14.461: Technological Change, Lecture 10
Modeling Creativity and Technological Leadership

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October 7, 2014.

Creative Innovations

- More than half a million patents per year granted by the USPTO but only a handful of those are truly transformative.
- E.g., in drugs and medical inventions, 223,452 patents between the years 1975 and 2001, but the median number of citations to these patents within the next five years was **four** (and with limited impact on the technology of the field).
- But the patent for "systems and methods for selective electrosurgical treatment of body structures" by the ArthroCare Corporation receive many more citations and has been transformative for surgical procedures.
- Similarly, Amazon's patent for "method and system for placing a purchase order via a communications network" (263 citations within the next five years) was a game changer for online business.

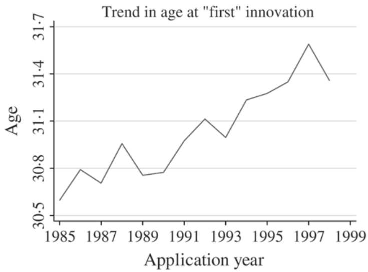
Modeling Creativity

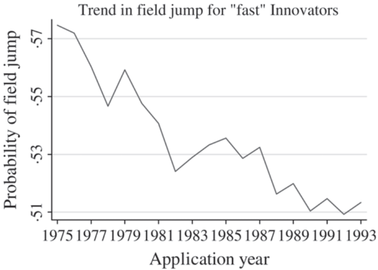
- What determines the creativity and productivity of innovations?
- What are the constraints faced by innovators and firms in pursuing creative innovations?
- Why are some firms and countries more creative?
- This lecture: some ideas and clues about this.

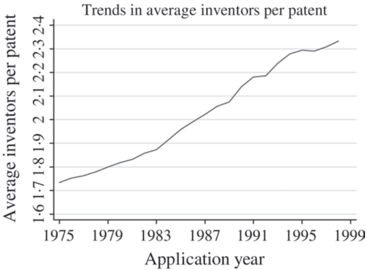
The Burden of Knowledge

- Jones (2009) provides evidence suggesting that innovation is becoming harder, more specialized and more team-based.
  - Age at first innovation has been steadily increasing.
  - Likelihood of an innovator switching technological fields has been decreasing.
  - Average number of innovators per patent (team size) has been increasing.

The Burden of Knowledge: Illustration







The Burden of Knowledge: Model Ideas

- Consider a model with quality ladders over several product lines, and suppose that innovation requires combining existing ideas from two or more randomly chosen product lines (Weitzman, 1998).
- An innovator needs to master all of the technologies. Suppose that the cost of this is proportional to total number of prior steps in the ladder. This is similar to what Jones calls *depth of knowledge.*
- If all technologies are relatively primitive, then an individual can master all product lines and thus quickly become an innovator.
- As technologies become more developed, each individual needs to spend more and more time mastering information, because there is more depth, and this means later innovations.
- After a while, it becomes impossible for individuals to do all of this mastering, in this case, each individual will specialize and then form bigger and bigger teams to do the combination of ideas.

Social Attitudes and Creativity

- Schumpeter (1934): a key determinant of creating innovations is a society's or an organization's **openness to disruption**—openness to new new ideas, innovations and practices and tolerance to disruptive or even rebellious behavior.
- Captured by Facebook's inscription on its headquarter walls:

  "move fast and break things."

- Such openness is a function of a company's "corporate culture," also influenced by society-wide institutions and policies and perhaps social norms ("national culture").
- Acemoglu, Akcigit and Celik (2013): modeling the choice between incremental and radical innovations and the effect of social attitudes and institutions on this.

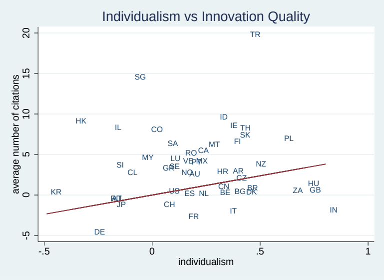
Related Ideas

- Gorodnichenko and Roland (2012): propose links between innovation and individualism and provide evidence using Hofstede's individualism data. But no focus on creative innovations, just reporting cross-country relationships with TFP and growth.
- There is also interesting empirical literature on age and creativity: Galenson and Weinberg (1999, 2001), Weinberg and Galenson (2005), Jones and Weinberg (2011), Jones (2010). The main finding is that scientists or artists have different *styles*, more reliant on creative genius, early in their careers, and more reliant on experience later in their careers.
  - Also, "early" Nobel prize winners have a different style of work than those who have received the Nobel prize for work done later in their careers.
- We will also discuss briefly issues related to technological leadership and creativity.

