Induced Innovation and International Environmental Agreements

Evidence from the Ozone Regime

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Motivations

- Global collective action problems
  - Some of the most pressing issues facing humanity
  - Progress has been limited (e.g., climate change, biodiversity...)
- There is one shining exception: the fight against ozone depletion
  - Ozone depletion caused by industrial gases: CFCs
  - Montreal Protocol negotiated in 1987
  - Stratospheric ozone on the recovery
- What role did science and innovation play in the ozone crisis?
  - Did the agreement induce innovation?
  - No quantitative analysis available until now
- Understanding how we can induce green innovations in the context of global collective action is critical
  - Because better technology is what leads to lower emissions

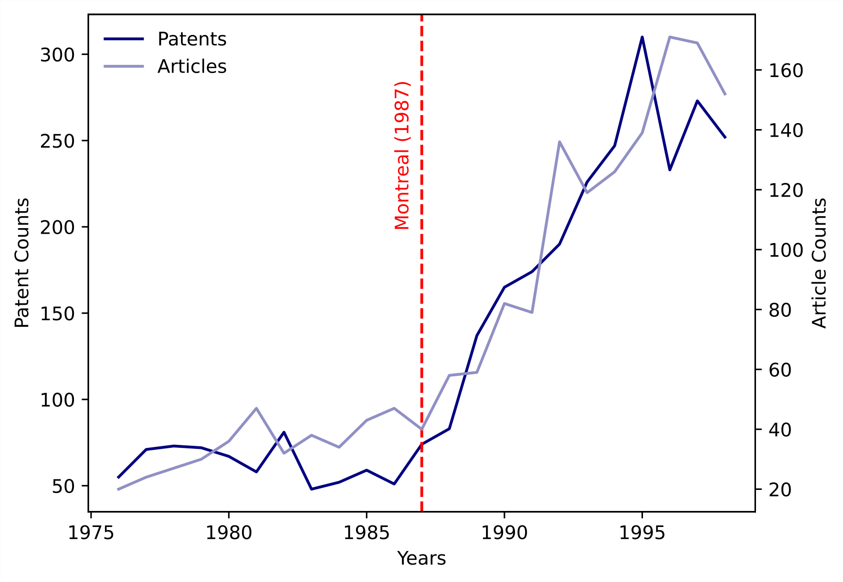
This Paper

- Question: Did Montreal foster science and innovation on CFC substitutes?
- Data: Full text of scientific articles and patents
- Methodology
  - Track documents mentioning CFC substitutes
  - Construct panel datasets: # documents mentioning molecule i in year t
- Identification of the causal effect
  - Difference-in-differences (DiD) and Synthetic Control Method (SCM)

    $\Rightarrow$ control units: Hazardous Air Pollutants (HAPs)
  - Topic modeling of the documents' text:

    $\Rightarrow$ molecule-level topic proportions to account for possible confounder
- Interpret the results in light of the theory on International Environmental Agreements
  - Modify workhorse model of IEAs by adding induced innovation

Results Preview: Patent and Article Counts Increase after 1987



Results Preview: DiD and SCM Estimates

Effects of the Montreal regime:

- Patents:

  $\approx$ 21 additional patents per year per substitute (from 1988 to 1992)
  Equivalent to almost 400% increase
  SCM result: about 135% increase

- Articles:

  $\approx$ 13 additional articles per year per substitute (from 1988 to 1995)
  Equivalent to almost 580% increase
  SCM result: almost 180% increase

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Background

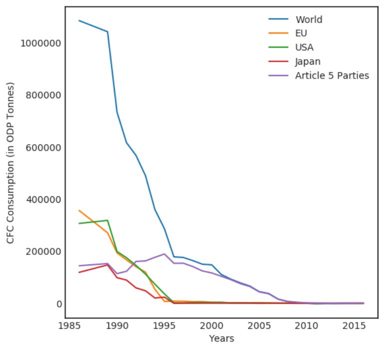
Relevant Literature

- Induced Innovation / Directed technological change
  - Porter Hypothesis: environmental regulations and innovation Ambec et al. 2013; Jaffe and Palmer 1997; Porter 1991; Porter and Van Der Linde 1995
  - Price or market size effects (Acemoglu 2002; Hicks 1932)
  - DTC and the Environment (Aghion et al. 2016; Jaffe et al. 2002; Newell et al. 1999; Popp 2010; Popp et al. 2010)
  - International environmental agreements (Dekker et al. 2012)
- Montreal Protocol and Ozone Crisis
  - Negotiations and diplomacy (Andersen and Sarma 2012; Benedick 2009)
  - Treaty structure (Barrett 1999, 2003; Murdoch and Sandler 2009; Wagner 2009)
  - Innovation (Gonzalez et al. 2015; Parson 2003; Taddonio et al. 2012)
  - Industries' reaction (Falkner 2005; Mulder 2005; Reinhardt and Vietor 1989a; Smith 1998)

Opinions on the Role of Innovation are Mixed

- Benedick (2009): *'(it) was evident (...) that the protocol was in fact moving industry in directions that two years earlier had been considered impossible.'*
- NYT (Aug 2002): *'(...) substitutes for the harmful chemicals were readily available (...)'*
- No existing quantitative studies

CFCs Consumption Dropped in the 1990s



Data: Ozone Secretariat, UNEP

CFC Atmo. Conc.

Industries:

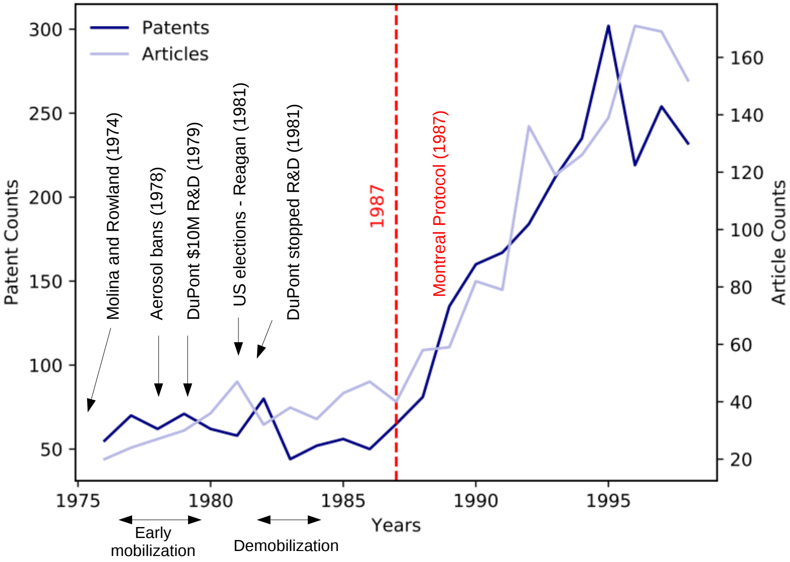
Foams, Refrigeration, Air-conditioning, Aerosols, Fire protection, Solvents

Market size:

- Entire market for CFCs: \$2B (world)
- Goods/services produced with CFCs: \$28B (US)
- Capital equipment: \$135B (US)

NB: 1988 estimations from Parson (2003)

Timeline



Patents
Articles
Patent Counts
Article Counts
Years
Molina and Rowland (1974)
Aerosol bans (1978)
DuPont $10M R&D (1979)
US elections - Reagan (1981)
DuPont stopped R&D (1981)
1987
Montreal Protocol (1987)
300
250
200
150
100
50
160
140
120
100
80
60
40
20
1975
1980
1985
1990
1995
Early
mobilization
Demobilization

Montreal: Low Ambition but Binding

- Montreal: reduction targets are not ambitious.
  - For CFC-11/12: Freeze by 1989, 50% cut by 1998
  - Ambition came later: London (1990), 100% phase-out by 2000

    More on other amendments
- Not ambitious but... "binding":
  - Trade restrictions with non-parties in products containing CFCs
  - Threat of banning trade in products made using CFCs

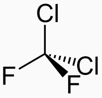
    $\Rightarrow$ Wagner (2016) argues this was the critical element that led to full participation.
- NB1: Domestic regulations came much later (e.g., EPA SNAP 1994)
- NB2: Montreal was not without some element of (political) surprise
  - The U.K. exited the European Community Presidency in Sept 1987

    Germany, Denmark and Belgium as the head negotiators
  - Reagan overrules his own administration and approves the agreement

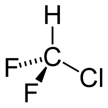
Data

Developping CFC Substitutes

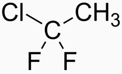
- Examples of CFCs and CFC substitutes:



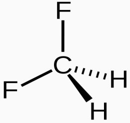
CFC-12



HCFC-22



HCFC-142b



HFC-32

$\Rightarrow$ Molecular structures of potential substitutes were known

Developping CFC Substitutes

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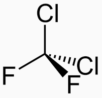
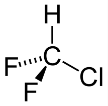
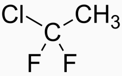


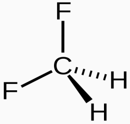
CFC-12



HCFC-22



HCFC-142b



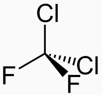
HFC-32

$\Rightarrow$ Molecular structures of potential substitutes were known

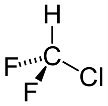
- Instead, the key technological challenges were about:
  - Making large scale production cost-efficient
  - Redesigning processes and equipment already installed
  - Learning about environmental acceptability and human toxicity

Developping CFC Substitutes

- Examples of CFCs and CFC substitutes:



CFC-12



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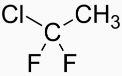

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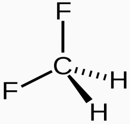


HFC-32

$\Rightarrow$ Molecular structures of potential substitutes were known

- Instead, the key technological challenges were about:
  - Making large scale production cost-efficient
  - Redesigning processes and equipment already installed
  - Learning about environmental acceptability and human toxicity
- I compile a list of 14 molecules identified as potential substitutes in a 1988 report on the atmospheric dynamics of potential substitutes

More Table About PAFT & AFEAS

Data: Tracking 14 CFC Substitutes in Patents and Articles

Patents:

- 2,605,925 US patent grants from 1976 to 2000 (USPTO)
  Sorted by *application* date
  3270 patents mentioning at least one CFC substitute
- Text of the abstract and summary description of the invention
- Capture new process and formula designs for CFC substitutes

Scientific Articles:

- 1,811,222 articles from 1970 to 2000 (Elsevier ScienceDirect)
  Disciplines: chemistry, chemical engineering, engineering, environmental science, materials science, physics
  1926 articles mentioning at least one CFC substitute
- Full text, author names, affiliations
- Cleaning: normalizing molecule names, discarding non-English documents
- Capture work on thermodynamic properties, toxicity profile, and environmental acceptability of CFC substitutes

Empirical Strategy: HAPs as a control group and the use of topic modelling

HAPs (Hazardous Air Pollutants) as Control Units

- Control molecules: HAPs (Hazardous Air Pollutants)
  - 171 molecules
  - Examples: benzene, chromium or formaldehyde
- Appropriate because:
  - No connection to ozone depletion

    I exclude three which at some point were suggested as substitutes (listed on the EPA website): chlorine, methylenechloride, trichloroethylene.
  - Often related to industrial activities similar to CFC substitutes

    Similar top-Level patent codes
- Regulated under the 1990 Clean Air Act due to human health issues
  - Initial schedule published in 1993
  - Most changes took place after 1997
  - Limit time series to 1992 for patents and 1995 for articles

Topic Modeling to Ensure Control Molecules are Similar

- Basic idea: look at the words mentioned in documents mentioning a particular molecule
  - Topic modeling captures what documents talk about
  - Therefore captures what molecules are about
- Algorithm: Latent Dirichlet Allocation

  (Blei 2012; Blei and Lafferty 2006, 2009)

  Returns the words contained in each topic

  Returns the proportion of topics contained in each document
- Use topic proportions
  - as control variables in DiD
  - as matching covariates in SCM

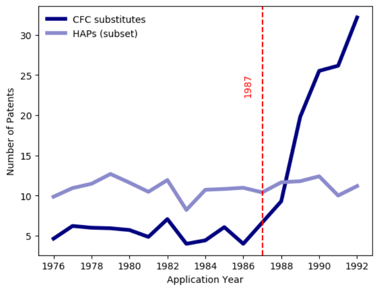
Topic Modeling | Variable Construction

Results: DiD and SCM

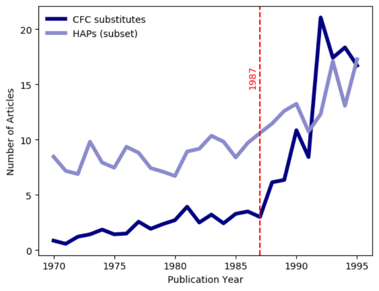
Similar Pre-Trends for CFC Substitutes and HAPs

- Treated group: N = 14 CFC substitutes
- Control group: Balance Table
  - Keep HAPs with average pre-period counts are of the same order of magnitude (ratio< 10) HAPs raw time series
  - Keep the 28 HAPs with the most similar pre-trend Subset

Patents



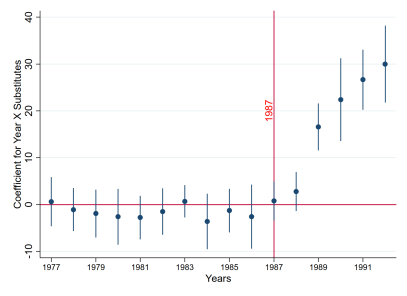
Articles



DiD Controlling for Topic Proportions

Patents

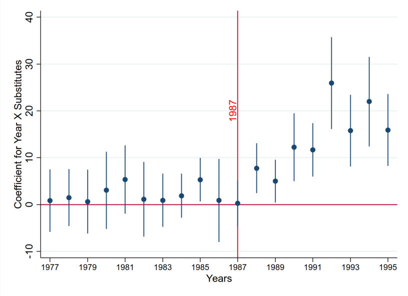
≈ 400% increase



Table

Articles

≈ 580% increase



Table

DiD Robustness Checks

- Lagged counts
- Counts weigthed by citations
- Counts weigthed by occurrences
- Counts weigthed by citations and occurrences

Table Patents Table Articles Graphs

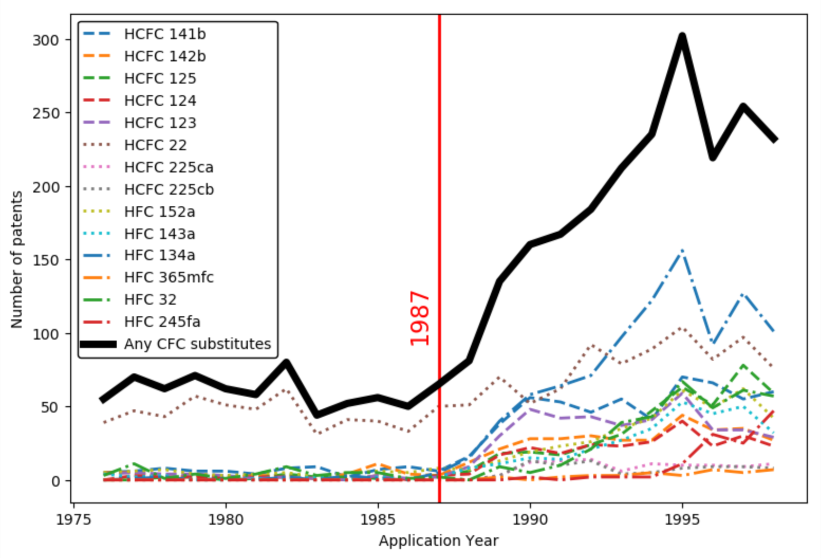
- Triadic patents only Graph and Table
- Zero-Inflated Negative Binomial instead of counts Patents Articles

Alternative Empirical Strategy: Synthetic Control Method

- Problem: observations in the DiD are not independent
  - Out of 3270 patents mentioning CFC substitutes, 1234 mention more than one CFC substitutes.
  - The DiD considers 5999 observations when, in reality, there are only 3270.
- Instead, consider the 14 CFC substitutes together (aggregated) as one treated unit
- SCM constructs a counterfactual molecule

SCM vs DiD SCM in practice

Aggregating the 14 Substitutes (Patents)



