Entry, Exit and Investment-Specific Technical Change

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Abstract

Across industries, this paper finds that the rate of investment-specific technical change (ISTC) is positively related to rates of entry and exit. This finding is consistent with industry dynamics along the balanced growth path of a general equilibrium, multi-industry model of the plant lifecycle, in which technology adoption is costly and the rate of ISTC varies across industries. Results are robust to allowing for structural change induced by technological progress. The model also generates lumpy investment as a result of technology adoption by incumbents.

JEL Codes: L16, O33, O41.

Keywords : Entry, exit, turnover, investment-specific technical change, entry costs, vintage capital, embodied technical change, selection, obsolescence, structural change, lumpy investment.

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"[Innovations] are, as a rule, embodied ... in new firms which generally do not arise out of the old ones but start producing beside them." Joseph A. Schumpeter (1912), *The Theory of Economic Development*, p66.

"To speak of technological progress in capital is simply to refer to changes in the quality of capital goods ...The mix of capital goods, and consequently the average quality change, varies greatly among industries; hence so does the average profitability of replacement of capital. Industries in which average quality of new capital goods changes most will, other things equal, have the highest replacement rate." Edward F. Denison (1964), *The Unimportance of the Embodied Question.*

1 Introduction

Entry and exit rates differ significantly across industries. Over the period 1963-1982, Dunne, Roberts and Samuelson (1988) find that five-year entry rates in US manufacturing data range from 21% in Tobacco to 60% in Scientific Instruments. High-entry industries are high-exit industries, suggesting that there exist industry-specific factors that lead them to differ systematically in terms of overall turnover. At the same time, little is known about these factors.

This paper finds a strong, positive link between industry rates of entry and exit and the pace of technical progress in the capital goods that the industry uses – the rate of *investment-specific technical change* (ISTC).[1] In addition, in countries in which the cost of entry is high, rates of entry and exit are suppressed in industries with high rates of ISTC, further indicating that ISTC is an important factor in the decision of whether (or when) to exit.

To the extent that a plant is locked into the vintage of capital that it uses, technological improvements in the production of capital goods may eventually drive the plant to obsolescence and hence closure. The paper formalizes this intuition in a general equilibrium model in which changing the vintage of capital used by a particular plant is costly. This vintage is referred to as a *technology.* In the model, an establishment is a technology-manager pair: the manager accumulates expertise with a given technology over time, and at any date may choose to upgrade to a newer technology – at the expense of accumulated expertise, as in Jovanovic and Nyarko

[1] ISTC is measured using quality-adjusted capital goods price data, as in Greenwood, Hercowitz and Krusell (1997) and Cummins and Violante (2002).

(1996). The manager may also choose to close the plant at any point – opting instead to open a new one, or to work.

If the technology at a given plant falls behind the frontier for its industry, its profits decline, and this decline is more rapid when the rate of ISTC is high. However, if it is costly to return to the technological frontier, establishments may optimally choose to lag behind for a while. This allows ISTC to affect lifecycle dynamics, the timing of exit, and hence the rate of turnover. When only new establishments may implement new technologies, as in a prototypical vintage capital model, the industry rate of ISTC is analytically shown to cause a higher equilibrium rate of industry turnover. When incumbents too may adopt the frontier technology, in a calibration of the model to US data, ISTC accounts for a significant proportion of the observed cross-industry variation in entry and exit rates. In addition, entry costs disproportionately affect turnover in high ISTC industries, as in the data.

It is natural to address the link between turnover and ISTC in a vintage-type model. Indeed, the results confirm a basic prediction of this widely-used class of models. At the same time, an application of vintage capital models to the phenomenon of turnover must overcome two obstacles. First, it is not clear that entry and exit are *essential* for ISTC to occur as, in practice, incumbents regularly adopt new equipment. Allowing new technologies to be introduced only via entry embodies Schumpeter's assertion in the epigraph, and greatly increases model tractability: nonetheless, it is not clear under what conditions the predictions of a vintage model for turnover are robust to allowing *incumbents* to adopt new technologies too. Second, Bartelsman and Doms (2000) observe that, if entrants begin at the technological frontier, they should be both larger and more productive than incumbents, whereas it is well known that entrants are typically smaller than average.

The model overcomes these obstacles by allowing incumbents to update, and by distinguishing between the productivity of each plant and the quality of the capital that it uses. In this case, several mechanisms link turnover with ISTC. One (already mentioned) is *obsolescence*: the more rapidly a plant falls behind the industry frontier, the sooner it may cease to be economically profitable. Another is *selection*: in an environment with heterogeneous plants, the types of plants that close when they become obsolete (instead of updating) may depend on the rate of ISTC. In the calibrated model, the link between ISTC and turnover turns out to be mainly due to obsolescence. The selection effect is weak unless high rates of ISTC are also related to higher adoption costs – as in, for example, Greenwood and Yorukoglu (1997). Interestingly, more rapid ISTC turns out to increase selection pressures precisely when entrants are small relative to incumbents, so that hurdling the "obstacle" concerning entrant size turns out to strengthen the relationship between ISTC and turnover generated by obsolescence alone.

In addition, allowing incumbents to update generates "lumpy" investment at the establishment level well-known since Doms and Dunne (1998). This pattern is typically modeled using non-convex capital adjustment costs, as in Khan and Thomas (2007) among others. In the current model, even though adjusting the quantity of capital itself is costless, the process of technology adoption itself generates this pattern – based on "technology adjustment costs". The model then predicts that industries that have higher rates of ISTC should display more "lumpy" investment – a prediction that turns out to be supported by the data.

As suggested by the epigraph, the sense that there *should* be a link between technical change and turnover goes back along way, and several papers do study such a link, including Mueller and Tilton (1969), Geroski (1989) and Audretsch (1991). However, those papers do not consider the rate of technical change as a determinant of long term industry differences in turnover and, in particular, none of them raises ISTC as an influence on lifecycle dynamics.[2] Campbell (1998) argues that ISTC may affect the *cyclical* behavior of aggregate entry and exit and Samaniego (2007) finds that turnover and ISTC are positively related in a calibrated one-sector general equilibrium model, but neither paper attempts to account for long term cross-industry differences in turnover. Jovanovic and Tse (2006) develop a model in which new industries with a high rate of ISTC experience an earlier wave of capital replacement: however, that model does not distinguish between exit and updating.

The model extends the framework of Hopenhayn and Rogerson (1993) to allow for multiple industries and for technical progress. In a survey of entry and exit, Geroski (1995) reports little success in relating differences in turnover rates to industry characteristics, mostly measures of profitability or entry barriers. In a general equilibrium context in which entrepreneurs select their target industry, the model shows that there can be significant differences in equilibrium turnover rates (based on differences in lifecycle dynamics) even when there are no differences in profitability nor entry barriers across sectors. The model assumes a preference structure that leads to stable industry shares: however, an extension shows that the results are robust to allowing for structural change induced by technological progress itself, as in Ngai and Pissarides (2007).

Section 2 surveys the empirical relationship between entry, exit, and the rate of ISTC. Section 3 introduces the model, while Section 4 characterizes the equilibrium and Section 5 studies the relationship between ISTC and turnover in the model. Section 6 concludes by analyzing the role of entry costs in the model, as well as

[2]Previous studies mostly focus on manufacturing data: the current analysis also considers entry and exit data for non-manufacturing industries.

structural change and investment lumpiness. All proofs are in the Appendix.

2 ISTC and Turnover in the Data

2.1 Data

This section examines the relationship between turnover and ISTC in the data. First, these variables are indeed related in cross section. Second, a differences-in-differences approach exploits cross-country and cross-industry variation in entry and exit. See the Appendix for further details on the data.

Rates of entry, exit and turnover are drawn from the Eurostat database, which is provided by the European Commission. It includes all establishments in the business register for each of 18 countries over the period $1997 - 2004$. Previous research on entry and exit mostly focuses on manufacturing data. Since manufacturing comprises less than half of GDP in industrialized economies, an advantage of the Eurostat data is that they also cover service and other industries, providing a more comprehensive view of entry and exit than most previous studies.

In what follows, the variable $Entry$ is the proportion of establishments active at a given date t that entered since date $t-1$, and the variable $Exit$ is the number of establishments that closed between $t-1$ and t, divided by the number of establishments active at date t. Both of these are averages over the sample period for each country-industry pair, to abstract from short term conditions. The variable $Turnover$ is the sum of these two measures.

For cross-sectional comparisons, the industry index of entry, exit or turnover is based on the industry fixed effect in a regression of country and industry dummy variables. For example, if $y_{j,c}$ is entry in industry j in country c, consider the regression:

$$y_{j,c} = \sum_c \alpha_c I_c + \sum_j \alpha_j I_j + \varepsilon_{j,c}$$

where I_c and I_j are country and industry indicator variables. The index of entry for industry j is then the coefficient α_j, added to the coefficient α_c for the median country.[3]

Following Greenwood, Hercowitz and Krusell (1997) and Cummins and Violante (2002), the measure of ISTC is the inverse growth rate of the quality-adjusted relative price of capital used by each industry, as measured in the United States. To control

[3] This leads to a median industry turnover value among manufacturing industries that is very close to the average turnover value in US manufacturing data used later in calibration.

for potential simultaneity or lags (see Appendix), the industry value is the average over the period $1987 - 1997$, the decade prior to the entry and exit data. For robustness, we will also consider the average over the entire post-war period $1947 - 2000$. The correlation between the two series is 91%, which supports the interpretation of the rate of ISTC as a long-term industry characteristic.

A potential difficulty relating technical change to turnover is the suggestion by Geroski (1989) that technical change may itself be a *response* to entry and exit, rather than a *cause* thereof, so that industries that experience high rates of turnover may generate a lot of innovation. This is unlikely to be true of investment-specific technical change, however. Industry ISTC measures are essentially weighted averages of ISTC measures for individual capital goods, where each good is used in many downstream industries. Hence, the rate of ISTC in a given type of capital good is unlikely to respond to conditions in any particular demanding industry.[4] In what follows, endogeneity is also addressed by measuring ISTC in the decade *before* the turnover measures.

The cross-country regressions below use two entry cost measures – from Djankov, La Porta, Lopez-de-Silanes and Shleifer (2002), and also from the World Bank (2006). Each reports the cost of starting a business as a proportion of GDP per capita. The former is measured in the 1990s, and the latter over the following decade. They are denoted EC^{DLLS} and EC^{WB} respectively. The correlation between them is 68%. Another institutional variable used later as an instrument is legal origin, as reported in the CIA World Factbook.

2.2 Results

2.2.1 Cross-section

Table 1 presents the industry data. Entry and exit rates are highly correlated, suggesting that they largely reflect differences in long-term, within-industry turnover rather than simply short term phenomena or structural change.[5] Of the 153 possible country pairs in the database, 82% of the cross-country correlations in rates of

[4]Endogeneity could still be a concern if high-ISTC industries also generate a lot of innovation themselves: however, Ilyina and Samaniego (2007) report that, among manufacturing industries, there is no significant relationship between ISTC and R&D intensity, as measured by the median ratio of R&D expenditures divided by capital expenditures among firms in Compustat. Computing this measure for the current industry partition, the correlation between ISTC and R&D intensity is only 5%. Results are similar using the median ratio of R&D spending to sales.

[5]The correlation between entry and exit rates reported in Dunne et al (1988) for US manufacturing industries is 74%. Brandt (2004) finds a similar relationship in OECD data and in an earlier edition of Eurostat which, as here, includes services.

