Macroeconomic Impact of Microeconomic Shocks: Beyond Hulten's Theorem

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Macroeconomic Impact of Shocks

- For economy with efficient equilibrium, Hulten (1978):

$$\mathrm{d}\log Y / \mathrm{d}\log A_i = sales_i / GDP = \lambda_i .$$

- First-order approximation (exact for Cobb-Douglas economies).
- Foundation for Domar aggregation:
  - Sales approximate sufficient statistics.
  - Details of production structure are irrelevant.
- "Bugbear" for production networks literature.
  (e.g. shocks to Walmart and electricity equally important)

What We Do

- Extend Hulten to second order to capture nonlinearities.
- General formula: reduced-form GE-elasticities of substitution.
- Mapping from micro to macro using a general structural model:
  - structural elasticites of substitution.
  - returns to scale.
  - factor market reallocation.
  - network linkages.
- Nonlinearities lead to asymmetric responses of output to shocks.
  - amplification of negative shocks, attenuation of positive shocks.
  - lower mean, negative skewness, excess kurtosis.
- Nonlinearities matter quantitatively:
  - $\times 10$ welfare costs of shocks from 0.05% to 0.6% of GDP.
  - $\times 3$ impact of 70's oil price shocks from -0.2% to -0.6% of GDP.
  - -20 percentage point reduction in aggregate TFP between 1948-2014.

What We Can Also Do

- Paper focuses on aggregate output, not co-movement, but can be characterized with same GE-elasticities.
- Paper maintains representative agent assumption.
- Paper abstracts away from RBC channels (elastic labor supply, capital accumulation), dynamics (reallocation).

Broader Agenda

- Nonlinearities in efficient economies.

  "*Macroeconomic Impact of Microeconomic Shocks: Beyond Hulten's Theorem*"

- Inefficient economies.

  "*Productivity and Misallocation in General Equilibrium*"

- Open economies/Heterogeneous Agents.

  "*Networks, Barriers, and Trade*"

- Micro-foundations of aggregate production functions and the Cambridge-Cambridge Capital controversy.

  "*The Microeconomic Foundations of Aggregate Production Functions*"

- Increasing Returns and Entry.

  "*Cascading Failures in Production Networks*"

  "*Darwinian Returns to Scale*"

  "*Entry versus Rents*"

Related Literature

- Long and Plosser (1983), Horvath (2000), Gomme and Rupert (2007).
- Jovanovic (1987), Durlauf (1993), Scheinkman and Woodford (1994), Horvath (1998), Dupor (1999).
- Gabaix (2011), Carvalho and Gabaix (2013), Acemoglu et al. (2012), Carvalho (2010), Acemoglu et al. (2017), Foerster et al. (2011), Atalay (2016), Bigio and La'O (2016), Baqaee (2016), Di Giovanni et al. (2014).
- Kremer (1993), Jones (2011), Jones (2013).
- Houthakker (1955), Oberfield and Raval (2014), Beraja et al. (2016).

Agenda

Framework

Illustrative Examples

- Macro-Substitution
- Input-output Mutlipliers

CES Networks

Quantitative Examples

- Business Cycles
- Oil Shocks
- Long-run Growth

Conclusion

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General Framework

- Perfectly competitive economy, representative consumer.
- Preferences represented by homothetic preferences

$$Y = \mathscr{D}\left(c_1, \ldots, c_N\right),$$

where c_i is consumption of good i.

- Consumer budget constraint

$$\sum_i p_i c_i = \sum_{i=1}^{M} w_i l_i + \sum_{i=1}^{N} \pi_i,$$

where p_i, w_i, and π_i are prices, wages, and profits.

General Framework

- Profits earned by the producer of good i:

$$\pi_i = p_i y_i - \sum_{k=1}^{M} w_k l_{ik} - \sum_{j=1}^{N} p_j x_{ij}.$$

- Each good i is produced using production function:

$$y_i = A_i F_i(l_{i1}, \ldots, l_{iM}, x_{i1}, \ldots, x_{iN}).$$

- A_i Hicks-neutral technology (Harrod-neutral as special case).
- x_{ij} intermediate inputs of good j used in the production of good i.
- l_{ik} labor of type k used by i.

Hulten's Theorem

Define $Y(A_1, \ldots, A_N)$ to be competitive equilibrium aggregate consumption function interpreted as output.

