

Lecture 2: Benchmark Heterogeneous Firm Model and Overview of Solution Methods

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Motivating Facts: Doms and Dunne (1998)

Measurement

- Use [Census data](#) from LRD, 1972 - 1988
 - After 1988, stopped collecting data on sales and retirements
- Construct capital stock using perpetual inventory method
 - Focus on balanced panel
- Analyze the [growth rate of capital](#) for plant i at time t

$$GK_{it} = \frac{i_{it} - \delta k_{it-1}}{0.5 \times (k_{it-1} + k_{it})}$$

Plant-Level Investment is Lumpy Across Plants

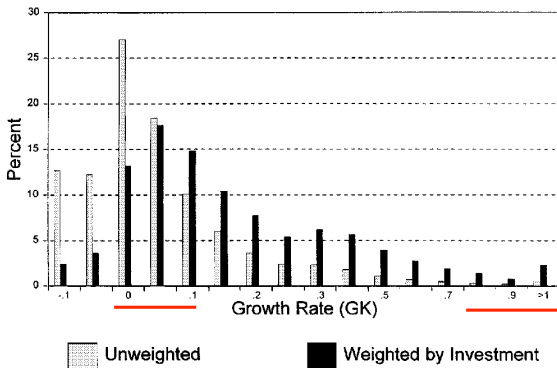
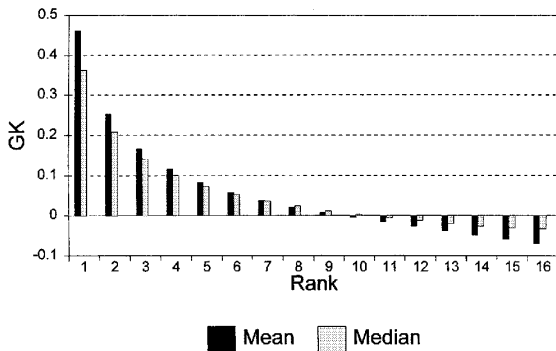


FIG. 1. Capital growth rate (GK) distributions: Unweighted and weighted by investment.

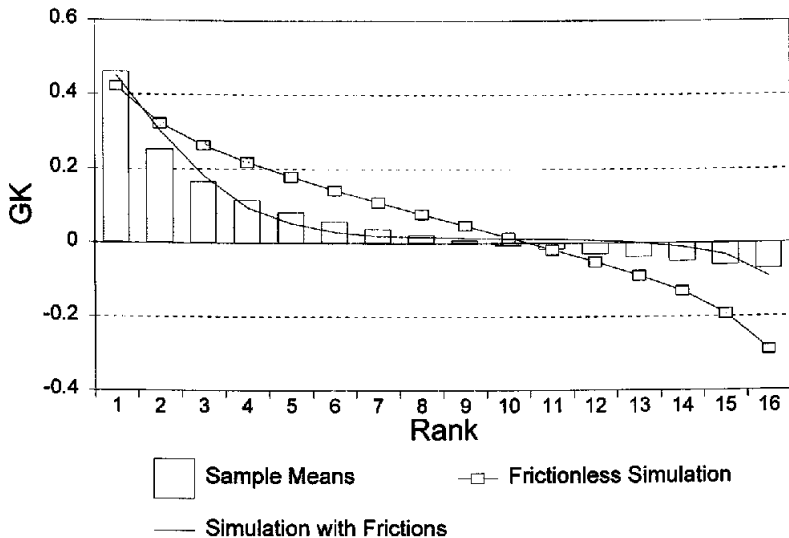
- 51.9% of plants increase capital $\leq 2.5\%$
- 11% of plants increase capital $\geq 20\%$

Plant-Level Investment is Lumpy Within Plants



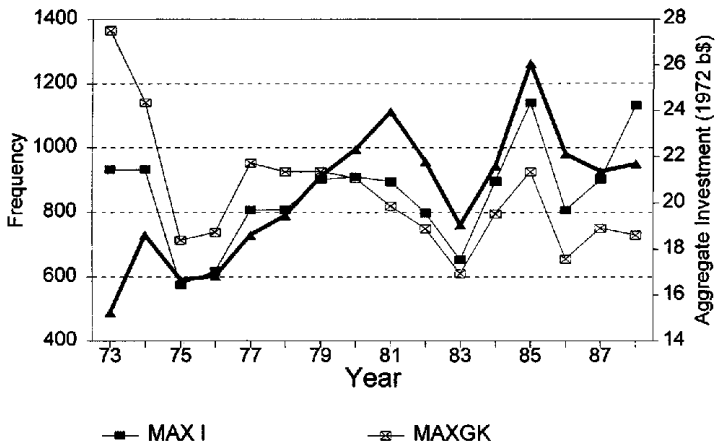
- Capital growth in largest investment episode nearly 50%
- In median investment episode approximately 0%

Plant-Level Investment is Lumpy Within Plants



simulation with frictions: add a fixed cost to invest, so if you only invest a little, it does not worth it. But if you invest a lot, it is worth.

