General Purpose Technologies and the Evolution of Science: Evidence from the Early Computers

Pedro Aldighieri and Franco Malpassi

Impact of General Purpose Technologies on Science

- General purpose technologies are large technological innovations with uses across many sectors (Bresnahan & Trajtenberg 1992; David 1990)
- Notable examples: steam engine, electric power, computing, AI
- Prior research focused mostly on economic impacts of GPTs (David 1990; Crafts 2004; Autor et al. 1998)
- Other research investigates how science contributes to technological innovation (Mokyr 2002, Rosenberg 1974, Watzinger & Schnitzer 2024)
- In this project, we explore the question of how GPTs affect science itself

This Project

- Focus on a large general purpose technological change: introduction of computers
- Study how adoption of computers at universities impacted research and researchers
  - Focus on the early and large mainframe computers
- Collect and digitize novel data on computer installations at universities up to 1970
- Investigate impact on research outcomes
- Exploit variation in timing of computer adoption across US universities

▸ Contribution to Literature

“There will never be enough problems, enough work for more than one or two of these computers.”

– Howard Aiken, late 40s, quoted in Stern (1981)

“It would appear that we have reached the limits of what is possible to achieve with computer technology, although one should be careful with such statements, as they tend to sound pretty silly in five years.”

– John von Neumann (1949)

Preliminary Findings

- Diffusion of computer technology on research was fast, but uneven
- Effects and usage are concentrated in a few areas, high-impact authors (5%) and papers (3.5%):
    - Early computer use heavily skewed towards Physical Sciences (Physics, Math, Engineering).
    - Computer papers garnered ~20% more citations.
    - Significantly more likely to be top-cited (Top 10%: +17%, Top 1%: +34%).
    - Computer adopters were more cited (3.5x), productive (4x), and broad
    - DiDs suggest computer adoption increased publications, citations, and top papers.
    - Increases were concentrated in Physical and Social Sciences.

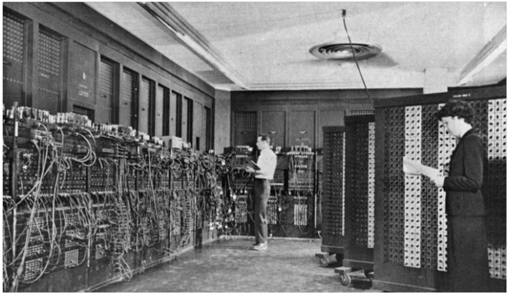
Historical Background

Revolution in Scientific Computing

- Pre-1945: Scientific research constrained by computational power
  - Manual computations and mechanical calculators, prone to error
  - Limited operations per minute, extensive user intervention
  - Large teams of human computers needed for complex tasks
- Sharp transformation with digital computers (late 1940s)
  - ENIAC (1946): First programmable computer, 1,000 times faster than predecessors (Grier 2005) ▸ Quote
  - IBM 650 (1953): First widely adopted computer, 2,000+ units sold

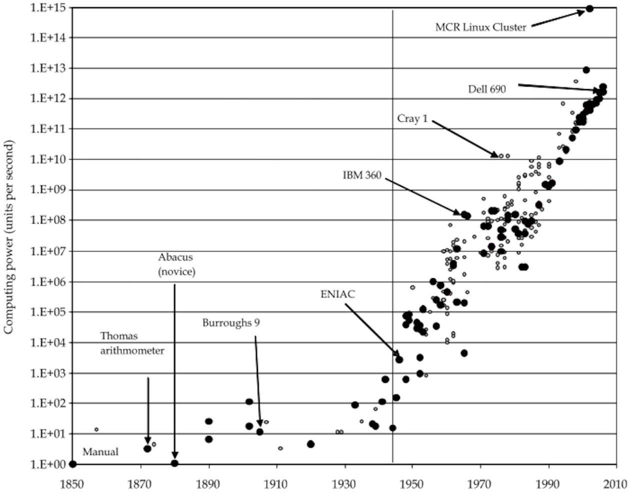
Boom in Computer Innovation: From the ENIAC to IBM

The ENIAC: 1945



IBM 650: 1953

Evolution of Computing Power



The Progress of Computing Power Measured in Computations Per Second (CPS)
Source: Nordhaus 2007

Impact on Research Fields

- Early computers made significant research contributions possible:
  - Chaos Theory: Edward Lorenz's experiments with weather models at MIT in the early 1960s
  - Particle Physics: Alder & Wainwright simulations at Lawrence Livermore (1957) showing crystallization of disordered fluids
  - Physical Chemistry: Ray Pepisnky's work on computers to improve x-ray crystallography at GWU in the early 1950s
  - Bioinformatics: Margaret Dayhoff's Protein Atlas (1965)
  - Economics: Lawrence Klein's econometric and macro forecasting models & GE simulations in the 1960s. Econ examples

Early Digital Computer Adoption by Universities

- High costs of computer installation led to staggered adoption of computers
  - Funding for computer installation obtained from private sources and federal aid such as NSF (Ceruzzi 1998)
- Mostly located in shared computer centers due to high cost and large size
  - NSF conditioned funding on university-wide availability (Roesser 1965)
- Researchers depended on universities or research centers for computer access
- First universities got digital computers in 1951 (MIT, GWU)
- By 1968, most universities had access to a computer

▸ Remote Access Example

Data

Datasets

The analysis draws on three data sources:

1. A novel, comprehensive database of computer installations in US universities
2. Database of scientific publications metadata (OpenAlex)
3. Supporting datasets on computer model features and university characteristics

Chris Hausler using PDP-8 at Carnegie Mellon, late 1960s

Computer Installations Database

- First database of computer installations in US higher education, up to 1971
- Information obtained from surveys of universities, main sources are: ▸ All
  - Computers & Automation magazine Rosters of Organizations
  - Data Processing Yearbooks university computer center surveys
  - University of Rochester Computer Center surveys ▸ Snapshot
  - Southern Education Board/NSF surveys by John Hamblen ▸ Snapshot
  - National Research Council's Roesser Report
- In total, 24 survey sources collected, digitized, and processed with 82 survey-year pairs, totaling 18,282 computer snapshots ▸ Database Sample
- Covers 1,180 US universities spanning 50 states, DC and Puerto Rico
- Covers all US doctoral granting institutions

Survey Coverage Timeline

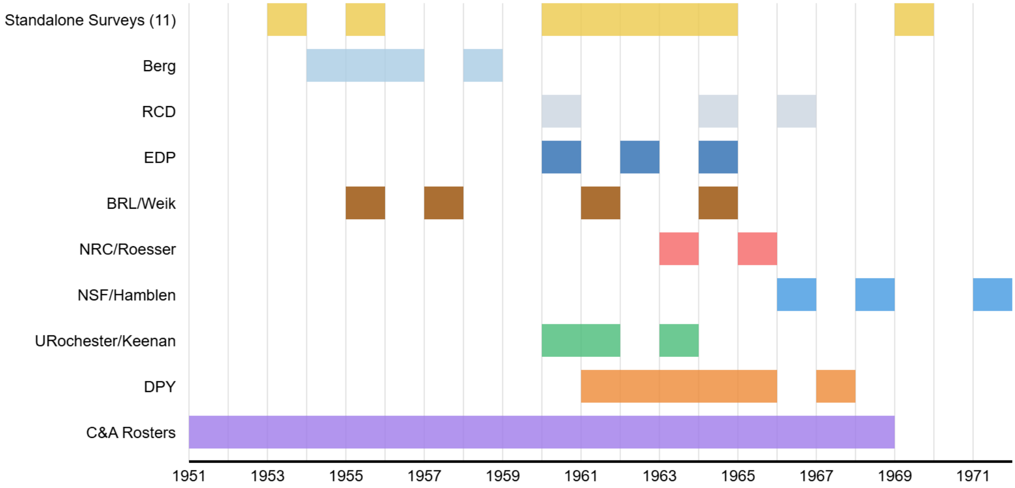


Figure 1: Yearly coverage of surveys in database. Refers to survey year of publication. Surveys not mentioned before include: Educational Programs and Facilities in Nuclear Science and Engineering (EDP); Research Centers Directory (RCD); Business Electronics Reference Guide (Berg). Standalone surveys refer to surveys that happened only once. ▸ All

Data Work: Past and Future

Installations data:

- Manually processing universities
- Verify and fill in gaps with supplementary sources:
  - University archives, digital collections;
  - Specialized magazines and publications (e.g. Digital Computer Newsletter)
  - Manufacturer sources (IBM, DEC, Burroughs)
- Processed 186 universities (2,200 installations) List
- Directly dated 74% of the sample installations

Supplementary data:

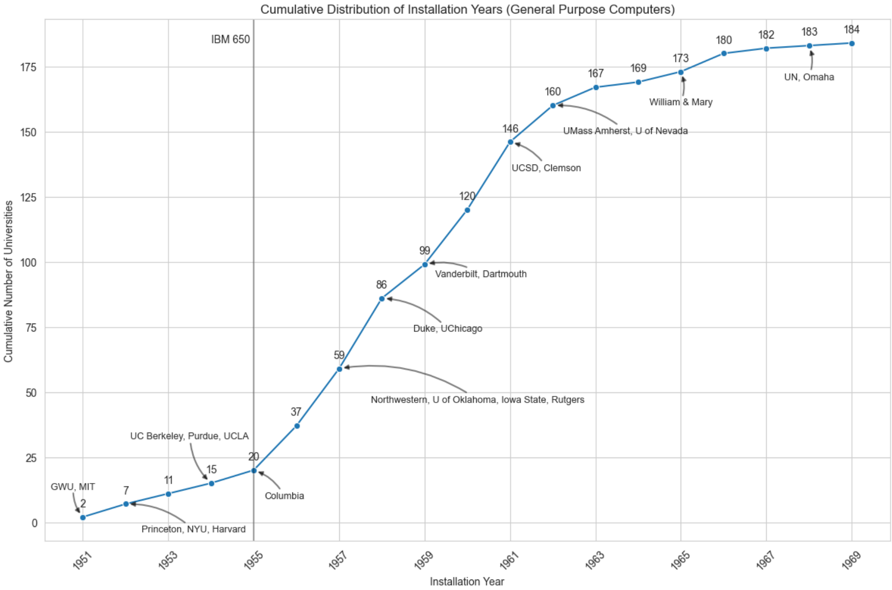
- Computer model features: computer quality and costs from historical surveys
- University characteristics: covariates from College Blue Books (Bleemer & Quincy 2024)

Publication Data

- We retrieve publication metadata from OpenAlex
  - Succeeded Microsoft Academic Graph (MAG) after its discontinuation in 2021
  - Used in recent literature (Lubzyk and Moser, 2024)
- Extract for each published paper:
  - Authors
  - Affiliations
  - Citations
  - Date of publication
  - Topics of research
- Covers 26 fields in Physical, Life, Medical, and Social sciences ▸ Publications over the years
- Filter papers between 1940-1970 with affiliation from universities in sample

Empirical Analysis & Findings

Digital Computer Adoption by US Universities, 1950-1970



Computer Installations Descriptive Statistics

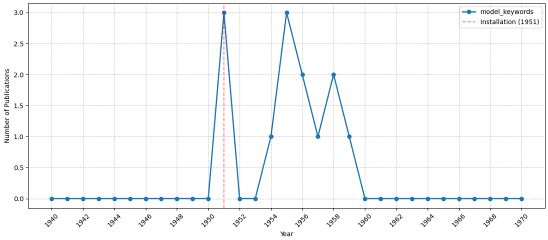
- IBM dominated with 58% of installations, DEC followed at 9%
- The IBM 650 was first computer for 49 universities (27%)
- Pre-1955: 12/16 universities (75%) built own computers
- 27 universities built 44 computers internally, mostly IAS-based
- Analog computers: 171 installations (8%)

	# Computers per university
mean	11.6
std	11.2
min	1
25%	5
50%	8
75%	15
max	83

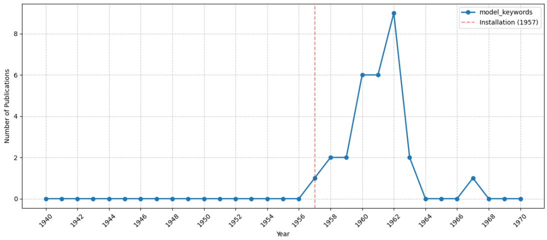
Computer-Related Keywords

- Out of ∼650,000 papers in our sample, we can search full-text for 73%
- Flag whether papers mention computer-related keywords like “digital computer” or “high-speed computing device” ▸ List
- We match 16,064 papers (3.5% of searcheable papers)
- To avoid false positives, also search for computer models installed at university
- Find that researchers start using computer immediately after installations

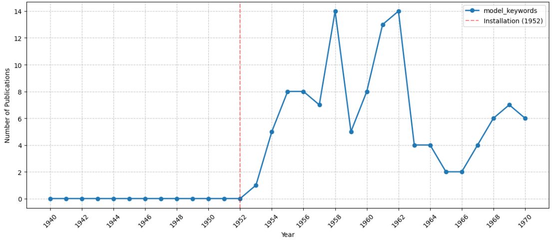
Computer Model Mentions Across Universities



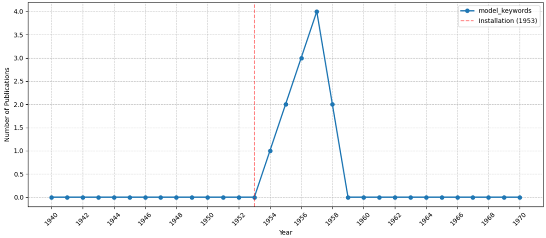
Massachusetts Institute of Technology



Northwestern University

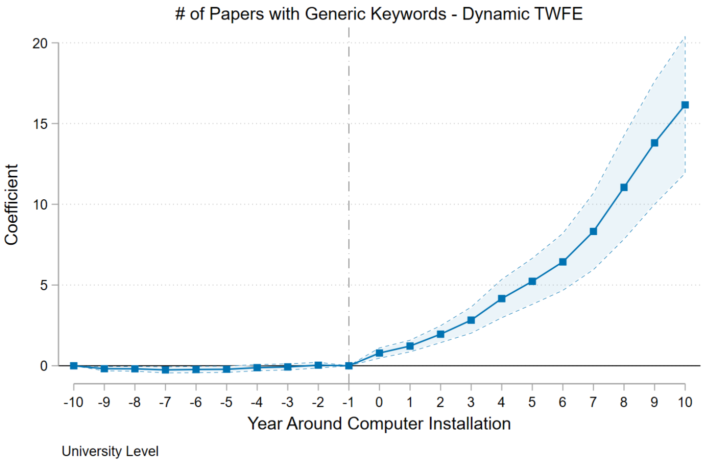


University of Illinois, Urbana-Champaign



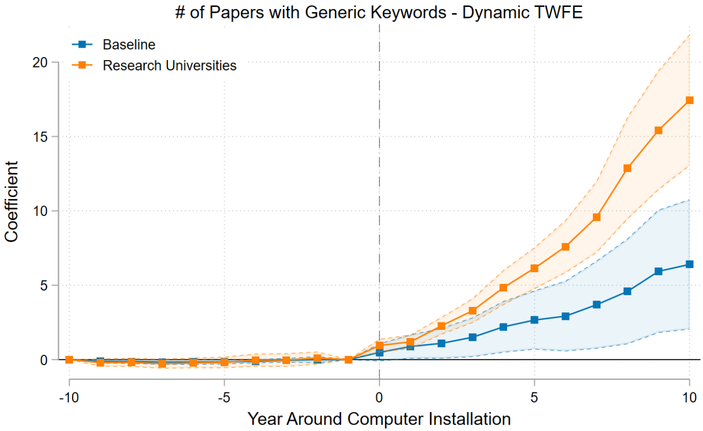
University of Michigan, Ann Arbor

Differences-in-Differences: Computer Related-Keywords



▸ CS ▸ Share

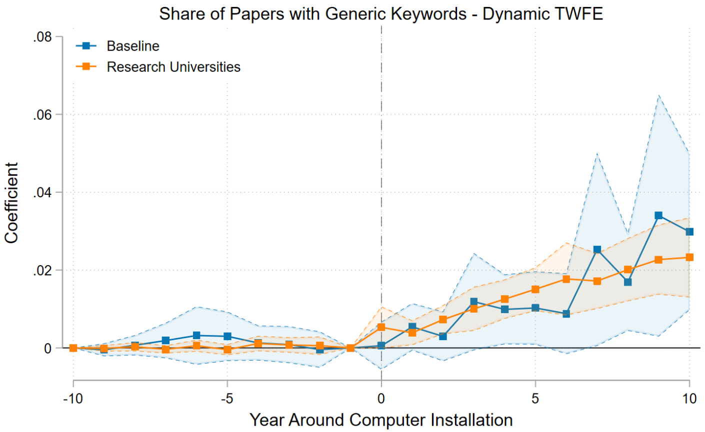
Differences-in-Differences: Computer Related-Keywords (by Category)



University Level

▸ CS

Differences-in-Differences: Share of Computer Related-Keywords (by Category)



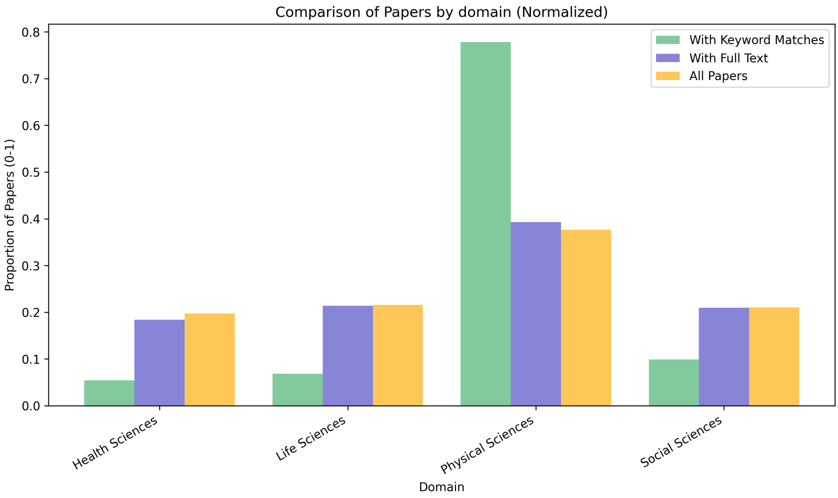
University Level

▸ CS

Paper-Level Patterns: Summary

- Computer papers skew heavily towards Physical Sciences (80% vs. 40% of total papers) ▸ Plot
- Medicine, biology relatively less-computer intensive ▸ Plot ▸ Word Cloud
- Computer keyword matches have a consistent 20% premium controlling for author, university, year, and field FE ▸ Plot ▸ Table
- After controls, computer papers on average: ▸ Table
  - 17% (34%) more likely to be a top 10% (1%) cited paper;
  - Have more breadth (5%), as measured by concepts;
- Author and affiliation results are small (2% higher) but significant.