Theorem (Hulten)

Let λ_i denote industry i's sales as a share of output, then

$$\frac{\mathrm{d}\log Y}{\mathrm{d}\log A_i} = \lambda_i.$$

GE Elasticity of Substitution

- For CRS function $f(A_1, \ldots, A_N)$ the Morishima elasticity of substitution:

$$\frac{1}{\rho_{ij}} = -\frac{\mathrm{d}\log(MRS_{ij})}{\mathrm{d}\log(A_i/A_j)} = -\frac{\mathrm{d}\log(f_i/f_j)}{\mathrm{d}\log(A_i/A_j)}.$$

- For output function $Y(A_1, \ldots, A_N)$, define *GE-elasticity of substitution*:

$$\frac{1}{\rho_{ij}} \equiv -\frac{\mathrm{d}\log(MRS_{ij})}{\mathrm{d}\log(A_i)} = -\frac{\mathrm{d}\log(Y_i/Y_j)}{\mathrm{d}\log(A_i)}.$$

- Hence

$$\frac{\mathrm{d}\log(\lambda_i/\lambda_j)}{\mathrm{d}\log A_i} = 1 - \frac{1}{\rho_{ij}}.$$

Input-Output Multiplier

Definition 1.1

Define input-output mutliplier

$$\sum_{i=1}^{N} \frac{\mathrm{d}\log Y}{\mathrm{d}\log A_i} = \sum_{i=1}^{N} \lambda_i = \xi .$$

- "Macro returns to scale": $\xi > 1$ implies reproducibility.
- ξ constant if and only if C homogenous of degree ξ.

Extending Hulten: Idiosyncratic Shocks

Theorem

$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d}(\log A_i)^2} = \frac{\lambda_i}{\xi} \sum_{j \neq i} \lambda_j \left(1 - \frac{1}{\rho_{ij}}\right) + \lambda_i \frac{\partial \log \xi}{\partial \log A_i}.$$

- General formula for second-order terms (nonlinearities) in terms of reduced-form GE-elasticities of substitution.
- Sales distribution not sufficient statistic.
- $\rho_{ij} = 1$, ξ constant, Cobb-Douglas, zero effect (knife-edge).

Macro Moments

Proposition

Suppose that $\log A_i$ are subject to idiosyncratic shocks with variance s_i^2. Then we have the following formula for the mean of output:

$$E(\log(Y/\overline{Y})) \approx \frac{1}{\xi}\sum_i \frac{s_i^2}{2\xi}\lambda_i \sum_{j\neq i}\lambda_j\left(1-\frac{1}{\rho_{ij}}\right)+\sum_i \frac{s_i^2}{2}\lambda_i\frac{\mathrm{d}\log\xi}{\mathrm{d}\log A_i}.$$

- See paper for:
  - more general mean formula for correlated shocks.
  - beyond mean, formulas for skewness and excess kurtosis.

Welfare Costs of Shocks

Proposition

Let $u : \mathbb{R} \to \mathbb{R}$ be a CRRA with parameter γ. Suppose TFP A has idiosyncratic shocks with variance s_k^2. Then the welfare costs of shocks are given by:

$$\frac{[E(u(Y)) - u(\overline{Y})]}{u'(\overline{Y})\overline{Y}} \approx \underbrace{-\frac{1}{2}\gamma \sum_k^N \lambda_k^2 s_k^2}_{\textit{Consumption nonlinearities}} + \underbrace{\frac{1}{2}\overline{Y} \sum_k^N \frac{\partial^2 Y}{\partial A_k^2} s_k^2}_{\textit{Production nonlinearities}},$$

where recall $\overline{Y} = Y(\overline{A})$.

- Nonlinearities in consumption: small cost in Lucas (1987).
- Nonlinearities in production: can be order of magnitude larger.

Agenda

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GE Elasticities of Substitution

- N goods produced using the production functions

$$\frac{y_i}{\overline{y}_i} = A_i \left(\frac{l_{is_i}}{\overline{l}_{is_i}} \right)^{1-\omega_g} \left(\frac{l_{ig}}{\overline{l}_{ig}} \right)^{\omega_g},$$

specific labor l_{is} and general labor l_{ig}.

- Output

$$\frac{Y}{\overline{Y}} = \left(\sum_{i=1}^{N} \omega_{0i} \left(\frac{c_i}{\overline{c}_i} \right)^{\frac{\theta_0 - 1}{\theta_0}} \right)^{\frac{\theta_0}{\theta_0 - 1}},$$

- Budget constraint:

$$\sum_k p_k c_k = \sum_k w L_k + \sum_k w_k l_k + \sum_k \pi_k.$$

GE Elasticities of Substitution

- Market-clearing conditions are

$$c_i = y_i, \quad \bar{l}_{s_i} = l_{is_i}, \quad \text{and} \quad \bar{l}_g = \sum_{i=1}^{N} l_{ig}.$$

- GE-elasticity of substitution is:

$$\rho_{ji} = \rho = \frac{\theta_0(1-\omega_g)+\omega_g}{\theta_0(1-\omega_g)+\omega_g+(1-\theta_0)}.$$