Frequency of Spikes Correlated with Aggregate Investment



Benchmark Model: Khan and Thomas (2008)

Model Overview

Heterogeneous Firms

- Fixed mass
- Idiosyncratic + aggregate productivity shocks
- Fixed capital adjustment costs

Representative Household

- Owns firms
- Supplies labor
- Complete markets

Heterogeneous Firms

decreasing returns to scale:
preventing the large firm taking over the economy

Production technology $y_{jt} = e^{z_t} e^{\varepsilon_{jt}} k_{jt}^{\theta} n_{jt}^{\nu}$, $\theta + \nu < 1$

- Idiosyncratic productivity shock $\varepsilon_{jt+1} = \rho_{\varepsilon} \varepsilon_{jt} + \omega_{jt+1}^{\varepsilon}$ where $\omega_{jt+1}^{\varepsilon} \sim N(0, \sigma_{\varepsilon}^2)$
- Aggregate productivity shock $z_{t+1} = \rho_z z_t + \omega_{t+1}^z$ where $\omega_{t+1}^z \sim N(0, \sigma_z^2)$ Both are AR1 shocks

Firms accumulate capital according to $k_{jt+1} = (1 - \delta)k_{jt} + i_{jt}$

- If $\frac{i_{jt}}{k_{jt}} \notin [-a, a]$, pay fixed cost ξ_{jt} in units of labor
- Fixed cost $\xi_{jt} \sim U[0, \bar{\xi}]$

Firm Optimization Problem: Recursive Formulation

$$v(\varepsilon, k, \xi; \mathbf{s}) = \max_n e^z e^\varepsilon k^\theta n^\nu - w(\mathbf{s})n \\ + \max \left\{ v^A(\varepsilon, k; \mathbf{s}) - w(\mathbf{s})\xi, v^N(\varepsilon, k; \mathbf{s}) \right\}$$

Firm Optimization Problem: Recursive Formulation

$$\begin{aligned}
 v(\varepsilon, k, \xi; \mathbf{s}) = & \max_n \overset{\text{how many workers to hire}}{e^z e^\varepsilon k^\theta n^\nu} - w(\mathbf{s})n \\
 & + \max \left\{ \underset{\text{If you pay the fixed cost}}{v^A(\varepsilon, k; \mathbf{s})} - w(\mathbf{s})\xi, \underset{\text{If you dont pay the fixed cost}}{v^N(\varepsilon, k; \mathbf{s})} \right\}
 \end{aligned}$$

$$v^A(\varepsilon, k; \mathbf{s}) = \max_{i \in \mathbb{R}} -i + \underset{\text{Stochastic discount factor}}{\mathbb{E}} [\Lambda(\mathbf{s}'; \mathbf{s}) v(\varepsilon', k', \xi'; \mathbf{s}') | \varepsilon, k; \mathbf{s}]$$

$$v^N(\varepsilon, k; \mathbf{s}) = \max_{i \in [-ak, ak]} -i + \mathbb{E} [\Lambda(\mathbf{s}'; \mathbf{s}) v(\varepsilon', k', \xi'; \mathbf{s}') | \varepsilon, k; \mathbf{s}]$$

Firm Optimization Problem: Recursive Formulation

$$v(\varepsilon, k, \xi; \mathbf{s}) = \max_n e^z e^\varepsilon k^\theta n^\nu - w(\mathbf{s})n \\ + \max \left\{ v^A(\varepsilon, k; \mathbf{s}) - w(\mathbf{s})\xi, v^N(\varepsilon, k; \mathbf{s}) \right\}$$

$$\hat{v}(\varepsilon, k; \mathbf{s}) = \max_n e^z e^\varepsilon k^\theta n^\nu - w(\mathbf{s})n \\ + \frac{\hat{\xi}(\varepsilon, k; \mathbf{s})}{\bar{\xi}} \left(v^A(\varepsilon, k; \mathbf{s}) - w(\mathbf{s}) \frac{\hat{\xi}(\varepsilon, k; \mathbf{s})}{2} \right) \\ + \left(1 - \frac{\hat{\xi}(\varepsilon, k; \mathbf{s})}{\bar{\xi}} \right) v^N(\varepsilon, k; \mathbf{s})$$

Household

Representative household who owns all firms in the economy

$$\max_{C(\mathbf{s}), N(\mathbf{s})} \frac{C(\mathbf{s})^{1-\sigma} - 1}{1-\sigma} - \chi \frac{N(\mathbf{s})^{1+\alpha}}{1+\alpha} \text{ such that}$$
$$C(\mathbf{s}) = w(\mathbf{s})N(\mathbf{s}) + \Pi(\mathbf{s})$$

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Complete markets implies that $\Lambda(\mathbf{s}'; \mathbf{s}) = \beta \left(\frac{C(\mathbf{s}')}{C(\mathbf{s})} \right)^{-\sigma}$

- Firms maximize their market value
- Market value given by expected present value of dividends using stochastic discount factor
- With complete markets, SDF is household's intertemporal marginal rate of substitution

Defining Recursive Competitive Equilibrium

What is the aggregate state **\mathbf{s}** ?

Defining Recursive Competitive Equilibrium

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- Aggregate shock z

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What is the law of motion for the \mathbf{s} ?

$$g'(\varepsilon', k') = \int \left[\mathbb{1} \{ \rho_\varepsilon \varepsilon + \sigma_\varepsilon \omega'_\varepsilon = \varepsilon' \} \right. \\ \left. \times \int \mathbb{1} \{ k'(\varepsilon, k, \xi; \mathbf{s}) = k' \} dG(\xi) \right] \\ \times p(\omega'_\varepsilon) g(\varepsilon, k) d\omega'_\varepsilon d\varepsilon dk$$

Recursive Competitive Equilibrium

A set of $\hat{v}(\varepsilon, k; z, g)$, $C(z, g)$, $N(z, g)$, $w(z, g)$, $\Lambda(z'; z, g)$, and $g'(z, g)$ s.t.