Distribution of Computer Papers Across Domains



Health Sciences | Life Sciences | Physical Sciences | Social Sciences | Biochemistry | Chemistry | Computer Science | Mathematics | Physics

Log Citations per Paper

Dep. var: Log Citations	(1) All Papers	(2) Fulltext Only	(3) All Papers	(4) Fulltext Only	(5) All Papers	(6) Fulltext Only
Computer Keyword Papers	0.306***	0.187***	0.324***	0.208***	0.323***	0.208***
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
R-squared	0.533	0.547	0.528	0.538	0.530	0.539
N	1,141,100	802,507	1,035,288	733,223	1,035,288	733,223
Fixed Effects:						
Author	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Field	No	No	Yes	Yes	Yes	Yes
University	No	No	No	No	Yes	Yes

SE clustered at the author level. ***p<0.01, **p<0.05, *p<0.1

▸ Linear ▸ Poisson ▸ No Author FE ▸ Back

Author-Level Patterns: Summary

- Comparing authors mentioning computers ("adopters") vs. those who don't, based on keyword matching.
- Computer adopters are systematically different, even after controlling for field, university, and cohort:
  - 4x publications, 3.5x citations, 65% higher H-index, 50% more affiliations ▸ Table
  - Adopters are more experienced & have more top 1% papers ▸ See Figures
  - Computer adopters show greater influence even prior to uni adoption, though gap is smaller ▸ Table
  - Early vs. late adopters show no significant difference among those publishing pre-adoption ▸ Table
- Intensive margin: $\uparrow$ computer papers $\rightarrow \uparrow$ outcomes ▸ Table

Author-Level Patterns: Life Cycle Outcomes

	(1) Log Works	(2) Log Cites	(3) H-Index	(4) # Topics	(5) # Affiliations
Computer Adopter	1.364***	1.463***	7.752***	5.247***	1.820***
	(0.0165)	(0.120)	(1.254)	(0.294)	(0.166)
Number of Works		0.00536**	0.0577**	0.0120**	0.00617**
		(0.00176)	(0.0185)	(0.00399)	(0.00204)
R-squared	0.309	0.437	0.533	0.292	0.327
Observations	316970	316970	316970	316970	316970
Mean of Dep. Var.	2.732	5.158	12.16	16.77	3.525
Affiliation FE	Yes	Yes	Yes	Yes	Yes
Cohort FE	Yes	Yes	Yes	Yes	Yes
Field FE	Topic	Topic	Topic	Topic	Topic

Standard errors clustered at the affiliation level. Outcomes are for the whole author life-span.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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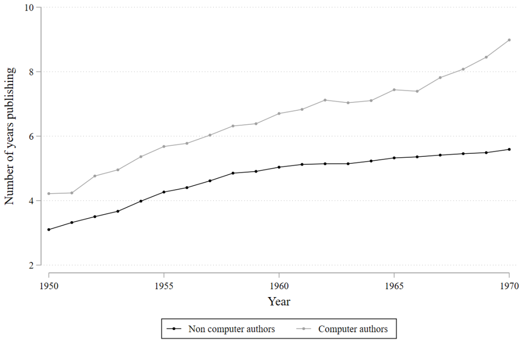
Author-Level Patterns: Top Citations & Experience

More Top 1% Cited Papers



Longer Publishing Careers (Experience)

▶ Back to Summary

Causal Effects

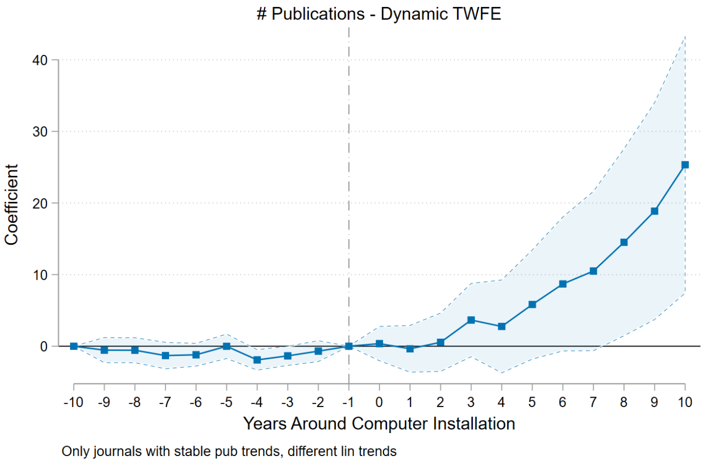
Empirical Strategy and Methods

- Binary Treatment: Year of first digital computer installation.
- All institutions in sample had computers by 1969
- Model Specifications:
  - Event Study:

$$Y_{i,t} = \beta_0 + \sum_{\tau=-T}^{T} \gamma_\tau I_{c,\tau} + \eta_i + \eta_t + \mu_{i,t}$$

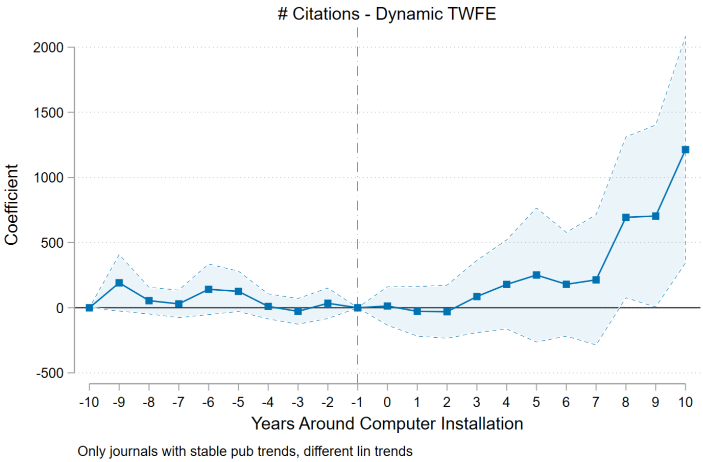
    with $I_{c,\tau} = 1$ when $t = \tau$ relative to the installation date ($\tau = 0$). Units i are universities or authors at year t; SE clustered at the unit level.
- Methods: Further implement new DiD estimators to account for staggered adoption and heterogeneous effects (Callaway & Sant'Anna 2021)
- Identifying assumption: Parallel trends
  - Additionally: No anticipation, No spillovers
- Plausible threat to identification
  - If treatment correlated with larger investments in some fields

Differences-in-Differences: Number of Publications



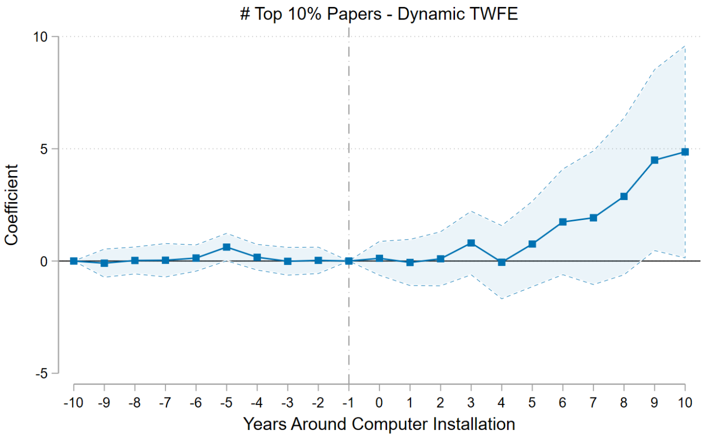
▸ PS ▸ SS ▸ HS ▸ LS

Differences-in-Differences: Number of Citations



PS SS HS LS

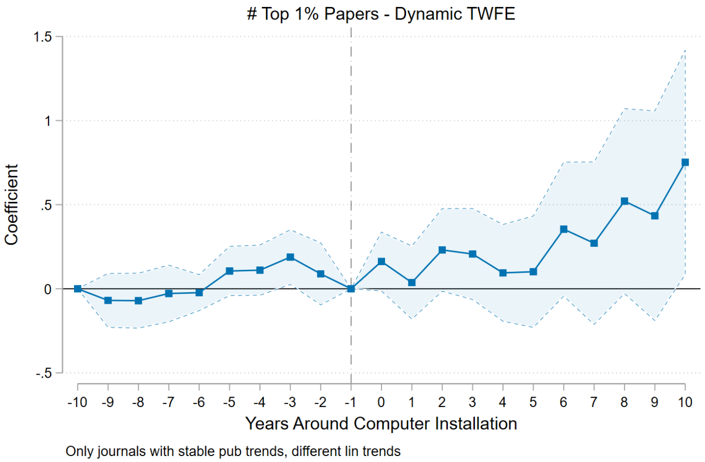
Differences-in-Differences: Number of Top 10% Papers



Only journals with stable pub trends, different lin trends

▸ PS ▸ SS ▸ HS ▸ LS

Differences-in-Differences: Number of Top 1% Papers



▸ PS ▸ SS ▸ HS ▸ LS

Other Outcomes

- “First stage”: researchers seem to adopt and mention computers right after installations
- We also look at team size, number of concepts and few other outcomes, but results are noisy
- Author-level DiDs are non-conclusive thus far
- Affiliation information is patchy and author disambiguation is challenging
- Consider getting external data on affiliations (World of Academia?)

