Aggregate Implications of Innovation Policy

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Intro

- Firm's investments in innovation
  - large relative to GDP
  - likely important factor in accounting for growth over time
- To what extent can we change path of macroeconomic growth over medium and long term by inducing firms to increase their investments in innovation?
- What is the optimal level of these investments?

This Paper

- Examine these questions using model of growth through innovative investments by firms that nests
  - Neo-Schumpeterian
  - Expanding Varieties
  - Innovative investment by entrant and incumbent firms
- Key features determining models' quantitative implications
  - Intertemporal Knowledge Spillovers
  - Social Depreciation of Innovation Expenditures
- Results helpful for understanding more complex models

Related literature

- Extended Klette-Kortum models good fit firm-level data
  - Lentz and Mortensen (2008), Acemoglu (2008), Ackigit and Kerr (2008), Ackigit and Aghion (2014), Garcia-Macia, Hsieh and Klenow (2015)
- Misallocation of innovation across firms
  - Acemoglu, Akcigit, Bloom and Kerr (2013), Peters (2013), Lentz and Mortensen (2014)
- Increase in innovation intensity and long-term trends
  - Jones and Williams (1998) Jones (2002)
- Knowledge spillovers
  - Jones (2005), Bloom, Schankerman, and Van Reenen (2013)
- Measured productivity and intangible capital
  - McGrattan and Prescott (2012, 2014)
- Sufficient statistics
  - Arkolakis, Costinot, Rodriguez-Clare (2012)

Outline

- Model
- Analytical characterization of transition dynamics
- Implications for socially optimal level of innovative investments
- Relation to more complex recent models

Production by Intermediate good firms

- Abstract model of firms to nest wide class of models
- Firm type $j = 1, 2, 3, \ldots,$
  - $n(j)$ products
  - $z_1(j)$, $z_2(j)$, ... , $z_{n(j)}(j)$ productivities
  - $\mu_1(j)$, $\mu_2(j)$, ... , $\mu_{n(j)}(j)$ markups
  - $\theta(j)$ heterogeneity in innovation technologies
- Production of intermediate good k by firm of type j

$$y_{kt}(j) = \exp(z_k(j)) k_{kt}(j)^{\alpha} l_{kt}(j)^{1-\alpha}$$

Aggregate Productivity

- State: measures of incumbents $\{N_t(j)\}_{j\geq 1}$
- Final good, $Y_t = \left(\sum_{j\geq 1}\sum_{k=1}^{n(j)} y_{kt}(j)^{(\rho-1)/\rho} N_t(j)\right)^{\rho/(\rho-1)}$

$$Y_t = Z_t L_{pt}^{1-\alpha} K_t^{\alpha} = C_t + K_{t+1} - (1-d_k) K_t$$

- $Z_t \equiv Z\left(\{N_t(j)\}_{j\geq 1}\right)$
  - example with constant markups

$$Z_t \equiv Z(\{N_t(j)\}_{j\geq 1}) = \left(\sum_{j\geq 1}\sum_{k=1}^{n(j)} \exp((\rho-1)z_k(j))N_t(j)\right)^{1/(\rho-1)}$$

Innovation by Intermediate Good Firms

- Measure of incumbents $\{N_t(j)\}_{j\geq 1}$
  - $\{y_{rt}(j)\}_{j\geq 1}$ innovative investment
- Measure of entrants $N_t(0)$
  - $\bar{y}_r(0)$ entry cost parameter
- Transition Law

$$\{N_{t+1}(j)\}_{j\geq 1} = T\left(\{y_{rt}(j)\}_{j\geq 1}, N_t(0); \{N_t(j)\}_{j\geq 1}\right)$$

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- Functions Z and T give aggregate productivity growth

$$g_{zt} \equiv \log Z_{t+1} - \log Z_t = G\left(\{y_{rt}(j)\}_{j\geq 1}, N_t(0); \{N_t(j)\}_{j\geq 1}\right)$$

