INCAE PhD SUMMER ACADEMY
DYNAMIC GAMES IN EMPIRICAL IO

Lecture 5B:
APPLICATIONS: DYNAMIC GAMES OF INNOVATION

Victor Aguirregabiria (University of Toronto)

June 24, 2022

DYNAMIC GAMES OF FIRMS' INNOVATION: OUTLINE

1. **Igami (JPE, 2017):**

   Creative destruction, cannibalization, and the incentives to innovate of incumbents and new entrants.

2. **Gettler & Gordon (JPE, 2011):**

   Competition & innovation in CPU industry: Intel vs AMD.

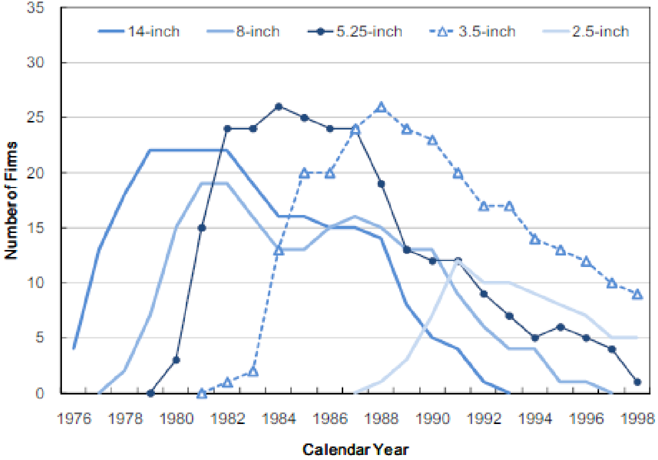
1. Creative destruction: incentives to innovate of incumbents and new entrants

Innovation and creative destruction (Igami, 2017)

- Innovation, the creation of new products and technologies, necessarily implies the "destruction" of existing products, technologies, and firms.
- The survival of existing products / technologies / firms is at the cost of preempting the birth of new ones.
- The speed of the innovation process in an industry depends on the dynamic strategic interactions between "old" and "new" products/technologies.
- Igami (JPE, 2017) studies these interactions in the context of the Hard-Disk-Drive (HDD) industry during 1981-1998.

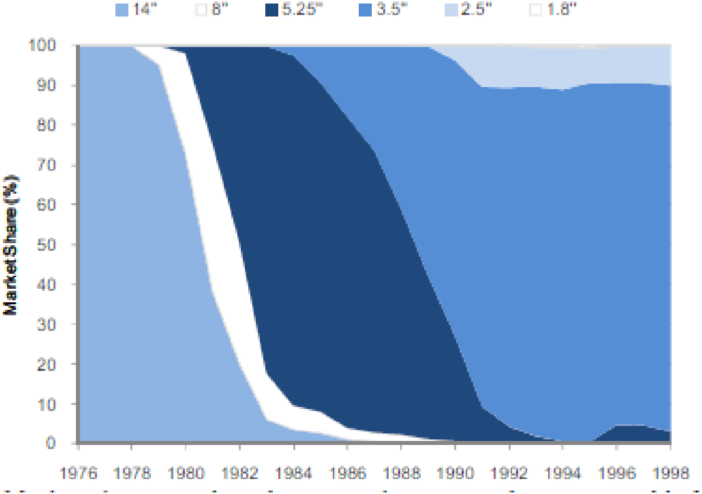
HDD: Different generations of products

Figure 2: Shifting Generations of Technology



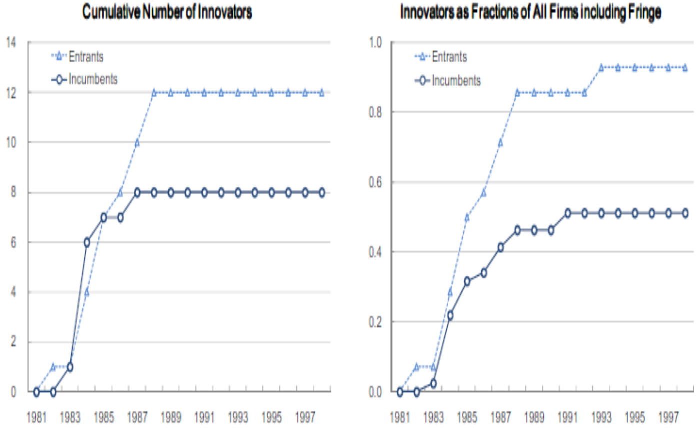
HDD: Different generations of products

Figure 12: Aggregate Market Share by Diameter



Adoption new tech: Incumbents vs. New Entrants

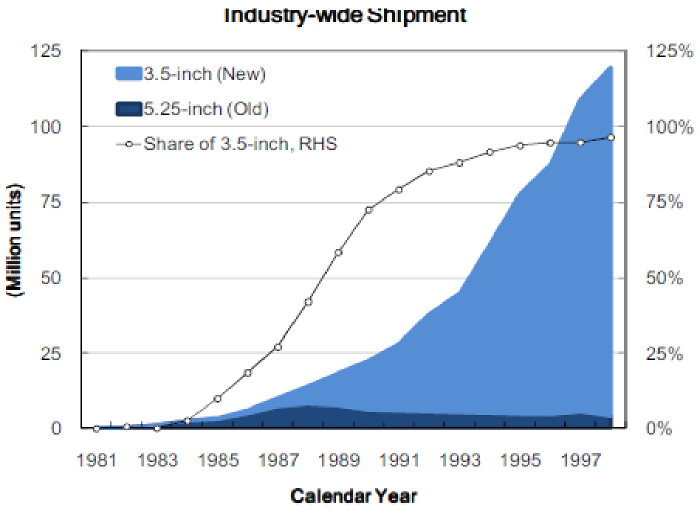
Figure 1: The Incumbent-Entrant Innovation Gap