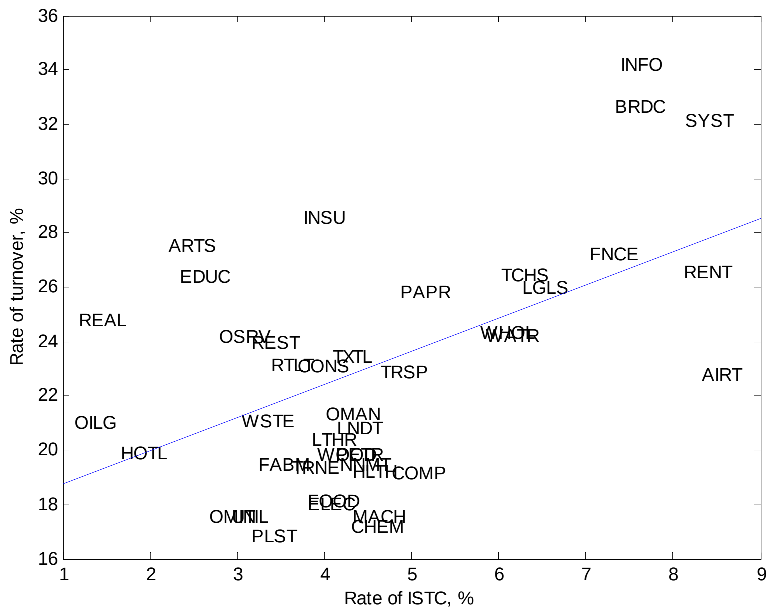

Figure 1: ISTC and Turnover. The rate of ISTC is the average rate of decline in the quality-adjusted price of capital used by each industry, computed using the procedure and data of Cummins and Violante (2002). The rate of turnover is the industry fixed effect based on Eurostat data.

turnover are significant at the 10% level, 76% at the 5% level and 63% at the 1% level. This indicates that there are systematic differences in entry and exit rates across industries, so that the lifecycles of establishments in a given industry in different countries may have common, possibly technological, determinants.

Strikingly, Figure 1 and Tables 1 – 3 report that entry, exit and turnover are very highly correlated with ISTC across industries – on average, and also at the country level. The correlation between ISTC and turnover is about 50%, and the R^2 is around 25%. This is true of manufacturing industries (45% correlation) and also of non-manufacturing industries (56%).

Industry	ISTC	Turnover	Entry	Exit
Oil and gas extraction	1.14	20.97	11.35	9.60
Real estate	1.18	24.76	15.20	9.56
Hotels	1.66	19.86	11.53	8.31
Arts, sports, amusement	2.21	27.52	17.20	10.31
Education	2.34	26.37	15.82	10.54
Other mining	2.68	17.54	9.62	7.92
Other services	2.79	24.15	14.44	9.70
Utilities	2.94	17.54	9.62	7.92
Waste disposal	3.05	21.06	12.42	8.63
Plastics	3.16	16.78	9.37	7.40
Restaurants	3.17	23.91	12.96	10.93
Primary and fabricated metal prod.	3.24	19.42	11.10	8.31
Retail Trade	3.39	23.09	11.90	11.17
Transport Equip.	3.63	19.32	11.16	8.15
Construction	3.70	23.04	13.72	9.30
Insurance, trusts	3.76	28.54	15.80	12.73
Food products	3.80	18.09	9.10	8.99
Electrical machinery	3.81	18.00	10.00	7.99
Leather	3.85	20.39	9.49	10.88
Wood products	3.92	19.81	10.63	9.17
Manuf n.e.c.	4.02	21.28	11.84	9.43
Textiles	4.10	23.40	11.94	11.45
Petroleum and coal products	4.13	19.79	11.90	7.88
Land transport	4.15	20.77	11.43	9.33
Nonmetal products	4.18	19.44	10.64	8.79
Chemicals	4.31	17.15	9.47	7.67
General Machinery	4.33	17.51	9.92	7.58
Healthcare	4.33	19.19	11.96	7.22
Transport support	4.64	22.87	13.48	9.38
Computers and electronic prod.	4.78	19.13	10.60	8.52
Paper, printing, software	4.88	25.78	15.59	10.18
Wholesale Trade	5.79	24.28	13.06	11.21
Water transport	5.86	24.18	13.18	10.98
Technical Services	6.03	26.40	16.02	10.37
Legal services	6.27	25.94	16.69	9.24
Finance (not insurance, trusts)	7.04	27.21	14.32	12.88
Broadcasting	7.33	32.60	21.21	11.38
Information and data processing	7.40	34.16	20.60	13.55
Rental services	8.12	26.54	14.89	11.64
Systems design	8.13	32.10	20.35	11.73
Air transport	8.33	22.77	12.38	10.37
Median value	4.02	22.77	11.96	9.43

Table 1 – Annual % rate of investment-specific technical change (ISTC) and turnover. ISTC is the quality-adjusted price of capital goods (relative to non-durables) used by each industry in the US, 1987-1997. Entry, exit and turnover are industry fixed effects plus the median country fixed effect (Denmark), 1997-2004. Sources – Eurostat, Cummins and Violante (2002) and the US Bureau of Economic Analysis.

	Entry	Exit	ISTC
Turnover	0.96*** (0.000)	0.85*** (0.000)	0.52*** (0.000)
Entry	-	0.67*** (0.000)	0.48*** (0.002)
Exit	-	-	0.49*** (0.001)

Table 2 – Correlations between turnover measures and ISTC. P-values are in parentheses. In all tables, one, two and three asterisks represent significance at the 10%, 5% and 1% levels respectively.

Country	Turnover	Entry	Exit
Belgium	0.70***	0.70***	0.47***
Czech Rep.	0.37**	0.27	0.33**
Denmark	0.70***	0.65***	0.75***
Spain	0.39**	0.47***	0.03
Italy	0.70***	0.67***	0.44***
Latvia	0.29*	0.23	0.31**
Lithuania	0.34**	0.30*	0.12
Hungary	0.28*	0.38**	0.05
Netherl.	0.77***	0.73***	0.75***
Portugal	0.40**	0.37**	0.26*
Slovenia	0.25	0.30*	-0.05
Slovakia	0.14	0.16	0.07
Finland	0.58***	0.54***	0.57***
Sweden	0.57***	0.54***	0.44***
UK	0.49***	0.50***	0.35**
Romania	0.59***	0.55***	0.21
Norway	0.59***	0.54***	0.43***
Switzerland	0.75***	0.63***	0.73***

Table 3 – Cross-industry correlations between ISTC and turnover, by country. The correlation between turnover and ISTC is significant in 16 of 18 cases.

2.2.2 Differences-in-differences

Research finds that the costs imposed by the regulation of entry vary significantly across countries. This suggests an indirect yet possibly powerful method for identifying the determinants of industry turnover, by exploiting cross-country differences in industry behavior and the regulation of entry.

Suppose that entry, exit, and technology adoption by incumbents all reflect profit maximizing *choices* made by entrepreneurs. For entrepreneurs, the opportunity cost of operating a particular plant includes the value of closing the plant and opening a new one. If the institutionally imposed cost of entry is high, this should increase the value of incumbency relative to new entry and, to the extent that exit can be delayed or avoided, may result in lower exit rates. This effect is termed *obsolescence*. In addition, to the extent that entry and exit reflect the introduction and replacement of technologies, entrepreneurs may avoid a high entry cost entirely by adopting new technologies at existing plants instead of exiting and (possibly) re-entering. This effect is termed *selection*. Hence, we might expect entry costs to reduce rates of exit disproportionately in industries in which the rate of ISTC is high. If a significant component of turnover reflects long-run factors, this should also be the case for rates of *entry*, and for overall turnover.

To test for these patterns, the differences-in-differences approach pioneered by Rajan and Zingales (1998) is adopted. Let $y_{j,c}$ be entry, exit or turnover for industry j in country c. Let I_c and I_j denote country and industry indicator variables, respectively. $ISTC_j$ measures the rate of ISTC in industry j, and EC_c measures entry costs in country c. Then, estimate the equation:

$$y_{i,c} = \sum_c \alpha_c I_c + \sum_j \alpha_j I_j + \beta_{ISTC} ISTC_j \times EC_c + \varepsilon_{j,c}. \quad (1)$$

If entry costs reduce establishment turnover primarily in industries where the rate of ISTC is high, then we would expect the coefficient β_{ISTC} on the interaction term between $ISTC_j$ and EC_c to be *negative*. By controlling for industry and country fixed effects, this should be the case regardless of other country- or industry-specific factors that might affect rates of turnover.[6]

[6] Fisman and Sarria-Allende (2004) also study the effects of entry costs using a differences-in-differences approach. However, they use the turnover rate (measured in the US) as an *independent* variable, interpreting it as an index of "natural" industry entry costs. Thus, their paper does not study the determinants of entry and exit rate differences. In addition, only manufacturing data are considered in that paper. When the industry share was used as the dependent variable instead of turnover in equation (1), there was no impact of the interaction between ETC and entry costs on industry shares, consistent with their results. When the industry share was included as an *independent* variable it was never significant.

The maintained assumption is that the rate of ISTC (or the ranking) is an industry characteristic that persists across countries. $ISTC_j$ is measured by computing the quality-adjusted price series for different types of capital, and creating an aggregate for each industry based on the weights of each good in the input-output tables. As a result, this assumption amounts to positing similar input–output tables across countries, and similar rates of technical progress in any given type of capital across countries. Since that the median rate of ISTC is about 4% per year, it is unlikely that significant differences in ISTC for the same industry across countries could be sustained for long in the absence of draconian import restrictions.[7]

The coefficient on the interaction term between ISTC and entry costs is negative and significant – see Tables $4-5$. This is regardless of whether turnover, entry or exit is the dependent variable in the regression. The fact that ISTC interacts with entry costs to generate differences in both entry and exit rates supports the notion that a significant portion of cross-industry differences in turnover represents a steady-state phenomenon. Repeating the regressions with ISTC measures from the entire post-war period yields much the same results, consistent with the hypothesis that ISTC is a long-run industry characteristic related to entry and exit rates. Results are also robust to the different measures of entry costs.

A potential concern in this context is policy endogeneity: it could be that entry costs vary across countries in a way that depends systematically upon patterns of entry and exit, exogenously determined. For instance, if for some reason establishment turnover rates across industries are compressed (so there are fewer firms experiencing very high rates of expected turnover), this may allow incumbents to lobby more effectively for the imposition of higher entry costs to discourage competition. A common instrument to control for this possibility is legal origin, see La Porta, Lopez-de-Silanes, Shleifer and Vishny (1998). The results when entry costs are instrumented using legal origin are even stronger in many cases: the interaction terms remain statistically significant and increase in magnitude.

[7] Also, recall that ISTC as measured in the US is correlated with turnover in 16 of the 18 countries in Eurostat.

ISTC measure	Turnover measure	Interaction coefficient	Obs	R^2
All industries. 1987-97	Turnover	-.70*** (0.007)	719	0.63
	Entry	-.34** (0.042)	724	0.62
	Exit	-.37*** (0.005)	721	0.49
All industries. 1947-2000	Turnover	-.59** (0.016)	719	0.63
	Entry	-.26* (0.078)	724	0.62
	Exit	-.34** (0.012)	721	0.49
All industries, instrumented with legal origin. 1987-97	Turnover	-.83*** (0.007)	719	0.63
	Entry	-.33* (0.074)	724	0.62
	Exit	-.50*** (0.004)	721	0.49
Manufacturing only. 1987-97	Turnover	-1.00** (0.044)	283	0.68
Manufacturing only, instrumented. 1987-97	Turnover	-2.09** (0.027)	283	0.68
Non-manuf only. 1987-97	Turnover	-.79** (0.014)	436	0.58
Non-manuf only, instrumented. 1987-97	Turnover	-0.85*** (0.006)	436	0.58

Table 4 – Effect on turnover of the interaction between ISTC and institutional entry costs, as measured by Djankov et al (2002). Country and industry fixed effects are omitted for brevity. P-values are reported in parentheses, and are corrected for heteroskedasticity using the Huber-White procedure.

ISTC measure	Turnover measure	Interaction coefficient	Obs	R^2
All industries. 1987-97	Turnover	-.70*** (0.002)	719	0.63
	Entry	-.30* (0.058)	724	0.62
	Exit	-.42*** (0.000)	721	0.49
All industries. 1947-2000	Turnover	-.64*** (0.003)	719	0.63
	Entry	-.28** (0.052)	724	0.62
	Exit	-.38*** 0.000)	721	0.49
All industries, instrumented with legal origin. 1987-97	Turnover	-1.38*** (0.007)	719	0.62
	Entry	-.53* (0.083)	724	0.62
	Exit	-.83*** (0.004)	721	0.48
Manufacturing only. 1987-97	Turnover	-.70* (0.074)	283	0.68
Manufacturing only, instrumented. 1987-97	Turnover	-3.13** (0.046)	283	0.67
Non-manuf only. 1987-97	Turnover	-.71** (0.017)	436	0.58
Non-manuf only, instrumented. 1987-97	Turnover	-1.40*** (0.006)	436	0.57

Table 5 – Effect on turnover of the interaction between ISTC and institutional entry costs, as measured by World Bank (2006). Country and industry fixed effects are omitted for brevity. P-values are reported in parentheses, and are corrected for heteroskedasticity using the Huber-White procedure.

