples of technological regress are rare in modern economies), we would prefer that it be accounted for in future inputs. Therefore, for our purposes we define technological change as an outcome that lowers the cost of investing in either physical or intangible capital.[1] Thus, examples of innovation include a blueprint for a new computer that is more efficient, a new drug that expands the firm's product line, and a new manufacturing process that expands the firm's stock of knowledge capital. In these examples, innovation lowers the cost of increasing the capital stock, either because the innovation is more cost-efficient than the existing stock or because it was not previously available—in which case it lowers the cost from infinity to something finite. Furthermore, our definition allows for investments in capital that do not represent innovation: Building a factory or increasing marketing expenditures need not be an innovative activity.

Section 2 reviews workhorse equilibrium asset pricing models that feature technological innovation or intangible capital. We draw two broad conclusions. First, technological innovation shocks propagate differently than standard total factor productivity (TFP) shocks—and therefore have distinct asset pricing implications. Second, in these workhorse models, intangible and

[1]Naturally, innovation is a partly endogenous event; more resources (i.e., capital) allocated to innovation likely increase its success. However, investment in innovation has some important differences from other types of investment. For instance, the return to investing in R&D is likely to be substantially riskier—and perhaps more skewed—than other types of capital accumulation. As such, we might expect that investments in innovation are more likely to be subject to financial constraints than capital expenditures (for a survey on empirical evidence, see Kerr & Nanda 2015). In addition, the profitability of these ideas may be revealed only gradually to economic agents, which can have important implications for asset returns (Pastor & Veronesi 2006, 2009).

physical capital share similar economic properties; their main difference is in how they map to the data. Section 3 reviews the main empirical approaches to measuring intangible capital and innovation outcomes, many of which exploit the information content in asset prices.

In Section 4, we focus on one aspect in which intangible capital and the innovation process differ from physical investments: the role of human capital. Many intangible assets are embodied in employees, so they are part of their human capital. Similarly, discovering new ideas is a much more human capital–intensive process than constructing a new factory. Since these types of human capital are likely a scarce resource, we expect their owners (i.e., inventors, managers, or entrepreneurs) to appropriate a considerable fraction of the rents generated by intangible capital and innovation. The fact that firm owners have to share these rents has implications for the prices of financial assets. Section 4 discusses these implications in more detail.

2. WORKHORSE MODELS

Consider a dynamic continuous-time economy which includes a representative household that consumes a single consumption good. The household has preferences given by

$$U_0 = \int_0^\infty e^{-\rho t} \frac{C_t^{1-\gamma}}{1-\gamma} \, \mathrm{d}t. \qquad 1.$$

There is no population growth; there is a measure one of workers who inelastically supply labor. None of these assumptions are crucial for what follows. The main insights are robust to extending the basic models for a leisure–labor choice, or using recursive preferences of the Epstein & Zin (1989) form.

2.1. The Neoclassical Growth Model with Adjustment Costs

To understand the implications of innovation or intangible capital for asset prices, it is instructive to first consider a model that lacks both. We begin our discussion by considering a model that has a single factor of production, which can be accumulated—homogeneous physical capital.

There is a representative firm which produces the final good according to

$$Y_t = K_t^{1-\beta} \, (Z_t \, L_t)^\beta, \qquad 2.$$

where L_t is labor and K_t is physical capital. The firm owns the capital stock and distributes all profits—net of labor and investment expenses—to households. The capital stock accumulates through investment and depreciates at rate δ; therefore,

$$\mathrm{d}K_t = \chi \, I_t \, \mathrm{d}t - \delta \, K_t, \mathrm{d}t. \qquad 3.$$

The production function in Equation 2 includes a shock to the productivity of labor, Z_t. Given the Cobb–Douglas specification, such a shock is essentially equivalent to a TFP shock. It is tempting to equate TFP with some type of intangible capital; here, we choose not to, because Z_t is not the outcome of an investment process but simply a random shock. Thus, we think of Z_t as the difference between output and all inputs into the production process.

Investment is subject to convex adjustment costs: To increase the capital stock by χI_t, the firm needs to spend $f(I_t, K_t)$ units of the capital good. We assume decreasing returns to capital accumulation—that is, convex costs:

$$f(I, K) = \frac{1}{1+\xi} \left(\frac{I}{K}\right)^{1+\xi} K, \qquad \xi \geq 0. \qquad 4.$$

The final good can be used for consumption or investment:

$$Y_t = C_t + f(I_t, K_t). \tag{5}$$

The model delivers a tight link between economic growth and asset prices through the process of capital accumulation. Let M_t denote the market value of the firm, which is equal to the value function of the firm's optimization problem:

$$M_t = M(K_t, Z_t) = \sup_{\{I_s, s \in [t,\infty])\}} E_0 \left[\int_t^{\infty} \frac{\pi_s}{\pi_t} ((1-\beta)Y_s - f(I_s, K_s))\, ds \right], \tag{6}$$

where π_t is the state-price density, equal to the marginal utility of equilibrium consumption. The first-order optimization condition then delivers

$$\frac{1}{\chi} \left(\frac{I_t}{K_t} \right)^{\xi} = \frac{\partial M(K_t, Z_t)}{\partial K_t} = \frac{M_t}{K_t}, \tag{7}$$

where the last equality follows from constant returns to scale in production and capital accumulation.

This equation, often referred to as the Q theory of investment relates the investment rate on the left with the marginal value of capital on the right. Plugging the above into the equation for capital accumulation, we obtain

$$\frac{\mathrm{d}K_t}{K_t} = -\delta\, \mathrm{d}t + \chi^{\frac{1+\xi}{\xi}} \left(\frac{M_t}{K_t} \right)^{\frac{1}{\xi}} \mathrm{d}t. \tag{8}$$

In equilibrium, a permanent positive shock to Z_t raises consumption, output, and investment on impact. This model, which we refer to below as the neoclassical model with convex adjustment costs, has long served as the benchmark in the literature on asset pricing models with production (Jermann 1998, Tallarini 2000, Kaltenbrunner & Lochstoer 2010).