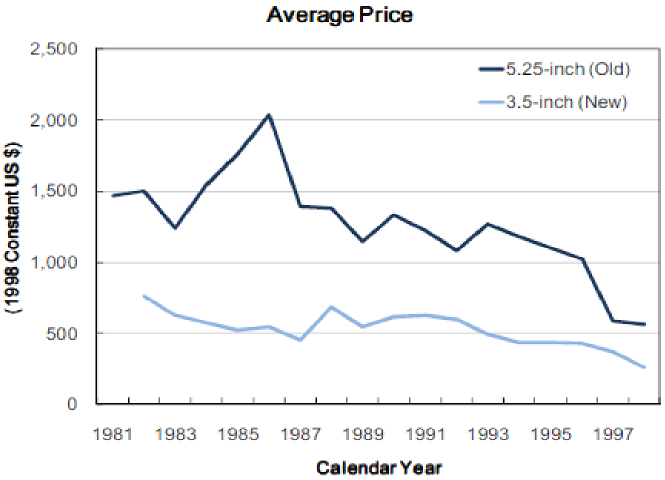
Adoption new tech: Incumbents vs. New Entrants (2)

- Igami focuses on the transition from 5.25 to 3.5 inch products.
- He consider three main factors that contribute to the relative propensity to innovate of incumbents and potential entrants.
- **Cannibalization.** For incumbents, the introduction of a new product reduces the demand for their pre-existing products.
- **Preemption.** Early adoption by incumbents can deter entry and competition from potential new entrants.
- **Differences in entry/innovation costs.** It can play either way. Incumbents have knowledge capital and **economies of scope**, but they also have **organizational inertia**.

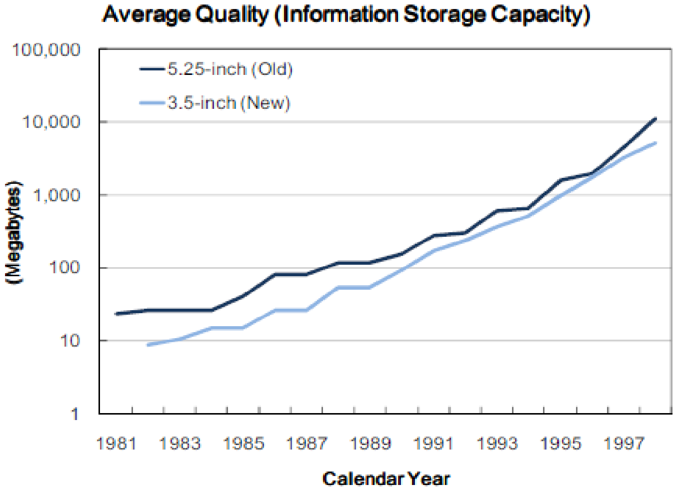
Market shares New/Old products



Average Prices: New/Old products



Average Quality: New/Old products



Model

- Endogenous state var: s_{it} = products produced.

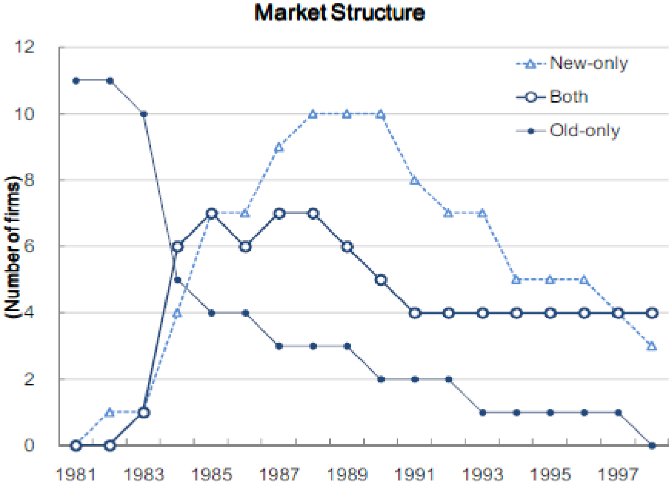
  $s_{it} \in \{ potential - entrant(pe);\ only\ old\ (old);\ only\ new\ (new);\ both$

- Market structure: $\{N_t^{pe}, N_t^{old}, N_t^{new}, N_t^{both}\}$.

- Timing within a period t:

  1. Incumbents compete (a la Cournot) $\rightarrow$ Period profits $\pi_t(s_{it}, s_{-it})$
  2. N_t^{old} firms simultaneously choose $a_{it}^{old} \in \{exit, stay, innovate\}$
  3. N_t^{both} observe a_t^{old} and simul. choose $a_{it}^{both} \in \{exit, stay\}$
  4. N_t^{new} observe a_t^{old}, a_t^{both} and simul. choose $a_{it}^{new} \in \{exit, stay\}$
  5. N_t^{pe} observe a_t^{old}, a_t^{both}, a_t^{new} and simul. choose $a_{it}^{pe} \in \{entry, noentry\}$.

