# Innovation, productivity, and growth

Bronwyn H. Hall
University of Maastricht and UC Berkeley

# Innovation and productivity

- Many papers looking at the link using data from the Community Innovation Survey and others like it
- My goal here:
  - Provide a framework for interpreting results
  - Draw some conclusions about how we might improve the data/analysis
  - Thoughts on macro implications

# Innovation and productivity

- What are the mechanisms connecting innovation and productivity?
  - Improvements within existing firms
    - Creation of new goods & services, leading to increased demand for firm's products
    - Process and organizational innovation leading to efficiency gains in production
  - Entry of more efficient firms
  - Entry of firms on technology frontier
  - Exit of less efficient firms

# Measuring innovation

- Large literature using R&D (capitalized) as a proxy for innovation input
  - Hall, Mairesse, Mohnen 2010 survey, *inter alia*
- Smaller literature using patents as a proxy for intermediate innovation output
- Both measures have well-known weaknesses, especially outside the manfacturing sector.
- Now we have more direct measures – do they help?

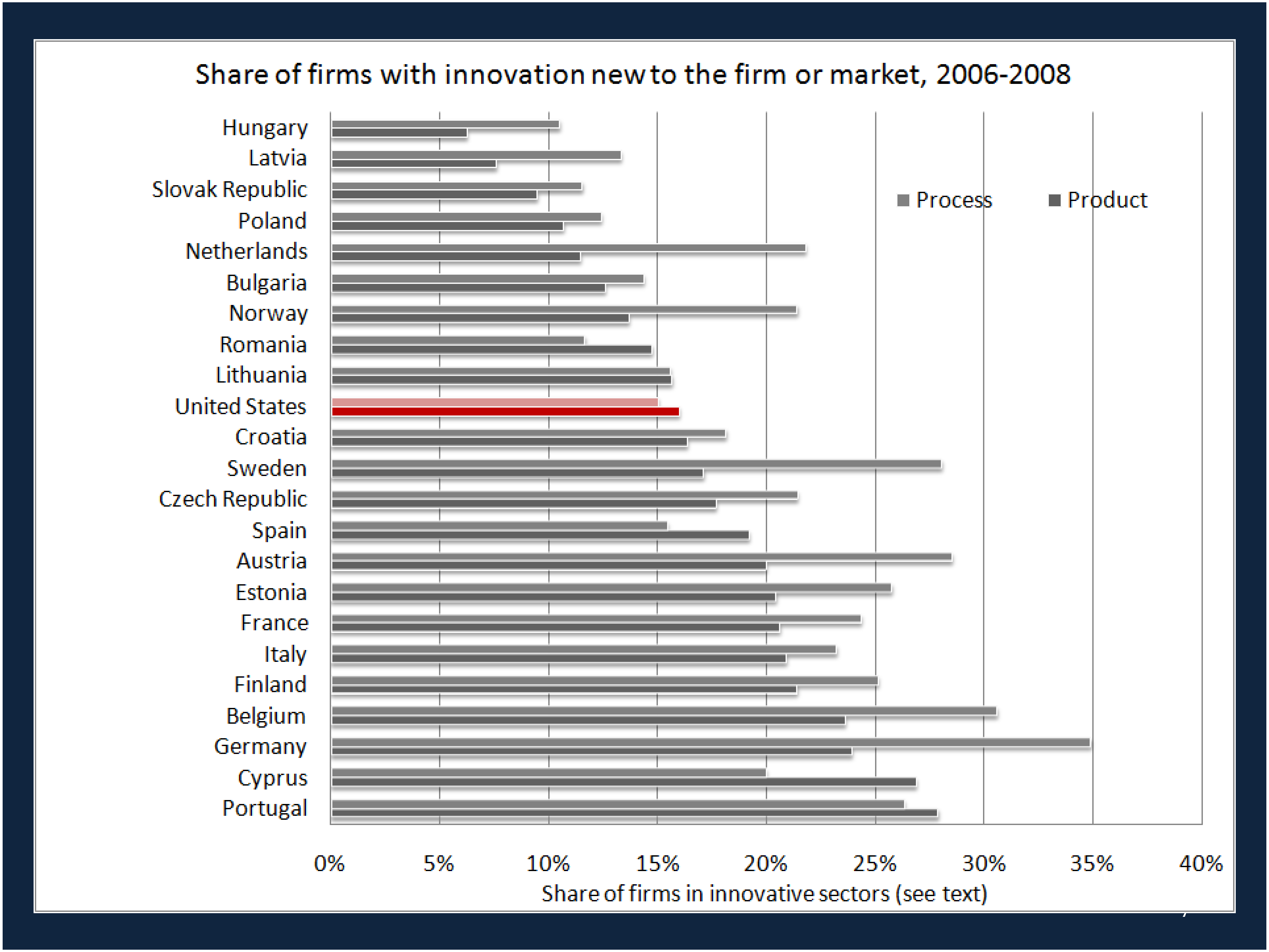
# Innovation surveys contain…..