- *Social Depreciation of Innovation Expenditures*

$$G_t^0 = G\left(\{0\}_{j\geq 1}, 0; \{N_t(j)\}_{j\geq 1}\right)$$

Aggregate Innovation Technology

- Aggregate productivity growth

$$\log Z_{t+1} - \log Z_t = G\left(\{y_{rt}(j)\}_{j\geq 1}, N_t(0); \{N_t(j)\}_{j\geq 1}\right)$$

- Research good used as input for innovation by firms

$$\sum_{j\geq 1} y_{rt}(j) N_t(j) + \bar{y}_r(0) N_t(0) = Y_{rt} = A_{rt} Z_t^{\gamma-1} L_{rt}$$

  - A_{rt} freely-available scientific knowledge
  - $\gamma \leq 1$ *intertemporal knowledge spillovers*
  - Price of research good $P_{rt} \equiv A_{rt}^{-1} W_t Z_t^{1-\gamma}$

Aggregate Innovation Technology

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- Labor allocation and innovation intensity of economy

$$s_{rt} \equiv \frac{P_{rt} Y_{rt}}{Y_t} = \kappa \frac{L_{rt}}{L_{pt}}$$

Positive implications of model

- Baseline allocations in a BGP: $\bar{g}_z$, $\bar{s}_r$, $\{\bar{y}_{rt}(j)\}$, $\{\bar{N}_t(j)\}$
- At $t = 0$, policy-induced change to s'_{rt}, $\{y'_{rt}(j)\}_{j\geq 1}$, $\{N'_t(j)\}_{j\geq 0}$
  - e.g. changes in subsidies to use of research good
- Approximate implied path $\left\{Z'_t\right\}_t^{\infty}$, $\left\{GDP'_t\right\}_t^{\infty}$

Two Key Equations

- Innovation intensity to Research output

$$\left(\log Y'_{rt} - \log \bar{Y}_r\right) = \bar{L}_p \left(\log s'_{rt} - \log \bar{s}_r\right) - (1-\gamma) \left(\log Z'_t - \log \bar{Z}_t\right)$$

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- Research output to productivity growth

$$g'_{zt} - \bar{g}_z \approx \mathscr{E}_{gt}\left(\log Y'_{rt} - \log \bar{Y}_{rt}\right) + \sum_{j\geq 1} \frac{\partial G}{\partial N(j)} \left(N'_t(j) - \bar{N}_t(j)\right).$$

  - Impact elasticity with respect to change in Y_{rt}

$$\mathscr{E}_{gt} = \sum_{j\geq 1} \frac{\partial G}{\partial y_r(j)} \bar{y}_{rt}(j) \frac{d \log y_{rt}(j)}{d \log Y_{rt}} + \frac{\partial G}{\partial N(0)} \bar{N}_t(0) \frac{d \log N_t(0)}{d \log Y_{rt}}$$

- Characterize dynamics with three key assumptions

First Key Assumption: Concavity

- G is concave from the origin
  - If innovation $(\{y_{rt}(j)\}_{j\geq 1}, N_t(0))$ increases proportionally for all firms, then growth rate (in logs) increases less than proportionally

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- Suppose innovation changes proportionatelly for all firms:

$$d \log y_{rt}(j) = d \log N_t(0) = d \log Y_{rt}$$

- Then impact elasticity is bounded by

$$\mathscr{E}_{gt} \leq \bar{g}_{zt} - G_t^0$$

- Intuition:
  - Going from $Y_r = 0$ to $\bar{Y}_r$ increases growth from G_t^0 to $\bar{g}_{zt}$
  - Concavity: marginal increase smaller than average effect

Example 1: Simple Quality Ladders

- Quality Ladders Model.
  - Innovation only by entrants

$$G = \frac{1}{\rho - 1} \log \left(\sigma N_t(0) \left(\exp(\Delta_z)^{\rho-1} - 1 \right) + 1 \right)$$

  - Social Depreciation $G^0 = 0$
- Exact Impact Elasticity

$$\mathscr{E}_{gt}^{QL} = \frac{1}{\rho - 1} \frac{\exp((\rho - 1)\bar{g}_z) - 1}{\exp((\rho - 1)\bar{g}_z)} \leq \bar{g}_z$$