2.2. Model with Expanding Varieties

Next, we consider the canonical model of endogenous growth (Romer 1990). In this model, growth can be sustained by a form of intangible capital—an expanding variety of intermediate goods. The final good is produced according to

$$Y_t = X_t^{1-\beta} (Z_t L_t)^{\beta}, \tag{9}$$

where, as above, Z_t is a productivity shock and L_t is labor. Instead of physical capital, output now depends on the effective supply of intermediate goods:

$$X_t = \left(\int_0^{N_t} x_{i,t}^{\nu} \right)^{\frac{1}{\nu}}, \qquad \nu \leq 1. \tag{10}$$

Here, N_t denotes the current measure of intermediate goods and $x_{i,t}$ denotes the quantity of the intermediate good that is produced in equilibrium. The output of the final good can be used for consumption C_t, production of intermediate goods $x_{i,t}$, or R&D G_t (R&D affects accumulation of intermediate goods, as specified below):

$$C_t + \int_0^{N_t} x_{i,t}\, \mathrm{d}i + G_t = Y_t. \tag{11}$$

The producers of intermediate goods have an exclusive license to produce good i and thus generate a stream of monopoly profits, Π_t. Each of them optimizes on quantities,

$$\Pi_t = \max_{x_{i,t}} p_t(x_{i,t})\, x_{i,t} - x_{i,t}, \qquad 12.$$

while taking the inverse demand curve $p_t(x_{i,t})$ as given. In a symmetric equilibrium (see, e.g., Dixit & Stiglitz 1977), all intermediate-good producers produce the same amount, and they charge the same price, while aggregate expenditures in intermediate goods are a constant fraction of output. In equilibrium, the output of intermediate goods depends on Z_t and N_t, and the aggregate output can be written as

$$Y_t = c\, Z_t\, N_t^{\alpha}, \qquad 13.$$

where constants c and α depend on model parameters. Examining Equation 13, we see that, similar to the standard neoclassical growth model, this model has one factor that can be accumulated over time: the measure of intermediate goods N_t.

As above, the dynamics of economic growth rate and asset prices depend on the equilibrium process of capital accumulation. In this model, the value of the stock market is equal to the value of the intermediate goods sector because production of the consumption good generates zero profits in equilibrium:

$$M_t = V_t\, N_t, \qquad V_t \equiv E_t \int_t^{\infty} e^{-\delta(s-t)}\, \frac{\pi_s}{\pi_t}\, \Pi_s\, \mathrm{d}s. \qquad 14.$$

Here, V_t denotes the equilibrium value of the license to produce an intermediate good, and π_t is the state-price density, which equals the marginal utility of equilibrium consumption.

Assumptions about the cost of developing new intermediate goods are largely isomorphic to assumptions about investment adjustment costs. To see this, consider the specification of Comin & Gertler (2006) and Kung & Schmid (2015). They assume that the return to investing in research G_t equals

$$\mathrm{d}N_t = -\delta N_t\, \mathrm{d}t + \frac{\chi}{\eta}\left(\frac{G_t}{N_t}\right)^{\eta} N_t\, \mathrm{d}t, \qquad \eta \in (0, 1). \qquad 15.$$

This specification implies decreasing returns to investment in research. A congestion effect raises the marginal cost of developing new products as the aggregate level of R&D intensity rises. In addition, the congestion effect depends on the total measure of intermediate goods N_t, implying that the marginal cost of R&D increases as the economy becomes more sophisticated. Equation 4, combined with the free-entry condition into the research sector, can be rewritten as

$$\frac{\mathrm{d}N_t}{N_t} = -\delta\, \mathrm{d}t + \chi^{\frac{1}{1-\eta}} \left(\frac{M_t}{N_t}\right)^{\frac{\eta}{1-\eta}} \mathrm{d}t. \qquad 16.$$

Equation 16 is the direct analog of the Q theory of investment—Equation 8, above. Since these models are mathematically equivalent, a shock to TFP Z_t in this model propagates to quantities and prices in a manner that is isomorphic to the previous model.

2.3. Model with Quality Improvements

In the setup described above, innovation takes the form of new goods. Yet, in practice, innovation often takes the form of improvements in existing goods or production methods. Therefore, we next consider a model that allows for innovation within product lines, based on the seminal papers by Grossman & Helpman (1991) and Aghion & Howitt (1992) (for a textbook treatment, see Acemoglu 2009). The structure of the economy is as above, except that the measure of intermediate goods is fixed at one, and the quality of each intermediate good varies over time.

The effective supply of intermediate goods is given by

$$X_t = \left(\int_0^1 q_{i,t} x_{i,t}^{\nu} \, \mathrm{d}i \right)^{\frac{1}{\nu}}, \qquad \nu \leq 1. \tag{17.}$$

Each good i can potentially be produced using technology of different vintages; $q_{i,t}$ denotes the leading quality index. A good with quality q is produced under constant returns to scale, with the marginal cost equal to $\psi\, q$. Since vintages of the same good are perfect substitutes, only the leading vintage is produced in equilibrium.

A similar analysis as in Section 2.2 shows that aggregate output equals

$$Y_t = c\, Z_t\, Q_t^{\alpha}, \tag{18.}$$

where Q_t represents the composite factor of production that can be accumulated over time:

$$Q_t \equiv \int_0^1 q_{i,t} \, \mathrm{d}i. \tag{19.}$$

Q_t thus corresponds to the average level of leading quality across goods, which can again be interpreted as intangible capital. Quality can be improved through research expenditures; the evolution of $q_{i,t}$ is given by

$$\mathrm{d}q_{i,t} = \chi\, q_{i,t}\, \mathrm{d}\Theta_{i,t}, \tag{20.}$$

where $\Theta_{i,t}$ is a Poisson count process with intensity $\lambda_{i,t}$, which depends, among other things, on research expenditures to improve good i at time t. A successful improvement in good i raises the quality of the good by a proportional factor χ. To illustrate the mathematical equivalence with the previous models, we assume that the probability of success in improving good i as a function of spending g_i is equal to

$$\lambda_{i,t} = \left(\frac{g_{i,t}}{q_i} \right)^{\eta}, \qquad 0 < \eta < 1. \tag{21.}$$

This specification implies that the required spending to improve good i is increasing in the leading level of quality—since we expect research on more advanced goods to be more difficult. Denoting the value of a new vintage of good i by $v_{i,t} = V_t\, q_i$, the zero-profit condition for new entrants leads to the following capital accumulation equation:

$$\frac{\mathrm{d}Q_t}{Q_t} = \chi^{\frac{1}{1-\eta}} \left(\frac{M_t}{Q_t} \right)^{\frac{\eta}{1-\eta}} \mathrm{d}t. \tag{22.}$$

Here, we have used the fact that the value of the stock market equals the value of the existing varieties, $M_t = V_t\, Q_t$. Comparing Equation 22 with Equations 8–16, we again notice the mathematical equivalence with both the expanding varieties model and the neoclassical growth model with adjustment costs.

2.4. Vintage Capital Models

So far, we have covered three models with physical and intangible capital accumulation. Given that these three models are mathematically equivalent, their implications for aggregate asset prices are the same. The reason is that in all three models the only exogenous source of risk is driven by TFP shocks. Here, we extend these models to incorporate shocks to the rate of technological innovation. To simplify exposition, we base our discussion on the first model discussed in Section 2.1 and ignore labor (i.e., we set $\beta = 0$). In that model, capital accumulation involves the acquisition of identical types of capital. Here, we allow for innovations that are embodied in new capital goods, as done by Solow (1960).

