Vintage Organization Capital

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Abstract

We argue that a firm's organization capital depends on the state of technology when the firm was born and on the technologies that have followed. We estimate vintage effects on the value of firms from 114 years of stock market data. We find

- a surprisingly strong upward trend in the stock-market share of the largest firms,
- a very large quantity of organization capital created by the 1920's vintage,
- strong indications that the 1970's and 1980's vintages will be followed by more complementary technologies, and
- major technological change since WW2 in the process by which organization capital is created.

1 Introduction

Most firms quoted on today's stock market were not around 100 years ago. Of those that do remain, many are household names; Con Edison (initial public offering occurred before 1885), General Electric (IPO in 1892), Westinghouse (1896), AT&T (1901) and US Steel (1901) are still with us, but most of the other members of their cohort are gone. Historically around five percent, the death rate of firms is now above ten percent. Figure 1 accounts for today's stock-market firms and their value by vintage. The early vintages do not account for much of today's value and (due to a survival of the fittest bias in the data) they account for an even smaller fraction of firms.

Now, why should *any* firm ever die, especially a large corporation? A firm's workforce, plant, and equipment do have to die or wear out, but why can't they always be replaced and the firm itself live on for ever? Presumably, a firm dies because it

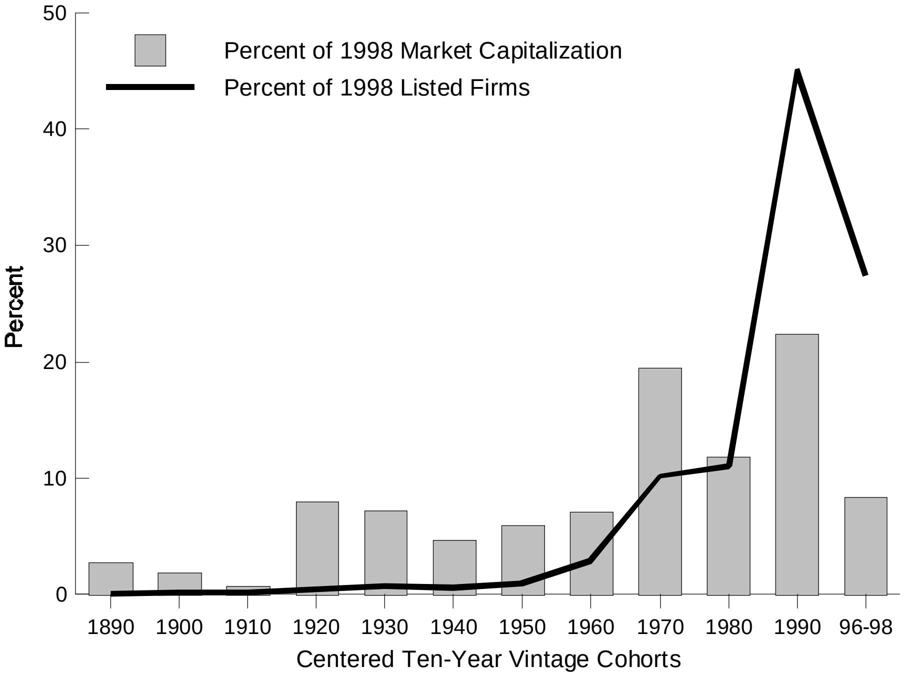

Figure 1: Vintage composition of U.S. national stock exchanges in 1998.

gets sick beyond repair.[1] The expertise that resides in that firm – its organization capital – may become obsolete. Moreover, as with other forms of capital, obsolescence depends on the pace of technological change, and on the capital's vintage.

"Organization capital," for our purposes, is whatever makes a collection of people and assets more productive together than apart. There are several reasons why this might be so. One is firm-specific human capital of workers (Becker 1962) and management (Prescott and Visscher 1980), another is firm-specific physical capital (Ramey and Shapiro 1996), and yet another is a cooperative disposition in the firm's workforce (Eeckhout 2000 and Rob and Zemsky 1997). For any of these reasons, workers, management, machines, and buildings may work better together than they would in other firms. Organization capital probably grows as the firm ages. We shall simply say that organization capital is the quality of the project that the firm undertakes at birth – the quality of the initial idea – and that this project is inseparable from the firm, roughly in the sense of Campbell (1998), Hopenhayn (1992), and Jovanovic (1982). The quality of the project does not change as the firm ages, but the market's valuation of that project may change over time.

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[1] Sometimes it exits through merger. In some periods more than half of the exits are mergers. The solid line would not be as steep if all firms that exited because of merger were still alive in 1998. The effect of mergers on the bar graph portion is less clear because the continuing entity usually keeps the name of the older merged partner.

We shall estimate that portion of organization capital that goes to the shareholder. A founder's idea for starting the firm becomes a part of the firm; the financiers (venture capitalist, bankers and shareholders) and employees then all modify the idea, and then they draw incomes from its use. After the firm's IPO, the residual income recipient is the shareholder, who receives that portion of the firm's net income that is not pledged to workers, management, lenders, and the government. What happens to the distribution of the rents is model-specific. For instance, Laffont and Martimort (1999) argue that as the firm ages, its employees and managers find it easier to collude against the shareholder. Our data allow us to value only the shareholder's portion of the firm's organization capital.

We define a firm's vintage as the date at which the firm had its IPO. Typically, a firm is founded well before that date, and incorporated before then as well, and so the idea upon which the firm is founded typically predates by several years its IPO date. On the other hand, a major motive for an IPO is to effect a large capital inflow and a large purchase of plant and equipment which will then be of the same vintage as the IPO data.[2]

If it is costly to adjust, a firm's organization capital will inevitably reflect conditions that prevailed at its IPO. The firm-founder's idea, and the plant and equipment acquired at the IPO stage will reflect state of the art technology, and the relative prices of inputs and raw materials that prevailed at the time. The firms organizational *form* (e.g., centralized and authoritarian vs. individual-incentives based) may also bear a vintage "imprint", as Carroll and Hannan (2000, ch. 9) stress in their study of Silicon Valley start-ups. It's clear that technology, factor supplies, relative prices, etc., all vary significantly over time, but it is less clear that their imprint on the firm should be "sticky" unless there are significant adjustment costs – costs of replacing workers and equipment, and costs to moving to new premises. Still, these costs must be large, because many a firm will disband, sell its assets off at a mere fraction of their internal use and impose on its members the costs of searching for new jobs, rather than face the costs of reorganizing internally.

Just like a Sotheby's auction will price a particular vintage of wine higher than another, so the stock market will reveal some good vintages and some not-so-good ones. Moreover, the relative ranking of vintages will depend on time. When capital cannot be resold, it induces technological inertia, and such inertia has been related to vintage physical capital by Solow (1960), to vintage human capital by David (1985), Chari and Hopenhayn (1991) and Parente (1994), and to organization capital by Carroll and Hannan (2000). Moreover, Reinganum (1983) has stressed that incumbents will be especially inert since they are the ones that have sunk the cost. A new tech-

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[2] For about 1000 IPO's in the 1980s and 1990s, Vissing-Jorgensen and Moskowitz (in progress) find that the percent of shares owned by a founder typically drops by about 1/3 at the IPO, from around 12% to 8%. This is mainly because the new shares issued at the IPO dilute the owners' share. Moreover, the capital drawn to the firm is probably even higher because the value of the firm's shares jumps at the time of the IPO.

nology therefore redistributes value from incumbents to new firms. And, of course, incumbents are, on our definition, of earlier vintage. Therefore, when it occurs, a redistribution from old to young firms is a sign that a new technology has arrived. Of course, technologies arrive more or less all the time, but some have mattered more than others. The railway, the telegraph and telephone, the processing techniques in metallurgy and polymer synthesis, and biomedical research are just a few of the innovations that have mattered a lot. But two are so fundamental as to be considered of "general purpose": Information technology, and electricity which came on in the 1890-1930 period when the nation switched from steam-powered to electric (and, to a lesser extent, diesel) equipment. This paper examines the nature of technological change and its impact on the U.S. economy from 1885 to the present as manifested in stock market fluctuations at the aggregate, vintage, and firm levels. Greenwood and Jovanovic (1999) and Hobijn and Jovanovic (1999) focused on the post-1970 period, but here we shall take a longer view.

Vintage effects are hard to find in wage data (Johnson 1980) and productivity data (Lee, 1977, Stephan 1991) because of the positive effect that experience has on performance. A new firm has a better technology but less experience, and the effects may cancel one another out. Vintage effects on lifetime performance should be easier to find in stock-prices, which are forward looking and therefore reflect discounted lifetime performance. They should also show up in mortality rates, especially during major technological transformations – such as the technological cycle in which the U.S. economy is currently engaged. In this case, the new technology was carried for a long time by young firms and only later started to infuse firms of earlier vintages.

To conduct a firm-level analysis of the stock market from 1885, we extend the data that is available from the University of Chicago's Center for Research in Securities Prices (CRSP) backward from its starting point in 1925. To do this, we collect annual observations for all common stocks traded on the New York Stock Exchange (NYSE) from the financial newspapers of the period. It is this unique firm-level information, which has until now been unavailable in an electronic format, that permits us to take a long view of technological change and draw its implications for the future path of the U.S. economy.

2 Technological Cycles and the Stock Market

A popular measure of stock-market performance, studied at length in, e.g., Barsky and De Long (1993), is the S&P 500 index which we present in Figure 2. The solid line is the S&P index since 1878, deflated by the CPI. The dashed line is the hindsight-endowed value of actual dividends paid and the 1996 value of the index.[3]

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[3] That is,

$$P_t^* = \sum_{s=t}^{1996} \beta^{s-t} D_s + \beta^{1996-t} P_{1996},$$

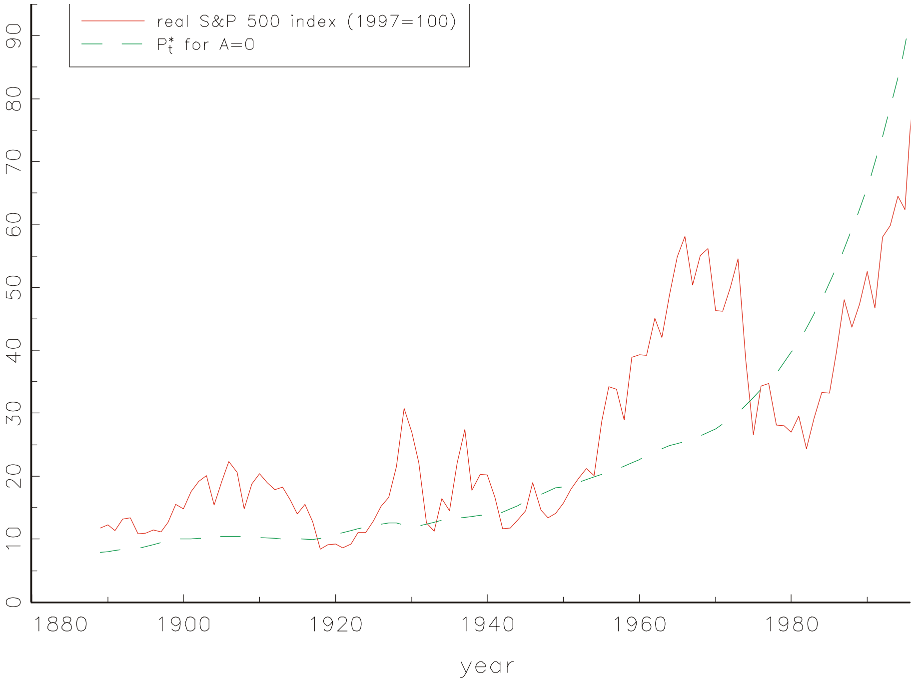

Figure 2: The S&P index and the "Perfect Foresight Price" P_t^*

The S&P 500 index comprises only the largest firms, and gives no information on the turnover of firms that it includes. Its eightfold rise over the period still understates the growing importance of the stock market as a source of capital. To make progress on the questions of vintage, survival, etc., we need individual company data. In particular, we shall study the evolution of listings, overall market value, and price performance of traded firms as each of the century's general technologies gained widespread use, focusing on subsets of the market as defined by firm size, vintage of entry, or incumbency at selected points in time.

2.1 Data on individual firms, 1885 - 1998

The challenge of collecting price and capitalization observations for individual NYSE-listed firms that traded between 1885 and 1925 has not been seriously taken up since the 1930s, when the Cowles Commission built price indices for common stocks from 1871. Since this was well before the age of electronic data storage, our use of firm-level data to illustrate the technological cycles behind the market's growth represent a step well beyond what has been possible in previous studies of New York's pre-

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where $\beta = 0.96$. Our choice of a 4% discount rate and assumption of no real-interest rate variation do not affect the substance of the conclusions.

CRSP equity market.[4] In particular, it allows us to track the value appreciations of individual firms and the vintages of entrants and incumbents to which they belong over a period of 114 years.