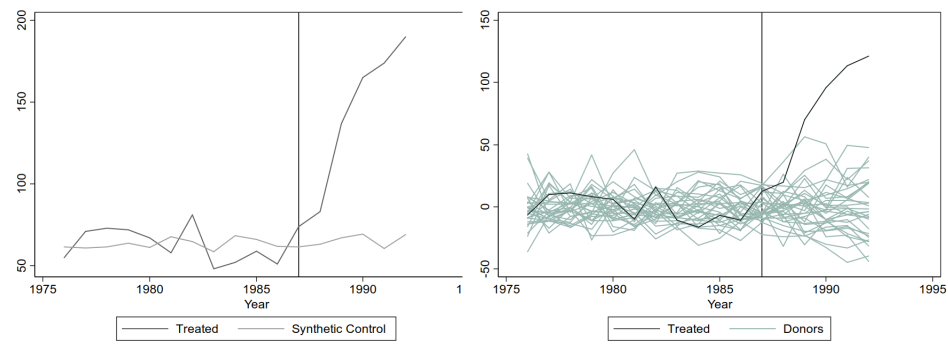
See Graph for Articles

Synthetic Control Method: Results

- Results:
  - 135% increase over 1988-1992 for Patents Graph
  - 177% increase over 1988-1995 for Articles Graph
- Robustness checks
  - Counts weigthed by citations Patents Articles
  - Counts weigthed by occurrences Patents Articles
  - Counts weigthed by citations and occurrences Patents Articles
  - Assuming anticipation Patents Articles
    - Redefine treatment year as 1985
    - Use years only until 1982 to fit the synthetic control

SCM Result: 135% increase over 1988-1992 for Patents

Close to 84 additional patents on average per year



More on Inference

Top HAPs on Inference

Back

Further Results: Secret Substitutes

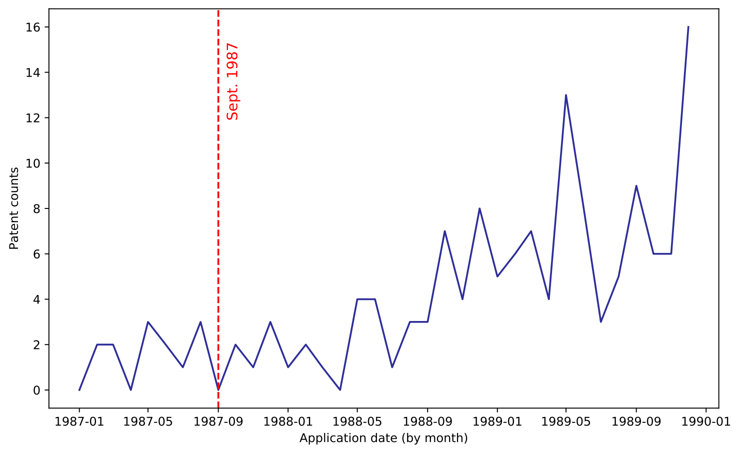
Were CFC Substitutes Kept "Secret"?

- Widely adopted narrative: DuPont and the industry endorsed CFC cuts because it had achieved a breakthrough.
- Hypothesis: R&D was done before and firms kept substitutes "hidden"
- Any evidence going in that direction?
  Parson (2003): "There is no evidence to support this claim, and substantial evidence to the contrary."
- Can we falsify this claim with patent observations?
    - Yes, if we assume trade secrets are not a powerful mechanism here

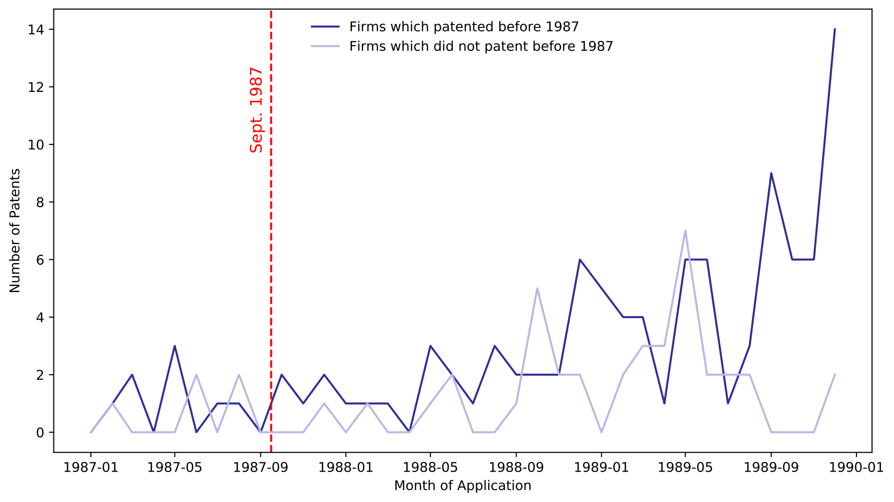
Trade Secrets: Hard to Keep in this Context (Parson 2003)

- Remaining barriers to developping CFC substitutes
  - Proving suitability for specific applications
    - Cannot be done in secret
    - Require partnerships with customers
  - Developping synthesis processes
    - Could potentially be done in secret
    - However: many competitors, all working on the same molecules
    - Incentives to be the first to patent
- If CFC substitutes were kept "secret":
  - Prediction 1: immediate peak patenting
    - At least in the few months following agreement
  - Prediction 2: incumbent advantage
    - Firms with prior patenting history should have higher peak

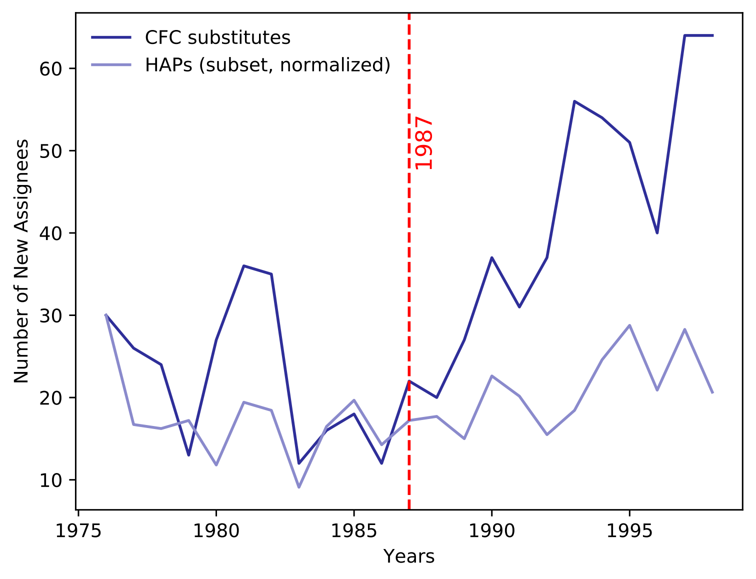
No immediate peak patenting



“First-Mover” advantages tend to build over time



Many “New Entrants” Start Patenting



Secret CFC substitutes: something of a "myth"?

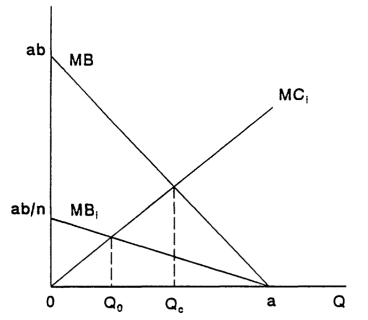
- "The most pervasive and most widespread myth surrounding the Montreal Protocol" (Grundmann 1998)
- What producers said...
  - Promising substitutes would cost two to five times more than CFCs [stated in 1980] (Parson 2003, p.54)
  - Estimated time to market substitutes of 5 to 10 years [stated in 1986] (ibid., p.127)
- Misunderstanding about the nature of the technological challenges:
  - Not about "finding" new molecules
  - Not about one silver-bullet molecule or process
  - Much experimentation needed still

Discussion and Conclusion

Summary

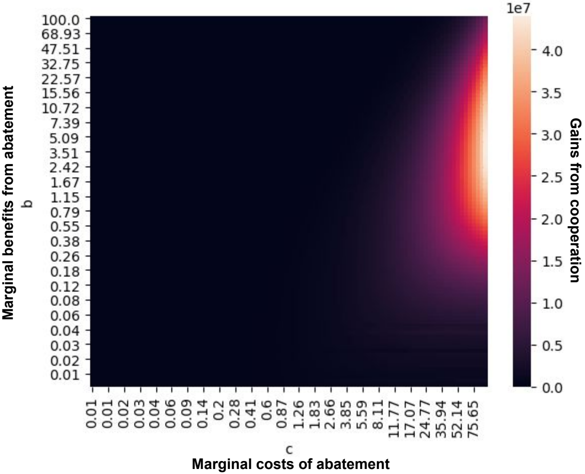
- The Montreal protocol triggered an increase in research and innovation on CFC substitutes
  - First quantitative evidence
  - Magnitude consistent with statement describing rapid development of substitutes as a "burst of industrial creativity" (Meadows et al. 1992)
- Inconsistent with the narrative of "CFC substitutes being available"
- How does this fit with the theory of IEAs?
- Can we learn any new lessons?

Theory of IEA: Montreal ≈ Unilateral actions



- Barrett (1994): Cooperation happens only when it's not needed...
- We don't get large coalitions when MC and MB are both steep
- Interpretation of Montreal in this context: it was successfully negotiated because it was close to what countries would have done
- But such a theory of IEA ignores the role of induced innovation

Theory of IEAs: Cooperation happens when the gains from cooperation are low Barrett (1994)



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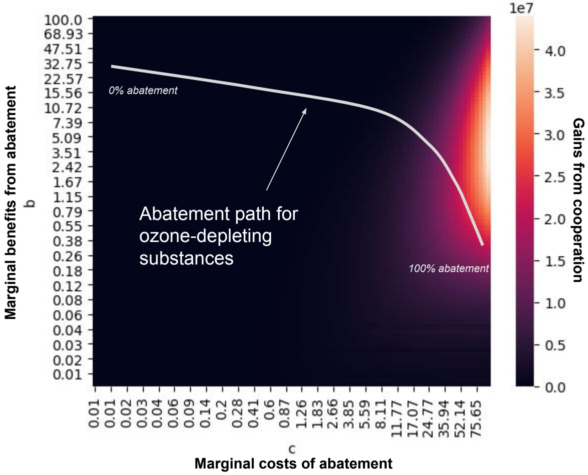
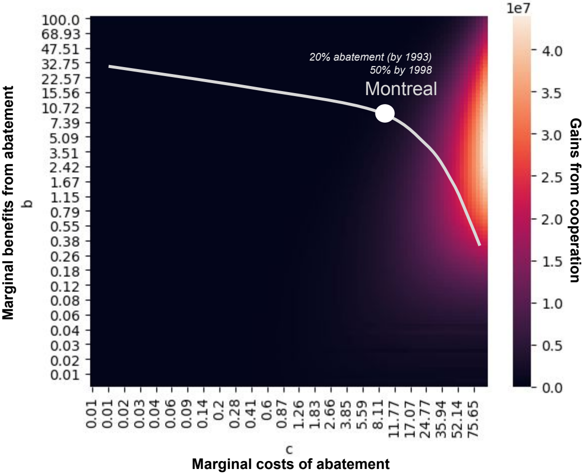
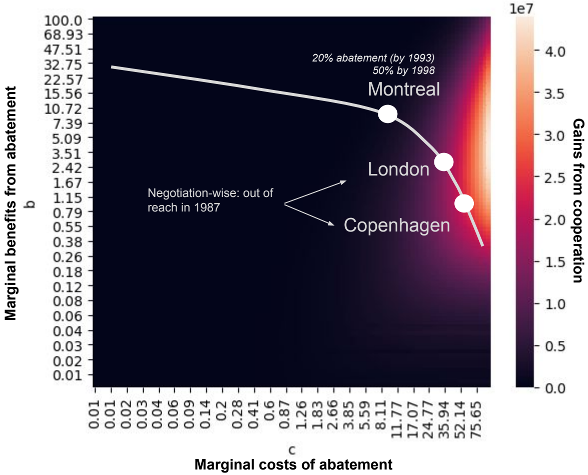


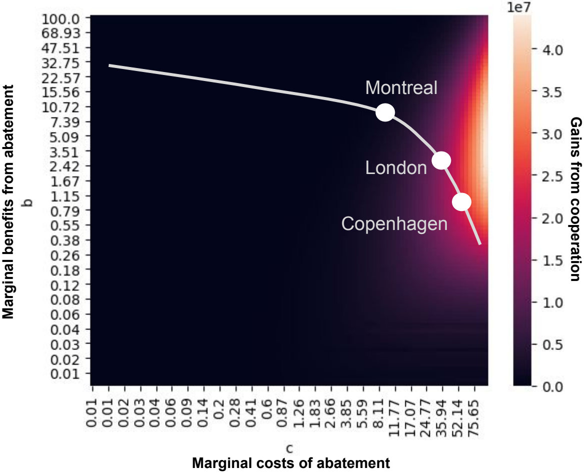
Theory of IEAs: Montreal was successfully negotiated because it was not "very ambitious"?



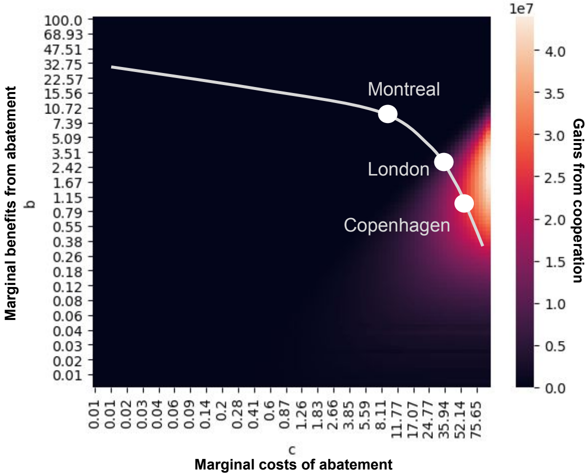
Theory of IEAs: More ambitious reductions are not negotiated.



Still, Montreal mattered because it induced innovation



Induced innovation leads to lower abatement costs



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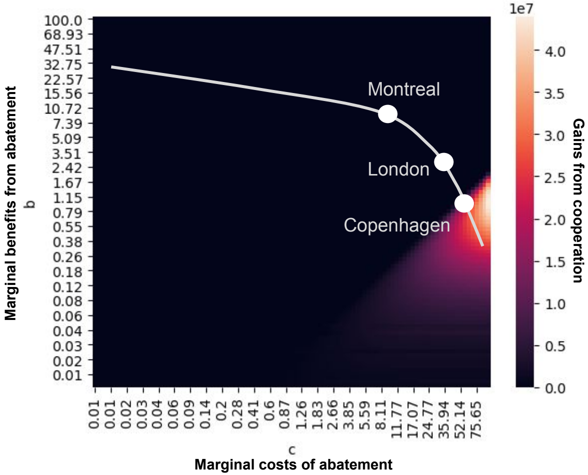

How to interpret results in light of IEA theory?

Modest Agreement $\Rightarrow$ Induced innovation $\Rightarrow$ Deeper Agreements

- Targets agreed in Montreal can be thought as not very ambitious
  - Maybe encoded unilateral actions (low costs, high benefits)
  - Consistent with IEA theory
- But targets were binding (trade measures)
  - Guaranteed a worlwide market for future substitutes
  - Required experimentation and R&D work
  - Induced innovation and lowered expected abatement costs
- Enabled more ambitious targets in 1990 and 1992

Lessons for other environmental problems?

- Cooperation problems with high MAC need not be doomed
  - Ozone cooperation was successful because the beginning of the MAC was expected to be low and binding treaty could be negotiated
  - That ascertained a worldwide market for subtitutes (even if small) which incentivized firms to invest in R&D which lowered abatement costs
- Small but binding commitments can induce innovation and lower costs
  - Unlikely that ambitious but non-binding pledges can do the same
  - Leveraged trade to create an enforcement mechanism (potential for a climate clubs à la Nordhaus (2015)?)
  - Focused very much so on one sector (the chemical industry)

Thank you!