It is interesting to check the robustness – or generality – of the results by seeing whether they hold if manufacturing and non-manufacturing industries are treated separately. While results are weaker in the smaller samples, the sign and significance of β_{ISTC} persists. Another question is whether these results apply only to the smallest establishments, or whether it is an industry-wide phenomenon. Entry, exit and turnover rates are recomputed using only establishments with 0-4, 1-4 or 1-9 employees. The sign of β_{ISTC} remains negative but is only significant when the entry cost measure of World Bank (2006) is used, although the Djankov et al (2002) measure is also significant in the instrumental variables regressions. Thus, it is not the case that the results are purely driven by churn at the bottom of the size distribution. That results are weaker when only looking at small establishments is consistent with evidence that small firms are particularly sensitive to short term macroeconomic conditions, as in Gertler and Gilchrist (1994) for example, which would cloud the effects of long-term factors on their lifecycle dynamics.

Both ISTC and entry costs are normalized by their means and standard errors. Hence, regression coefficients can be interpreted as follows. According to the Djankov et al (2002) measure of institutional entry costs, Sweden and Italy occupy the 25th and 75th percentiles respectively. In terms of industry ISTC, the 25th percentile is occupied by Transportation Equipment, whereas the 75th percentile is occupied by Retail Trade. In the median country, if entry costs were to drop from the level of Italy to the level of Sweden, the annual rate of turnover would converge between transportation equipment and retail trade by 0.3%, according to the instrumental variables regression.

The difference in annual industry turnover between the 25th and 75th percentiles is 2.9%. Thus, the magnitude of the interaction between entry costs and ISTC is an order below the magnitude of cross-industry variation in rates of entry and exit. This suggests that the ranking of industries according to turnover should not differ significantly across countries in spite of the interaction between entry costs and ISTC – as reported earlier in this section.

3 Economic Environment

3.1 Overview

There is a continuum of plants of endogenous mass that live in discrete time, populating $J > 1$ industries. Time is indexed by t and the length of time between periods is Δ, so that $t \in \{0, \Delta, 2\Delta, 3\Delta, ...\}$.[8] A plant is a technology, implemented by a manager/entrepreneur with a degree of success that is stochastic yet persistent.

In the model, a technology is a *level* of investment-specific technical change. There is a capital sector that converts the aggregate good into capital goods. The efficiency of capital production differs by industry and varies across technologies.[9] To change the vintage of their technology, plants must update it: updating, however, may decrease their expertise, part of which is vintage-specific. Also, at any point, the manager may choose to close the plant if the payoff from her outside option exceeds that of continuation. As a result, plants may find it optimal to be temporarily "locked" into a particular technology, investing in capital of a type that is not at the industry frontier, and eventually updating or exiting depending on the efficiency of implementation.

3.2 Households and investment

There is an aggregate good y_t which is the composite of the output of the J industries:

$$y_t = \prod_{j=1}^{J} \left(\frac{y_{jt}}{\omega_j} \right)^{\omega_j}, \omega_j > 0, \sum_{j=1}^{J} \omega_j = 1. \tag{2}$$

It can be used for consumption c_t or for investment i^j_{xt} in capital goods for any industry j of type x. The stock of each type of capital evolves according to

$$k^j_{x,t+1} = i^j_{xt} x + e^{-\delta\Delta} k^j_{xt} \tag{3}$$

so that capital depreciates by a factor $\left(1 - e^{-\delta\Delta}\right)$ each period. Thus, at any date, one unit of foregone consumption may be converted into x units of capital of type x in any industry j. There is a frontier level of x which varies by industry, denoted $\bar{x}^j_t$. It changes over time at rate g_j, so that $\bar{x}^j_t = \bar{x}^j_0 e^{-g_j t}$. Parameter g_j is the rate of investment-specific technical change experienced by industry j.

Preferences over consumption are

$$\sum_{t=0}^{\infty} e^{-\rho t} \frac{c_t^{1-\kappa} - 1}{1 - \kappa} dt, \, \kappa > 0 \tag{4}$$

[8] The reason for this time structure is as follows. $\Delta > 0$ is convenient for calibration, and for proving existence of the endogenous distribution of plants using standard recursive methods. On the other hand, analytical results concerning obsolescence can only be obtained as $\Delta \to 0$.

[9] The Appendix presents an extension in which some of the industries themselves produce capital goods, and the capital used by each industry is a composite of these goods. The empirical results apply when the manufacturing sector is excluded, so the model can also be interpreted as addressing a more limited phenomenon applying outside manufacturing.

The rate of time preference is ρ. $1/\kappa$ is the intertemporal elasticity of substitution.

Each household begins period t with k_{xt}^{j} units of capital of each type (x, j). Each type commands a rental rate Δr_{xt}^{j}. A household is also endowed with one unit of labor each period, which may be used to earn a wage Δw_t or used in entrepreneurship. Households earn income by renting capital and labor to establishments, and by earning profits π_t from the establishment it owns if the agent is an entrepreneur.

Their budget constraint is

$$p_t c_t + \sum_{j=1}^{J} \sum_{x=0}^{\bar{x}_t^j} p_t i_{xt}^{j} \leq (1 - l_t) \Delta w_t n_t + \Delta \sum_{j=1}^{J} \sum_{x=0}^{\bar{x}_t^j} r_{xt}^{j} k_{xt}^{j} + \pi_t \tag{5}$$

where l_t is time spent working.

Agents select consumption, investment and labor allocations so as to maximize (4), subject to (5).

3.3 Production

Each plant is characterized by a technology x, and the manager's success in implementing it z_t. Variables z_t and x define the plant, and may not be traded.[10] The plant's production function is

$$\Delta A_{jt} z_t k_t^{\alpha_k} n_t^{\alpha_n}, \ \alpha_k + \alpha_n < 1 \tag{6}$$

where k_t is the quantity of efficiency units of capital that it uses, and n_t is labor. $A_{jt} = A_{j0} e^{\varsigma_j t}$ is a measure of disembodied technology. Thus, g_j is the industry rate of investment-specific technical change (ISTC), and ς_j is the industry rate of disembodied technical change (DTC).

Let p_{jt} be the competitive price of good j. The plant's profits in period t are $\pi^j(x, z_t)$ where

$$\pi^j(x, z_t) = \Delta \max_{k_t, n_t} \left\{ A_{jt} p_{jt} z_t k_t^{\alpha_k} n_t^{\alpha_n} - r_{xt}^{j} k_t - w_t n_t \right\} \tag{7}$$

Thus, although x does not enter into the production function, it affects profits because it is the rate at which the economy can produce the capital goods that the establishment uses, which is reflected in the equilibrium rental rate of capital Δr_{xt}^{j}.

[10] Andre Faria (2007) develops a model of mergers and acquisitions based on the transferrability of z_t. The model abstracts from mergers as, empirically, they tend to occur in waves associated with episodes of regulatory change: see Andrade et al (2001).

In equilibrium, more efficient technologies will be associated with cheaper capital, providing an incentive to use the frontier technology *caeteris paribus*.

However, technology adoption is costly. At the end of any period, the establishment may choose to update its technology x to the frontier, at the cost of a proportion $\zeta_l < 1$ of its expertise z_t. Thus, some accumulated knowledge may no longer apply to the new technology.

Finally, establishments face a stochastic learning ladder, which they may climb or descend. With probability $\left(1 - e^{-\Delta\eta}\right)$, they may obtain a new level of productivity z_{t+1}, drawn from a distribution $f\left(z_{t+1}|z_t\right)$ with support $z_t \in [z_l, z_h]$, $z_l \geq 0$, $z_h < \infty$. Otherwise, with probability $e^{-\Delta\eta}$, $z_{t+1} = z_t$. Thus, if a firm adopts a new technology its expertise the following period is $z_{t+1} = \zeta_l z_t$ unless it receives a new draw from f, in which case its productivity the following period is drawn from the distribution $f\left(z_{t+1} \div \zeta_l | z_t\right)$. Assuming that $\int z_{t+1} f\left(z_{t+1}|z_t\right) dz_{t+1} > z_t$, f may be interpreted as a stochastic learning process.

Some authors have argued that the rate of ISTC is positively related to adoption costs,[11] which suggests that the adoption cost parameter ζ_l may be a function of g_j. Allow $\zeta_l = \zeta_l\left(g_j\right)$, where $\zeta_l'\left(\cdot\right) \leq 0$, so that the numerical experiments can assess whether this relationship is important for model behavior.

3.4 Entry and Exit

Agents in this environment may either work, or create and operate up to $\bar{c} > 0$ plants. Creating a plant requires a delay of length d, after which profits begin to flow. Let $E = 1 - e^{-\rho d}$. E is the *cost of entry.* This formulation captures the finding of Djankov et al (2002) that cross-country variation in entry costs largely takes the form of bureaucratic delays.

Establishments start their lives with a value of z_t drawn from a common distribution ψ, and with the frontier technology. At any point in time, the entrepreneur may close the establishment, earning a continuation payoff W_t to be discussed in more detail below. Once born, establishments also close exogenously with probability $\Delta\chi$ each period, in which case the entrepreneur may return to work in any industry, or open another plant. That entrepreneurs are not tied to any particular industry and move in and out of the labor market is consistent with the behavior documented by Lazear (2005).

In equilibrium, entrepreneurialism in any sector experiencing entry must carry the same expected benefit as labor. The return from operating an establishment

[11] See Greenwood and Yorukoglu (1997), Greenwood and Jovanovic (2001) and Bessen (2002).

is stochastic: however, assuming complete insurance markets, there is no income uncertainty for individual agents. Hence, in equilibrium,

$$W_t = \bar{c} \times \max_{j \leq J} \int V^j \left(\bar{x}_t^j, z_t\right) \psi\left(z_t\right) dz_t \left(1 - E\right) \tag{8}$$

Let ε_t^j be the mass of entrants at date t. If in equilibrium there is entry into any two sectors j and j', then it must be that

$$\int V^j \left(\bar{x}_t^j, z_t\right) \psi\left(z_t\right) dt = \int V^{j'} \left(\bar{x}_t^{j'}, z_t\right) \psi\left(z_t\right) dz_t \tag{9}$$

In equilibrium, prices p_{jt} are such that this free entry condition is satisfied with equality.

If agents participate in the labor force, they earn a flow of income w_t. Expected lifetime income from labor is then

$$W_t = \sum_{\tau=0}^{\infty} e^{-\sum_{s=0}^{\tau} i(s+t)\Delta} \Delta w_{\tau+t} dt, \tag{10}$$

where $i\left(t\right)$ is the interest rate at date t.

4 Equilibrium

Equilibrium decision rules imply a law of motion for the measure $\mu_{t+1}^j = \Gamma^j \left(\mu_t^j\right)$ where Γ aggregates the decisions of individual plants. At any date, let M_t^j be the set of establishments in operation, and let m be any establishment. Define for any two dates t, t'

$$\Xi_{t,t'} = \left\{m : m \in M_t^j, m \notin M_{t'}^j\right\} \tag{11}$$

Thus, for $\Delta > 0$, $\Xi_{t-\Delta,t}$ is the set of establishments that exited between time $t-\Delta$ and t, whereas $\Xi_{t,t-\Delta}$ is the set of establishments that entered between those dates. Let $\mu_t^j\left(X\right)$ be the measure of any set $X \subseteq M_t^j$ of establishments. Thus, the *share* of plants that do not reach time t is $\frac{\mu_{t-\Delta}^j\left(\Xi_{t-\Delta,t}\right)}{\mu_t^j\left(M_t^j\right)}$, and the share of establishments at time t that were born since time $t-\Delta$ is $\frac{\mu_t^j\left(\Xi_{t,t-\Delta}\right)}{\mu_t^j\left(M_t^j\right)}$.

Definition 1 *Industry rates of entry and exit are:*

$$Entry_t = \frac{\mu_t^j\left(\Xi_{t,t-\Delta}\right)/\mu_t\left(M_t^j\right)}{\Delta} \tag{12}$$

$$Exit_t = \frac{\mu_{t-\Delta}^j\left(\Xi_{t-\Delta,t}\right)/\mu_t\left(M_t^j\right)}{\Delta} \tag{13}$$

Definition 2 *A stationary equilibrium (balanced growth path, or BGP) is a measure* μ^{j*} *for each industry, a mass of entrants* ε^{j*} *and prices* $\left\{p_{jt}^*\right\}_{t=0}^{\infty}$ *such that the labor market clears, the measure replicates itself, all households maximize* (4) *subject to* (5) *given prices and expectations, and aggregate output* y_t *grows at a constant rate.*

This definition is similar to that in Hopenhayn and Rogerson (1993) except that the model distinguishes between industries. Also, because rates of investment-specific and disembodied technical change differ across industries, relative prices will diverge even along a balanced growth path (as in Greenwood et al (1997), for example).