Market Structure: New/Old products



Model [2]

- Given these choices, next period market structure is obtained, s_{t+1}, and demand and cost variables evolve exogenously.

- **Why imposing an order of move?** This Assumption, together with:

  - Finite horizon T.

  - Homogeneous firms within type (up to i.i.d. private shocks).

  implies that there is a **unique Markov Perfect equilibrium**.

- This is very convenient for estimation (Igami uses a standard/Rust Nested Fixed Point Algorithm for estimation) and especially for counterfactuals.

Model: Demand

- Simple logit model of demand. A product is defined as a pair {technology, quality}, where technology $\in \{old, new\}$ and *quality* (x) represents different storage sizes.

- Estimation:

$$\ln\left(\frac{share_{jt}}{share_{0t}}\right) = \alpha_1\ p_{jt} + \alpha_2\ 1_j^{new} + \alpha_3\ x_{jt} + \xi_{jt}$$

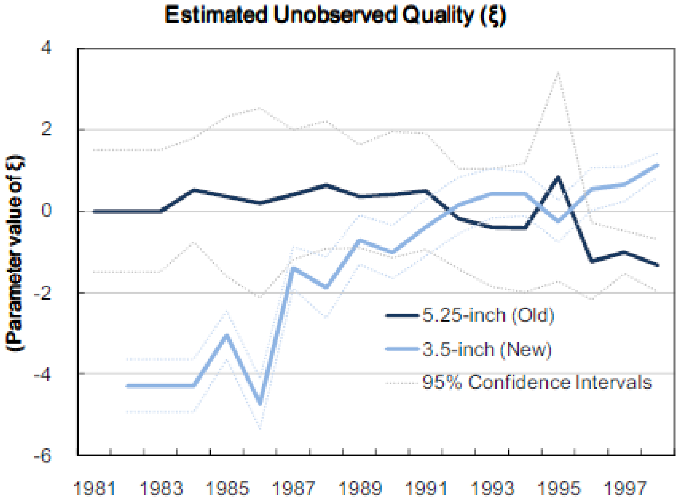
- Data: 72 quarters and 4 regions (broad market definition).

- IVs: Hausman-Nevo. Prices in other regions.

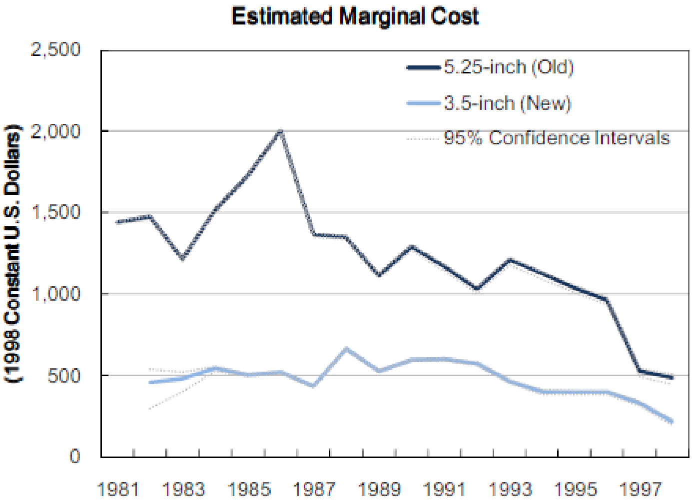
Estimates of Demand

Market definition:	Broad		Narrow	
Estimation method:	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)
Price ($000)	-1.66^{***}	-2.99^{***}	$-.93^{**}$	-3.28^{***}
	(.45)	(.55)	(.46)	(.63)
Diameter = 3.5-inch	$.84^{*}$	.75	1.75^{***}	$.91^{**}$
	(.46)	(.45)	(.31)	(.38)
Log Capacity (MB)	.18	$.87^{***}$	.04	1.20^{***}
	(.33)	(.27)	(.26)	(.31)
Year dummies	*Yes*	*Yes*	*Yes*	*Yes*
Region/user dummies	–	–	*Yes*	*Yes*
Adjusted R^2	.43	.33	.50	.28
Number of obs.	176	176	405	405
Partial R^2 for Price	–	.32	–	.16
P-value	–	.00	–	.00

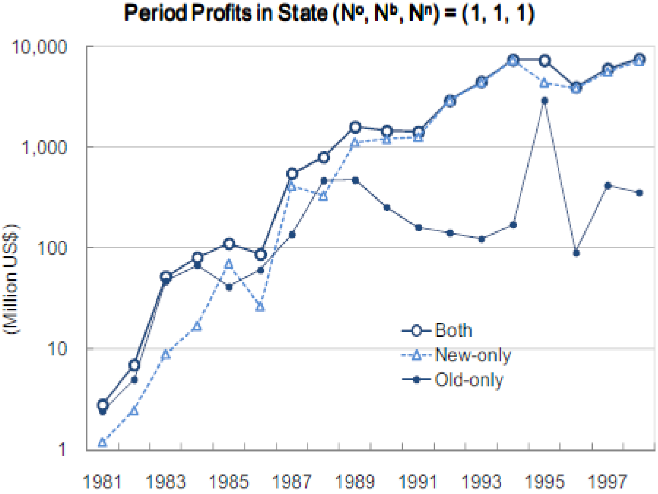
Evolution of unobserved Quality (epsi)



Evolution of Marginal Costs



Evolution of Period Profits [keeping market structure]