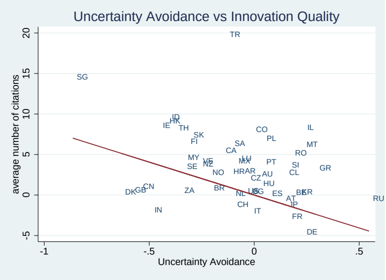
Cross-Country Motivation

- In cross-country data, we can look at various different measures to capture these ideas.
  1. Individualism:
     - Edmund Burke: individualism as the cause for the community to "crumble away, be disconnected into the dust and powder of individuality".
     - Alexis de Tocqueville: individualism in America resulting from the recognition of individual rights and freedoms and restrained government.
     - Hofstede's index of individualism: "preference for a loosely-knit social framework in which individuals are expected to take care of themselves and their immediate family only".
  2. Hofstede's index of uncertainty avoidance.
  3. New measure of average age of top managers—as a proxy for an open corporate culture.
  4. Institutional variables, such as rule of law.

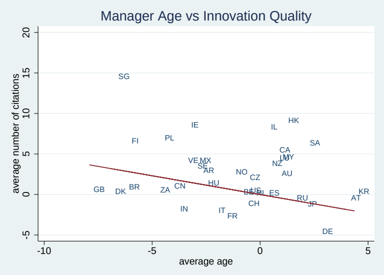
Cross-Country Patterns

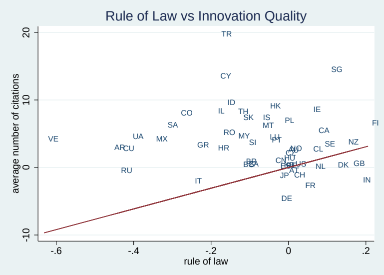


(a) Individualism vs Innovation Quality



(b) Uncertainty Avoidance vs Innovation Quality





Outline of Theory

- A model of endogenous innovations with a choice between incremental and radical innovations.
- Incremental innovations run into diminishing returns within a *technology cluster*.
- Radical innovations start new technology clusters by recombining ideas.
- Related to Innovator's Dilemma by Christensen (and Arrow's replacement effect), radical innovation less likely from more productive firms (thus some clues about changes in technological leadership at the firm level).
    - Also more original, building on broader knowledge, and will receive more citations in the future.

Outline of Theory (continued)

- Young managers for the comparative advantage and radical innovations (more recent knowledge base, less wedded to existing technologies and practices).
    - Assignment of managers to firms by age.
- But also key is firm type ("corporate culture"): only some type of firms can undertake radical innovations.
- Also institutional factors are important.

Theory: Additional Predictions

- Replacement effect and technology effect:
  - Radical innovation more likely when current technology is less profitable because of Arrow's replacement effect.
  - Radical innovation more likely when more innovations in the past because this implies more likely to have run into diminishing returns to incremental innovations.

Firm-Level Evidence

- Focus on average manager age of a company (from the Compustat).
- Several different measures of creative innovations (described below).
- Confirm cross-country patterns with better data and perhaps cleaner variation,
    - Though still only correlations, since manager age related to company characteristics.
- Fairly robust correlations.
- Also broadly consistent with replacement and technology effects.

Model

- Economy consists of continuum of product lines along the circle $\mathcal{C}$.
- Each product line has a quality q_j.
- Profits for a monopolist with a leading-edge product quality q_j:

$$\pi(q_j) = \pi q_j.$$

- Two types of firms (θ_H, θ_L), distinguished by their "corporate culture" determining their openness to disruption and radical innovation.
  - $\theta_H = 1 > \theta_L = 0$
  - follows a Markov chain, with transition rates ν_L and ν_H.

Managers

- When a manager is born, she acquires knowledge of the average technology in the period that she is born:

$$\bar{q}_b \equiv \int_{\mathcal{C}} q_{jb} dj.$$

- Manager of age $a \equiv t - b$ has two contributions:
  1. cost reduction by the amount of $f(a)\bar{q}_t$.
  2. producing more radical innovations

Innovations

- Firms choose between two types of innovations:
  1. *incremental innovations:* improvements within a given *technology cluster*.
  2. *radical innovations*: starts a new technology cluster.
- Incremental innovation:
  - Arrives at the rate ξ
  - Improves the latest quality q_j:

$$q_{j,t+\Delta t} = q_{j,t} + \eta_n(q_j, \bar{q}_t)$$

where

$$\eta_n(q_j, \bar{q}_t) = \left[\kappa \bar{q}_t + (1-\kappa)\, q_j\right] \eta \alpha^n$$

and $\alpha < 1$ and n is the number of prior incremental innovations in this technology cluster.

Innovation: Radical Innovations

- Radical innovation arrives at the rate $\theta\psi$ when pursuing incremental innovations, and at the rate

$$\theta\left[\psi+\Lambda\frac{\bar{q}_b}{\bar{q}_t}\right], \tag{1}$$

when pursuing radical innovations.

  - θ : Firm type, corporate culture, openness to disruption
  - $\frac{\bar{q}_b}{\bar{q}_t}\equiv\bar{q}^a$: impact of manager as a function of its age
  - $\Lambda<1$: institutional restrictions on manager's radical innovation
  - Implication: low-type firms with $\theta_L=0$ never generate radical innovations and high-type firms generate radical innovations at the rate ψ even when pursuing incremental innovations.