We return to the original source of the Cowles data, *The Commercial and Financial Chronicle*, to recover annual prices and par values for NYSE-listed firms from 1885-1924. *The Chronicle* is the most comprehensive source of price information for individual securities, but does not include book capitalizations for individual firms. For those, we turn to three other sources: *Bradstreet's* for 1885-1896, *The New York Times* for 1897-1911, and *The Annalist* for 1912-1924. These additional sources also make it possible to fill in many price observations that are missing from *The Chronicle*. To maintain the broadest possible coverage, we use the average of the high and low prices in December of each year from the annual summary of the course of securities prices published by *The Chronicle.*[5] By dividing the book value of the outstanding stock for each common issue by its par value and then multiplying by the December price, a view of the market valuations of various segments of the organized capital market can be constructed in a straightforward manner. The resulting dataset, though limited to annual data, actually includes more common stocks than the CRSP files in 1925, which is the point where we join data from the two sources.

The availability of items required to compute anuual measures of market capitalization for individual firms limits the scope of our analysis to NYSE-listed firms until 1962. The American Stock Exchange (AMEX) enters the CRSP database in 1962, and the system operated by the National Association of Securities Dealers (NASDAQ) follows in 1972. The discontinuous nature of firm listings in these years clearly turns up in Figure 3, which shows the number of firms in our sample per million of population and the ratio of their total market capitalization to GNP (with GNP estimates from Balke and Gordon (1986)). The discontinuities are unfortunate because the AMEX has formally existed since 1952 and had its origins in the New York Curb Association, which had become an important force in the New York securities market since its founding in 1908. Further, the over-the-counter market in less actively traded equities as well as competing curbstone and organized markets (such as the

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[4] More recent studies, however, have begun the process of building a more complete view of securities prices in other regional markets during this period. See, for example, Rousseau (1999, 2000) on Boston's equity market.

[5] If a December price is unavailable in a given year due to limited trading, we use the average of high and low prices from November, October or September if available. We use the last price observed in each year when we recover missing prices from our secondary sources (i.e., *The Annalist*, *The New York Times*, or *Bradstreet's)*. The CRSP market capitalization arrays also use the last prices observed in each year. The imprecise timing of the earlier observations in both the pre-CRSP and early years of the CRSP data combine with averaging in the pre-CRSP period to introduce the types of timing biases described in Working (1960) to annual indices of price performance. Since our econometric models use annual data sampled near the end of the calendar year to compute the total market value of stocks that entered the market over given periods, these biases will be less severe in our aggregates than they might be in a chained price index, and we will ignore them here.

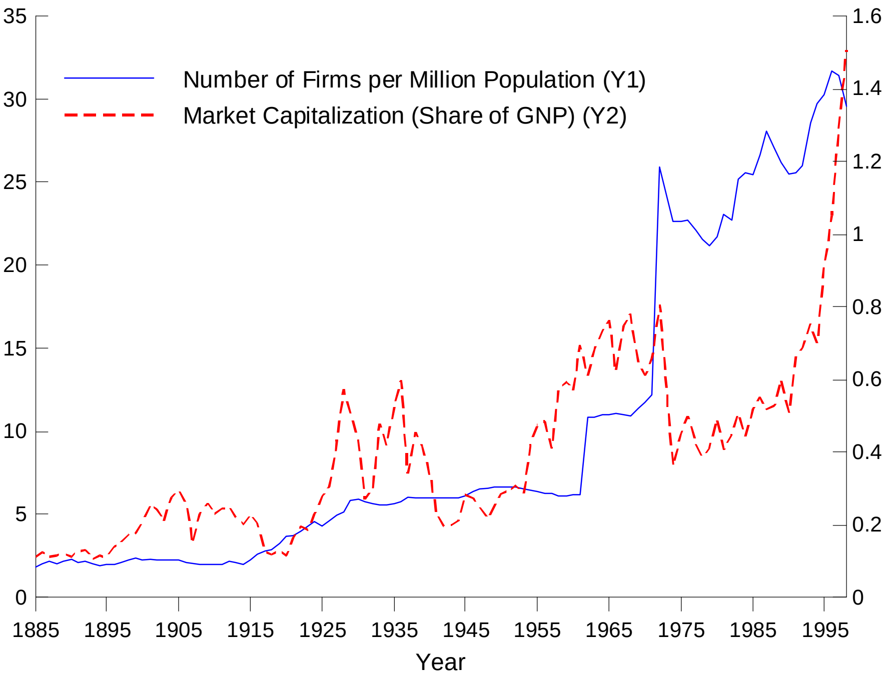

Figure 3: Number and market capitalization of common stocks listed on the NYSE 1885-1998, AMEX 1962-1998, and NASDAQ 1972-1998. Sources: The CRSP files, and various issues of *The Annalist*, *Bradstreet's*, *The Commercial and Financial Chronicle*, and *The New York Times*.

Consolidated Exchange) as a group rivaled and at times even dominated the NYSE as the key player in the New York securities market of the nineteenth century. Our focus on the NYSE before 1962 is necessary, however, because the outstanding amounts of stock for most firms traded in New York's informal securities markets are unknown, and we would need this information, along with any available prices and par values, to trace the path of individual market valuations.[6] Further, the discontinuities are far less prominent in the ratio of market capitalization to GNP, which suggests that the introduction of the AMEX and NASDAQ to the CRSP files involved mostly small firms.

The ratio of market capitalization to GNP dips after the electrical and information technologies "arrive." In the case of electrification, it is reasonable to associate the arrival with the completion of the first large hydroelectric development in the United

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[6] The Cowles Commission (1939, p. 6) recognized the difficulties of even constructing price indices for this early period due to the incomplete and unreliable nature of price quotations that were available in the financial press for the Curb Exchange, and choose to focus on the construction of price indices for NYSE-listed common stocks only. The same source notes that trades in NYSE-listed stocks were about sixty-seven percent of all stock trades in the United States over the 1929-33 period, with more than half of the remaining activity taking place on the Curb Exchange.

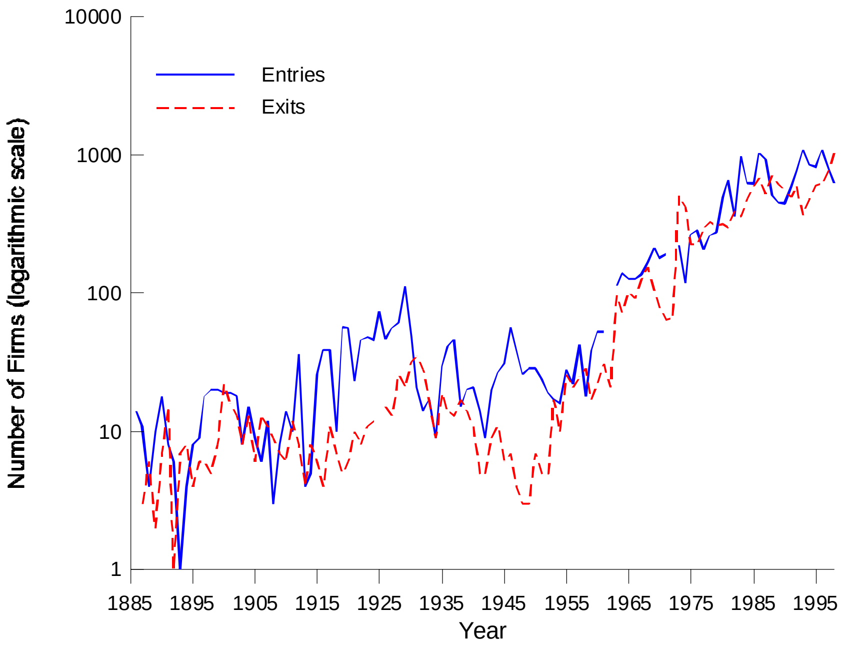

Figure 4: Annual entries and exits from the NYSE 1885-1998, AMEX 1962-1998, and Nasdaq 1972-1998. See Fig. 3 for data sources.

States at Niagara Falls in 1895, which at that time served the energy needs of heavy industry (Devine, 1990). This event was pivotal because it revealed the potential of electricity in industrial applications and established alternating current as the dominant delivery system. Both affected public expectations about the future of the new "general purpose technology" (GPT). Interestingly, market capitalization rises between 1895 and 1902, perhaps as a result of optimism surrounding electrification, but then does not advance for nearly two more decades. The number of listed firms is flat throughout the early years of electrical revolution, but rises sharply after 1915. Nelson (1959) attributes the flatter appearance of total NYSE listings in the decade surrounding the turn of the century to the offsetting effects of new industrial entries and the exit of many industrials and rails via merger. The rise in the number of firms that is not reflected in market capitalization may reflect the entry of new firms that adopted the new GPT with relative ease and later encouraged larger firms to undergo the considerable fixed costs associated with updating their capital.[7]

The aggregative nature of Figure 3 masks a pattern of substantive and continuous entry and exit in our sample. Figure 4 shows this activity on a logarithmic scale.[8]

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[7] The Cowles (1939) sectoral price indices indicate that firms on the rapidly-expanding industrial list outperformed both the rail/transport and utilities sectors by a wide margin after 1915.

[8] The addition of the AMEX and NASDAQ to the samples contribute to totals of 910 entries in 1962 and 2,957 entries in 1972, both of which have been omitted from Figure 3. We also exclude

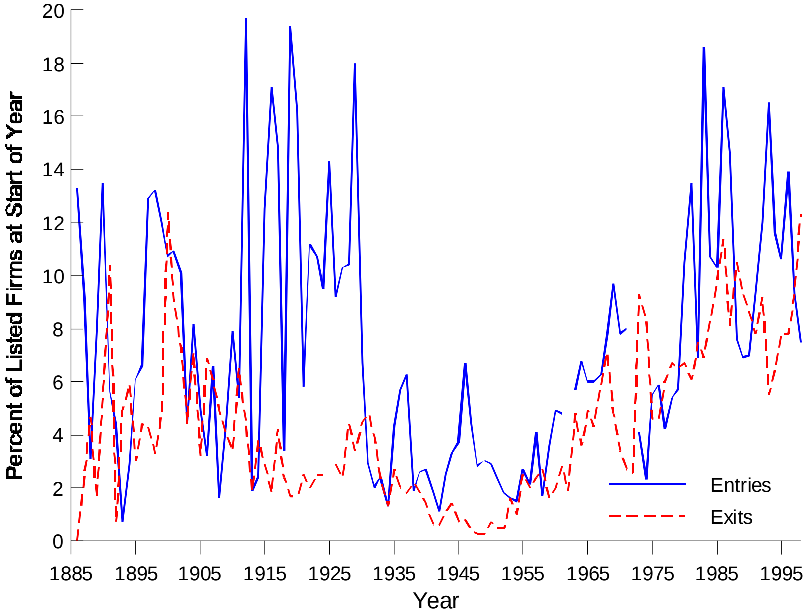

Figure 5: Annual firm entries and exits as a percent of listed firms. See Fig. 3 for data sources.

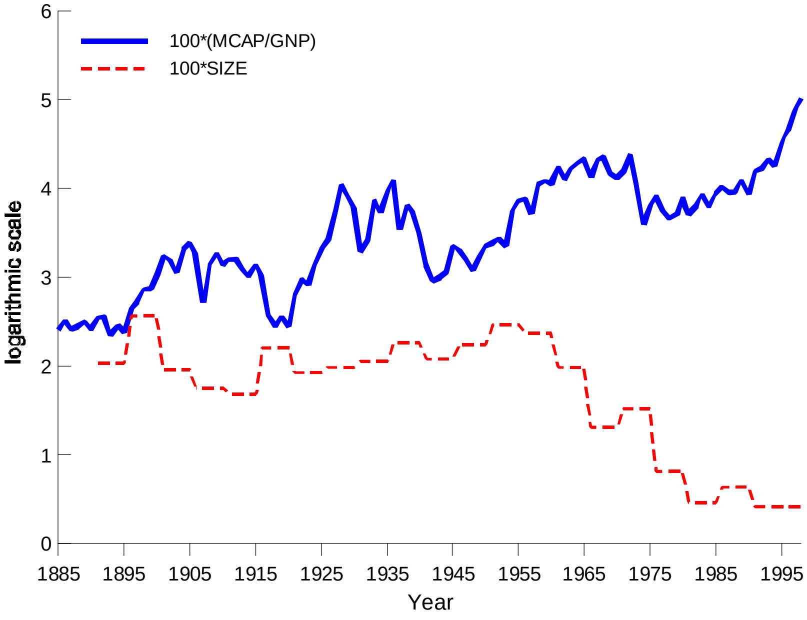

Figure 6: The ratio of market capitalization to gross national product 1885-1998, and the average size of the smallest one-third of entrants with respect to the average listed firm for five-year vintages, 1886-90 to 1990-95. See Fig. 3 for data sources.

The most marked shifts in entry growth occur in the two decades before the 1929 crash and after 1954, and neither shift can be attributed to the inclusion of the AMEX or NASDAQ in our sample. Figure 5, which depicts entries and exits as percentages of firms listed in each year, indicates that entries were proportionally largest between 1915 and 1929, and that these levels were not again approached until the mid-1980s. Both expansions coincide with periods during which electricity and IT saw widespread adoption. The exits that occurred immediately before these events were frequent enough to arrest growth in the number of listed firms. The data are thus consistent with a cycle in which organization capital of older vintages leaves the market in the early years of a new technology and is replaced with a considerable lag by capital of a new vintage.