  - approaches $\bar{g}_z$ as $\rho \to 1$
  - approaches 0 as $\rho \to \infty$
- Impact Elasticity tightly bounded if model applied to advanced economies

Example 2: Simple Expanding Varieties

- Expanding Varieties Model
  - Innovation only by entrants
  - Entrants imitate fraction λ of $Z_t^{\rho-1}$
  - Exogenous growth Δ_z and exit δ_f of incumbents

$$G = \frac{1}{\rho - 1} \log\left(\left(1 - \delta_f\right) \exp\left(\left(\rho - 1\right) \Delta_z\right) + \lambda N_t\left(0\right)\right)$$

  - $G^0 < 0$ linked to employment share of incumbents

- Exact impact elasticity

$$\mathcal{E}_{gt}^{EV} = \frac{1}{\rho - 1} \frac{\exp((\rho - 1)\bar{g}_z) - \exp((\rho - 1) G^0)}{\exp((\rho - 1)\bar{g}_z)} \leq \bar{g}_z - G^0$$

- Impact elasticity can be several times bigger than in Quality Ladders Model

Second Key Assumption: Conditional Efficiency

- Given Y_{rt}, then $\{y_{rt}(j)\}_{j\geq 1}, N_t(0)$ solves

$$\max G\left(\{y_{rt}(j)\}_{j\geq 1}, N_t(0); \{N_t(j)\}_{j\geq 1}\right)$$

subject to

$$\sum_{j\geq 1} y_{rt}(j)N_t(j) + \bar{y}_r(0)N_t(0) = Y_{rt}$$

- If baseline allocation is conditionally efficient, then $\mathscr{E}_{gt}$ is independent of how the change in the output of the research good is allocated across incumbent and entering firms

$$\mathscr{E}_{gt} = \lambda_t \bar{Y}_{rt}$$

- Previous bound holds

Alternative first key assumption: Concavity in Entrants

- G concave with respect to entry
- Alternative bound on impact elasticity

$$\mathcal{E}_{gt} \leq \left(\bar{g}_{zt} - G_t^0\right) \frac{\bar{Y}_{rt}}{\bar{Y}_{rt} - Y_{rt}^0}$$

  - Y_{rt}^0 aggregate use of research good when entry low enough to implement growth G_t^0
  - $Y_{rt}^0 < 0$ (tighter bound) when incumbents have lower average cost of innovation

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- Paper: illustrate with Klette-Kortum, Atkeson-Burstein models
  - Given $\bar{g}_z$ and ρ, $\mathscr{E}_{gt}^{KK} \leq \mathscr{E}_{gt}^{QL}$

Example 3: Klette-Kortum

- Quality ladders model
  - Innovation by entrants and incumbents
  - Simple version in which all incumbents invest same per product

$$G = \frac{1}{\rho - 1} \log\left(\sigma(d(y_{rt}(1)) + N_t(0))\left(\exp(\Delta_z)^{\rho-1} - 1\right) + 1\right)$$

  - Social Depreciation $G^0 = 0$
  - Conditional efficiency if $d'(\bar{y}_r(1)) = 1/\bar{y}_r(0)$ – equil: entrants and incumbents subsidized at same rate
  - $d(y_r)$ concave implies
    - Both concavity assumptions satisfied
    - $Y_r^0 < 0$, so $\frac{\bar{Y}_{rt}}{\bar{Y}_{rt} - Y_t^{\mathbf{0}}} \leq 1$
  - Exact elasticity

$$\mathscr{E}_{gt}^{KK} = \frac{1}{\rho - 1} \frac{\exp((\rho - 1)\bar{g}_z) - 1}{\exp((\rho - 1)\bar{g}_z)} \frac{\bar{Y}_r}{\bar{Y}_r - Y^0}$$

- Given ρ and $\bar{g}_z$, $\mathscr{E}_{gt}^{KK} \leq \mathscr{E}_{gt}^{QL}$

Results so far

- Innovation intensity to Research output

$$\left(\log Y'_{rt} - \log \bar{Y}_r\right) = \bar{L}_p \left(\log s'_{rt} - \log \bar{s}_r\right) - (1-\gamma)\left(\log Z'_t - \log \bar{Z}_t\right)$$