1. **Firm optimization:** Taking $\Lambda(z'; z, g)$ and $w(z, g)$ as given, $\hat{v}(\varepsilon, k; z, g)$ solves Bellman equation
2. **Household optimization:** $w(z, g)C(z, g)^{-\sigma} = \chi N(z, g)^\alpha$
3. **Market clearing:**

$$N(z, g) = \int n(\varepsilon, k; z, g)g(\varepsilon, k)d\varepsilon dk$$

$$C(z, g) = \int (y(\varepsilon, k, \xi; z, g) - i(\varepsilon, k, \xi; z, g))dG(\xi)g(\varepsilon, k)d\varepsilon dk$$

$$\Lambda(z'; z, g) = \beta \left(\frac{C(z', g'(z, g))}{C(z, g)} \right)^{-\sigma}$$

4. **Consistency:** $g'(\varepsilon, k)$ satisfies law of motion for distribution

Model Parameterization

| Desc. | Value | Desc. | Value |
|-------------------------------|---------------------------------|---|-------|
| β Discount factor | .961 | ρ_z Aggregate TFP AR(1) | .859 |
| σ Utility curvature | 1 | σ_z Aggregate TFP AR(1) | .014 |
| α Inverse Frisch | $\lim \alpha \rightarrow 0$ | $\bar{\xi}$ Fixed cost | .0083 |
| χ Labor disutility | $\Rightarrow N^* = \frac{1}{3}$ | a No fixed cost region | .011 |
| ν Labor share | .64 | ρ_ϵ Idiosyncratic TFP AR(1) | .859 |
| θ Capital share | .256 | σ_ϵ Idiosyncratic TFP AR(1) | .022 |
| δ Capital depreciation | .085 | | |

Overview of Computational Methods

Computing Equilibrium

- Key challenge: aggregate state g is infinite-dimensional

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- Key challenge: aggregate state g is infinite-dimensional
- Two steps:
 1. Compute steady state without aggregate shocks \implies distribution constant at g^*
 2. Compute full model with aggregate shocks \implies distribution varies over time

Steady State Recursive Competitive Equilibrium

A set of $v^*(\varepsilon, k)$, C^* , N^* , w^* , and $g^*(\varepsilon, k)$ such that

1. **Firm optimization:** Taking w^* as given: $v^*(\varepsilon, k)$ solves Bellman equation
2. **Household optimization:** Taking w^* as given: $w^*(C^*)^{-\sigma} = \chi(N^*)^\alpha$
3. **Market clearing:**

$$N^* = \int n(\varepsilon, k) g(\varepsilon, k) d\varepsilon dk$$

$$C^* = \int (y(\varepsilon, k, \xi) - i(\varepsilon, k, \xi)) dG(\xi) g^*(\varepsilon, k) d\varepsilon dk$$

4. **Consistency:**
 $g^*(\varepsilon, k)$ satisfies law of motion for distribution given g^*

Hopenhayn-Rogerson (1993) Algorithm

Start with guess of w^*

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- Solve **firm optimization** problem $\implies v^*(\varepsilon, k), n^*(\varepsilon, k), k'(\varepsilon, k, \xi)$

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Start with guess of w^*

- Solve **firm optimization** problem $\implies v^*(\varepsilon, k), n^*(\varepsilon, k), k'(\varepsilon, k, \xi)$
- Use $k'(\varepsilon, k, \xi)$ to compute **stationary distribution** $g^*(\varepsilon, k)$ by iterating on law of motion
- Compute implied labor demand $N^d = \int n^*(\varepsilon, k) g^*(\varepsilon, k) d\varepsilon dk$

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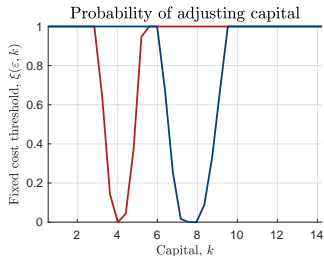
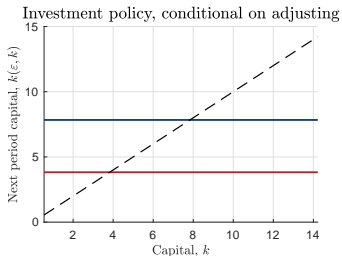
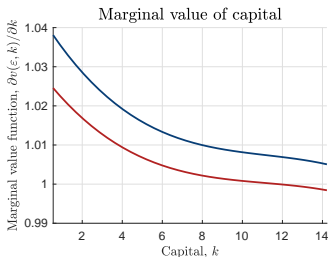
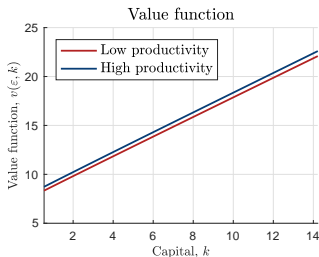
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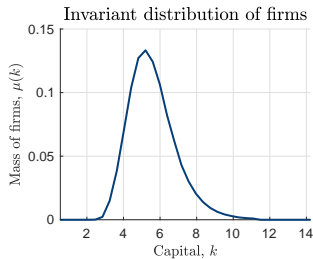
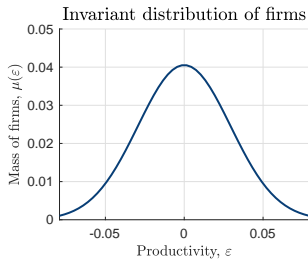
Update guess of w^* based on $N^d - N^s$

Iterate to convergence

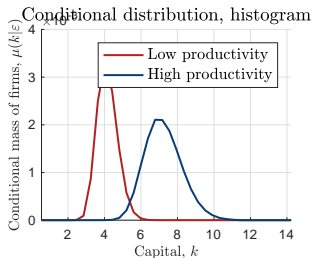
Steady State Decisions



Steady State Distribution



The positive skewness comes from fixed costs



Full Model with Aggregate Shocks

- Outside of steady state,
 - Distribution g varies over time \implies
how to approximate distribution?
 - Law of motion for g is complicated \implies
how to approximate law of motion?