Figure 6 offers further support for a gradual lowering of entry barriers to the equity markets, and especially in the early phases of a new technology's life cycle. Here, we compute the average size of the smallest one-third of entrants in each year, divide by the average size of all listed firms, and then average these ratios over five-year periods. The resulting step function indicates a remarkable decline in entry size after 1945, and the inflection point corresponds to the change in entry growth seen in Figure 4. Again, the timing of the shift is not related to changes in the inclusiveness of our sample, and has a strikingly close inverse relationship with the general deepening of the postwar equity market. Also noteworthy is a decline in the size of entrants between 1900 and 1915, which is when smaller industrial firms began to enter the stock market, albeit not very successfully at first. Nevertheless, equity market participants viewed the potential of these new industrial firms with optimism and provided them an environment in which subsequent growth would be possible.

3 Model

We now present a Robinson Crusoe model which, as in Lucas (1978), has an interpretation for a decentralized, multi-agent economy. Crusoe plants trees which combine with physical capital to produce fruit. A tree bears fruit each year that it lives. The aggregate value of a vintage of trees is simply the value of all the trees planted at that date.

The exogenous growth model has one variable factor – physical capital – which can be moved costlessly from tree to tree, and in which the only technological shock is to the organization capital of the latest vintage, and we shall assume that foresight about all future realizations of these shocks is perfect. One part of the quality of the trees will be determined exogenously by the then-frontier technology, and this part we shall associate with the usual "capital-embodied" shock to technology. Another

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the 79 apparent "exits" recorded in 1925, which reflect the narrower coverage of the CRSP data at the point of joining with our earlier dataset.

part of the quality of the trees will be subject to choice, and this part we shall call "organization capital."

It turns out that variation in the relative fortunes of various vintages of firms is substantial in the data, and that the model must include a form of obsolescence stronger than a one-sector model can produce. In a one sector model, variation in how a stream of dividends is valued stems entirely from movements in the marginal utility of consumption. Such movements are too small to generate the sorts of price movements that we observe, and so we are going to need a multi-sector model. To build intuition, however, we shall present the one-sector model first. Once this is done, the multi-sector version will be easy.

3.0.1 Case 1: One final good

The final good is denoted by y_t, and Crusoe's consumption of it by c_t. Crusoe maximizes his lifetime utility

$$\sum_{t=0}^{\infty} \beta^t U(c_t).$$

A tree's output of fruit depends on its quality, θ, and on its capital input, k, as follows:

$$y = \theta^{1-\alpha} k^{\alpha}. \tag{1}$$

A tree's quality has a vintage-specific component z and an idiosyncratic component ε, distributed with density $f(\varepsilon)$:

$$\theta = z_v \varepsilon.$$

The density f is fixed over time. Once planted, a tree's quality does not change. Crusoe generally plants new trees each year because, since $\alpha < 1$, returns to capital at a location diminish. Trees take a period to mature, but then randomly at a rate δ, so that at date t, only a fraction $(1-\delta)^{t-1-v}$ have survived. Thus projects' exit hazard is, for now, exogenous. [9]

Physical capital evolves as follows:

$$k_{t+1} = (1-\delta_k) k_t + q_t x_t,$$

and aggregate output, Y_t, is divided between consumption, investment in physical capital, and investment in organization capital:

$$Y_t = c_t + x_t + \phi_t n(s_t),$$

where ϕ_t is the fixed cost of starting up a project and

$$n(s) = \int_s^{\infty} f(\varepsilon) d\varepsilon$$

is the number of new projects we have in the event that s is the quality of the worst project funded.

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[9] If we added a fixed cost to the production function (1) this would cause Crusoe to abandon some trees.

Interpretation This is an exogenous growth model with three sources of technological change:

1. *In structures*: z_t is a technology parameter embodied in trees grown at date t. A tree is like a factory built at date t using state-of-the-art technology. "Trees" here are like "structures" in Gort *et al* (1999), or "plants" in Atkeson and Kehoe (1999) or Cooley *et al* (1998). We expect z_t to increase over time.
2. *In equipment*: q_t is a technology parameter for the equipment produced at date t, and it, too should increase over time. Equipment is not project-specific. We have followed Gort *et al* (1999) in modeling the two vintage shocks to equipment and structures.
3. *In organization capital*: ϕ_t is the cost of creating this capital. We shall let
$$h(s) = \int_s^\infty \varepsilon f(\varepsilon)\, d\varepsilon$$
be the organizational capital created when the marginal project is s. The project-specific parameter ε is like the firm-specific parameter in Campbell (1998), Hopenhayn (1992), and Jovanovic (1982).[10] A fall in ϕ_t may reflect better communications, or a lower physical-capital requirement of new start-ups.

Each type of technological change can generate long run growth on its own, as we show in the appendix where we study balanced growth.

Crusoe's decision problem Each period, Crusoe spreads his capital among trees of all vintages so as to maximize total output

$$Y_t = \max_{k_v(\varepsilon)} \left\{ \sum_{v=-\infty}^{t-1} (1-\delta)^{t-1-v} \int_{s_v}^\infty (z_v \varepsilon)^{1-\alpha} \left[k_v(\varepsilon)\right]^\alpha f(\varepsilon)\, d\varepsilon \right\},$$

subject to his capital availability at that date:

$$\sum_{v=-\infty}^{t-1} (1-\delta)^{t-1-v} \int_{s_v}^\infty k_v(\varepsilon) f(\varepsilon)\, d\varepsilon \leq k_t.$$

The following "aggregation" result follows immediately after one takes the FOC with respect to $k()$:

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[10] It seems that ϕ_t has fallen since WW2, which could be why the debt-equity ratio of American firms has fallen since the war, (Figure 2 of Hall (1999) shows that as a fraction of all securities, debt falls from 18% in 1948 to about 5% in 1998) why the number of firms on the stock exchange has risen rapidly (our Figure 3) and why the entering size of firm (the dashed line in Figure 6) has fallen.

Claim 1

$$Y = A_t^{1-\alpha} k_t^{\alpha},$$

where

$$A_t = \sum_{v=-\infty}^{t-1} (1-\delta)^{t-1-v} z_v h(s_v) \tag{2}$$

Then

$$\begin{aligned} c_t &= A_t^{1-\alpha} k_t^{\alpha} - x_t - \phi_t n(s_t) \\ &= A_t^{1-\alpha} k_t^{\alpha} - \frac{(k_{t+1} - (1-\delta_k) k_t)}{q_t} - \phi_t n(s_t), \end{aligned}$$

and, from (2), the law of motion for A_t is

$$A_{t+1} = (1-\delta) A_t + z_t h(s_t) \tag{3}$$

which we can express as

$$s = \xi(z, A, A'),$$

so that $\frac{\partial \xi}{\partial A'} = -\frac{1}{zsf(s)}$ and $\frac{\partial \xi}{\partial A} = (1-\delta)\frac{1}{zsf(s)}$. The Bellman equation pertaining to Crusoe's decision problem is

$$V_t(k, A) = \max_{k', A'} \left\{ U\left(A^{1-\alpha} k^{\alpha} - \frac{k' - (1-\delta_k) k}{q_t} - \phi_t [1 - F\{[\xi(z_t, A, A')]\}] \right) + \beta V_{t+1}(k', A') \right\}.$$

This problem is now unconstrained. Its two first-order conditions are

$$-\frac{1}{q_t} U'(c_t) + \beta \frac{\partial V_{t+1}}{\partial k_{t+1}} = 0,$$

and,

$$-\frac{\phi_t}{z_t s_t} U'(c_t) + \beta \frac{\partial V_{t+1}}{\partial A_{t+1}} = 0.$$

The envelope theorem gives us

$$\frac{\partial V_t}{\partial k} = \left(\alpha A_t^{1-\alpha} k_t^{\alpha-1} + \frac{(1-\delta_k)}{q_t} \right) U'(c_t)$$

and

$$\frac{\partial V_t}{\partial A} = \left((1-\alpha) A_t^{-\alpha} k_t^{\alpha} + \frac{\phi_t}{z_t s_t} \right) U'(c_t).$$

Updating these two expressions to $t+1$ and substituting into the previous two gives us the two first order conditions purged of the unknown function V:

$$\frac{1}{q_t} U'(c_t) = \beta \left(\alpha \left(\frac{k_{t+1}}{A_{t+1}} \right)^{\alpha-1} + \frac{1-\delta_k}{q_{t+1}} \right) U'(c_{t+1}), \tag{4}$$

and

$$-\frac{\phi_t}{z_t s_t} U'(c_t) + \beta \left((1-\alpha) \left(\frac{k_{t+1}}{A_{t+1}} \right)^{\alpha} + \frac{(1-\delta)\phi_{t+1}}{z_{t+1} s_{t+1}} \right) U'(c_{t+1}) = 0 \tag{5}$$

Decentralizing the allocation Defining the rate of interest r_t by $\frac{1}{1+r_t} = \frac{\beta U'(c_{t+1})}{U'(c_t)}$, we combine the two conditions into one:

$$1 + r_t = q_t \left(\alpha \left(\frac{k_{t+1}}{A_{t+1}} \right)^{\alpha-1}_{t+1} + \frac{(1-\delta_k)}{q_{t+1}} \right) = \frac{z_t s_t}{\phi_t} \left((1-\alpha) \left(\frac{k_{t+1}}{A_{t+1}} \right)^{\alpha} + \frac{(1-\delta)\,\phi_{t+1}}{z_{t+1} s_{t+1}} \right)$$

This is an arbitrage condition for three different forms of saving:

1. Earn $1 + r_t$ dollars per dollar saved in the bank
2. Convert the dollar into q_t machines, use them to produce $q_t \alpha \left(\frac{k_{t+1}}{A_{t+1}} \right)^{\alpha-1}_{t+1}$ units of tomorrow's output, liquidate the undepreciated machines and collect $1/q_{t+1}$ dollars per liquidated machine
3. Convert the dollar into $1/\phi_t$ trees of quality $z_t s_t$ each, get their dividends tomorrow and then sell them. Trees are the "residual income recipients" and their share of output is $(1-\alpha)$. The quantity $(1-\alpha) \left(\frac{k_{t+1}}{A_{t+1}} \right)^{\alpha}$ is the rise in the trees' share of total output. The quantity $\frac{(1-\delta)\phi_{t+1}}{z_{t+1} s_{t+1}}$ is the resources that Crusoe can save tomorrow by having the additional trees survive from the previous period.

Under this interpretation capital will "rent" at the rate $r + \delta_k$, which is in fact Crusoe's shadow price for using it during the period. Valuing the capital input at this price, the net revenue from a tree is

$$\begin{aligned} \pi(\theta, r) &= \max_k \left\{ \theta^{1-\alpha} k^{\alpha} - (r + \delta_k)\, k \right\} \\ &= (1-\alpha)\, y(\theta, r) \end{aligned}$$

where $y(\theta, r)$ is the tree's output:

$$y(\theta, r) = \theta \left(\frac{\alpha}{r + \delta_k} \right)^{\alpha/(1-\alpha)}$$

for as long as the tree is alive. Multiplying by the probability of survival, the expected present value of the remaining profits of a tree that is still alive at date t is

$$(1-\alpha) \sum_{j=1}^{\infty} \beta^j (1-\delta)^j \frac{U'(c_{t+j})}{U'(c_t)} y(\theta, r)$$

Crusoe is fully diversified with respect to idiosyncratic risks, and he can perfectly forecast the (c_t, r_t) sequence. This will also be the price of the individual asset. The value of all vintage v trees, however, depreciates as time passes by, and so its value at date t is

$$\begin{aligned} P_{t,v} &= (1-\alpha) \sum_{j=1}^{\infty} \beta^j (1-\delta)^{t+j} \frac{U'(c_{t+j})}{U'(c_t)} \int_{s_v}^{\infty} y(z_v \varepsilon, r_{t+j})\, f(\varepsilon)\, d\varepsilon \\ &= (1-\alpha)(1-\delta)^t z_v \int_{s_v}^{\infty} \varepsilon f(\varepsilon)\, d\varepsilon \sum_{j=1}^{\infty} \beta^j (1-\delta)^j \frac{U'(c_{t+j})}{U'(c_t)} \left(\frac{\alpha}{r_t + \delta_k} \right)^{\alpha/(1-\alpha)} \end{aligned}$$

Inspecting this formula, it's clear that aside from the depreciation term $(1-\delta)^t$, the only reason why $P_{t,v}$ will depend on time is the fluctuations in interest rates. That is, the only type of obsolescence that this model can produce is through movements in the interest rate. Moreover, the relative value of any pair of vintages v and $v'$is a constant

$$\frac{P_{t,v}}{P_{t,v'}} = (1-\delta)^{v-v'} \frac{z_v}{z_{v'}} \frac{h(s_v)}{h(s_{v'})},$$

independent of time. However, consider, e.g., Figure 19. It plots values not of vintages, but cumulative vintages, but, nevertheless, we see that the 1930 incumbents did much better than the 1910 incumbents. To get such outcomes, we must broaden the model.