Equilibrium with $\kappa = 1$, $\psi = 0$, and $\nu = 0$

- Focus on *stationary equilibrium*.
- To understand the main economic forces, let us also first focus on the case in which $\kappa = 1$ and $\psi = 0$, $\nu_L = 0$ and $\nu_H = 0$ so that radical innovations only if pursuing a radical innovation strategy, improvements in productivity independent of current productivity, and no transitions between types.
- This model has a structure similar to Klette-Kortum's framework, where the value of the firm can be expressed as the sum of the values of each one of the firm's products.
- This significantly simplifies the analysis.

Equilibrium: Low-Type Values

- Low-type value function for a product line

$$r V_L(q_j, n) - \dot{V}_L(q_j, n) =$$
$$\max_{a \geq 0} \left\{ \pi q_j + \bar{q}_t f(a) - w_{a,t} \right\} + \xi \begin{bmatrix} V_L(q_j + \bar{q}_t \eta \alpha^n, n+1) \\ - V_L(q_j, n) \end{bmatrix} - \tau V_L(q_j, n$$

where τ is the aggregate creative destruction rate.

- Equilibrium managerial wage satisfy

$$w_{a,t} = \bar{q}_t f(a).$$

- Substituting this into the value function:

$$r V_L(q_j, n) - \dot{V}_L(q_j, n) =$$
$$\pi q_j^n + \xi \left[V_L(q_j + \bar{q}_t \eta \alpha^n, n+1) - V_L(q_j, n) \right] - \tau V_L(q_j, n).$$

Low-Type Values

Proposition

The value function for low types the following form

$$V_L(q_j, n) = Aq_j + B\bar{q}_t\alpha^n$$

where

$$B \equiv \frac{\xi\eta}{r - g + \tau + \xi(1-\alpha)}$$

and

$$A \equiv \frac{\pi}{\tau + r}.$$

High-Type Values

- For high-types:

$$
\begin{aligned}
& rV_H(q_j, n) - \dot{V}_H(q_j, n) = \\
& \max \left\{ \begin{array}{c} \pi q_j + \max_{a \geq 0} \left\{ \begin{array}{c} \bar{q}_t f(a) - w_{a,t} \\ +\xi \left[V_H(q_j + \bar{q}_t \eta \alpha^n, n+1) - V_H(q_j, n) \right] \end{array} \right\}; \\ \pi q_j + \max_{a \geq 0} \left\{ \bar{q}_t f(a) + \Lambda \bar{q}_a \theta \mathbb{E} V_H(\bar{q}_t) - w_{a,t} \right\} \end{array} \right. \\
& -\tau V_H(q_j, n).
\end{aligned}
$$

- Here $\mathbb{E} V_H(\bar{q}_t)$ is the expected (average) value of a new product line at time t.

Managers and Innovation

- Equation (1) implies that younger managers have the comparative advantage in radical innovation.
- Then there will exist a maximum age a^* such that only managers below this age will work in firms attempting radical innovation.
- Then profit maximization for high-type firms implies for all $a < a^*$:

$$\bar{q}_t f\left(a^*\right) + \Lambda \bar{q}_{a^*} \theta_H \mathbb{E} V_H(\bar{q}_t) - w_{a^*,t} = \bar{q}_t f\left(a\right) + \Lambda \bar{q}_a \theta \mathbb{E} V_H(\bar{q}_t) - w_{a,t}.$$

and the oldest manager working for radical innovation earns

$$w_{a^*,t} = \bar{q}_t f\left(a^*\right).$$

Managerial Wages

- Hence

$$w_{a,t} = \begin{cases} \bar{q}_t f(a) & \text{for} \quad a > a^* \\ \bar{q}_t f(a) + \Lambda \theta_H \left[\bar{q}_a - \bar{q}_{a^*} \right] \mathbb{E} V_H(\bar{q}_t) & \text{for} \quad a \leq a^* \end{cases} \tag{2}$$

- Substituting into the high-type value function, we get

$$rV_H(q_j, n) - \dot{V}_H(q_j, n) =$$
$$\max \left\{ \begin{array}{c} \pi q_j + \xi \left[V_H(q_j + \bar{q}_t \eta \alpha^n, n+1) - V_H(q_j, n) \right]; \\ \pi q_j + \Lambda \bar{q}_{a^*} \theta \mathbb{E} V_H(\bar{q}_t) \end{array} \right\} - \tau V_H(q_j, n)$$

High-Type Values

Proposition

The high-type value function takes the following form

$$V_H\left(q_j, n\right) = \tilde{A}q_j + \bar{q}_t\tilde{B}\left(n\right), \tag{3}$$

where

$$\tilde{A} = \frac{\pi}{r+\tau},$$

and $\tilde{B}\left(n\right)$ *is given by*

$$\left(r-g+\tau\right)\tilde{B}\left(n\right) = \begin{cases} \xi\left[\tilde{A}\eta\alpha^{n+1} + \tilde{B}\left(n+1\right) - \tilde{B}\left(n\right)\right] & \text{for } n < n^* \\ \Lambda\bar{q}_{a^*}\theta_H\left[\left(1+\eta\right)\tilde{A} + \tilde{B}\left(0\right)\right] & \text{for } n \geq n^* \end{cases},$$

where $n^* \in \mathbb{Z}_{++}$ *is the number of incremental innovations within a technology cluster at which there is a switch to radical innovation such that*

$$n^* = \lceil n' \rceil \text{ s. t. } \xi\left[\tilde{A}\eta\alpha^{n'+1} + \tilde{B}\left(n'+1\right) - \tilde{B}\left(n'\right)\right] = \Lambda\bar{q}_{a^*}\theta_H\left[\left(1+\eta\right)\tilde{A} + \tilde{B}\left(0\right)\right]$$