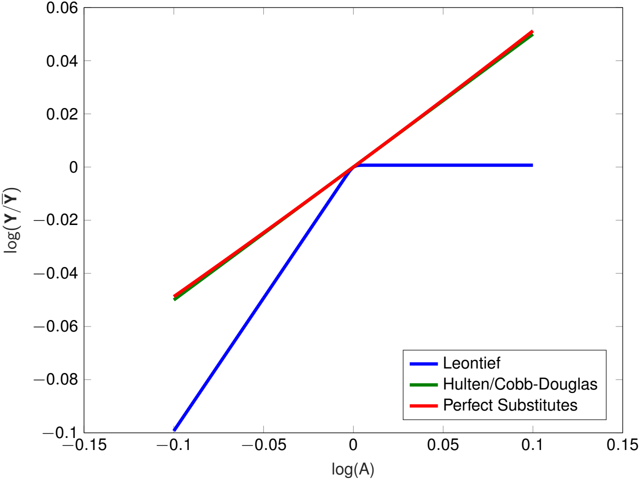
- Hence,

$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d}\log A_i^2} = \frac{\mathrm{d}\,\lambda_i}{\mathrm{d}\log A_i} = \lambda_i(1-\lambda_i)\left(1-\frac{1}{\rho}\right).$$

- To build intuition, consider polar cases with $\omega_g = 1$ and $\omega_g = 0$.

Lesson #1: Micro-Elasticity of Substitution Matters

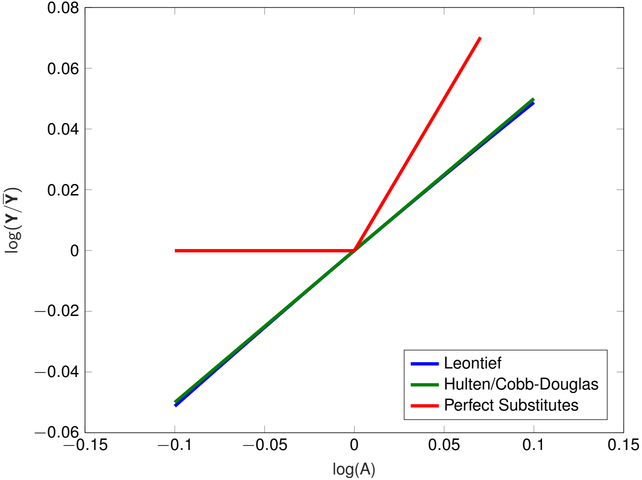
$$\omega_g = 0 \implies \rho = \theta_0.$$



$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d} \log A_i^2} = b_i(1 - b_i)\left(1 - \frac{1}{\theta_0}\right).$$

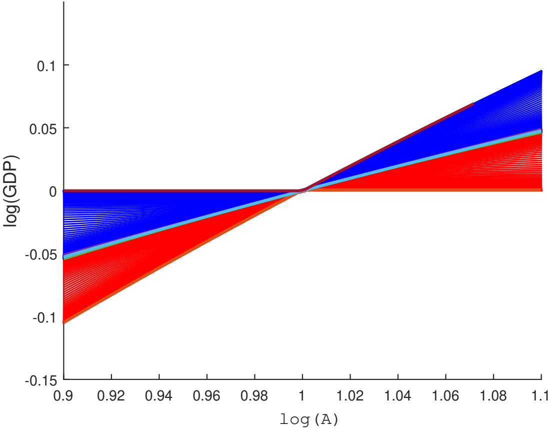
Lesson #2: Reallocation Matters

$$\omega_g = 1 \implies \rho = \frac{1}{2-\theta_0}.$$



$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d} \log A_i^2} = b_i (1 - b_i) (\theta_0 - 1).$$

Varying Reallocation Parameter



- All these economies are equivalent to a first order.

$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d} \log A_i^2} = b_i(1 - b_i)\left(1 - \frac{1}{\rho}\right).$$

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- Framework
- Illustrative Examples
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  - Input-output Mutlipliers
- CES Networks
- Quantitative Examples
  - Business Cycles
  - Oil Shocks
  - Long-run Growth
- Conclusion

The role of ξ

- So far, $\xi = 1$, constant macro returns to scale.
- For most applications, $\xi > 1$: intermediate goods, capital, trade.
- In many applications, ξ restrictted to be constant: Gomme and Rupert (2007), Aghion and Howitt (2008), Jones (2011), Gabaix (2011), Acemoglu et al. (2012), Kim et al. (2013), Bartelme and Gorodnichenko (2015).