Specifically, capital is no longer homogeneous; there are multiple vintages of capital which differ in their productivity. The productivity of capital of vintage $\tau \leq t$ is given by

$$Y_{\tau,t} = Z_t \, \chi_\tau \, K_{\tau,t}, \qquad 23.$$

where $K_{\tau,t}$ is the stock of capital of vintage τ at time t, and χ_τ is the productivity of vintage τ. The total output in the economy is given by

$$Y_t = \int_{-\infty}^{t} Y_{\tau,t} \, \mathrm{d}\tau. \qquad 24.$$

An attractive aspect of the Solow (1960) model is its aggregation properties. Define an aggregate (quality-adjusted) capital stock as

$$K_t \equiv \int_{-\infty}^{t} \chi_\tau \, K_{\tau,t} \, \mathrm{d}\tau = \int_{-\infty}^{t} \chi_\tau \, I_\tau \, e^{-\delta(t-\tau)} \, \mathrm{d}\tau \qquad 25.$$

so that aggregate output can be written as

$$Y_t = Z_t \, K_t. \qquad 26.$$

The dynamic evolution of K_t is given by

$$\mathrm{d}K_t = \chi_t \, I_t \, \mathrm{d}t - \delta \, K_t \, \mathrm{d}t. \qquad 27.$$

Contrasting Equation 27 with Equation 3, above, we see that the vintage capital model is isomorphic to a model where the productivity of investment varies over time. Thus, one way to incorporate an innovation shock into the standard model is to introduce a second source of uncertainty—an investment-specific technology (IST) shock χ_t. It is straightforward to extend the models in Sections 2.2 and 2.3 to capture a similar type of shock, modeled as a productivity shock to the research sector and a shock to the cost of improving the quality of intermediate goods, respectively.

A positive innovation shock to χ_t lowers the cost of expanding the effective capital stock K_t. Importantly, a shock to χ_t is conceptually different from a shock to TFP Z_t. That is, a shock to Z_t affects all vintages of capital equally; by contrast, a shock to χ_t affects only the productivity of new vintages of capital. Thus, shocks to χ_t have no immediate impact on output and affect it only once they are embodied in the capital stock. Hence, output increases gradually in response to a positive permanent shock to χ_t. By contrast, since the return of investment has increased, investment rises on impact, with a contemporaneous decline in consumption. The decline in consumption is temporary, as higher productivity of new vintages of capital raises the level of output and consumption in the long run.

Papanikolaou (2011) explores the risk premium associated with IST shocks. He finds that the sign of the risk premium depends on household preferences. In the case of power utility, the risk premium is negative. High realizations of χ_t are states of the world in which the marginal value of wealth is high because the return to investment is high; thus, the economy values a dollar more in these states than when investment opportunities are low. In the case of recursive preferences, the sign is ambiguous. If both the elasticity of intertemporal substitution (EIS) and the coefficient of risk aversion are sufficiently low, states characterized by good real investment opportunities will also be states of high marginal value of wealth. The intuition is that a low value of the EIS and risk aversion imply that households would like to smooth consumption paths across time rather than across states, and thus value that extra unit of wealth more when they face an endogenously steep consumption profile. Conversely, when both the EIS and risk aversion are high, investors are relatively unconcerned about smoothing over time, but are worried about smoothing across states. A positive investment shock then represents a state of the world where the marginal value of consumption is low, since in those states their continuation utility is high.

A positive shock to χ_t can also lead to a fall in the stock market. This decline may occur if the value of the installed capital stock K_t accounts for a significant component of the value of the stock market. As the new capital improves in quality, the value of the old capital falls. The fact that the value of the stock market declines following positive news about future economic growth may appear counterfactual, yet it need not be so. Greenwood & Jovanovic (1999) and Hobijn & Jovanovic (2001) argue that the information technology (IT) revolution led to a drop in market valuation of incumbent firms in the late 1960s—the reason is that the market anticipated that the firms that were going to benefit the most from the IT revolution did not yet exist. Nevertheless, the long-run responses of both consumption and the stock market are positive. Garleanu, Panageas & Yu (2011) show how a model with embodied technical change can lead to a more robust relation between consumption and stock market returns at lower frequencies.

To better understand this displacement effect in the context of the expanding variety model, note that the value of the firm can be decomposed as a sum of the value of its existing product portfolio (assets in place) and the present value of profits generated by new products. Importantly, the profit flow from owning a license to produce an intermediate good evolves according to

$$\frac{\mathrm{d}\Pi_t}{\Pi_t} = \frac{\mathrm{d}Z_t}{Z_t} - (1-\alpha)\,\frac{\mathrm{d}N_t}{N_t}. \tag{28.}$$

As long as there is sufficient substitutability across goods—that is, ν is sufficiently high that $\alpha < 1$—the profitability of a single intermediate good is declining in the total measure of intermediate goods. The reason this happens is that there are fixed factors of production (labor); as more goods enter the market, competition among firms drives up the cost of labor and lowers profits. Thus, a fall in the cost of developing new products leads to a fall in the value of existing goods. By contrast, the part of the value of the firm that is derived from the value of future products—that is, future growth opportunities—rises.

Models with such a displacement effect can have rich cross-sectional implications. Papanikolaou (2011) argues that if firms differ in the contribution of installed capital versus growth opportunities to firm value, they will be differentially exposed to an innovation shock χ_t. By contrast, a TFP shock Z_t has mostly a symmetric effect on both sources of firm value. Kogan & Papanikolaou (2013, 2014) build structural models of the firm, in which the fraction of growth opportunities to total firm value correlates with observable firm characteristics. Their calibrated models can replicate several reduced-form empirical facts documented in the empirical asset pricing literature—for example, the value premium puzzle—under the assumption that the risk premium associated with IST shocks is negative. Garleanu, Kogan & Panageas (2012) propose a general equilibrium model of displacement shocks in the context of the expanding varieties model (Loualiche 2014). Bena, Garlappi & Gruning (2015) study the interaction of displacement shocks with the level of product market competition. Section 4.2 discusses these implications in more detail in the context of a simplified model.

2.5. Discussion

The workhorse models described above share strong similarities. All three models feature a close link between the rate of capital accumulation—and hence economic growth and equilibrium consumption—and asset prices. The rate of growth depends on the private return to investing in either physical capital or R&D. Any economic shock that increases these private values will lead to higher growth. Naturally, there is a strong equilibrium link between growth and asset prices. Asset prices correspond to the present value of future profits. Therefore, the growth rate of the economy affects asset prices. Furthermore, as long as the marginal cost of creating new capital, ideas, or goods is not constant, the marginal value of installed capital (i.e., Tobin's Q, or the value of intermediate goods) fluctuates—a necessary condition to generate sufficiently volatile asset returns. More importantly, in this case the economy features predictable fluctuations in economic growth, or long-run risk. Such low-frequency movements in consumption growth, combined with nonseparable preferences of the Epstein & Zin (1989) type, have been quite successful in delivering realistic equity premia in endowment economies (Bansal & Yaron 2004). Similar implications follow in models where production is modeled explicitly (Kaltenbrunner & Lochstoer 2010).