- Data on innovation:
  - Product or process new to firm/market (yes/no)
  - Share of sales during past 3 years from new products
  - More recent surveys have expenditures on various kinds of innovation investments
- Data on productivity and employment:
  - Usually sales per worker (labor productivity)
  - Sometimes TFP (adjusted for changes in capital)
  - Issues arising from deflation and level of aggregation
    - of goods, and of enterprises

More info: Mairesse and Mohnen (2010)

# Raw data

- Next slide – share of process and product innovators in selected sectors:
  - Manufacturing, telecommunications, computer services and software publishing, finance, and some technical professional services
  - As close as we can get to matching OECD coverage to US coverage
- Suggests the difficulty in measuring innovation with a dummy



Share of firms with innovation new to the firm or market, 2006-2008
Process
Product
Hungary
Latvia
Slovak Republic
Poland
Netherlands
Bulgaria
Norway
Romania
Lithuania
United States
Croatia
Sweden
Czech Republic
Spain
Austria
Estonia
France
Italy
Finland
Belgium
Germany
Cyprus
Portugal
0%
5%
10%
15%
20%
25%
30%
35%
40%
Share of firms in innovative sectors (see text)

# Interpretive framework

- Innovation-productivity regression use revenue productivity data
  – Include coarse sectoral dummies
  – Relative within-sector price changes not accounted for
  – Quality change not generally accounted for
- In the case of innovative activity, omitting price change at the firm level is problematic
- Present an alternative analysis - derived from Griliches and Mairesse 1984

# Conventional productivity eq

$$q_{it} = a_{it} + \alpha c_{it} + \beta l_{it} \qquad i = entity, t = time$$

$q$ = log value added (sometimes just output)

$c$ = log tangible capital

$l$ = log labor input

$a_{it}$ = TFP (total factor productivity)

Coefficients $\alpha$, $\beta$ measured as shares (growth accounting) or by regression (econometric)

# Revenue productivity

If firms have market power and idiosyncratic prices, we observe real revenue $r$, not output $q$:

$$r = p + q \qquad \text{(all in logs)}$$

Add a CES demand equation: $q_{it} = \eta p_{it}$ , $\eta < 0$

Then the revenue productivity relationship is

$$r_{it} = \frac{\eta + 1}{\eta}(a_{it} + \alpha c_{it} + \beta l_{it})$$

If demand is inelastic ($0 > \eta > -1$), revenue falls with increased output

# Adding innovation

Add two terms involving knowledge stock:

- process: $\gamma k_{it}$ in the production function, $\gamma>0$
- product: $\varphi k_{it}$ in the demand function, $\varphi>0$

This yields the following revenue function:

$$r_{it} = \left(\frac{\eta+1}{\eta}\right)(a_{it} + \alpha c_{it} + \beta l_{it}) + \left(\frac{\gamma(\eta+1)-\varphi}{\eta}\right)k_{it}$$

Product improvement ($-\varphi/\eta$) always positive

Process improvement ($\gamma(\eta+1)/\eta$) could be small or even negative

# Implication for prices

Recall that $q_{it} = \eta p_{it} + \varphi k_{it}$

Then

$$p_{it} = \left(\frac{1}{\eta}\right)\left(a_{it} + \alpha c_{it} + \beta l_{it}\right) + \left(\frac{\gamma - \varphi}{\eta}\right) k_{it}$$

If demand elasticity is constant, price falls with innovation if $\gamma$-$\varphi$ > 0 (recall $\eta$<0)