- Research output to Productivity growth
  - Conditional Efficiency implies allocation of innovative investment does not matter

$$g'_{zt} - \bar{g}_z \approx \mathscr{E}_{gt}\left(\log Y'_{rt} - \log \bar{Y}_r\right) + \sum_{j \geq 1} \frac{\partial G}{\partial N(j)} \left(N'_t(j) - \bar{N}_t(j)\right)$$

  - Concavity bounds impact elasticity, $\mathscr{E}_{gt} \leq \left(\bar{g}_{zt} - G_t^0\right)$
    - Or even tighter bound if incumbents have lower average cost of innovation
- To characterize dynamics, assume $\frac{\partial G}{\partial N(j)} = 0$
- Key assumption 3 satisfied by our three examples

Putting these results together

$$\log Z'_{t+1} - \log \bar{Z}_{t+1} = \sum_{k=0}^{t-1} \Gamma_k \left(\log s'_{rt-k} - \log \bar{s}_r\right)$$

Impact effect: $\Gamma_0 = \bar{L}_p \mathscr{E}_{0g}$

Decay: $\Gamma_{k+1} = [1 - (1-\gamma)\mathscr{E}_{g0}]\, \Gamma_k$

Endogenous growth:

$$\log Z'_{t+1} - \log Z'_t - \bar{g}_z = \Gamma_0 \left(\log s'_{rt} - \log \bar{s}_r\right)$$

Long-term impact permanent change in s_r: $\bar{L}_p / (1-\gamma)$

GDP dynamics

- Suppose K/Y fixed

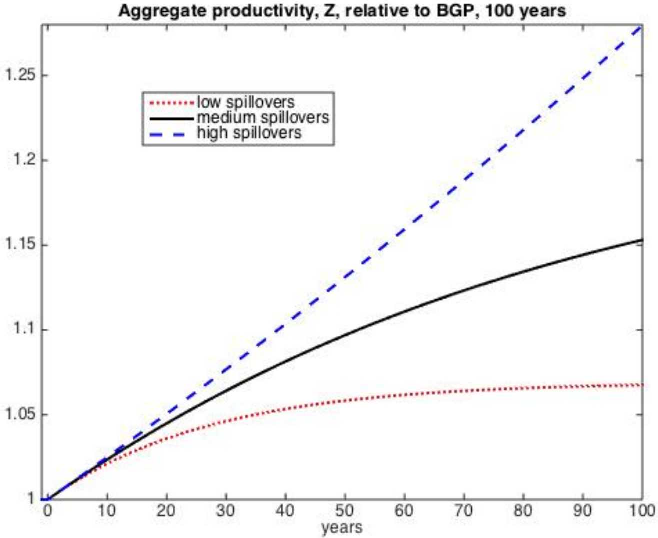
$$\log GDP'_t - \log G\bar{D}P_t = \frac{1}{1-\alpha}\left(\log Z'_t - \log \bar{Z}_t\right) - \bar{L}_r\left(\log s'_{rt} - \log \bar{s}_r\right)$$

- Tradeoff: GDP $\uparrow$ with productivity, $\downarrow$ with innovation investment