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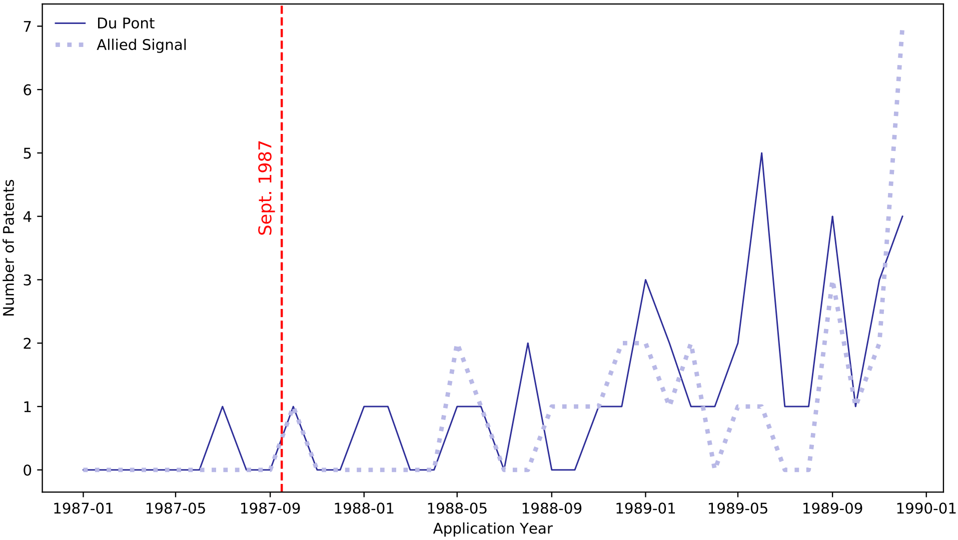
Why would firms be in favor of a constraining treaty?

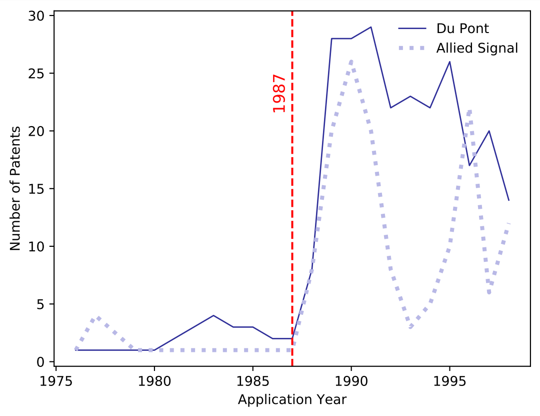
- Firms don't oppose a "reasonable" agreement
  - Low targets, and in the future
  - Leveling the playing field with their international competitors
  - Strategic business incentives (Parson 2003):
    Goodbye to cheap commodities (CFCs) and hello higher-margin chemical (with patent-induced monopolies)
  - They can pass down costs to consumers
    $\Rightarrow$ For firms, this resembles a coordination game

Du Pont/Allied: No Immediate Peak Patenting



Dominant players DuPont and Allied info

Du Pont/Allied: Patenting Concentrates in 1989-1991



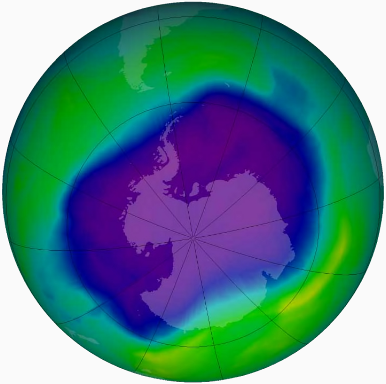
"The rate of development of alternatives will correspond to the pressure applied; until now, there has been no pressure".

written in 1986 by two Du Pont officials in C&EN (Parson 2003)

Citation Monthly

What Role for Consumer Pressure?

- 1985: large depletion of ozone over Antarctica detected
- March 1988: the ozone "hole" is attributed to CFCs

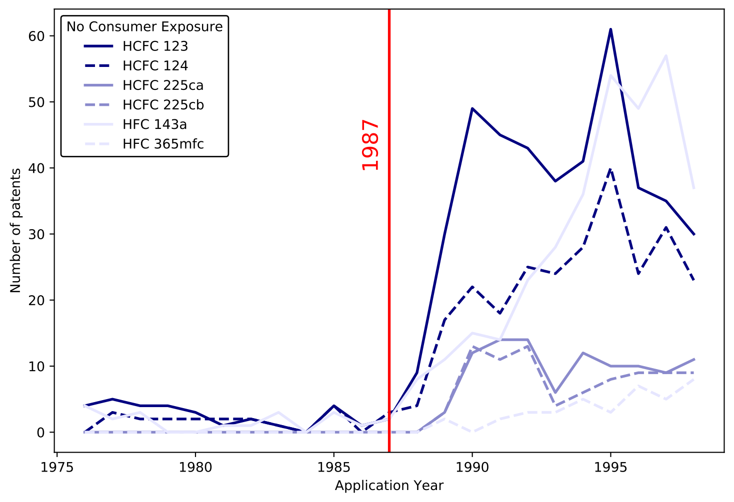


- Heightened level of public awareness and consumer pressure
- To what extent consumer pressure drove innovation on CFC substitutes after 1987?

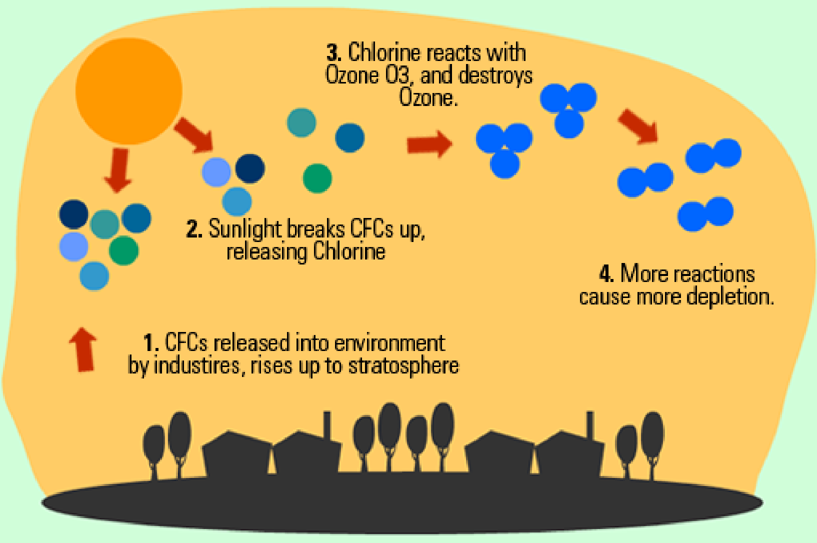
Not All Molecules or Applications are Consumer Exposed

- EPA SNAPs Website: 1801 requests for substance-application approval
- e.g. HCFC-225cb for Electronics Cleaning
- I manually classify applications as consumer exposed or not (or indeterminate)
- I identify 6 CFC substitutes that are credibly not consumer exposed
- Typical applications include: Centrifugal Chillers, Industrial Process Refrigeration, Foam Blowing Agents for Rigid Polyurethane, Precision Cleaning

Strong Increases for Molecules Not Exposed to Consumers



CFCs Destroy Ozone in the Stratosphere



Impact of ozone loss: skin cancers, cataracts, productivity losses in agriculture/fisheries

Source: http://www.eschooltoday.com/

Searching for the Many Possible Names Molecules May Have

- Molecules can have many names.
- e.g.: HCFC-22 has 39 possible names.
- Automatic script to collect all possible names from SciFinder (American Chemical Society).
- Search for all these names after light cleaning: More about cleaning steps

CAS Registry Number 75-45-6

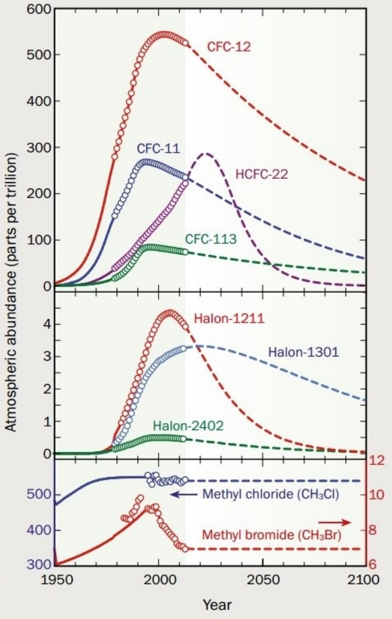
$C H Cl F_2$

Methane, chlorodifluoro-

Other Names

Chlorodifluoromethane
Algeon 22
Algofrene 22
Algofrene 6
Arcton 22
Arcton 4
CFC 22
Daiflon 22
Difluorochloromethane
Difluoromethyl chloride
Difluoromonochloromethane
Dymel 22
Electro-CF 22
F 22 (halocarbon)
FC 22
FC 22 (halocarbon)
FKW 22
Flugene 22
Forane 22
Freon 22
Freon R 22
Frigen 22

Atmospheric Concentrations of ODSs are Going Down



Source:
World Meteorological Organization (2014)

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The Path to an Agreement

- 1974: chlorofluorocarbons (CFCs) catalyze the destruction of ozone

  No empirical evidence at the time (Molina and Rowland 1974)
- End of the 1970s: short-lived initial mobilization
  - Aerosol bans (USA, Canada, Scandinavia)
  - Research programs for substitutes (e.g., DuPont 1979 $10M)
- Early 1980s: mobilization diminished
  - Scientific uncertainties
  - Anti-regulatory mood (Reagan and Thatcher)
  - R&D programs are terminated
- International negotiations
  - 1985: Vienna Convention

    No binding reductions. A framework for negotiations.
  - 1987: Montreal protocol

    Binding reduction targets to phase-out CFCs
    - The U.K. exited the European Community Presidency in Sept 1987
    - Reagan overrules his own administration and approves the agreement

Back

Montreal: An Element of Surprise

- Benedick (2009) argues the success of the negotiations were hard to predict until the last moments.
- The U.K. exited the European Community Presidency in Sept 1987

  Germany, Denmark and Belgium as the head negotiators
- Reagan overrules his own administration and approves the agreement

  Some suggested his experiences of skin cancer weighed on his decision

Back

Ozone Depleting Substances Regulated in the 1990s

1990 London

Annex B Group 1	10 other CFC chemicals
Annex B Group 2	Carbon tetrachloride
Annex B Group 3	Methyl chloroform

1992 Copenhagen

Annex C Group 1	40 HCFCs
Annex C Group 2	34 HBFCs
Annex E	Methyl bromide (freeze)

1995 Vienna

Annex E	Methyl bromide (phase-out)

Targets ◂ Back

Ozone Depleting Substances Targets

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Chemicals	1987 Montreal Protocol	1990 London Revisions	1992 Copenhagen Revisions	1995 Vienna Revisions	1995 Vienna (article 5)
Annex A/I Chlorofluorocarbons 11,12,113,114,115	baseline 1986 freeze 1989 20% 1993 50% 1998	baseline 1986 freeze 1989 50% 1995 85% 1997 ...	baseline 1986 freeze 1989 75% 1994 100% 1996	no change	baseline 1995/97 freeze 1999 50% 2005 85% ...
Annex A/II Halons 1211, 1301, 2402	baseline 1986 freeze 1992	baseline 1986 freeze 1992 50% 1995 100% 2000	baseline 1986 freeze 1992 100% 1994	no change	baseline 1995/97 freeze 2002 50% 2005 100% ...
Annex B/I Other CFCs 10 chemicals	no controls	baseline 1989 20% 1993 85% 1997 100% 2000	baseline 1989 20% 1993 75% 1994 100% 1996	no change	baseline 1998/2000 20% 2003 85% 2007 100%...
Annex B/II Carbon tetrachloride		baseline 1989 85% 1995 100% 2000	baseline 1989 85% 1995 100% 1996	no change	baseline 1998/2000 85% 2005 100% 2010
Annex B/III Methyl chloroform		baseline 1989 freeze 1993 30% 1995 70% 2000 ...	baseline 1989 freeze 1993 50% 1994 100% 1996	no change	baseline 1998/2000 freeze 2013 30% 2005 70% ...
Annex C/I Hydrochlorofluorocarbons 40 chemicals	no controls	mandatory reporting nonbiding resolution on pase-out: 2020 if pos...	baseline 1989 freeze 1996 35% 2004 65% 2010 90% 201...	baseline 1989 one change	baseline 2015 freeze 2016 100% 2040
Annex C/II Hydrobromofluorocarbons 34 chemicals	no controls	no controls	100% 1996	no change	100% 1996
Annex E Methyl bromide	no controls	no controls	baseline 1991 freeze 1995	baseline 1991 freeze 1995 25% 2001 50% 2005	baseline 1995/98 freeze 2002

About the 14 Potential Substitutes

- 8 HCFCs and 6 HFCs
- Molecules not “new-to-the-world”
- e.g. 1934 US Patent: ”method of producing refrigeration which comprises evaporating in the vicinity of a body to be cooled and subsequently condensing (HCFC-22).”
- Molecules are “new-to-the-industry”
- e.g. HCFC-123
    - Potential substitute for CFC-11 in refrigeration
    - Similar vapor pressure implied no need to change equipment
    - No commercial experience
    - First commercial synthesis route patented by DuPont in 1988
    - Large production plant in 1990

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Details About Some CFC Substitutes

Substitute	PAFT	AFEAS	Substitute for	Notes
HCFC-22	No, already marketed, toxicology known	Yes	Included in Annex C. CFC-11, CFC-12 in foams	cheapest, fastest substitute, already at large scale production at the end of 1986 but due to toxicity concerns, not appropriate for aerosol use. FDA approved it for foams in 1988 for fast foods and for grocery display packaging.
HCFC-142b	No, already marketed, toxicology known	Yes	CFC-11, CFC-12 but not ideal	Included in Annex C. Considered because already at small scale production in 1986 but their thermodynamic propertiesare very different and would have required changes in equipment and process. DuPont 1988 process for coproduction of HCFC 141b and 142b
HCFC-123	Yes	Yes	CFC-11 in refrigeration	Included in Annex C. Vapor pressure similar to CFC-11 and CFC-12 implied no need to change equipment. However no commercial experience. estimated at \$1.5-2/lb in 1986. DuPont patent commercial synthesis route 1988. large plant in 1990 for production. Still some toxicity concerns.

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Details About Some CFC Substitutes (Part 2)

Substitute	PAFT	AFEAS	Substitute for	Notes
HFC-152a	No, already marketed, toxicology known	Yes	CFC-11, CFC-12 but not ideal	Considered because already at small scale production in 1986 but their thermodynamic propertiesare very different and would have required changes in equipment and process.
HFC-134a	Yes	Yes	CFC-12 in refrigeration (car AC)	vapor pressure similar to CFC-11 and CFC-12 implied no need to change equipment. However no commercial experience. estimated at $3/lb in 1986. oct 1990 first commercial plant ICI, then DuPont. Both DuPont and ICI announced important catalyst breakthroughs in 1992, which roughly doubled their capacity.
HCFC-141b	Yes	Yes	CFC-11 in foams	Included in Annex C. Vapor pressure similar to CFC-11 and CFC-12 implied no need to change equipment. However no commercial experience. DuPont 1988 process for coproduction of HCFC 141b and 142b. Appeared to be the most promising alternative initially (1987-1988) but in late 1988 its ODP was found much higher than thought (about 10 percent). EPA banned its use as a solvent in 1993. required phase out of production by 2003. Moderate inflammability.

Details About Some CFC Substitutes (Part 3)

Substitute	PAFT	AFEAS	Substitute for	Notes
HCFC-124	Yes	Yes	CFC-114 in refrigeration and sterilization	Included in Annex C. Less suitable propertie but could be used in blends
HCFC-125	Yes	Yes	CFC-115 in refrigeration and sterilization	less suitable properties but could be used in blends
HCFC-225ca	No, second rank candidate	Yes		Included in Annex C.
HCFC-225cb	No, second rank candidate	Yes		Included in Annex C.
HFC-32	No, second rank candidate	Yes	refrigeration	considered in blends for refrigeration. Inflammability and compressor discharge made it problematic alone. Both DuPont an ICI opened HFC-32 plants in the summer of 1992. by 1993, DuPont, Allied, ICI, and Atochem were all marketing various patente refrigerant blends

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PAFT and AFEAS

- Manufacturers allowed to cooperate
  - Authorization from antitrust officials
  - Two working groups to study the feasibility of various alternatives
- PAFT
  Program for Alternative Fluorocarbon Toxicity Testing
  - Created in January 1988
  - Goal: assessing the toxicity of five possible alternatives
- AFEAS
  Alternative Fluorocarbon Environmental Acceptability Study
  - Created in December 1988
  - Goal: investigate the atmospheric dynamics of twelve potential CFC substitutes

◂ Back

Normalizing Molecule Names

- Molecules can have many names.
- e.g.: HCFC-22 has 39 possible names.
- Automatic script to collect all possible names from SciFinder (American Chemical Society).