Estimates of Dynamic Parameters

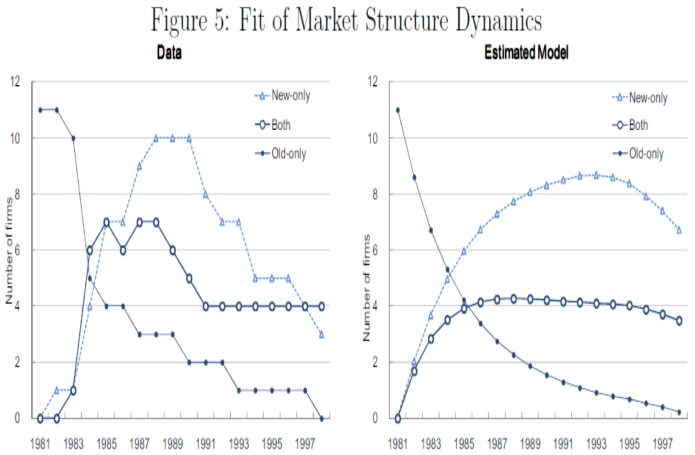
Table 4: Estimates of the Dynamic Parameters

($ Billion)	Maximum Likelihood Estimates		
	(1)	(2)	(3)
Assumed order of moves:	Old-Both-New-PE	PE-New-Both-Old	PE-Old-Both-New
Fixed cost of operation (ϕ)	0.1474	0.1472	0.1451
	[−0.02, 0.33]	[−0.02, 0.33]	[−0.03, 0.33]
Incumbents' sunk cost (κ^{inc})	1.2439	1.2370	1.2483
	[0.51, 2.11]	[0.50, 2.10]	[0.51, 2.11]
Entrants' sunk cost (κ^{ent})	2.2538	2.2724	2.2911
	[1.74, 2.85]	[1.76, 2.87]	[1.78, 2.89]
Log likelihood	−112.80	−112.97	−113.46

Estimates of Dynamic Parameters

- Estimates are pretty robust to changes in the order of move within a period.
- Cost for innovation is smaller for incumbents than for new entrants ($\kappa^{inc} < \kappa^{pe}$). Economies of scope seem more important than organizational inertia.
- Magnitude of entry costs are comparable to the annual R&D budget of specialized HDD manufacturers, e.g., Seagate Tech: between $\$0.6B - \$1.6B$.

Estimated Model: Goodness of fit



Counterfactuals

- **Removing Cannibalization [two separate firms – spinoff]**

  - Substantial positive effect on incumbents' propensity to innovate.

  - Now incumbents (INC) have higher propensity to innovate than potential entrants (PE).

- **Removing Preemption [Change INC's beliefs on PE's CCPs. INC believe PE's CCPs do not depend on INC's entry decision]**

  - Reduces substantially the propensity to innovate of incumbents.

- Cannibalization is the main factor that explain the lower innovation propensity of incumbents. The strength of this effect more than offset the preemption motive and the lower entry cost of incumbents.

2. Competition and Innovation: Intel & AMD (Goettler & Gordon, 2011)

Introduction

- Competition between Intel & AMD in **PC microprocessor industry**.
- Incorporates product durability as a potentially important factor for innovation (**endogenous technological obsolescence**).

  - Most of the demand during 1993-2004 ($> 89\%$) was upgrading.

- Two main forces driving innovation:

  (a) **Quality competition** between firms for the technological frontier.

  (b) PCs have little physical depreciation. Firms have the incentive to innovate to **generate technological depreciation** of consumers' owned PCs, to encourage upgrading.

- Duopolists face both forces, whereas a monopolist faces only the latter **but in a stronger way** (monopoly prices).

The PC microprocessor industry

1. **Important role in economic growth**.

   - Computer equipment industry generated 25% of U.S. productivity growth in 1960-2007.

2. Interesting also from the point of view of **antitrust**.

   - In 2004, AMD sued Intel claiming anti-competitive practices:
   * AMD's claim: Intel rewarded PC manufacturers that exclusively use Intel microprocessors (foreclosure).

   - In 2009, Intel settled these claims with $1.25 B payment to AMD.

3. **Quality and innovations are easier to measure**.

   - Innovations in microprocessors are directly measured via improved performance on benchmark tasks. Most important: **CPU speed**.

The PC microprocessor industry (2/3)

- Market is a **duopoly**: AMD + Intel market shares = 95%
- Firms have **high R&D intensities**.

  - **R&D/Revenue ratios:** (1993-2004): AMD 20% ; Intel 11%
- Innovation is rapid: new products are released nearly every quarter.
- **Gordon Moore's law**: CPU speed doubles every 7 quarters.
- **Positive spillovers**: AMD and Intel extensively cross-license each other's technologies.

The PC microprocessor industry (3/3)

- Part of demand comes from the exogenous arrival of new (young) consumers to the market (**first time PC buyers**).

- A very important part of the demand comes from (old) consumers **replacing / upgrading their PC/CPU**.

  In 2004, 82% of PC purchases were replacements.

- **Replacement is endogenous**: speed of frontier microprocessors that encourages consumers to upgrade.

- **Intertemporal Price Discrimination (IPD); Replacement cycles**:
  - After introducing a new product, upgrading is slow because IPD.
  - Eventually, replacement demand drops and prices drop too (IPD).
  - Firms must release a new product to rebuild replacement demand.