Proposition 1 *There exists a balanced growth path with positive, constant rates of entry and exit into all sectors.*

The proof of the proposition derives from a series of conditions that are then shown to be consistent with equilibrium. First, for profitability to be proportional across industries requires prices to grow at a pace inversely linked to rates of ISTC and disembodied technical change. Specifically, along a BGP,

$$p_{jt} = p_{j0}e^{-\left(\alpha_k g_j + \varsigma_j\right)t} \tag{14}$$

This implies that the decision problem of the establishment is stationary. The measure of establishments in a given subset of the type space is constant over time which, in combination with the decision variables, enables an expression for μ_t^j – net of a constant Q. Finally, for a given wage, product prices and demand are given. The proof shows that there is a unique constant Q that clears the labor market.

Proposition 2 *At any date, the rental rate of capital is decreasing in the vintage, at a rate that is proportional to* g_j*.*

This result is central to the establishment dynamics of the model. Establishments using more advanced capital benefit through cheaper capital services than their competitors. On the other hand, the fact that updating to the frontier is costly implies that establishments gradually fall away from the frontier, whereas some of their competitors – either because they just updated or because they are recent entrants – may use more advanced capital than they do. The price of output declines along with the cost of production across the industry, whereas any given establishment only benefits from decreased costs if it decides to update – which may not be optimal in every period. As a result, g_j introduces a downward trend in the marginal revenue product of the establishment over time, net of other aspects of establishment dynamics.

This also suggests that rates of entry and exit may not be related to the industry rate of *disembodied* technological progress ς_j, since it is *not* costly to adjust. Again, the price of the output of industry j is driven by the dynamics of the industry as a whole, implying that the price of output declines at a rate that offsets ς_j. However, since all establishments are at the frontier with respect to disembodied technical progress, this has no influence on their lifecycle decisions.

Lemma 1 *On a balanced growth path, an establishment's updating and exit decisions depend only upon parameters indexed by industry j and the age of technology a, not the date.*

At any date, the value of an establishment may be written recursively, and rewritten in terms of the technology's age a instead of the level of ISTC x. Solving for optimal input use, the lemma shows that the establishment's updating and exit behavior is the solution to the problem:

$$V^j(a,z) = \max_T \left\{ \Pi^j(a,z,T) + e_s^{-(\rho+\eta+\chi)(T-a+\Delta)} \max\left\{U^j(a,z)\right\}, W^j \right\} \tag{15}$$

where T is the planned point in time at which the technology becomes obsolete. Π^j represents profits up until that point,

$$\begin{aligned} \Pi^j(a,z,T) &= e^{(\rho+\eta+\chi)a} \left\{ \sum_{t=a}^{T} \Delta e^{-(\rho+\eta+\chi)t} \left[z_t^{\frac{1}{1-\alpha_n-\alpha_k}} e^{-\left(\frac{\alpha_k g_j}{1-\alpha_n-\alpha_k}\right)t} \right.\right. \\ &\quad \left.\left. + \left(1-e^{-\eta\Delta}\right) E_{z'} V^j(t,z') + \left(1-e^{-\chi\Delta}\right) E_{z'} V^j(0,z')(1-E) \right] \right\} \end{aligned} \tag{16}$$

while U^j is the value of updating and W_j is the value of exit:

$$\begin{aligned} U^j(a,z) &= e^{-\chi\Delta} \left[e^{-\eta\Delta} V^j(0, z\zeta_l) + \left(1-e^{-\eta\Delta}\right) \int V^j(0, z'\zeta_l)\, df(z'|z) \right] \\ &\quad + \left(1-e^{-\chi\Delta}\right) W^j. \\ W^j &= \int V^j(0,z')\, d\psi(z')(1-E) \end{aligned}$$

Let $T^*(\Delta)$ be the solution to the problem in equation (15) of when to update or exit.

Notice that prices do not enter problem (15), as suggested by the earlier discussion. A crucial reason for this is that the value to an entrepreneur of closing an establishment is equal to the opportunity cost of entering other industries and, by optimal sectorial choice, that this in turn is equal to the value of re-entering the same industry. It is not necessary that the entrepreneur be able to re-enter the same industry, only that *other* entrepreneurs have a choice over which industry to enter.

Let $\Upsilon^* \in \{0,1\}$ equal one if the plant optimally updates, and let $X^* \in \{0,1\}$ equal one if the plant optimally exits. We are interested in which firm- and industry-specific parameters affect these rules.

Lemma 2 *The optimal updating strategy Υ^* is an (S,s) policy, censored by the exit rule X^*, where X^* is decreasing in z_t.*

Equilibrium lifecycle dynamics are as follows. The plant is born, and climbs a (stochastic) productivity ladder while simultaneously falling behind the technological frontier. Eventually, learning is sufficiently offset by price declines due to technical progress at the industry level that the plant shrinks until it either updates or – if z is sufficiently low – closes.

Lemma 3 *T^*, Υ^* and X^* are contingent upon z_t and on g_j, but not ω_j, A_{j0}, nor ς_j.*

It follows from Lemma 3 and from the fact that equilibrium spending shares on each type of good j are constant that:

Proposition 3 *On a BGP, entry and exit rules depend on g_j, but do not depend on ω_j (preferences), on A_{j0}, nor on ς_j.*

5 ISTC and Turnover in the Model

This section has several objectives. In a simple version of the model, equilibrium entry and exit rates are proven to be positively related to g_j. This result also holds in a calibration of the general model to US data. In addition, plants in the calibrated model turn out to display investment spikes when they update, and the presence these spikes is also positively linked to g_j.

5.1 Entry and exit in a typical vintage capital model

To characterize the impact of ISTC on the timing of exit, assume for now that:

Assumption 1 $z_l = z_h$, and $\zeta_l = 0$.

Under Assumption 1, there is no learning and no updating. As in a typical vintage capital model, only entrants have access to the frontier technology and, absent any variation in z_t, they are larger than incumbents. This focuses the model on *when*, rather than *whether*, to exit. Also, let $\Delta \to 0$ so, in the limit, the updating rule $T^*(0) = \lim_{\Delta \to 0} T^*(\Delta)$ is a continuous function of parameters.

Proposition 4 *Under Assumption 1, $T(0)$ is strictly decreasing in g_j, and rates of entry and exit are strictly increasing in g_j.*

Corollary 1 *Under Assumption 1, rates of entry and exit are strictly increasing in the rate of decline of the relative price of capital experienced by each industry.*

Two effects impact whether high g_j involves earlier exit. Establishments fall behind the frontier at a rate that depends on g_j, which encourages earlier exit. On the other hand, a high value of g_j also lowers the profits from re-entry, which discourages exit. The proof shows that the first effect dominates the second.[12]

The example above clarifies the dynamics introduced by ISTC, by abstracting from other aspects of establishment lifecycle dynamics. In particular, under Assumption 1, plants shrink until they exit. David Evans (1987a) does find that exiting establishments tend to shrink in the periods before exit. However, surviving establishments tend to grow over time, something from which the example abstracts. To assess whether these results are robust to allowing for other dynamics requires a calibration of the model, to be presented next.

5.2 The model with updating

Returning to the general model without Assumption 1, where $z_l \leq z_h$, and $\zeta_l \geq 0$, suppose $\Delta \to 0$. Now, establishments in industry i solve the problem:

$$V^j(a,z) = \max_T \left\{ \Pi^j(a,z,T) + e_s^{-(\rho+\eta+\chi)(T-a)} \max \left\{ U^j(a,z) \right\}, W^j \right\}$$

where

$$\begin{aligned} \Pi^j(a,z,T) &= e^{(\rho+\eta+\chi)a} \left\{ \int_a^T e^{-(\rho+\eta+\chi)t} \left[z_t^{\frac{1}{1-\alpha_n-\alpha_k}} e^{-\left(\frac{\alpha_k g_j}{1-\alpha_n-\alpha_k}\right)t} \right. \right. \\ &\quad \left. \left. + \eta E_{z'} V^j(t,z') + \chi E_{z'} V^j(0,z')(1-E) \right] dt \right\} \end{aligned} \quad (17)$$

[12] Industries with a high capital share should also experience more entry and exit, something that is consistent with the results of Audretsch (1991). This is because the rate at which a plant's profitability falls behind the frontier is $\frac{\alpha_k g_j}{1-\alpha_n-\alpha_k}$.

and

$$U^j(a,z) = V^j(0, z\zeta_l). \tag{18}$$

The analogue of Proposition 4 can no longer be proven analytically. Still, two additional channels may affect the industry rate of entry and exit. First, if plants may update and may differ in terms of z_t, the set of establishments that exit may depend on g_j. The impact of this selection effect on turnover is ambiguous, and depends on the following condition. Establishments will exit (instead of updating) if $z \leq z^*$ where

$$(1-E)\int V^j(0,z)\,\psi(z)\,dz = V^j(0, z^*\zeta_l). \tag{19}$$

If $\frac{dz^*}{dg} > 0$, then higher rates of ISTC are associated with a larger set of establishments exiting. z^* is endogenous and depends on ψ, so z^* cannot be derived analytically. However, taking the total derivative of (19) with respect to g_j,

$$\frac{dz^*}{dg} = \frac{(1-E)\int V_g^j(0,z)\,\psi(z)\,dz - V_g^j(0, z^*\zeta_l)}{\zeta_l V_z^j(0, z^*\zeta_l)}. \tag{20}$$

It is straightforward to show that $V_z^j(0, z^*\zeta_l) > 0$, and that V_g^j is negative and larger in magnitude for larger z.[13] Thus, a higher value of g_j leads to plants with a broader set of productivity values exiting $\left(\frac{dz^*}{dg} > 0\right)$ provided that z^* is "large" relative to the shock values drawn by entrants. This dovetails nicely with the fact that low initial shock values are a natural feature of many models that wish to match the higher exit rates among entrants documented by Dunne, Roberts and Samuelson (1989) among others.

Second, there will also be a threshold z^{**} such that establishments drawing $z \leq z^{**}$ exit as soon as their shock value is revealed. z^{**} is given by

$$(1-E)\int V^j(0,z)\,\psi(z)\,dz = V^j(0, z^{**}). \tag{21}$$

Clearly $z^{**} = z^*\zeta_l$ so that, once more, $\frac{dz^{**}}{dg} > 0$ provided that z^{**} is "large" relative to the shock values drawn by entrants – and, since $\frac{dz^{**}}{dg} = \zeta_l \frac{dz^*}{dg}$ the two derivatives always share the same sign. Thus, depending on the form of ψ, higher rates of ISTC may also induce stronger selection among firms, so that a larger proportion of the type space exits instead of updating once its technology has become obsolete.

[13] See Lemma 4 in the Appendix.

5.3 Calibration

The model is now calibrated to US industry and macroeconomic data. Detailed data on industry dynamics are mostly available only for the manufacturing sector. Hence, the model is calibrated for a "typical" manufacturing industry, by assuming that g_j takes the median value for the manufacturing industry (the median and the mean are both about 4%), and choosing the remaining parameters so that this industry behaves as the manufacturing sector does on average. Varying g_j while keeping other parameters constant then indicates how much of cross-industry turnover differences is attributed by the model to cross-industry variation in g_j.

Period length is one year, and $\Delta = 1$. Let $\eta = 1$. z is drawn from a grid of 100 points, where $z \in [0, 1]$.

Computing industry exit rates requires calibrating the distribution ψ of entrant productivity and the process f that changes productivity thereafter. ψ is modeled as a log normal distribution truncated at the end points, with mean μ_ψ and standard error σ_ψ. f is modeled as a stochastic learning process, following the interpretation of Dunne et al (1989) of the fact that firms tend to grow faster early in life. Assume that

$$\log z_{t+1} = \nu \log z_t + \varepsilon_{t+1}$$

where the disturbances ε_{t+1} are normal with mean zero and standard deviation σ_ε, but the distribution is truncated so that $z_t \in [0, 1] \, \forall t$.[14]

To calibrate the model requires values for μ_ψ, σ_ψ, ν, σ_ε, ζ_l, η, χ, E and ρ. Some of these parameters can be mapped into the model directly from the data:

1. α_k and α_n are chosen as follows. A value of $\alpha_n = 63\%$ lies in the mid-range of estimates of the labor share. As for α_k, the Bureau of Economic Analysis reports that income from equity and proprietorships has averaged 12% of GDP since the 1950s. Identifying this with $1 - (\alpha_k + \alpha_n)$ yields $\alpha_k = 25\%$.