Variable ξ

- Assume

$$\frac{y_1}{\bar{y}_1} = A_1 \left(\omega_{1l} \left(\frac{l_1}{\bar{l}_1} \right)^{\frac{\theta_1 - 1}{\theta_1}} + (1 - \omega_{1l}) \left(\frac{x_1}{\bar{x}_1} \right)^{\frac{\theta_1 - 1}{\theta_1}} \right)^{\frac{\theta_1}{\theta_1 - 1}},$$

- Market-clearing

$$y_1 = c_1 + x_1 \quad \text{and} \quad \bar{l} = l_1 .$$

- The steady-state input-output multiplier

$$\xi = 1 + (1 - \omega_{1l}) + (1 - \omega_{1l})^2 + \ldots = 1/\omega_{1l}$$

decreases with the labor share ω_{1l} and increases with the intermediate input share $1 - \omega_{1l}$.

Variable ξ

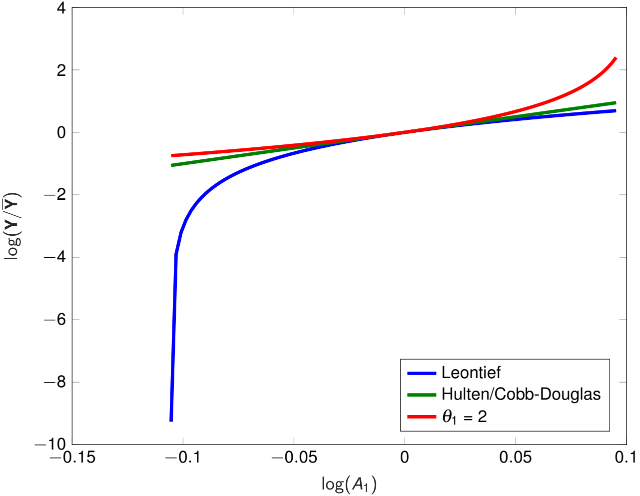
- Hulten's theorem implies that

$$\frac{d \log Y}{d \log A_1} = \xi .$$

Proposition

$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d} \log A^2} = \left(\frac{1}{\overline{a}} - 1\right)(\theta - 1) = (\xi - 1)(\theta - 1).$$

Variable input-output multiplier



For this calibration, $\bar{a} = 0.1$.

Agenda

Networks

- General nested CES economy.
- "Relabel" each CES nest to be a new sector with elasticity θ_i.
- Input-output matrix
$$\Omega_{ij} = \frac{p_j x_{ij}}{p_i y_i}.$$
- Leontief inverse
$$\Psi = (I - \Omega)^{-1} = \sum_{n=0}^{\infty} \Omega^n.$$
- Ω_{ij} and Ψ_{ij} direct and total reliance of i on j.
- Domar weights are $\lambda = b'\Psi$.

Networks

- To understand these models, two sets of equations are key: *Forward* and *Backward* equations.

- Let α denote the factor shares. Then *forward* equations:

$$\mathrm{d}\log p_i = -\mathrm{d}\log A_i + \sum_j \Omega_{ij}\,\mathrm{d}\log p_j + \sum_f \alpha_{if}\,\mathrm{d}\log \Lambda_f,$$

  or

$$\mathrm{d}\log P = \Psi\left(\alpha\,\mathrm{d}\log \Lambda - \mathrm{d}\log A\right).$$

  This implies Hulten's theorem

$$\mathrm{d}\log Y = -b'\,\mathrm{d}\log P = \lambda'\,\mathrm{d}\log A + \Lambda'\,\mathrm{d}\log \Lambda.$$

Networks – Forward Equations

- Next, we need to understand the *backward* equations:

$$\mathrm{d}\log\lambda = f(\mathrm{d}\log P).$$

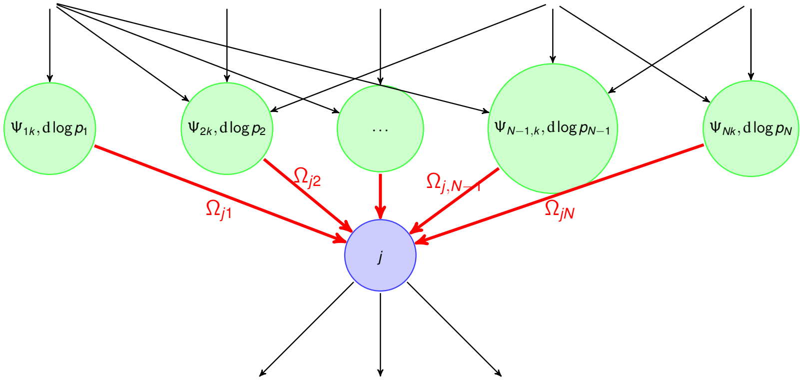
To characterize the backward equations, we need *input-output covariance operator*:

$$Cov_{\Omega^{(j)}}(\Psi_{(k)}, \mathrm{d}\log P) = \sum_i \Omega_{ji}\Psi_{ik}\,\mathrm{d}\log p_i - \left(\sum_i \Omega_{ji}\Psi_{ik}\right)\left(\sum_i \Omega_{ji}\,\mathrm{d}\log p_i\right).$$