Stationary Equilibrium Characterization

Proposition

- *Low-type firms ($\theta = \theta_L$) hire "old" managers ($a > a^*$), pursue incremental innovations.*
- *High-type firms pursue radical innovations on product lines with more than n^* prior incremental innovations, and hire "young" managers ($a \leq a^*$), generating radical innovations at the rate $\Lambda \bar{q}^a$.*
- *A higher Λ (corresponding to the society being less restrictive towards radical innovations) will reduce n^* (so that a higher fraction of high-type firms will pursue radical innovation), and will increase the wages of young managers (because there is greater demand for the knowledge-base of young managers).*

General Characterization

- Now let us return to the general model and start with the case $\kappa = 1$.

Proposition

- *Low-type firms* ($\theta = \theta_L$) *hire "old" managers* ($a > a^*$)*, and pursue incremental innovations.*
- *High-type firms pursue incremental innovations on product lines with less than* n^* *prior incremental innovations, hire "old" managers and generate radical innovations at the rate* ψ*, and pursue radical innovations on lines with more than* n^* *prior incremental innovations, hire "young" managers* ($a \leq a^*$)*, and generate radical innovations at the rate* $\psi + \Lambda \bar{q}^a$*.*
- *A higher* Λ *reduces* n^**.*

- Within-firm prediction: following a switch from low to high type, first an increase in radical innovations, and then after some more incremental innovations, a switch to a young manager and a further increase in radical innovations.

General Equilibrium

- Determine aggregate growth rate and stationary distribution of firms.
- Equilibrium rate of entry x (exogenous or endogenous). Entrants replace an existing product line drawn uniformly at random, and then realized that type, high or low, with probability ζ and $1-\zeta$.
- Define aggregate creative destruction rate as

$$\tau = x + \int_0^{a^*} \Lambda \bar{q}_a \theta dF(a).$$

- Decomposed into creative destruction rates from low- and high-type firms:

$$\tau^L = x(1-\zeta) \quad \text{and} \quad \tau^H = x\zeta + \int_0^{a^*} \Lambda \bar{q}_a \theta_H dF(a).$$

- Clearly $\tau = \tau^H + \tau^L$.

Stationary Distributions

- Denote the fraction of product lines occupied by high- and low-type firms with n prior incremental innovations by μ_n^H and μ_n^L.
- Naturally

$$\sum_{n=0}^{\infty}\left[\mu_n^H+\mu_n^L\right]=1.$$

- Stationary distributions for high types given by

$$\begin{array}{rclll}
\underline{\text{Outflow}} & & \underline{\text{Inflow}} & & \\
(\tau+\xi)\,\mu_0^H & = & \tau^H & \text{for} & n=0 \\
(\tau+\xi)\,\mu_n^H & = & \xi\mu_{n-1}^H & \text{for} & n^*>n>0 \\
\tau\mu_{n^*}^H & = & \xi\mu_{n^*-1}^H & \text{for} & n=n^* \\
\mu_n^H & = & 0 & \text{for} & n>n^*
\end{array}$$

Stationary Distributions (continued)

- For low types:

$$
\begin{array}{ccccc}
\underline{\text{Outflow}} & & \underline{\text{Inflow}} & & \\
(\tau+\xi)\,\mu_0^L & = & \tau^L & \text{for} & n=0 \\
(\tau+\xi)\,\mu_n^L & = & \xi\mu_{n-1}^L & \text{for} & n>0
\end{array}
$$

- These can be solved for the following geometric distributions for high- and low-type firms:

$$
\begin{aligned}
\mu_n^L &= \left[\frac{\xi}{\tau+\xi}\right]^n \frac{\tau^L}{\tau+\xi} \text{ and} \\
\mu_n^H &= \begin{cases} \left[\frac{\xi}{\tau+\xi}\right]^n \frac{\tau^H}{\tau+\xi} & \text{for } n<n^* \\ \left[\frac{\xi}{\tau+\xi}\right]^n \frac{\tau^H}{\tau} & \text{for } n=n^* \end{cases}.
\end{aligned}
$$

Aggregate Growth Rate

- Growth driven by quality improvements. That is,

$$Y_t = \frac{L}{1-\beta}\bar{q}_t.$$

- During $\Delta t > 0$, the average quality evolves according to the following law of motion:

$$\bar{q}_{t+\Delta t} = \bar{q}_t + \eta\bar{q}_t \left[x + \mu^H_{n^*} Q\Lambda\theta\right] \Delta t + \bar{q}_t \xi\eta\Delta t \left[\sum_0^{n^*} \mu^H_n \alpha^n + \sum_0^{\infty} \mu^L_n \alpha^n\right] + o(\Delta$$

where $Q \equiv \frac{1}{F(a^*)} \int_0^{a^*} \bar{q}_a dF(a)$

- Then, the stationary equilibrium aggregate growth rate is:

$$g = \eta\left[x + \mu^H_{n^*} Q\Lambda\theta\right] + \xi\eta\left[\sum_0^{n^*} \mu^H_n \alpha^n + \sum_0^{\infty} \mu^L_n \alpha^n\right].$$

Equilibrium with $\kappa < 1$

- Insights similar with $\kappa < 1$, but some new results.