However, as far as asset prices are concerned, there is no qualitative difference between the equilibrium models that emphasize intangible versus physical capital accumulation as the main driver of medium-run fluctuations. That said, even though such models are largely similar mathematically, their mapping to the data depends on how the variables are interpreted. For example, the quantitative implications of these models for asset prices depend on whether investment in the model refers to capital expenditures or spending on R&D. This perspective raises new empirical challenges, as intangible capital and technological innovation are difficult to measure. Section 3 summarizes recent progress along this dimension.

Our view is that there exist important qualitative differences between intangible and physical capital. For instance, creating new intangibles through R&D is likely to be substantially more human capital intensive compared with investing in new physical capital. Furthermore, it is quite likely that part of intangible capital itself is embodied in key employees. For example, new manufacturing processes or management practices typically rely on several key employees; if these employees were to leave the firm, a part of the firm's intangibles would be lost. If intangible capital is partially embodied in key employees, then a fraction of it cannot be pledged to outside investors (Hart & Moore 1994). This distinction can render firms with more intangible capital riskier, introduce additional financial frictions, and have general equilibrium implications about the pricing of economic shocks. Section 4, below, explores such issues further.

3. MEASUREMENT

In this section, we provide a brief overview of the methods used to measure technological innovation and intangible capital.

3.1. Intangible Capital

Researchers interested in models with intangibles have typically followed one of two approaches: Either impute intangible capital as a latent variable based on other moments (see, e.g., McGrattan 2017 for a recent example), or tackle the measurement problem directly using a variety of approaches. Here, we discuss the latter strategy.

3.1.1. Approaches based on expenditures. One of the most popular ways of measuring intangible capital relies primarily on expenditure data. Under this approach, one constructs the intangible capital stock X_t from expenditures G_t by using the perpetual inventory method:

$$X_{t+1} = (1 - \delta) X_t + G_t. \qquad 29.$$

In implementing Equation 29, one must also make assumptions about the depreciation rate δ and the initial capital stock X_0. In general, measuring the appropriate rate of depreciation is challenging. The Bureau of Economic Analysis (BEA) uses a depreciation rate of 15% in its construction of the R&D capital stock, though recent research suggests this may be an underestimate (Li & Hall 2016). Given the high depreciation rates of R&D, the choice of the initial capital stock is less important; typically, studies set it equal to some multiple of G_1.

An example of this methodology is the approach followed by the BEA in expanding the National Income and Product Accounts to include investment in software. In constructing expenditure data, the BEA includes the estimated costs of software created by firms for their own use, as well as purchases of prepackaged software. To measure the former, the BEA relies on detailed Bureau of Labor Statistics (BLS) occupational data on employment and wage earnings of programmers and systems analysts in selected industries, along with an assumption that these individuals spend approximately 50% of their time on software development (Parker & Grimm 2000).

Building on research by Nakamura (2001) and Corrado, Hulten & Sichel (2005, 2009), Corrado & Hulten (2014) consider a broader definition of intangibles and expand the growth accounting framework to include intangible capital. They find that firms' investment in intangibles investment outpaced physical investment during the past 30 years. Given their expanded definition of the capital stock, which includes investments in innovation, approximately one-fourth of the growth in output per hour can be accounted for by intangibles alone. Their estimates imply that capital deepening has been the dominant factor in the growth of labor productivity.

Recent studies have constructed measures of intangibles at the firm level using broadly available accounting data and the perpetual inventory method. Hulten & Hao (2008) and Eisfeldt & Papanikolaou (2012) construct a measure of intangible capital based on accumulating selling, general, and administrative (SG&A) expenditures. Peters & Taylor (2017) build on their work to construct a measure of Tobin's Q adjusted for intangible capital—similar to Megna & Klock (1993). Belo, Lin & Vitorino (2014) accumulate advertising expenditures to construct a measure of brand value.

3.1.2. Exploiting asset prices. The conventional perpetual inventory method has the advantage of simplicity. However, it is not without shortcomings. This method implicitly assumes that different vintages of investment contribute equally, and separably, to the capital stock. If there are technology improvements in the production of new intangibles, we would need to adjust expenditure data for quality improvements. Furthermore, the rate of depreciation δ reflects two distinct processes: decay and replacement. For instance, a production process may exhibit no economic decay, but it may be discarded once an improved method is introduced. Thus, alternative approaches that incorporate information from financial markets can add value.

An early example is presented by Griliches (1981), who examines the contribution of R&D spending to market values. His approach builds on hedonic regression methods: He estimates the cross-sectional relation between stock market valuations (Tobin's Q) and measures of intangibles. In particular, he assumes that the value of the firm is additive in the value of physical capital K_t and intangible capital G_t:

$$V_{i,t} = Q_t \, (K_{i,t} + \gamma_t \, G_{i,t}). \qquad 30.$$

If we divide Equation 30 by the book value of physical capital, and take logs, we end up with the following estimation equation:

$$\log\left(\frac{V_{i,t}}{K_{i,t}}\right) = \log Q_t + \log\left(1 + \gamma_t \frac{G_{i,t}}{K_{i,t}}\right) + \varepsilon_{i,t}. \qquad 31.$$

Here, Q_t and γ_t can be thought of as shadow or hedonic price measures associated with the book measures of the two types of capital. Hall (1993) extends the analysis of Griliches (1981) and considers additional specifications. She documents that the stock market valuation of R&D capital in US manufacturing firms fell during 1986–1991 relative to the earlier period.

Other research has considered alternative measures of the stock of intangible capital. For instance, Hall, Jaffe & Trajtenberg (2005) use citation-weighted patent stocks as alternative measures of intangibles; their main finding is that firms with higher citation-adjusted patent stocks have higher valuations. Nicholas (2008) examines how the market valuation of intangibles—that is, γ_t in Equation 30—varied between 1910 and 1939. Brynjolfsson, Hitt & Yang (2002) consider measures of IT capital and organizational practices. Their estimates imply that each dollar of computer capital is associated with approximately \$12 of market value; they interpret these magnitudes as suggestive of the presence of substantial intangible assets, adjustment costs, or other omitted components of market value correlated with computer assets.