Input-Output Covariance

Input-output variance operator:

$$Cov_{\Omega^{(j)}}(\Psi_{(k)}, \mathrm{d}\log P) = \sum_i \Omega_{ji}\Psi_{ik}\,\mathrm{d}\log p_i - \left(\sum_i \Omega_{ji}\Psi_{ik}\right)\left(\sum_i \Omega_{ji}\,\mathrm{d}\log p_i\right).$$



Backward Equations

- The backward equations are given by

$$\mathrm{d}\lambda_i = \sum_{k=0}^{N} (1-\theta_k)\lambda_k Cov_{\Omega^{(k)}}(\Psi_{(i)}, \mathrm{d}\log P),$$

- Now we can plug in the forward equations and we are done.
- In the one factor world, this is easy

$$\mathrm{d}\log P = -\Psi\, \mathrm{d}\log A$$

One Factor, Full Reallocation

Proposition

$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d}\log A_j \,\mathrm{d}\log A_i} = \frac{\mathrm{d}\lambda_i}{\mathrm{d}\log A_j} = \sum_{k=0}^{N} (\theta_k - 1)\lambda_k Cov_{\Omega^{(k)}}(\Psi_{(i)}, \Psi_{(j)}),$$

and in particular

$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d}\log A_i^2} = \frac{\mathrm{d}\lambda_i}{\mathrm{d}\log A_i} = \sum_{k=0}^{N} (\theta_k - 1)\lambda_k Var_{\Omega^{(k)}}(\Psi_{(i)}).$$

- Centrality measure mixing network and elasticities.
- Can also compute macro elasticities of substitution (see paper).

Network Irrelevance Result

Proposition

Suppose a single factor, $\theta_j = \theta$ for every j, and factor-augmenting shocks. Then

$$\frac{Y}{\overline{Y}} = \left(\sum_{i=0}^{N} \overline{\lambda}_i A_i^{\theta-1} \right)^{\frac{1}{\theta-1}},$$

where $\overline{\lambda}_i$ is the steady-state Domar weight of i. Then

$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d}\log A_j \, \mathrm{d}\log A_i} = \frac{\mathrm{d}\lambda_i}{\mathrm{d}\log A_j} = (\theta - 1)\lambda_i (1(i = j) - \lambda_j),$$

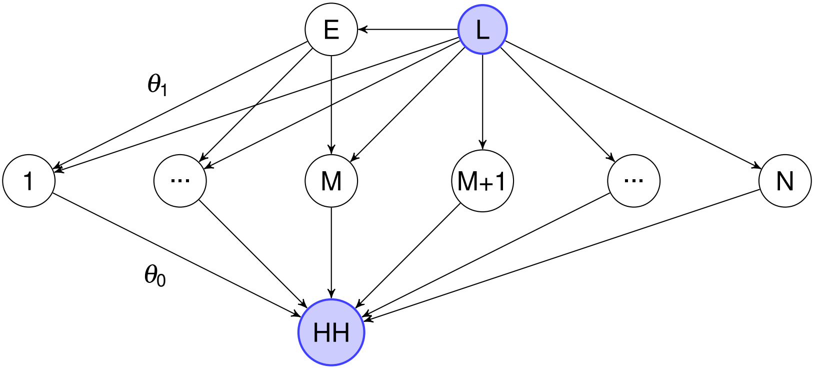
and in particular

$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d}\log A_i^2} = \frac{\mathrm{d}\lambda_i}{\mathrm{d}\log A_i} = \sum_{j=0}^{N} (\theta_j - 1)\lambda_j Var_{\Omega^{(j)}}(\Psi_{(i)}) = (\theta - 1)\lambda_i (1 - \lambda_i).$$

- Extends Hulten network irrelevance to second-order.

"Universal" Input Example

One factor, full reallocation, two elasticities $\theta_1 \ll \theta_0$.



$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d} \log A_E^2} = (\theta_0 - 1)\lambda_E \left(\frac{N}{M} - 1 \right) \lambda_E + (\theta_1 - 1)\lambda_E \left(1 - \frac{N}{M}\lambda_E \right),$$

$$= (\theta_0 - 1)\lambda_E(1 - \lambda_E) - (\theta_0 - \theta_1)\lambda_E \left(1 - \frac{N}{M}\lambda_E \right).$$

Direction of Diffusion

Proposition

Assume that there is one factor and full reallocation. If industries k and l sell the same share to all other industries and the household, then

$$\frac{\mathrm{d}\log Y}{\mathrm{d}\log A_k} = \frac{\mathrm{d}\log Y}{\mathrm{d}\log A_l},$$

and

$$\frac{\mathrm{d}^2\log Y}{\mathrm{d}\log A_k^2} = \frac{\mathrm{d}^2\log Y}{\mathrm{d}\log A_l^2}.$$

- Key: downstream diffusion under CRS.
- Limited Re-allocation, multiple factors or DRS breaks it.