Data

- Proprietary data from a market research firm specializing in the microprocessor industry.
- Quarterly data from Q1-1993 to Q4-2004 (48 quarters).
- Information on:

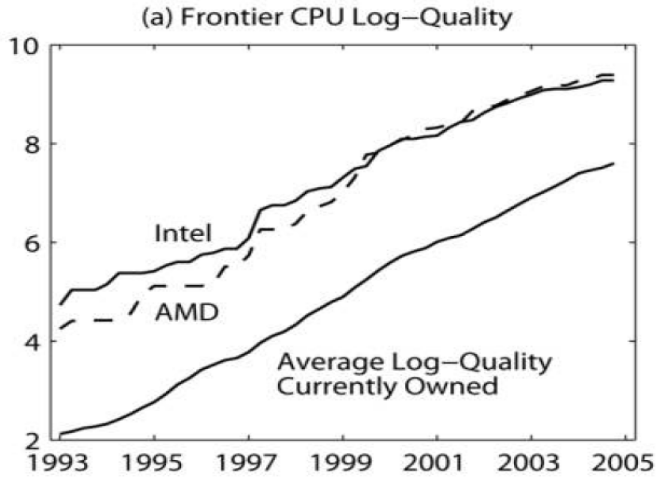
  - Shipments in physical units for each type of CPU;
  - Manufacturers' average selling prices (ASP);
  - **Production costs**;
  - CPU characteristics (e.g., speed).

- All prices and costs are converted to base year 2000 dollars.
- Quarterly R&D investment levels, obtained from firms' annual reports.

Moore's Law

- Intel co-founder Gordon Moore predicted in 1965 that the number of transistors in a CPU (and therefore the CPU speed) would double every 2 years.
- Next slide shows "Moore's law" over the 48 quarters in the data.
- Quality is measured using processor speed.
- Quarterly % change in CPU speed: Intel = 10.2%; AMD = 11%.
- Note that there "plateaus" in evolution of frontier quality.

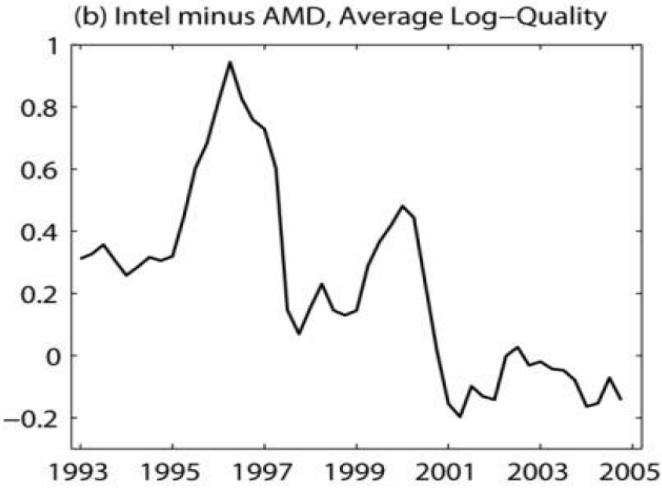
Moore's Law (Frontier CPU speed)



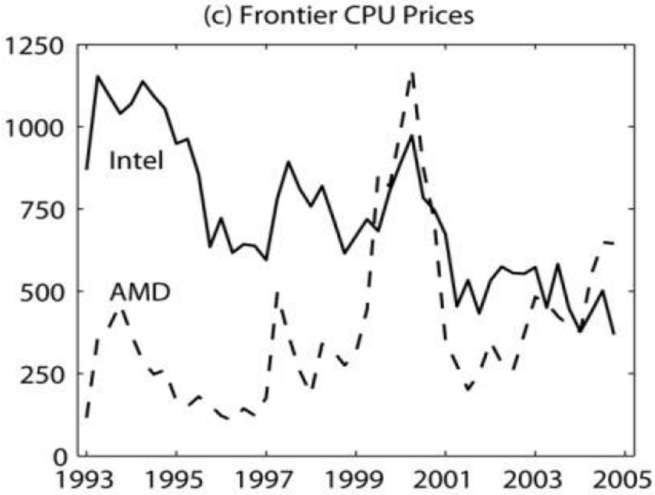
Differential log-quality between Intel and AMD

- Intel's initial quality advantage is moderate in 1993–94.
- Then, it becomes larger in 1995-96 when Intel releases the Pentium.
- AMD's responded in 1997 introducing the K6 processor that narrows the gap.
- But parity is not achieved until the mid-2000 when AMD released the Athlon.

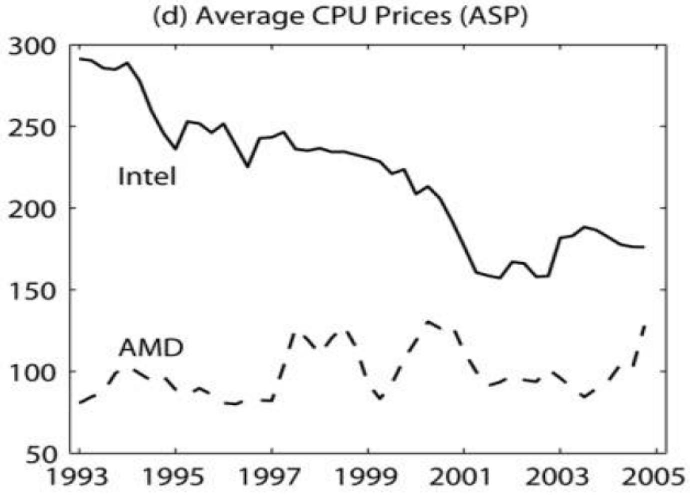
Differential log-quality between Intel and AMD [2]