Proposition

Consider the economy with $\kappa < 1$. Then, for a product line with current quality q operated by a high-type firm, the manager will be younger and will pursue radical innovation when the number of prior incremental innovations is greater than or equal to $n_t^*(q)$, where $n_t^*(q)$ is increasing in q. That is, a high-type firm is more likely to pursue radical innovation when its current productivity is lower and the number of its prior innovations in the same cluster is higher.

- Predictions related to the replacement effects and the innovator's dilemma.

Firm-Level Results

- Baseline **balanced** sample comprises 279 with complete information between 1995 and 2000.
- **Unbalanced** sample extended to 1992-2004 for all firms with CEO age or patent information.
- Use average manager/CEO age as proxy for a corporate culture that is more open to disruption.
- All regressions are weighted by patent counts and include: firm age, log employment, log sales, log patent counts, and four-digit SIC dummies.
- Robust standard errors are in parentheses.

Firm-Level Results

Table 2: Baseline Firm-Level Regressions

	Innovation Quality	Superstar Fraction	Tail Innovation	Generality
CEO age	-0.278	-0.300	-0.151	-0.183
	(0.088)	(0.141)	(0.054)	(0.055)
firm age	-0.219	-0.238	-0.063	0.029
	(0.078)	(0.106)	(0.029)	(0.046)
log employment	-1.599	-4.813	-0.908	-4.574
	(1.937)	(3.376)	(0.793)	(1.500)
log sales	1.833	5.215	0.743	4.421
	(1.425)	(2.645)	(0.650)	(1.331)
log patent	1.073	0.093	0.662	-0.696
	(0.769)	(1.336)	(0.356)	(0.633)
R^2	0.88	0.81	0.79	0.83
N	279	279	279	279

Firm-Level Results

Table 5: Firm-Level Panel Regressions

	Innovation Quality	Superstar Fraction	Tail Innovation	Generality
Panel C: CEO Age (Fixed Effects), Unbalanced Firm Sample, 1992-2004				
CEO age	-0.188	-0.149	-0.076	0.036
	(0.044)	(0.051)	(0.023)	(0.029)
R^2	0.78	0.80	0.44	0.85
N	7,111	7,111	5,803	6,232
Panel F: CEO Age and Lead CEO Age (Fixed Effects), Unbalanced Firm Sample, 1992-2				
CEO age	-0.113	-0.084	-0.042	0.042
	(0.042)	(0.048)	(0.019)	(0.029)
lead CEO age	-0.125	-0.109	-0.043	-0.007
	(0.049)	(0.044)	(0.022)	(0.028)
R^2	0.78	0.81	0.48	0.85
N	5,409	5,409	4,849	5,097

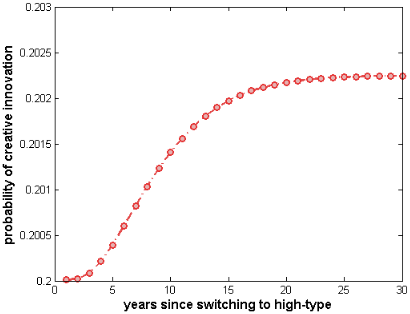
Table 8: Patent-Level Panel Regressions

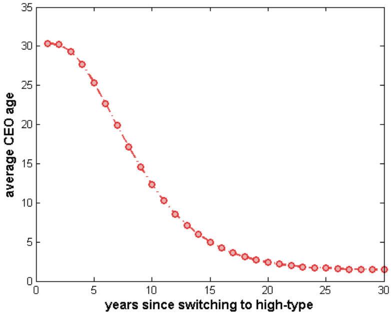
	Innovation Quality	Tail Innovation (Above 99)	Tail Innovation (Above 90)	Generality
Panel E: CEO Age and Inventor Age, Unbalanced Firm Sample, 1992-2004				
CEO age	-0.119	-0.317	-1.218	0.028
	(0.036)	(0.126)	(0.388)	(0.022)
inventor age	-0.233	-0.438	-2.876	-0.019
	(0.026)	(0.121)	(0.321)	(0.022)
R^2	0.14	0.03	0.09	0.15
N	316,516	316,516	316,516	263,641

Indirect Inference: Causal vs Sorting Effects

- Sorting or the causal effect of manager age?
- We use indirect inference procedure utilizing the structure of our model to obtain an estimate of the size of this causal effect of manager age on creative innovations.
- **Exogenous Calibration**
  - discount rate to $\rho = 0.02$
  - normalize $\pi = 1$
  - entry rate $x = 0.05$
  - exit rate δ : fit and exponential distribution to the age distribution of managers in our sample.
- **Indirect Inference:** With the remaining parameters, we target:
  - sales per worker growth
  - share of young managers (age < 45)
  - probability of switching to younger manager
  - ratio of the coefficients of lead to current CEO age of Table 5F.