More about cleaning steps | Back

CAS Registry Number 75-45-6

$C\,H\,Cl\,F_2$

Methane, chlorodifluoro-

Other Names

Chlorodifluoromethane
Algeon 22
Algofrene 22
Algofrene 6
Arcton 22
Arcton 4
CFC 22
Daiflon 22
Difluorochloromethane
Difluoromethyl chloride
Difluoromonochloromethane
Dymel 22
Electro-CF 22
F 22 (halocarbon)
FC 22
FC 22 (halocarbon)
FKW 22
Flugene 22
Forane 22
Freon 22
Freon R 22
Frigen 22

Cleaning to Search and Count Molecules

- Lowercase
- Replace , $-()$ by empty strings
  E.g.: "3-Amino-2,5-dichlorobenzoic acid" becomes "3amino25dichlorobenzoic acid"
- Replace any other type of punctuation by a space
- Additional step for articles: Detect reference list and remove.
  Rule of thumb: if the word 'references' in text, and if located after 80% of the rest: truncate
- Search for any of the possible names collected through SciFinder

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Most Frequent Patent Codes Mentioning CFC Substitutes

ICL	Count	Description
C07C	357	Acyclic or carbocyclic compounds
C08J	156	General processes of compounding
C09K	147	Materials for applications not otherwise provided for
C08G	84	Compounds of unknown constitution
C10M	73	Lubricating compositions

- Most codes belong to the C class ("Chemistry, Metallurgy")
- Subclasses "C07" and "C08" refer in particular to the preparation of organic compounds:
  e.g., C07C 19/00: Acyclic saturated compounds containing halogen atoms
- Only patents with at least 3 molecule occurrences are used here.

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Most Cited Patents Mentioning CFC Substitutes

Citation	Year	Assignee	Title
104	1995	Glaxo Group Limited, United Kingdom	Aerosol formulations containing P134a and salbutamol
103	1995	Glaxo Group Limited, United Kingdom	Aerosol formulations containing P134a and particulate medicaments
102	1987	Allied-Signal Inc., United States of America	Refrigeration lubricants
101	1995	Glaxo Group Limited, United Kingdom	Aerosol formulations containing propellant 134a and fluticasone
97	1995	Riker Laboratories, Inc., United States of America	Medicinal aerosol formulations

- Pharmaceuticals applications (e.g. aerosol formulation of a drug) are the most cited.
- Only patents with at least 3 molecule occurrences are used here.

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Most Cited Articles Mentioning CFC Substitutes

Citation	Year	Title	Journal	Affiliation 1st author
1298	1987	Advances in the preparation of biologically active organofluorine compounds	Tetrahedron	Academia, USA
509	1992	Organic peroxy radicals: Kinetics, spectroscopy and tropospheric chemistry	Atmospheric Environment Part A, General Topics	Academia, DE-UK-FR
419	1982	Evaporative heat transfer, pressure drop and critical heat flux in a small vertical tube with R-113	International Journal of Heat and Mass Transfer	GE Global Research, USA
401	1992	Environmental catalysis	Applied Catalysis B: Environmental	Air Products and Chemicals, Inc., USA
346	1993	Synthesis of chiral and bioactive fluoroorganic compounds	Tetrahedron	University, Italy
333	1996	Methods for the synthesis of gem-difluoromethylene compounds	Tetrahedron	James Black Foundation, UK
329	1992	Fluorinated organometallics: Perfluoroalkyl and functionalized perfluoroalkyl organometallic reagents in organic synthesis	Tetrahedron	Academia, USA

Only articles with at least 3 molecule occurrences are used here.

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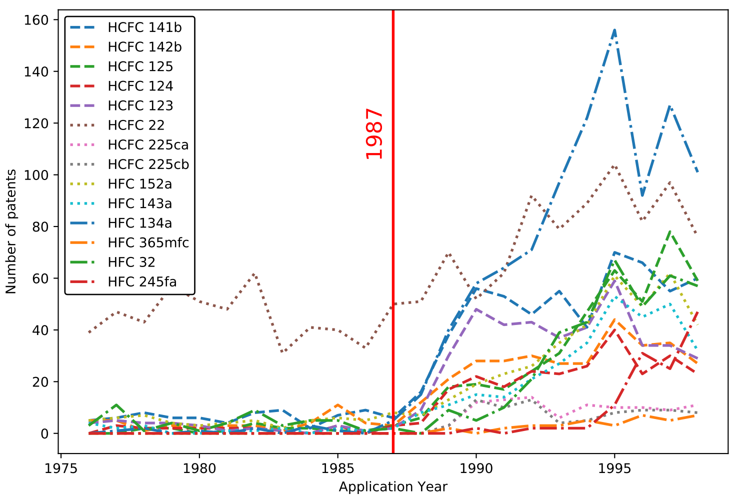
About 550% Increase on Average for Patent Counts



First Differences

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First Differences Estimation (Patents)

	(1)	(2)
Post 1987	29.51	6.10
	(2.11)	(2.63)
Post 1987 x Years		3.95
		(0.44)
Years		-0.03
		(0.25)
Molecule FE	Yes	Yes
Bootstraped	Yes	Yes
R-squared	0.64	0.74
Observations	322	322

Standard errors in parentheses
Bootstrapped standard errors in parentheses.
Dependent variable: Number of Patents.
Variable 'Years' is relative to 1987.
Time period: 1976 to 1998

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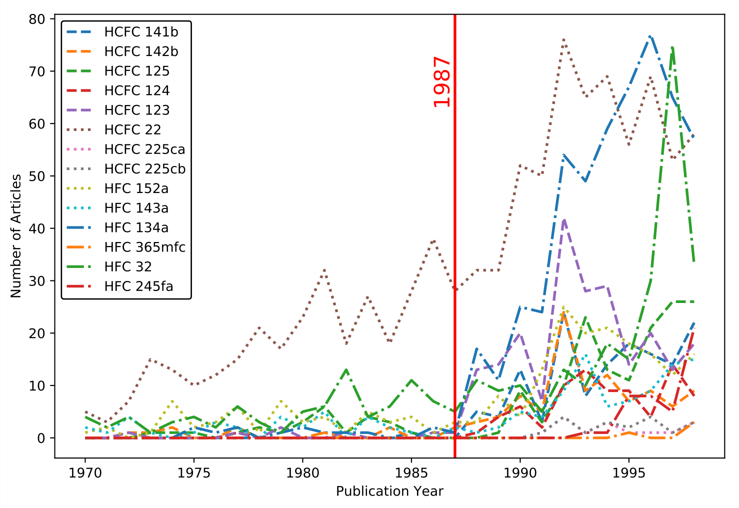
Almost 600% Increase on Average for Article Counts



First Differences

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First Differences Estimation (Articles)

	(1)	(2)
Post 1987	13.02	2.11
	(1.07)	(1.58)
Post 1987 x Years		1.44
		(0.28)
Years		0.16
		(0.06)
Molecule FE	Yes	Yes
Bootstraped	Yes	Yes
R-squared	0.58	0.63
Observations	406	406

Standard errors in parentheses
Bootstrapped standard errors in parentheses.
Dependent variable: Number of Articles.
Variable 'Years' is relative to 1987.
Time period: 1970 to 1998

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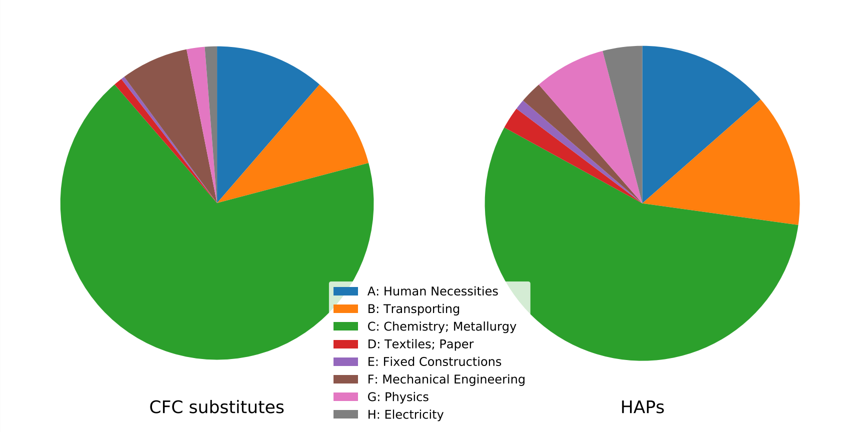
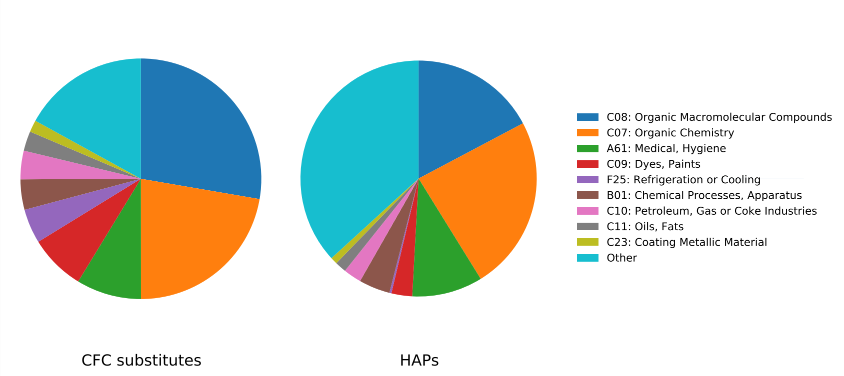
HAPs and CFC Substitutes Have Similar Top-Level Patent Codes



International Patent Classification.

Second-level codes ◂ Back

HAPs and CFC Substitutes: Similar Second-Level Patent Codes.



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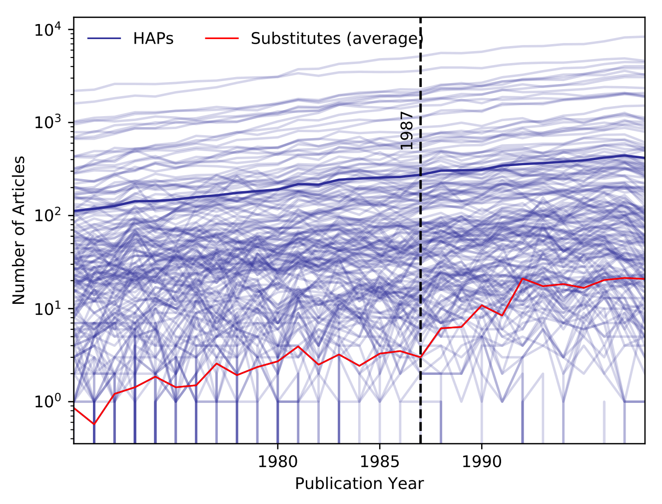
Appropriate HAPs will have Comparable Articles Counts



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Using Topic Modeling to Proxy Molecule Characteristics

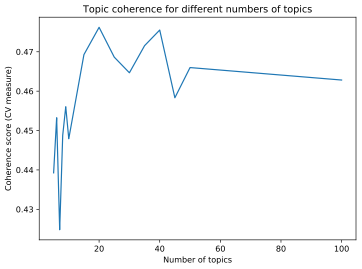
- Clean the text of patents and articles

  Involves tokenizing, taking bigrams, lemmatizing

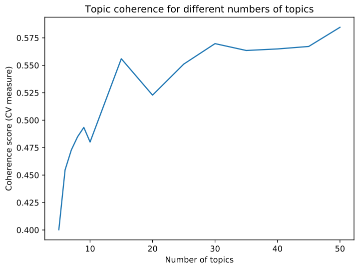
  More about cleaning steps
- Build LDA models for different numbers of topics

  Number of topics: 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, 40, 45, 50, 100
- Select model with best coherence score

Patents: 20 topics



Articles: 15 topics



- Obtain topic proportions for each document
- Aggregate topic proportions at the molecule level

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Cleaning for Topic Modelling

- Lowercase and replace any punctuation by a space
- Replace any number by the string "_NUMBER_"
- Use Spacy's tokenizer in Python to tokenize strings
- Remove stopwords

  List from Python's sklearn package (ENGLISH_STOP_WORDS)
- Remove tokens strictly smaller than 5 characters
- Additional step for articles: remove tokens that are longer than 15 characters
- Additional step for articles: drop non-English articles

  Use Google's CLD2 library in Python
- Build bigram model (minimum count of 5 occurrences)
- Use Spacy's lemmatizer in Python to lemmatize ngrams
- Build dictionnary: filtering no less than in 10 documents and not more than into 60% of the corpus

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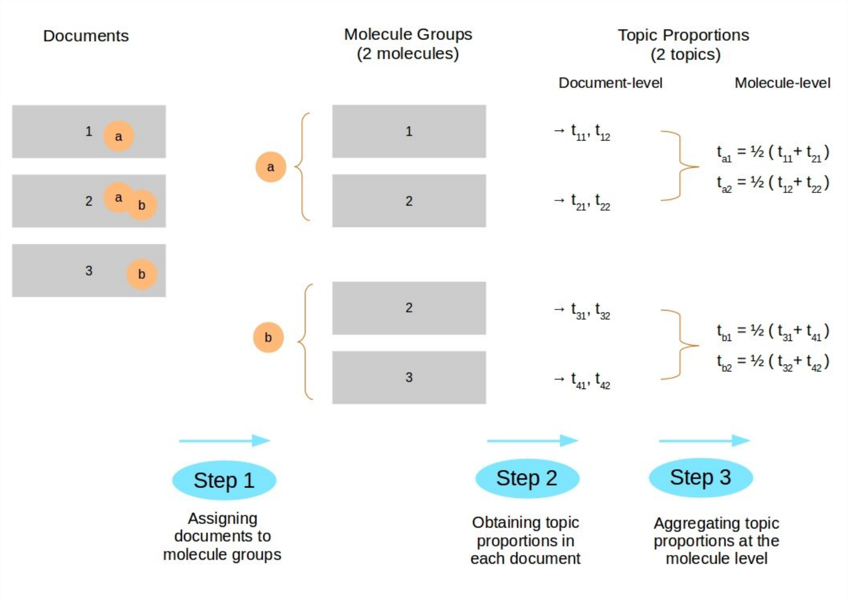
Topic Proportions Calculated at the Molecule Level



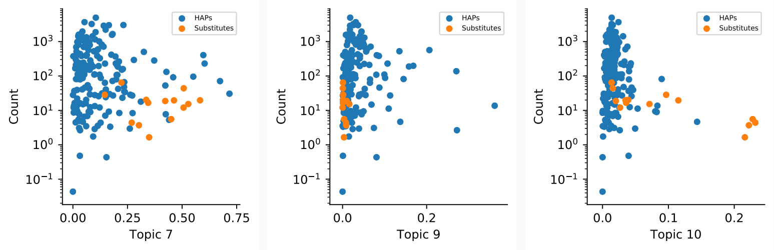
Top Words in Selected Topics (Patents: left; Articles: right)

	Words	Probability
	polymer	0.0161
	catalyst	0.0123
Topic 1	carbon	0.0095
	weight	0.0094
	atom	0.0087
	metal	0.0084
	membrane	0.0082
Topic 2	solution	0.0071
	particle	0.0067
	surface	0.0065
	formula	0.0118
	carbon	0.0092
Topic 3	atom	0.0088
	substitute	0.0086
	amine	0.0077
	agent	0.0147
	composition	0.0112
Topic 4	active	0.0064
	weight	0.0062
	water	0.0052