Multiple Factors, Limited Reallocation

Proposition

$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d} \log A_k^2} = \sum_j (\theta_j - 1)\lambda_j Var_{\Omega^{(j)}}(\Psi_{(k)})$$

$$+ \sum_j (\theta_j - 1)\lambda_j Cov_{\Omega^{(j)}} \left(\sum_f \Psi_{(f)} \frac{\mathrm{d} \log \Lambda_f}{\mathrm{d} \log A_k}, \Psi_{(k)} \right).$$

- New terms arising from changes in factor shares (prices) given by

$$\frac{\mathrm{d} \log \Lambda}{\mathrm{d} \log A_k} = \Gamma \frac{\mathrm{d} \log \Lambda}{\mathrm{d} \log A_k} + \delta_{(k)},$$

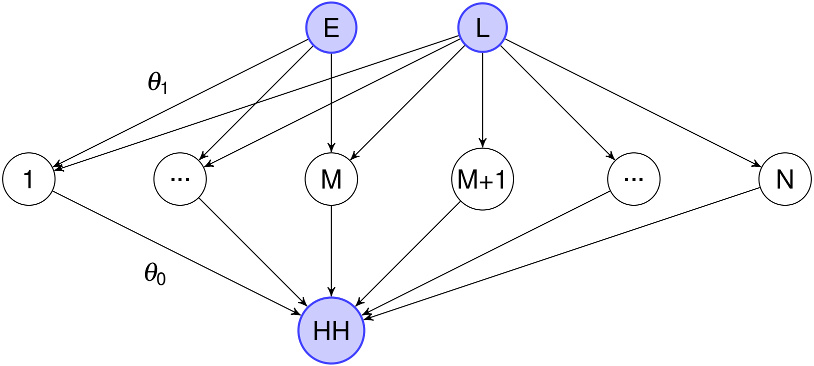
$$\Gamma_{f,g} = \sum_j (\theta_j - 1)\lambda_j Cov_{\Omega^{(j)}} \left(\Psi_{(f)}, \Psi_{(g)} \right),$$

$$\delta_{fk} = \sum_j (\theta_j - 1)\lambda_j Cov_{\Omega^{(j)}} \left(\Psi_{(f)}, \Psi_{(k)} \right).$$

- Can compute macro factor elasticities of substitution (see paper).

"Universal" Energy Example

- Two factors: electricity and labor.
- Sectors use energy and labor with elasticity $\theta_1 < 1$.
- Final demand uses downstreams sectors with elasticity $\theta_0 \gg \theta_1$.



$$\frac{\mathrm{d}^2 \log Y}{\mathrm{d} \log A_E^2} = \frac{\mathrm{d}\Lambda_E}{\mathrm{d} \log A_E^2} = \frac{(\theta_0 - 1)\Lambda_E(1-\Lambda_E) - (\theta_0 - \theta_1)\Lambda_E\left(1 - \frac{N}{M}\Lambda_E\right)}{\theta_0 - (\theta_0 - \theta_1)\frac{\left(1-\frac{N}{M}\Lambda_E\right)}{1-\Lambda_E}}.$$

Beyond CES

- Define the *substitution* operator for j as

$$\Phi_j(\Psi_{(k)}, \Psi_{(l)}) = \left(\sum_{\substack{x,y \\ x \neq y}} \Omega_{jx}\Omega_{jy}(1 - \sigma^j(x,y))\Psi_{xl}\Psi_{yk} \right),$$

$$= \frac{1}{2} E_{\Omega^{(j)}} \left((1 - \sigma^j(x,y))(\Psi_k(x) - \Psi_k(y))(\Psi_l(x) - \Psi_l(y)) \right),$$

where $\Psi_k(x) = \Psi_{xk}$.

- Φ_j similar to covariance:
  - symmetric;
  - bilinear;
  - $\Phi_j = 0$ if an argument is constant.