2. ρ is the rate of time preference, which is related to the equilibrium return on capital. Greenwood et al (1997) use a value of 7%. The US NIPA report economic growth of 2.2% per year over the post-war period, implying that $\rho = 4.5\%$.

[14] To see how this is a learning process, consider this formulation:

$$\log z_{t+1} = \log z_t - (1 - \nu) \log z_t + \varepsilon_{t+1}$$

where ε_{t+1} is drawn from a normal distribution, truncated so as to keep $z_{t+1} \leq 1$. The extent to which firms are likely to increase is lower depending on their size. If $\nu < 1$ then firms will be drawn towards $z = 1$, which is the upper bound.

3. Waddell, Ritz, Norton and Wood (1966) report that it takes about a year to set up a plant in most industries. As for institutional entry costs, Djankov et al (2002) report that the formal cost of entry is under 1% of GDP for the US. Hence, $d = 1$, so $E = 1 - e^{-\rho}$. One year is also the time-to-build assumed in Kydland and Prescott (1982) and Campbell (1998).

Parameter	Value
μ_ψ	0.084
σ_ψ	1.56
ν	0.75
σ_ε	0.2
χ	0.089
ζ_l	0.377
g_j	0.04
α_k	0.25
α_n	0.63
ρ	0.045
d	1

Table 6 – Calibration parameters

The remaining parameters are matched so that the behavior of industry growth rates is similar to a typical manufacturing industry, using simulated annealing – see Bertsimas and Tsitsiklis (1992). These six parameters are μ_ψ, σ_ψ, ζ_l, ν, σ_ε, and χ. The six statistics to be matched are:

1. the exit rate among the young (establishments aged 0-5 years), as reported in Brown, Haltiwanger and Lane (2006).

2. the average growth rate – from Evans (1987a).

3. the average growth rate among the young – from Evans (1987a).

4. the "lumpiness" of investment. Doms and Dunne (1998) report that the share of plants experiencing an increase in the capital stock of 30% or higher is 6%.[15] This requires the model to fit not just the mean and standard deviation

[15] The published version reports a different number, but entrants and exiters are excluded from that sample. 6% is the value in the panel that includes entry and exit.

of growth rates but also the skewness of the growth rate distribution. As discussed later, lumpiness in the model is related to the frequency of updating by incumbents.

5. the log standard deviation of growth rates – from Evans (1987b).

6. the average exit rate (Brown et al (2006)).

Table 6 reports the resulting parameters, and Table 7 the model statistics. The matches are generally quite tight. Interestingly, average size among entrants is only 2/3 of the average size among all plants. This is in spite of the fact that entrants adopt the frontier technology, as in a canonical vintage capital model. The average updating lag is 5.4 years, so that the "updating rate" (conditional on not exiting) is about the same as the exit rate.

In the model, the exogenous exit rate is $\chi = 8.9\%$. Thus, annual turnover of about 4% is endogenous and due to ISTC, the remainder being attributed to factors that are not modeled explicitly. This implies that industry exit rates must be greater than or equal to 8.9% in the model. The minimum long term industry exit rate in the data (as measured by the minimum industry turnover rate divided by two) is very close, at 8.7%.

Statistic	US data	Model
Exit rate (young)	17%	18%
Exit rate	16%	13%
Growth rate (young)	6%	6%
Growth rate	2%	2%
Growth rate, log s.d.	-2	-2
Plants with investment lumps	6%	5%

Table 7 – Model statistics used in calibration.

5.4 Results

5.4.1 Entry, exit and ISTC

We wish to see first of all whether g_j is positively related to entry and exit in the calibrated model, which allows for updating as well as entry as a means of technology adoption. If so, to what extent can the model account for cross-industry variation in rates of entry and exit?

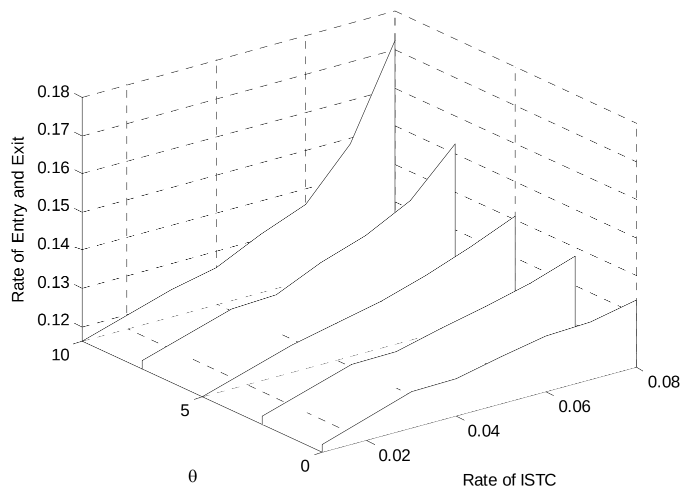

Figure 2: Rate of entry and exit, depending on the rate of ISTC and on the relationship between ISTC and adoption costs (θ).

Entry and exit rates are positively related to g_j in the model. Cummins and Violante (2002) report rates of ISTC ranging from 1% to 8% across industries. In the model, this generates a range of entry rates from 11.8% to 13.4% per year. Thus, even though most firms are in fact growing in the calibrated economy, and although incumbents have the option to update instead of exiting, a higher rate of ISTC nonetheless increases industry turnover. In the data entry rates range from 8.7% to 17.1%, so the model covers about 20% of the range. This is similar to the R^2 of the regressions between ISTC and turnover.

5.4.2 Adjustment costs and ISTC

Several authors have pointed out that higher rates of ISTC are likely to be related to higher adoption costs. In a one-sector general equilibrium model, Samaniego (2007) finds that allowing adoption costs to respond to the rate of ISTC can be important for its impact on technology adoption decisions. Hence, allow $\zeta_l = \zeta_l(g_j)$, $\zeta_l' \leq 0$. Henceforth set $\zeta_l(g_j) = \bar{\zeta} + \theta g_j$, where for a given value of θ the value of $\bar{\zeta}$ is chosen so that $\zeta_l(g_j)$ equals the benchmark value for the median g_j.

Greenwood and Jovanovic (2001) find that investments in information technology had a rate of return of about 2000% in the late 1990s, interpreting this as an indicator

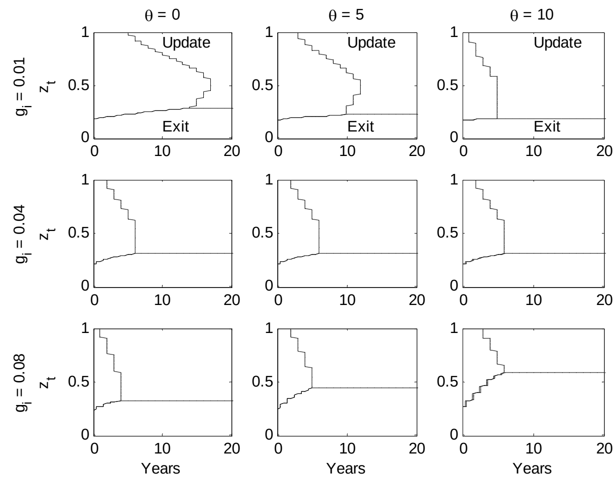

Figure 3: Decision rules for different rates of ISTC g_j and different values of the adoption cost parameter θ. The exit threshold z^* is visibly more sensitive to changes in g_j when θ is high, whereas the date of updating or exit T^* is more sensitive to g_j when θ is low.

of unmeasured adoption costs. When $\theta = 8$ the difference between adoption costs in an economy with $g_j = 0.01$ and one with $g_j = 0.08$ is a factor of 5. Considering that information technology comprises over half of measured capital investment in the US suggests that $\theta \in [0, 10]$ covers the empirically relevant range.

Since adoption costs discourage updating vis-a-vis exit, it is to be expected that $\theta > 0$ might be associated with a wider divergence of cross-industry turnover rates generated by g_j. See Figure 2. For $\theta = 10$, the model entry rates range from 11.4% to 17.2%, which covers 67% of the range of entry and exit rates in the data. Thus, the model accounts for about 20%-70% of cross-industry variation in entry and exit rates, depending on θ.

Selection and obsolescence play very different roles depending on the value of θ. In the baseline, where $\theta = 0$, selection plays very little role in the link between turnover and ISTC. Observe the leftmost column of Figure 3, where the line separating regions of the type space corresponding to exit and updating depend very little on the value of g_j. Similarly, in Table 8, only a very small proportion of plants lies between the value of z^* corresponding to $g_j = 4\%$ and the values of z^* corresponding to other values of g_j. There are large differences in profitability between plants with different values of z and, when θ is low, z is the main determinant of *which* plants exit, whereas

g_j governs the *timing* of exit and of updating. On the other hand, for high values of θ the proportion of plants affected by the shift in z^* is much larger, indicating that selection has a greater impact. When θ is high, because updating costs depend so much on g_j, a change in g_j also corresponds to an increase in the eventual costs of continuation, which further strengthens the selection effect.

By contrast, obsolescence is very important when $\theta = 0$: observe the large differences in the dates at which plants update or exit depending on the value of g_j, in the first column of Figure 3. When $\theta = 10$, these dates hardly vary with g_j at all.

To sum up, high values of θ allow ISTC to account for the majority of industry differences in turnover. On the other hand, if we focus on the proportion of industry differences that can be explained by ISTC in the regressions, then the data are consistent with low values of θ. Thus, the model suggests that obsolescence (not selection) is the primary channel linking ISTC to turnover.

	$\theta = 0$	$\theta = 5$	$\theta = 10$
$g_j = 0.01$	0.8%	2.2%	2.9%
$g_j = 0.04$	0%	0%	0%
$g_j = 0.08$	0.3%	9.1%	32.9%

Table 8 – Proportion of plants affected by the equilibrium change in z^* relative to the baseline value of g_j, which is 0.04.

6 Discussion

6.1 Structural Change

In the model, the rate of ISTC (g_j) is positively related to turnover rates when ISTC is embodied in the plant. In addition, the rate of disembodied technical change (ς_j) is not. This is partly related to the assumed preference structure, whereby industry shares are parametrically determined. This is consistent with the absence of a significant relationship between industry composition and entry costs found by Fisman and Sarria-Allende (2004). At the same time, Ngai and Pissarides (2007) show that, when agents have CES preferences, a BGP is consistent with structural change whereby industries grow or shrink as a share of GDP depending on their rates of technical change.

Allowing for structural change leads to some new insights. Suppose as in Ngai and Pissarides (2007) that

$$y_t = \left(\sum_{j=1}^{J} \omega_j y_{jt}^{\frac{\upsilon-1}{\upsilon}} \right)^{\frac{\upsilon}{\upsilon-1}}, \; \omega_j > 0, \; \sum_{j=1}^{J} \omega_j = 1, \; \upsilon > 0. \tag{22}$$

Along a balanced growth path, changes in product prices offset technical change so that equation (14) still holds. Consequently, along a BGP, all the results of this paper continue to hold regarding the plant entry, exit and updating rules. However, if $\upsilon \neq 1$, the existence proof of Proposition (1) would no longer be able to take equilibrium sector shares as determined by ω_i: shares would vary at every date. While hazard rates are equal for all cohorts, entry and exit rates will no longer be equal at all dates when there is structural change: entry will exceed exit in growing sectors. This is because the size of a firm of type (a, z) in industry j will not change over time: rather, it is the extensive margin (number of plants) that varies in transition.

Let $\mu_t^j \left(M_t^j \right)$ be the mass of all plants in industry j at time t, so that $g_\mu^j = \log \mu_{t+1}^j \left(M_{t+1}^j \right) - \log \mu_t^j \left(M_t^j \right)$ is the growth rate of plants in industry j.