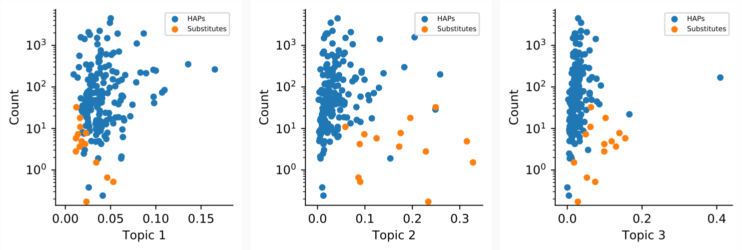
	Words	Probability
	compound	0.0162
	extract	0.0072
Topic 1	structure	0.0068
	product	0.0061
	methyl	0.0056
	surface	0.0155
	material	0.0096
Topic 2	layer	0.0086
	film	0.0075
	process	0.0062
	laser	0.0129
	signal	0.0102
Topic 3	sample	0.0097
	pulse	0.0092
	radical	0.0081
	gifhttps	0.0351
	thumbnail	0.0282
Topic 4	downsample	0.0270
	smlhttps	0.0190
	stripin	0.0175

Topics Uncover Outlier Molecules

Patents



Articles



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Balance Table CFC Substitutes vs. HAPs for Patents

	HAPs	CFC substitutes	Difference	T-stat
Counts	10.88	5.36	5.52***	(4.47)
Counts (occurrence weighted)	11.75	4.19	7.56***	(5.27)
Counts (citation weighted)	15.53	9.15	6.38***	(3.44)
Counts (3-year citation weighted)	11.47	4.15	7.32***	(4.90)
Topic 1 (w. mean)	0.03	0.02	0.01	(0.98)
Topic 2 (w. mean)	0.04	0.01	0.03*	(2.56)
Topic 3 (w. mean)	0.10	0.02	0.08***	(6.91)
Topic 4 (w. mean)	0.03	0.04	-0.01	(-0.95)
Topic 5 (w. mean)	0.04	0.01	0.03**	(3.21)
Topic 6 (w. mean)	0.11	0.03	0.08***	(5.16)
Topic 7 (w. mean)	0.11	0.37	-0.26***	(-10.41)
Topic 8 (w. mean)	0.08	0.02	0.05***	(3.95)
Topic 9 (w. mean)	0.04	0.01	0.04***	(3.77)
Topic 10 (w. mean)	0.03	0.04	-0.01	(-1.16)
Topic 11 (w. mean)	0.02	0.04	-0.03***	(-3.67)
Topic 12 (w. mean)	0.01	0.01	0.00	(0.80)
Topic 13 (w. mean)	0.06	0.05	0.00	(0.06)
Topic 14 (w. mean)	0.12	0.02	0.10***	(5.41)
Topic 15 (w. mean)	0.01	0.01	-0.00	(-0.40)
Topic 16 (w. mean)	0.06	0.10	-0.03*	(-2.14)
Topic 17 (w. mean)	0.02	0.01	0.00	(0.38)
Topic 18 (w. mean)	0.04	0.00	0.03**	(3.22)
Topic 19 (w. mean)	0.02	0.07	-0.05***	(-7.30)
Topic 20 (w. mean)	0.04	0.12	-0.07***	(-4.86)

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Balance Table CFC Substitutes vs. HAPs for Articles

	HAPs	CFC substitutes	Difference	T-stat
Count	5.98	2.19	3.79***	(8.48)
Counts (occurrence weighted)	6.17	1.18	4.99***	(9.56)
Counts (citation weigh)	5.39	2.17	3.22***	(3.79)
Topic 1 (w. mean)	0.03	0.01	0.02***	(4.50)
Topic 2 (w. mean)	0.02	0.07	-0.04***	(-4.97)
Topic 3 (w. mean)	0.02	0.10	-0.08***	(-8.67)
Topic 4 (w. mean)	0.13	0.11	0.03	(1.36)
Topic 5 (w. mean)	0.05	0.06	-0.01	(-0.89)
Topic 6 (w. mean)	0.04	0.18	-0.13***	(-11.95)
Topic 7 (w. mean)	0.04	0.09	-0.05***	(-4.28)
Topic 8 (w. mean)	0.03	0.01	0.02***	(3.94)
Topic 9 (w. mean)	0.19	0.05	0.14***	(5.71)
Topic 10 (w. mean)	0.07	0.03	0.04***	(3.44)
Topic 11 (w. mean)	0.03	0.14	-0.11***	(-11.35)
Topic 12 (w. mean)	0.14	0.03	0.11***	(6.61)
Topic 13 (w. mean)	0.13	0.03	0.10***	(5.14)
Topic 14 (w. mean)	0.02	0.03	-0.01	(-1.19)
Topic 15 (w. mean)	0.05	0.07	-0.02*	(-2.01)

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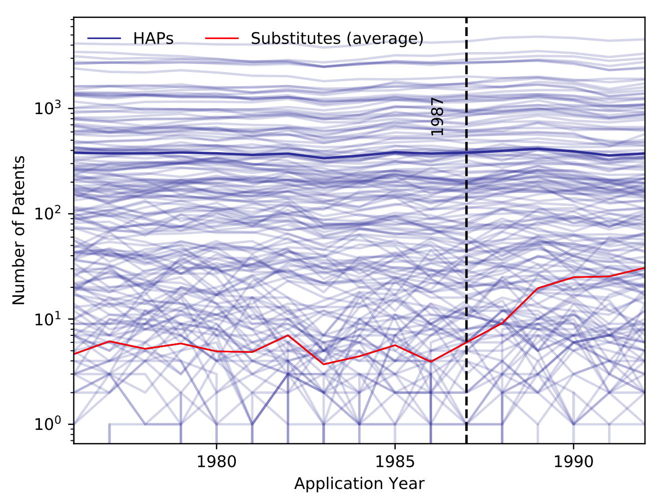
Appropriate HAPs will have Comparable Patent Counts



In practice, there is high heterogeneity in patent counts among HAPs.

Articles ◀ Back

Selecting HAPs With Most Similar Pre-Trends

- Calculate the mean pre-trend slope for CFC substitutes between 1976 and 1985
  ≈ -0.04 for patents and ≈ 0.17 for articles
- Calculate the pre-trend slope for each HAP between 1976 and 1985
  Only for HAPs with counts of similar magnitude
- Rank HAPs according to how similar their slope is to the mean slope for CFC substitutes
- Select 28 HAPs with most similar slope
  $\Rightarrow 42 = 2\times$ size of treated group (14)

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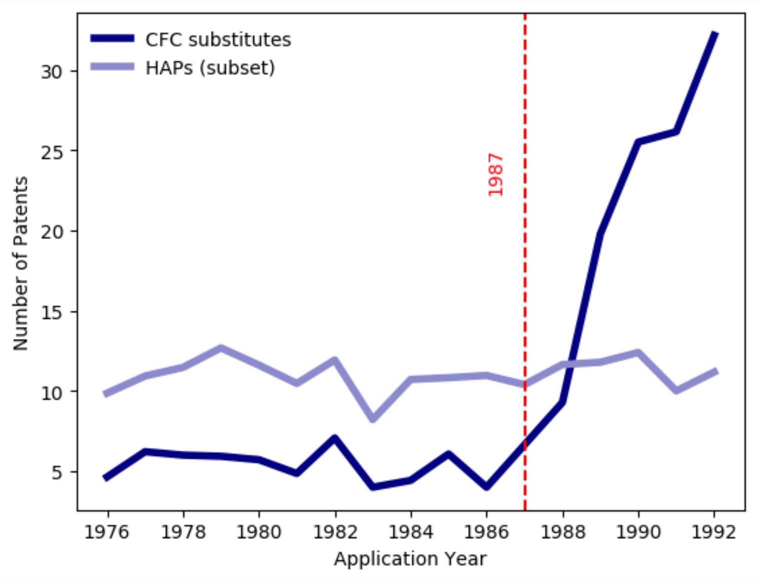
Similar Pre-Trends in Patents for CFC substitutes and HAPs



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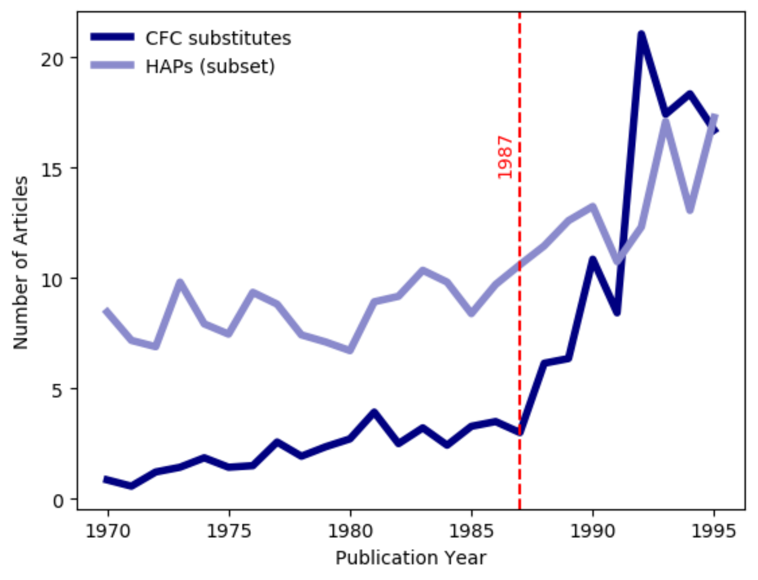
Similar Pre-Trends in Articles for CFC substitutes and HAPs



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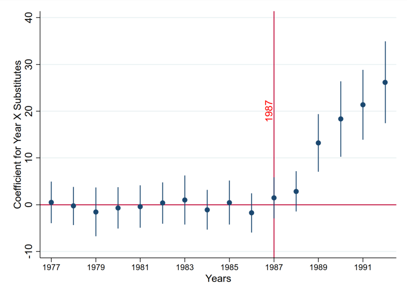
DiD Coefficient Plots

Patents

≈ 309% increase



Articles

≈ 348% increase

Table

Table

DiD Reg Equation

DiD Regression Specification

$$Count_{m,g,t} = \alpha + \beta_0 \cdot D_m \cdot Post_t + \lambda_t + \lambda_m + \epsilon_{m,g,t} \qquad (1)$$

- $Count_{m,g,t}$ is the number of documents with molecule m belonging to molecule group g, in year t
- D_m equals 1 if the molecule belongs to the treated group
- $Post_t$ equals 1 if $t > 1987$
- λ_t are years fixed effects
- λ_m are molecule fixed effects

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DiD Results for Patents

	(1) Counts	(2) Counts	(3) Counts	(4) Counts
Post 1987 x Substitutes	16.54	21.12	0.46	3.44
	(1.74)	(2.06)	(2.68)	(2.49)
Post 1987 x Substitutes x Years			5.23	5.77
			(1.01)	(0.83)
Substitutes x Years			0.05	-0.00
			(0.12)	(0.13)
Years			-0.07	-0.09
			(0.06)	(0.07)
Post 1987			1.18	1.21
			(0.65)	(0.76)
Year FE	Yes	Yes	No	No
Molecule FE	Yes	Yes	Yes	Yes
Topics (weighted)	No	Yes	No	Yes
Bootstraped	Yes	Yes	Yes	Yes
R-squared	0.84	0.86	0.85	0.87
Observations	714	595	714	595

Standard errors in parentheses

Bootstrapped standard errors in parentheses.

Dependent variable: Number of Patents.

DiD Results for Articles

	(1)	(2)	(3)	(4)
Post 1987 x Substitutes	7.58	12.63	-0.27	1.44
	(1.12)	(1.69)	(1.63)	(2.48)
Post 1987 x Substitutes x Years			1.82	2.06
			(0.38)	(0.50)
Substitutes x Years			-0.03	0.11
			(0.08)	(0.16)
Years			0.18	0.21
			(0.03)	(0.04)
Post 1987			0.97	0.91
			(0.45)	(0.51)
Year FE	Yes	Yes	No	No
Molecule FE	Yes	Yes	Yes	Yes
Topics (weighted)	No	Yes	No	Yes
Bootstraped	Yes	Yes	Yes	Yes
R-squared	0.63	0.64	0.63	0.64
Observations	1092	846	1092	846

Standard errors in parentheses

Bootstrapped standard errors in parentheses.

Dependent variable: Number of Articles.

Variable 'Years' is relative to 1987.

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DiD Results for Patents: Robustness Checks

	(1) Count	(2) Count	(3) Cit	(4) Occ	(5) Cit-Occ
Post 1987 x Substitutes	21.12	13.00	29.85	33.45	44.91
	(2.06)	(1.71)	(3.38)	(3.79)	(6.70)
Count (lag 1)		0.39			
		(0.07)			
Count (lag 2)		0.27			
		(0.07)			
Year FE	Yes	Yes	Yes	Yes	Yes
Molecule FE	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	Yes	Yes	Yes	Yes	Yes
Bootstraped	Yes	Yes	Yes	Yes	Yes
R-squared	0.86	0.90	0.78	0.70	0.66
Observations	595	528	595	595	595

Bootstrapped standard errors in parentheses. Time period: 1976 to 1992

Back

DiD Results for Articles: Robustness Checks

	(1) Count	(2) Count	(3) Cit	(4) Occ	(5) Cit-Occ
Post 1987 x Substitutes	12.63	5.10	12.22	17.62	18.11
	(1.69)	(1.25)	(3.38)	(2.71)	(4.43)
Count (lag 1)		0.34			
		(0.05)			
Count (lag 2)		0.34			
		(0.08)			
Year FE	Yes	Yes	Yes	Yes	Yes
Molecule FE	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	Yes	Yes	Yes	Yes	Yes
Bootstraped	Yes	Yes	Yes	Yes	Yes
R-squared	0.64	0.75	0.34	0.49	0.37
Observations	846	790	846	846	846

Standard errors in parentheses. Time period: 1970 to 1995

Back

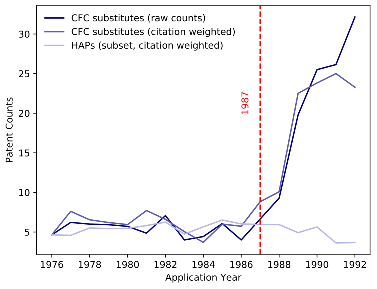
Citation and Occurrence-Weighted Counts

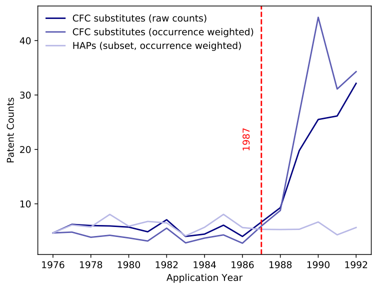
Back

Citation-weighted

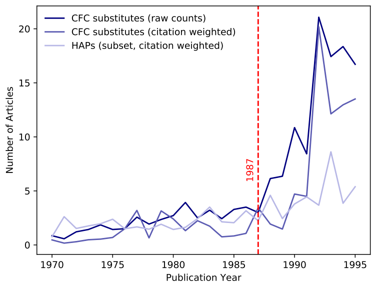
Occurrence-weighted

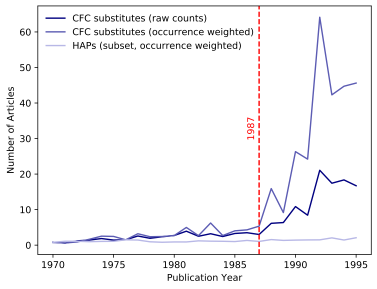
Patents





Articles





Counts with Higher Thresholds of Occurrences

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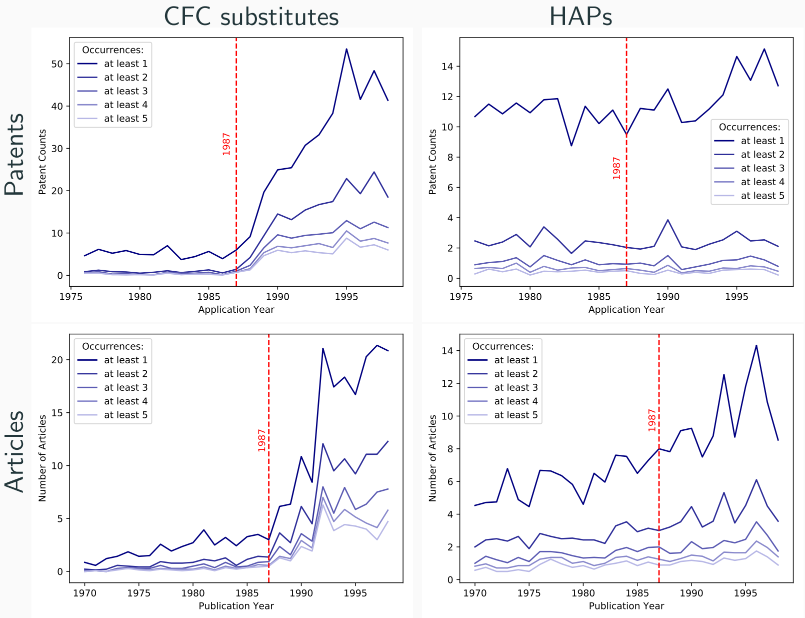

