14.461: Technological Change, Lecture 9
Climate Change and Technology

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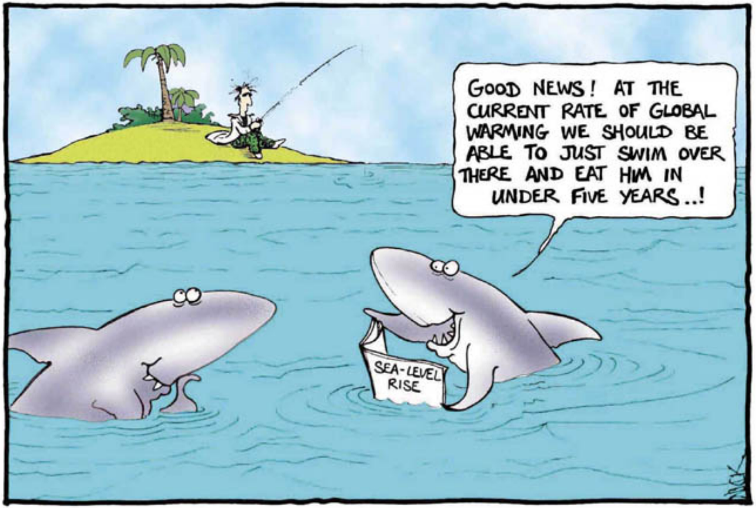
Motivation (I)

- Consensus about climate change due greenhouse gas emissions.



Motivation (II)

- But also increasing recognition that most of the action will come to transition to clean technology.
- How to switch to clean technology in the best (welfare maximizing)

Motivation (III)

- Empirical work: possible switch away from dirty to clean technologies in response to changes in prices and policies.
  - Newell, Jaffe and Stavins (1999):
    - following the oil price hikes, innovation in air-conditioners towards more energy effcient units
  - Popp (2002):
    - higher energy prices associated with a significant increase in energy-saving innovations
  - Hassler, Krusell and Olovsson (2011):
    - trend break in energy-saving factor productivities after high oil prices
  - Aghion et al. (2012):
    - significant impact of carbon taxes on the direction of innovation in the automobile industry.

Motivation (III)

- A systematic investigation necessitates:
  - micro model
    - with carbon emissions and potential climate change,
    - where clean and dirty technologies compete, and
    - research incentives (and the direction of technological change) are endogenous.
  - micro data
    - for the modeling of competition in production and innovation,
  - quantitative analysis
    - to study the impacts of various policies.
- This lecture: two models—first about the conceptual issues (less micro and no data) and the second more about micro structure of technology choices, estimation and quantitative analysis.

Exogenous Growth Approaches

- Economic analyses using computable general equilibrium models with exogenous technology (and climatological constraints; e.g., Nordhaus, 1994, 2002).
- Key issues for economic analyses: (1) economic costs and benefits of environmental policy; (2) costs of delaying intervention (3) role of discounting and risk aversion.
- Various conclusions:
  1. **Nordhaus approach:** intervention should be limited and gradual; small long-run growth costs.
  2. **Stern/Al Gore approach:** intervention needs to be large, immediate and maintained permanently; large long-run growth costs.
  3. **Greenpeace approach:** only way to avoid disaster is zero growth.

Endogenous and directed technology

- Very different answers are possible.
  1. Immediate and decisive intervention is necessary (in contrast to Nordhaus)
  2. Temporary intervention may be sufficient (in contrast to Stern/Al Gore)
  3. Long-run growth costs may actually be very limited (in contrast to all of them).
  4. Two instruments—not one—necessary for optimal environmental regulation.

Why?

- Two sector model with "clean" and "dirty" inputs with two key externalities
- *Environmental externality*: production of dirty inputs creates environmental degradation.
- Researchers work to improve the technology depending on expected profits and "**build on the shoulders of giants in their own sector**".
  - → *Knowledge externality*: advances in dirty (clean) inputs make their future use more profitable.
- Policy interventions can **redirect technological change** towards clean technologies.

Why? (Continued)

1. Immediate and decisive intervention is necessary (in contrast to Nordhaus)
   - → without intervention, innovation is directed towards dirty sectors; thus gap between clean and dirty technology widens; thus cost of intervention (reduced growth when clean technologies catch up with dirty ones) increases
2. Temporary intervention may be sufficient (in contrast to Stern/Al Gore), long-run growth costs limited (in contrast to all of them)
   - → once government intervention has induced a technological lead in clean technologies, firms will spontaneously innovate in clean technologies (if clean and dirty inputs are sufficiently substitutes).
3. Two instruments, not one:
   - → optimal policy involves both a carbon tax and a subsidy to clean research to redirect innovation to green technologies
   - → too costly in terms of foregone short-run consumption to use carbon tax alone

Model (1): production

- Infinite horizon in discrete time (suppress time dependence for now)
- Final good Y produced competitively with a clean intermediary input Y_c, and a dirty input Y_d

$$Y = \left(Y_c^{\frac{\varepsilon-1}{\varepsilon}} + Y_d^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}$$

- Most of the analysis: $\varepsilon > 1$, the two inputs are substitute.
- For $j \in \{c, d\}$, input Y_j produced with labor L_j and a continuum of machines x_{ji}:

$$Y_j = L_j^{1-\alpha} \int_0^1 A_{ji}^{1-\alpha} x_{ji}^{\alpha} di$$

- Machines produced **monopolistically** using the final good

Model (2): consumption

- Constant mass 1 of infinitely lived representative consumers with intertemporal utility:

$$\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} u(C_t, S_t)$$

where u increasing and concave, with

$$\lim_{S \to 0} u(C, S) = -\infty; \frac{\partial u}{\partial S}(C, \bar{S}) = 0$$

Model (3): environment

- Production of dirty input depletes environmental stock S:

$$S_{t+1} = -\xi Y_{dt} + (1+\delta) S_t \quad \text{if} \quad S \in (0, \bar{S}) . \tag{1}$$

- Reflecting at the upper bound $\bar{S}$ $(< \infty)$: baseline (unpolluted) level of environmental quality.
- Absorbing at the lower bound $S = 0$.
- $\delta > 0$: rate of "environmental regeneration" (measures amount of pollution that can be absorbed without extreme adverse consequences)
- S is general quality of environment, inversely related to CO2 concentration (what we do below for calibration).