If we are willing to make additional assumptions about the structure of adjustment costs, we can make further progress by exploiting the firms' optimality conditions. Hall (2001) follows this approach to construct a measure of the total capital stock—the sum of physical and intangible capital. Rather than using expenditure data to measure the quantity of capital, he treats it as a latent variable. He assumes convex adjustment costs, so the total cost of increasing the capital stock by I_t is equal to

$$I_t + c\left(\frac{I_t}{K_{t-1}}\right) K_{t-1}. \qquad 32.$$

Under Equation 32, the optimality conditions of the firm imply the familiar investment–Q relation:

$$c'\left(\frac{K_t - (1-\delta)K_{t-1}}{K_{t-1}}\right) = q_t - 1, \qquad \text{where} \quad q_t \equiv \frac{V_t}{K_t}. \qquad 33.$$

Hall 's key insight is that, given last period's capital stock K_{t-1} and the total market value of capital V_t, one can infer the current capital stock K_t and its marginal value q_t from Equation 33.

Hall (2001) considers several values for adjustment costs and allows for some variation in the price of installed relative to uninstalled capital. Given reasonable assumptions for the size of adjustment costs, his estimates imply that the bulk of stock market values in the late 1990s came from a large quantity of intangible capital. More generally, he finds that capital productivity and capital accumulation was high in the 1950s and 1960s, and again in the 1980s and 1990s. In addition, though, his estimates imply periods of capital disasters, periods where the capital stock, or its price, fell sharply. Some of these periods, for instance, 1973–1974, coincide with technological revolutions that could have lowered the value of the installed capital stock (Greenwood & Jovanovic 1999, Hobijn & Jovanovic 2001). However, in other instances, such as the Great Recession of 2008–2009, his analysis likely omits other factors in play, such as fluctuations in risk premia.

Last, Hall's approach implies that the owners of firms' financial securities can appropriate all the rents from intangible capital. This assumption can be debated; if firm owners can appropriate only a fraction of the rents from intangible capital—with the remainder accruing to key firm employees—then this approach can understate the value of intangibles (Eisfeldt & Papanikolaou 2014).

3.2. Technological Innovation

We next examine direct measures of technological change.

3.2.1. Patent statistics. Perhaps the most popular method in broadly measuring the outcome of innovative activity is patent statistics. In his comprehensive survey of the literature on patent statistics, Griliches (1998, Ch. 13, p. 287) writes:

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

Patent data have the advantage that they incorporate detailed information on new inventions, and thus have, at least in theory, considerable potential as measures of innovative activity. Nevertheless, there are at least two major problems in using patent data for economic modeling. First, mapping a given patent to a specific product or industry classification is quite challenging. This is primarily a technical problem; researchers have historically tackled it with assumptions on how certain technology classes map to industry groups.

The second, substantially harder problem is that patents display inherent variability in their technical and economic significance. Most of them reflect only marginal improvements; others prove to be extremely valuable. Indeed, Shea (1999), when constructing direct measures of technology innovation using patent counts, finds only a weak relationship with measures of TFP. This fact is hardly surprising, since time-series indices of patent counts are mechanically affected by varying standards of novelty imposed by the US Patent and Trademark Office (USPTO) (Hall & Ziedonis 2001). Thus, using patent data for economic modeling requires weighting them appropriately. Currently, the most popular way of constructing these weights is based on forward citations—citations by future patents that build on the invention—often with some adjustment for patent cohort or technology class (Hall, Jaffe & Trajtenberg 2005). These adjustments are often necessary because there are differences in the propensity of patents to cite one another across fields, and also because of data truncation. However, such adjustments often prove insufficient to correct for biases in measurement (Lerner & Seru 2017).

3.2.2. Approaches based on relative prices. In the context of physical capital, one approach to measuring technological innovation relies on relative price indices. Consider the model with vintage capital described in Section 2.4. Examining Equation 27 more closely, we see that the IST shock χ_t affects the rate of transforming current output into installed capital. In particular, in the case of constant returns to scale in investment—that is, $\xi = 0$ in Equation 4—the relative price of investment, in consumption units, is equal to $1/\chi_t$.

The relative price of equipment exhibits a secular decline in the postwar sample. Motivated by this fact, Greenwood, Hercowitz & Krusell (1997) argue that capital-embodied technology shocks play an important role in long-run growth. Several empirical studies have argued that IST shocks account for a substantial part of business-cycle and medium-term fluctuations in economic growth (Greenwood, Hercowitz & Krusell 2000, Justiniano, Primiceri & Tambalotti 2009). Naturally, there are some very important caveats. Measuring investment-specific technical change using the relative price of equipment relies on some fairly strong assumptions. First, as discussed above, only in the case of constant returns to investment does the relative price of investment measure technical change.

Second, Equation 25 implies that the relative price series should be adjusted for quality improvements. If not, IST shocks inferred from the relative price series will understate the degree of investment-specific technical change. Given that many technological innovations in the capital goods sector manifest as quality improvements, this adjustment is particularly important. In the data, adjusting for quality improvements remains a challenge. The BEA adjusts for quality improvements by using hedonic regressions (Moulton 2001). The original series constructed by Gordon (1990) contains some adjustment for quality based on the price of used capital goods. But extensions to this series—for instance, by Cummins & Violante (2002)—rely on linearly extrapolating Gordon's adjustments. Though such adjustments may be somewhat successful in adjusting long-term trends—or average growth rates—it is rather doubtful that the resulting series accurately measures short- and medium-term fluctuations in χ_t. This point is forcefully made by Nordhaus (1997), who argues that official price and output data miss the really large (in his words, "tectonic") advances in technology. Along these lines, Bils & Klenow (2001) compare the rates of quality improvement in a sample of 66 durable goods, and find that the official BLS price estimates missed approximately 60% of the quality improvements.

Third, such measurement relies on the definition of capital. Currently, the BEA excludes many intangibles from its definition of capital and investment expenditures. Yet, as discussed in Section 3.1, intangible capital is as important for growth as physical capital. Naturally, constructing quality-adjusted price series for investments in intangible goods is at least as challenging as making quality adjustments for physical investment goods.

3.2.3. Exploiting asset prices. Another approach to measuring technological progress is to combine data on innovation outcomes with data on asset prices. Using asset prices allows for an estimate of the marginal value of a quantity measure of innovation (say, a patent). One of the earliest examples of this approach is presented by Pakes (1985), who examines the relation between patents and the stock market rate of return in a sample of 120 firms during the 1968–1975 period. His estimates imply that, on average, an unexpected arrival of one patent is associated with an increase in the firm's market value of \$810,000.