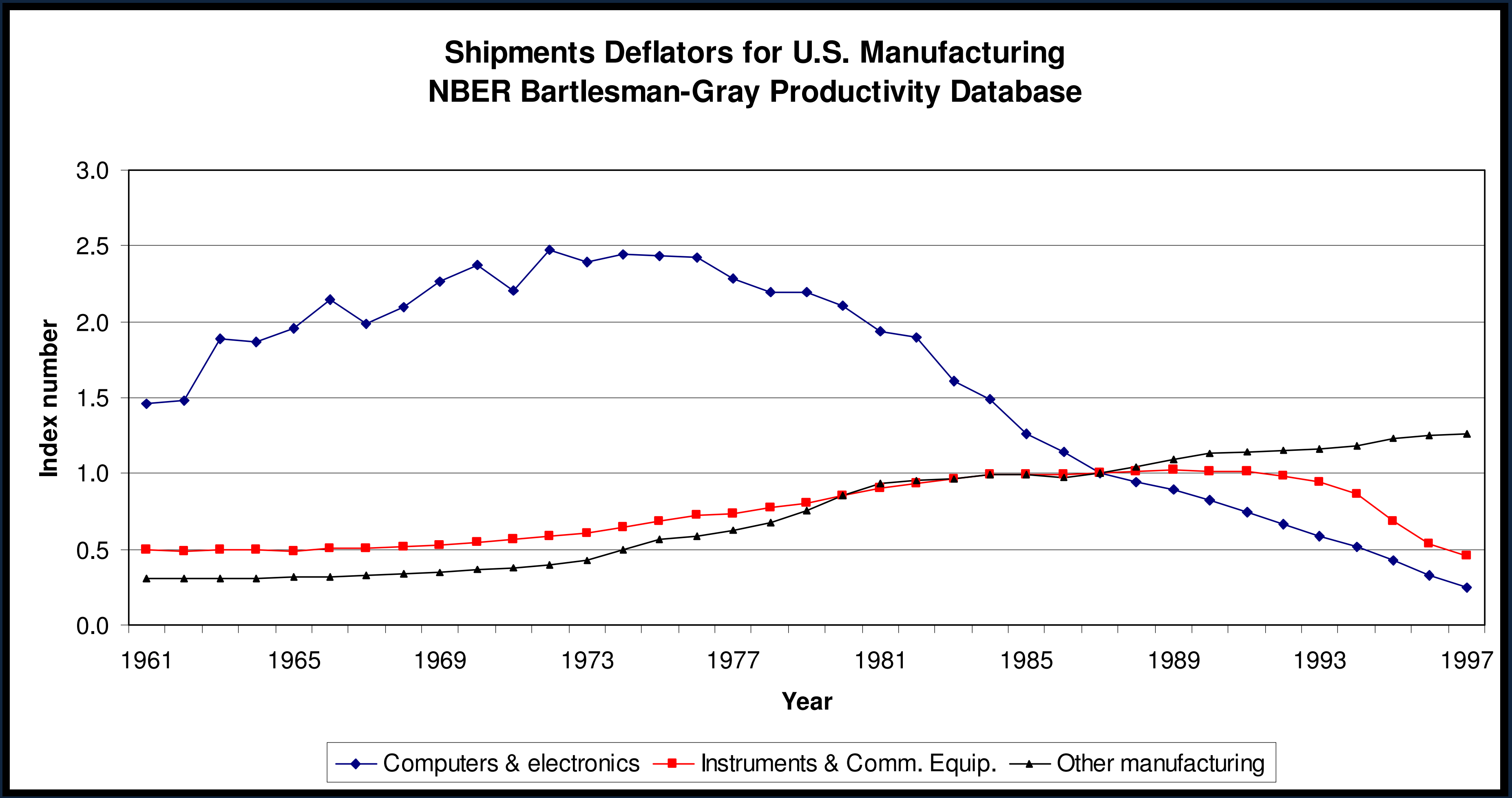
That is, if efficiency enhancement effect outweighs product improvement effect

Impact of innovation on price greater the more inelastic is demand, c.p.

# An example of price impact

- U.S. deflators for the computer hardware industry and the communications equipment industry are hedonic (account for quality change)
  - see next slide
- Deflate firm sales by these 2-digit deflators instead of one overall deflator
- Result: true productivity is substantially higher than revenue productivity, because of hedonic price declines in the computer/electronics sector
- Benefits of "Moore's Law"

# Hedonic Price Deflator for Computers



# Estimated R&D Elasticity – U.S. Manufacturing Firms

| | Revenue | Quantity | Price |
|---|---|---|---|
| Period | Dep. Var = Log Sales | Dep. Var = Log Sales deflated | Difference |
| 1974-1980 | -.003 (.025) | .102 (.035) | -0.099 |
| 1983-1989 | .035 (.030) | .131 (.049) | -0.096 |
| 1992-1998 | .118 (.031) | .283 (.041) | -0.165 |