Model (4): innovation

- At the beginning of every period scientists (of mass $s = 1$) work either to innovate in the clean or the dirty sector.
- Given sector choice, each randomly allocated to one machine in their target sector.
- Every scientist has a probability η_j of success (without congestion).
  - if successful, proportional improvement in quality by $\gamma > 0$ and the scientist gets monopoly rights for one period, thus

$$A_{jit} = (1 + \gamma) A_{jit-1};$$

  - if not successful, no improvement and monopoly rights in that machine randomly allocated to an entrepreneur who uses technology

$$A_{jit} = A_{jit-1}.$$

  - simplifying assumption, mimicking structure in continuous time models.

Model (5): innovation (continued)

- Therefore, law of motion of quality of input in sector $j \in \{c, d\}$ is:

$$A_{jt} = \left(1 + \gamma \eta_j s_{jt}\right) A_{jt-1}$$

- **Note:** *knowledge externality*; "building on the shoulders of giants," but importantly "**in own sector**"
    - Intuition: Fuel technology improvements do not directly facilitate discovery of alternative energy sources

Assumption

A_{d0} sufficiently higher than A_{c0}.

- Capturing the fact that currently fossil-fuel technologies are more advanced than alternative energy/clean technologies.

Laissez-faire equilibrium: direction of innovation

- Scientists choose the sector with higher expected profits Π_{jt}:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d} \underbrace{\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}}}_{\text{price effect}} \underbrace{\frac{L_{ct}}{L_{dt}}}_{\text{market size effect}} \underbrace{\frac{A_{ct-1}}{A_{dt-1}}}_{\text{direct productivity effect}}$$

  - The direct productivity effect pushes towards innovation in the more advanced sector
  - The price effect towards the less advanced, price effect stronger when ε smaller
  - The market size effect towards the more advanced when $\varepsilon > 1$

Laissez-faire equilibrium (continued)

- Use equilibrium machine demands and prices in terms of technology levels (state variables) and let $\varphi \equiv (1-\alpha)(1-\varepsilon)$ (<0 if $\varepsilon > 1$):

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d}\left(\frac{1+\gamma\eta_c s_{ct}}{1+\gamma\eta_d s_{dt}}\right)^{-\varphi-1}\left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{-\varphi}.$$

- Implications: innovation in relatively advanced sector if $\varepsilon > 1$

Laissez-faire equilibrium production levels

- Equilibrium input production levels

$$
\begin{aligned}
Y_d &= \frac{1}{\left(A_c^{\varphi} + A_d^{\varphi}\right)^{\frac{\alpha+\varphi}{\varphi}}} A_c^{\alpha+\varphi} A_d; \\
Y &= \frac{A_c A_d}{\left(A_c^{\varphi} + A_d^{\varphi}\right)^{\frac{1}{\varphi}}}
\end{aligned}
$$

- Recall that $\varphi \equiv (1-\alpha)(1-\varepsilon)$.
- In particular, given the assumption that A_{d0} sufficiently higher than A_{c0}, Y_d will always grow without bound under laissez-faire
  - If $\varepsilon > 1$, then all scientists directed at dirty technologies, thus $g_{Y_d} \rightarrow \gamma\eta_d$

Environmental disaster

- An environmental "**disaster**" occurs if S_t reaches 0 in finite time.

Proposition

Disaster.

The laissez-faire equilibrium always leads to an environmental disaster.

Proposition

The role of policy.

1. *when the two inputs are strong substitutes* $(\varepsilon > 1/(1-\alpha))$ *and* $\bar{S}$ *is sufficiently high, a temporary clean research subsidy will prevent an environmental disaster;*
2. *in contrast, when the two inputs are weak substitutes* $(\varepsilon < 1/(1-\alpha))$, *a temporary clean research subsidy cannot prevent an environmental disaster.*

Sketch of proof

- Look at effect of a temporary clean research subsidy
- Key role: **redirecting technological change**; innovation can be redirected towards clean technology
- If $\varepsilon > 1$, then subsequent to an extended period of taxation, innovation will remain in clean technology
- Is this sufficient to prevent an environmental disaster?

Sketch of proof (continued)

- Even with innovation only in the clean sector, production of dirty inputs may increase
  - *on the one hand:* innovation in clean technology reduces labor allocated to dirty input $\Rightarrow Y_d \downarrow$
  - *on the other hand*: innovation in clean technology makes final good cheaper an input to production of dirty input $\Rightarrow Y_d \uparrow$
  - which of these two effects dominates, will depend upon ε.
- With clean research subsidy (because $\varepsilon > 1$ and thus $\varphi < 0$):

$$Y_d = \frac{1}{\left(A_c^{\varphi} + A_d^{\varphi}\right)^{\frac{\alpha+\varphi}{\varphi}}} A_c^{\alpha+\varphi} A_d \rightarrow A_c^{\alpha+\varphi}$$

- If $\alpha + \varphi > 0$ or $\varepsilon < 1/(1-\alpha)$, then second effect dominates, and long run growth rate of dirty input is positive equal to $(1 + \gamma\eta_c)^{\alpha+\varphi} - 1$
- If $\alpha + \varphi < 0$ or $\varepsilon > 1/(1-\alpha)$, then first effect dominates, so that Y_d decreases over time.

Cost of intervention and delay

- Concentrate on strong substitutability case $(\varepsilon > 1/(1-\alpha))$
- While A_{ct} catches up with A_{dt}, growth is reduced.
- T: number of periods necessary for the economy under the policy intervention to reach the same level of output as it would have done within one period without intervention
- If intervention delayed, not only the environment gets further degraded, but also technology gap A_{dt-1}/A_{ct-1} increases, growth is reduced for a longer period.

Complementary case

- Suppose instead that clean and dirty inputs are complements, i.e., $\varepsilon < 1$.
- Innovation is directed towards the more backward sector
  - price effect dominates the direct productivity effect and market size effect now favors innovation in the more backward sector
  - typically innovation first occurs in clean, then in both, asymptotically balanced between the two sectors.
- Asymptotic growth rate of dirty input: $g_{Y_d} \to \gamma\eta_c\eta_d / (\eta_c + \eta_d) < \gamma\eta_d$ (growth rate in substitute case): disaster occurs sooner than in the substitute case.
- ... but it is unavoidable using only a temporary clean research subsidy.
  - If the clean sector is the more advanced, innovation will take place in dirty once the subsidy is removed, and long-run growth rate of dirty input remains the same.