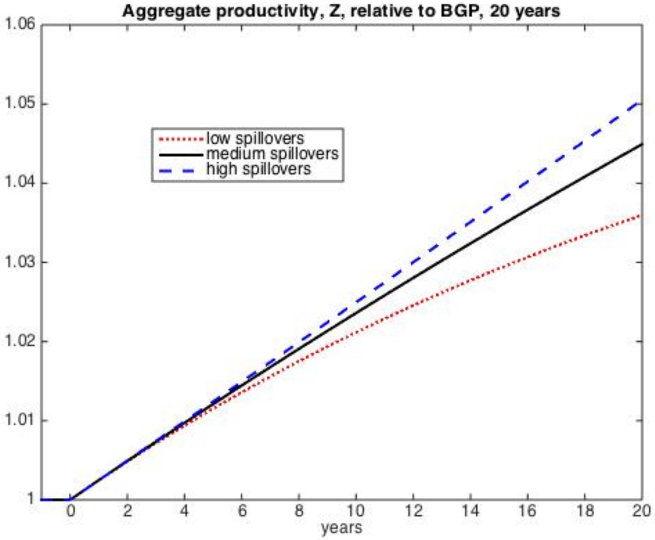
Using these results: numerical example

- Baseline annual growth $\bar{g}_z = 0.0125$
- Social Depreciation $G^0 = 0$
- $\mathscr{E}_g = 0.0122$ close to upper bound $\bar{g}_z - G^0$
- $\Gamma_0 = \mathscr{E}_g \bar{L}_p = .01$
- Vary spillover $\gamma = -2$, $\gamma = 0$, $\gamma \to 1$
  - Z long-run elasticity ranges from 1/4 to infinity
- Innovation subsidy raises s_{rt} permanently starting at date $t = 0$ from 11% to 14%
  - $\Delta \log s_r = \log s_{rt} - \log \bar{s}_r = 0.24$
- Analytic impulse response (constant K/Y).