GMM-system estimation with lag 3 & 4 instruments.
Sample sizes: 7156, 6507, and 6457 observations

Conclusion: much of the R&D in computing hardware went to lower prices for consumers ($\gamma$-$\varphi > o$)

# What do the data say?

Results from a large collection of papers that used the CDM model for estimation (Crepon Duguet Mairesse 1998):

- Innovation survey data reveals that some non-R&D firms innovate and some R&D firms do not innovate
- Data is usually cross-sectional, so simultaneity between R&D, innovation, and productivity
- Sequential model: R&D→innovation→productivity

# CDM model

- Proposed originally by Crépon, Duguet and Mairesse (CDM, 1998)
- Relationship among
  - innovation input (mostly, but not limited to, R&D)
  - innovation output (process, product, organizational)
  - productivity levels (sometimes growth rates)
- Closer look at the black box of the innovation process at the firm level:
  - unpacks the relationship between innovation input and productivity by looking at the innovation output

# The model parts

1. The determinants of R&D choice: whether to do it and how much to do.
2. Knowledge production function with innovation variables as outcomes as a function of predicted R&D intensity.
3. Production function including the predicted innovation outcomes to measure their contribution to the firm's productivity.

   Need bootstrap s.e.s if sequentially estimated.

# CDM model applied to CIS data

- Estimated for 15+ countries
- Confirmed high rates of return to R&D found in earlier studies
- Like patents, innovation output statistics are much more variable ("noisier") than R&D,
  - R&D tends to predict productivity better, when available
- Next few slides summarize results for regressions of individual firm TFP on innovation
- Source: Hall (2011), *Nordic Economic Policy Review*

# Productivity-innovation relationship in TFP levels

| *Sample* | *Time period* | *Elasticity with respect to innov sales share* | *Process innovation dummy* |
|---|---|---|---|
| Chilean mfg sector | 1995-1998 | 0.18 (0.11)* | |
| Chinese R&D-doing mfg sector | 1995-1999 | 0.035 (0.002)*** | |
| Dutch mfg sector | 1994-1996 | 0.13 (0.03)*** | -1.3 (0.5)*** |
| Finnish mfg sector | 1994-1996 | 0.09 (0.06) | -0.03 (0.06) |
| French mfg sector | 1986-1990 | 0.07 (0.02)*** | |
| French Hi-tech mfg # | 1998-2000 | 0.23 (0.15)* | 0.06 (0.02)*** |
| French Low-tech mfg # | 1998-2000 | 0.05 (0.02)*** | 0.10 (0.04)*** |
| German K-intensive mfg sector | 1998-2000 | 0.27 (0.10)*** | -0.14 (0.07)** |
| Irish firms # | 2004-2008 | 0.11 (0.02)*** | 0.33 (0.08)*** |
| Norwegian mfg sector | 1995-1997 | 0.26 (0.06)*** | 0.01 (0.04) |
| Swedish K-intensive mfg sector | 1998-2000 | 0.29 (0.08)*** | -0.03 (0.12) |
| Swedish mfg sector | 1994-1996 | 0.15 (0.04)*** | -0.15 (0.04)*** |
| Swedish mfg sector | 1996-1998 | 0.12 (0.04)*** | -0.07 (0.03)*** |
| Swedish service sector | 1996-1998 | 0.09 (0.05)* | -0.07 (0.05) |

Source: author's summary from Appendix Table 1.

# Innovative sales share and process innovation included separately in the production function.

# TFP levels on innov sales share

- Robustly positive, supports the view that product innovation shifts the firm's demand curve out
  – Elasticities range from 0.04 to 0.29 with a typical standard error of 0.03
  – K-intensive and hi-tech firms have higher elasticities (=> equalized rates of return)
- Coefficient of process innovation dummy usually insignificant or negative, suggesting either inelastic demand or