Conclusion & Next Steps

Next Steps

- Use Survey of Earned Doctorates and Pro-Quest to look at graduate students
  - Relatively immobile, single affiliation
  - Consistent background and quality across cohorts
- Start using paper full-text for analysis:
  - Classify papers into tasks, type of computer usage
  - Measure substitution vs. innovation patterns
  - Broader outcomes: theory vs. empirics; acceleration of scientific frontier; downstream effects of computers?

Conclusion

- Computer diffusion was rapid but uneven, concentrated in few areas and high-impact authors.
- Research use begins immediately after university computer acquisition.
- By the 1960s, most top universities had computers, but usage remained low (< 5%).
- Early adopters were highly selected (greater impact, breadth, influence).
- Strong correlation between computer use and paper quality/breadth.
- DiDs suggest effects are not merely correlational.
- Findings indicate both selection effects (who adopts) and causal effects (computer impact) on research quality/productivity.

Appendix

Contribution to Literature

- **Factors Affecting Scientific Direction & Quality** (e.g., Azoulay et al. 2019; Borjas & Doran 2012; Truffa & Wong 2024...)
  - Analyze effects of a major **technological change** (early computers) on research **research**.
  - Study the **fundamental impact** of initial computer access, distinct from marginal improvements (e.g., Boudou & Mckeon 2024).
- **Determinants of Scientists' Career Trajectories** (e.g., Abramitzky et al. 2024; Borjas & Doran 2012; Waldinger 2010...)
  - Focus on how **technological change interacts** with scientist characteristics to shape **long-run career outcomes**.
- **History of Academic Computing** (e.g., Agar 1996; Ceruzzi & Haigh 2021; Aspray & Williams 1994...)
  - Provide first **comprehensive historical evidence** on the **adoption of early computers across universities**.

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Remote Access at Oregon State

This need is partially alleviated in a somewhat unsatisfactory manner by computational facilities provided through the IBM 7094 at Western Data Processing Center (WDPC) on the UCLA campus. … While this facility theoretically provides the capability for solution of large problems, … the time delay and cost in sending and receiving data, limited transmission time (only up to 1-1/2 hours per day) and lack of direct access to the computer make this arrangement unsatisfactory. … Several faculty members have spent considerable time and money traveling to WDPC to debug programs.

Computer Facility Grant Proposal of Oregon State University to NSF, June 1965

▸ Back

Testing the Princeton's IAS

"During the testing of the arithmetic unit [of the MANIAC] in 1948, the team tested it against von Neumann himself. As they entered in more and more complicated terms, von Neumann finally erred, proving to their collective satisfaction "the power of matter over mind.""

– Bigelow (1980)

▸ Back

Petition for IBM 650 at NU

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Economics:

1. The acceleration principle and other determinants of investment: an econometric analysis of capital expenditures, capital expenditure plans, sales expectations, sales changes, profits and other related data collected in the McGraw-Hill capital expenditure surveys.

2. The trade cycle model with some empirically derived coefficients for high order difference equations.

3. Empirical demand functions, from cross sectional and time series price and income data.

Professors: R. L. Basmann, R. Eisner

Proposed Uses of Computer by Economics Department at Northwestern, 1957
Source: Northwestern University Archives

Database Sample Snapshot

department	computer	manufactu	year_insta	month_ins	year_deco	month_de	average_h	lowest_sn	lowest_sn	highest_sr	highest_sr	source
Vogelback Computing Center	CDC 3400/8090	CDC	1964	january			273	1965	january	1966	september	hamblen (1966, 1968)
Vogelback Computing Center	EAI PACE Analog	EAI						1962	september	1964	february	edp (1962); dpy (1964)
Vogelback Computing Center	IBM 1401	IBM	1962					1961	july	1965	january	nrc (1963, 1965); dpy (
Vogelback Computing Center	IBM 1401	IBM						1965	january	1965	january	nrc (1965)
Medical School	IBM 1620/1710	IBM						1964		1965	january	dpy (1964); nrc (1965)
Administrative Data Processing	IBM 360/30	IBM	1966					1968	may	1968	may	hamblen (1968)
Vogelback Computing Center	IBM 650	IBM	1958					1957	june	1962	may	amsn (1960); datamat
Vogelback Computing Center	IBM 709	IBM	1961	july	1964	august	273	1960	july	1966	september	hamblen (1966); nrc (
Vogelback Computing Center	LGP-30	Librascope						1963	january	1965	january	nrc (1963, 1965); dpy (

Figure 2: Installations of Computers at Northwestern University. Some columns have been removed for readability.

▸ Back

Hamblen Survey, 1966, Back

1964-65 COMPUTER SURVEY--SOUTHERN REGIONAL EDUCATION BOARD COMPUTER SCIENCES PROJECT
CONTRACT NSF C465

ITEM I-A-4,5,6 COMPUTERS INSTALLED AND ON ORDER FOR RESEARCH AND INSTRUCTIONAL USES

CTL 1 TYPE 1 LEVEL 4

INSTITUTION		COMPUTER SYST.	YEAR INST	TO BE REPLACED	LEASE	PURCH	BOTH	1964-65 AVG.USE HRS/MO
OKLA STATE UNIVERSITY		IBM 1410	64	X	*			288
STILLWATER OKLAHOMA	74074	IBM 1620	63			*		450
		IBM 7040	65					
UNIVERSITY OF OKLAHOMA		IBM 1410	62	X	*			492
NORMAN OKLAHOMA	73069	IBM 1620	62		*			300
		IBM 360/40	67					
		IBM 360/65	68					
OREGON STATE UNIVERSITY		ALW III-E	57			*		200
CORVALLIS OREGON	97331	IBM 1620	61				*	200
		IBM 1410	64	X	*			100
		CDC 3300	66					
		PDP 8	00					
UNIVERSITY OF OREGON		IBM 1620	60			*		
EUGENE, OREGON	97403	IBM 360/50	66					
		PDP 7	66					
PENNSYLVANIA STATE UNIVERSITY		IBM 7074	61	X		*		720
UNIVERSITY PARK PA	16802	IBM 7074	62	X	*			240
		IBM 1401	62	X		*		650
		IBM 1410	64	X	*			650
		IBM 1620	63	X	*			80
		IBM 1620	62		*			150
		IBM 360/67	68					
		IBM 360/50	66					

Keenan Survey, 1963

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1. NAME OF UNIVERSITY University of Illinois
2. MAILING ADDRESS Urbana, Illinois (service branch)

PART I – GENERAL INFORMATION

1. DIRECTOR OR PERSON IN CHARGE J.N. Snyder
   (A) DEGREE AND ACADEMIC FIELD Ph.D.-Physics
   (B) ACADEMIC POSITION Res. Prof.
   (C) REPORTS TO Head of Digital Computer Lab.
2. DATE CENTER OR LABORATORY ESTABLISHED 1948
   (A) TAX SUPPORTED yes
   (B) APPROX. FLOOR AREA - MACHINE ROOM 1000 SQ. FT. CLASSROOM SQ. FT.
   OFFICES 1500 SQ. FT. USER WORKROOM 1000 SQ. FT.
   LIBRARY SQ. FT. (OTHER) SQ. FT.
   STORAGE SQ. FT.
   (C) COMPUTERS IBM 7094 HRS./MONTH USED 500
   IBM 1401 (2) 500
   (Illiac II, IBM 1401) (100 100)
   (D) PERCENT OF EQUIP. OWNED 100 LEASED
   (E) MAJOR EQUIPMENT ON ORDER none EXPECTED DELIVERY

PART II – PERSONNEL INFORMATION

1. NUMBER OF STAFF MEMBERS DESIRABLE
   (A) ANALYSTS 4 (C) OPERATORS 18
   (B) PROGRAMMERS 10 (D) CLERICAL 6
2. REGULAR POSITIONS

REGULAR POSITIONS	DEGREE–SUBJ. AREA	COMPUT. EXPER.	HRS/WK.	MO/YR.	JOINT APPT.
Dir.	Ph.D.-Physics	12 yrs.	40	9	Physics
	Ph.D.-Physics	6 yrs.	40	9	Physics

Full Data Source References

1. **c&a:** Computers and Automation Rosters of Organizations in the Computer Field (1951–1953; 1956–1968).
2. **hamblen:** Inventory of Computers in U.S. Higher Education – “Computers in higher education: report by the Southern Regional Education Board commissioned by the NSF” (1966).
3. **keenan:** Thomas A. Keenan Surveys – University of Rochester Annual Survey of University Computing Centers (1960; 1961; 1963).
4. **nrc:** National Research Council’s Roesser Report – Digital Needs in Universities and Colleges (1966; covers 1963 and 1965).
5. **amsn:** American Mathematical Society Notices Survey – Survey of High Speed Computers in Universities (1962).
6. **onr:** Survey of Automatic Digital Computers by the Office of Naval Research (1953).
7. **weik:** Survey of Domestic Electronic Digital Computing Systems (Weik Surveys) by the Ballistic Research Labs (1955; 1957; 1961; 1964).
8. **fsu:** A study of administrative uses of computers in colleges and universities (1962) by Florida State University.
9. **ibmarchives:** IBM 650s installation data from IBM sources (circa 1956).
10. **mie:** Mathematics in Education 1961 survey by the US Department of Health, Education, and Welfare.
11. **datamation:** Datamation 1962 survey – reporting results from the AMS notices survey and one survey by Ohio State University.
12. **ba:** Business Automation Magazine Aug/1962 survey – a survey of universities on computers and courses.
13. **edp:** Educational Programs and Facilities in Nuclear Science and Engineering – three surveys (1960–1964) covering installations and additional information.
14. **dfpmm:** Data Processing for Management – a general interest magazine from American Data Processing, Inc. with a section on installations.
15. **dpy:** Data Processing Yearbooks – surveys of university facilities and courses (1961, 1962, 1963, 1964, 1965, 1967, etc.), with certain editions titled “Computer Yearbook and Directory” (1965–66 and 1967–68).