Capitalization-GDP ratio M_t/Y_t. Let $M_t = \sum_{v<t} P_{t,v}$ be total capitalization. Since exactly $(1-\alpha)$ fraction of output goes on dividends, if all trees were traded on the stock market, we would have (taking an approximation of a constant rate of interest r so that if $R = 1/(1+r)$, $\frac{U'(c_{t+j})}{U'(c_t)} = \left(\frac{R}{\beta}\right)^j$) the upper bound on Market capitalization

$$\frac{M_t}{Y_t} \leq (1-\alpha) \sum_{j=1}^{\infty} \beta^j (1-\delta)^j \frac{U'(c_{t+j})}{U'(c_t)} \approx \frac{1-\alpha}{1-R(1-\delta)}.$$

In fact, Figure 3 shows that this ratio has risen by a factor of about 10, reflecting the influx of capital into the stock market.

3.0.2 Case 2: Fruits as distinct intermediate goods

We now assume that each vintage of trees bears a different type of fruit which combines with other types of fruit to produce a single final good – say fruit juice. We shall assume that fruit juice is homogeneous, and that it is made using production function

$$Y_t = G(y_{t,t-1}, y_{t,t-2}, ..., y_{t,v}, ...),$$

where $y_{t,v}$ is the date-t fruit produced by vintage-v trees. Assuming that G has constant returns to scale and that the final goods sector is competitive, the date-t price of fruit of vintage v is

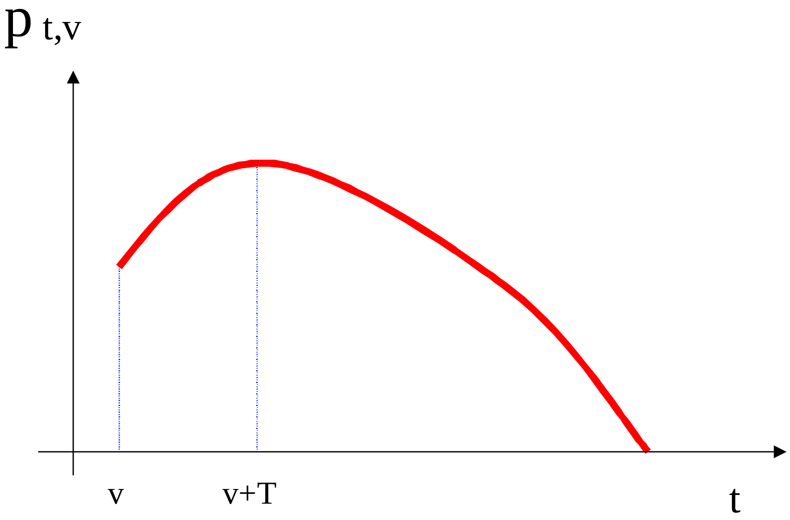
$$p_{t,v} \equiv \frac{\partial G^t}{\partial y_v} = G_{t-v}\left(\frac{y_{t,t-1}}{y_{t,v}}, \frac{y_{t,t-2}}{y_{t,v}}, ..., 1, ...\right), \tag{6}$$

where G_{t-v} is the derivative of G with respect to its $t-v$'th argument, and where we have used homogeneity of degree zero of the derivatives of G.

The stock market does not include all the capital of a given vintage, and so we cannot solve for these prices in terms of the technology shocks without further assumptions (not made here) about the fraction of capital in each vintage that is traded on the stock market. In what follows, we shall simply treat these prices as given, and we should remember that they depend on how technology evolves.

Likely time paths for $p_{t,v}$ If vintage v is a good one, it is likely to be followed by innovations that are complementary to it in production. In that case its rental $p_{t,v}$ will rise as a function of t. Later on, after T periods, say, it may be superseded by a better, complementary technology which, as it is followed by complementary innovations, may effectively replace fruit of vintage v entirely by reducing its price to zero. We show such a time path in the diagram below, which will motivate the functional form of our regressions. This is because the properties of $p_{t,v}$ carry over, to some extent to $P_{t,v}$ which is the discounted partial sum of the area under the curve in the diagram. [11] Since Crusoe has perfect foresight about the aggregate shocks, there are some limits on the upward movements on $P_{t,v}$. Since dividends are nonnegative, $P_{t,v}$ cannot rise faster than at the rate of interest, but there is no limit to how fast $P_{t,v}$ can decline, which would happen if $p_{t,v}$ were to become zero beyond some date.

This is more or less what happens in Helpman and Trajtenberg (1999), at regular intervals T, and we can get it here by a suitable choice of G in (6), in which complementary technologies appear in adjacent periods T in number, but in which each group of T is a substitute with other groups of T technologies.



Time path of the marginal product of vintage-v fruit

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[11] But $P_{t,v}$ can also rise for reasons that our model omits – e.g., a rising productivity of trees as a function of their age and unexpected changes in dicvidends.

Tree prices Capital rentals are measured in units of the final good. Now, a tree of quality θ and vintage v delivers date-t dividends

$$\begin{aligned}\pi^t(\theta, r) &= \max_k \left\{p_{t,v}\theta^{1-\alpha}k^\alpha - (r_t + \delta_k)k\right\} \\ &= \theta p_{t,v}^{1/(1-\alpha)}(1-\alpha)\left(\frac{\alpha}{r_t+\delta_k}\right)^{\alpha/(1-\alpha)}\end{aligned}$$

That is, it is as if the quality of the tree at date t is $\theta p_{t,v}^{1/(1-\alpha)}$. The quality now depends on time through the relative price of the fruit. This price variation depends, in turn, on what sorts of new vintages – substitutes or complements – of fruit are born. The expected present value of the profits is.

$$\sum_{j=1}^{\infty}\beta^j(1-\delta)^j\frac{U'(c_{t+j})}{U'(c_t)}\theta p_{t+j,v}^{1/(1-\alpha)}(1-\alpha)\left(\frac{\alpha}{r_t+\delta_k}\right)^{\alpha/(1-\alpha)}.$$

The total value of vintage v is

$$\begin{aligned}P_{t,v} &= \sum_{j=1}^{\infty}\beta^j(1-\delta)^{t+j}\frac{U'(c_{t+j})}{U'(c_t)}\int_{s_v}^{\infty}\pi\left(z_v\varepsilon p_{t+j,v}^{1/(1-\alpha)}, r_{t+j}\right)f(\varepsilon)\,d\varepsilon \qquad (7) \\ &= (1-\alpha)z_v\int_{s_v}^{\infty}\varepsilon f(\varepsilon)\,d\varepsilon\,(1-\delta)^{t-v}\sum_{j=1}^{\infty}\beta^j\frac{U'(c_{t+j})}{U'(c_t)}p_{t+j,v}^{1/(1-\alpha)}\left(\frac{\alpha}{r_t+\delta_k}\right)^{\alpha/(1-\alpha)}\end{aligned}$$

so that now the normalized variable is

$$w_{t,v} = (1-\delta)^{t-v}\frac{\sum_{j=1}^{\infty}\beta^j\frac{U'(c_{t+j})}{U'(c_t)}p_{t+j,v}^{1/(1-\alpha)}\left(\frac{\alpha}{r_{t+j}+\delta_k}\right)^{\alpha/(1-\alpha)}}{\sum_{j=1}^{\infty}\beta^j\frac{U'(c_{t+j})}{U'(c_t)}p_{v+j,v}^{1/(1-\alpha)}\left(\frac{\alpha}{r_{v+j}+\delta_k}\right)^{\alpha/(1-\alpha)}}. \qquad (8)$$

The size of the marginal entrant, $\bar{S}_v$ We can measure the size of the firm at entry in terms of the value at IPO. The smallest entering firm is of quality $z_v s_v$, and which should have an IPO value of.

$$S_v = z_v s_v\sum_{j=1}^{\infty}\beta^j(1-\delta)^j\frac{U'(c_{t+j})}{U'(c_t)}p_{t+j,v}^{1/(1-\alpha)}(1-\alpha)\left(\frac{\alpha}{r_t+\delta_k}\right)^{\alpha/(1-\alpha)}.$$

A natural estimate for this variable is the smallest recorded IPO at date v but estimating it this way is plagued by possible measurement error and other influences that our model excludes which are often the most present among the very observations that are recorded as being in the tails. So, we shall estimate it instead by the mean of the bottom third of the entering distribution. We choose one-third because our sample does not have that many firms in the early years. We shall denote our estimate by $\bar{S}_v$. We shall use it in our regressions.

3.0.3 Formulating the vintage regressions

Our vintage regressions will be based on (7) and on (8). First we shall evaluate (7) at the trend consumption and mean interest rate.

Constant r approximations Suppose the interest rate is constant, and write $R = 1/(1+r)$. Then Crusoe's optimal savings decisions[12] implies that

$$\frac{U'(c_{t+j})}{U'(c_t)} = \left(\frac{R}{\beta}\right)^j,$$

and, so, letting

$$\mu = (1-\alpha)\left(\frac{\alpha}{r_t+\delta_k}\right)^{\alpha/(1-\alpha)}, \quad \text{and} \quad Z_v = z_v \int_{s_v}^{\infty} \varepsilon f(\varepsilon)\, d\varepsilon,$$

the formulas become

$$P_{t,v} = \mu Z_v (1-\delta)^{t-v} \sum_{j=1}^{\infty} R^j p_{t+j,v}^{1/(1-\alpha)} \tag{9}$$

and

$$w_{t,v} = (1-\delta)^{t-v} \frac{\sum_{j=1}^{\infty} R^j p_{t+j,v}^{1/(1-\alpha)}}{\sum_{j=1}^{\infty} R^j p_{v+j,v}^{1/(1-\alpha)}}. \tag{10}$$

The first equation has an additive vintage-specific parameter Z_v, the second does not. Our regressions assume that we can approximate the remaining terms involving t and v by a quadratic in the variable $t-v$. Taking logarithms in (9) and (10) equation of the form:

$$\ln P_{t,v} \approx \beta_{0,v} + \beta_{1,v}(t-v) + \beta_{2,v}(t-v)^2 + \beta_3 \ln \bar{S}_v + \beta_4 \ln \frac{M_t}{Y_t},$$

and

$$\ln w_{t,v} \approx \gamma_0 + \gamma_{1,v}(t-v) + \gamma_{2,v}(t-v)^2 + \gamma_3 \ln \bar{S}_v + \gamma_4 \ln \frac{M_t}{Y_t}.$$

The vintage-specific variable $\bar{S}_v$ is supposed to track s_v. The variable $\frac{M_t}{Y_t}$ is supposed to proxy for the tendency for capitalization to be in stocks rather than in bonds.

Note that for $\beta_{1,v}$ or a $\gamma_{1,v}$ to be positive would mean that a vintage temporarily gains value in this model. Thus, $p_{t,v}$ must, for a while, be rising faster than the growth-augmented rate of discount. On this interpretation, great vintages are those that were then followed by waves of "adaptation" type vintages that were complementary and that therefore raised the value of the fruit of that vintage.

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[12] which solve the problem max $\sum \beta^t U(c_t)$ s.t. $\sum R^t c_t \leq$ Initial Wealth.

4 Small vs. Large Incumbents

4.1 Entry barriers to stock listing and the pace of technological adoption

Early on, the IT revolution was led by small firms, many of which have since grown into large ones. Was this also true of electrification? In asking this, we should remember that one hundred years ago, the financial playing field favored the large, established firm much more than it does today. The rise of smaller firms later on may have been due partly to changes in the law (such as the Sherman antitrust act of 1890 and the transparency forced on the market by the Securities Act of 1933) but it probably stemmed more from growth in the expertise with which business is financed.

In our model, the state of the technology of financing is summarized by the parameter ϕ_t which should be declining through time. The capital market was not nearly as deep even in the 1920's as it is today – some 50 percent of Americans own stock today, whereas only three or four percent owned stocks in the 1920's, and even less in the 1890's. Moreover, Wall Street's financial expertise was concentrated in a few large banks. The market was thus less well prepared to float shares of smaller firms, and the big bankers of the era as a rule shied away from new issues by unknown companies.

Navin and Sears (1955), for example, discuss the formation of the industrial market in New York around the turn of the century, and find that only large firms and combines were usually able to capture the attention of the nation's early financiers. Nelson (1959) notes that only 19.6 percent of all consolidations during the first merger wave traded on the NYSE sometime in the next three years. In addition, between 1897 and 1907 the total value of cash issues to the general public ($392 million) was only 11.6 percent of the value of securities that were exchanged for the assets and securities of other companies. When seen in light of Figure 6, then, it appears that the small company had a harder time a century ago. Other, less direct evidence, suggests this too. New products are often created by new companies, and Agarwal and Gort (1999) give evidence that a new product diffuses through the economy much faster today than it would have a century ago, leading us to expect a more protracted playing out of events in the electricity era. And Gates (1999, p. 118) provides evidence that computers are penetrating the household sector faster than electricity did – not least because computer prices have declined at a much faster rate since 1970 than electricity prices did after 1890. As size-related barriers to public listing were more formidable for small firms at the turn of the century than they are today, it is likely that entrants could replace the missing market capital only at a much later stage of electricity's adoption.