*(more likely)* measurement error in the innovation variables

# Productivity-innovation using dummies

| *Sample* | *Time period* | *Product innovation dummy* | *Process innovation dummy* |
|---|---|---|---|
| Argentinian mfg sector | 1998-2000 | -0.22 (0.15) | |
| Brazilian mfg sector | 1998-2000 | 0.22 (0.04*** | |
| Estonian mfg sector | 1998-2000 | 0.17 (0.08)** | -0.03 (0.09) |
| Estonian mfg sector | 2002-2004 | 0.03 (0.04) | 0.18 (0.05)*** |
| French mfg sector | 1998-2000 | 0.08 (0.03)** | |
| French mfg sector | 1998-2000 | 0.06 (0.02)*** | 0.07 (0.03)** |
| French mfg sector | 1998-2000 | 0.05 (0.09) | 0.41 (0.12)*** |
| French mfg sector | 2002-2004 | -0.08 (0.13) | 0.45 (0.16)*** |
| French service sector | 2002-2004 | 0.27 (0.52) | 0.27 (0.45) |
| German mfg sector | 1998-2000 | -0.05 (0.03) | 0.02 (0.05) |
| Irish firms # | 2004-2008 | 0.45 (0.08)*** | 0.33 (0.08)*** |
| Italian mfg sector | 1995-2003 | 0.69 (0.15)*** | -0.43 (0.13)*** |
| Italian mfg sector SMEs | 1995-2003 | 0.60 (0.09)*** | 0.19 (0.27) |
| Mexican mfg sector | 1998-2000 | 0.31 (0.09)** | |
| Spanish mfg sector | 2002-2004 | 0.16 (0.05)*** | |
| Spanish mfg sector | 1998-2000 | 0.18 (0.03)*** | -0.04 (0.04) |
| Swiss mfg sector | 1998-2000 | 0.06 (0.02)*** | |
| UK mfg sector | 1998-2000 | 0.06 (0.02)*** | 0.03 (0.04) |

# TFP level results with dummies

- Product dummy supports innovation sales share result, although noisier.
- There is substantial correlation between product and process innovation, especially when they are instrumented by R&D and other firm characteristics.
- Correlated measurement error may lead to bias in both coefficients (upward for the better measured one and downward for the other)

# Summary

- Elasticity wrt innovative sales center on (0.09, 0.13)
  - higher for high tech and knowledge-intensive
  - Lower on average for low tech and developing countries, but also more variable
- With product innovation included, process innovation often negative or zero
- Without product innovation, process innovation positive for productivity
- When not instrumented, little impact of innovation variables in production function (unlike R&D)
  - See Mairesse & Mohnen (2005), Hall et al. (2012)
- TFP growth rates
  - Similar results, somewhat lower and noisier

# Discussion

- Innovation dummies at the firm level may be too noisy a measure to be useful.
  - Share of sales due to new products is more informative.
  - What measure would be useful (and reportable) for process innovation?
- Further exploration with innovation investment (instead of R&D) is warranted

# Aggregation

- How does individual firm relationship aggregate up to macro-economy?
  - productivity gains in existing firms
  - exit and entry
- Aghion et al (2009); Gorodnichenko et al (2010)
  - Competition and entry encourages innovation unless the sector is very far behind
- Djankov (2010) survey – cross country
  - stronger entry regulation and/or higher entry costs associated with fewer new firms, greater existing firm size and growth, lower TFP, lower investment, and higher profits

# Entry and exit

- Haltiwanger & co-authors have developed decompositions that are useful
- Foster, Haltiwanger, and Syverson (2008) – US data
  - Distinguish between revenue and quantity, and include exit & entry
  - Revenue productivity understates contribution of entrants to real productivity growth because entrants generally have lower prices
  - Demand variation is a more important determinant of firm survival than efficiency in production (consistent with productivity impacts)

# Future work?

- Full set of links between innovation, competition, exit/entry, and productivity growth not yet explored
- Bartelsman et al. (2010): Size-productivity more highly correlated within industry if regulation is "efficient"
  - Evidence on Eastern European convergence
  - Useful approach to the evaluation of regulatory effects without strong assumptions
- Similar analysis could assess the economy-wide innovation impacts

# BACKUP SLIDES

## The CDM Model and employment effects

# A brief overview of the CDM model

Three blocks of equations

1. equations explaining the "R&D" decision and the amount of R&D performed
2. Innovation output equations (KPF) with R&D as input
3. Productivity equation, in which innovation output indicators appear as explanatory variables

Estimation is recursive using single equation blocks, or simultaneous.

# Econometrics (1)

Only some firms report R&D; use standard selection model:

Selection eq

$$RDI_i = \begin{cases} 1 & if \quad RDI_i = w_i\alpha + \varepsilon_i > \overline{c} \\ 0 & if \quad RDI_i = w_i\alpha + \varepsilon_i \leq \overline{c} \end{cases}$$

Conditional on doing R&D, we observe the level:

$$RI_i = \begin{cases} RD_i^* = z_i\beta + e_i & if \quad RDI_i = 1 \\ 0 & if \quad RDI_i = 0 \end{cases}$$

Assume joint normality => generalized tobit or Heckman selection model for estimation.

