# 14.461: Technological Change, Lecture 9
# Climate Change and Technology

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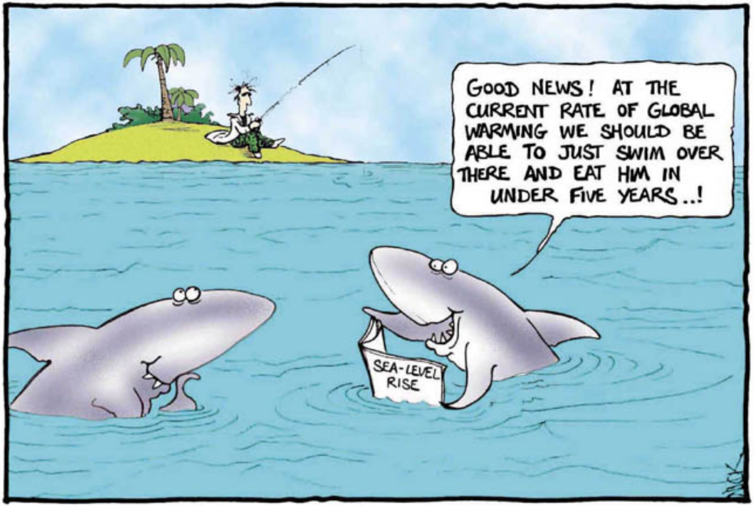
# Motivation (I)

- 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 a "welfare maximizing" way?

# 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 $S$:

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

- 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 $\eta_j$ 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**"—extreme state dependence.
    - 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 $\Pi_{jt}$:

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

  - The direct productivity effect pushes towards innovation in the more advanced sector
  - The price effect towards the less advanced, price effect stronger when $\varepsilon$ 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 $g_{Y_d} \to \gamma\eta_d$

# 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 $\varepsilon$.
- 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.
- More generally, significant welfare costs from delay (based on calibration).

# 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.**

*A 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 by lumpsum taxes).*

1. *If $\varepsilon > 1$ and the discount rate $\rho$ 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, $\tau_t$, is temporary if $\varepsilon > 1/(1-\alpha)$ but not if $1 < \varepsilon < 1/(1-\alpha)$.*

- Interpretation: two instruments for two margins—carbon tax for the intra-temporal one and research subsidies for the intertemporal one. But importantly, both are **temporary**.

# Carbon tax

- Optimal carbon tax schedule is given by

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

  - $\lambda_t$ is the marginal utility of a unit of consumption at time $t$
  - $\omega_{t+1}$ 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 $t+1$.
- *Why temporary?* If $\varepsilon > 1/(1-\alpha)$, dirty input production tends towards 0 and environmental quality $S_t$ reaches $\overline{S}$ in finite time and thus $\omega_t \to 0$, carbon tax becomes null in finite time.
- *Why two instruments?* 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.
- 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 specializes 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 $y_{it}$:

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

# 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 $\tau_t^{j}$ 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 $\mu_n$ : 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

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

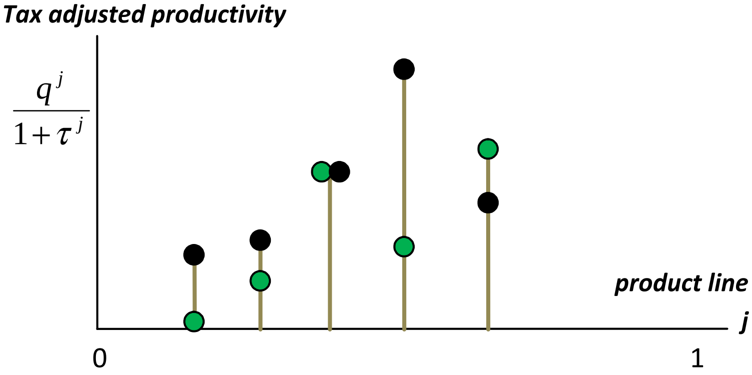
- $\Longleftrightarrow$

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

- $\Longleftrightarrow$

$$n_{it} > m_t.$$

# Innovation, the Quality Ladder and Dynamics



# Firms and R&D (I)

- Firm $f$: collection of leading-edge technologies (Klette & Kortum, 2004).
- $u_{ft}^{j}$ : # of leading-edge technologies.
- Poisson flow rate of $X_t^j$ innovations:

$$X_t^j = \theta \left( H_t^j \right)^{\eta} \left( u_t^j \right)^{1-\eta},$$

  - $H_t^j$ : 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:

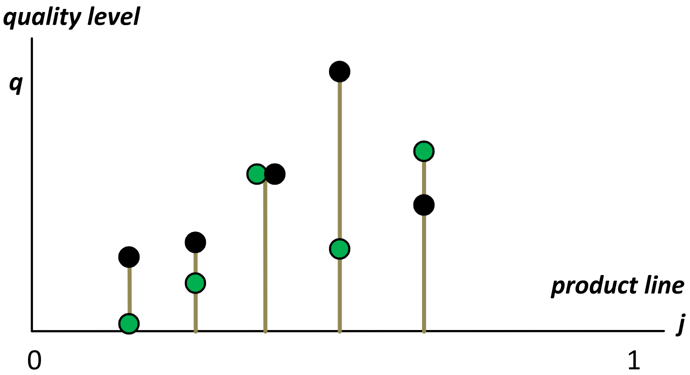
$$C_t\left(u_t, x_t^j\right) = \left(1 - s_{It}^j\right) w_t^s u_t \left[\left(x_t^j\right)^{\frac{1}{\eta}} \theta^{-\frac{1}{\eta}} + F_I\right],$$

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

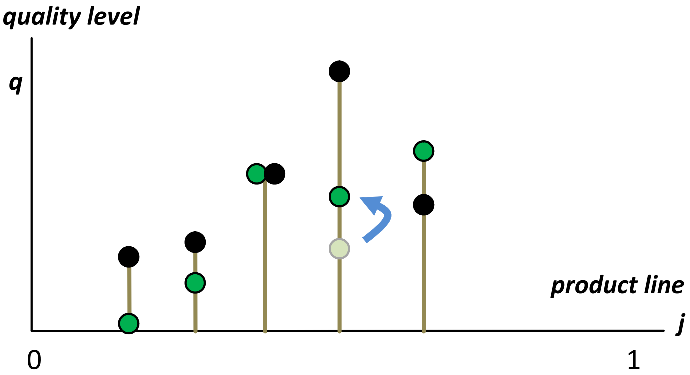
# Firms and R&D (III)

- 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 $\alpha$.
- incremental innovation improves quality by $\lambda > 1$.
- breakthrough makes the firm leapfrog the frontier technology.

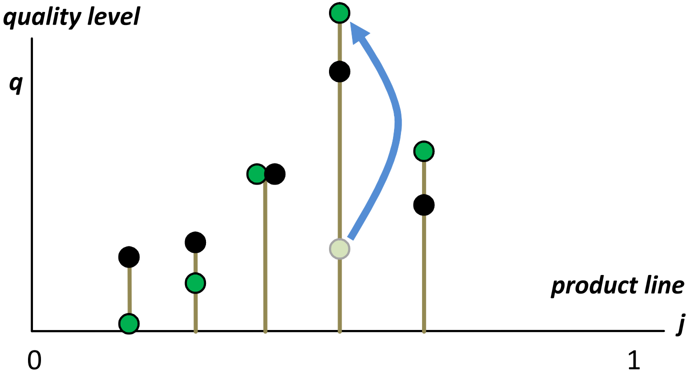
# Innovation, the Quality Ladder and Dynamics



# 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

- Dirty production $y_{it}^{d}$ emits $\kappa$ units of carbon per intermediate output, so total amount of carbon emission is

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

- 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:

$$\begin{aligned}\Gamma_t^c &\equiv \sum\nolimits_{n\leq m} \mu_{nt} + \alpha \left(1 - \sum\nolimits_{n\leq m} \mu_{nt}\right) \mathbb{I}_{(m\geq 0)} \\ \Gamma_t^d &\equiv \sum\nolimits_{n\geq m} \mu_{nt} + \alpha \left(1 - \sum\nolimits_{n\geq m} \mu_{nt}\right) \mathbb{I}_{(m\leq 0)}\end{aligned}$$

# Equilibrium Innovation Decision (I)

- Full model: forward-looking innovation decisions.
- Here, let us focus on the cases which firms are **myopic** and maximize instantaneous profits.
- 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 $(\lambda)$
  - lower scientists wages $(w_t^s)$
  - *policy:* subsidies to research increase clean innovation $\left(s_{It}^c\right)$.
- Through the $\Gamma_t^j$'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 $\Longrightarrow$ $\Gamma_t^c$ very small $\Longrightarrow$ discouraging clean innovation
     - Hence clean innovation will naturally self-reinforce over time.