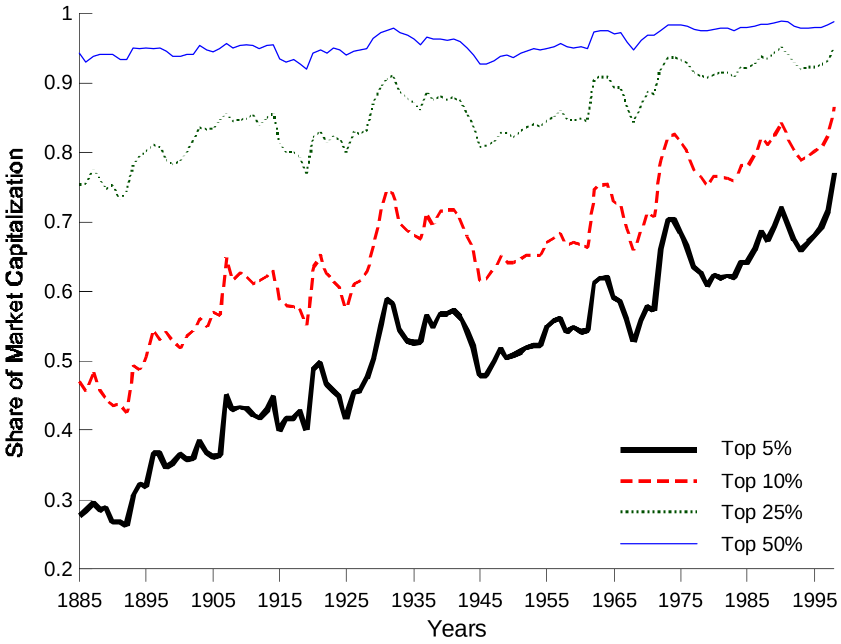

Figure 7: Kuznets curves upper percentiles of the size distribution of listed firms, 1885-1998.

4.2 The role of small and large firms

The previous paragraphs discuss the ease of entry into the stock market. We now ask how small incumbents have fared relative to the large incumbents. We would expect the small incumbent to be more flexible and to respond faster to a new technology than a large incumbent would. It is also possible that the adoption of new technologies by smaller firms has affected the U.S. economy most forcefully through its indirect influence on the decisions of larger firms. This is because new firms can enter the market and demonstrate the viability of a new technology while avoiding the fixed costs of conversion and retraining, which in turn gives rise to the development of complementary products. When the benefits of the new technology finally become clear and the cost of conversion low enough, more established firms choose to adopt. Because older firms wait for the technology to become established, they adopt it more easily, and quickly regain the market's favor early in the process of catch-up with their smaller competitors. This is what seems to have happened since 1982, and we can look for it more systematically in light of the next two figures that portray the Kuznets curves pertaining to various size-classes.

For example, Figure 7 presents Kuznets curves for the upper percentiles of the firm size distribution that are consistent with such a pattern of adoption. A striking feature is the steady gain of the largest five percent of firms in market capitalization despite the tendency for entrants to become ever smaller after 1955. The electrifi-

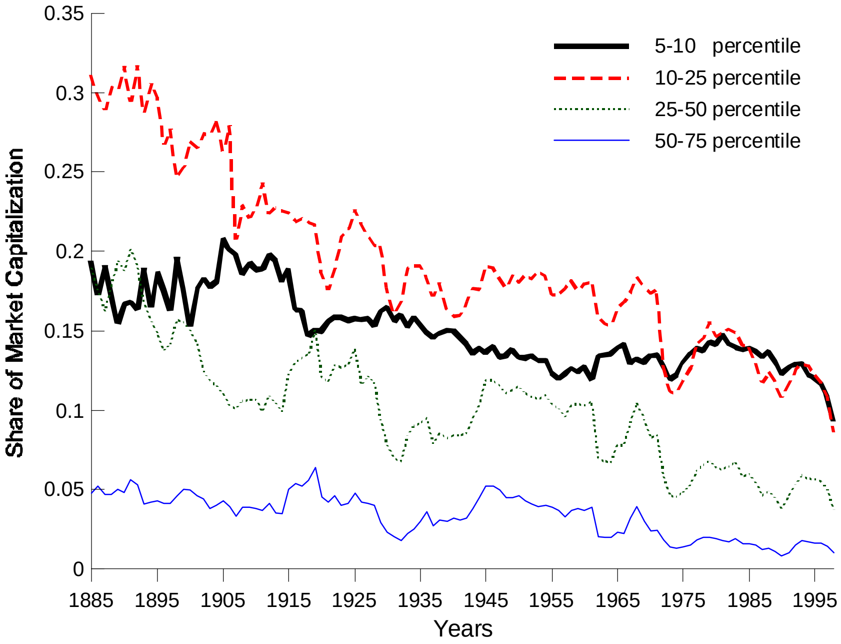

Figure 8: Kuznets curves for interior segments of the size distribution of listed firms, 1885-1998.

cation era began with gains by the top five percent between 1894 and 1900. This surely reflects to some extent consolidations associated with the first merger wave (1896-1901), but may also reflect a rosy outlook among investors about the future of electrical technology. In fact, it is possible that electrification shifted investor perceptions of future comparative advantage and played an important role in merger activity. The top five percent did not gain appreciably between 1907 and 1920 as the challenges of bringing electrical systems on-line became more obvious, but rose sharply again in the 1920s. The top five percent behave similarly from the late 1960s through 1990, in this case gaining when IT first "arrives," falling as the difficulties of conversion of older physical and organization capital become clear, and rising sharply after 1985. By this time computers had come to be integral components of any large business.

Figure 8 depicts a few interior segments of the firm size distribution, and shows that the 5-10 and 10-25 percent segments saw their values decline sharply between 1907 and 1920. Remarkably, as the larger firms struggled, the 25-50 and 50-75 percent segments saw their market shares *rise* only to drop off sharply after 1920! This pattern is also consistent with new and small firms leading the way in adopting new technologies, only to be dominated later by larger ones that survive. Of course, some smaller firms of 1907-1920 flourished and entered the top five percent in the 1920s, but such exceptional cases involved rapid and enormous upward movement

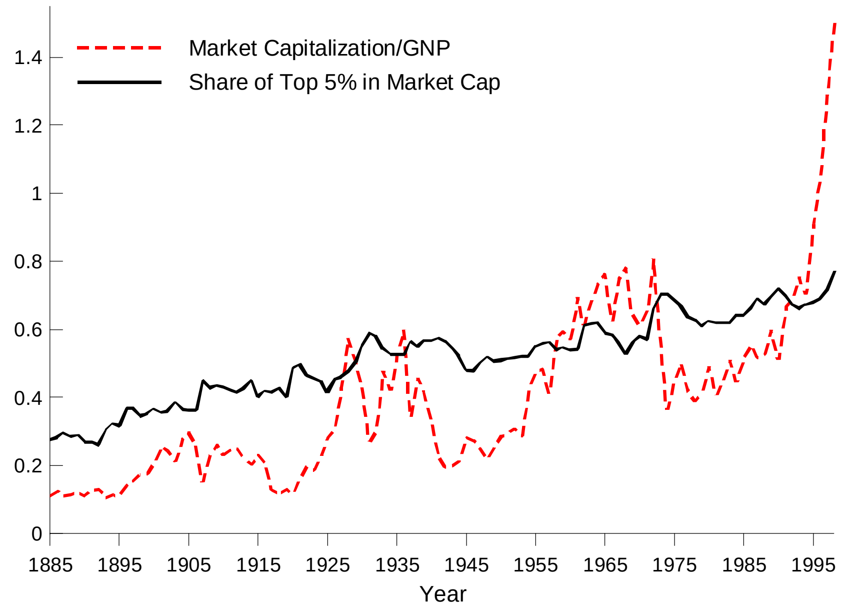

Figure 9: The top five percent of the size distribution and the share of market capitalization in GNP, 1885-1928.

through the size distribution and cannot adequately explain the clear pattern in the aggregates. Interestingly, in the early years of the IT revolution, all but the largest five percent gained market share between 1975 and 1983 or so, but the large firms quickly recovered their shares.

Since the top five percent of firms came to command a large and increasing share of the stock market, one might anticipate shifts in the size distribution to be related to the growth of market capitalization itself. Figure 9, however, which plots the top five percent against the ratio of capitalization to GNP, shows at best a weak contemporaneous association between the two series.

Instead, the cross-correlations of the Kuznets curves with market depth, displayed in Table 1 after detrending all variables, are consistent with our story of lags in the responses of larger and established firms to new technologies. In particular, the top 5, 10, 25, and 50th percentiles (columns 1-4) respond only with a lag to increases in market capitalization, while increases in the 10-25 percent segments and 25-50 percent segments appear to lead positive deviations of the market from trend. Further, the smaller firms (columns 6-8) perform above trend after a decline in the market. These patterns lend themselves to the interpretation that when new technologies arrive, large firms are hit first as smaller firms begin to perform more strongly. As these successes begin to raise market capitalization once again, the large firms adopt the technology and recover their shares.

Table 1: Simple Correlations between market capitalization/GNP and past (-) or future (+) values of Kuznets curve shares (x) of firms in selected percentile segments of the size distribution.

All variables detrended

x(-5)	-.095	-.106	-.042	.094	-.058	.162	.119	-.073
x(-4)	-.118	-.120	-.031	.095	-.037	.207	.104	-.078
x(-3)	-.101	-.101	.004	.133	-.027	.216	.076	-.113
x(-2)	-.071	-.076	.044	.173	-.036	.220	.041	-.156
x(-1)	-.038	-.045	.077	.195	-.033	.202	.006	-.180
x(0)	.063	.030	.120	.201	-.090	.107	-.054	-.190
x(+1)	.206	.176	.264	.316	-.049	-.001	-.198	-.314
x(+2)	.306	.278	.369	.398	-.020	-.065	-.304	-.400
x(+3)	.341	.320	.392	.392	.013	-.120	-.342	-.397
x(+4)	.358	.354	.409	.388	.071	-.166	-.372	-.394
x(+5)	.353	.350	.390	.352	.067	-.180	-.369	-.360
%iles	top 5	top 10	top 25	top 50	5-10	10-25	25-50	50-75

x = share of total market capitalization

5 Vintage and value

5.1 Generations of incumbents and entrants

The Kuznets curves presented in section 4.2 suggest that young firms may play an important role in accelerating the diffusion of new ideas by avoiding the costs associated with modifying or replacing old capital, including the equipment, structural and organizational varieties. Nevertheless, it is primarily the large firms that reap the long-term rewards of widespread adoption. Figure 10, which depicts the share of 10-year cohorts of incumbents in the ratio of market capitalization to GNP, also supports this interpretation. For example, since the 1890 incumbents see their shares drop rapidly after electricity's "arrival" in the mid-1890s, much of the market value retained by the 1900 and 1910 cohorts prior to 1920 can be attributed to later entrants. When electrical technologies became widely adopted around 1920, entrants in subsequent years then combined with the largest survivors to dominate the market, while much of the capital of earlier vintages was destroyed. Those that survived the market disturbances of the early 1930s then maintained their shares for the next two decades – a time during which entry and exit were quite limited. This cycle recurs in the 1960s, when the survivors of the depression and the postwar boom begin to see their old organizational capital deteriorate as information techology appeared on the horizon. New firms quickly adopted the technology, but financial barriers to

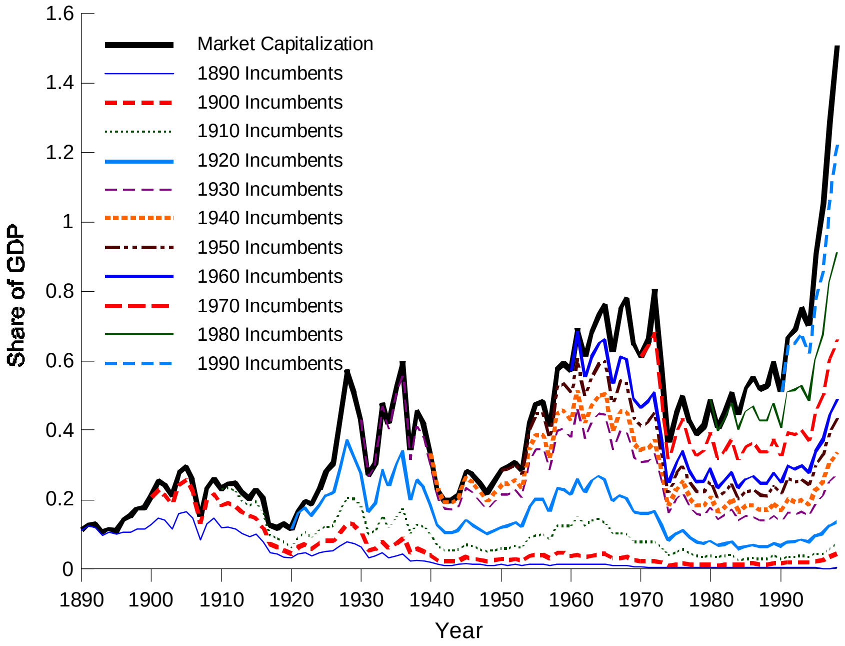

Figure 10: Shares of ten-year cohorts of incumbents in market capitalization, 1885-1998.

entry made it difficult for them to list shares on an organized exchange for some time. Driven by new listings between 1970 and 1980, however, the 1980 and 1990 incumbents performed extremely well and now account for most of the stock market's value.