DiD Robustness: Triadic Patents

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	(1)	(2)
Post 1987 x Substitutes	9.47	3.37
	(1.13)	(1.99)
Post 1987 x Substitutes x Years		2.81
		(0.64)
Substitutes x Years		-0.28
		(0.12)
Years		0.58
		(0.06)
Post 1987		-1.56
		(0.55)
Year FE	Yes	No
Molecule FE	Yes	Yes
R-squared	0.71	0.72
Observations	714	714

Standard errors in parentheses.
Dependent variable: Number of Triadic Patents.
Variable 'Years' is relative to 1987.
Time period: 1976 to 1992

DiD Robustness: Zero-Inflated Negative Binomial for Patents

	(1) Count	(2) Count	(3) Count	(4) Citations	(5) Occurrences	(6) Citations-Occurren
Post 1987 x Substitutes	1.733***	1.619***	1.317***	1.614***	2.211***	2.181***
	(0.132)	(0.129)	(0.130)	(0.142)	(0.172)	(0.175)
Count (lag 1)			0.015***			
			(0.003)			
Count (lag 2)			0.008**			
			(0.004)			
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Molecule FE	Yes	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	No	Yes	Yes	Yes	Yes	Yes
R-squared						
Observations	714	595	528	595	595	595

Zero-inflated negative binomial regression.
Dependent variable: Number of Patents.
Time span: 1976 to 1992

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DiD Robustness: Zero-Inflated Negative Binomial for Articles

	(1) Count	(2) Count	(3) Count	(4) Citations	(5) Occurrences	(6) Citations-Occurren
Post 1987 x Substitutes	1.197***	0.827***	0.506***	1.407***	1.456***	2.163***
	(0.143)	(0.124)	(0.124)	(0.274)	(0.157)	(0.220)
Count (lag 1)			0.009**			
			(0.004)			
Count (lag 2)			0.012***			
			(0.004)			
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Molecule FE	Yes	Yes	Yes	Yes	Yes	Yes
Topics (weighted)	No	Yes	Yes	No	Yes	No
R-squared						
Observations	840	676	613	840	676	840

Zero-inflated negative binomial regression.
Dependent variable: Number of Articles.
Time span: 1976 to 1995

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SCM vs. DiD

Back

1. Individual CFC substitutes vs aggregate quantities
   - DiD tells a story about the average CFC substitute
   - DiD captures uncertainty about the aggregate data
   - Here, aggregate data is observed: the 14 CFC substitutes
     $\Rightarrow$ Use SCM to construct a counterfactual molecule that would best mimics the evolution of the CFC substitutes in aggregate
2. Observations in the DiD are not independent
   - Patents and articles often mention several CFC substitutes (in the same document)
   - Example for Patents: almost 40% of patents mention more than one CFC substitutes

Details

Observations in DiD are not Independent

Back

- Patents:
  - Out of 3270 patents mentioning CFC substitutes, 1234 mention more than one CFC substitutes.
  - The DiD considers 5999 observations when, in reality, there are only 3270.
- Articles:
  - Out of 998 patents mentioning CFC substitutes, 226 mention more than one CFC substitutes.
  - The DiD considers 1266 observations when, in reality, there are only 998.

SCM in Practice

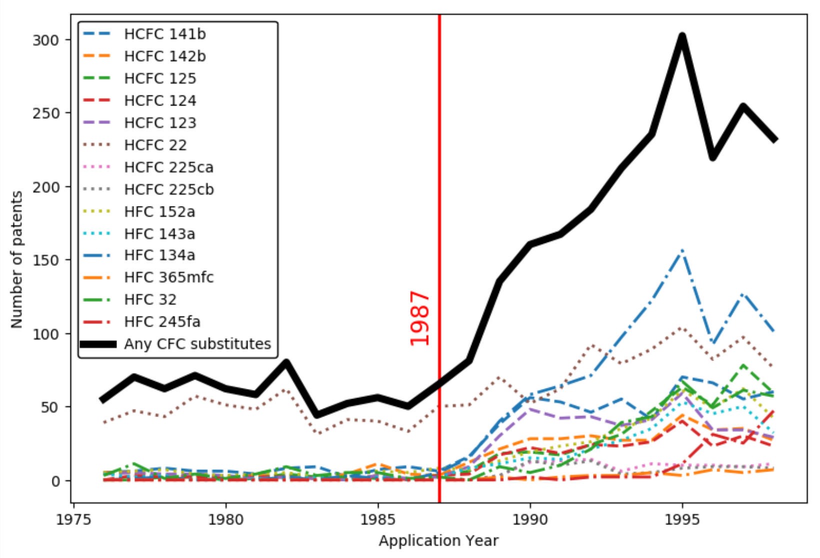
Back

- Developed by Abadie et al. (2010, 2015) and Abadie and Gardeazabal (2003) Intuition Theory
- Key idea (with an example):
  - Outcome: Y_{1t}, count of patents on CFC substitutes in year t
  - Control / Donor pool: 3 HAPs (e.g.: a, b, c)
  - Weights are chosen s.t. treated unit and synthetic control are similar:

$$Y_{1t} \approx \mu_a \times Y_{at} + \mu_b \times Y_{bt} + \mu_c \times Y_{ct}$$

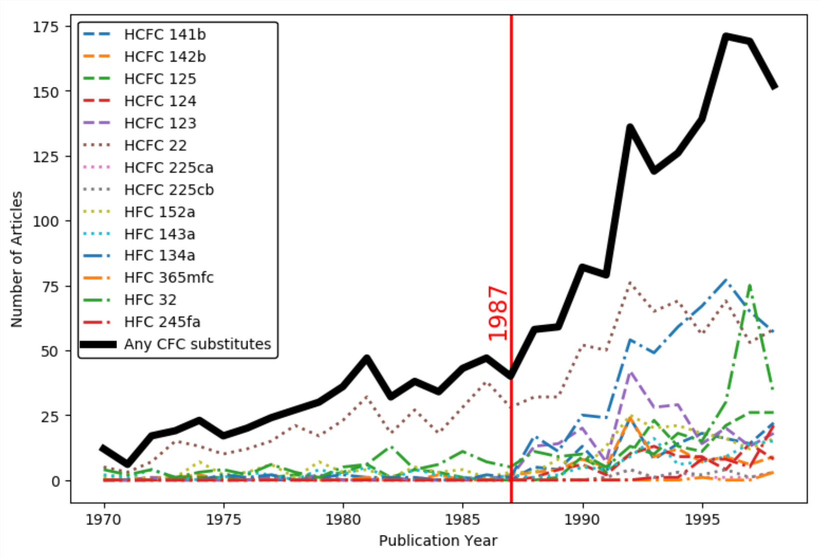
- Donor pool No extrapolation
  - 30 HAPs closest to aggregate CFC Substitute
  - Closest in terms of count
- Variables used to fit synthetic controls Variable Weights
  - Count (each year up to 1985)
  - Topic proportions (average in the pre-period)

Aggregating the 14 Substitutes (Patents)



See Graph for Articles

Aggregating the 14 Substitutes (Articles)



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SCM Theory: Intuition

- Y_{it}^N: # documents on molecule i in year t if no intervention
- Factor model: $Y_{it}^N = \delta_t + \theta_t Z_i + \lambda_t \mu_i + \epsilon_{it}$
  - δ_t: an unknown common factor w constant loadings across units
  - θ_t: vector of unknown parameters
  - Z_i: vector of observed covariates (not affected by intervention)
  - λ_t: unobserved common factors
  - μ_i: vector of unknown factor loadings
  - ϵ_{it}: unobserved transitory shocks at the region level with zero mean
- DiD: λ_t constant; μ_i eliminated by time difference
- Unbiased estimator of Y_{1t}^N:
  - A synthetic control s.t. $\sum_{j=2}^{J+1} w_j^* Z_j = Z_1$ and $\sum w_j^* \mu_j = \mu_1$
  - How to fit μ_1?
  - In practice, we fit Y_{11} ... Y_{1T_0} and Z_1

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SCM Theory

- Y_{it}: # documents on molecule i in year t
- J+1 molecules. Treated molecule denoted with 1. J controls.
- Treatment effect: $\alpha_{it} = Y_{it}^T - Y_{it}^N$
  Y_{it}^N, Y_{it}^T: resp. if no intervention and if intervention
  Challenge: estimate Y_{it}^N
- Abadie et al. (2010) show that:

$$Y_{1,t}^N \approx \sum_{j=2}^{J+1} w_j^* Y_{jt} \tag{2}$$

with w^* s.t. $\sum_{j=2}^{J+1} w_j^* Y_{jt} = Y_{1,t}$ and $\sum w_j^* Z_j = Z_1$
when the scale of transitory shocks small relative to number of pre-intervention periods

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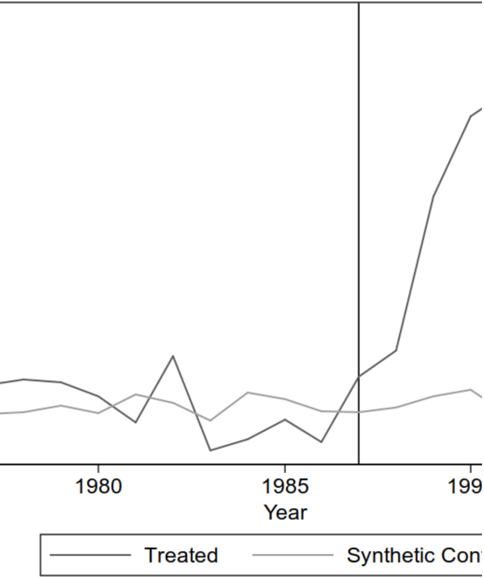
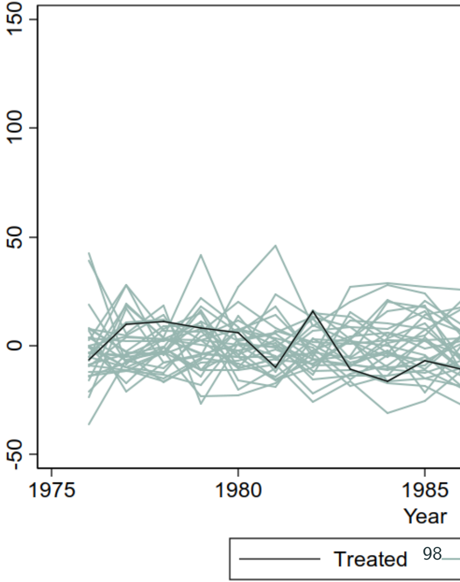
SCM Result: 135% increase over 1988-1992 for Patents

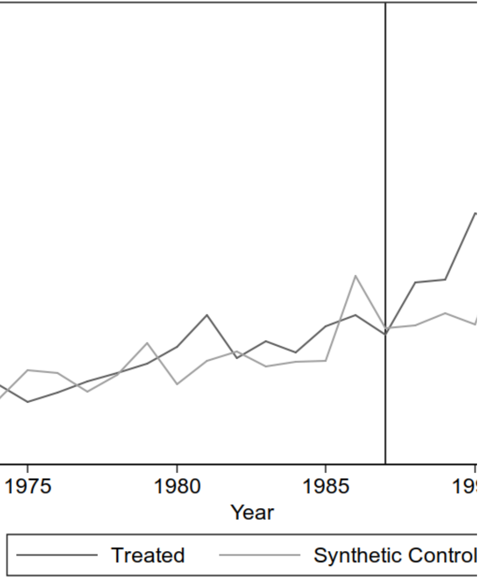
Close to 64 additional patents on average per year

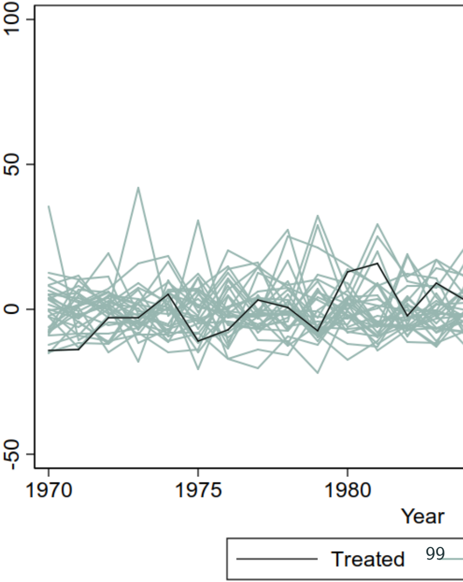




SCM: 177% increase over 1988-1995 for Articles

Close to 49 additional articles on average per year





SCM: Extrapolation Check for Patents

Note: SCM constrains weights to sum to one.

Variables (pre-1986 average)	Substitutes	HAPs Mean	HAPs Min	HAPs Max	HAPs Std.Dev.
Count	34.36	59	36.45	87.55	19.19
Topic 1 (weighted mean)	0.01	0.04	0.01	0.1	0.03
Topic 2 (weighted mean)	0.14	0.04	0	0.19	0.05
Topic 3 (weighted mean)	0.07	0.08	0.01	0.18	0.04
Topic 4 (weighted mean)	0.08	0.01	0	0.03	0.01
Topic 5 (weighted mean)	0.03	0.02	0	0.08	0.02
Topic 6 (weighted mean)	0.26	0.06	0.01	0.14	0.04
Topic 7 (weighted mean)	0.07	0.19	0.01	0.74	0.21
Topic 8 (weighted mean)	0.01	0.09	0	0.33	0.09
Topic 9 (weighted mean)	0.05	0.03	0	0.09	0.03
Topic 10 (weighted mean)	0.02	0.02	0	0.1	0.02
Topic 11 (weighted mean)	0.09	0.04	0	0.2	0.04
Topic 12 (weighted mean)	0.04	0.01	0	0.03	0.01
Topic 13 (weighted mean)	0.04	0.06	0.01	0.3	0.07
Topic 14 (weighted mean)	0.04	0.04	0.01	0.11	0.03
Topic 15 (weighted mean)	0.04	0.01	0	0.04	0.01
Topic 16 (weighted mean)	NaN	0.08	0.02	0.23	0.06
Topic 17 (weighted mean)	NaN	0.01	0	0.02	0.01
Topic 18 (weighted mean)	NaN	0.02	0	0.07	0.02
Topic 19 (weighted mean)	NaN	0.02	0	0.07	0.02
Topic 20 (weighted mean)	NaN	0.14	0.02	0.57	0.16

SCM: Extrapolation Check for Articles

Note: SCM constrains weights to sum to one.