More recently, Kogan et al. (2017) performed a reverse exercise, using market values to infer appropriate weights for adjusting patenting output for differences in economic value. Their approach aims to identify the value of a given patent based on the change in the firm's stock market valuation around a narrow window following a successful patent application. Specifically, on the patent issue date, the market learns that the patent application has been successful. Absent any other news, the firm's stock market reaction ΔV on the day the patent j is granted would be given by

$$\Delta V_j = (1 - \pi_j)\,\xi_j, \qquad 34.$$

where π_j is the market's ex ante probability assessment that the patent application is successful and ξ_j is the dollar value of patent j. The firm stock returns around the patent issuance event can be written as $R_j = v_j + \varepsilon_j$, where v_j denotes the value of patent j—as a fraction of the firm's market capitalization—and ε_j denotes the component of the firm's stock return that is unrelated to the patent. Kogan et al. (2017) impose distributional assumptions on v_j and ε_j to recover an estimate of v_j, and construct ξ_j as

$$\xi_j = (1 - \bar{\pi})^{-1}\,\frac{1}{N_j} E[v_j | r_j]\; M_j. \qquad 35.$$

Here, M_j is the market capitalization of the firm that is issued patent j on the day prior to the announcement of the patent issuance; N_j is the number of patents issued to the same firm on the same day as patent j; and $\bar{\pi}$ is the unconditional probability of a successful patent application—approximately 56% in the 1991–2001 period. One can then accumulate estimated patent values at the firm level to construct a flow measure of technological innovation in year t:

$$A_{f,t} = \frac{\sum_{j \in P_{f,t}} \xi_j}{B_{ft}}, \qquad 36.$$

where $B_{f,t}$ is a measure of firm size—market capitalization or the book value of assets.

Kogan et al. (2017) show that differences in innovation outcomes are associated with substantial heterogeneity in subsequent firm growth and creative destruction. Here, we replicate and extend their results. We estimate

$$\log\left[\frac{1}{|h|}\sum_{\tau=1}^{h} \Pi_{f,t+\tau}\right] - \log \Pi_{f,t} = a_h A^{sm}_{f,t} + b_h A^{sm}_{I\setminus f,t} + c_h Z_{ft} + u_{ft+h}, \qquad 37.$$

where $A^k_{I\setminus f,t}$ is innovation by competing firms in the same industry—that is, the so-called leave-out mean of Equation 36 across other firms in the same Standard Industrial Classification code at the 3-digit level (SIC3) industry. We make two changes to the Kogan et al. (2017) specification. In particular, in our specification the dependent variable in Equation 37 equals the growth in the average level of profits over the next h years, rather than the profit level after h years. We make this change to emphasize permanent, as opposed to transitory, shocks to firm profitability. Furthermore, since firms may implement some productivity improvements prior to their patent being issued, we date patents according to the year when patent applications were filed. None of these modifications substantively affect our findings. The rest of the specification closely follows that of Kogan et al. (2017).

Figure 1 plots the response of firm profitability to innovation by the firm and its competitors, respectively. The results are consistent with the models described in Section 2. We see that future firm profitability is strongly related to the firm's own innovative output. The magnitudes are substantial; for instance, a one-standard-deviation increase in the firm's innovation is associated with an increase of approximately 8% in the average level of profits over the next decade. Similar to the findings of Kogan et al. (2017), the estimates of b suggest that innovation is associated with a substantial degree of creative destruction. In particular, a one-standard-deviation increase in innovation by the firm's competitors is associated with a decline of approximately 5% in the level of profits over the same period. Importantly, innovation is unrelated to past trends in profitability—that is, the estimated coefficients are economically insignificant for $h < 0$.

4. LIMITED RISK SHARING

We next consider asset pricing models in which part of the cash flows that are generated by intangible capital and innovation is not captured by firm owners. The asset pricing models described in this section build on the idea that human capital is inalienable—that is, the product of human capital cannot be fully pledged to outside investors (Hart & Moore 1994).

4.1. Valuation of Intangible Capital

Part of intangible capital is embodied in a firm's key employees. Eisfeldt & Papanikolaou (2012) propose a model in which the cash flows from intangible capital are shared between top talent

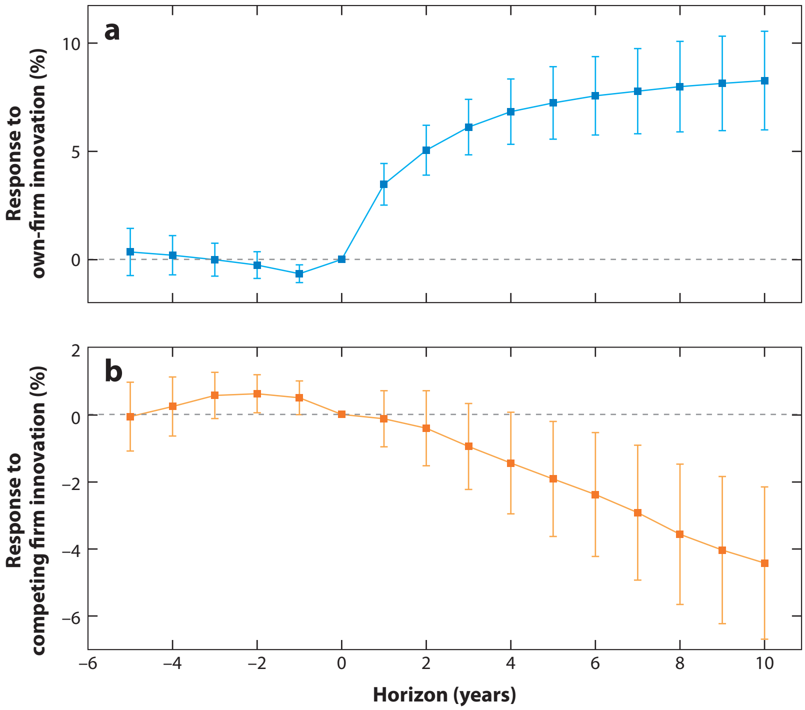

Figure 1

Response of firm profitability to innovation by the firm and its competitors. (*a*) Own-firm innovation. (*b*) Innovation by competing firms.

and firm owners. Eisfeldt & Papanikolaou (2012) term this form of intangible capital "organization capital"—though perhaps it more closely corresponds to human capital that is partly specific to the firm. Due to this firm specificity, shareholders may be able to capture some of the benefits generated by organization capital. However, since capital consists of a body of knowledge that is embodied in key talent, it is never fully owned by the firm. In contrast to physical capital, employees can threaten to leave the firm when their outside opportunities are better than their expected payoff from remaining in the firm. As the profitability of new ventures improves, the outside opportunities of key talent also improve, so the share of economic benefits that accrue to shareholders falls.

Here, we consider a simplified version of the model by Eisfeldt & Papanikolaou (2012). There exists a continuum of firms that produce a common output good using physical capital K and intangible capital X according to

$$y_{i,t} = Z_t K_i + Z_t e^{\varepsilon_i} X_i. \qquad 38.$$

Both capital stocks are subject to an aggregate, disembodied technology shock Z_t, which follows a geometric random walk. Here, ε_i denotes the productivity of the firm's stock of intangible capital X_i in the current firm.