Full Data Source References (cont.)

16. **rcd:** Research Centers Directory (1960, 1964, 1966) – surveys of university centers and labs in US and Canadian universities.
17. **berg:** Business Electronics Reference Guide – surveys from 1954, 1955, 1956, and 1958 covering business and universities (the 1958 guide includes installation dates).
18. **UChicago:** Survey of Numerical Weather Prediction (1955) by the University of Chicago.
19. **adpeh:** U.S. House of Representatives, Subcommittee on Government Operations (1965) – Hearings on H.R. 4845 (snapshot in 1964).
20. **uedpeh:** Hearing before the Subcommittee on Census and Government Statistics of the Committee on Post Office and Civil Service (1963) – Use of electronic data processing equipment (snapshot in 1963).
21. **hcp:** Report from Task Force on Hydrologic Computer Programs (1963) (snapshot in 1963).
22. **cfuhef:** U.S. Congress, Joint Committee on Atomic Energy (1972) – AEC authorizing legislation fiscal year 1973 hearings (covers 1969 computers).

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Universities In Sample

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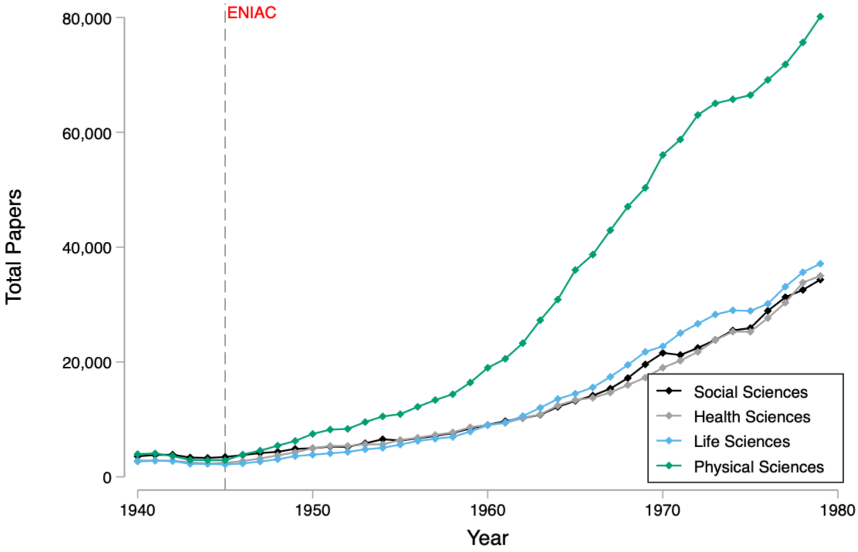
Abilene Christian College
American University
Amherst College
Arizona State University
Auburn University
Baruch College
Baylor University
Boston College
Boston University
Brandeis University
Brigham Young University
Brown University
Bryn Mawr College
California Institute Of Technology
California State University, Los Angeles
Carnegie Institute Of Technology
Carnegie Mellon University
Case Institute Of Technology
Case Western Reserve University
CUNY
Clark University
Clemson University
College Of William And Mary
Colorado School Of Mines
Colorado State University
Columbia University
Cornell University
Dartmouth College
Duke University
Emory University
Fairleigh Dickinson University
Florida State University
Foothill College
Fordham University
Franklin Institute
George Washington University
Georgetown University
Georgia Institute Of Technology
Georgia State University
Harvard University
Harvey Mudd College
Haverford College
Howard University
Illinois Institute Of Technology
Indiana Institute Of Technology
Indiana University, Bloomington
Iowa State University
Jackson State College
Johns Hopkins University
Kansas State University
Kent State University
Lehigh University
Long Island University
Louisiana State University
Lowell Technological Institute
Marquette University
Massachusetts Institute Of Technology
Michigan State University
Mississippi State University
Missouri University Of Science And Technology
Montana State University
New Mexico Institute Of Mining And Technology
New Mexico State University
New School For Social Research
New York State College Of Agriculture At Cornell University
New York University
North Carolina State University
North Dakota State University
Northeastern University
Northern Illinois University
Northwestern University
Ohio University
Oklahoma State University
Oregon State University
Pennsylvania State University
Pomona College
Princeton University
Providence College
Purdue University
Queensborough Community College
Rensselaer Polytechnic Institute
Rice University
Rose Polytechnic Institute
Rutgers University
Saint Louis University
San Diego State University
Smith College
South Dakota State University
Southern Illinois University
Southern Methodist University
Stanford University
State University Of New York At Buffalo
Stephen F. Austin State College
Stevens Institute Of Technology
Swarthmore College
Syracuse University
Temple Junior College
Texas A&M University
Texas College Of Arts And Industries
Texas Tech
The King'S College - Pennsylvania
The Ohio State University
Tufts University
Tulane University
University Of Akron
University Of Alabama
University Of Alaska
University Of Arizona
University Of Arkansas
UC, Berkeley
UC, Davis
UC, Irvine
UC, Los Angeles
UC, Riverside
UC, San Diego
UC, San Francisco
UC, Santa Barbara
UC, Santa Cruz
University Of Chicago
University Of Cincinnati
University Of Colorado Boulder
University Of Connecticut
University Of Delaware
University Of Denver
University Of Florida
University Of Georgia
University Of Hawaii
University Of Houston
University Of Idaho
University Of Illinois, Urbana-Champaign
University Of Iowa
University Of Kansas
University Of Kentucky
University Of Louisville
University Of Maine
University Of Maryland
University Of Massachusetts At Amherst
University Of Miami
University Of Michigan, Ann Arbor
University Of Minnesota
University Of Mississippi
University Of Missouri
University Of Nebraska
University Of Nebraska, Omaha
University Of Nevada
University Of New Hampshire
University Of New Mexico
University Of North Carolina At Chapel Hill
University Of North Dakota
University Of Notre Dame
University Of Oklahoma
University Of Oregon
University Of Pennsylvania
University Of Pittsburgh
University Of Puerto Rico, College Of Agriculture And Mechanic Arts, Mayagüez
University Of Puerto Rico, Río Piedras
University Of Puget Sound
University Of Rhode Island
University Of Rochester
University Of South Carolina
University Of South Florida
University Of Southern California
University Of Southwestern Louisiana
University Of Tennessee
University Of Texas, Austin
University Of Utah
University Of Vermont
University Of Virginia
University Of Washington
University Of Wisconsin, Madison
University Of Wisconsin-Milwaukee
University Of Wyoming
Utah State University
Vanderbilt University
Vassar College
Virginia Polytechnic Institute
Washington And Lee University
Washington State University
Washington University Of Saint Louis
Wayne State University
Wesleyan University
West Virginia University
Western Michigan University
Western Reserve University
Wichita State University
Williams College
Yale University

Publications by Field



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List of Keywords Used

- List of keywords searched:
  1. electronic computer(s)
  2. digital computer(s)
  3. automatic computer(s)
  4. high-speed computer(s)
  5. high speed computer(s)
  6. computer program(s)
  7. mainframe computer(s)
  8. high-speed computing device(s)

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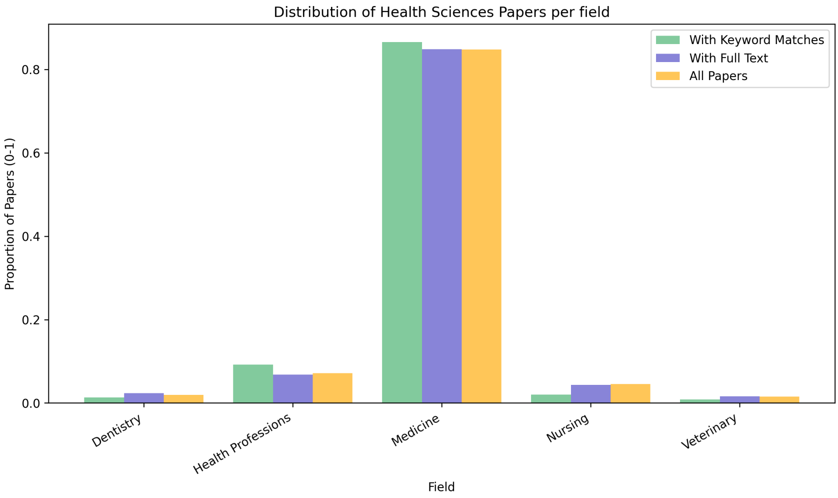
Distribution of Papers in Health Sciences