Beyond CES

Proposition

For a general economy,

$$\frac{\mathrm{d}\,\lambda_i}{\mathrm{d}\log A_k} = -\sum_{j=0} \Phi_j(\Psi_{(k)}, \Psi_{(i)}) + \sum_f \sum_j \Phi_j(\Psi_{(i)}, \Psi_{(f)}) \frac{\mathrm{d}\log \Lambda_l}{\mathrm{d}\log A_k}.$$

where

$$\frac{\mathrm{d}\,\Lambda_f}{\mathrm{d}\log A_k} = -\sum_{j=0} \Phi_j(\Psi_{(k)}, \Psi_{(f)}) + \sum_l \sum_j \Phi_j(\Psi_{(l)}, \Psi_{(f)}) \frac{\mathrm{d}\log \Lambda_l}{\mathrm{d}\log A_k}.$$

Agenda

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Simulation

- Final demand

$$\frac{Y}{\overline{Y}} = \left(\sum_{i=1}^{N} \omega_{0i} \left(\frac{c_i}{\overline{c}_i} \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}.$$

- The production function of industry i is

$$\frac{y_i}{\overline{y}_i} = A_i \left(\omega_{il} \left(\frac{l_i}{\overline{l}_i} \right)^{\frac{\theta-1}{\theta}} + (1-\omega_{il}) \left(\frac{\hat{X}_i}{\overline{X}_i} \right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}},$$

  labor inputs l_i and intermediate inputs $\hat{X}_i$.
- The composite intermediate input X_i is given by

$$\frac{X_i}{\overline{X}_i} = \left(\sum_{j=1}^{N} \omega_{ij} \left(\frac{x_{ij}}{\overline{x}_{ij}} \right)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}},$$

  intermediate inputs x_{ij} from industry j used by industry i.

Simulation

- Set $\theta_j = \theta = 0.5, \varepsilon_i = \varepsilon = 0.001$, and $\sigma = 0.9$ drawing on Atalay (2016), Boehm et al. (2015), Barrot and Sauvagnat (2016), Comin et al. (2015).
- Impose no-movement in labor for benchmark (Acemoglu et al. (2016), Autor et al. (2016), Notowidigdo (2011)).
- Use the 88-sector US KLEMS annual input-output data from 1960-2005, with sector-level TFP data constructed using Jorgenson et al. (1987) methodology by Carvalho and Gabaix (2013).
- Sectoral TFP (annual or quadrennial) shocks to be $\log \mathcal{N}(-\Sigma_{ii}/2, \Sigma_{ii})$, where Σ_{ii} is sample variance of $\Delta \log TFP$ for industry i.
- Check that $\sigma_\lambda = \sum_i \overline{\lambda}_i \sigma_{\lambda_i}$ matches data.

Simulation Results

$(\sigma, \theta, \varepsilon)$	Mean	Std	Skew	Ex-Kurtosis	σ_λ
Full Reallocation - Annual					
(0.7, 0.3, 0.001)	-0.0023	0.011	-0.10	0.1	0.090
(0.9, 0.5, 0.001)	-0.0022	0.011	-0.08	0.0	0.069
(0.9, 0.6, 0.2)	-0.0020	0.011	-0.05	0.0	0.056
(0.99, 0.99, 0.99)	-0.0013	0.011	0.01	0.0	0.001
No Reallocation - Annual					
(0.7, 0.3, 0.001)	-0.0045	0.012	-0.31	0.4	0.171
(0.9, 0.5, 0.001)	-0.0034	0.012	-0.18	0.1	0.115
(0.9, 0.6, 0.2)	-0.0024	0.011	-0.11	0.1	0.068
(0.99, 0.99, 0.99)	-0.0011	0.011	0.00	0.0	0.001
Annual Data	-	0.015	-	-	0.13

Simulation Results

$(\sigma, \theta, \varepsilon)$	Mean	Std	Skew	Ex-Kurtosis	σ_λ
Full Reallocation - Quadrennial					
(0.7,0.3,.0.001)	-0.0118	0.026	-0.4	0.4	0.307
(0.9, 0.5, 0.001)	-0.0113	0.026	-0.28	0.4	0.176
(0.9, 0.6, 0.2)	-0.0100	0.026	-0.23	0.2	0.133
(0.99, 0.99, 0.99)	-0.0058	0.025	0.01	0.0	0.003
No Reallocation - Quadrennial					
(0.7, 0.3, 0.001)	-0.0270	0.037	-2.18	12.7	0.404
(0.9, 0.5, 0.001)	-0.0187	0.030	-1.11	3.6	0.267
(0.9, 0.6, 0.2)	-0.0129	0.027	-0.44	0.7	0.154
(0.99, 0.99, 0.99)	-0.0057	0.025	0.00	0.0	0.002
Quadrennial Data	-	0.030	-	-	0.27

Histograms

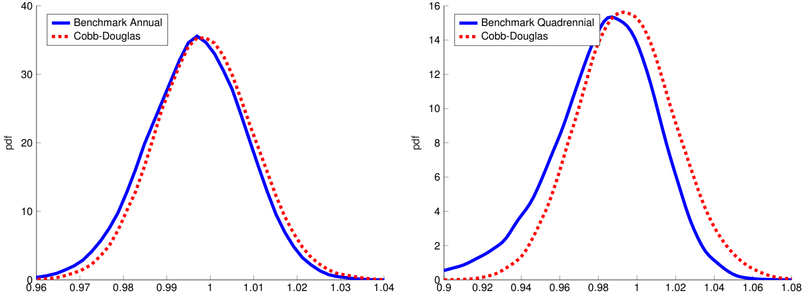

Figure: The left panel shows the distribution of *GDP* for the annual model. The right panel shows these for shocks for quadrennial shocks.