# Econometrics (2)

Output of the KPF are various binary innovation indicators or the share of innovative sales. For example,

$$DI_i = \boxed{RD_i^*}\gamma + X_i\delta + u_i$$

*DI* = Dummy for innovation (process, product, organizational)

Why include the latent R&D variable *RD**?

1. Account for informal R&D effort that is often not reported
2. Instrument for errors in variables and simultaneity

Estimation is via multivariate probit

# Econometrics (3)

Production function:

$$y_i = \pi_1 k_i + \sum_j \pi_{2j} DI_{ij} + Z_i \varphi + \nu_i$$

$y$ = log sales per employee

$k$ = log capital stock per employee

$DI$ are predicted probabilities of innovation from second step or predicted share of innovative sales (with logit transform)

$Z$ includes size, age, industry, region, year, wave

Estimated by OLS

# What about employment?

Assume capital $C$ and knowledge stock $K$ are predetermined. Can show optimal labor choice is

$$l_{it} = \left(1 - \frac{\eta+1}{\eta}\beta\right)^{-1}\left[\left(\frac{\eta+1}{\eta}\right)\alpha c_{it} + \left(\frac{\gamma(\eta+1)-\varphi}{\eta}\right)k_{it}\right] + const$$

Similar conclusion for labor as for output (if demand is elastic or not very inelastic):

– Product improvement ($-\varphi/\eta$) always positive
– Process improvement ($\gamma(\eta+1)/\eta$) can be negative

# 2. Employment

- Uses an equation in growth rates, allowing for price changes:

$$l-\left(g_1-\pi\right)=\alpha_{0i}+\alpha_1 D_{proc}+\frac{\beta}{\left(1+\varphi_2\right)}\frac{g_2}{\left(1+\pi\right)}+\left[u-\varphi_1\left(1+\pi\right)\right]$$

$l$ = employment growth ($i$ = industry)
$\pi$ = growth of sector price deflator
$g_1$, $g_2$ = growth in sales of old, new products
$D_{proc}$ = dummy for process innovation
$\beta$ = relative efficiency of producing new vs old products
$\varphi_1$, $\varphi_2$ = rel. change in price of old, new products
If $\varphi_2>0$, the quality improvement of the new prod is passed to consumers via higher prices (lower employment impact, c.p.)
If $\varphi_2<0$, quality improvement leads to lower "effective" prices

# Results for Europe

Manufacturing sector firms 1998-2000

| | Italy | France | Spain | Germany | UK |
|---|---|---|---|---|---|
| Growth of sales of new products | 0.94 (0.04) | 0.98 (0.06) | 1.02 (0.04) | 1.01 (0.07) | 0.98 (0.05) |
| D (process) | 0.2 (0.9) | -0.3 (1.6) | 2.5 (1.8) | -6.2 (2.9) | -3.9 (1.9) |
| N of firms | 4618 | 4631 | 4548 | 1319 | 2493 |

Labor efficiency of production of old and new products roughly the same (except possibly in Italy)

Process innovation has no impact in Italy, France, and Spain, leads to reduced labor in Germany & UK (increased efficiency)

=> Suggests the importance of labor market regulation, although effects are fairly small.

# Decomposition of e growth

$$\bar{l} = \hat{\alpha}_{0i} + \left(\overline{g_1 - \pi}\right) + \hat{\alpha}_1 \bar{D}_{proc} + \widehat{\frac{\beta}{(1+\varphi_2)}}\overline{\frac{g_2}{(1+\pi)}}$$

Manufacturing sector firms 1998-2000

| | Italy | France | Spain | Germany | UK |
|---|---|---|---|---|---|
| Average employment growth (%) | 2.5 | 8.3 | 14.2 | 5.9 | 6.7 |
| *Due to……* | | | | | |
| Industry specific trend | -5.6 | -1.9 | -5.7 | -7.5 | -5.0 |
| Output growth of old products (non-innov.) | 5.7 | 4.8 | 12.2 | 6.0 | 8.3 |
| Process innovation without product | 0.1 | -0.1 | 0.3 | -0.6 | -0.4 |
| Product innovation | 2.4 | 5.5 | 7.4 | 8.0 | 3.9 |