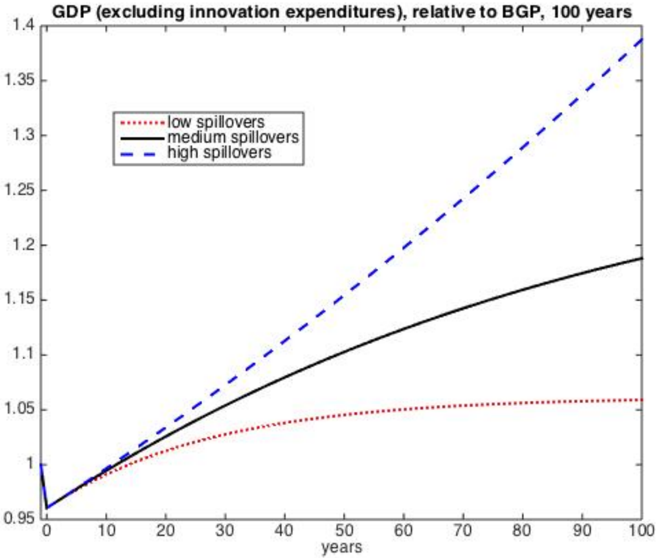
Aggregate productivity: 100 years



Aggregate productivity: 20 years



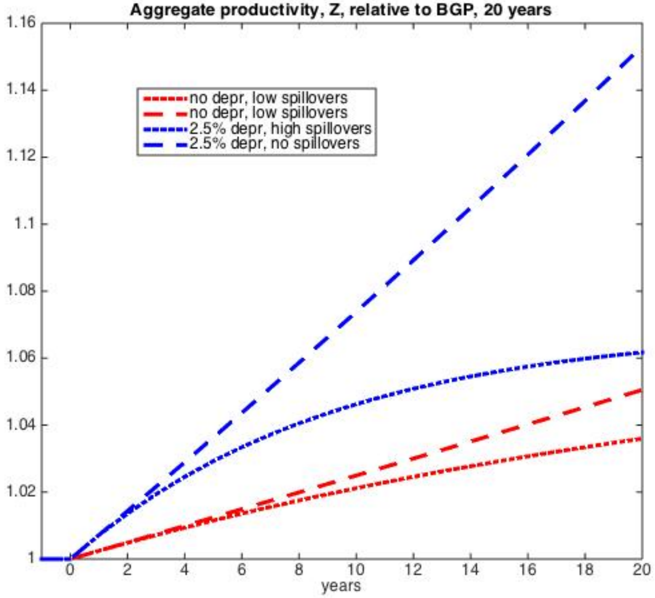
GDP: 100 years



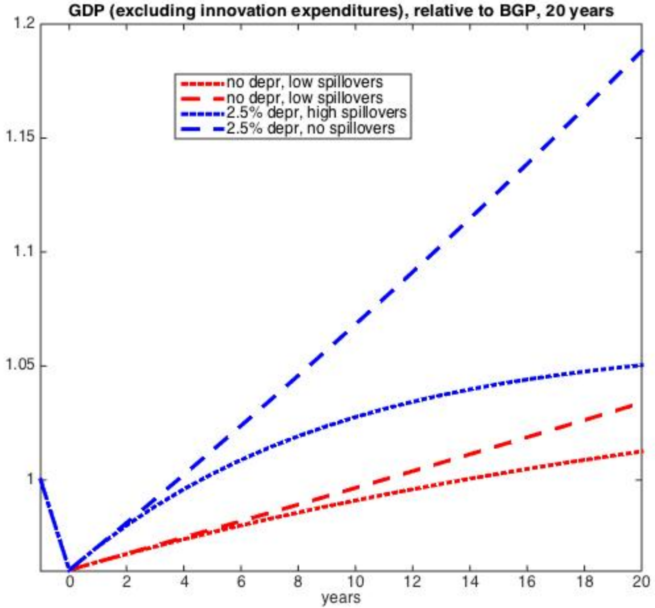
2.25% social depreciation

- Expanding varieties: $\rho = 4$ and 10% employment by entering products
- Impact elasticity $\mathscr{E}_g$ increases from 0.0122 to 0.033
- Impact effect Γ_0 increases from 0.01 to 0.028

2.25% social depreciation: Aggregate Productivity 20 years



2.25% social depreciation: GDP 20 years



Welfare: Optimal Innovation Intensity

- Optimality perturb $\log s'_{r0}$ only, Δ welfare = zero

$$\left[\sum_{k=0}^{\infty} \tilde{\beta}^{1+k} \frac{\Gamma_k}{1-\alpha} - \bar{L}_r\right] \left(\log s'_0 - \log \bar{s}_r\right) = 0$$

- Gap between BGP interest and growth rates $\tilde{\beta}$
- Optimal BGP allocation satisfies

$$s_r^* = (1-\alpha)\frac{L_r^*}{L_p^*} = \frac{\tilde{\beta}\mathscr{E}_g^*}{1-\tilde{\beta}\left[1-(1-\gamma)\mathscr{E}_g^*\right]}$$

- Huge range of implications depending on $\tilde{\beta}$ and γ
- If small $\mathscr{E}_g^*$, then disconnect between s_r^* and 20 year response

Example 3: Klette-Kortum Failure of Conditional Efficiency

- Quality Ladders Model
  - Innovation by entrants and incumbents
- Conditional Efficiency $d'(\bar{y}_r(1)) = 1/\bar{y}_r(0)$
- If $d'(\bar{y}_r(1)) \neq 1/\bar{y}_r(0)$ then additional welfare gain
  - can achieve same growth rate $\bar{g}_z$ with permanently lower Y_r and higher consumption by reallocating to

$$d'(\bar{y}_r(1)) = 1/\bar{y}_r(0)$$

  - need to know details of innovation technology G and baseline allocation to implement this gain with industrial policies
  - in numerical examples, can get big effects

Lentz and Mortensen 2014

- Estimated Klette-Kortum model
- Incumbent types have large and small innovation step sizes
  - Equilibrium is not conditionally efficient (assumption 2)
  - Distribution of incumbents impacts growth rate (assumption 3)
- Endogenous growth $\gamma = 1$
- No social depreciation
- Estimated elasticity of productivity growth w.r.t. Y_r moving from equilibrium to social optimum

$$\frac{g_z^* - \bar{g}_z}{\log Y_r^* - \log \bar{Y}_r} = 0.0125 < \bar{g}_z$$

- Smaller elasticity than from baseline quality-ladders model

Conclusion

- Wide class of growth models
  - Simple approximation to transition dynamics
- Two key sufficient statistics:
- Impact elasticity
  - baseline growth rate
  - social depreciation of innovation expenditures
  - incumbents' average cost of innovation
- Intertemporal knowledge spillovers
  - price deflator for research output
- Useful benchmark for evaluating quantitative implications of richer new growth models