Undirected technical change

- Compare with a model where scientists randomly allocated across sectors so as to ensure equal growth in the qualities of clean and dirty machines, thus $g_{Y_d} \to \gamma\eta_c\eta_d / (\eta_c + \eta_d) < \gamma\eta_d$

Proposition

The role of directed technical change.
When $\varepsilon > 1/(1-\alpha)$*:*

1. *An environmental disaster under laissez-faire arises earlier with directed technical change than in the equivalent economy with undirected technical change.*
2. *However, a temporary clean research subsidy can prevent an environmental disaster with directed technical change, but not in the equivalent economy with undirected technical change.*

Optimal environmental regulation

Proposition

Optimal environmental regulation.

The social planner can implement the social optimum through a "carbon tax" on the use of the dirty input, a clean research subsidy and a subsidy for the use of all machines (all taxes/subsidies are financed lump sum).

1. *If* $\varepsilon > 1$ *and the discount rate* ρ *is sufficiently small, then in finite time innovation ends up occurring only in the clean sector, the economy grows at rate* $\gamma\eta_c$ *and the optimal subsidy to clean research,* q_t, *is temporary.*
2. *The optimal carbon tax,* τ_t, *is temporary if* $\varepsilon > 1/(1-\alpha)$ *but not if* $1 < \varepsilon < 1/(1-\alpha)$.

- Interpretation.

Carbon tax

- Optimal carbon tax schedule is given by

$$\tau_t = \frac{\omega_{t+1}\xi}{\lambda_t p_{dt}},$$

  - λ_t is the marginal utility of a unit of consumption at time t
  - ω_{t+1} is the shadow value of one unit of environmental quality at time $t+1$, equal to the discounted marginal utility of environmental quality as of period $t+1$

- If $\varepsilon > 1/\left(1-\alpha\right)$, dirty input production tends towards 0 and environmental quality S_t reaches $\overline{S}$ in finite time, carbon tax becomes null in finite time.
- If gap between the two technologies is high, relying on carbon tax to redirect technical change would reduce too much consumption.

Exhaustible resources

- Polluting activities (CO2 emissions) often use an exhaustible resource (most importantly, oil).
- Dirty input produced with some exhaustible resource R:

$$Y_d = R^{\alpha_2} L_d^{1-\alpha} \int_0^1 A_{di}^{1-\alpha_1} x_{di}^{\alpha_1} di,$$

  with $\alpha_1 + \alpha_2 = \alpha$.
- The resource stock Q_t evolves according to

$$Q_{t+1} = Q_t - R_t$$

- Extracting 1 unit of resource costs $c(Q_t)$ (with $c' \leq 0$, $c\,(0)$ finite). As Q_t decreases, extracting the resource becomes increasingly costly.

Main results

- With exhaustible resources, environmental disaster could be averted without policy intervention because increasing prices of the scarce exhaustible resources could automatically redirect technological change.
- Nevertheless, optimal policy very similar with or without exhaustible resources.

Two-country case

- Two countries: North (N), identical to the economy studied so far, and that the South (S) imitating Northern technologies.
- Thus there are two externalities:

1. *environmental externality*: dirty input productions by both contribute to global environmental degradation

$$S_{t+1} = -\xi \left(Y_{dt}^{N} + Y_{dt}^{S} \right) + (1+\delta) S_t \text{ for } S \in (0, \bar{S}).$$

2. *knowledge externality*: South imitates North' technologies $\Longrightarrow$ ratio of expected profits from imitation in the two sectors in the South

$$\frac{\Pi_{ct}^{S}}{\Pi_{dt}^{S}} = \frac{\kappa_c (p_{ct}^{S})^{\frac{1}{1-\alpha}} L_{ct}^{S} A_{ct}^{N}}{\kappa_d (p_{dt}^{S})^{\frac{1}{1-\alpha}} L_{dt}^{S} A_{dt}^{N}}$$

Main results

- Do we need global coordination to avert an environmental disasters?
  - In autarky, the answer is no because advances in the North will induce the South to also switch to clean technologies.
  - But free trade may undermine this result by creating **pollution havens**—the South can be encouraged to specialize even more in dirty technologies because of environmental policy in the north.

Modeling competition between clean and dirty technologies

- Now a more micro-based model of competition between clean and dirty technologies that can be estimated from firm-level data (for the energy sector in the United States) on
  - R&D expenditures,
  - patents,
  - sales,
  - employment,
  - firm entry and exit.
- Data sources:
  - Longitudinal Business Database and Economic Censuses,
  - the National Science Foundation's Survey of Industrial R&D,
  - the NBER Patent Database.
- Also, a more realistic model of the carbon cycle.
- This will allow more systematic counterfactual policy experiments.

Preferences

- Infinite-horizon economy in continuous time.
- Representative household:

$$U = \int_0^\infty \exp(-\rho t) \ln C_t dt.$$

- Inelastic labor supply, no occupational choice:
  - Unskilled labor: for production: measure 1, earns w_t^u
  - Skilled labor: measure L^s, earns w_t^s.
    - cover fixed and variable costs of R&D.
- Hence the budget constraint is

$$C_t \leq w_t^u + L^s \cdot w_t^s + \Pi_t$$

- Closed economy and no investment, resource constraint: $Y_t = C_t$.

Final Good Technology

- Unique final good Y_t :

$$\ln Y_t = -\gamma\left(S_t - \bar{S}\right) + \int_0^1 \ln y_{it}\, di,$$

y_{it} : quantity of intermediate good i.

$S_t \geq \bar{S}$: atmospheric carbon concentration.

$\bar{S} > 0$: preindustrial level.

Intermediate Good Technology (I)

- Intermediate good y_{it}:

$$y_{it} = \begin{cases} y_{it}^{c} & \text{with **clean** technology, or} \\ y_{it}^{d} & \text{with **dirty** technology} \end{cases}$$

Intermediate Good Technology (II)

- Firm f can produce intermediate i with either a clean or dirty, $j \in \{c, d\}$:

$$y_{it}^{j}(f) = q_{it}^{j}(f)\, l_{it}^{j}(f)$$

  - $l_{it}^{j}(f)$: production workers
  - $q_{it}^{j}(f)$: labor productivity.