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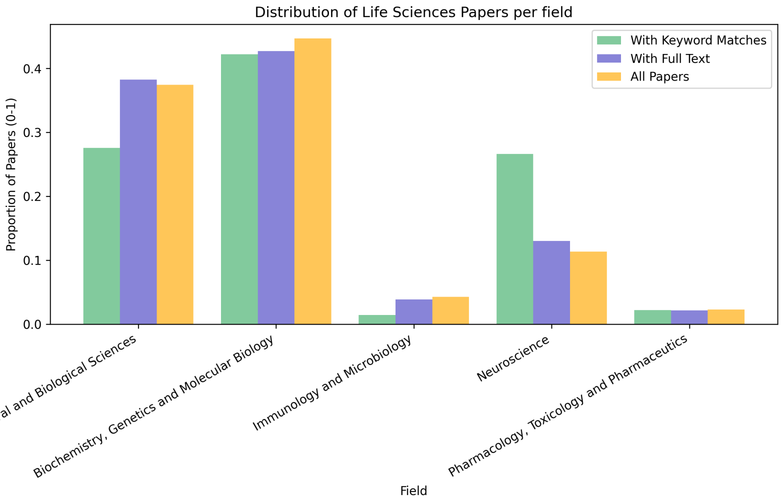
Distribution of Papers in Life Sciences



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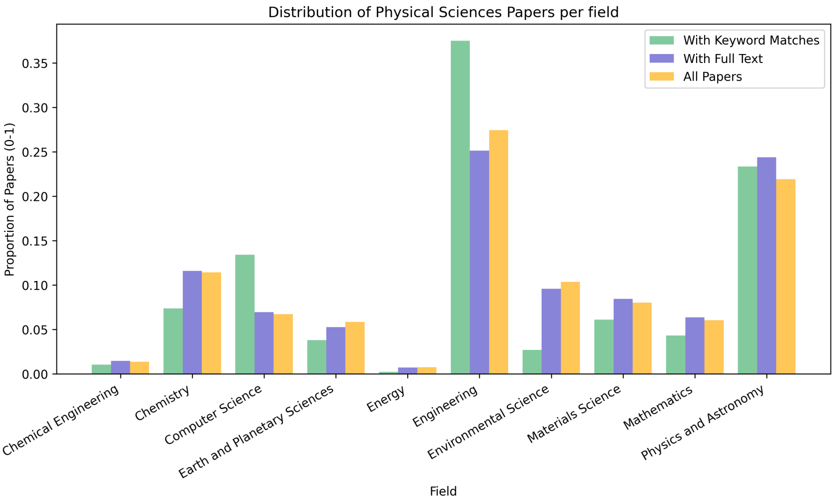

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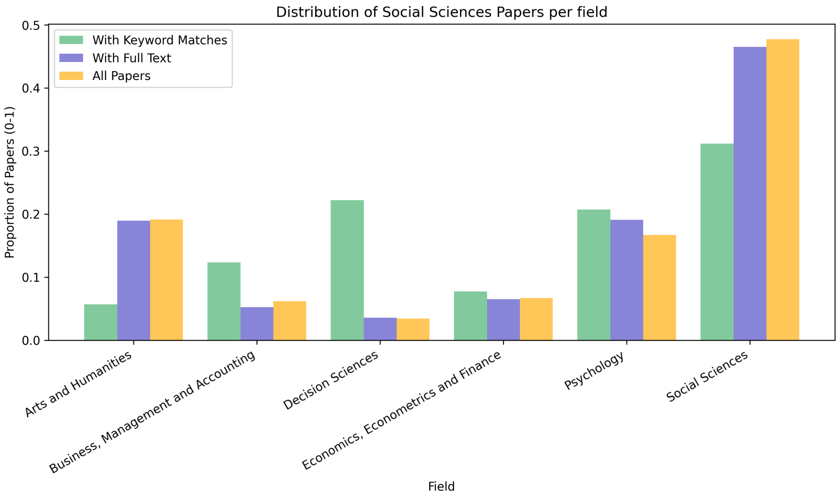

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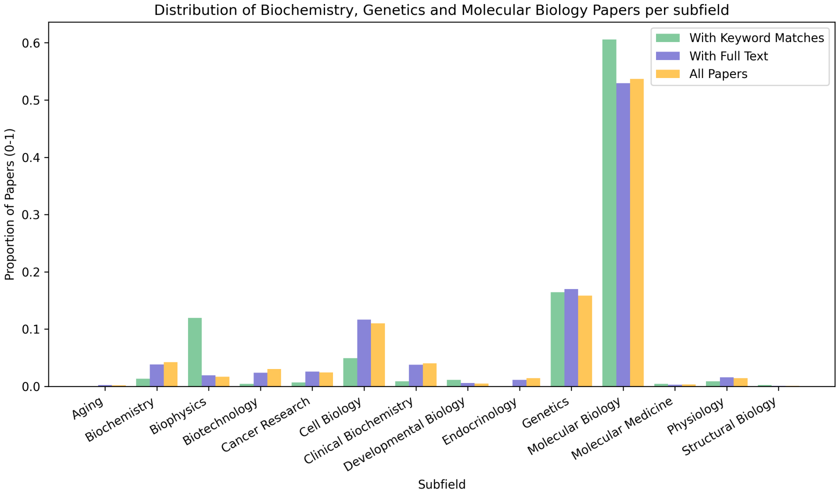
Distribution of Papers in Biochemistry, Genetics and Molecular Biology



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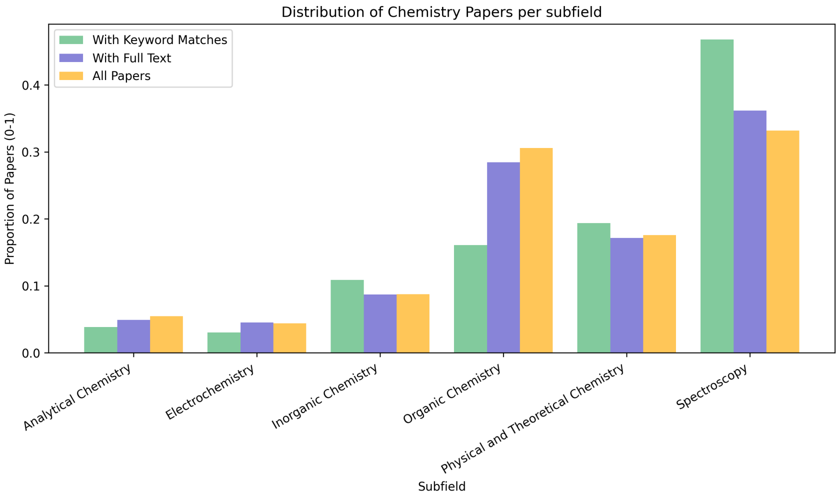
Distribution of Papers in Chemistry



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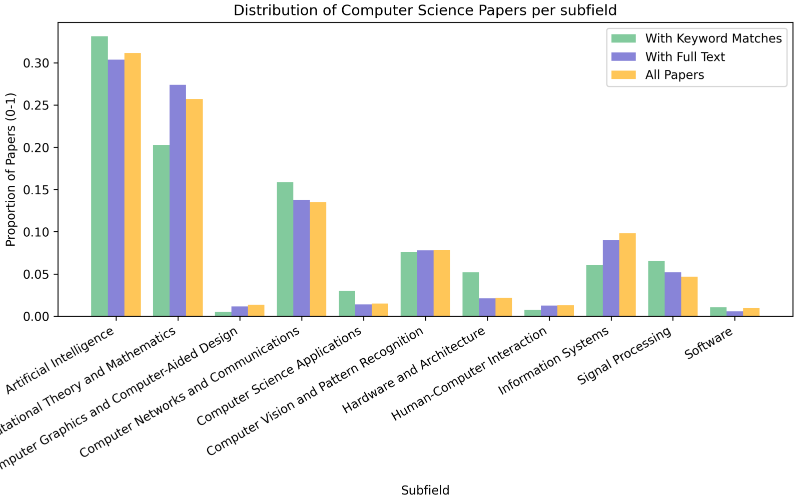
Distribution of Papers in Computer Science



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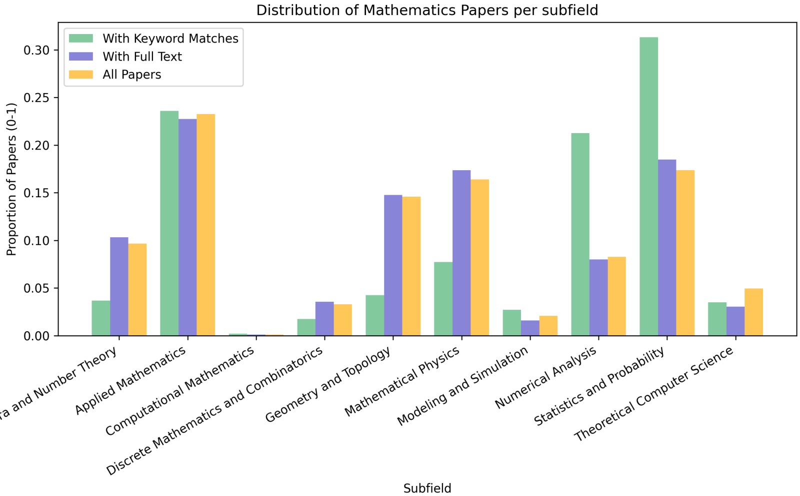
Distribution of Papers in Mathematics