Indirect Inference: Identification





- **Thought experiment:** A firm wishing to hire a young manager is prevented from doing so.
- **Finding:** Causal effects explain less than 1% of the relationship between CEO age and creative innovations—, the rest being due to corporate culture and sorting effects .
- Consistent with the importance of corporate culture, it is a combination of inventor age and CEO age that matters for creative innovations.

Stock of Knowledge and Opportunity Cost Effect

- Is it—as predicted by theory—currently less productive firms that are more likely like you to switch to radical innovation?

Table 10: Stock of Knowledge, Opportunity Cost, and Creative Innovations, Unbalanced Firm Sample, 1992-2004

	Innovation Quality	Superstar Fraction	Tail Innovation	Generality
CEO age	-0.180	-0.216	-0.087	-0.044
	(0.027)	(0.027)	(0.017)	(0.016)
log sales	1.465	2.081	0.285	1.201
	(0.449)	(0.611)	(0.272)	(0.328)
log patent	-0.394	-0.072	0.391	-0.020
	(0.193)	(0.257)	(0.136)	(0.151)
CEO age	-0.005	-0.071	-0.016	-0.037
× log patent	(0.014)	(0.021)	(0.011)	(0.011)
CEO age	0.024	0.079	0.009	0.044
× log sales	(0.017)	(0.021)	(0.012)	(0.011)
R^2	0.67	0.55	0.31	0.77
N	7,111	7,111	5,803	6,232

Cross-country Results

- Similar patterns at the cross-country level.

Table 11: Baseline Cross-Country Regressions

	Innovation Quality	Superstar Fraction	Tail Innovation	Generality
	Panel A: Average Manager Age			
manager age	-0.484	-0.960	-0.225	-0.278
	(0.225)	(0.221)	(0.058)	(0.056)
log income per capita	-0.491	-0.702	-0.136	0.211
	(1.153)	(1.066)	(0.291)	(0.468)
secondary years of schooling	-1.000	-1.359	-0.291	-0.231
	(1.481)	(1.462)	(0.396)	(0.341)
log patent	2.232	2.331	0.591	1.072
	(0.706)	(0.695)	(0.193)	(0.222)
R^2	0.74	0.82	0.80	0.80
N	37	37	37	37

Modeling Technological Leadership

- Acemoglu, Robinson and Verdier (2014): consider a model of international technological diffusion, where countries can benefit from the world technology frontier on the basis of limited innovations or engage in more radical innovations that push the world technology frontier forward.
- To encourage more radical innovations, society needs to provide greater rewards entrepreneurs (more entrepreneurial inequality) which is costly.
- Main result: the world equilibrium will often be asymmetric, one or a few countries undertaking the bulk of the radical innovations with a more "cutthroat" style capitalism, while followers can adopt a more "cuddly" style capitalism.
    - Followers may in fact be better off, because of better risk sharing. But this is made possible by the fact that they are "free riding" on the more radical innovations of the technological leader.

The Model

- Version of Romer's endogenous technological change model with multiple countries.
- An infinite-horizon continuous time economy with non-overlapping generations of agents who live for an instant, work, produce, consume and then die.
- There are J countries in the world indexed by $j = 1, 2, ..., J$. The aggregate production function at time t in country j is

$$Y_j(t) = \frac{1}{1-\beta}\left(\int_0^{N_j(t)} x_j(\nu, t)^{1-\beta} d\nu\right) L_j^\beta,$$

  where $L_j = 1$ is labor input, which varies across regions, $N_j(t)$ denotes the number of machine varieties available to country j at time t ("technological know-how" of country j).
- $x_j(\nu, t)$ is the total amount of machine variety ν used in country j at time t and fully depreciates after use.

The Model (continued)

- Each machine variety in economy j is owned by a technology monopolist, "entrepreneur," which will sell machines embodying this technology at the profit maximizing (rental) price $p_j^x(\nu, t)$ within the country.
- Marginal cost of production of any variety: $\psi \equiv 1 - \beta$ in terms of the final good.

Preferences

- Suppose workers can simultaneously work as entrepreneurs. Each worker/entrepreneur i has utility function

$$U\left(C_{j,i}\left(t\right), e_{j,i}\left(t\right)\right) = \frac{\left[C_{j,i}\left(t\right)\left(1-\gamma e_{j,i}\left(t\right)\right)\right]^{1-\theta}-1}{1-\theta}.$$

- To interpret this utility function, suppose that each worker/entrepreneur exerts some effort $e_{j,i}\left(t\right) \in \{0,1\}$ in order to acquire one of the existing machines already available to the country (one of the existing $N_j\left(t\right)$) or adopt or invent a new one.
- Effort $e_{j,i}\left(t\right) = 1$ costs $\gamma > 0$, while $e_{j,i}\left(t\right) = 0$ a zero cost.

