```julia
using Distributions, PlutoUI, Symbolics, Latexify, DataFrames,
    Plots, PlotThemes, ImageShow, ImageIO, FileIO
```

# Environmental Preferences and Technological Choices: Is Market Competition Clean or Dirty?

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# Abstract

We investigate the effects of consumers' environmental concerns and market competition on firms' decisions to innovate in "clean" technologies. Agents care about their consumption and environmental footprint; firms pursue greener products to soften price competition. Acting as complements, these forces determine R&D, pollution, and welfare. We test the theory using panel data on patents by 8,562 automobile-sector firms in 41 countries, environmental willingness-topay, and competition. As predicted, **exposure to prosocial attitudes fosters clean innovation, all the more so where competition is strong**. Plausible increases in both together can spur it as much as a large fuel-price increase.

# Exploring the theoretical model

$[t,\ y,\ k_f,\ \gamma,\ \delta,\ c,\ z,\ \kappa]$

```
@variables t y k_f γ δ c z κ # declare some variables
```

- time t, output y, cumulative investments $k_f$
- consumer environmental preferences δ
- size of a leading-edge environmental innovation γ
- marginal cost of labor $c$
- $z$ the investment flow per period = the probability of successful innovation
- κ some measure of ideas/managerial capacity that makes innovation more costly

# Variable definitions

**Emissions**: The production or consumption of one unit of good with environmental quality $q$ generates $x = 1/q$ units of polluting emissions.

**Quality** for a firm $f$ that has the cumulative number of investments $k_f \in N$ is given by:

$$\gamma^{k_f}$$

Firms choose to invest or not in each period. In any period, firms can copy the other firm's *previous* technologies. Let's assume a duopoly with firms A and B.

Then, in any period $t$, the maximum of $|k_A - k_B|$ must be less than or equal to 1. Since, if it was greater than 1, one of the firms could have copied a better technology than the one it has.

## How does quality change with a change in $\gamma$ or $k_f$?

We can differentiate this function wrt. to $\gamma$ or $k_f$ to see how changes in preferences or cumulative investments affect quality

```
q_f′(a) = Symbolics.derivative(q_f((γ, k_f)), a; simplify = true);
```

$$\gamma^{k_f} \log\left(\gamma\right)$$

```
q_f′(k_f)
```

$$\gamma^{-1+k_f} k_f$$

```
q_f′(γ)
```

So we see that

$\frac{\delta q_f}{\delta k_f} = \gamma^{k_f} \log\left(\gamma\right)$, and $\frac{\delta q_f}{\delta \gamma} = \gamma^{(k_f - 1)} k_f$, which are both greater than 0.

## Costs

To produce *1 unit of quality-adjusted output*, a firm must use the following units of labor (with wage normalized to 1):

> Note that we assume **labor** is the only input.

$$\gamma^{-k_f \delta} c$$

```
L((c, γ, k_f, δ))
```

`dLdk_f =`

$$\left( -\gamma^{-k_f \delta} c \delta \log\left(\gamma\right) < 0 \right)$$

# How do consumers value product quantity & quality?

With $y$ being the quantity produced and $q$ the quality of the product, consumers value a quantity-quality combination of that product at $yq^{\delta}$.

Revenue per sector is normalized to 1.

```
u_i((y,a)) = y * q_f((γ, (k_f+a) * δ));
```

# The choice to invest

For any $z \leq 1$, investing $\kappa z^2/2$ units of labor leads to a probability $z$ of inventing a technology that is $\gamma$ times cleaner; and a $1 - z$ probability of no progress. This means that investing z leads to quality:

$$\gamma^{1+k_f} z + \gamma^{k_f} (1 - z)$$

$$\gamma^{k_f} z (1 + k_f) + \gamma^{-1+k_f} k_f (1 - z)$$

```
Invest′(γ) # quality is increasing in the size of the leading-edge innovation γ
```

$$\gamma^{1+k_f} z \log(\gamma) + \gamma^{k_f}(1-z)\log(\gamma)$$

```
Invest′(k_f)
```

# Consider an oligopoly with firms A and B.

And consider an *unleveled sector* where, for example, $k_A = k_B + 1$ which means that firm A has invested $\kappa z^2/2$ units of labor to produce a technology that is $\gamma$ times cleaner.