Proposition 5 *When preferences satisfy equation* (22)*, a balanced growth path exists. Along this path,*

$$g_\mu^i - g_\mu^j = (\upsilon - 1) \left[(\alpha_k g_i + \varsigma_i) - (\alpha_k g_j + \varsigma_j) \right] \tag{23}$$

Thus if $\upsilon < 1$, the number of plants in industry i will shrink relative to industry j if and only if technical change (as measured by $\alpha_k g_i + \varsigma_i$) is more rapid in sector i. The opposite holds if $\upsilon > 1$. If $\upsilon \to 1$ then there is no structural change.

Structural change could alter the ability of the model to account for cross-industry differences in entry and exit rates, for three reasons. One is that it allows differences in ς_j to affect rates of entry and exit. If $\upsilon < 1$, this might counteract the results if g_i and ς_i are positively correlated. Second, if $\upsilon < 1$, then industries with high values of g_i would themselves be industries that shrink, which would offset the relationship between entry and ISTC (although it might enhance the relationship with exit). The opposite holds if $\upsilon > 1$. Finally, structural change implies that some industries will be skewed towards (or away from) younger plants, and the effect of these differences in composition on equilibrium exit rates is a priori unclear.

The impact of structural change on the model results can be assessed as follows. The model can be used to compute equilibrium behavior and hazard rates for each industry using the values of g_j in Table 1. Then, given a value for υ, equation (23) indicates the gap between entry and exit rates for each industry, relative to a benchmark. The benchmark used was the median value of $\alpha_k g_j + \varsigma_j$. This yields the growth rate of the number of firms in each industry. Then, given equilibrium decisions rules, the law of motion for μ_t^j can be amended to account for the steadily increasing (or decreasing) mass of entrants over time in each industry. Industry rates of entry and exit can then be computed.

Values of ς_j are drawn from the TFP growth estimates of Jorgenson, Ho, Samuels and Stiroh (2006).[16] TFP and ISTC are uncorrelated in the data (-6.9%), suggesting that structural change is unlikely to affect results through variation in ς_j except by adding "noise." Let $\upsilon = 0.3$.[17] An issue that comes up is that the industry Computers and Electronic Products is an extreme outlier in terms of measured TFP (9% higher than the next highest industry), so that it was also an outlier in terms of structural change in the model (it shrinks by 5% more than the next fastest-shrinking industry). In the data this is not the case. This could be a measurement problem, or it could be that the output of this industry has different substitutability properties compared to other goods, or is experiencing structural change for different reasons over the period during which entry and exit rates were computed. Thus, results both with and without this industry are reported.

	Model			
	With comp.		Without comp.	
Data	Entry	Exit	Entry	Exit
ETC	25% (0.116)	37%** (0.018)	55%*** (0.000)	71%*** (0.000)
Entry	47%*** (0.002)	44%*** (0.004)	71%*** (0.000)	65%*** (0.000)
Exit	50%*** (0.000)	48%*** (0.001)	71%*** (0.000)	67%*** (0.000)

Table 9 – Correlations between model statistics and the data, under structural change.

[16] Greenwood et al (1997) argue that TFP measurements that do not account for ISTC may attribute a portion of ISTC to TFP. Hence, ς_j is the residual in a regression of g_j on the TFP measure of Jorgenson et al (2006).

This exercise excludes Rental Services and Other Services as the mapping between the industry classification used herein and that of Jorgenson et al (2006) was unclear.

[17] Regressing $\alpha_k g_j + \varsigma_j$ on the difference between entry and exit rates reported in the data yielded a value of $\upsilon = 0.67$, with a P-value of 0.112. If the industry Computers and Electronic Products was eliminated, then the value was $\upsilon = 0.89$, with a P-value of 0.012. Ngai and Pissarides estimate in a 3-sector model that $\upsilon = 0.3$. Out of all these values, the one that yields the largest divergences from stationary behavior is $\upsilon = 0.3$.

Results are reported in Table 9. Excluding Computers and Electronic Products, turnover and ISTC are highly correlated even when there is structural change in the model. Thus, model results are robust to allowing for technology-induced structural change. Including Computers and Electronic Products, relationships are weaker but still mostly significant. Interestingly, the relationship with ISTC is weaker for entry than for exit when there is structural change, consistent with the fact that the empirical results are also generally weaker for entry than for exit.

6.2 ISTC, Lumpiness and Exit

Not only does a higher rate of ISTC lead to earlier exit in the model: among plants that do not close, it also leads to earlier updating. This too has a significant impact on lifecycle dynamics, even though it does not lead to exit. Instead, it leads to a significant "spike" in investment at the establishment level.

It is known since at least Doms and Dunne (1998) that establishment level investment is "lumpy," i.e. characterized by periodic spikes. A "spike" is defined as a year in which investment expenditures exceed 30% of the establishment capital stock. These "spikes" are generally modeled using non-convex adjustment costs as, for example, in Khan and Thomas (2007). In the model, such spikes may occur because of large changes in z_t or because of updating but, in practice, all the spikes in the benchmark economy are due to updating as variance in z_t is relatively low.

Figure 4 shows that, in the benchmark economy ($\theta = 0$), the frequency of investment lumps is positively related to the rate of ISTC. This is the case even when adjustment costs are increasing in g_j, except when θ is so high that updating is actually discouraged by increases in g_j. This is intuitive, if turnover and investment spikes both reflect significant changes in the technology in use at the establishment level. Thus, a positive relationship between the rate of ISTC and the frequency of investment spikes can be viewed as an independent prediction of the calibrated model, in addition to the positive relationship between ISTC and turnover.

To look at whether investment is disproportionately lumpy in industries with high rates of ISTC, "lumpiness" is measured using US data from Compustat. Over the period 1997-2004, identify whether each firm in the database experiences an investment "spike", as defined by Doms and Dunne (1998). The index *Lumpy* for industry j is the proportion of firms in j that experienced any spikes at all over the period.[18] Compustat covers all publicly traded firms in the US so that, while

[18] "Investment" is DATA128 (capital expenditures) and "capital stock" is DATA8 (net property, plant and equipment). The median annual industry value of this variable across manufacturing industries is 6%, strikingly similar to the value reported by Doms and Dunne (1998).

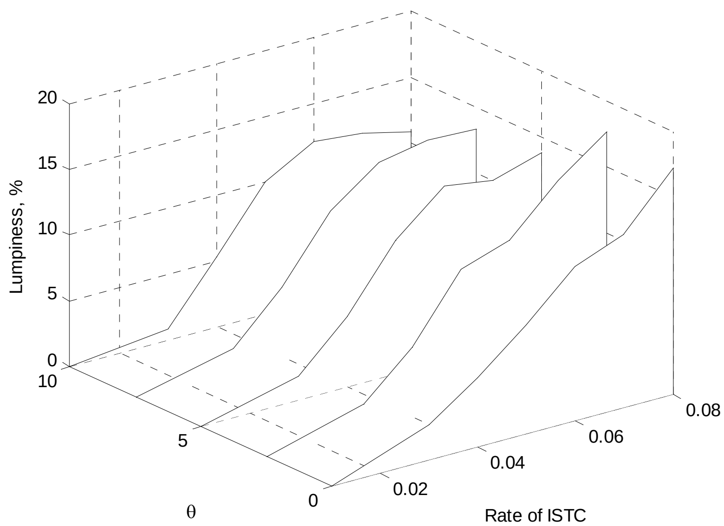

Figure 4: Investment lumpiness: the proportion of firms in the model economy that display an investment "spike" each year, depending on g_j and on θ.

not being a representative sample of US firms, firms in Compustat are likely to be financially unconstrained, so that their behavior reflects fundamentally technological factors. The unit of observation in Compustat is the firm, so that multi-unit firms may not display spikes due to aggregation. This may not be a concern as, to the extent that plants run by the same firm share z_t – the definition of a firm, according to theories such as Faria (2007) and Hopenhayn (2007) – updating across these plants will likely be synchronized. Nonetheless, lumpiness is also computed for small firms only, as measured by employment. The disadvantage of the size-based measures is that there are very few firms in Compustat in some industries below certain size thresholds, so these measures are likely to be noisy. Table 11 shows that lumpiness is indeed positively related to turnover and to ISTC, in spite of all these caveats. Moreover, it is not related to the Jorgenson et al (2006) TFP growth measure, as anticipated by the model.

Size	Turnover	ISTC	TFP
All	.43*** (.002)	.40*** (.005)	.10 (.494)
≤ 500	.30** (.028)	.36*** (.007)	.18 (.193)
≤ 250	.25* (.100)	.32** (.041)	.09 (.546)
≤ 50	.27* (.071)	.28* (.074)	.11 (.455)

Table 11 – Correlations between lumpiness, turnover and technical change, based on US data and the rates of entry and exit computed earlier.

6.3 ISTC and Policy: An Application to entry costs

Section 2 reports that entry costs reduce turnover in industries in which ISTC is rapid, compared to industries in which it is sluggish. The same happens in the model economy. Raising the entry cost from one to two times GDP has two effects. First, it suppresses entry and exit in the model. Second, this drop is more pronounced for higher values of ISTC: when $g_j = 1\%$ entry drops by 1.3%, whereas when $g_j = 8\%$ entry drops by 1.8%. These changes are smaller than cross industry differences in turnover, so the model suggests that entry and exit rates should be decreasing in entry costs, and more compressed when entry is costly, yet still increasing in g_j. This is exactly what we find in the data.

A long-standing debate going back at least to Denison (1964) questions the policy relevance of ISTC. The debate relates to whether changes in investment rates over time are likely to change the distribution of capital quality enough to have significant macroeconomic impact: Denison (1964) suggests that changes in investment rates should little affect aggregate economic outcomes because of cross-industry differences in the rate of ISTC. In the model, policy can affect aggregates even in the absence of any fluctuations – because policy may affect the lifecycle dynamics of plants and the "business demography" of the economy.

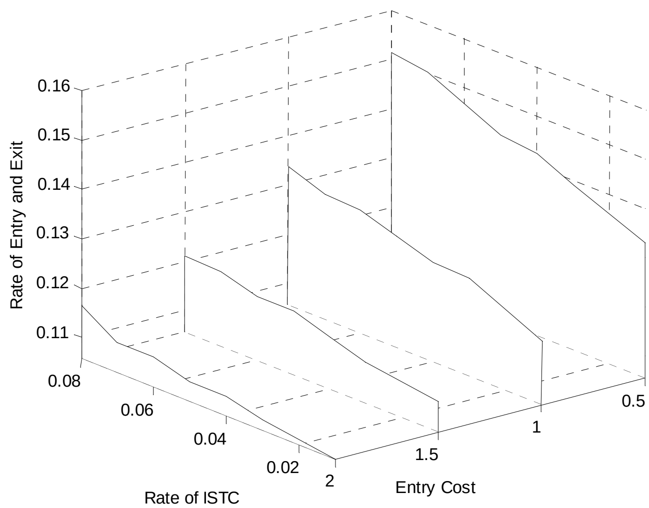

Figure 5: Rate of entry and exit, depending on the rate of ISTC and on the level of entry costs as a percentage of GDP. The graph assumes that $\theta = 0$. Flatter curves for higher entry costs are consistent with the empirically observed interaction between entry costs and ISTC.

For example, consider the role of entry costs in the model. Djankov et al (2002) find that entry costs appear negatively related to GDP levels across countries. The same may be true in the model economy: in Figure 5, an increase in entry costs delays exit, so that a certain proportion of plants is operating with an older technology than otherwise.

From the US NIPA, compute the share of GDP made up by each of the 41 industries in the data set (which map into the demand parameters $\{\omega_j\}_j$).[19] Given the change in updating and exit behavior in each industry predicted by the model based on industry values of g_j, the change in steady state *aggregate* GDP can be computed from a change in entry costs using these shares.

Table 10 reports that entry costs can have a significant impact on GDP through the obsolescence channel. According to the Djankov et al (2002) measure, institutional entry costs range up to 80% of GDP per head (or $d = 1.8$) for countries in the sample, so entry costs can reduce steady state GDP by about 1% in the sample, or up to 1.4% in an economy with entry costs of around 200% of GDP per capita (or $d = 3.0$ as in Egypt or Vietnam). Thus, the effects of high entry costs on GDP through the obsolescence channel are of roughly the same magnitude as the effects of firing costs found by Hopenhayn and Rogerson (1993) in a one-sector model, suggesting that ISTC can be of policy-relevance even in the absence of fluctuations in investment rates. Interestingly, results do not depend on the value of θ: while the link between ISTC and adoption costs is important for turnover, it does not appear to be important for policy, at least as far as entry costs are concerned.