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how to approximate law of motion?
- Will provide overview of three approaches in the literature:
 1. **Krusell-Smith**: approximate distribution with moments (used in Khan and Thomas 2008)
 2. **Reiter methods**: perturbation w.r.t. the distribution (used in Winberry 2018; will discuss details on Friday if time)
 3. **MIT shocks**: perfect foresight transition paths (used in Ottonello-Winberry 2018; will discuss on Friday)

Krusell and Smith (1998)

- Typical approach to dealing with challenge: Krusell-Smith (1998)
 - Approximate distribution with **moments**, e.g. $g(\varepsilon, k) \approx \bar{K}$
 - Approximate law of motion with **parametric form**
 $\log \bar{K}' = \alpha_0 + \alpha_1 z + \alpha_2 \log \bar{K}$
 - Approximate prices with **parametric form**
 $\log C = \gamma_0 + \gamma_1 z + \gamma_2 \log \bar{K}$ and $\log w = \eta_0 + \eta_1 z + \eta_2 \log \bar{K}$

Solve for the coefficients as part of the model

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- **Overview of the algorithm:**
 - Start with guess of α , γ , and η
 - Solve **firm optimization** $\Rightarrow \hat{v}(\varepsilon, k; z, \bar{K}), n(\varepsilon, k; z, \bar{K}), k'(\varepsilon, k, \xi; z, \bar{K})$
 - **Simulate** large panel of firms using $n(\varepsilon, k; z, \bar{K}), k'(\varepsilon, k, \xi; z, \bar{K})$
 - Compute aggregate time series z_t, \bar{K}_t, C_t, w_t
 - Update α , γ , and η using OLS on simulated series
 - Iterate to convergence on α , γ , and η
- Assess accuracy using, e.g., **R^2 of forecasting rules**

- Approximate distribution with [parametric family](#):

$$g(\varepsilon, k) \cong g_0 \exp\{g_1^1 (\varepsilon - m_1^1) + g_1^2 (\log k - m_1^2) + \\ \sum_{i=2}^{n_g} \sum_{j=0}^i g_i^j \left[(\varepsilon - m_1^1)^{i-j} (\log k - m_1^2)^j - m_i^j \right]\}$$

→ Aggregate state approximated by $(z, g(\varepsilon, k)) \approx (z, \mathbf{m})$

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- Compute law of motion + prices directly by [integration](#)

- Approximate distribution with **parametric family**:

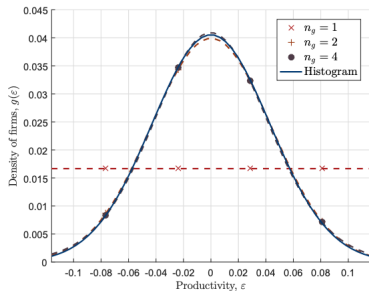
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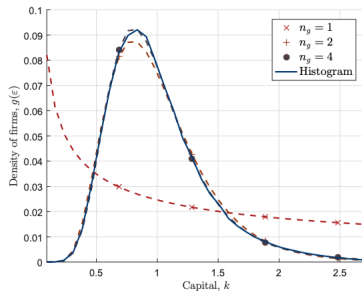
- Compute law of motion + prices directly by **integration**
- Compute aggregate dynamics using **perturbation methods**
 - Solve for steady state in **Matlab**
 - Solve for aggregate dynamics using **Dynare**

Winberry (2018)

(a) Marginal distribution of productivity

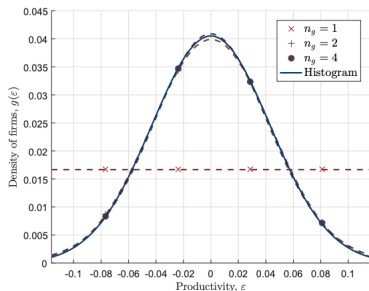


(b) Marginal distribution of capital

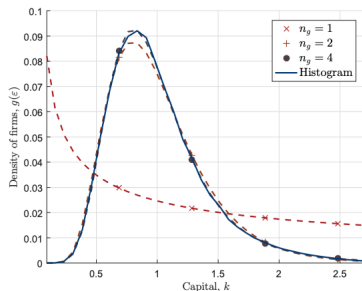


Winberry (2018)

(a) Marginal distribution of productivity



(b) Marginal distribution of capital



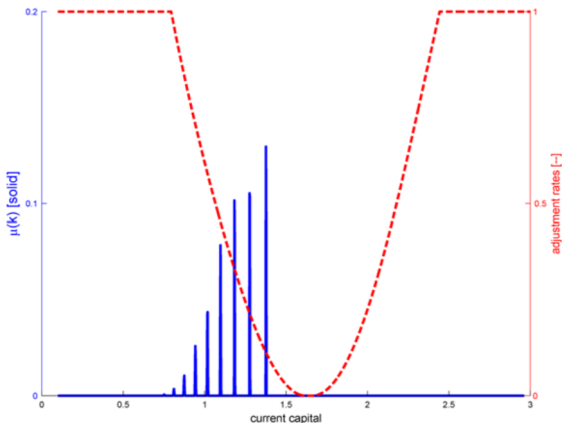
- Run time $\approx 20 - 40$ seconds for accurate approximation
- Fast enough for [likelihood-based estimation](#)
- Codes at my [website](#)

MIT Shocks (aka Transition Paths)