Figure 11 presents the real market value of the same 10-year incumbent cohorts, but this time we normalize the value of each cohort to one in the starting year. Though the appreciation of each cohort will be affected by the state of the market at the starting date, the figure still offers some insight about the relative quality of each group's orgnization capital. Specifically, the 1920, 1980 and 1990 cohorts appreciate most dramatically following their introduction.

5.2 Econometric estimation of vintage effects

In this section, we estimate vintage effects with an econometric formulation of the model presented in Section 3. The analysis shows that the firms which enter the stock market before the arrival of a new GPT see their market valuations evolve less favorably than those which enter later in the technological cycle. Our first specification captures the vintage shocks with the form

$$\ln\left(P_{t,v}\right) = \beta_{0,v} + \beta_{1,v}\left(t-v\right) + \beta_{2,v}(t-v)^2 + \beta_3 \ln \bar{S}_v + \beta_4 \ln\left(\frac{M}{Y}_t\right) + \varepsilon_{t,v} \qquad (11)$$

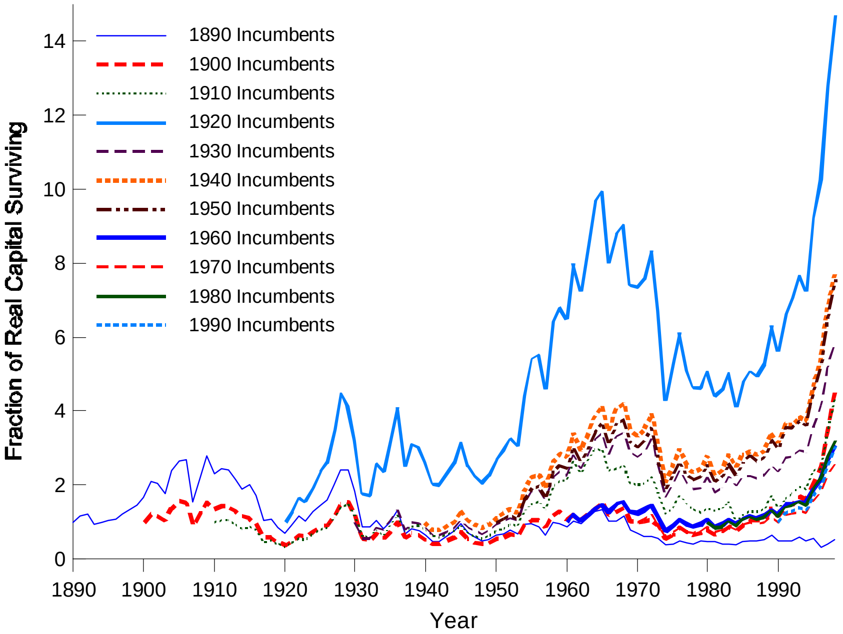

Figure 11: Fractions of real market capitalization retained by incumbents of ten-year cohorts in subsequent years, 1885-1998.

where v represents a particular vintage, or in our case groups of firms which enter the stock market in given five or ten-year periods. $P_{t,v}$ is the real (deflated by the implicit price deflator) market value of all firms in a given vintage. $\bar{S}_v$, which is included to control for the ease with which new firms can obtain lisitng status on an organized exchange, is measured at the time of entry for each vintage. We construct $\bar{S}_v$ by first averaging the value of the bottom third of entering firms in the size distribution for each year and dividing by the average size of listed firms in the entire sample. We then average these results over the years during which we define a vintage (i.e., $\bar{S}_0$ for vintages defined as firm that enter the stock market over five-year periods would be an average of the annual measures from 1886 to 1890). M/Y, the ratio of total market capitalization to GNP, varies over time and is thus common across observations for all living vintages. The $\beta_{i,v}$ are vintage-specific coefficients that capture the effects of the vintage technology shock on the total market value of each cohort and specify the trajectory of its market valuation with respect to both linear and quadratic measures of age (t-v). We estimate using ordinary least squares.

Table 2

Five-Year Vintage $P_{t,v}$ Regressions, 1886-1998

Dep. variable $\ln(P_{t,v})$	No Truncation estimate	No Truncation t-stat.	10-year Truncation estimate	10-year Truncation t-stat.
vintage dummies ($\beta_{0,v}$)				
1886-1890	-1.901	-15.36	-1.207	-8.19
1891-1895	-1.863	-14.70	-1.902	-11.80
1896-1900	-0.622	-4.85	-0.724	-5.16
1901-1905	-1.802	-12.40	-1.466	-10.43
1906-1910	-2.326	-15.23	-1.913	-13.84
1911-1915	-1.278	-10.42	-0.746	-5.09
1916-1920	-0.626	-4.66	-0.391	-2.65
1921-1925	-0.638	-4.84	0.070	0.49
1926-1930	-0.541	-4.14	-0.374	-2.61
1931-1935	-1.347	-10.46	-1.550	-9.88
1936-1940	-0.936	-6.93	-1.077	-7.48
1941-1945	-0.869	-6.47	-0.952	-6.49
1951-1955	-0.568	-3.96	-0.551	-3.60
1956-1960	-0.605	-3.91	-0.566	-3.91
1961-1965	0.267	1.23	0.136	0.97
1966-1970	0.046	0.23	0.247	1.71
1971-1975	0.044	0.15	-0.011	-0.07
1976-1980	-0.924	-2.65	-1.071	-6.33
1981-1985	0.116	0.33	0.117	0.73
No. observations	1218		208	
Adjusted R^2	.976		.996	

Note: the table presents estimates and standard t-statistics for the vintage-specific variables ($\beta_{0,v}$) in equation (11). The vintage effects are measured relative to the omitted 1946-1950 cohort. The left panel includes each vintage from its starting date until 1998, while the right column truncates the observations for each vintage after ten years.

Table 2 presents the vintage effects ($\beta_{0,v}$) for cohorts specified every five years, with the results in the left column using all of the observations that are available over the life of each vintage. In the right column we report the $\beta_{0,v}$ coefficients for a specification that omits the quadratic $(t\text{-}v)^2$ interactions and truncates observations for each vintage after ten years. The omission is reasonable given the reduced size of the truncated sample and the reduced importance of quadratic effects over the shortened time horizon. This second formulation weights all but the final (1986-

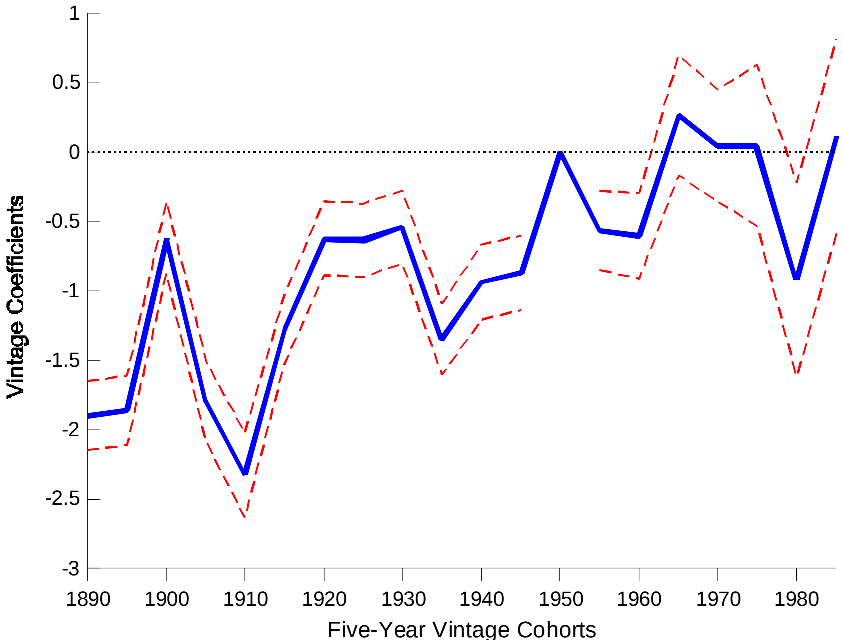

Figure 12: Estimated vintage-specific shocks ($\beta_{0,v}$) for five-year vintages in the $P_{t,v}$ regression model, 1886-1998.

1990) five-year vintage equally in the regression (i.e., there are only 8 subsequent observations covering 1991 through 1998 for the final vintage). Figures 12 and 13 plot the $\beta_{0,v}$ with two standard error bands. The inclusion of an unrestricted intercept in both specifications allows the convenient interpretation of each β_v as the size of a shock relative to that of the omitted 1946-50 vintage.

The vintage coefficients have an upward drift, which is consistent with a model of rapid technological progress. At the same time, Figures 12 and 13 exhibit fluctuations that are consistent with the patterns discussed in section 5.1. In particular, the jazz age vintages (1916-20 and 1921-25) are local maxima for the pre-WWII vintages. Further, the 1981-85 vintage, which was born when information technology was being widely adopted, appears to have the most productive organizational capital of any vintage, and followed a much less favorable 1976-80 vintage. Nearly all vintage effects significantly differ from that of the omitted 1946-1950 vintage.

Figure 14 presents the vintage coefficients from the same specification as (11), but in this case vintages are associated with firms that enter the market over ten-year periods. Though these alternative estimates do not fluctuate as sharply as those in the five-year vintage model, they share an upward drift and either fall off, as in the case of electrification, or level off, as in the case of IT, immediately before the new technologies permeated the workplace and the home.

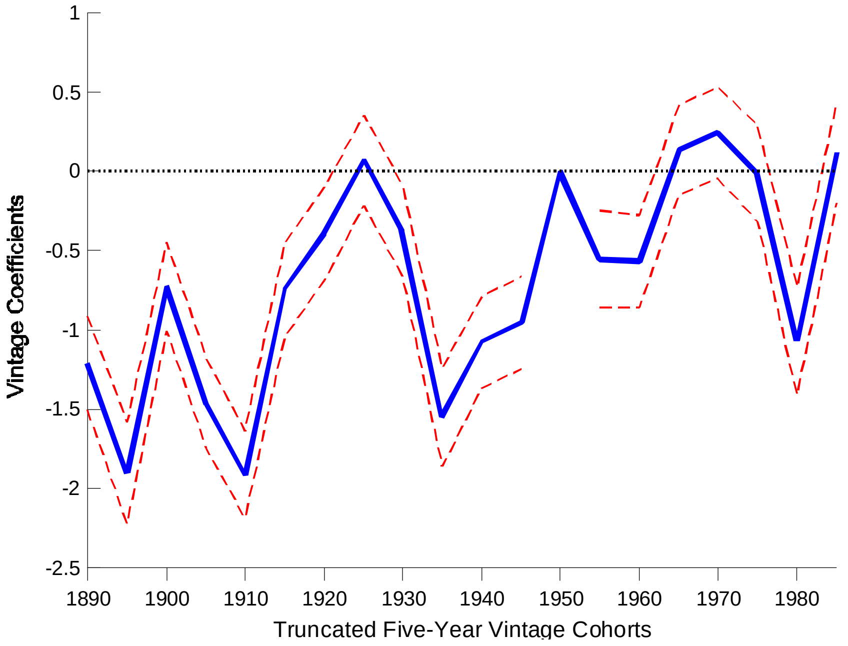

Figure 13: Estimated vintage-specific shocks ($\beta_{\mathbf{0},v}$) for five-year vintages truncated after ten years in the $\mathrm{P}_{t,v}$ regression model, 1886-1998.

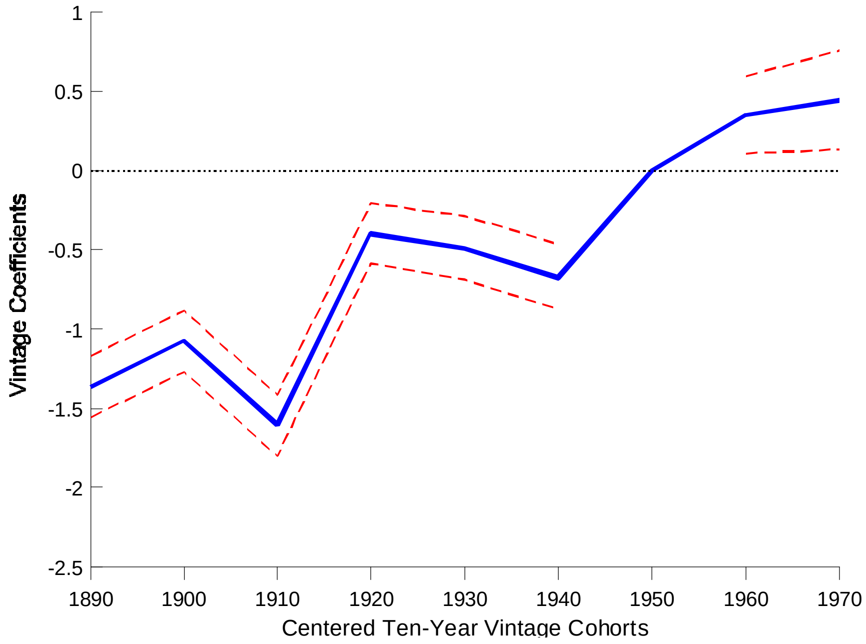

Figure 14: Estimated vintage-specific shocks ($\beta_{\mathbf{0},v}$) for ten-year cohorts of stock market entrants in the $\mathrm{P}_{t,v}$ regression model, 1886-1998.