	Entry cost d					
θ	1.0	1.25	1.5	2.0	2.5	3.0
0	0	-0.3	-0.5	-0.8	-1.1	-1.4
5	0	-0.3	-0.5	-0.8	-1.2	-1.5
10	0	-0.3	-0.5	-0.8	-1.2	-1.6

Table 10 – Percentage change in GDP due to entry costs, relative to GDP in the benchmark economy.

6.4 Concluding Remarks

This paper is motivated by two observations. First, cross-industry differences in entry and exit rates remain largely unexplained. Second, vintage capital models

[19] This exercise excludes the share of GDP made up for by government services, which averaged 13% over the postwar period. $\bar{c}$ is set so that entrepreneurs compose about 2% of the labor force in the benchmark economy, as reported by Gollin (2002). Then, $\bar{c} = 0.099$.

generally have a strong prediction: that, if technical progress is somehow embodied in the plant, it should be positively related to rates of entry and exit. The paper concentrates upon the case of technical progress in the production of the capital goods used by each industry, finding support for this prediction. The paper thus draws a relationship between entry, exit and ISTC, a factor that Greenwood et al (1997) among others have found to account for a significant portion of economic growth. At the same time, there may be forms of technical change that are embodied in assets other than capital *per se*. For example, it would be interesting to see how far one can explain industry differences in entry and exit rates using differences in research or knowledge intensity.

A Appendix

A.1 Proofs

The proof of Proposition 1 is a consequence of the propositions and lemmata below.
Proof of Proposition 2. The household's first order condition for investment implies that for any industries i and j

$$\frac{r_x^i}{r_{x'}^j} = \frac{x'}{x} \tag{24}$$

where time subscripts are omitted for brevity. This is because the return to capital must be equal and, since the cost of capital in terms of consumption is linear in x^{-1}, that means the return to a unit of capital must also be linear in x^{-1} for there to be investment (or disinvestment) in all types. Moreover it means that the interest rate depends only on the level of x, not on the industry. Thus, in particular,

$$r_x^j = \frac{\bar{x}_t^j}{x} r_{\bar{x}_t^j}^j \tag{25}$$

or, for any technology $\tau \leq t$, from (24),

$$r_{xt}^j = r_{\bar{x}_0^j}^j e^{-g_j \tau} \tag{26}$$

where $r_{\bar{x}_0^j}^j$ is the interest rate on capital of vintage zero. Thus, capital is relatively more expensive to rent for plants with older technology. Note that τ here is defined as the date at which the establishment's technology was on the frontier, and we can rewrite the establishment's problem in those terms instead of in terms of x. ■

Proof of Lemmata 1, 2 and 3. Notice that production is a static decision. Thus

$$\pi(z_t, x_t) = \max_{n_t, k_t} \left\{ A_{jt} p_{jt} z_t k_t^{\alpha_k} n_t^{\alpha_n} - r_{xt}^j k_t - w_t n_t \right\} \tag{27}$$

$$n_t = \left(\frac{\alpha_n A_{jt} p_{jt} z_t k_t^{\alpha_k}}{w_t} \right)^{\frac{1}{1-\alpha_n}} \tag{28}$$

so, plugging in this result yields

$$\pi(z_t, x_t) = \max_{n_t, k_t} \left\{ C \left(p_{jt} A_{jt} z_t k_t^{\alpha_k} \right)^{\frac{1}{1-\alpha_n}} - r_{j0} e^{-g_j \tau} k_t \right\}$$

where $r_{j0} = r_{\bar{x}j0}^j$. Let $\alpha = \frac{\alpha_k}{1-\alpha_n}$, $C = \left(\frac{\alpha_n^{\frac{\alpha_n}{1-\alpha_n}} - \alpha_n^{\frac{1}{1-\alpha_n}}}{w_t^{\frac{\alpha_n}{1-\alpha_n}}} \right)$. Then, optimal capital use is $k_t = \left(\frac{\alpha C (p_{jt} A_{jt} z_t)^{\frac{1}{1-\alpha_n}}}{r_{x,t}} \right)^{\frac{1}{1-\alpha}}$. Plugging this back in yields

$$\pi(z_t, x_t) = (p_{jt} A_{jt} z_t)^{\frac{1}{1-\alpha_n-\alpha_k}} \frac{C^{\frac{1}{1-\alpha}}}{r_{x,t}^{\frac{\alpha_k}{1-\alpha_n-\alpha_k}}} \left[\alpha^{\frac{\alpha_k}{1-\alpha_n-\alpha_k}} - \alpha^{\frac{1-\alpha_n}{1-\alpha_n-\alpha_k}} \right] \tag{29}$$

Now, given that $r_x^j = r_{j0} e^{-g_j \tau}$, this becomes

$$\pi(z_t, x_t) = (p_{jt} A_{jt} z_t)^{\frac{1}{1-\alpha_n-\alpha_k}} \frac{C^{\frac{1}{1-\alpha}}}{\left(r_{j0} e^{-g_j \tau} \right)^{\frac{\alpha_k}{1-\alpha_n-\alpha_k}}} \left[\alpha^{\frac{\alpha_k}{1-\alpha_n-\alpha_k}} - \alpha^{\frac{1-\alpha_n}{1-\alpha_n-\alpha_k}} \right] \tag{30}$$

Suppose labor is the numeraire. Then the value of an entrant must be constant over time, so that, if ϕ_j is the growth rate of p_{jt} then

$$\phi_j = -g_j \alpha_k - \varsigma_j, \; p_{jt} = p_{j0} e^{-(\alpha_k g_j + \varsigma_j) t} \tag{31}$$

Then, if $B_j = C^{\frac{1}{1-\alpha}} \left[\alpha^{\frac{\alpha_k}{1-\alpha_n-\alpha_k}} - \alpha^{\frac{1-\alpha_n}{1-\alpha_n-\alpha_k}} \right] (p_{j0} A_{j0})^{\frac{1}{1-\alpha_n-\alpha_k}} r_{j0}^{\frac{-\alpha_k}{1-\alpha_n-\alpha_k}}$,

$$\pi(z_t, \tau, t) = B_j z_t^{\frac{1}{1-\alpha_n-\alpha_k}} \left(e^{-\alpha_k g_j (t-\tau)} \right)^{\frac{1}{1-\alpha_n-\alpha_k}} \tag{32}$$

Let $a = t - \tau$ be the age of the establishment's technology (with respect to the frontier). Then,

$$\pi(z_t, a) = B_j z_t^{\frac{1}{1-\alpha_n-\alpha_k}} e^{-\frac{\alpha_k g_j}{1-\alpha_n-\alpha_k} a} \tag{33}$$

or, setting $\gamma_j = \frac{\alpha_k g_j}{1-\alpha_n-\alpha_k}$ and $s_t = z_t^{\frac{1}{1-\alpha_n-\alpha_k}}$,

$$\pi(z_t, a) = B_j s_t e^{-\gamma_j a} \tag{34}$$

Thus, here, establishment profits depend only on z and on the distance from the industry frontier. With this under our belts, we can write the establishment's problem recursively, impose condition (8) for industry j, and divide through by B_j to obtain value function (15), which does not depend on the date, only on industry parameters. ■

Proof of Proposition 3. Corollary of Lemma 3 ■

Proof of Proposition 1. First consider the measure over establishments at date t. It follows the transition equation

$$\begin{aligned}
\mu^j_{t+\Delta}(S,T) \;=\; & \int_{(s,t-\Delta)\in(S,T)} e^{-\chi\Delta}\varepsilon_j \psi(s)\,dt \\
& + \int_{(s,t-\Delta)\in(S,T)} e^{-\chi\Delta}e^{-\eta\Delta}\left(1-\Upsilon(s,t)\right)\left(1-X(s,t)\right)d\mu^j_t(s,t) \\
& + \int_s \int_{(s',t-\Delta)\in(S,T)} e^{-\chi\Delta}\left(1-e^{-\eta\Delta}\right) \\
& \times\left(1-\Upsilon(s',t)\right)\left(1-X(s',t)\right)f(s'|s)\,d\mu^j_t(s,t) \\
& + I(0\in T)\int_{\substack{s\in S\\ t<\infty}} e^{-\chi\Delta}e^{-\eta\Delta}\Upsilon(s,t)\left(1-X(s,t)\right)d\mu^j_t(s,t) \\
& + I(0\in T)\int_s \int_{(s',t-\Delta)\in(S,T)} e^{-\chi\Delta}\left(1-e^{-\eta\Delta}\right) \\
& \times\Upsilon(s',t)\left(1-X(s',t)\right)f(s'|s)\,d\mu^j_t(s,t)
\end{aligned} \tag{35}$$

where S is a Borel subset of the type space over z (redefined in terms of s) and T is a subset of ages. Abusing notation somewhat, f and ψ are now redefined with respect to s rather than z.

This satisfies the requirements of Theorems 1 and 2 from Hopenhayn and Prescott (1992), so a fixed point μ^*_j exists and is unique, given a constant volume of entrants ε_j.

Set the numeraire $w_t = 1$. As shown by Ngai and Pissarides (2007) the consumer's solution implies that across goods i, j, $\frac{p_i c_i}{p_j c_j} = \frac{\omega_i}{\omega_j}$, so $p_j c_j = \omega_j s_c$ where s_c is total spending on consumption and the demand for each good j is $c_j = s_c \frac{\omega_j}{p_j}$. Hence, whatever spending on consumption might be, the share of each good is fixed. Define

$p_c \equiv \frac{s_c}{c} = \prod_{j=1}^{J} p_j^{\omega_j}$. Now in a BGP it must be that their income is growing. So, for constant labor, need $c_t^{-\kappa} w_t/p$ to be constant over time, so $g_p = g_c^{-\kappa} g_w$. Setting $w = 1$ to be the numeraire, then $g_p = g_c^{-\kappa}$. Recall that p_{jt} drops over time at rate $-\phi_j$. Given a constant mass of establishments μ_j^*, real output grows at rate $-\phi_j$, so this equation holds provided $c_{j0} = s_c \frac{\omega_j}{p_{j0}}$. Now p_{j0} is given by the entry condition (8), so shares of consumption are given and

$$p_c = \prod_{j=1}^{J} p_j^{\omega_j} \tag{36}$$

$$= \left[\prod_{j=1}^{J} p_{j0}^{\omega_j}\right] e^{\sum_j \phi_j \omega_j t} \tag{37}$$

so real consumption grows at a constant rate $\kappa \sum_j \phi_j \omega_j$, and the share of each type of good is constant and given by p_{j0}. Notice that the output of each establishment is not linear in p_{j0} (it is strictly convex) so that for any p_{j0} there is a unique mass of establishments in that industry that can satisfy demand for a given value of consumption spending s_c. (which pins down the entry rates ε_j). Conversely, given a total mass of establishments s_c and the distribution of establishments over industries is given. Preferences are such that a constant share of income is invested, so it remains to check that income is constant (in units of labor) and that the labor market clears. Turning to the budget constraint, income in (in units of labor) is constant provided the measure over establishments is constant. Income is linear in the total number of establishments. Hence, the number of establishments that clears the labor market is the equilibrium number, which leads to equilibrium values of income, spending, and all other variables as above. Such a number exists because labor supply is inelastic – see Hopenhayn and Rogerson (1993). ■

Proof of Proposition 4. As $\Delta \to 0$, the establishment's problem approaches the continuous time problem

$$V^j(a,s) = e^{(\rho+\chi)a} \max_T \left\{ \int_a^T e^{-(\rho+\chi)a} \left[s e^{-\gamma_j t} + \chi W \right] dt \right. \tag{38}$$

$$\left. e^{-(\rho+\chi)T} W \right\}, \ W = V^j(0,s)(1-E) \tag{39}$$

Although this is a continuous time problem, it can be approached using discrete time recursive methods. The first order conditions for T given W are

$$s e^{-\gamma_j T} + \chi W = (\rho+\chi) W.$$

so that T is decreasing in W. Suppose W is the payoff assuming that $\gamma_j = 0$. That is strictly larger than $V^j(0,s)(1-E)$, so the true solution (if it exists) necessarily has T larger than T^{**}, which is the solution to that problem.

Now consider the same problem subject to $T \in [T^{**}, \infty)$, and write the Bellman equation

$$\begin{aligned} BV^j(0,s) &= \max_{T \in [T^{**},\infty)} \left\{ \int_0^T e^{-(\rho+\chi)a} s e^{-\gamma_j t} dt + \chi W \right. && (40) \\ & \left. e^{-(\rho+\chi)T} W \right\}, \; W = V^j(0,s)(1-E) && (41) \end{aligned}$$

where B is the Bellman operator. Blackwell's conditions are satisfied (because T is bounded) so B is a contraction and the problem has a unique solution.