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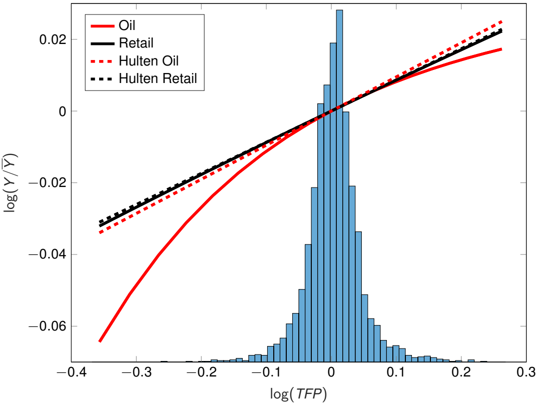
CES Networks

Quantitative Examples

- Business Cycles
- Oil Shocks
- Long-run Growth

Conclusion

Oil v. Retail



- Intuition: low micro-elasticity of substitution, universal input.
- Consistent with large asymmetric effects of oil shocks (Hamilton, 2003), even without frictions.

Reduced-form Impact of Oil Shocks

Proposition

Up to the second order in the vector Δ, we have

$$\log\left(Y(A+\Delta)/Y(A)\right) = \frac{1}{2}\left[\lambda(A+\Delta)+\lambda(A)\right]' \log(\Delta) + O(\log(\Delta)^3).$$

Reduced-form Impact of Oil Shocks

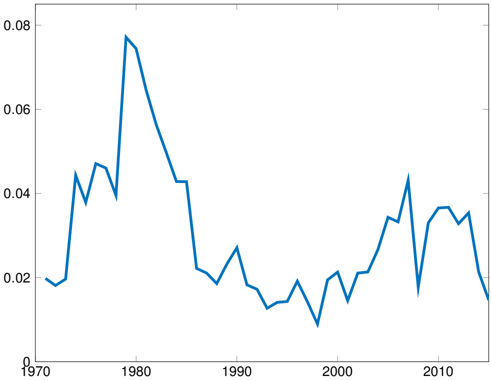


Figure: Global expenditures on crude oil as a fraction of world GDP.

- First-order effect: $1.8\% \times -13\% \approx -0.2\%$.
- Second-order effect: $\frac{1}{2}(1.8\% + 7.6\%) \times -13\% \approx -0.6\%$.

Agenda

Nonlinearities and Cost Disease

- "Nonlinear" measure of aggregate TFP growth

$$\Delta \log TFP^{\text{nonlinear}} = \sum_{i=1}^{N} \sum_{t=1948}^{2013} \lambda_{i,t} (\log A_{i,t+1} - \log(A_{i,t})).$$

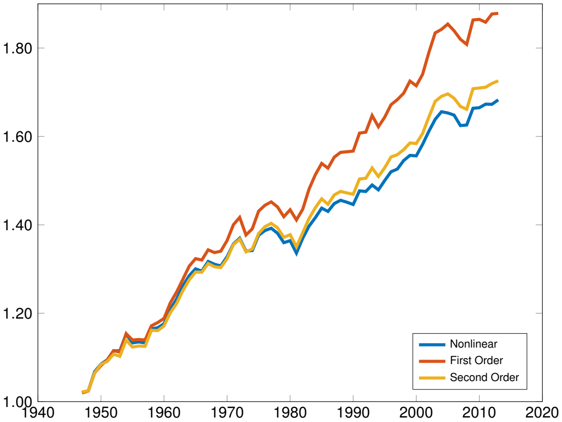
- Approximation, by discrete left Riemann sums, of the exact aggregate TFP growth, given by

$$\sum_{i=1}^{N} \int_{1948}^{2014} \lambda_{i,t} d \log A_{i,t}.$$

- If economy was log-linear, TFP growth is

$$\Delta \log TFP^{\text{1st order}} = \sum_{i=1}^{N} \lambda_{i,1948} (\log A_{i,2014} - \log A_{i,1948}),$$

Baumol's Cost Disease



- Baumol's cost disease: slow growth sectors get big.
- Structural change: non-homothetic preferences.

Agenda

- Framework
- Illustrative Examples
  - Macro-Substitution
  - Input-output Mutlipliers
- CES Networks
- Quantitative Examples
  - Business Cycles
  - Oil Shocks
  - Long-run Growth
- Conclusion

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