- **MIT shock** = unexpected innovation Δz_0 at $t = 0$
+ perfect foresight transition path back to steady state
- In this model, characterized by $\{w_t\}_{t=0}^{\infty}$ and $\{C_t\}_{t=0}^{\infty}$
 1. Solve **firm's problem** by backward iteration
 2. Given $\{\hat{v}_t(\varepsilon, k)\}_{t=0}^{\infty}$, **simulate decisions** to get $n_t^d(\varepsilon, k)$, $y_t(\varepsilon, k) - i_t(\varepsilon, k)$, and $g_t(\varepsilon, k) \implies$ get aggregates
 $N_t^d = \int n_t^d(\varepsilon, k) g_t(\varepsilon, k) d\varepsilon dk$ and
 $C_t^s = \int (y_t(\varepsilon, k) - i_t(\varepsilon, k)) g_t(\varepsilon, k) d\varepsilon dk$
 3. **Equilibrium**: $N_t^d = N_t^s$ and $C_t^s = C_t$
- Computational method: set $T =$ large enough and **iterate over path of $\{w_t\}_{t=0}^T$ and $\{C_t\}_{t=0}^T$**
- Converges to true IRF as $\Delta z_0 \rightarrow 0$

Results

Complicated Impulse Responses with Fixed Prices

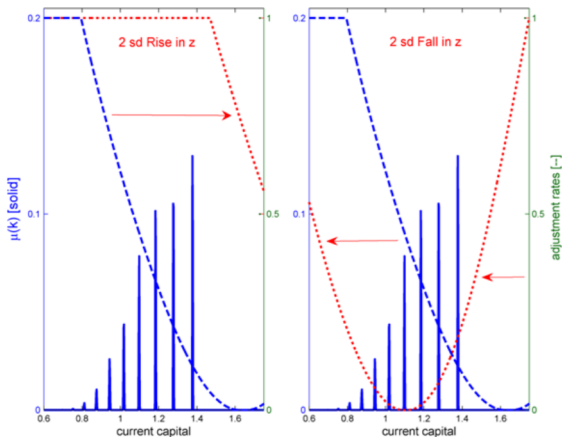


capital depreciate, so all firms are away from k^* , then some will adjust, some will not, those not depreciate again ...

Distribution in model with no idiosyncratic productivity shocks

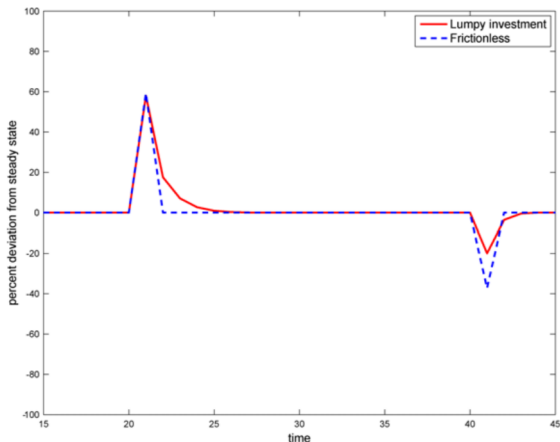
Investment decision characterized by adjustment hazard

Complicated Impulse Responses with Fixed Prices



Response of aggregate investment to shock depends on interaction of initial distribution and adjustment hazards

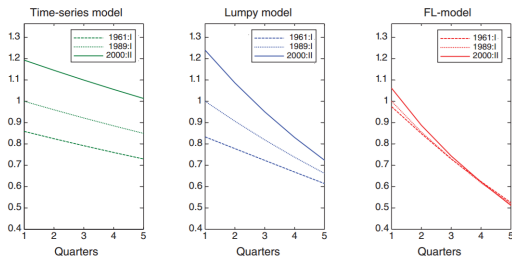
Implication: Sign Dependence



Aggregate investment more responsive to positive than negative shocks

Not true in frictionless model

Implication: State Dependence



From Bachmann, Caballero, and Engel (2013)

$$\frac{I_t}{K_t} = \sum_{j=1}^p \phi_j \frac{I_{t-j}}{K_{t-j}} + \sigma_t e_t$$

$$\sigma_t = \alpha_1 + \eta_1 \frac{1}{p} \sum_{j=1}^p \frac{I_{t-j}}{K_{t-j}}$$

Aggregate Nonlinearities with Fixed Prices

- Both of these are examples of nonlinear aggregate dynamics
 - Linear model has constant loading on aggregate shock

Aggregate Nonlinearities with Fixed Prices

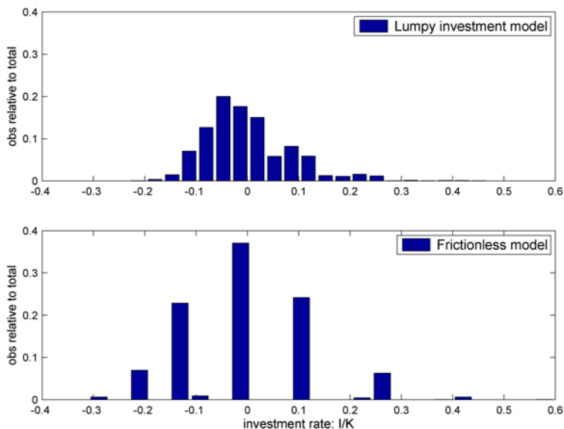
- Both of these are examples of nonlinear aggregate dynamics
 - Linear model has constant loading on aggregate shock
- Some evidence in aggregate data
 - Sign and state dependence \rightarrow distribution of $\frac{l_t}{K_t}$ positively skewed
 - State dependence \rightarrow dynamics of $\frac{l_t}{K_t}$ feature conditional heteroskedasticity

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 - Sign and state dependence \rightarrow distribution of $\frac{I_t}{K_t}$ positively skewed
 - State dependence \rightarrow dynamics of $\frac{I_t}{K_t}$ feature conditional heteroskedasticity
- My view: time series evidence is suggestive at best
 - Predictions are about extreme states, which are rare
 - But that is exactly when we care about these predictions!
 \Rightarrow rely on cross-sectional data + carefully specified general equilibrium model