Let T^* be the solution. Its derivative with respect to g satisfies

$$-\gamma T_g - T = \frac{W_g}{W}.$$

Solving for W,

$$\begin{aligned} W\left[\frac{1}{1-E} - e^{-\rho T}\right] &= \int_0^T e^{-\rho a}\left[s e^{-\gamma_j t}\right] dt && (42) \\ W &= \frac{s\left[1 - e^{-(\rho+\gamma_j)T}\right]}{(\rho+\gamma_j)\left[\frac{1}{1-E} - e^{-\rho T}\right]} && (43) \end{aligned}$$

and

$$W_g = \frac{-sTe^{-(\rho+\gamma_j)T}(\rho+\gamma_j) - s\left[1 - e^{-(\rho+\gamma_j)T}\right]}{(\rho+\gamma_j)^2\left[\frac{1}{1-E} - e^{-\rho T}\right]} \qquad (44)$$

So $T_g < 0$ if and only if

$$T = \frac{Te^{-(\rho+\gamma_j)T}(\rho+\gamma_j) + \left[1 - e^{-(\rho+\gamma_j)T}\right]}{(\rho+\gamma_j)\left[1 - e^{-(\rho+\gamma_j)T}\right]} \qquad (45)$$

As $g \to 0$, $T \to \infty$ so this becomes

$$1 > \frac{e^{-(\rho+\gamma_j)T}\rho + \frac{1}{T}}{\rho} = 0 \qquad (46)$$

so the condition is satisfied. More generally, the inequality implies

$$\left(\rho+\gamma_j\right)\left[1-2e^{-\left(\rho+\gamma_j\right)T}\right]T>\left[1-e^{-\left(\rho+\gamma_j\right)T}\right] \tag{47}$$

so define $\hat{T}$ as

$$\left(\rho+\gamma_j\right)\left[1-2e^{-\left(\rho+\gamma_j\right)\tau}\right]\hat{T}=\left[1-e^{-\left(\rho+\gamma_j\right)\tau}\right] \tag{48}$$

If there exist g such that $T_g > 0$ then there must exists a g such that $T = \hat{T}$. However, the only solution to this equation is $\hat{T} = 0$, and T is always positive, so we have a contradiction. The remainder of the proof is to show that the steady state entry and exit rate is increasing in T^*. The exit rate as $\Delta \to 0$ is $\lim_{\Delta\to+0}\tilde{\xi}(\Delta)/\Delta$, where $\tilde{\xi}(\Delta)=\frac{\varepsilon_i\int_{T^*-\Delta}^{T^*}e^{-\chi T^*}dt}{e_{i\varepsilon}/\chi}$, so that $\lim_{\Delta\to+0}\frac{\tilde{\xi}(\Delta)}{\Delta}=\xi e^{-\zeta T^*}$. ■

Lemma 4 *V_g^j is negative and larger in magnitude for larger z.*

Proof. Without loss of generality let $\Delta = 1$ and let β be the discount factor along a BGP. Let $D(a, s_t) = U(s_t) - E_{s+1}V(a, s_{t+1})$. Then, if B is the Bellman operator, D is the fixed point $D : \tilde{D} = B\tilde{D}$ of

$$\begin{aligned} B\tilde{D}(a,s_t) &= E_{s_{t+1}}\left\{\gamma s_{t+1}-\gamma^{-\tau}s_{t+1}\right\} \\ &\quad +\beta E_{s_{t+2}}\max\left\{\begin{array}{c} W,\tilde{D}(a+1,s_{t+1})+ \\ E_{s_{t+1}}V(1,s_{t+1}),E_{s_{t+1}}V(1,s_{t+1}) \end{array}\right\} \\ &\quad -\beta E_{s_{t+2}}\max\left\{\begin{array}{c} W,\tilde{D}(a+1,s_t)+E_{s_{t+1}}V(a+1,s_{t+1}), \\ E_{s_{t+1}}V(a+1,s_{t+1}) \end{array}\right\} \end{aligned}$$

where V is taken as given. B is a contraction that satisfies Blackwell's conditions and which can be shown to be increasing in s because both V and $\{\gamma s_{t+1} - \gamma^{-\tau}s_{t+1}\}$ are. ■

Proof of Proposition 5. Note that price profiles (24) and (31) continue to apply, so that Lemmata 1, 2 and 3 hold. Thus, given w_t and setting it to one (as the numeraire), the same market clearing price levels obtain as before. Consequently, plant sizes are constant over time along a BGP even if there is structural change and, as the labor allocation in one industry rises or falls over time, it is the number of plants that adjusts accordingly. Let $T_{jt} = e^{\left(\alpha_k g_j+\varsigma_j\right)t}$. Following the proof of Ngai and Pissarides (2007), it can be shown that relative labor allocations across industries depend on relative values of T_{jt}, so that

$$\frac{\mu_t^i\left(M_t^i\right)}{\mu_t^j\left(M_t^j\right)}=c_{ij}\frac{\omega_i^{\upsilon}T_{it}^{\upsilon-1}}{\omega_j^{\upsilon}T_{jt}^{\upsilon-1}} \tag{ni}$$

where c_{ij} is a constant that depends on initial conditions in each industry. Thus, taking logs and time-differencing,

$$g_{\mu}^{i}-g_{\mu}^{j}=(\upsilon-1)\left[(\alpha_{k}g_{i}+\varsigma_{i})-(\alpha_{k}g_{j}+\varsigma_{j})\right] \tag{49}$$

Thus if $\upsilon < 1$, industry i will shrink relative to industry j if and only if technical change (as measured by $\alpha_k g_i + \varsigma_i$) is more rapid in sector i. The opposite holds if $\upsilon > 1$. If $\upsilon = 1$ then there is no structural change and we are in the case studied earlier. Existence follows from Ngai and Pissarides (2007), which pins down the paths for labor allocations and hence for $\mu_t^i\left(M_t^i\right)$. ■

A.2 Data Appendix

Entry and exit rates are computed from Eurostat. An observation in Eurostat is an "enterprise," defined as "the smallest combination of legal units that is an organisational unit producing goods or services, which benefits from a certain degree of autonomy in decision-making, especially for the allocation of its current resources. An enterprise carries out one or more activities at one or more locations. An enterprise may be a sole legal unit." (Council Regulation (EEC), No. 696/93, Section III A of 15.03.1993). Birth rate: number of enterprise births in the reference period (t) divided by the number of enterprises active in t. Death rate: number of enterprise deaths in the reference period (t) divided by the number of enterprises active in t. Turnover rate: the sum of the birth rate and the death rate.

Cummins and Violante (2002) construct quality-adjusted capital goods prices for 26 types of equipment goods types. The industry rage of ISTC is based on aggregating these prices by industry, using the BEA industry-level capital flow tables, divided by the NIPA consumption and services deflator. The measure can be constructed with or without structures, following Cummins and Violante (2002) in using the official price series for structures. The empirical work was repeated using only data on equipment, finding generally similar results, slightly stronger for the cross-industry comparisons, and slightly weaker for the differences-in-differences regressions.

The industry classification of the BEA input-output tables (which are used to construct the ISTC measure) and by Eurostat do not exactly coincide. The 41 industries reported represent the join of the two classification systems.

A.3 Model with capital goods industries

Observe that the structure of capital accumulation in this model resembles that of Greenwood et al (1997), except that there are distinct capital stocks for each sector.

There is an additional difference between the two models. In Greenwood et al (1997) there is only one technology for converting consumption into investment, which improves over time. In this model, however, that is not the case: establishments have a *choice* over this technology, whereas the set of available technologies expands over time.

An interpretation of the capital accumulation structure is as follows. Suppose there are N_K types of capital good. Each industry j uses an industry-specific capital composite based on these N_K goods. The frontier productivity of each capital type $k \in N_K$ improves over time. Thus, at any date, one unit of the numeraire may be used to produce $A_{k\tau} = A_{k0} e^{\varsigma_k \tau}$ units of capital of type k, vintage τ. Let $q^j_{\tau t}$ equal new units of capital for use in sector j of vintage τ, so that

$$k^j_{\tau,t+1} = q^j_{\tau t} + e^{-\delta \Delta} k^j_{\tau t}. \tag{50}$$

New capital for use in industry j is a composite of the N_k types of capital good:

$$q^\tau_{jt} = \prod_{k \in N_K} \left(\frac{y^\tau_{kjt}}{\omega_{jk}} \right)^{\omega_{jk}}, \omega_{jk} > 0, \sum_{k \in N_K} \omega_{jk} = 1. \tag{51}$$

Thus, a plant in industry j is built of a mix of different capital goods.

Then households maximize

$$\max \left\{ p^\tau_{jt} \prod_{k \in N_K} \left(\frac{y^\tau_{kjt}}{\omega_{jk}} \right)^{\omega_{jk}} - \sum_{k \in N_K} p^\tau_{kt} y^\tau_{kjt} \right\} \tag{52}$$

where p^τ_{jt} is the shadow price of the capital composite used by industry j, of vintage τ. The FOC are

$$\omega_{jk} p^\tau_{jt} q^\tau_{jt} = p^\tau_{kt} y^\tau_{kjt} \tag{53}$$

so that the share of spending on each type is ω_{jk}. So, if total spending on new capital is X, then $y^\tau_{kjt} = \frac{\omega_{jk} X}{p^\tau_{kt}}$ and we have

$$p^\tau_{jt} \prod_{k \in N_K} \left(\frac{1}{p^\tau_{kt}} \right)^{\omega_{jk}} = \sum_{k \in N_K} \omega_{jk} \tag{54}$$

Over time, or comparing across vintages,

$$g_{p^\tau_{jt}} = \prod_{k \in N_K} \left(g_{p^\tau_{kt}} \right)^{\omega_{jk}} \tag{55}$$

$$\log g_{p^\tau_{jt}} = \sum_{k \in N_K} \omega_{jk} \log \left(g_{p^\tau_{kt}} \right) \tag{56}$$

so that the growth rate in the relative price of composite capital used by any industry is the average of the growth rate in the prices of the goods used, weighted by their shares. This is exactly how the relative price series are constructed in the empirical section of this paper, following Cummins and Violante (2002).

Under this interpretation, it is straightforward to show that the relative price of frontier capital of each type $k \in N_K$ declines at rate ς_k, so that

$$g_j = \sum_{k \in N_K} \omega_{jk} \varsigma_k. \tag{57}$$

Thus, ISTC represents nothing other than increases in the efficiency of capital good production.

Alternatively, the model economy could be written to explicitly contain N_k capital-producing industries, although not doing so significantly simplifies the exposition.

Suppose that there are J consumption industries as before, and also N_k capital-producing industries. In each industry there is a disembodied productivity frontier $A_{jt} = A_{j0} e^{\varsigma_j t}$, and firms may produce goods using any technology $A_{j\tau} \leq A_{jt}$. There is a price p_{jt}^{τ} for each good, that may vary by vintage τ.

For consumption goods, at any date, for any two vintages τ and τ', prices will be proportional to $A_{j\tau}$ and $A_{j\tau'}$. As a result, consumers will not purchase goods of any vintage $\tau < t$. For capital goods, on the other hand, this is not necessarily the case (as before), because firms are temporarily locked into their capital vintage. Regardless of which vintage a capital goods firm chooses to produce, however, it will make the same profits, because free entry implies that $A_{j\tau} p_{jt}^{\tau} = A_{j\tau'} p_{jt}^{\tau'}$, so marginal revenue products are the same regardless of the vintage produced.

The existence proof then needs to change in two ways. First, g_j must be derived from ς_k for the capital-producing industries. This involves some simple matrix algebra. Second, for given aggregate spending, we know how much spending there will be on capital goods of each type from the NIPA. Since this is linear in the number of firms, this does not complicate the proof.

One last difference concerns the reversibility of investment. If capital goods depreciate more slowly than the rate at which demand for them decreases over time, then the equilibrium time paths of capital goods prices may not be exponential if investment is not reversible. For these time paths to hold, investment in capital goods must be reversible according to the same marginal rates of transformation used to create them.

Thus, the model with capital goods amounts to assuming that (a) investment is reversible, and (b) firms may produce any vintage of their good.

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