- marginal cost of production is

$$MC_{it}^{j} = \left(1 + \tau_{t}^{j}\right) \frac{w_{t}^{u}}{q_{it}^{j}}$$

where τ_{t}^{j} is the tax rate on technology j.

Intermediate Good Technology (III)

- Produce with technology $j \in \{c, d\}$ if

$$\frac{\left(1+\tau_t^{-j}\right) w_t^u}{q_{it}^{-j}} > \frac{\left(1+\tau_t^{j}\right) w_t^u}{q_{it}^{j}}$$

- i.e., produce with **dirty** technology iff

$$\frac{q_{it}^d}{q_{it}^c} > \frac{1+\tau_t^d}{1+\tau_t^c}.$$

Quality Ladder

- Innovations improve quality by multiples of $\lambda > 1$.
- n_{it}^{j} improvements leads to

$$q_{it}^{j} = \lambda^{n_{it}^{j}},$$

  where $q_{i0}^{j} = 1$.
- Hence

$$\frac{q_{it}^{d}}{q_{it}^{c}} = \lambda^{n_{it}}$$

  $n_{it} \equiv n_{it}^{d} - n_{it}^{c}$.
- Define μ_n : fraction of n-step industries.

Carbon Tax

- For tractability, tax rates are:

$$1 + \tau_t^j = \lambda^{m_t^j}.$$

- Hence:

$$\frac{1 + \tau_t^d}{1 + \tau_t^c} = \lambda^{m_t},$$

where $m_t \equiv m_t^d - m_t^c$.

Production Decision

- Produce with technology $j = dirty$ if

$$\frac{q_{it}^{d}}{q_{it}^{c}} > \frac{1+\tau_t^{d}}{1+\tau_t^{c}}$$

- $\iff$

$$\lambda^{n_{it}} > \lambda^{m_{it}}$$

- $\iff$

$$n_{it} > m_t .$$

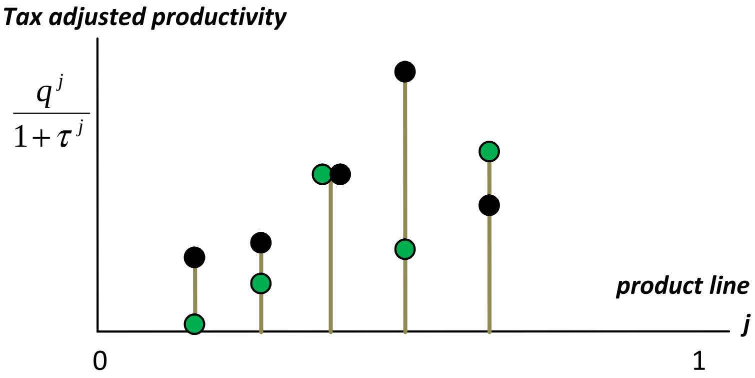
Production Decision

- Alternatively, produce with technology $j = dirty$ if:

$$\frac{q_{it}^{d}}{q_{it}^{c}} > \frac{1+\tau_t^d}{1+\tau_t^c} \iff \frac{q_{it}^{d}}{1+\tau_t^d} > \frac{q_{it}^{c}}{1+\tau_t^c}$$

i.e., compare tax-adjusted productivities.

Innovation, the Quality Ladder and Dynamics



Firms and R&D (I)

- Firm f: collection of leading-edge technologies (Klette & Kortum, 2004).
- u^j_{ft} : # of leading-edge technologies.
- Poisson flow rate of X^j_t innovations:

$$X^j_t = \theta \left(H^j_t \right)^{\eta} \left(u^j_t \right)^{1-\eta},$$

  - H^j_t : number of scientists
  - $\eta \in (0, 1)$, and $\theta > 0$.
- Fixed R&D cost of $u_t F_l$ scientists for operation.

Firms and R&D (II)

- Total cost:

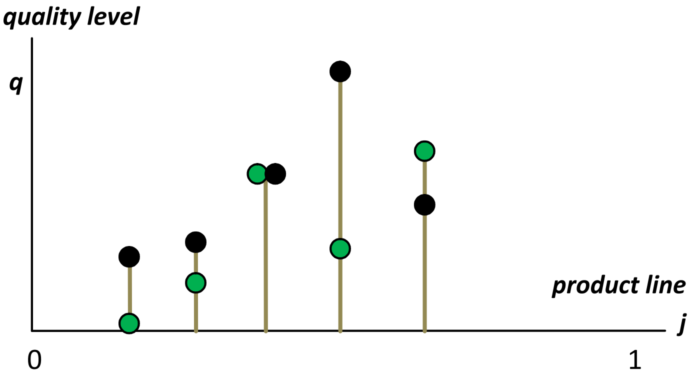
$$C_t\left(u_t, x_t^j\right) = \left(1 - s_{It}^j\right) w_t^s u_t \left[\left(x_t^j\right)^{\frac{1}{\eta}} \theta^{-\frac{1}{\eta}} + F_I\right],$$

$x_t^j \equiv X_t^j / u_t^j$: innovation intensity.
s_{It}^j : government subsidy.

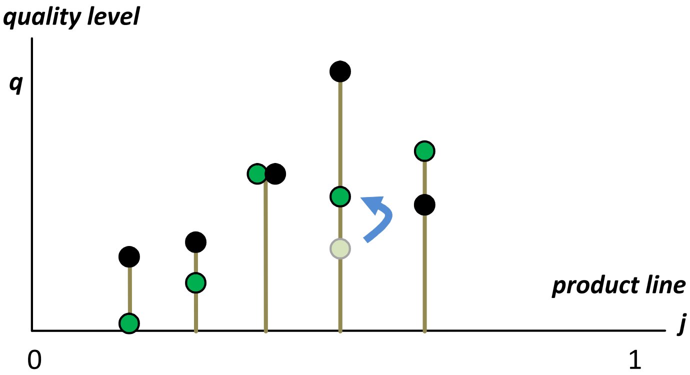
Firms and R&D (III)

- Innovations are *directed* across technologies,
- yet *undirected* within technologies.
- A successful innovation
  - adds a new product line to the firm's portfolio, and
  - leads to one of two types of innovation:
    1. *incremental* with probability $1-\alpha$
    2. *breakthrough* with probability α.
- incremental innovation improves quality by $\lambda > 1$.
- breakthrough makes the firm leapfrog the frontier technology.