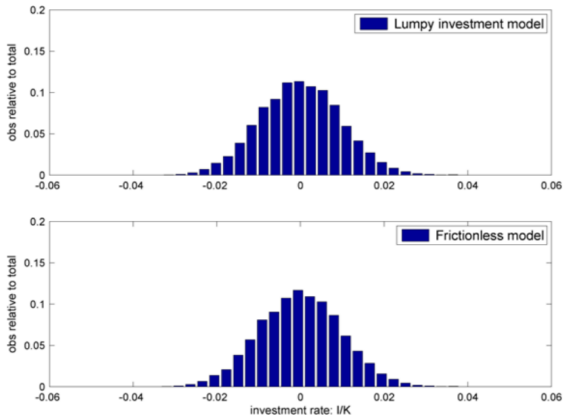
Distribution of Aggregate $\frac{I_t}{K_t}$ with Fixed Prices

Partial equilibrium: different from frictionless model



Distribution of Aggregate $\frac{I_t}{K_t}$ in General Equilibrium

In GE, very similar distribution of investment



Distribution of Aggregate $\frac{I_t}{K_t}$ in General Equilibrium

TABLE III
ROLE OF NONCONVEXITIES IN AGGREGATE INVESTMENT RATE DYNAMICS

| | Persistence | Standard Deviation | Skewness | Excess Kurtosis |
|---------------------------------------|-------------|-----------------------|----------|--------------------|
| <i>Postwar U.S. data</i> ^a | 0.695 | 0.008 | 0.008 | -0.715 |
| A. Partial equilibrium models | | | | |
| PE frictionless | -0.069 | 0.128 | 0.358 | 0.140 |
| PE lumpy investment | 0.210 | 0.085 | 1.121 | 2.313 |
| B. General equilibrium models | | | | |
| GE frictionless | 0.659 | 0.010 | 0.048 | 0.048 |
| GE lumpy investment | 0.662 | 0.010 | 0.067 | -0.074 |

^aData are annual private investment-to-capital ratio, 1954–2005, computed using Bureau of Economic Analysis tables.

Business Cycles Nearly Identical to Representative Firm

TABLE IV
AGGREGATE BUSINESS CYCLE MOMENTS

| | Output | TFP ^a | Hours | Consump. | Invest. | Capital |
|--|---------|------------------|-------|----------|---------|---------|
| A. Standard deviations relative to output ^b | | | | | | |
| GE frictionless | (2.277) | 0.602 | 0.645 | 0.429 | 3.562 | 0.494 |
| GE lumpy | (2.264) | 0.605 | 0.639 | 0.433 | 3.539 | 0.492 |
| B. Contemporaneous correlations with output | | | | | | |
| GE frictionless | | 1.000 | 0.955 | 0.895 | 0.976 | 0.034 |
| GE lumpy | | 1.000 | 0.956 | 0.900 | 0.976 | 0.034 |

^aTotal factor productivity.

^bThe logarithm of each series is Hodrick–Prescott-filtered using a weight of 100. The output column of panel A reports percent standard deviations of output in parentheses.

Why Do the Nonlinearities Disappear?

General equilibrium price movements

- Time-varying elasticity comes from large movements in adjustment hazard
- [Procyclical real interest rate](#) and wage restrain those movements

$$1 + r_t = \frac{1}{\mathbb{E}_t[\Lambda_{t,t+1}]}$$

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General equilibrium price movements

- Time-varying elasticity comes from large movements in adjustment hazard
- [Procyclical real interest rate](#) and wage restrain those movements

$$1 + r_t = \frac{1}{\mathbb{E}_t[\Lambda_{t,t+1}]}$$

Specification of adjustment costs

- Calibrated adjustment costs [small](#)

Why Do the Nonlinearities Disappear?

General equilibrium price movements [Winberry (2018)]

- Time-varying elasticity comes from large movements in adjustment hazard
- **Procyclical real interest rate** and wage restrain those movements

$$1 + r_t = \frac{1}{\mathbb{E}[\Lambda_{t,t+1}]}$$

Specification of adjustment costs [Bachmann, Caballero, and Engel (2013)]

- Calibrated adjustment costs **small**

Bachmann, Caballero, and Engel (2013)

- Argue Khan and Thomas' calibration of adjustment costs responsible for irrelevance result
- Calibrate larger adjustment costs and recover aggregate nonlinearities

Bachmann, Caballero, and Engel (2013)

- Argue Khan and Thomas' calibration of adjustment costs responsible for irrelevance result
- Calibrate larger adjustment costs and recover aggregate nonlinearities
- Argument based on decomposition between AC smoothing and PR smoothing
 - Frictionless partial equilibrium model excessively volatile
 - AC smoothing: dampening due to adjustment costs
 - PR smoothing: dampening due to price movements
- Measure AC smoothing in data and target in calibration → higher adjustment costs

Model

Production technology $y_{jt} = e^{z_t} e^{\epsilon_{st}} e^{\epsilon_{jt}} k_{jt}^{\theta} n_{jt}^{\nu}, \theta + \nu < 1$

- Idiosyncratic productivity shock $\epsilon_{jt+1} = \rho_{\epsilon} \epsilon_{jt} + \omega_{jt+1}^{\epsilon}$ where $\omega_{jt+1}^{\epsilon} \sim N(0, \sigma_{\epsilon}^2)$
- Aggregate productivity shock $z_{t+1} = \rho_z z_t + \omega_{t+1}^z$ where $\omega_{t+1}^z \sim N(0, \sigma_z^2)$
- Sectoral productivity shock $\epsilon_{st+1} = \rho_{\epsilon} \epsilon_{st} + \omega_{st+1}^{\epsilon}$ where $\omega_{st+1}^{\epsilon} \sim N(0, \sigma_{\epsilon_s}^2)$