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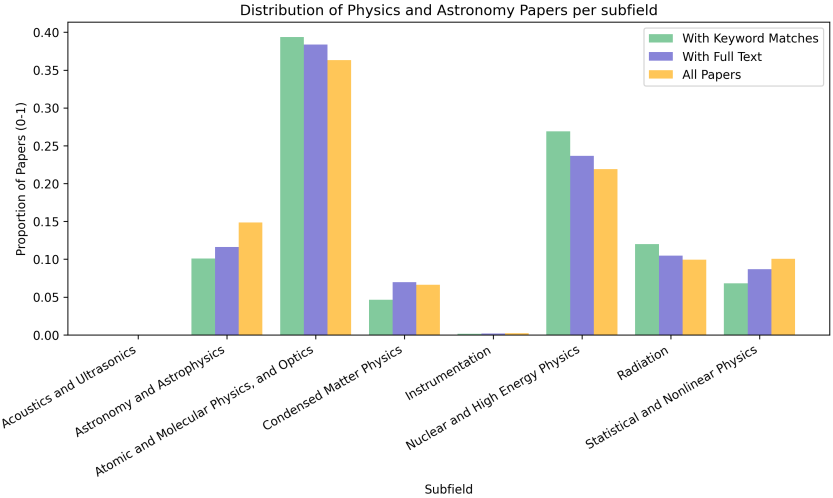
Distribution of Papers in Physics and Astronomy



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Microsoft Academic Graph Concept Wordcloud

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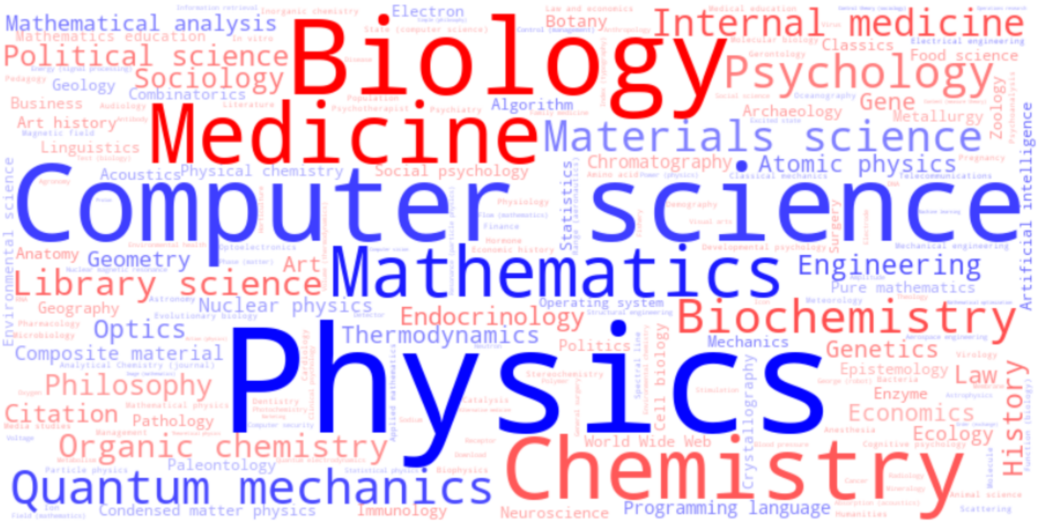
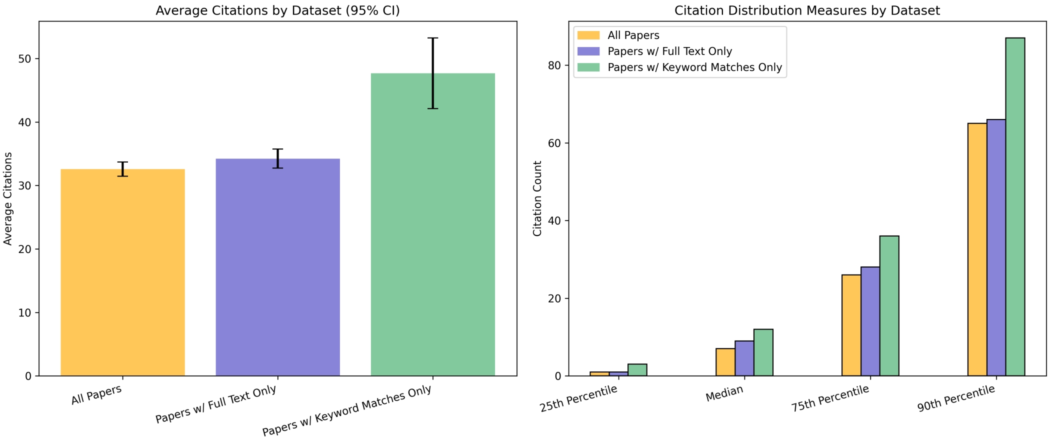


Citations in Computer Papers



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Paper-Level Patterns: Other Outcomes

	(1) Top 10% Pub	(2) Top 1% Pub	(3) # Authors	(4) # Concepts	(5) # Affiliations
Computer Keyword Papers	0.0549***	0.0101***	0.0775***	0.627***	0.0411***
	(0.00397)	(0.00172)	(0.00903)	(0.0531)	(0.00666)
R-squared	0.352	0.247	0.592	0.424	0.581
Observations	749463	749463	749463	749463	749463
Mean of Dep. Var.	0.282	0.0292	3.139	11.53	1.786
Author FE	Yes	Yes	Yes	Yes	Yes
University FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Field FE	Field	Field	Field	Field	Field
Sample	Fulltext	Fulltext	Fulltext	Fulltext	Fulltext

SE are clustered at the author level.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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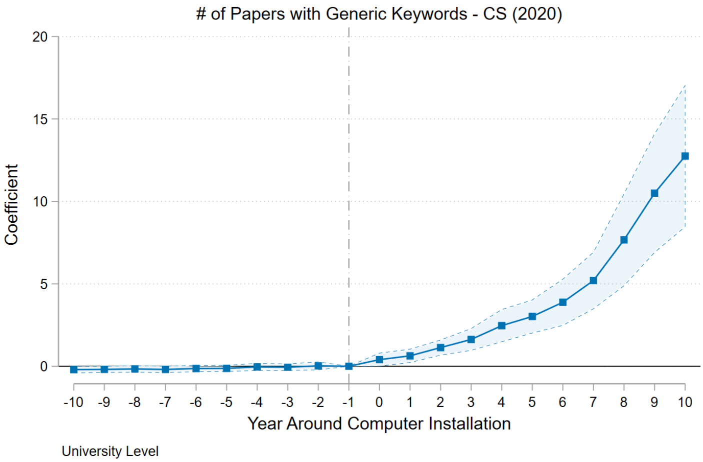
Callaway Sant'Anna (2020): Computer Related-Keywords



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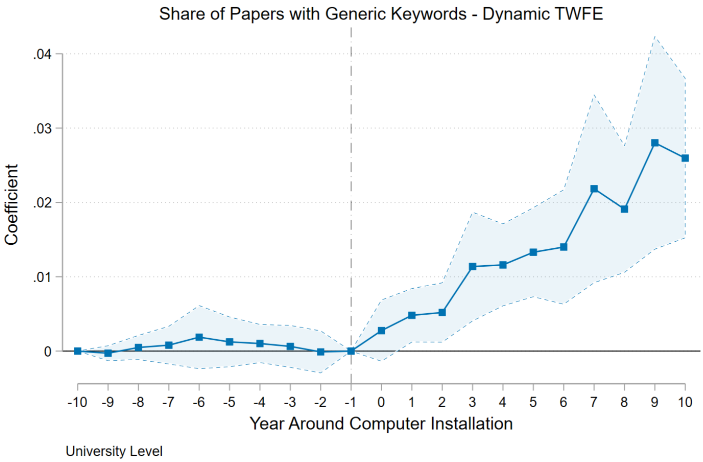
Differences-in-Differences: Share of Computer Related-Keywords



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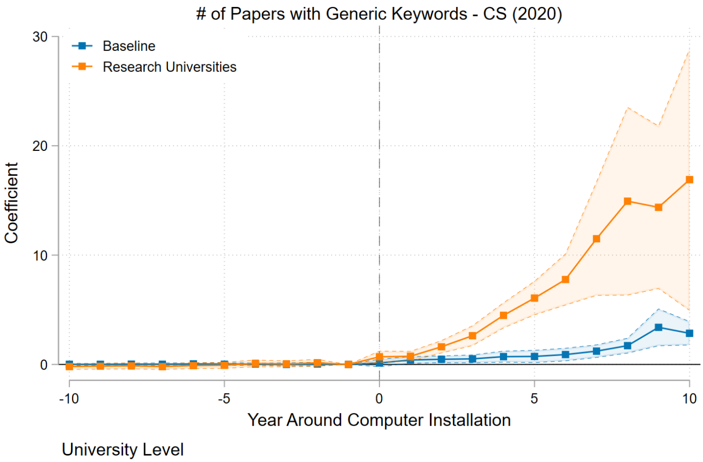
Callaway Sant'Anna: Computer Related-Keywords (by Category)



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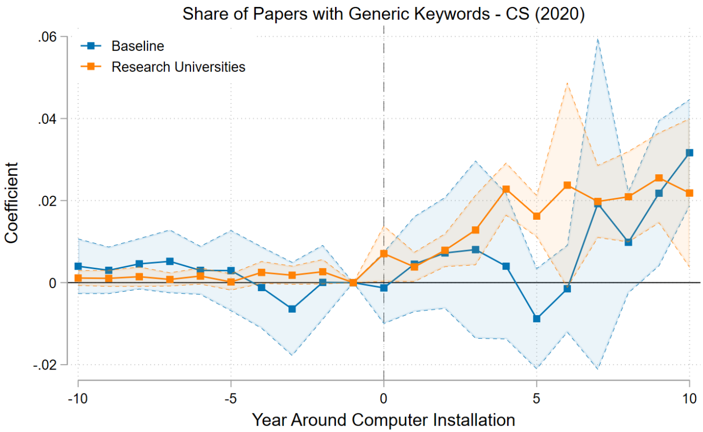
Callaway Sant'Anna: Share of Computer Related-Keywords (by Category)