# Empirical Strategy

- Focus on the model would forward-looking behavior.
- 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: $L^s, \alpha, \eta$.
  3. match patent data to generate initial distribution: $\mu_n$
  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

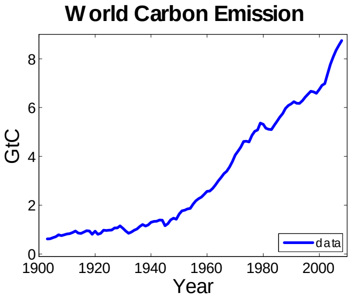
# Carbon Cycle Match

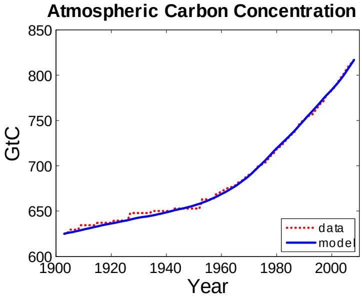
We use the following to match the carbon concentration:

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

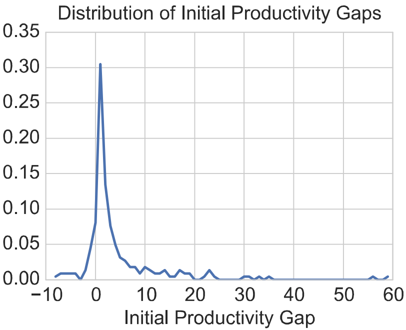
where

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



# Initial Distribution of Technology Gaps




Distribution of initial productivity gaps between clean and dirty technologies across product lines (a positive number indicates a lead for dirty technology)

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

Table 2. Parameter Estimates

| **Parameter** | **Value** | **Parameter** | **Value** |
|---|---|---|---|
| $\theta$ | 0.958 | $F_E$ | 0.040 |
| $\lambda$ | 1.063 | $R_0$ | 13549 |
| $F_I$ | 0.002 | $\zeta$ | 0.016 |

Note: This table presents the parameter estimates from SMM.

# Moments in the Data and Model

Table 3. Moment Matching

| **Moments** | **Model** | **Data** | **Moments** | **Model** | **Data** |
|---|---|---|---|---|---|
| Entry Share | 0.014 | 0.013 | Agg. Growth | 0.012 | 0.012 |
| Exit Rate | 0.032 | 0.018 | $\text{Emissions}_{2008}$ | 8.461 | 8.749 |
| R&D/Sales | 0.065 | 0.066 | $g_{Emissions}$ | 0.023 | 0.024 |

.

# Non-targeted Moments

TABLE 4A. ENTRANT SIZE RATIO TO INCUMBENTS

| | *Ratio of Median Sizes* | |
|---|---|---|
| **Size Measure:** | **Model** | **Data** |
| Employment | 0.18 | 0.03 |
| Sales | 0.18 | 0.20 |
| Sales per Employee | 1.13 | 1.05 |

Note: This table compares non-targeted moments in the model and the data.

# Non-targeted Moments (continued)

Table 4B. Comparison of Growth Distribution

| *Employment Growth Probability* | | | | | |
|---|---|---|---|---|---|
| **Change 5-Years** | **Model** | **Data** | **Change 5-Years** | **Model** | **Data** |
| Decrease 75% | 0.25 | 0.11 | Increase 25% | 0.26 | 0.31 |
| Decrease 50% | 0.30 | 0.15 | Increase 50% | 0.20 | 0.20 |
| Decrease 25% | 0.38 | 0.26 | Increase 75% | 0.17 | 0.14 |
| | | | Increase 100% | 0.10 | 0.11 |

Note: This table compares non-targeted moments in model and data.

# Climate Dynamics in the Laissez-faire Economy

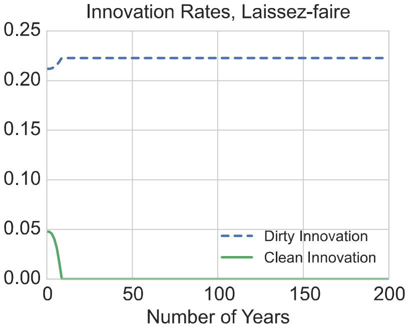



Figure 4. Innovation rates under laissez-faire.

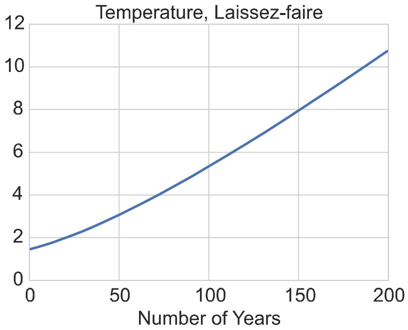



Figure 5. The time path of temperature increases under laissez-faire.