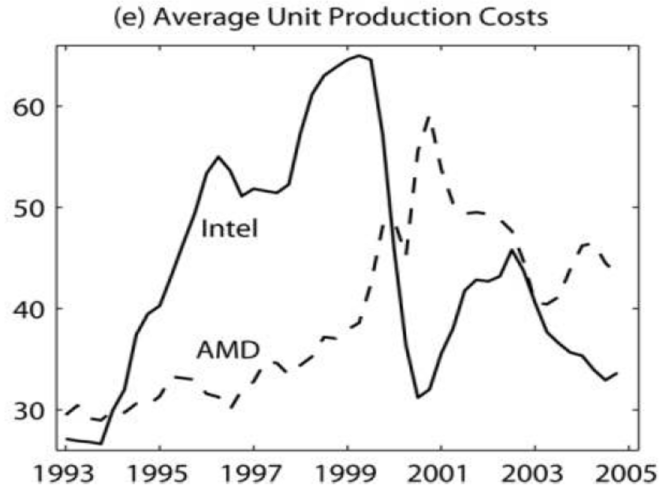
CPU Prices – Frontier Products



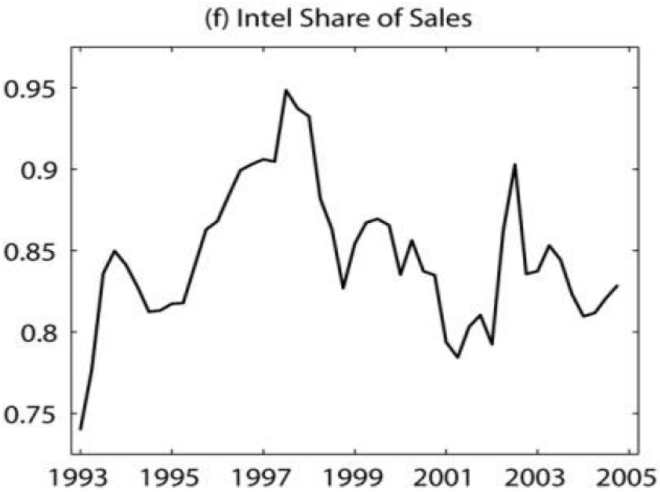
Average CPU Prices



Average Unit Production Costs



Intel Market Share



Model: General features

- Dynamic **oligopoly with differentiated & durable products**.
- Each firm sells a single product and invests in R&D to improve quality.
- q_{jt} = firm j's quality as measured by the **logarithm of speed of the best product** sold by this firm.

$$\text{log quality: } q_{jt} \in \{0,\ \delta,\ 2\delta,\ 3\delta, \ldots\}$$

- If investment successful, $q_{j,t+1} = q_{jt} + \delta$; otherwise, $q_{j,t+1} = q_{jt}$.
- Consumers: **Product durability**. Utility of no-purchase choice is determined by quality of microprocessor consumer owns.

Model: General features (2)

- Δ_t = Distribution of consumers according to owned quality, q^*.

  $\Delta_t = [\#$ consumers with $q^* = 0$; $\#$ consumers with $q^* = \delta$; ...]

- $q^* = 0$ means consumer does not own a computer.

- In principle, the state space of Δ_t is unbounded and grows over time endogenously with technological progress.

- To bound this space, authors assume a maximum distance $c * \delta$ between q_t^* and frontier quality $q_t^{max} \equiv max\{q_{AMD,t}, q_{Intel,t}\}$, such that:

$$q_t^* \in \{ 0, \; q_t^{max} - c\,\delta, \; q_t^{max} - (c-1)\,\delta, \; ..., \; q_t^{max} \}$$

Model: General features (3)

- Firms and consumers are forward looking.

- Consumer i's state space consists of $(q_{it}^{*}, q_t, \Delta_t)$:

  - q_{it}^{*} = Quality of her currently owned product;
  - $q_t = 2 \times 1$ vector of firms' current qualities;
  - Δ_t = distribution of consumers' owned qualities.

- Δ_t is part of the consumers' state space because it affects expectations on future prices.

- State space for firms is (q_t, Δ_t).

- Given these state variables firms simultaneously choose prices p_{jt} and investment x_{jt}.

Model: Consumer Demand

- Authors: *"We restrict firms to selling only one product because the computational burden of allowing multiproduct firms is prohibitive"*.

- Consumers own no more than one microprocessor at a time. Utility for a consumer i from firm j's new product with quality q_{jt} is given by:

$$u_{ijt} = \gamma \ q_{jt} - \alpha \ p_{jt} + \xi_j + \varepsilon_{ijt}$$

- Utility from the no-purchase option is:

$$u_{i0t} = \gamma \ q_{it}^{*} + \varepsilon_{i0t}$$

- A consumer maximizes her intertemporal utility given her beliefs about the evolution of future qualities and prices given (q_t, Δ_t).

Consumer Demand: Intertemporal Price Discrimination (IPD)

- The demand model does not incorporate ex-ante (persistent) heterogeneity in comsumers' preferences.
- Despite this, **the model generates endogenously incentives for firms to use IPD**.
- This is because consumers are "ex post" heterogeneous in owned q^*.
- Every period t, consumers with low q^* are willing to pay more for an upgrade.
- However, introducing persistent (ex-ante) heterogeneity in demand system would increase firms' inventive to IPD.