A key part of this model is that the share of cash flows from intangible capital that accrues to firm owners, versus key employees, varies over time. Eisfeldt & Papanikolaou (2012) model these fluctuations as arising from shocks to the outside option of key employees, who can leave and start a new firm. Specifically, new technologies that improve the frontier efficiency of intangible capital emerge over time. Managers can choose to leave the firm, buy the physical capital from existing firm owners, and own and operate a firm with a level of efficiency $\varepsilon_i = \chi_t$. Key talent optimally chooses the time τ at which to exercise their option to upgrade to the frontier technology. For simplicity, we assume that χ_t follows a geometric random walk, the option to upgrade to the frontier technology is costless, and this option can be exercised only once. Given these assumptions, employees exercise the option to leave the firm once the frontier technology is sufficiently productive, $\chi_t \geq \bar{\chi}_i$.

The value of an existing firm equals the sum of the value of physical capital plus the value of intangible capital that accrues to shareholders:

$$V_{it}^S = V_{it}^K + V_{it}^X. \tag{39}$$

We next solve for these two pieces separately. The value of physical capital V^K equals the present value of the cash flows accruing from physical capital discounted at the risk-adjusted rate $\bar{r}$:

$$V_{it}^K = E_t \int_t^\infty \frac{\pi_s}{\pi_t} Z_s K_i \, \mathrm{d}s = \frac{Z_t}{\bar{r}} K_i. \tag{40}$$

Shareholders own the claim to the firm's physical capital K_i; thus, they can fully appropriate its rents. However, they can only partially capture the value of intangible capital:

$$V_{it}^X = \frac{Z_t}{\bar{r}} \left(e^{\varepsilon_i} + \frac{\sigma_\chi}{\sqrt{2\,\bar{r}}} e^{\bar{\chi} + \frac{\sqrt{2\,\bar{r}}}{\sigma_\chi}(\chi_t - \bar{\chi})} - e^{\chi_t} \right) X_i. \tag{41}$$

Examining Equation 41, we see that the value of the firm to shareholders is decreasing in the level of the frontier technology shock χ. The reason is that a shock to χ_t increases the outside option of key talent but does not increase the productivity of key employees if they remain with the current firm. As a result, the cash flows that accrue to shareholders fall with χ_t.

In sum, Eisfeldt & Papanikolaou (2012) propose a theory of valuation of intangible capital that is based on the assumption that the cash flows it generates are fuzzy—that is, they cannot be explicitly pledged to outside investors. The model implies that equity in firms that derive most of their value from intangible capital is riskier, since key employees can threaten to leave. Under certain assumptions, this difference in risk can imply that firms with a higher fraction of intangibles to physical capital X/K earn higher risk premia than do firms with lower levels of intangible share. In the data, Eisfeldt & Papanikolaou (2012) find that firms with a higher intangible capital share—proxied by accumulated SG&A expenditures—have higher risk-adjusted returns. This fact is consistent with a negative risk premium on the frontier technology shock.

4.2. General Equilibrium Implications

Technological innovation is a process that heavily relies on human capital. As result, the economic value that is generated by new ideas cannot be fully pledged to outside investors. This market incompleteness has general equilibrium implications, both for pricing of technological innovation and for the dynamics of income inequality.

Kogan, Papanikolaou & Stoffman (2018) explore these ideas in a general equilibrium model. The key feature of their model is incomplete markets: Each period, a small measure of agents—the inventors—are randomly endowed with a blueprint for a new project.[2] Since these blueprints are valuable, yet inventors cannot contract ex ante to share these rents with the rest of the economy,

[2]These inventors should be interpreted broadly. The term encapsulates all parties that share the rents from new investment opportunities besides the owners of the firm's publicly traded securities. For example, the

their model implies that firm owners reap only part of the benefits, yet all of the costs, of creative destruction.

Here, we present a simplified, two-period version of their model, following Kogan & Papanikolaou (2018). There are two vintages of technologies, old and new. Output is produced using labor as the sole input. There exists a large set of firms that collectively have access to both technologies, as we discuss below. In the first period, only the old technology is available. Firms produce output according to

$$Y^j_{o,t} = \left(X_t L^j_{o,t}\right)^{1-\alpha}, \quad t = 0, 1, \tag{42.}$$

where $\alpha \in (0, 1)$ and $L^j_{o,t}$ is the corresponding labor input. Labor markets are frictionless, and firms can hire any amount of labor they need, at the equilibrium wage W_t. Z_t is the economy-wide labor-augmenting productivity shock. We set $Z_0 = 1$.

The new technology is available only in the second period. However, only some firms have access to the new technology; others operate only the old technology in both periods. At time $t = 1$, identical new-technology projects arrive in the economy—as many as the old-technology projects. At $t = 1$, each new-technology project j produces output according to

$$Y^j_{n,1} = \chi_1^{\alpha} \left(X_1 L^j_{n,1}\right)^{1-\alpha}, \tag{43.}$$

where $\chi_1 \in (0, \bar{\chi})$ is a positive random variable realized at time $t = 1$. Here, χ_1 represents the vintage-specific technology shock, as in the model described in Section 2.4. A fraction $\omega \in (0, 1)$ of firms own new-technology projects, one project per firm. Thus, collectively these firms introduce a fraction ω of new-technology projects into the economy. For simplicity, we assume that this fraction is relatively small; that is,

$$\omega < \frac{1-\alpha}{1+\alpha\bar{\chi}}. \tag{44.}$$

Last, labor can be flexibly allocated between the old and new technologies.

The economy is populated by two types of agents, investors and workers, who live for two periods. There is a large number of investors with logarithmic preferences over consumption C_0 and C_1; they maximize

$$\ln C_0 + \mathrm{E}_0[\ln C_1]. \tag{45.}$$

Investors collectively own all the firms in existence at time $t = 0$. Workers in this economy inelastically supply a fixed amount of labor in each period. Each worker sells her labor services to the firms, and does not participate in financial markets. We normalize the aggregate supply of labor to one in each period.

The market for ideas is incomplete. In the second period, a very small number of randomly chosen agents—investors and workers—innovate and create new-technology projects. For simplicity, we assume that these innovators form an infinitesimal fraction of the total population (a zero-measure set). Thus, when an investor formulates her investment and consumption plans at time $t = 0$, she does not expect to innovate in the second period. This assumption simplifies the

term applies to highly skilled personnel who generate new inventions or business ideas, entrepreneurs and start-up employees who extract a large share of the surplus created by new ideas, angel investors and venture capitalists who help bring these ideas to market, and corporate executives who decide how to optimally finance and implement the new investment opportunities.

analysis and does not qualitatively affect the results. Collectively, inventors create a fraction $(1 - \omega)$ of all new-technology projects in the second period—that is, the projects that are not owned directly by the firms (and their shareholders). We assume that innovators monetize their projects by selling them at the fair market value to existing firms. These transactions do not affect firm value.