# Optimal Policy (I)

- Take a social discount rate of $\rho = 1\%$ (as in Nordhaus's analysis).

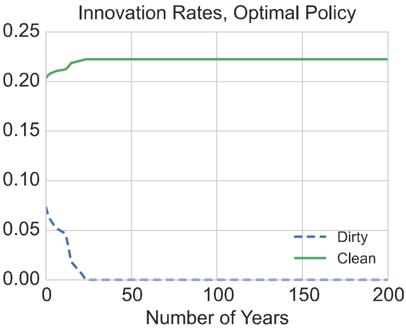



Figure 7. Innovation rates under optimal policies.

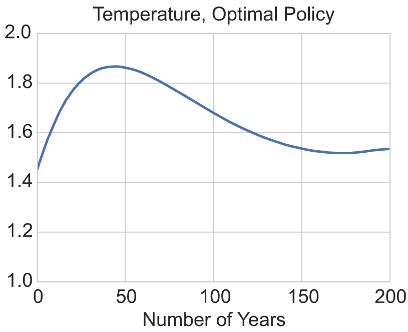



Figure 8. The time path of temperature increases under optimal policies.

# Optimal Policy (II)

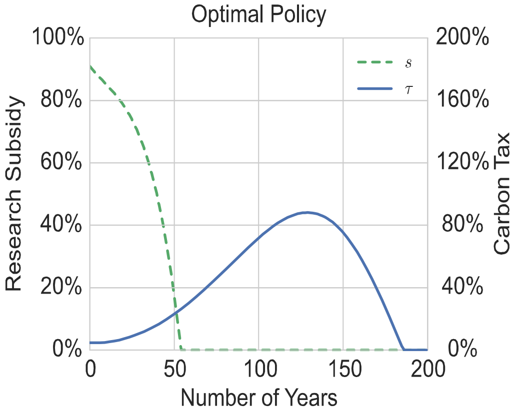



Figure 6. Optimal policies (carbon taxes and research subsidies).

# Counterfactual Policy Analysis (I)

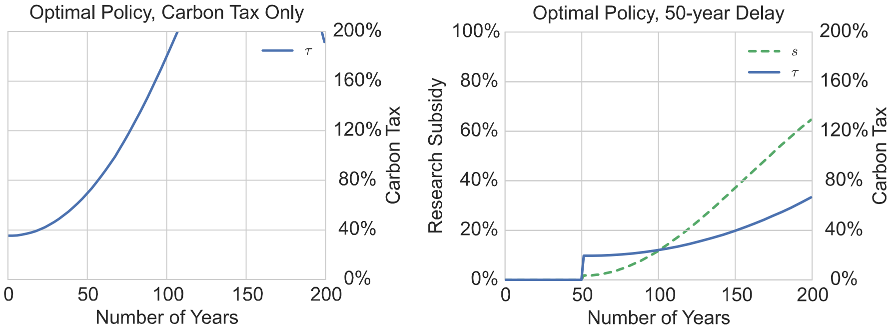
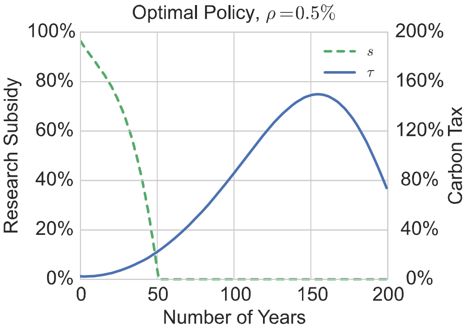



Figure 9. Constrained optimal policies following a 50-year delay and with only carbon taxes; both cost about 2% in terms of consumption



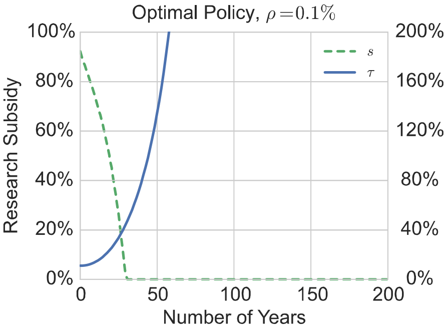




Figure 11. Optimal policies under a social discount rate of 0.5% and 0.1%.

# 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 can have sizable welfare costs.
- Delaying policy intervention by 50 years can also have very large welfare costs.