Table 3
Five-Year Vintage $W_{t,v}$ Regressions, 1886-1998

Dep. variable	No Truncation		10-year Truncation	
$\ln(W_{t,v})$	estimate	t-stat.	estimate	t-stat.
constant	-1.5181	-9.45	-1.4323	-8.02
ln(M/Y)	0.7776	36.91	0.4883	9.86
$\ln(\bar{S}_v)$	0.4344	7.48	0.1186	2.22
age×vintage $\left(\gamma_{1,v}\right)$				
1886-1890	0.0336	18.61	0.0404	3.32
1891-1895	0.0302	13.07	0.1071	8.50
1896-1900	-0.0111	-5.38	0.0641	5.59
1901-1905	0.0437	19.07	0.0275	2.39
1906-1910	0.0460	18.22	0.0253	2.03
1911-1915	-0.0048	-1.79	-0.0285	-2.39
1916-1920	0.0586	20.58	0.1253	10.90
1921-1925	0.0219	7.02	0.0011	0.09
1926-1930	0.0008	0.24	-0.0395	-3.34
1931-1935	-0.0041	-1.03	-0.0059	-0.50
1936-1940	0.0299	6.85	0.0361	3.13
1941-1945	0.0137	2.70	0.0191	1.60
1946-1950	0.0311	5.03	0.0874	6.52
1951-1955	-0.0393	-5.60	-0.0081	-0.57
1956-1960	-0.0255	-3.21	-0.0003	-0.02
1961-1965	-0.0326	-3.03	-0.0372	-3.08
1966-1970	-0.0353	-2.76	-0.0351	-3.03
1971-1975	0.0924	4.64	0.0621	4.74
1976-1980	-0.0096	-0.32	-0.0294	-2.02
1981-1985	0.0312	0.72	0.0113	0.81
1986-1990	0.1479	1.73	0.1027	5.14
age^2×vintage $(\gamma_{2,v})$				
1886-1890	-0.0006	-31.64	..	..
1891-1895	0.0001	-2.66	..	..
1896-1900	0.0001	1.95	..	..
1901-1905	-0.0003	-10.77	..	..
1906-1910	-0.0004	-12.12	..	..
1911-1915	-0.0000	-0.31	..	..
1916-1920	-0.0005	-11.55	..	..
1921-1925	-0.0001	-1.85	..	..
1926-1930	0.0002	2.76	..	..
1931-1935	0.0004	5.29	..	..
1936-1940	-0.0002	-2.36	..	..

Table 3 (continued)
Five-Year Vintage $W_{t,v}$ Regressions, 1886-1998

Dep. variable	No Truncation		10-year Truncation	
$\ln(W_{t,v})$	estimate	t-stat.	estimate	t-stat.
age$^2\times$vintage ($\gamma_{2,v}$)				
1941-1945	0.0001	0.46	..	..
1946-1950	-0.0002	-1.34	..	..
1951-1955	0.0010	5.20	..	..
1956-1960	0.0007	2.89	..	..
1961-1965	0.0009	2.34	..	..
1966-1970	0.0017	3.04	..	..
1971-1975	-0.0019	-1.97	..	..
1976-1980	0.0019	1.03	..	..
1981-1985	-0.0004	-0.12	..	..
1986-1990	-0.0053	-0.45	..	..
No. observations	1218		208	
Adjusted R^2	.930		.773	

Note: the table presents estimates and standard t-statistics for all regressors in equation (12). The left panel includes each vintage from its starting date until 1998, while the right column truncates the observations for each vintage after ten years.

Given that the vintage shocks are large, it is useful to rearrange equation (11) next to remove the large component that is reflected in the size of each cohort, and then focus on the slope and curvature parameters for each vintage. As discussed in Section 3, we can do this by normalizing the real market value of a vintage with its initial value, which is taken as the market value of the entrants in the final year over we define a vintage. We then have the following specification for $W_{t,v} = (P_{t,v}/P_{v,v})$:

$$\ln(W_{t,v}) = \gamma_{0,v} + \gamma_{1,v}(t-v) + \gamma_2(t-v)^2 + \gamma_3 \ln\left(\bar{S}_v\right) + \gamma_4 \ln\left(\frac{M}{Y}_t\right) + \varepsilon_{v,t} \qquad (12)$$

In this case, the inclusion of a common intercept does not lead to perfect collinearity with any linear combination of other regressors, and we can estimate the absolute slope and curvature coefficients for every vintage.

Table 3 presents estimates for the parameters in (12) by ordinary least squares for five-year vintages. Again, all available observations for each vintage are included in the regression presented in the left panel, while the model in the right panel truncates

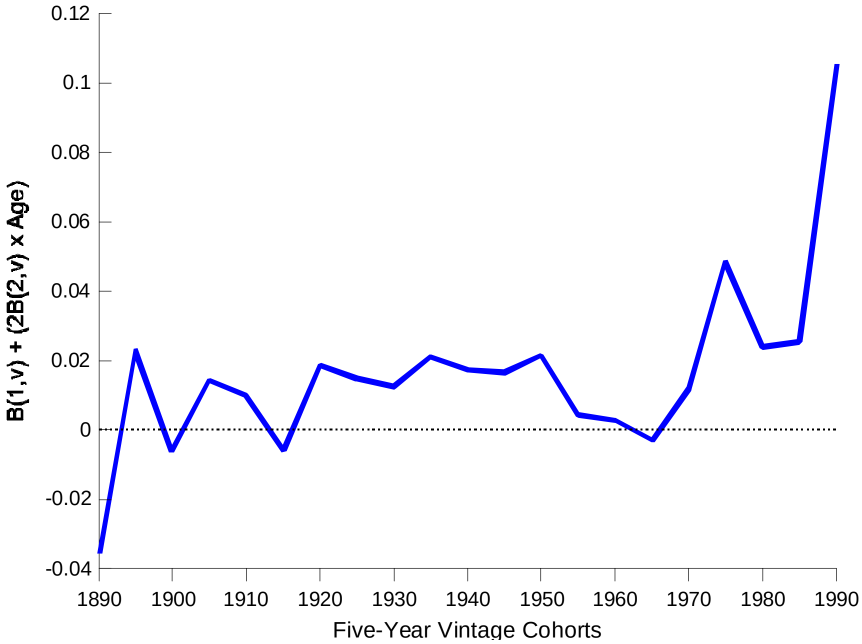

Figure 15: Effects of vintage×age and vintage×age^2 interactions $(\gamma_{1,v} + 2\gamma_{2,v}(t-v))$ evaluated at the mean in the five-year vintage $\mathrm{W}_{t,v}$ regression model, 1886-1998.

vintage observations after ten years and omits the *(t-v)*^{2} interaction terms. As would be expected, the linear slope coefficients in the left panel always differ in sign from the quadratic interaction terms. The coefficients on both terms are also significantly different from zero for a majority of vintages. Figures 15 illustrates the combined effects of the slope and curvature interactions with the vintage dummies by evaluating their derivative at the mean of the distributions for *t-v* and *(t-v)*^{2} in the starting year for each vintage. Here, the combined effects show that the performance of the vintages prior to 1916-1920 fluctuate within a narrow range, but then remain positive and do not begin to drop off until entry of the 1950-55 vintage. The trajectories are also markedly lower for the vintages that precede 1961-1965 than for those that follow. Since the vintages that follow the adoption of IT appreciate most rapidly, our model suggests that the quality of the organizational capital of the later entrants rationalizes a positive outlook for the current stock market.

Table 4 presents estimates for a model with ten-year vintages that uses all of the available vintage observations. Here, the combined effects of the slope and curvature parameters on the growth trajectory are even more striking. In particular, the trajectories fall from the the levels observed for the 1886-1895 vintage as frictions associated with electricity's adoption lowered the values of incumbent firms, but rise after 1915. The decline in the quality of vintage capital prior to the IT revolution is also clear, and the rise after its arrival is quite sharp.

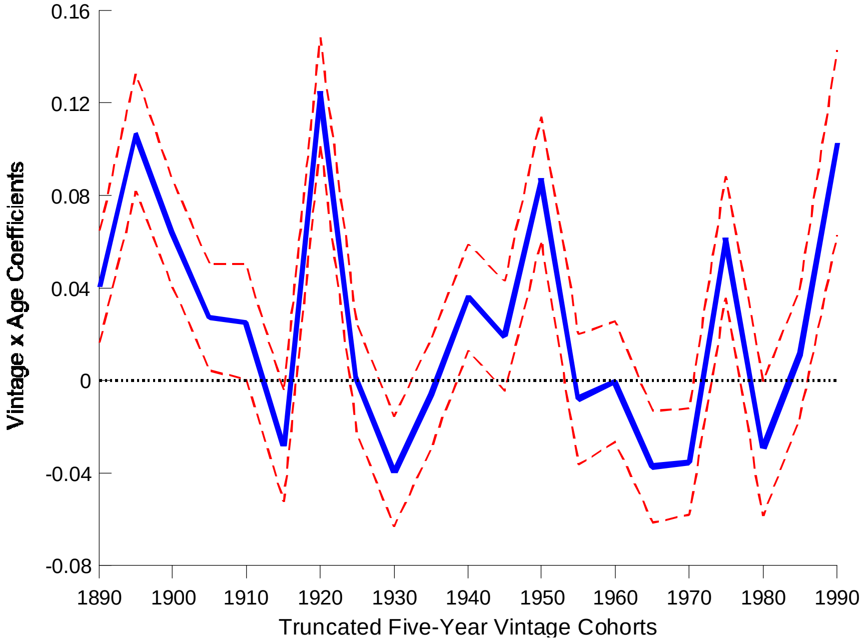

Figure 16: Vintage×age interactions ($\gamma_{1,v}$) in the five-year vintage $W_{t,v}$ regression model, 1886-1998.

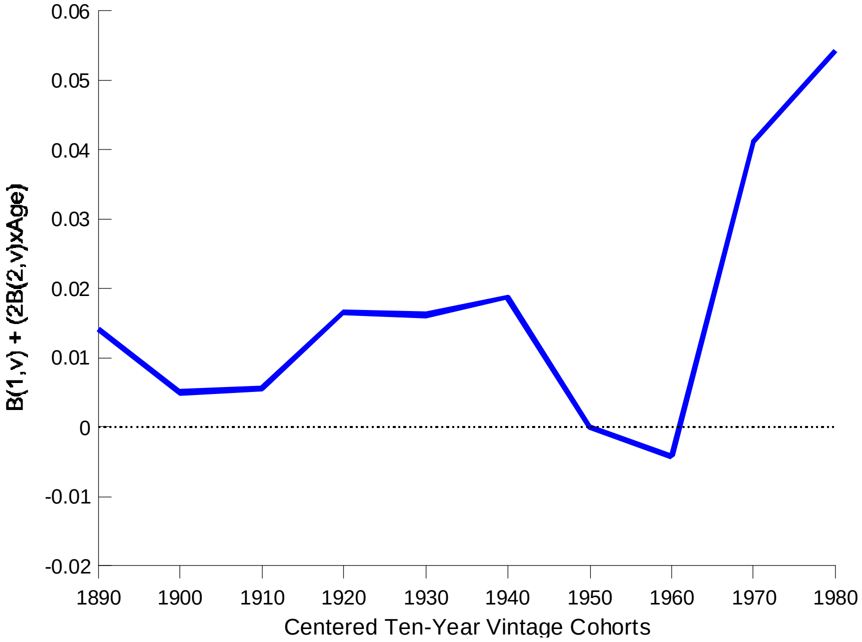

Figure 17: Effects of vintage×age and vintage×age^2 interactions ($\gamma_{1,v} + 2\gamma_{2,v}(t - v)$) evaluated at the mean in the ten-year vintage $W_{t,v}$ regression model, 1886-1998.