Variables (pre-1986 average)	Substitutes	HAPs Mean	HAPs Min	HAPs Max	HAPs Std.Dev.
Count	34.36	31.38	22.27	41.82	4.85
Topic 1 (weighted mean)	0.01	0.04	0.01	0.11	0.03
Topic 2 (weighted mean)	0.14	0.03	0.01	0.07	0.02
Topic 3 (weighted mean)	0.07	0.02	0	0.1	0.02
Topic 4 (weighted mean)	0.08	0.1	0.02	0.31	0.08
Topic 5 (weighted mean)	0.03	0.04	0	0.13	0.04
Topic 6 (weighted mean)	0.26	0.05	0.01	0.18	0.05
Topic 7 (weighted mean)	0.07	0.04	0	0.24	0.05
Topic 8 (weighted mean)	0.01	0.03	0	0.08	0.02
Topic 9 (weighted mean)	0.05	0.13	0.03	0.45	0.13
Topic 10 (weighted mean)	0.02	0.08	0.01	0.25	0.07
Topic 11 (weighted mean)	0.09	0.03	0	0.08	0.02
Topic 12 (weighted mean)	0.04	0.13	0.04	0.32	0.07
Topic 13 (weighted mean)	0.04	0.16	0.01	0.49	0.15
Topic 14 (weighted mean)	0.04	0.06	0.01	0.29	0.07
Topic 15 (weighted mean)	0.04	0.05	0	0.14	0.04

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SCM: Weights Assigned to Variables in Optimization

Patents

	Variable Weight
Topic 1	0.02
Topic 2	0.04
Topic 3	0.05
Topic 4	0.10
Topic 5	0.03
Topic 6	0.02
Topic 7	0.10
Topic 8	0.04
Topic 9	0.01
Topic 10	0.03
Topic 11	0.01
Topic 12	0.04
Topic 13	0.03
Topic 14	0.04
Topic 15	0.02
Topic 16	0.01
Topic 17	0.02
Topic 18	0.08
Topic 19	0.27
Topic 20	0.01
Count	0.02

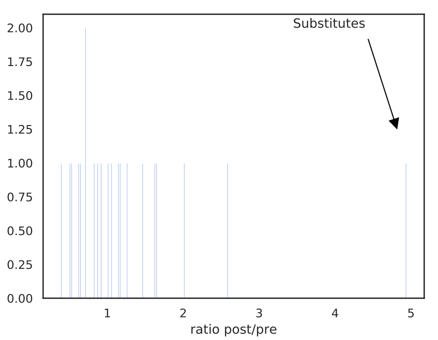
Articles

	Variable Weight
Topic 1	0.06
Topic 2	0.06
Topic 3	0.07
Topic 4	0.07
Topic 5	0.06
Topic 6	0.07
Topic 7	0.02
Topic 8	0.05
Topic 9	0.02
Topic 10	0.07
Topic 11	0.13
Topic 12	0.05
Topic 13	0.12
Topic 14	0.04
Topic 15	0.07
Count	0.05

Back

SCM and Inference

- Method akin to "placebo" tests (Abadie et al. 2010, 2015):
  - Take a control unit and consider it is "treated"
  - Construct a synthetic control $\Rightarrow$ "placebo" treatment effect
  - Do this for all control units $\Rightarrow$ distribution of placebo effects
- Compare treated unit to placebo units
  - Or compare $ratio_j = \frac{post-RMSPE_j}{pre-RMSPE_j}$
  - p-value: fraction of placebos with ratio larger than the treated unit
- Distribution of post/pre RMSPE ratios:



e.g., p-value equals 1/168 ($\approx$ 0.01)

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Pre-RMSPE

- Synthetic control must match the treated unit

  That is: $\sum_{j=2}^{J+1} w_j^* Y_{jt} = Y_{1,t}$ and $\sum w_j^* Z_j = Z_1$ must hold
- Measure of lack of fit: pre-RMSPE
  - Root Mean Square Prediction Error before treatment
  - Subscript 1 denotes the treated unit
  - Pre-RMSPE of unit 1:

$$\sqrt{\frac{1}{T_0}\sum_{t=1}^{T_0}(Y_{1t} - \sum_{j=2}^{J+1} w_j^* Y_{jt})^2} \tag{3}$$

where T_0 is the number of pre-treatment periods.

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Top HAPs in the Synthetic Control for Patents

HAPs	Weight	Description
Calcium cyanamide	0.327	Used as a fertilizer, defoliant, herbicide, fungicide, and pesticide; in the manufactureand refining of iron; and in the manufacture of calcium cyanide, melamine, and dicyandiamide.
Polychlorinated biphenyls	0.206	Group of chemicals characterized by non-flammability, stability, high boiling point and electrical insulating properties. Hundreds industrial applications: electrical and heat transfer, paints, plastics.
Methyl bromide	0.140	Used as a fumigant in soil to control fungi, nematodes, and weeds; inspace fumigation of food commodities (e.g., grains); and in storage facilities (such as mills, warehouses,vaults, ships, and freight cars) to control insects and rodents.
Benzidine	0.116	Production of dyes, especially azo dyes in the leather, textile, and paper industries
o-Xylenes	0.103	Used in the production of ethylbenzene, as solvents in products such as paints andcoatings, and are blended into gasoline.

Note: Molecule descriptions sourced from the EPA

Articles

Top HAPs in the Synthetic Control for Articles

HAPs	Weight	Description
Bromoform	0.503	Used as a fluid for mineral ore separation, as a laboratory reagent and in the electronics industry in quality assurance programs. Was used as a solvent for waxes, greases, and oils, as an ingredient in fire-resistant chemicals and in fluid gauges. Also used as an intermediate in chemical synthesis, as a sedative and cough suppression agent.
1,4-Dichlorobenzene	0.332	Used mainly as a fumigant for the control of moths, molds and mildews, and as a space deodorant for toilets and refuse containers. Also used as an intermediate in the production of other chemicals, in the control of tree-boring insects, and in the control of mold in tobacco seeds.
Trifluralin	0.165	Herbicide. Mostly used on cotton, soybeans and some fruits and vegetables

Note: Molecule descriptions sourced from the EPA

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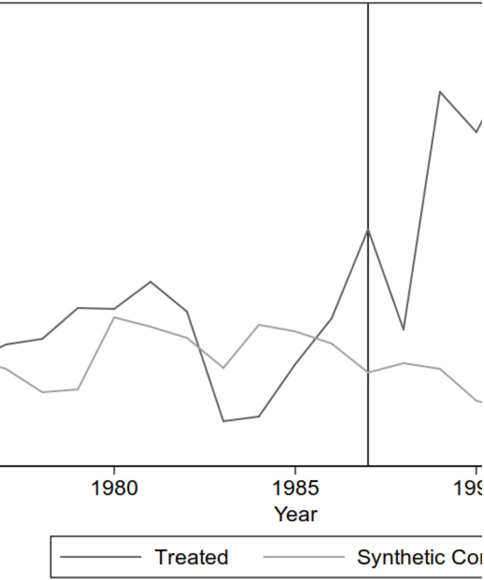
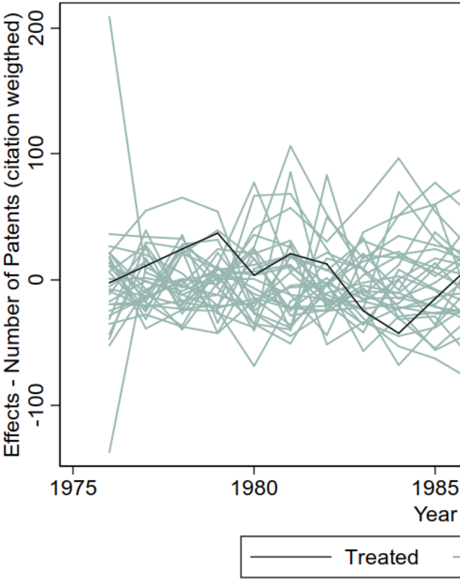
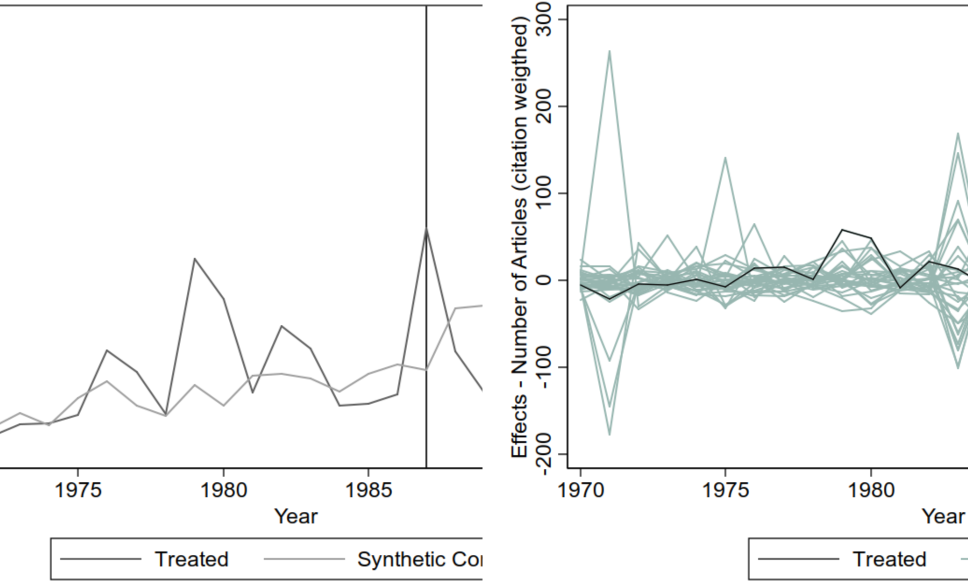
SCM Robustness: Citation-Weighted Counts for Patents

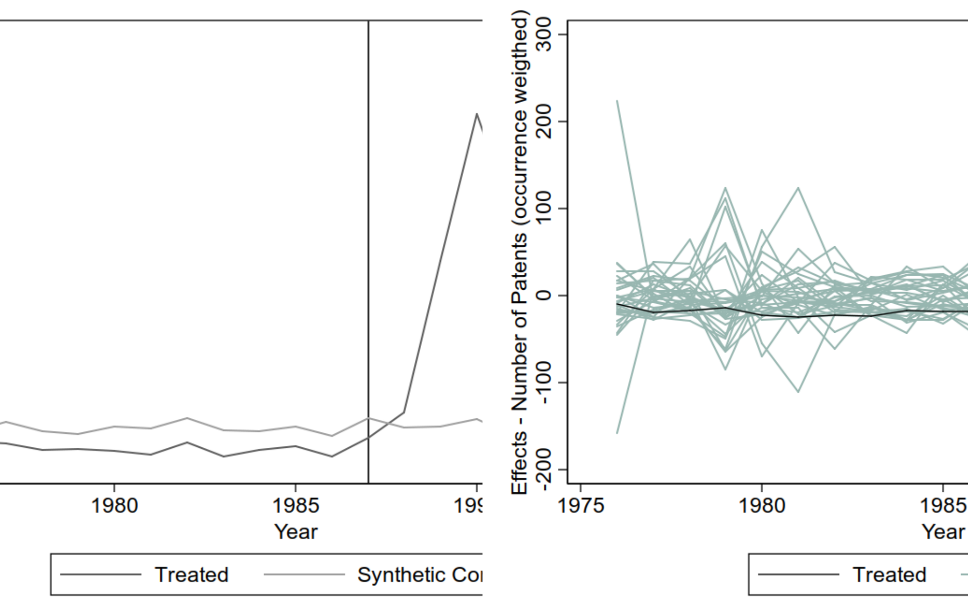




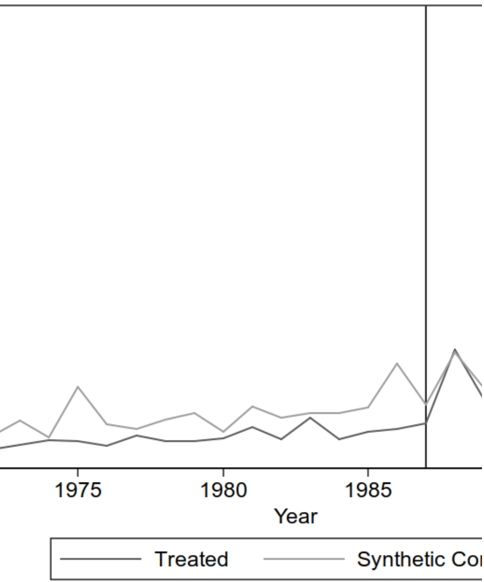
SCM Robustness: Citation-Weighted Counts for Articles

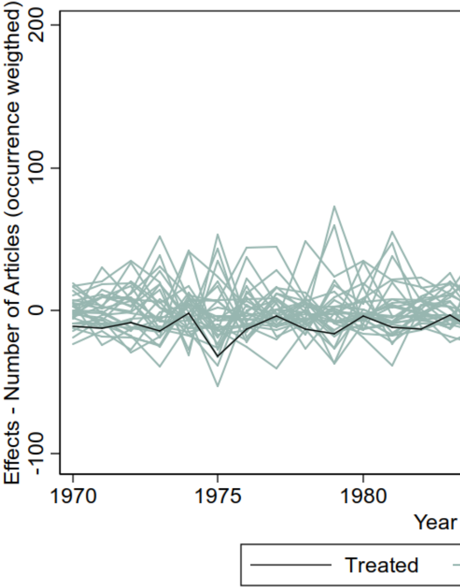


SCM Robustness: Occurrence-Weighted Counts for Patents

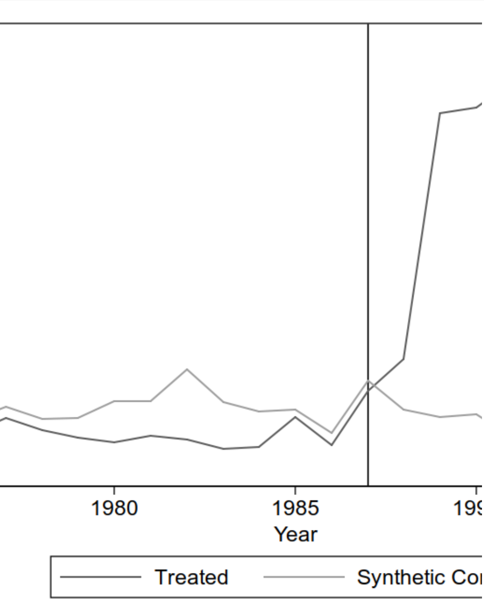


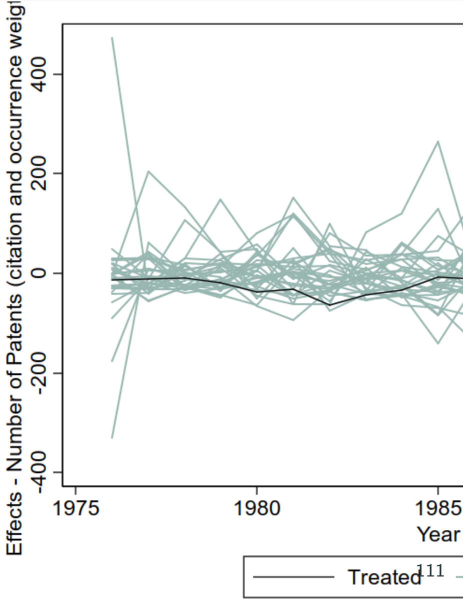
SCM Robustness: Occurrence-Weighted Counts for Articles