Now, firm A has a product that is more valued by consumers.

Since we know that consumers value firm A's good at $yq^\delta = y\gamma^{\delta(k_A)}$, that firm A can capture all demand (by assumption), and that the firm has cost $c$, it can engage in *limit pricing* because it has the following quality advantage over firm B:

$$\left(\frac{\gamma^{1+k_f}}{\gamma^{k_f}}\right)^\delta$$

```
(q_f((γ, k_f + 1))/q_f((γ, k_f)))^δ
```

> Note that this quality advantage just equals $\gamma^\delta$.

## Limit pricing

The firm with the lowest price/quality ratio gets all demand and, because of competitive pressure, chooses price so that entry is not profitable. Since it has quality advantage $\gamma^\delta$ compared to its competitor, it can engage in *limit pricing* and choose the monopoly price:

```
pᴹ =
```

$$\gamma^\delta c$$

Demand is:

```
yᴹ =
```

$$\frac{1}{\gamma^\delta c}$$

Profits are:

```
πᴹ =
```

$$\frac{-c+\gamma^{\delta}c}{\gamma^{\delta}c}$$

```
πᴹ = yᴹ*(pᴹ - c)
```

$$\frac{\gamma^{-1+\delta}\delta}{\gamma^{2\delta}}$$

```
dπᴹd(γ) |> simplify
# profits are increasing in γ, the size of the leading-edge environmental innovation
```

$$\frac{\gamma^{\delta}\log\left(\gamma\right)}{\gamma^{2\delta}}$$

```
dπᴹd(δ) |> simplify
# and profits are increasing in consumer preferences for green technologies
```

# Level of competition

$\Delta$ is a measure of the level of competition between the two firms. A higher $\Delta$ implies that each firm's profit when in a duopolistic market is approaching zero (as $\Delta \to 1$, then $\pi_D \to 0$. And conversely, as $\Delta$ approaches $\frac{1}{2}$, then the two firms become closer to splitting evenly the monopoly profits, which indicates perfect collusion (lack of competition).

```
π_D(Δ) = (1 - Δ) * πᴹ;
```

```
p(Δ) = c / (1 - 2*π_D(Δ));
```

```
output(Δ) = 1/p(Δ);
```

Duopoly **profits** | Δ =

$$\frac{\left(1-\Delta\right)\left(-1.0+\gamma^{\delta}\right)}{\gamma^{\delta}}$$

Duopoly **price** | Δ:

$$\frac{\gamma^{\delta}c}{2.0-\gamma^{\delta}-2.0\Delta+2.0\gamma^{\delta}\Delta}$$

Duopoly **output** | Δ:

$$\frac{2.0 - \gamma^{\delta} - 2.0\Delta + 2.0\gamma^{\delta}\Delta}{\gamma^{\delta}c}$$

# Escaping competition through clean innovation

When the sector is *leveled* – when $k_A = k_B$ – only one of the two firms is given the opportunity to innovate in each period. $\forall z$ s.t. $0 \leq z \leq 1$, the cost of innovation is $\kappa z^2/2$ and leads to monopoly profits with probability $z$.

So, the firm solves the following maximization problem:

$\max_{z\in[0,1]}\{z\pi^M + (1-z)\pi_D(\Delta) - \kappa z^2/2\}$

Let's let Julia solve this for us:

dπdz =

$$\frac{-c+\gamma^{\delta}c}{\gamma^{\delta}c} + \frac{-(1-\Delta)\left(-c+\gamma^{\delta}c\right)}{\gamma^{\delta}c} - z\kappa$$

Notice that the optimal z, denoted by $\hat{z}$, is just the difference in a firm's monopoly profit and duopoly profit divided by $\kappa$, but can never exceed 1.