Effort and Innovation

- The outcome of the high effort, $e_{j,i}(t) = 1$, is risky.
- The entrepreneur is "successful" with probability q_1 and unsuccessful with the complementary probability. $e_{j,i}(t) = 0$ leads to success with the smaller probability $q_0 < q_1$.
- Since workers can simultaneously function in entrepreneurial and production jobs there is no occupational choice (and since choosing zero effort is costless, all workers will engage in entrepreneurial activity).
- Each individual will therefore receive income from entrepreneurship plus regular wage income.

Technological Progress

- A successful entrepreneur in country j generates

$$\dot{N}_j(t) = \eta_j (N(t))^{\phi} (N_j(t))^{1-\phi},$$

  new machines where $N(t)$ is an index of the world technology frontier, to be endogenized below, $\eta_j > 0$ for all j, and $\phi > 0$ and common to all economies. Focus on the case in which $\eta_j = \eta$.
- Thus technological know-how of country j advances as a result of the R&D entrepreneurs in the country as well as world knowledge.
- Denoting the fraction of entrepreneurs choosing high effort in country j at time t by $e_j(t)$, technological advances as

$$\dot{N}_j(t) = \eta_j (N(t))^{\phi} (N_j(t))^{1-\phi} (q_1 e_j(t) + q_0(1 - e_j(t))).$$

- The growth of the world technology frontier is given by

$$G(N_1(t), ..., N_J(t)) = \max\{N_1(t), ..., N_J(t)\}.$$

Reward Structures

- Given $N_j(t)$, computing an equilibrium allocation ("static equilibrium allocation") is straightforward (just using constant markups from the Dixit-Stiglitz structure and full employment).
- Suppose that each country chooses a *reward structure*, which corresponds to a reward to each entrepreneur as a function of their success/failure.
- This amounts to choosing just two numbers subject to its budget constraint:

1. $R_s(t) =$ total income if successful at time t,
2. $R_u(t) =$ total income is unsuccessful at time t.

Cutthroat and Cuddly Reward Structures

- All else being equal $R_s(t) = R_u(t)$ is preferred for consumption smoothing, but would generate low innovation/adoption.
- Instead, the greater is the gap $R_s(t) / R_u(t)$ the more innovative effort will be exerted. But this is of course costly from the consumption smoothing viewpoint.
- Trade-off: If all countries choose an egalitarian, *cuddly society* structure, with $R_s(t) / R_u(t)$ small, then the world will grow very slowly.
- If on the other hand, all countries choose very large $R_s(t) / R_u(t)$, i.e., no welfare state and a *cutthroat society*, then there will be more rapid growth in the world economy.

Equilibrium Given Reward Structures

Proposition

Suppose that the reward structure for each country is constant over time (i.e., for each j, $R_s^j(t)/R_u^j(t) = r_j$) or asymptotically constant. Then starting from any initial conditions $(N_1(0), ..., N_J(0))$, the world economy converges to a unique stationary distribution $(n_1^*, ..., n_J^*)$, where $n_j(t) \equiv N_j(t)/N(t)$ and $\dot{N}(t)/N(t) = g^*$, and $(n_1^*, ..., n_J^*)$ and g^* are functions of $(r_1, ..., r_J)$. Moreover, g^* is only a function of the most innovative country's reward structure, r_ℓ.

The Country Social Planner's Problem

- Suppose that all countries choose their reward structures once to maximize
$$\int_0^\infty e^{-\rho t}\left(\int U\left(C_{j,i}\left(t\right), e_{j,i}\left(t\right)\right) di\right) dt,$$
where ρ is the discount factor of the fictitious social planner.
- In order to induce individuals to choose the high effort level the reward structure must be set by the social planner such that
$$\begin{aligned} & \frac{1}{1-\theta}\left(q_1 R_s\left(t\right)^{1-\theta} + \left(1-q_1\right) R_u\left(t\right)^{1-\theta}\right)\left(1-\gamma\right)^{1-\theta} \\ \geq \quad & \frac{1}{1-\theta}\left(q_0 R_s\left(t\right)^{1-\theta} + \left(1-q_0\right) R_u\left(t\right)^{1-\theta}\right). \end{aligned}$$
- Equivalently:
$$r\left(t\right) \equiv \frac{R_s\left(t\right)}{R_u\left(t\right)} \geq \left(1 + \frac{1-\left(1-\gamma\right)^{1-\theta}}{q_1\left(1-\gamma\right)^{1-\theta} - q_0}\right)^{\frac{1}{1-\theta}} \equiv A.$$
- A measures how "high-powered" the reward structure is.

Creating Incentives (continued)

- Now combining this with the resource constraint, to provide incentives for innovation, we need

$$R_s(t) = \frac{BA}{q_1 A + (1 - q_1)} N_j(t), \; R_u(t) = \frac{B}{q_1 A + (1 - q_1)} N_j(t),$$

  where B is a constant.