Model: Consumer Demand (3)

- Market shares for consumers currently owning q^* are:

$$s_{jt}(q^*) = \frac{\exp\{v_j(q_t, \Delta_t, q^*)\}}{\sum_{k \in \{0, Intel, AMD\}} \exp\{v_k(q_t, \Delta_t, q^*)\}}$$

- Using Δ_t to integrate over the distribution of q^* yields the market share of product j.

$$s_{jt} = \sum_{q^*} s_{jt}(q^*) \; \Delta_t(q^*)$$

- Transition rule of Δ_t. By definition, next period Δ_{t+1} is determined by a known closed-form function of Δ_t, q_t, and s_t.

$$\Delta_{t+1} = F_{\Delta}(\Delta_t, q_t, s_t)$$

Model: Firms' per period profits

- The period profit function (not including investment costs) is:

$$\pi_j(p_t, q_t, \Delta_t) = M \; s_j(p_t, q_t, \Delta_t) \; [p_{jt} - mc_j(q_{jt})]$$

- The specification of the marginal cost is:

$$mc_j(q_{jt}) = \lambda_{0j} - \lambda_1 (q_t^{\max} - q_{jt})$$

- Parameter $\lambda_1 \geq 0$ captures that being in the frontier (i.e., $q_{jt} = q_t^{max}$) implies higher unit production costs. Or equivalently, marginal cost is smaller for the non-frontier firm.

Model: Firms' Innovation process

- Relationship between investment in R&D (x_{jt}) and log-quality improvement ($\Delta q_{jt+1} = q_{jt+1} - q_{jt}$).

- Log-Quality improvement can take two values, 0 or δ.

- The probability that $\Delta q_{jt+1} = \delta$ is (Pakes & McGure, 1994):

$$\chi_j(x_{jt}, q_{jt}) \;=\; \frac{a_j(q_t)\; x_{jt}}{1 + a_j(q_t)\; x_{jt}}$$

where $a_j(q_t)$ is the "investment efficiency" function:

$$a_j(q_t) \;=\; a_{0,j}\;\; \max\left[1,\; a_1\;\left(\frac{q_t^{max} - q_{jt}}{\delta}\right)^{1/2}\right]$$

- It is decreasing in q_{jt} (i.e., $a_1 > 0$) to capture the idea of increasing difficulty of advancing the frontier relative to catching up.

Model: Firms' Bellman equation

- Let $W_j(q_t, \Delta_t)$ be the value function. The Bellman equation is:

$$W_j(q_t, \Delta_t) = \max_{x_{jt}, p_{jt}} \left[\pi_j(p_t, q_t, \Delta_t) - x_{jt} + \beta \, \mathbb{E}_t \left[W_j(q_{t+1}, \Delta_{t+1}) \right] \ \right]$$

- The decision variables are continuous, and the best response function should satisfy the F.O.C.

$$\begin{aligned} \frac{\partial \pi_{jt}}{\partial p_{jt}} + \beta \, \frac{\partial \mathbb{E}_t \left[W_{j,t+1} \right]}{\partial p_{jt}} &= 0 \\ \frac{\partial \pi_{jt}}{\partial x_{jt}} - 1 + \beta \, \frac{\partial \mathbb{E}_t \left[W_{j,t+1} \right]}{\partial x_{jt}} &= 0 \end{aligned}$$

Model: Markov Perfect Equilibrium

- (1) firms' and consumers' equilibrium strategies depend only on current payoff relevant state variables (q_t, Δ_t).
- (2) consumers have rational expectations about firms' policy functions.
- (3) each firm has rational expectations about competitors' policy functions and about the evolution of the ownership distribution.

Estimation

- Marginal cost parameters (λ_0, λ_1) are estimated in a first step because the dataset includes data on unit production costs.

- The rest of the structural parameters,

$$\theta = (\gamma,\ \alpha,\ \xi_{intel},\ \xi_{amd},\ a_{0,intel},\ a_{0,amd},\ a_1)$$

- Demand: γ, α, ξ_{intel}, ξ_{amd}; Investment innovation efficiency: $a_{0,intel}$, $a_{0,amd}$, a_1.

- θ is estimated using **Indirect Inference** or **Simulated Method of Moments (SMM)**.

Estimation: Moments to match

- Mean of innovation rates $q_{j,t+1} - q_{jt}$ for each firm.
- Mean R&D intensities $x_{jt} / revenue_{jt}$ for each firm.
- Mean of differential quality $q_{intel,t} - q_{amd,t}$, and share of quarters with $q_{intel,t} \geq q_{amd,t}$.
- Mean of gap $q_t^{\max} - \overline{\Delta}_t$.
- Average prices, and OLS estimated coefficients of the regressions of p_{jt} on $q_{intel,t}$, $q_{amd,t}$, and average $\overline{\Delta}_t$.
- OLS estimated coefficients of the regression of $s_{intel,t}$ on $q_{intel,t} - q_{amd,t}$.