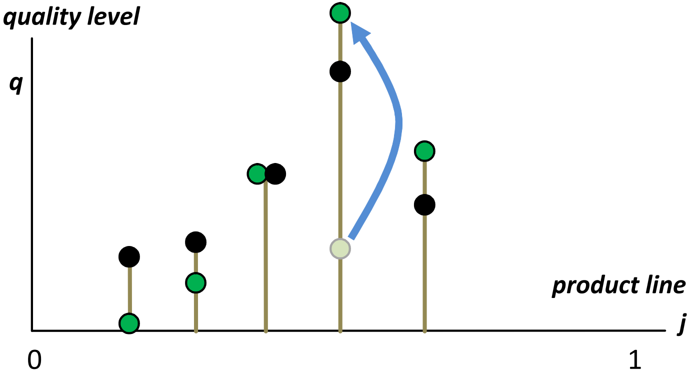
Innovation, the Quality Ladder and Dynamics



Incremental Innovation



Radical Innovation



Free Entry

- Endogenously determined mass of entrants E_t^j invests in R&D by paying fixed cost F_E and the variable cost $\left(X_{Et}^j\right)^{\frac{1}{\eta}} \theta^{-\frac{1}{\eta}}$ in terms of skilled labor and enter at the rate X_{Et}^j.

The Carbon Cycle (I)

- Dirty production y_{it}^d emits κ units of carbon per intermediate output:

$$K_t = \int_0^1 \kappa y_{it}^d di,$$

  - K_t : total amount of carbon emission at time t

The Carbon Cycle (II)

- The atmospheric carbon concentration S_t is (Golosov et al., 2011)

$$S_t = \int_0^{t-T} (1 - d_l) K_{t-l} dl, \tag{2}$$

  - where the amount of carbon emitted l years ago still left in the atmosphere is:

$$d_l = (1 - \varphi_P) \left[1 - \varphi_0 e^{-\varphi l} \right]$$

  - $\varphi_P \in (0, 1)$: share of permanent emission
  - $(1 - \varphi_P) \varphi_0$: transitory component that remains in the first period
  - $\varphi \in (0, 1)$: the rate of decay of carbon concentration over time.

Equilibrium Profits (I)

- Unit elastic demand. Thus the profits are

$$
\begin{array}{llll}
\pi_{it}^{c} = \tilde{Y}_t \frac{\lambda-1}{\lambda} & \pi_{it}^{d} = 0 & \text{if} & m_{it} > n_{it} \\
\pi_{it}^{c} = 0 & \pi_{it}^{d} = \tilde{Y}_t \frac{\lambda-1}{\lambda} & \text{if} & m_{it} < n_{it} \\
\pi_{it}^{c} = 0 & \pi_{it}^{d} = 0 & \text{if} & m_{it} = n_{it}
\end{array}
$$

where $\tilde{Y}_t \equiv Y_t \exp\left(\gamma\left(S_t - \bar{S}\right)\right)$ is net aggregate output.

Equilibrium Profits (II)

- Not every successful innovation leads to profitable production for two reasons:
  1. innovation occurs in technology j which is behind technology $-j$,
  2. potential zero markup if the tax-adjusted labor productivities are the same with the two technologies.
- Probabilities of positive return to a successful innovation:

$$\Gamma_t^c \equiv \sum_{n\leq m} \mu_{nt} + \alpha \left(1 - \sum_{n\leq m} \mu_{nt}\right) \mathbb{I}_{(m\geq 0)}$$
$$\Gamma_t^d \equiv \sum_{n\geq m} \mu_{nt} + \alpha \left(1 - \sum_{n\geq m} \mu_{nt}\right) \mathbb{I}_{(m\leq 0)}$$

Equilibrium Innovation Decision (I)

- For expositional clarity , assume that firms maximize instantaneous profits (i.e., "**myopic**").
- Full model will relax this assumption.
- Define the expected value of a successful innovation as

$$\bar{v}_t^j = \Gamma_t^j \pi_{it}^j$$

- Thus equilibrium incumbent innovation decision for $j \in \{c, d\}$:

$$\max_{X_t^j \geq 0} \left\{ X_t^j \bar{v}_t^j - \left(1 - s_{It}^j\right) w_t^s \left[\left(X_t^j\right)^{\frac{1}{\eta}} \theta^{-\frac{1}{\eta}} \left(u_t^j\right)^{\frac{\eta-1}{\eta}} + \mathbb{I}_{\left(X_t^j > 0\right)} u_t^j F_I \right] \right\}$$

Equilibrium Innovation Decision (II)

- Conditional on investing in R&D, the equilibrium innovation rate is

$$x_{It}^{j} = \left(\frac{\bar{v}_t^j \eta \theta^{\frac{1}{\eta}}}{\left(1 - s_{It}^j\right) w_t^s} \right)^{\frac{\eta}{1-\eta}} = \left(\Gamma_t^j \frac{\lambda - 1}{\lambda} \tilde{Y}_t \frac{\eta \theta^{\frac{1}{\eta}}}{w_t^s \left(1 - s_{It}^j\right)} \right)^{\frac{\eta}{1-\eta}}.$$

  Similar for entrant innovation. Increasing in:
  - Higher net output $\left(\tilde{Y}_t\right)$,
  - higher markups (λ)
  - lower scientists wages (w_t^s)
  - *policy:* subsidies to research increase clean innovation $\left(s_{It}^c\right)$.
- Through the Γ_t^j's,
  1. carbon taxes $\left(\tau^d\right)$ increase clean innovation (reduce dirty innovation).
  2. innovation is path-dependent:
     - large technology gaps $\Longrightarrow$ $\sum_{n \leq m} \mu_{nt}$ very small $\Longrightarrow$ Γ_t^c very small $\Longrightarrow$ discouraging clean innovation
     - Hence clean innovation will naturally self-reinforce over time.