Given our assumptions, the equilibrium stochastic discount factor (SDF) is given by

$$\frac{\pi_1}{\pi_0} = \frac{C_0}{C_1} = X_1^{\alpha-1} \frac{(1+\chi_1)^{1-\alpha}}{1+\omega\chi_1}. \qquad 46.$$

Examining Equation 46, we see that, as long as the owners of the first-generation technology have only a limited claim on the new technology (our assumption in Equation 44 holds), the equilibrium SDF π_1/π_0 is increasing in χ_1. Thus, even though a positive shock to χ_1 increases output in the second period, investors in the first period wish to purchase insurance against high realizations of χ_1.

To understand this result, consider the perspective of investors at time zero. From their perspective, a key market is missing: They cannot trade with the future innovators to share the uncertain benefits of innovation. Because the probability that a given investor will be an innovator in the second period is essentially zero—given our assumption of a measure zero set of inventors—she will price assets disregarding that possibility. Her consumption in the second period thus equals

$$C_1 = \alpha X_1^{1-\alpha} \frac{1+\omega\,\chi_1}{(1+\chi_1)^{1-\alpha}}. \qquad 47.$$

The investor's consumption in the second period, Equation 47, reflects her wealth: She collects profits of all the old-technology projects, as well as a fraction ω of the new-technology projects—which she owns by virtue of owning all the firms in the economy at time $t = 0$. However, she does not capture the rents from the fraction $1 - \omega$ of the new-technology projects; these accrue to the lucky few agents who successfully innovate in the second period.

Similar to the models with vintage capital discussed in Section 2.4, this model has implications for the risk premia associated with claims to the old and new technologies. In the second period, the two technologies compete. In general, this competition may result in falling prices of output and rising costs of input. Here, because both technologies produce the same good, the price of output of the old technology at time $t = 1$ (in units of the consumption good) is fixed at one and is not affected by the entry of the new technology. However, the cost of inputs (the equilibrium wage) is affected by competition between the two technologies. If the new technology turns out to be highly productive (χ_1 is high), then the equilibrium wage rises and profits of the projects operating the old technology decline. That is, the equilibrium return to the old-technology projects,

$$R_1^o = X_1^{1-\alpha}(1+\chi_1)^{\alpha-1}\mathrm{E}_0\left[(1+\omega\chi_1)^{-1}\right] - 1, \qquad 48.$$

is decreasing in χ_1. By contrast, profits of the new-technology projects increase in the higher productivity shock χ_1, since any increase in equilibrium wages is more than offset by the higher productivity of the new technology:

$$R_1^n = X_1^{1-\alpha} \frac{\chi_1(1+\chi_1)^{\alpha-1}}{\mathrm{E}_0\left[\chi_1(1+\omega\chi_1)^{-1}\right]} - 1. \qquad 49.$$

Given the equilibrium SDF in Equation 46, claims to the new-technology projects have a lower expected return than the claim on the profits of the old-technology projects:

$$\mathrm{E}_0[R_1^n] < \mathrm{E}_0[R_1^o]. \qquad 50.$$

The model's asset pricing implications are a direct corollary of Equations 48–50. Firms in this model derive their value from their ownership of old- and new-technology projects. For simplicity, consider two types of firms in our model, which deliver identical cash flows in the first period but differ by whether they can access the new technology in the second period. We can think of the claim on the old technology as the firm's assets in place, while the claim on the time-one new technology represents firm's growth opportunities.

A firm that does not own any new-technology projects is a pure claim on the old technology. In our model, a fraction $(1-\omega)$ of all firms are of such type. Based on the above analysis, equilibrium return on this firm is given by (Equation 48):

$$R_1^v = R_1^0. \tag{51}$$

We refer to such firms as value firms, since their time-zero valuations are relatively low,

$$P_0^v = \alpha \, \mathrm{E}_0 \left[\frac{1}{1+\omega\,\chi_1} \right], \tag{52}$$

and as we show below, their expected rate of return is relatively high.

A firm that does own a claim on the new-technology projects—a growth firm—derives its value from both assets in place and growth opportunities. A fraction ω of all firms in our model are growth firms. Their time-zero value is relatively high:

$$P_0^g = \alpha \, \mathrm{E}_0 \left[\frac{1+\chi_1}{1+\omega\,\chi_1} \right]. \tag{53}$$

The return on growth firms is a weighted average of returns on the pure old- and new-technology claims:

$$R_1^g = \frac{P_0^v}{P_0^g} R_1^o + \left(1 - \frac{P_0^v}{P_0^g}\right) R_1^n. \tag{54}$$

Thus, according to Equation 50, expected returns on growth firms are lower than value firms.

In addition to the value premium, the model also generates the value factor (Fama & French 1993, 1995). To see this, we can linearize the model and obtain a two-factor arbitrage pricing theory (APT)-style representation:

$$\ln(1+R_1^o) = (1-\alpha)\ln X_1 + (\alpha-1)\ln(1+\chi_1) + \text{const.}, \tag{55}$$

$$\ln(1+R_1^n) = (1-\alpha)\ln X_1 + (\alpha-1)\ln(1+\chi_1) + \ln\chi_1 + \text{const.} \tag{56}$$

The two systematic return factors correspond to the two types of productivity shocks: labor augmenting (X_1) and vintage specific, or embodied (χ_1).

All firms in this model have the same loading (APT beta) on the labor-augmenting shock X_1. Growth firms have positive betas on the embodied shocks χ_1 through their ownership of claims on new-technology projects, while value firms have negative betas because of their exposure to displacement risk created by the new technology. The equilibrium return on the market portfolio is a weighted average of the returns on the two types of firms:

$$R_1^m = \frac{\omega P_0^g}{\omega P_0^g + (1-\omega)P_0^v} R_1^g + \frac{(1-\omega)P_0^v}{\omega P_0^g + (1-\omega)P_0^v} R_1^v. \tag{57}$$

Because any rotation of the two factors yields a valid APT model, we take the market return as the first factor. We can then form the second factor by using a self-financing long–short portfolio of growth and value firms. This portfolio has zero exposure to the labor-augmenting shock, and a positive beta on the embodied shock. It thus serves as a mimicking portfolio for the new technology shock.

5. CONCLUSION

We have discussed asset pricing implications of models with intangible capital and technological innovation. Our goal has been to highlight the economic differences between intangible and physical capital, and how technological innovation may propagate in more distinct ways than a TFP shock. In doing so, we have focused on the role that human capital plays in the generation of new ideas and the embodiment of intangibles.

Our review has not attempted to cover an important related area of research, which deals with implications of technological progress for economic inequality. Imperfect sharing of innovation risk, which we highlight in the context of asset pricing, is also essential to understanding how technological progress affects inequality patterns. This area of the literature is growing in scope and importance, and deserves a detailed discussion that is beyond the scope of this article.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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