Model

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- Sectoral productivity shock $\epsilon_{st+1} = \rho_\epsilon \epsilon_{st} + \omega_{st+1}^\epsilon$ where $\omega_{st+1}^\epsilon \sim N(0, \sigma_{\epsilon_s}^2)$

Firms **accumulate capital** according to $k_{jt+1} = (1 - \delta)k_{jt} + i_{jt}$

- If don't pay fixed cost, must undertake maintenance investment $\chi \times \delta k_{jt}$
- Otherwise, pay fixed cost ξ_{jt} in units of labor
- Fixed cost $\xi_{jt} \sim U[0, \bar{\xi}]$

Calibration

Set most parameters **exogenously**

Choose σ_z , $\bar{\xi}$, and χ to match degree of **AC-smoothing**

- Identify AC-smoothing using **volatility of sectoral investment rates**
 - Aggregated enough to capture interaction of distribution and hazards
 - Small enough to not generate price response

Calibration

Set most parameters **exogenously**

Choose σ_z , $\bar{\xi}$, and χ to match degree of **AC-smoothing**

- Identify AC-smoothing using **volatility of sectoral investment rates**
 - Aggregated enough to capture interaction of distribution and hazards
 - Small enough to not generate price response
- Targets:
 1. Volatility of aggregate investment rate
 2. Average volatility of sectoral investment rates
 3. **Amount of conditional heteroskedasticity**

AC vs. PR Smoothing Decomposition

TABLE 6—SMOOTHING DECOMPOSITION

| Model | AC smoothing/total smoothing (in percent) | | |
|---|--|------|---------|
| | LB | UB | Average |
| Khan-Thomas-lumpy annual | 0.0 | 16.1 | 8.0 |
| Khan-Thomas-lumpy annual, our $\bar{\xi}$ | 8.1 | 59.2 | 33.7 |
| Our model annual ($\chi = 0$), Khan and Thomas' $\bar{\xi}$ | 0.8 | 16.0 | 8.4 |
| Our model annual ($\chi = 0$) | 18.9 | 75.3 | 47.0 |
| Our model annual ($\chi = 0.25$) | 19.1 | 75.7 | 47.4 |
| Our model annual ($\chi = 0.50$) | 19.9 | 76.6 | 48.3 |
| Our model quarterly ($\chi = 0$) | 14.5 | 80.9 | 47.7 |
| Our model quarterly ($\chi = 0.25$) | 15.4 | 80.9 | 48.2 |
| Our model quarterly ($\chi = 0.5$) | 15.4 | 81.0 | 48.2 |

$$UB = \log [\sigma(\text{none})/\sigma(\text{AC})] / \log [\sigma(\text{none})/\sigma(\text{both})]$$

$$LB = 1 - \log [\sigma(\text{none})/\sigma(\text{PR})] / \log [\sigma(\text{none})/\sigma(\text{both})]$$

Calibrated Adjustment Costs

TABLE 4—THE ECONOMIC MAGNITUDE OF ADJUSTMENT COSTS—ANNUAL

| Model | Adjustment costs/ unit's output (in percent) (1) | Adjustment costs/ unit's wage bill (in percent) (2) |
|--------------------------------------|---|--|
| This paper ($\chi = 0$) | 38.9 | 60.9 |
| This paper ($\chi = 0.25$) | 12.7 | 19.8 |
| This paper ($\chi = 0.50$) | 3.6 | 5.6 |
| Caballero-Engel (1999) | 16.5 | — |
| Cooper-Haltiwanger (2006) | 22.9 | — |
| Bloom (2009) | 35.4 | — |
| Khan-Thomas (2008) | 0.5 | 0.8 |
| Khan-Thomas (2008) "Huge Adj. Costs" | 3.7 | 5.8 |

Notes: This table displays the average adjustment costs paid, conditional on adjustment, as a fraction of output (left column) and as a fraction of the wage bill (right column), for various models. Rows 4–6 are based on table IV in Bloom (2009). For Cooper and Haltiwanger (2006) and Bloom (2009) we report the sum of costs associated with two sources of lumpy adjustment: fixed adjustment costs and partial irreversibility. The remaining models only have fixed adjustment costs.

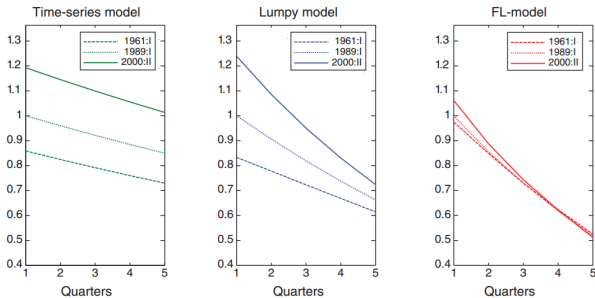
Aggregate Nonlinearities

TABLE 5—HETEROSCEDASTICITY RANGE

| Model | $\log(\sigma_{95}/\sigma_5)$ |
|--|------------------------------|
| <i>Data</i> | <i>0.3021</i> |
| This paper ($\chi = 0$) | 0.1830 |
| This paper ($\chi = 0.25$) | 0.2173 |
| This paper ($\chi = 0.50$) | 0.2901 |
| Quadratic adj. costs ($\chi = 0$) | 0.0487 |
| Quadratic adj. costs ($\chi = 0.25$) | 0.0411 |
| Quadratic adj. costs ($\chi = 0.50$) | 0.0321 |
| Frictionless | 0.0539 |
| Khan-Thomas (2008) | 0.0468 |

Notes: This table displays heteroscedasticity range ($\log(\sigma_{95}/\sigma_5)$) for the data (row 1) and various model specifications that vary in terms of the maintenance parameter χ and the adjustment technology for capital: fixed adjustment costs (rows 2–4), quadratic adjustment costs (rows 5–7), a frictionless model, and the Khan-Thomas (2008) model. The adjustment costs for the models in rows 2–7 have been calibrated to match aggregate and sectoral investment rate volatilities.