Full model with forward-looking R&D decisions

- Generalizes to forward-looking firms.
- Value function of a firm with a vector of tech gaps $\vec{n}^j \equiv \left[n_1^j, \ldots, n_{u_t^j}^j \right]$:

$$
rV^j_{\vec{n}^j,t} - \dot{V}^j_{\vec{n}^j,t} =
\left\{
\begin{array}{c}
\sum_{i=1}^{u} \left[\begin{array}{c}
\pi^j_{n_i,t} + z^j_t \left(V^j_{\vec{n}^j_{-i}} - V^j_{\vec{n}^j,t} \right) \\
+ z^{-j}_t (1-\alpha) \left(V^j_{\vec{n}^j_{-i} \cup \left\{ n^j_i - 1 \right\},t} - V^j_{\vec{n}^j_i,t} \right) \\
+ z^{-j}_t \alpha \left(V^j_{\vec{n}^j_{-i},t} - V^j_{\vec{n}^j_i,t} \right)
\end{array} \right] \\
+ \int \max_{x^j_t \geq 0} \left[\begin{array}{c}
u^j_t x^j_t \left(V^j_{\vec{n}^j \cup \left\{ n^j_{u+1} \right\},t} - V^j_{\vec{n}^j,t} \right) - \\
\left(1 - s^j_{I,t} \right) u^j_t w^s_t \left(\left(x^j_t \right)^{\frac{1}{\eta}} \theta^{-\frac{1}{\eta}} + \mathbb{I}_{(x^d_{n,t} > 0)} F_{I,t} \right)
\end{array} \right] dF_{I,t}.
\end{array}
\right.
$$

Empirical Strategy

- The model has 14 parameters/variables to be determined:

$$\{\rho, \bar{S}, \gamma, \varphi, \varphi_0, \varphi_P, \kappa, L^s, \alpha, \eta, \theta, \lambda, F_I, F_E\} \text{ and } \{\mu_{n0}\}_{n=-\infty}^{\infty}$$

- Proceed in four steps:
  1. external calibration: $\rho, \bar{S}, \gamma, \varphi, \varphi_0, \varphi_P, \kappa$
  2. direct estimation from micro data: L^s, α, η.
  3. match patent data to generate initial distribution: μ_n
  4. simulated method of moments: $\theta, \lambda, F_I, F_E$

Data & Sample (I)

- Data:
  - Longitudinal Business Database and Economic Censuses,
  - National Science Foundation's Survey of Industrial R&D,
  - NBER Patent Database.
- Sample:
  - Innovators in the US Energy Sector
  - Build unbalanced panel with six periods: 1975-1979, . . . , 2000-2004
  - Firms must be innovative in first period observed
  - Collect operating data, R&D expenditures, and innovations by period

Data & Sample (II)

- Energy sector
  - start with the patent data,
  - classify patents into energy-related patents,
  - classify patents as dirty vs clean using 150,000 USPCs,
  - match patents to firms using name-location matching algorithm,
  - classify firms as dirty vs clean using their patent portfolio,
  - using 400 SIC3, construct dirty and clean patent stock.

Data & Sample (III)

- Sample properties
  - 6228 observations from 1576 firms
  - 19% of all U.S. R&D industrial expenditures
  - 70% of industrial patents for the energy sector

Parameters

PAR.	VALUE	TARGET
ρ	1% and 0.1%	Nordhaus and Stern
$\bar{S}$	581 GtC	Preindustrial carbon stock
γ	5.3×10^{-5} GtC^{-1}	$4^o C$ increase about 4-5% GDP drop
φ_P	20%	Permanent emission IPCC (2007)
φ }	0.006636	carbon's half life of 30 years
φ_0 }	0.4576	Evolution of carbon stock 1900-2000
L^s	5.5%	S&E workers in energy sector
η	45%	Reg R&D$ and Scientist count on SIC#
α	4%	prob of major entry patent (>90 percentile)
μ_n	see figure	patent stock count by SICs

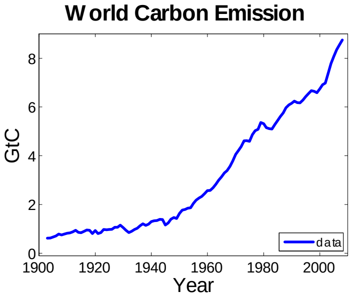
Carbon Cycle Match

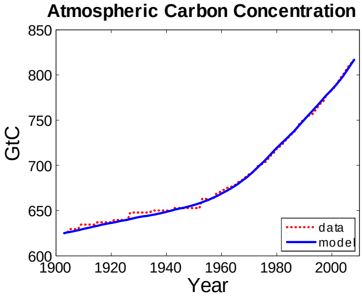
We use the following to match the carbon concentration:

$$S_t = \int_0^{t-1900} (1 - d_l) K_{t-l} dl + S_{1900}, \ \ t \in [1900, 2008] .$$

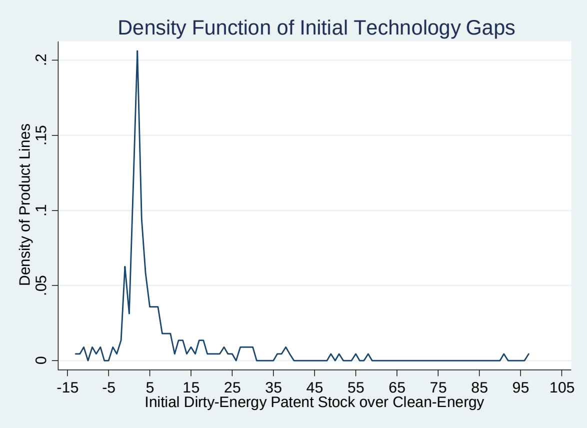
where

$$d_l = (1 - \varphi_P) \left[1 - \varphi_0 e^{-\varphi l}\right] .$$





Initial Distribution of Technology Gaps



Clean lead in 6%, and dirty lead in 60% of product lines, but in some cases by quite a lot.