Empirical and predicted moments

TABLE 1
EMPIRICAL AND SIMULATED MOMENTS

Moment	Actual	Actual Standard Error	Fitted
Intel price equation:			
Average Intel price	219.7	5.9	206.2
$q_{\text{Intel},t} - q_{\text{AMD},t}$	47.4	17.6	27.3
$q_{\text{Intel},t} - \bar{\Delta}_t$	94.4	31.6	43.0
AMD price equation:			
Average AMD price	100.4	2.3	122.9
$q_{\text{Intel},t} - q_{\text{AMD},t}$	−8.7	11.5	−22.3
$q_{\text{AMD},t} - \bar{\Delta}_t$	16.6	15.4	5.9
Intel share equation:			
Constant	.834	.007	.846
$q_{\text{Intel},t} - q_{\text{AMD},t}$	.055	.013	.092
Potential upgrade gains:			
Mean $(\bar{q}_t - \hat{\Delta}_t)$	1.146	.056	1.100
Mean innovation rates:			
Intel	.557	.047	.597
AMD	.610	.079	.602
Relative qualities:			
Mean $q_{\text{Intel},t} - q_{\text{AMD},t}$	1.257	.239	1.352
Mean $\mathcal{I}(q_{\text{Intel},t} \geq q_{\text{AMD},t})$	.833	.054	.929
Mean R&D/revenue:			
Intel	.114	.004	.101
AMD	.203	.009	.223

Parameter estimates

TABLE 2
PARAMETER ESTIMATES

Parameter	Estimate	Standard Error
Price, α	.0131	.0017
Quality, γ	.2764	.0298
Intel fixed effect, ξ_{Intel}	−.6281	.0231
AMD fixed effect, ξ_{AMD}	−3.1700	.0790
Intel innovation, $a_{0,\text{Intel}}$	.0010	.0002
AMD innovation, $a_{0,\text{AMD}}$	.0019	.0002
Spillover, a_1	3.9373	.1453
Stage 1 marginal cost equation:		
Constant, λ_0	44.5133	1.1113
$\max(0, q_{\text{competitor},t} - q_{\text{own},t})$, λ_1	−19.6669	4.1591

Parameter estimates (2)

- Demand: Dividing γ by α: consumers are willing to pay \$21 for enjoying during 1 quarter a $\delta = 20\%$ increase in log quality.
- Dividing $\xi_{intel} - \xi_{amd}$ by α: consumers are willing to pay \$194 for Intel over AMD.
- The model needs this strong brand effect to explain the fact that AMD's share never rises above 22 percent in the period during which AMD had a faster product.
- Intel and AMD's innovation efficiencies are estimated to be .0010 and .0019, respectively, as needed for AMD to occasionally be the technology leader while investing much less.

Counterfactuals: Industry Outcomes under Different Scenarios

TABLE 3
INDUSTRY OUTCOMES UNDER VARIOUS SCENARIOS

	AMD-Intel Duopoly (1)	Symmetric Duopoly (2)	Monopoly (3)	No Spillover Duopoly (4)	Myopic Pricing: AMD-Intel (5)	Myopic Pricing: Monopoly (6)
Industry profits ($ billions)	408	400	567	382	318	322
Consumer surplus (CS)	2,978	3,012	2,857	3,068	2,800	2,762
CS as share of monopoly CS	1.042	1.054	1.000	1.074	.980	.967
Social surplus (SS)	3,386	3,412	3,424	3,450	3,118	3,084
SS as share of planner SS	.929	.906	.940	.916	.828	.819
Margins, $(p - mc)/mc$	3.434	2.424	5.672	3.478	2.176	2.216
Price	194.17	146.73	296.98	157.63	140.06	143.16
Frontier innovation rate	.599	.501	.624	.438	.447	.438
Industry investment ($ millions)	830	652	1,672	486	456	787
Mean quality upgrade (%)	261	148	410	187	175	181
Intel or leader share	.164	.135	.143	.160	.203	.211
AMD or laggard share	.024	.125		.091	.016	

From current duopoly (1) to Intel Monopoly (3)

- Innovation rate increases from 0.599 to 0.624
- Mean quality upgrade increases 261% to 410%
- Investment in R&D: increases by 1.2B per quarter: more than doubles.
- Price increases in \$102 (70%)
- Consumer surplus declines in \$121M (4.2%)
- Industry profits increase in \$159M
- Social surplus increases in \$38M (less than 1%)

From current duopoly (1) to symmetric duopoly (2)

- Innovation rate declines from 0.599 to 0.501
- Mean quality declines from 261% to 148%
- Investment in R&D: declines by 178M per quarter
- Price declines in \$48 (24%)
- Consumer surplus increases in \$34M (1.2%)
- Industry profits decline in \$8M
- Social surplus increases in \$26M (less than 1%)

From current scenario (1) to myopic pricing

- It reduces prices, increases CS, and reduces firms' profits.
- Innovation rates and investment in R&D decline dramatically.
- Why? The higher induce firms to innovate more rapidly.
- Prices are higher with dynamic pricing because firms want to preserve future demand.

Counterfactuals

- The finding that innovation by a monopoly exceeds that of a duopoly reflects two features of the model:

  - the monopoly must innovate to induce consumers to upgrade;

  - the monopoly is able to extract much of the potential surplus from these upgrades because of its substantial pricing power.

- If there were a steady flow of new consumers into the market, such that **most demand were not replacement, the monopoly would reduce innovation below that of the duopoly**.

Summary of results

- The rate of innovation in product quality would be 4.2% higher if Intel were a monopolist, consistent with Schumpeter.
- Without AMD, higher margins spur Intel to innovate faster to generate upgrade sales.
- As in Coase's (1972) conjecture, product durability can limit welfare losses from market power.
- This result, however, depends on the degree of competition from past sales. If **first-time purchasers were to arrive sufficiently faster, innovation in an Intel monopoly would be lower**, not higher, since upgrade sales would be less important.