Aggregate Nonlinearities



$$\frac{I_t}{K_t} = \sum_{j=1}^p \phi_j \frac{I_{t-j}}{K_{t-j}} + \sigma_t e_t$$

$$\sigma_t = \alpha_1 + \eta_1 \frac{1}{p} \sum_{j=1}^p \frac{I_{t-j}}{K_{t-j}}$$

Aggregate Nonlinearities

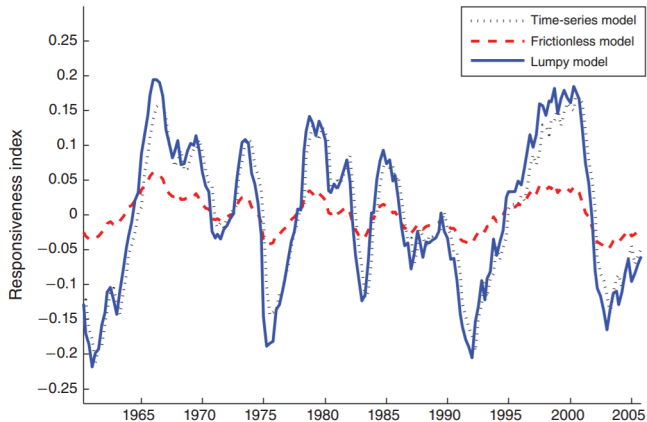


FIGURE 3. TIME PATHS OF THE RESPONSIVENESS INDEX

Aggregate Nonlinearities

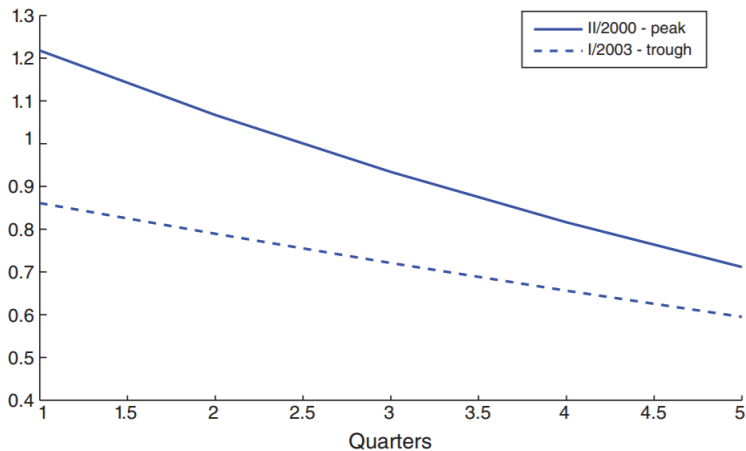


FIGURE 7. IMPULSE RESPONSES OF THE AGGREGATE INVESTMENT RATE
IN THE 2000 BOOM-BUST CYCLE

Winberry (2018)

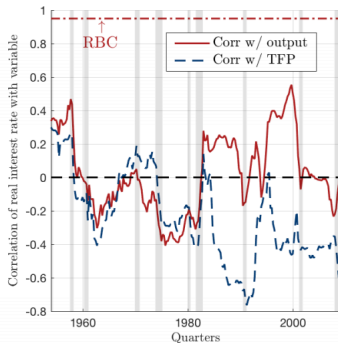
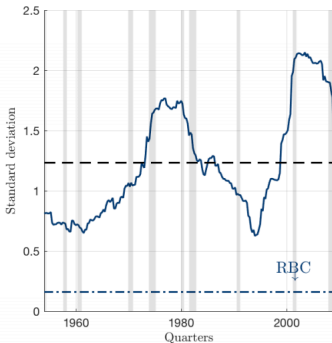
- Argues that procyclical interest rate inconsistent with data
- When consistent with data recover aggregate nonlinearities

Winberry (2018)

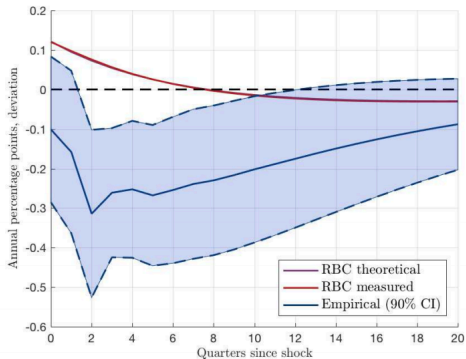
- Argues that procyclical interest rate inconsistent with data
- When consistent with data recover aggregate nonlinearities

| | $\sigma(r_t)$ | $\rho(r_t, y_{t-1})$ | $\rho(r_t, y_t)$ | $\rho(r_t, y_{t+1})$ |
|---------------|---------------|----------------------|------------------|----------------------|
| <i>T-bill</i> | 2.18% | -0.08 | -0.17 | -0.251 |
| <i>AAA</i> | 2.34% | -0.29 | -0.37 | -0.40 |
| <i>BAA</i> | 2.43% | -0.32 | -0.41 | -0.45 |
| <i>Stock</i> | 24.7% | -0.24 | -0.14 | 0.02 |
| <i>RBC</i> | 0.16% | 0.61 | 0.97 | 0.74 |

Rolling Windows of r_t Dynamics



IRF of r_t to TFP Shock



Takeaways from this Lecture

- Specification of **benchmark heterogeneous firm model**
 - Individual vs. aggregate states
 - Role of the distribution in the aggregate state variable
 - Steady state: constant aggregates, but lots of churning at individual level
- Overview of how people **solve heterogeneous agent models**
- Response of aggregate investment to shocks **depends on distribution of firms**, which changes over the business cycle
 - Less responsive in recessions