Simulated Method of Moments Estimates

- Four parameters estimated from four moments (three from microdata and one aggregate):

Simulated Method of Moments		
Parameter	**Description**	**Value**
θ	Innovation productivity	0.500
λ	Innovation step size	1.075
F_I	Fixed cost of incumbent R&D	0.002
F_E	Fixed cost of entry	0.035

Moments in the Data and Model

Moment Matching		
Moments	**Model**	**Data**
Entry Share	0.013	0.013
Exit Rate	0.018	0.018
Average R&D/Sales	0.066	0.066
Aggregate Sales/Worker Growth	0.007	0.012

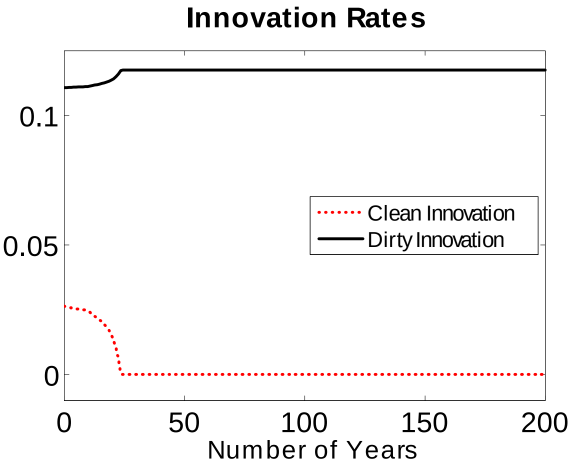
Non-targeted Moments

Comparison of Growth Distribution

Change over 5-Years:	Employment Growth Probability Model	Data
Decrease 75% or more	0.17	0.11
Decrease 50% or more	0.20	0.15
Decrease 25% or more	0.27	0.25
Increase 25% or more	0.24	0.31
Increase 50% or more	0.17	0.20
Increase 75% or more	0.15	0.14
Increase 100% or more	0.08	0.11

Notes: Table compares non-targeted moments in model and data.

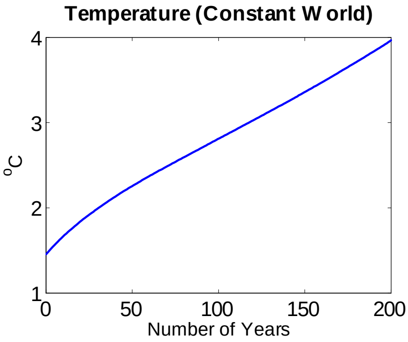
Climate Dynamics in the Laissez-faire Economy (I)



Climate Dynamics in the Laissez-faire Economy (II)

Formula to compute the temperature changes:

$$\Delta temperature = \frac{\lambda \left(\ln S_t - \ln \bar{S} \right)}{\ln 2}.$$



Optimal Policy (I)

- We consider two policies
  - Carbon tax: τ_t^d
    - multiples of the innovation step size $\lambda \implies 1 + \tau_t^d = \lambda^{m_t}$.
  - Clean R&D subsidy: s_t^c.
    - It is a continuous variable $s_t^c \in [0, 1]$.
    - Same subsidy rate for both entrants $\left(s_{Et}^c\right)$ and incumbents $\left(s_{It}^c\right)$.
- We use two baseline discount rates for social planner.
  - $\rho = 1\%$: similar to Nordhaus (1994, 2008).
  - $\rho = 0.1\%$: similar to Stern (2007)
- private discount rate is always 1%.

Optimal Policy (II)

- We consider two alternatives
  1. Constant policy: $\tau_t^d = \tau^d$ and $s_t^c = s^c$.
  2. Time-varying policy: 3 time cutoffs and 4 policy levels:

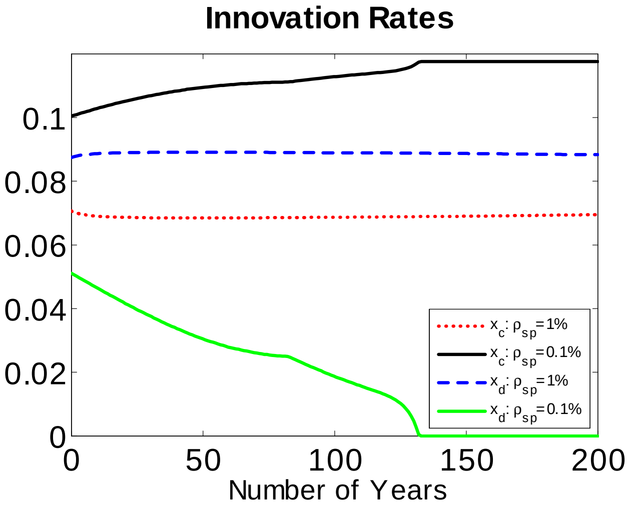
$$\tau_t^d = \begin{cases} \tau_1^d \text{ for } t \in [0, t_1^\tau) \\ \tau_2^d \text{ for } t \in [t_1^\tau, t_2^\tau) \\ \tau_3^d \text{ for } t \in [t_2^\tau, t_3^\tau) \\ \tau_4^d \text{ for } t \in [t_3^\tau, \infty) \end{cases} \text{ and } \left(\tau_t^d, s_t^c\right) = \begin{cases} s_1^c \text{ for } t \in [0, t_1^s) \\ s_2^c \text{ for } t \in [t_1^s, t_2^s) \\ s_3^c \text{ for } t \in [t_2^s, t_3^s) \\ s_4^c \text{ for } t \in [t_3^s, \infty) \end{cases}$$

Optimal Constant Policy (I)

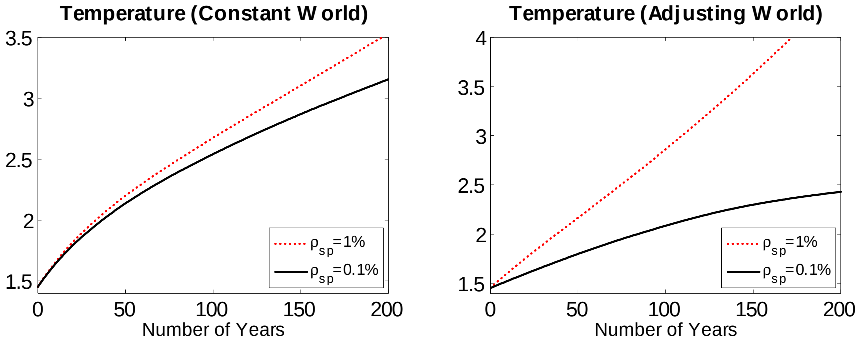
Optimal Constant Policy

	$\rho_{sp} = 1\%$	$\rho_{sp} = 0.1\%$
τ	16%	44%
s	61%	95%

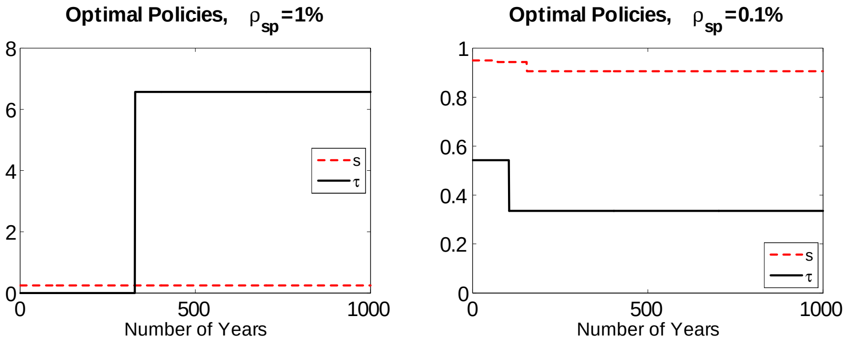
Optimal Constant Policy (II)