ẑ =

$$\frac{\frac{-c+\gamma^{\delta}c}{\gamma^{\delta}c} + \frac{-(1-\Delta)\left(-c+\gamma^{\delta}c\right)}{\gamma^{\delta}c}}{\kappa}$$

```
ẑ = Symbolics.solve_for(dπdz ~ 0, z)
```

Simplifying, we can see that $\hat{z}$ can be written as:

$$\frac{\gamma^{2\delta}\Delta - \gamma^{\delta}\Delta}{\gamma^{2\delta}\kappa}$$

```
ẑ |> simplify
```

```
I(Δ) = Δ*πᴹ/κ # define investment flow
# the investment flow per period is just z(Δ);
```

# Aggregate flow of investments per period

The flow of investments per period is just the proportion of sectors where innovation will occur:

$$\frac{-\Delta + \gamma^{\delta}\Delta}{\gamma^{\delta}\kappa}$$

```
I(Δ) |> expand |> simplify
```

```
I′(a) = Symbolics.derivative(I(Δ), a) # make a function to take the derivative of I(Δ);
```

# Per-period investment is increasing in Δ and δ

## and the two forces *complement each other*

> Recall that Δ is the measure of the level of competition, and δ is a measure of the strength of consumers' social-responsibility concerns

`dIdΔ =`

$$\left(\frac{-1.0 + \gamma^{\delta}}{\gamma^{\delta}\kappa} > 0\right)$$

`dIdδ =`

$$\left(\frac{\gamma^{\delta}\Delta \log\left(\gamma\right)}{\gamma^{2\delta}\kappa} > 0\right)$$

`d²IdδdΔ =`

$$\left(\frac{\log\left(\gamma\right)}{\gamma^{\delta}\kappa} > 0\right)$$

```
@variables Δ;
```

## Interpretation

The above equations show that **more competition** as well as **stronger preferences for green technologies** each increase the level of investment in such technologies and therefore the level of innovation.

> But how do the two influence the levels of *pollution* and *welfare*?

# Pollution and welfare

Total emissions normalized by total expenditure are given by:

$$[1 - I(\Delta)]y(\Delta) + I(\Delta)y^M/\gamma$$

```
X (generic function with 1 method)
```

```
X(Δ) = (1 - I(Δ))*output(Δ) + I(Δ)*yᴹ/γ
```

```
X′(a) = Symbolics.derivative(X(Δ), a); # the derivative of total emission w.r.t variable a (input by user)
```

$$\frac{-c+\gamma^{\delta}c}{\gamma^{2\delta}c^{2}\gamma\kappa} + \frac{\frac{\left(1+\frac{-\Delta\left(-c+\gamma^{\delta}c\right)}{\gamma^{\delta}c\kappa}\right)\left(-2c+2\gamma^{\delta}c\right)}{\gamma^{\delta}c} + \frac{\left(1+\frac{-2(1-\Delta)\left(-c+\gamma^{\delta}c\right)}{\gamma^{\delta}c}\right)\left(c-\gamma^{\delta}c\right)}{\gamma^{\delta}c\kappa}}{c}$$

```
X′(Δ)
```

$$\frac{\left(1+\frac{-\Delta\left(-c+\gamma^{\delta}c\right)}{\gamma^{\delta}c\kappa}\right)\left(\left(-2+2\Delta\right)\log\left(\gamma\right) - \gamma^{\delta}c\frac{-2(1-\Delta)\left(-c+\gamma^{\delta}c\right)}{\gamma^{2\delta}c^{2}}\log\left(\gamma\right)\right) + \left(1+\frac{-2(1-\Delta)\left(-c+\gamma^{\delta}c\right)}{\gamma^{\delta}c}\right.}{c}$$

```
X′(δ)
```

The equations here get quite messy, so an immediate interpretation is not very obvious. Let's see if we can play around with some parameters to see how the level of emmissions changes with a change in competition, for example.

# Competition and its effects

By increasing competition in *leveled sectors*, those in which firms are neck-and-neck, competition increases pollution.