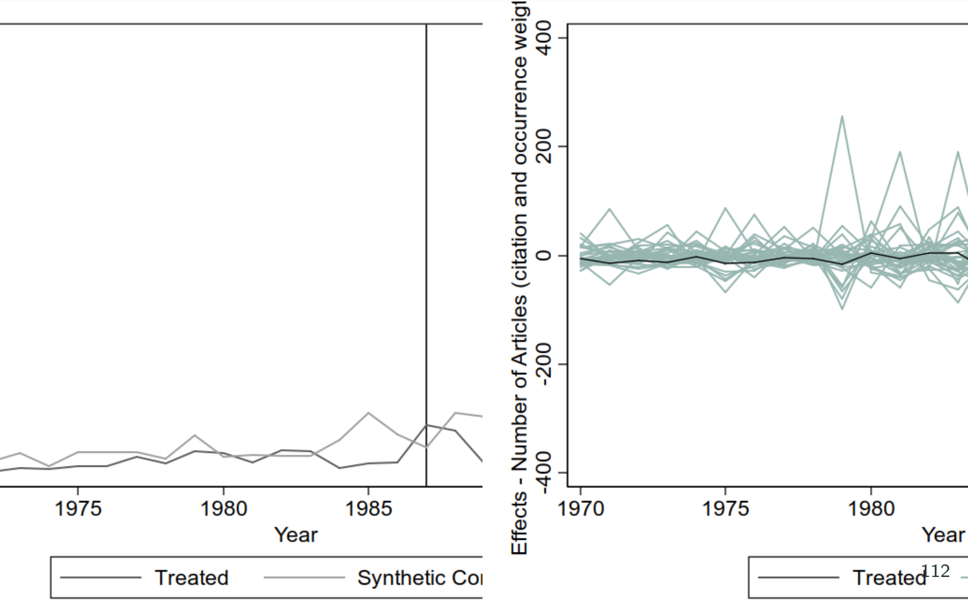


SCM Robustness: Citation-Occurrence-Weighted Counts for Patents

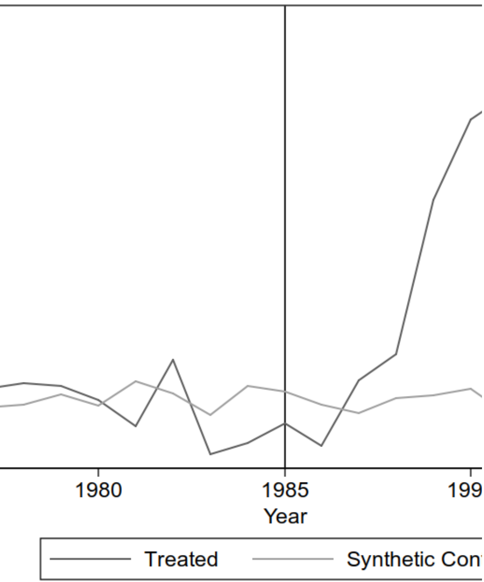


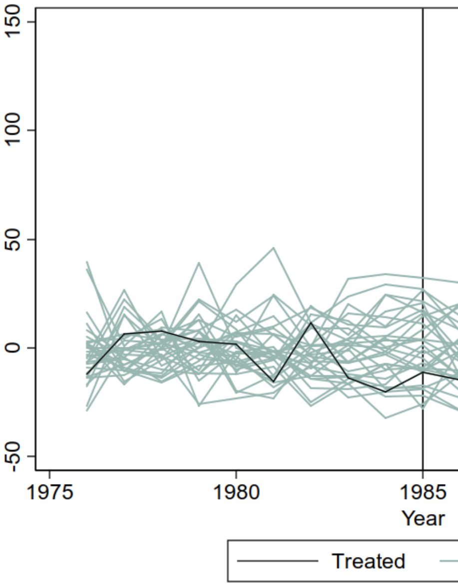


SCM Robustness: Citation-Occurrence-Weighted Counts for Articles

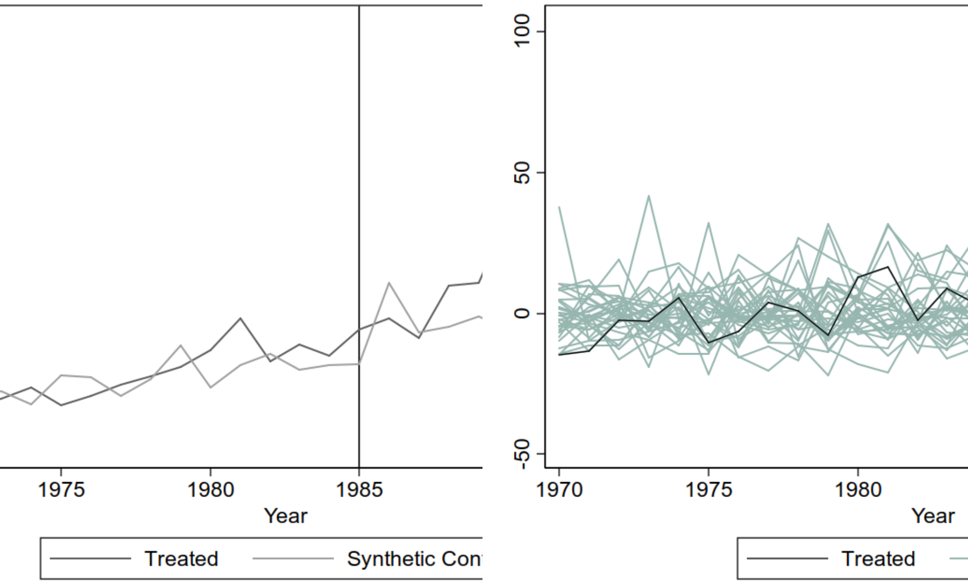


SCM Robustness: Anticipation for Patents

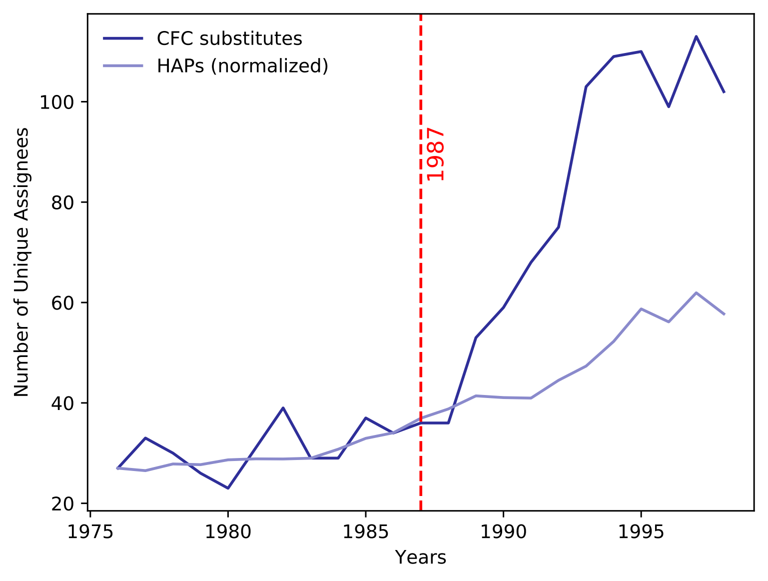




SCM Robustness: Anticipation for Articles



Unique assignees



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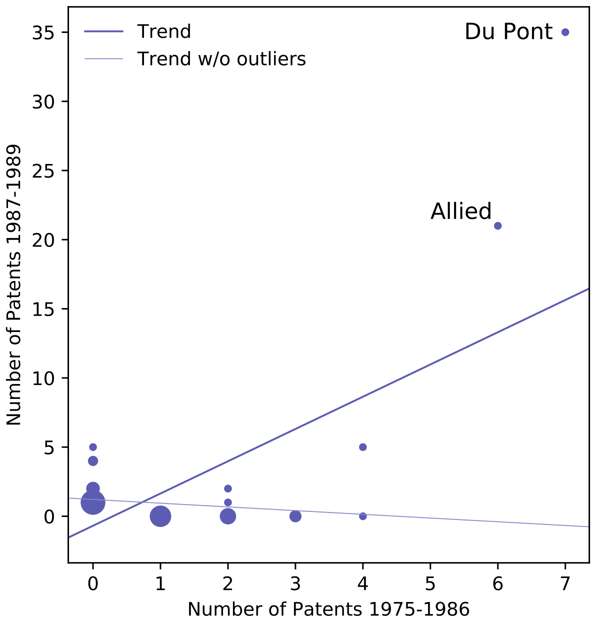
The Big Players: Du Pont and Allied



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Du Pont and Allied

- Du Pont Freon® Products Division (Reinhardt and Vietor 1989b):
  - 2% of Du Pont revenues in 1987
    2.2% (1986), 1.7% (1985), 1.8% (1984)
  - 2% of corporate assets
  - 0.9% of Du Pont's employees
  - About half of the US market in 1986
- Allied: second top US producer
  about half Du Pont production's capacity in 1986

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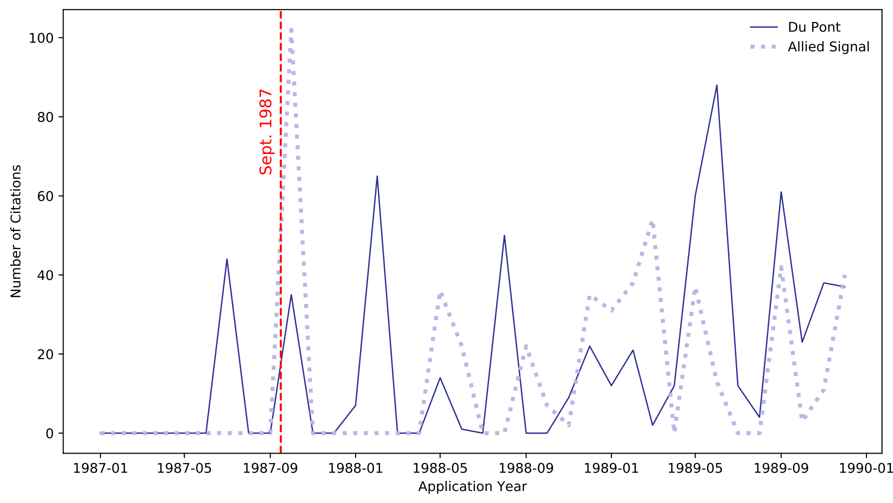
Du Pont/Allied: Some Highly Cited Patents in 1987



See these highly cited patents | Raw counts | Yearly citation weighted | Back

Du Pont/Allied: Some Highly Cited Patents in 1987

- Du Pont Oct 1987 patent (HCFC-123, HCFC-124)

  An improved gas-phase process for the manufacture of 1,1,1-trifluorodichloroethane and/or 1,1,1,2-tetrafluorochloroethane by contacting a suitable tetrahaloethylene and/or pentahaloethane with hydrogen fluoride in the presence of Cr.sub.2 O.sub.3, prepared by pyrolysis of (NH.sub.4).sub.2 Cr.sub.2 O.sub.7, the reaction being conducted under controlled conditions whereby the production of pentafluoroethane is minimized.

- Allied Oct 1987 patent (HCFC-134a)

  Compression refrigeration equipment using tetrafluoroethane as a working fluid employs polyoxyalkylene glycols which are at least difunctional with respect to hydroxyl groups and a molecular weight between 300 and 2000. The mixtures of the glycols with the refrigerant will be miscible in the range from -40.degree. C. to at least + 20.degree. C.

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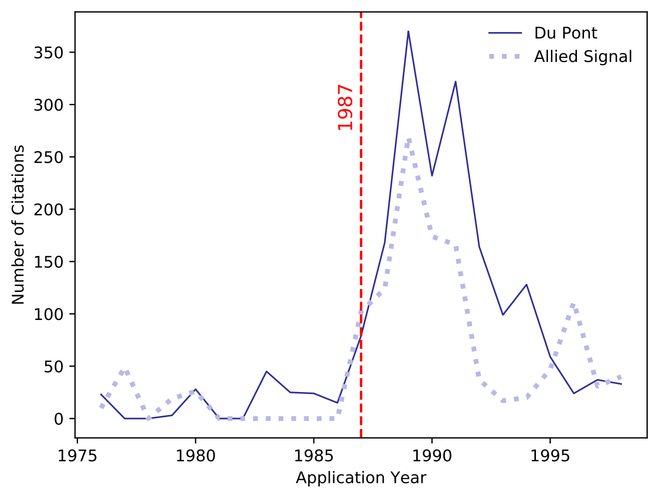
Du Pont/Allied: Highly Cited Patents are in 1989-1991



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Ozone vs Climate Change: Solving the Puzzle

- Why have we solved ozone depletion and not climate change?
  Short answer: an effective treaty is missing for climate change
- What is so special about the Montreal Protocol (esp. wrt to Kyoto)?
  Short answer: an enforcement mechanism (through trade restrictions) and side effects to induce developing countries to join in
- How come countries agreed to sign and ratify such a treaty?
  This is a longer answer, but the USA definitively played a key role.
- Why did the USA agree to sign and ratify Montreal?
  Short answer: Montreal was not very ambitious. Possibly just codified unilateral actions. Possibly an element of luck too with Reagan.
- Why did countries accept to significantly increase ambitions?
  Short answer: ozone hole + innovation

How come countries agreed to sign and ratify such a treaty?

Factors making free-riding not as bad in ozone:

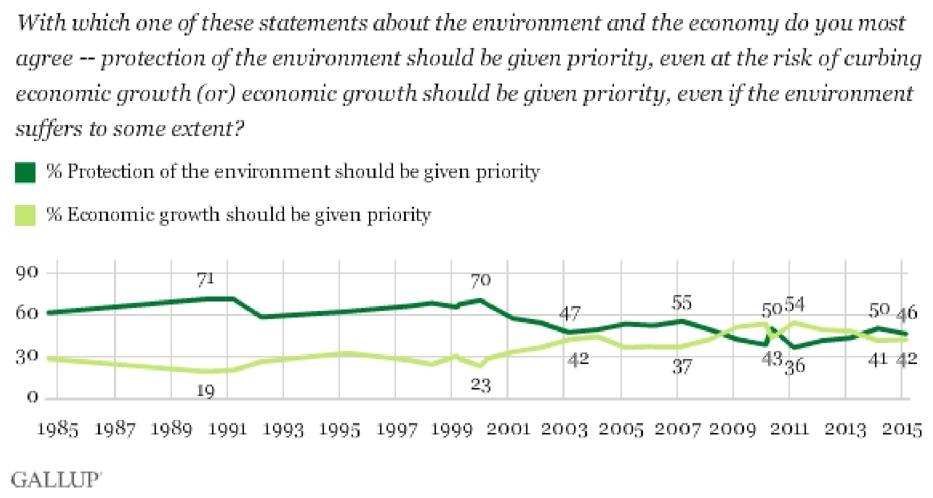
- Every country would suffer from ozone depletion (even CFC producing countries)
- Inter-generational aspect not as stark as CC
- Differences in public opinion in terms of environment vs growth
- Lower number of key players and main polluter (USA) played a leading role

Ozone vs Climate Change

- Ozone and climate change often compared
  - Both: global public goods
  - Both: scientific uncertainties
  - Treaty structure: binding (Montreal) vs. non-binding (Kyoto, Paris)
    Montreal vs. Kyoto told by Google
- Why a binding treaty was reached for ozone and never for climate?
  - Claim: nature of the required technological change
    Specific claim: little technological uncertainty at Montreal
  - Contribution of this paper:
    - Technological uncertainties were also large in the case of ozone
    - Montreal induced innovation which eventually is what solved the crisis
    - Actors did not know ex-ante that it would be easy
  - More important difference:
    $\Rightarrow$ Market structure of regulated industries
    - Ozone: business units within firms had to disappear (CFCs, ...)
    - Climate: entire sectors have to disappear (coal, oil, ...)

Montreal vs. Kyoto through Google | Gallup environment vs growth

Protecting the Environment or Economic Growth?



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SCM Assumption: No Interferences

Assumption

No interference between units

- Research on CFC substitutes does not crowd out research on HAPs
- Robustness check:
  - 75% CFC substitutes assignees never patented on Top HAPs

    Details

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Interference is Very Unlikely (Patents)

- Compare assignees for CFC substitutes vs assignees for HAPs
  - Focus on top HAPs entering the synthetic control
    Top HAPs Patents Top HAPs Articles
  - Assignee names in patent records are not standardized
  - I use fuzzy matching (Python)

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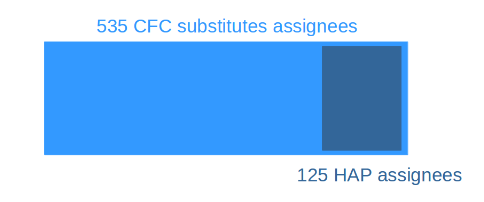

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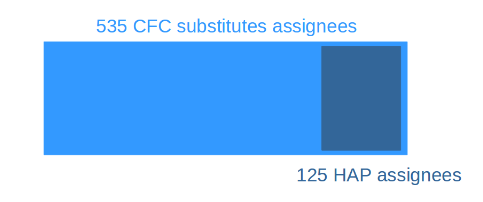

- Examples of assignees shared by CFC substitutes and top HAPs:

3M
Allied Chemical
BASF

Dow Chemical
Procter & Gamble

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Further Results: CFCs Regulated Under Montreal

- **Annex A:** 8 molecules regulated under Annex A in 1987
  e.g.: CFC-11, CFC-12.
- **Annex B:** 12 molecules regulated under Annex B in 1990
  e.g.: carbon tetrachloride.

Question

Did Montreal foster research output related to Annex A and B compounds?

- Unclear ex-ante:
  - weaker incentives to develop technologies based upon them
  - stronger incentives to develop technologies for recycling or more efficient use
- I find no clear positive or negative impact.

Annex A: Table | Graph Raw Patents | Graph Placebo Patents | Graph Raw Articles | Graph Placebo Articles
Annex B: Table | Graph Raw Patents | Graph Placebo Patents | Graph Raw Articles | Graph Placebo Articles
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