- Then expected utility under "cutthroat" and "cuddly" reward structures, denoted by $s = c$ and $s = o$, are

$$W_j^c(t) = \omega_c N_j(t)^{1-\theta} - \frac{1}{1-\theta} \text{ and } W_j^o(t) = \omega_o N_j(t)^{1-\theta} - \frac{1}{1-\theta},$$

  where

$$\omega_c \equiv \frac{\left(q_1 A^{1-\theta} + (1 - q_1)\right)(1-\gamma)^{1-\theta}}{\left(q_1 A + (1 - q_1)\right)^{1-\theta}} \frac{B^{1-\theta}}{1-\theta} \text{ and } \omega_o \equiv \frac{B^{1-\theta}}{1-\theta}.$$

Growth under the Different Incentive Structures

- Now the growth rate of technology of country j adopting reward structure $s_j \in \{c, o\}$ can be derived as

$$\dot{N}_j(t) = g_{s_j} N(t)^{\phi} N_j(t)^{1-\phi}$$

  where the growth rates $g_{s_j} \in \{g_c, g_o\}$ are given by

$$g_o \equiv q_0 \eta, \text{ and } g_c \equiv q_1 \eta.$$

- This reiterates that at any point in time, country choosing a cutthroat reward structure will have a faster growth of its technology stock.

Assumptions

Assumption 2:

$$\rho - (1-\theta)\, g_c > 0.$$

Assumption 3:

$$\frac{\omega_c}{\rho - (1-\theta) g_c} > \frac{\omega_o}{\rho - (1-\theta) g_o}.$$

Assumption 4: $N_\ell(t) = \max\{N_1(t), ..., N_J(t)\}$ for all t.

- This specifies a selection rule: the same country, ℓ, *remains the technology leader throughout*.

Main Result

Proposition

Let

$$\widetilde{m} \equiv (1-\theta)\frac{(\omega_o - \omega_c)\, g_c + (g_c - g_o)\,\omega_c}{(\omega_o - \omega_c)\,(\rho + \phi g_c)}.$$

Then the leader country ℓ always chooses cutthroat rewards.

1. *If $\widetilde{m} < \frac{g_o}{g_c}$, there exist $\overline{m} < g_o/g_c$ and $0 \leq T < \infty$ such that for $n_j(0) < \overline{m}^{1/\phi}$, each follower $j \neq \ell$: chooses cutthroat rewards for all $t < T$, and cuddly for all $t \geq T$; for $n_j(0) \geq \overline{m}^{1/\phi}$, it chooses cuddly for all t. In all cases, $n_j(t) \to (g_o/g_c)^{1/\phi}$.*
2. *If $\frac{g_o}{g_c} < \widetilde{m} < 1$, there exists $0 < T < \infty$ such that for $n_j(0) <(>) \widetilde{m}^{1/\phi}$, each follower $j \neq \ell$: first chooses cutthroat (cuddly) and then when $n_j(T) = \widetilde{m}^{1/\phi}$, it adopts a "mixed" reward structure and stays at $n_j(t) = \widetilde{m}^{1/\phi}$ for all $t \geq T$.*
3. *If $\widetilde{m} > 1$, then the reward structure of country j is cutthroat for all t.*

Phase Diagram

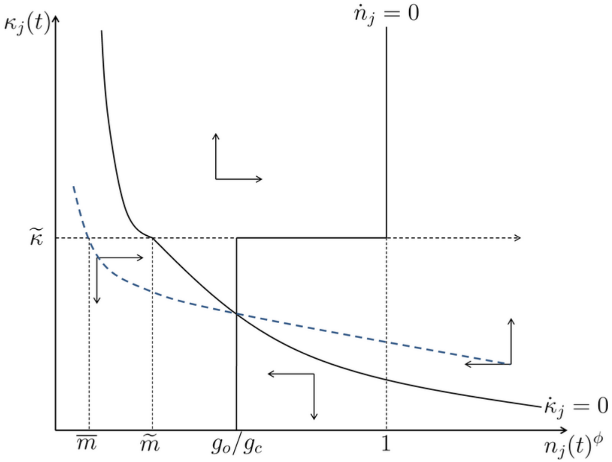


Figure 1: Phase diagram: part 1 of Proposition 2.

Intuition

- When $\widetilde{m} < g_o/g_c$, the world equilibrium is asymmetric: the leader, country ℓ, always chooses cutthroat rewards, and asymptotically all followers choose cuddly rewards.
- When country ℓ chooses cutthroat incentives, its discounted value is $\frac{\omega_c}{\rho-(1-\theta)g_c}$. If it were to choose cuddly incentives, the world growth rate would be $g_o < g_c$, yielding a discounted value of $\frac{\omega_o}{\rho-(1-\theta)g_o}$. Assumption 3 implies that ℓ prefers the first option. Intuitively, country ℓ's actions have a *growth effect* on the world economy (and thus on itself).
- However, given the diffusion of technology across countries, once country ℓ chooses cutthroat incentives, the choice of reward structure for other countries has only a *level effect*: a country choosing a cutthroat reward structure would increase its position relative to country ℓ but not its permanent growth rate.

Conclusion

- The tail of innovations might be much more important for knowledge creation and growth, and we still only have a limited understanding of what determines these tail innovations.
- Much that can be done theoretically and empirically on creativity of the nations and the effect of economic trade-offs, social attitudes and institutions on creativity.
- Important area to be explored: internal organization of firms and creativity.