Optimal Constant Policy (III)



Optimal Time-Varying Policy (I)



Optimal Time-Varying Policy (II)

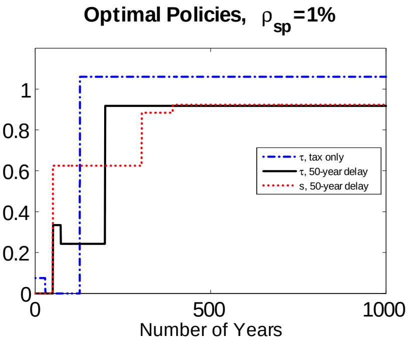
Welfare costs of Cons Pol relative to TV

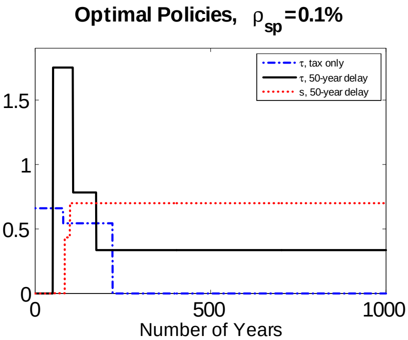
$\rho_{sp} = 1\%$	$\rho_{sp} = 0.1\%$
16%	0.3%

Counterfactual Policy Analysis (I)

- 3 counterfactual exercises:
  1. **Carbon tax only**: policymaker uses only time-varying carbon tax.
  2. **50 year delay**: policymaker plans to take action starting in 50 years with both time-varying policies.
  3. **Business as usual**: we keep the current policies in place forever.

Counterfactual Policy Analysis (II)





Counterfactual Policy Analysis (III)

WELFARE COSTS

Carbon Tax Only		50-year Delay	
$\rho_{sp} = 1\%$	$\rho_{sp} = 0.1\%$	$\rho_{sp} = 1\%$	$\rho_{sp} = 0.1\%$
4.2%	3.4%	8.0%	16.6 %

- Avoiding R&D subsidiy has a significant welfare cost.
- Delaying policy intervention is even worse, particularly for low discount rate.

Implications of US "Business-as-Usual" Policies (I)

- Estimate of current subsidy:
  - In our sample period of 30 years, 49% of clean R&D and 11% of dirty R&D is federally funded. We take the current subsidy as

$$1 - s = \frac{1 - 49\%}{1 - 11\%} \implies s = 43\%.$$

- Estimate of current carbon tax:
  - Policy makers estimate the social cost of carbon as $143 per ton of carbon dioxide.
  - Total emission is around 1.58 billion tons of carbon dioxide.
  - Total sales around $1 trillion.
  - Hence the estimated tax is

$$\tau = \frac{143 \times 1.58 \times 10^9}{10^{12}} \approx 24\%.$$

Implications of US "Business-as-Usual" Policies (II)

WELFARE COSTS

$\tau = 24\%,\ s = 43\%$		$\tau = 0,\ s = 43\%$	
$\rho_{sp} = 1\%$	$\rho_{sp} = 0.1\%$	$\rho_{sp} = 1\%$	$\rho_{sp} = 0.1\%$
18%	8%	100%	100%

- Too much carbon tax and too little R&D subsidy compared to optimal constant policy: $\tau^d = 16\%$ and $s^c = 61\%$.

Conclusion

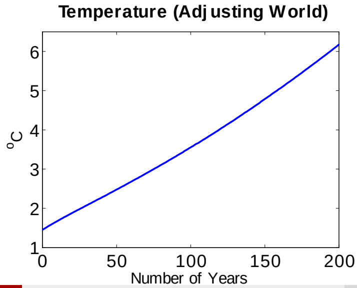
- Optimal policy in the presence of endogenous and directed technological change may rely heavily on R&D subsidy as well as carbon tax.
- Intuition:
  - carbon tax generates static distortion: Leads to reallocation into less productive technology $\Longrightarrow$ Loss of current consumption
  - R&D subsidy generates dynamic distortion: innovate without any growth for a while until clean takes over.
- Current policy estimates are overtaxing carbon and undersubsidizing R&D.
- Avoiding R&D subsidy has sizable welfare costs (3.4%-4.2%)
- Delaying policy intervention by 50 years has very large welfare costs (8%-16.6%)

Rest of the World?

- US emission is around 15% of the world emission.
- Foreign emission has no effect on policy rankings: $S_t = S_t^{Domestic} + S_t^{Foreign}$:

$$Y_t = e^{-\gamma\left(S_t^{Domestic}+S_t^{Foreign}-\bar{S}\right)} \exp\left(\int_0^1 \ln y_{it} di\right) \Longrightarrow$$

$$U_t = \ln C_t = -\gamma S_t^{Foreign} - \gamma\left(S_t^{Domestic} - \bar{S}\right) + \int_0^1 \ln y_{it} di$$



Are These Conclusions too Optimistic?

- Perhaps. Only more empirical work can tell.
- But things to watch out for:
  - Research subsidies may be ineffective→then more reliance on carbon tax
  - Research might be much lower→then more reliance on carbon tax
  - There is in practice a lot of uncertainty associated with new technologies→then more reliance on carbon tax
  - There may be less room for "building on the shoulders of giants'" in green technologies→then more reliance on carbon tax
  - Elasticity of substitution may be lower→then more reliance on carbon tax

If Technology Is so Powerful, Can We Afford Delay?