> As competition increases, $\uparrow \Delta \implies \downarrow$ prices, $\uparrow$ output $\implies \uparrow$ pollution since more goods are consumed.

**But**, the fear of lower profits gives firms a high incentive to invest in R&D, which means that the probability of successful innovation $z$ is higher. When these successful innovations occur, emissions are reduced.

The way that emissions and welfare change depends on the level of $\kappa$.

κ₁ =

$$\frac{-c+\gamma^{\delta}c}{\gamma^{\delta}c}$$

κ₂ =

$$1-\frac{1}{2}\gamma^{-\delta}\left(1+\frac{1}{\gamma}\right)$$

$$\left(1-\frac{1}{2}\gamma^{-\delta}\left(1+\frac{1}{\gamma}\right) > \frac{-c+\gamma^{\delta}c}{\gamma^{\delta}c}\right)$$

- κ₂ > κ₁

# How do emissions change based on changes in:

- κ, the measure of (lack of) ideas/managerial capacity that makes innovation more costly?
- Marginal cost c?
- Level of competition Δ?
- Consumer preferences for green technology δ?
- The size of the leading-edge environmental innovation γ?

Remember that $\gamma > 1$ and $\delta > 1 \implies c < \gamma^{\delta}c$

## Visualizing the model

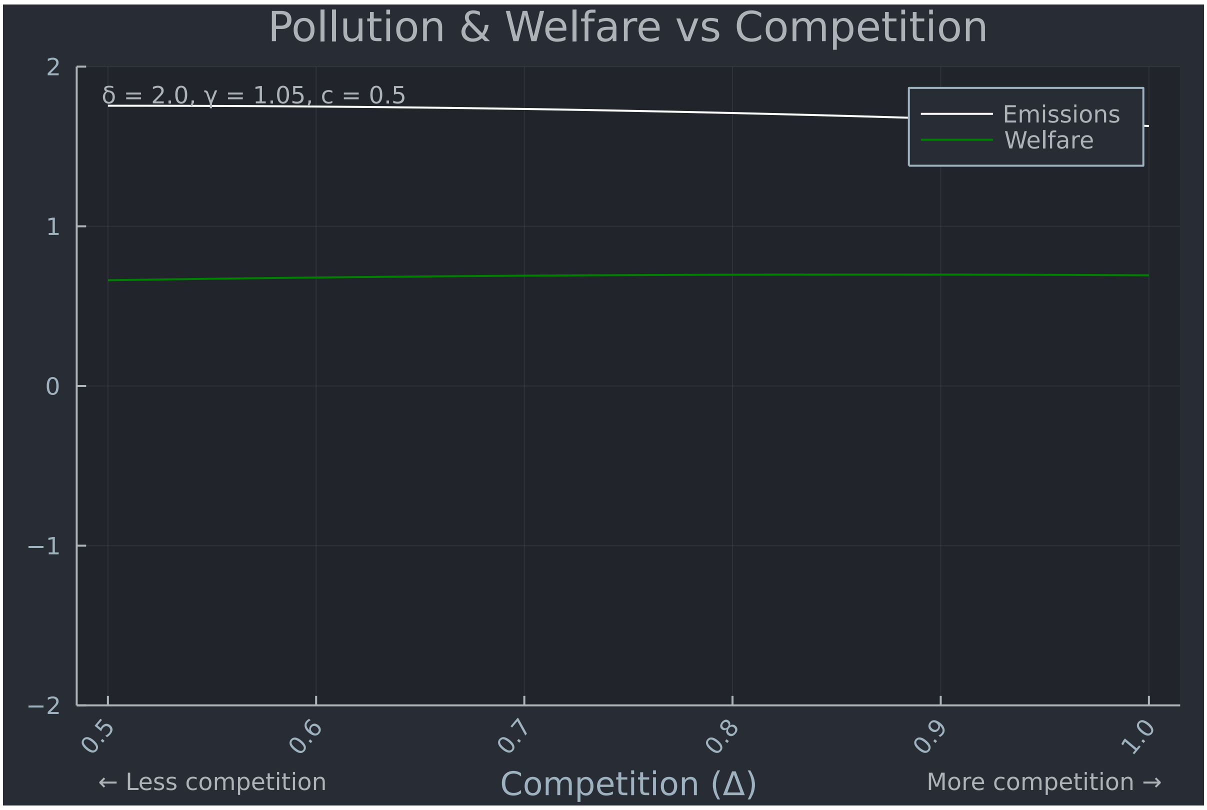
Marginal cost of production c = 0.5

Size of leading-edge innovation γ = 1.05

Consumer preferences for greener technology δ = 2.0

The cost of innovating κ =

1 + ((1//2)*c - (1//2)*c*(γ^δ)) / (c*(γ^δ)) - (1//2)*(γ^(-δ))*(1 + 1 / γ)




Adjust the limits of the y axis below ↓:

```
Main.PlutoRunner.Bond[
    1: -2
    2: 2
]
```

**Delta** = 0.75

Assuming that $\delta = 2.0$, $\gamma = 1.05$, $c = 0.5$, $\Delta = 0.75$, and $\kappa = 1 + ((1//2)*c - (1//2)*c*(\gamma\wedge\delta)) / (c*(\gamma\wedge\delta)) - (1//2)*(\gamma\wedge(-\delta))*(1 + 1 / \gamma)$, then:

## Emissions 1.7233

## Welfare: 0.6943

By tweaking the model, we can see the main results of the paper:

### Proposition 2

- for $\kappa < \kappa_2 - \kappa_1/2$, aggregate pollution $X(\Delta)$ decreases monotonically;
- for $\kappa > \kappa_2 - \kappa_1/2$, $X(\Delta)$ increases monotonically
- for $\kappa \in (\kappa_2 - \kappa_1/2, \kappa_2 + \kappa_1/2)$, $X(\Delta)$ is hump-shaped; moreover, it is minimized at $\Delta = 1$ (versus $\Delta = 1/2$) if and only if $\kappa < \kappa_2$;
- for all $\kappa \in [\kappa_1, \kappa_2]$, $X(\Delta)$ is minimized at $\Delta = 1$.

---

### Proposition 3

- Aggregate pollution $X(\Delta)$ decreases with consumer's social-responsibility concern $\delta$.

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### Proposition 4

- For $\kappa \in [\kappa_1, \kappa_2 - \kappa_1/2]$, social welfare $W$ increases monotonically with competition $\Delta$.

# Social welfare

U =

$$\left(1 + \frac{-\Delta\left(-c + \gamma^{\delta}c\right)}{\gamma^{\delta}c\kappa}\right)\log\left(\frac{1 + \frac{-2(1-\Delta)\left(-c+\gamma^{\delta}c\right)}{\gamma^{\delta}c}}{c}\right) + \frac{\Delta\left(-c + \gamma^{\delta}c\right)\log\left(\frac{\gamma^{\delta}}{\gamma^{\delta}c}\right)}{\gamma^{\delta}c\kappa}$$

```
U = (1 - I(Δ))*log(output(Δ)) + I(Δ)*log(γ^δ * yᴹ)
```

$$\frac{\left(c - \gamma^{\delta}c\right)\log\left(\frac{1+\frac{-2(1-\Delta)\left(-c+\gamma^{\delta}c\right)}{\gamma^{\delta}c}}{c}\right)}{\gamma^{\delta}c\kappa} + \frac{\left(-c + \gamma^{\delta}c\right)\log\left(\frac{\gamma^{\delta}}{\gamma^{\delta}c}\right)}{\gamma^{\delta}c\kappa} + \frac{\frac{\left(1+\frac{-\Delta\left(-c+\gamma^{\delta}c\right)}{\gamma^{\delta}c\kappa}\right)\left(-2c+2\gamma^{\delta}c\right)}{\frac{1+\frac{-2(1-\Delta)\left(-c+\gamma^{\delta}c\right)}{\gamma^{\delta}c}}{c}}}{\gamma^{\delta}c^{2}}$$

```
Symbolics.derivative(U, Δ)
```