Table 4

Ten-Year Vintage $W_{t,v}$ Regressions, 1886-1998

Dep. variable $\ln(W_{t,v})$	estimate	t-stat.
constant	-0.4977	-1.93
ln(M/Y)	0.8071	28.63
$\ln(\bar{S}_v)$	0.8881	9.23
age×vintage ($\gamma_{1,v}$)		
1886-1895	0.0214	9.42
1896-1905	0.0116	4.94
1906-1915	0.0276	10.48
1916-1925	0.0322	10.26
1926-1935	0.0012	0.31
1936-1945	0.0087	1.72
1946-1955	-0.0416	-5.56
1956-1965	-0.0275	-2.75
1966-1975	0.1278	6.34
1976-1985	0.2339	4.32
age^2×vintage ($\gamma_{2,v}$)		
1886-1895	-0.0001	-2.88
1896-1905	-0.0001	-2.31
1906-1915	-0.0003	-8.33
1916-1925	-0.0002	-4.79
1926-1935	0.0002	2.77
1936-1945	0.0001	0.97
1946-1955	0.0011	5.84
1956-1965	0.0008	2.17
1966-1975	-0.0035	-3.67
1976-1885	-0.0013	-3.03
No. observations	580	
Adjusted R^2	.888	

Note: the table presents estimates and standard t-statistics for all regressors in equation (12).

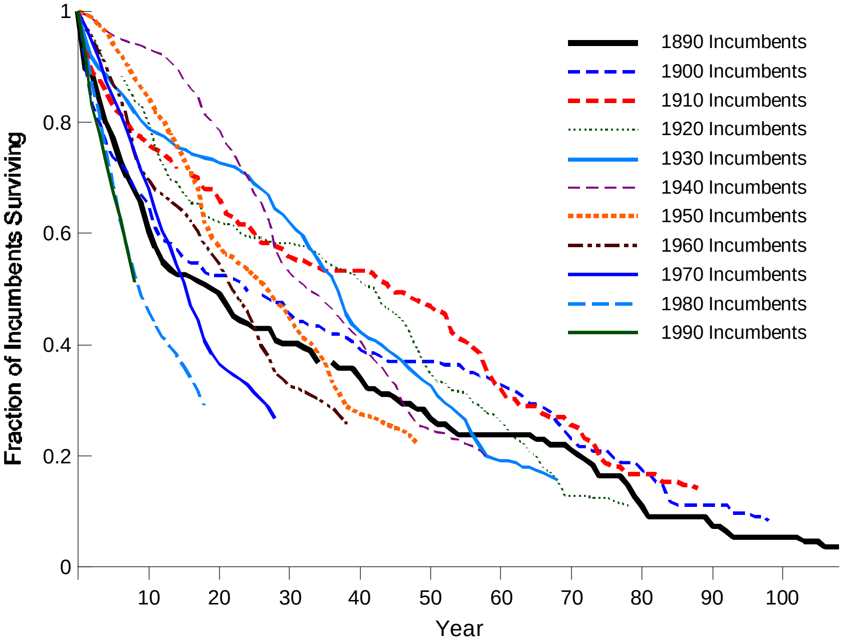

Figure 18: Fractions of incumbents of twenty-year cohorts surviving in subsequent years, 1885-1998.

6 Vintage and firm survival

The IT revolution was bad news for the stock-market incumbents of the early 1970's. Was the same thing true at the dawn of the electrification era? Again, one has to note some structural differences between then and now. We noted that the financial system had made it harder for a small firm to enter using a costly new technology. A reduced threat of entry made it easier for inefficient incumbent firms to survive and easier for them to resist the new electricity-based technology. Directly and indirectly, then, the barrier to entry slowed down the diffusion of electrical technology, and this is one reason why electricity spread more slowly than the computer is spreading today.

Not having to worry about entrants, an inefficient incumbent firm would, however, still have faced the threat of takeover. This may be one explanation for the turn-of-the-century merger wave. The aggregate data suggest that the turn-of-the-century merger wave was less successful than the wave of the 1980's which was followed by a strong recovery in the relative stock-market performance of large firms. Did the market decline over the first two decades of the century because (as the experience of the early 1970's suggests) older firms were slow to adopt the new technology? If this was indeed the reason for the decline, the mergers that occurred around 1900 probably failed as a disciplining device.

Figures 19 and 20 present the fractions of incumbents of twenty- and ten-year

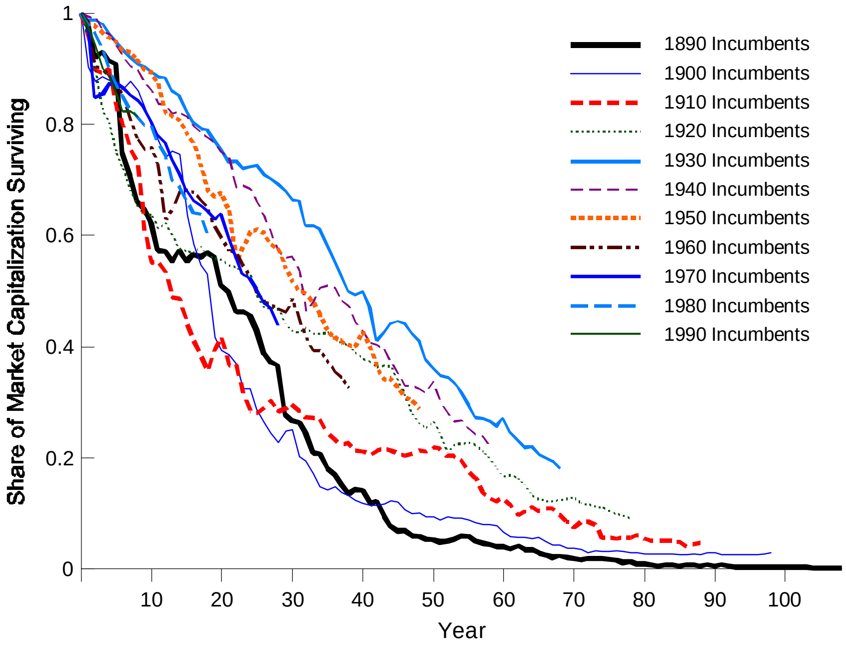

Figure 19: Shares of total market capitalization retained by incumbents in ten-year cohorts, 1885-1998.

vintages from 1890 to 1990 that retained their listing status in subsequent years. Here, the improved survival rates of new entrants after 1910 were clearly not accompanied by widespread improvements in the survival of firms in the market as a whole. In fact, while the incumbents of 1905, 1910, and 1915 fared better than those of previous vintages, the 1910 incumbents had a lower survival rate than 1905 incumbents! The weak performance of incumbents between 1895 and 1910 is further reflected in Figures 20 and 21, which show the shares of total non-rail market capitalization retained by the same incumbents. The sharp declines in these shares to some extent reflect the growth of this market via entry, especially after 1915, but add further support to our observation that the rise of the 1920's can be attributed largely to firms that entered after 1920.

Interpreting the plots in Figures 19-22 requires some care because the speed with which the incumbent loses stock-market share depends not just on how efficient he is compared to the entrant, but also on how hard it is for the entrant to have his IPO on the stock market. IPOs became easier during the electrification era and, indeed, they have been getting easier since (and to a large extent because of) the advent of the computer. At the very least, however, the preliminary evidence leaves open the possibility that the first merger wave, which was necessary to improve firm efficiency as electrification took hold, was an inadequate policing device because it took the market the better part of two more decades to remove the underperformers.

The "discipline" hypothesis holds that mergers take place in order that the targets will reorganize. Since Nelson shows that the majority of mergers involved food and kindred products, chemicals, petroleum products and primary metals, which would have involved increasing electrification, the merger movement seems to have failed as an attempt to impose this discipline on those sectors. We consider examination of these effects to be an important topic for future research.

7 Conclusions

Some surprises have emerged from our preliminary study. First, the top 5% of firms have gained market share steadily, even though so many more firms are now in the stock market, and the size of the stock market has risen much faster than GDP. The implication seems to be that the large firm controls a far larger portion of the US economy than was the case 100 years ago in the heyday of unfettered capitalism, J.P.Morgan, Rockefeller, etc.

Our vintage analysis has tried (in a rough way) to decompose a vintage's value into the amount of organization capital created at the time (the z_v and the $h(s_v)$ variables), and the time path of the market's valuation of the output of that vintage of firm (the subsequent time path of $p_{t,v}$). The analysis of the P equations showed that the 1920's were a very good decade, in terms of organizational capital created at the time, perhaps the best relative to trend. But the later analysis suggests that the 1970s and 1980s vintages are the ones that will be followed by the greatest number of subsequent complementary inventions.

We found some evidence that new technology is first carried in by smaller firms, and some more modest evidence that the stock-market share of large firms rises in good times and falls in bad times, suggesting that market drops are indeed times when value is redistributed from the large company to smaller ones.

We found evidence of technological progress in the organization capital sector (fall in ϕ), especially since WW 2, at least as reflected by a rising incidence of small-firm entry into the stock market. A comparison with capital formation in the economy at large awaits us.

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8 Appendix: Notes on balanced growth

Assume that $\gamma_q, \gamma_\phi, \gamma_z$ are exogenous constants. Let's derive the growth variables along the balanced path when it exists. By "γ_b", we mean the growth factor of variable "b". When we say that something is "constant", we are referring to the balanced growth path. We shall describe a path along which c grows at the growth factor γ. Let $\lambda > 1$, and suppose that for

$$f(\varepsilon) = \varepsilon^{-(1+\lambda)},$$

Then

$$h(s) = \int_s^\infty \varepsilon^{-\lambda} d\varepsilon = \frac{s^{1-\lambda}}{\lambda-1} \tag{12}$$

so that (since $\lim_{s\to 0} h(s) = +\infty$), the supply of potential projects is infinite.

The 7 unknown growth rates are $\gamma, \gamma_A, \gamma_k, \gamma_\nu, \gamma_h, \gamma_\eta$ and γ_s. From (12),

$$\gamma_h = \gamma_s^{1-\lambda} \tag{13}$$

From the evolution of k,

$$\gamma_k = 1 - \delta_k + \frac{qx}{k}, \tag{14}$$

c,y, x grows at the rate γ, and from (14)

$$\gamma\gamma_q = \gamma_k \tag{15}$$

From $Y = c + x + \phi\nu$, where $\nu = \int_s^\infty f(\varepsilon)\, d\varepsilon$ is the number of projects. Then

$$\gamma = \gamma_\phi \gamma_\nu \tag{16}$$

From $Y = A^{1-\alpha}k^{\alpha}$,

$$\gamma = \gamma_A^{1-\alpha}\gamma_k^{\alpha} \tag{17}$$

From $A' = (1-\delta)A + \int_s^{\infty} z\varepsilon f(\varepsilon)\,d\varepsilon$, $\gamma_A = 1 - \delta + \frac{zh}{A}$where $h = \int_s^{\infty} \varepsilon f(\varepsilon)\,d\varepsilon$. Then $\frac{zh}{A}$ is a constant so that

$$\gamma_z\gamma_h = \gamma_A \tag{18}$$

From

$$1 + r_t = q_t\left(\alpha\left(\frac{k_{t+1}}{A_{t+1}}\right)^{\alpha-1} + \frac{(1-\delta_k)}{q_{t+1}}\right) = \frac{z_t s_t}{\phi_t}\left((1-\alpha)\left(\frac{k_{t+1}}{A_{t+1}}\right)^{\alpha} + \frac{(1-\delta)\,\phi_{t+1}}{z_{t+1}s_{t+1}}\right)$$

and $\frac{U'(c)}{\beta U'(c')} = \frac{1}{\beta}\gamma^{\sigma}$,

$$\frac{1}{\beta}\gamma^{\sigma} = \alpha q\left(\frac{k'}{A'}\right)^{\alpha-1} + \frac{1-\delta_k}{\gamma_q} = \eta\left((1-\alpha)\left(\frac{k'}{A'}\right)^{\alpha} + \frac{(1-\delta)}{\eta'}\right)$$

where $\eta = \frac{zs}{\phi}$, so that

$$\gamma_\eta\gamma_\phi = \gamma_z\gamma_s$$

The first of these equations implies that $q\left(\frac{k'}{A'}\right)^{\alpha-1}$ is a constant, which means that

$$\gamma_q = \frac{\gamma_k^{1-\alpha}}{\gamma_A^{1-\alpha}}, \tag{19}$$

and the second implies that $\eta\left(\frac{k}{A}\right)^{\alpha}$ is a constant, which means that

$$\gamma_\eta = \frac{\gamma_A^{\alpha}}{\gamma_k^{\alpha}} \tag{20}$$

So, we have 8 equations in 8 unknowns – the seven growth rates and the ratio $\frac{qx}{k}$.

8.1 Special case of $\gamma_z = \gamma_q = 1$

An special case is when technological progress occurs in organization alone. That is, , and $\gamma_\phi < 1$. Then the capital output ratio is fixed, and h must grow at the same rate as output and consumption, and so must the costs of creating new vintages

$$\gamma = \gamma_A = \gamma_k = \gamma_h = \gamma_\phi\gamma_\nu$$

and since $\gamma_\eta = 1$, this means that $\gamma_s = \gamma_\phi$. But from (13) this means that $\gamma_h = \gamma_\phi^{1-\lambda}$. Therefore the growth factor for consumption and income is $\gamma_\phi^{1-\lambda}$, which exceeds 1 because $\lambda > 1$ and $\gamma_\phi < 1$.