University Level

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Citations per Paper – No Author Fixed-Effects

Table 1: Effect of Keyword Matches Flag on Cited By Count (Standard Errors in Parentheses)

	All Papers	All Papers	Fulltext Only	Fulltext Only
Computer Keyword Papers	10.78	10.34	9.11	9.04
	(3.08)	(3.14)	(3.11)	(3.21)
R-squared	0.0017	0.0021	0.0015	0.0018
N	616,582	616,582	450,152	450,152
Fixed Effects:				
Field	Yes	No	Yes	No
Subfield	No	Yes	No	Yes
Year	Yes	Yes	Yes	Yes
University	Yes	Yes	Yes	Yes

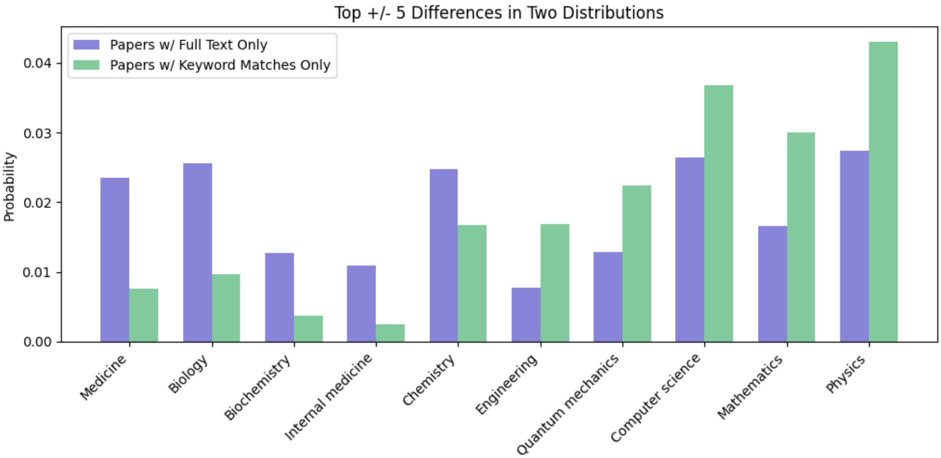
Citations per Paper

Dep. var: Citations	(1) All Papers	(2) Fulltext Only	(3) All Papers	(4) Fulltext Only	(5) All Papers	(6) Fulltext Only
Computer Keyword Papers	8.496***	8.915***	9.087***	9.852***	9.012***	9.824***
	(2.856)	(2.770)	(3.015)	(2.920)	(3.014)	(2.913)
R-squared	0.267	0.159	0.334	0.162	0.334	0.162
N	1,141,100	802,507	1,035,288	733,223	1,035,288	733,223
Fixed Effects:						
Author	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Field	No	No	Yes	Yes	Yes	Yes
University	No	No	No	No	Yes	Yes

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 2: Effect of Computer Keyword Papers on Cited By Count (SE Clustered at the Author Level)

Microsoft Academic Graph Concept Relative Distributions



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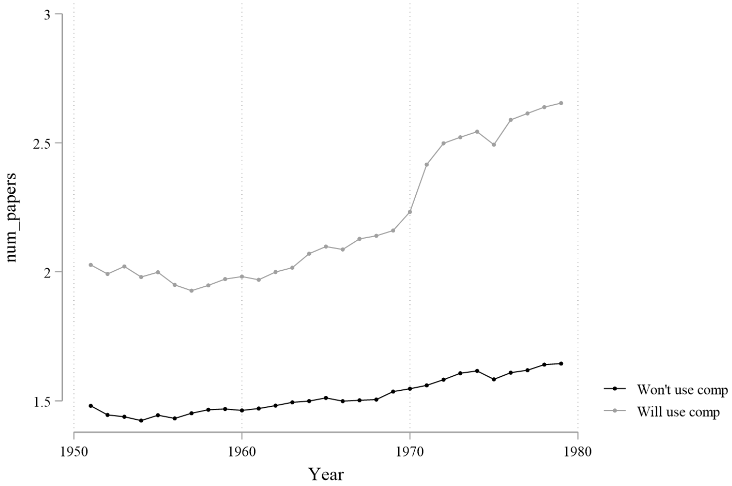
Citations per Paper – Poisson Model

Dep. var: Log Citations	(1) All Papers	(2) Fulltext Only	(3) All Papers	(4) Fulltext Only	(5) All Papers	(6) Fulltext Only
Computer Keyword Papers	0.178*** (0.058)	0.178*** (0.054)	0.182*** (0.058)	0.190*** (0.055)	0.183*** (0.057)	0.194*** (0.052)
N	1,058,189	753,322	989,123	710,351	989,123	710,351
Fixed Effects:						
Author	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Field	No	No	Yes	Yes	Yes	Yes
University	No	No	No	No	Yes	Yes

***p<0.01, **p<0.05, *p<0.1

Table 3: Effect of Computer Keyword Papers on Cited By Count
(SE Clustered at the Author Level)

Appendix: Author Patterns - Papers Published



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Appendix: Author Patterns - Average Citations

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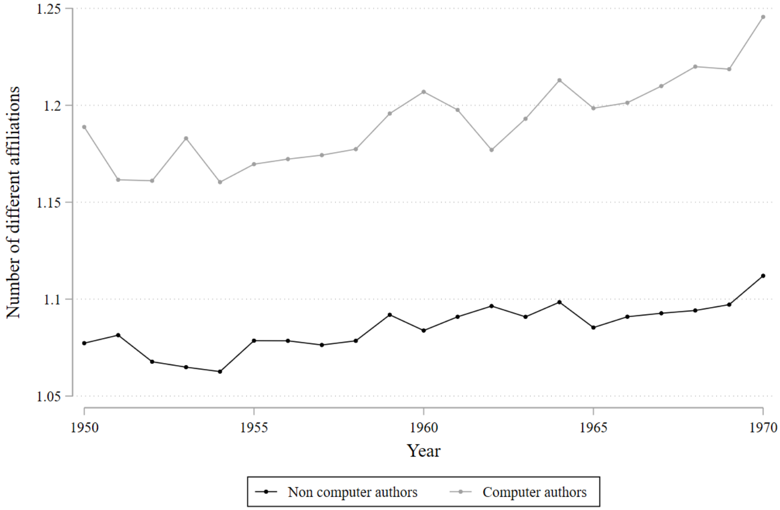
Appendix: Author Patterns - Number of Affiliations



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Appendix: Author Patterns - Intensive Margin

	(1) Log Works	(2) Log Cites	(3) H-Index	(4) Topics Ct	(5) Affiliations Ct
Computer Paper Count	0.188***	0.181***	1.166***	0.553***	0.258***
	(0.00790)	(0.0256)	(0.250)	(0.0639)	(0.0294)
Number of Works		0.00553**	0.0582**	0.0128**	0.00631**
		(0.00185)	(0.0189)	(0.00435)	(0.00208)
R-squared	0.280	0.417	0.524	0.269	0.317
Observations	316970	316970	316970	316970	316970
Mean of Dep. Var.	2.732	5.158	12.16	16.77	3.525
Affiliation FE	Yes	Yes	Yes	Yes	Yes
Cohort FE	Yes	Yes	Yes	Yes	Yes
Field FE	Topic	Topic	Topic	Topic	Topic

Standard errors clustered at the affiliation level.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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Appendix: Author Patterns - Outcomes at University Computer Adoption Year

	(1) Log Works	(2) Log Cites	(3) H-Index	(4) Top 1% Pubs	(5) Top 10% Pubs
Computer Adopter	0.227***	0.592***	1.652***	0.576**	0.0967***
	(0.0182)	(0.0364)	(0.161)	(0.177)	(0.0217)
Number of Works		0.000731*	0.00350	0.00347	0.000412
		(0.000369)	(0.00184)	(0.00204)	(0.000242)
R-squared	0.344	0.251	0.246	0.169	0.0964
Observations	122159	134521	134521	122159	122159
Mean of Dep. Var.	1.530	3.460	4.438	2.581	0.267
Affiliation FE	Yes	Yes	Yes	Yes	Yes
Cohort FE	Yes	Yes	Yes	Yes	Yes
Field FE	Topic	Topic	Topic	Topic	Topic

Standard errors clustered at the affiliation level. Adoption year is calulated using the lowest university computer installation year among all affiliations.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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Appendix: Author Patterns - Adoption Lags

	(1) Log Works	(2) Log Cites	(3) H-Index	(4) # Topics	(5) # Affiliations
Adoption Lag (Freq)	0.00817	0.0109	-0.0391	0.0713***	-0.0405*
	(0.00440)	(0.00628)	(0.0368)	(0.0179)	(0.0177)
Number of Works		0.00515***	0.0782***	0.00283***	0.0118***
		(0.000364)	(0.00427)	(0.000380)	(0.000983)
R-squared	0.373	0.601	0.759	0.341	0.524
Observations	6141	6141	6141	6141	6141
Mean of Dep. Var.	4.358	7.271	23.65	24.01	6.636
Affiliation FE	Yes	Yes	Yes	Yes	Yes
Cohort FE	Yes	Yes	Yes	Yes	Yes
Field FE	Topic	Topic	Topic	Topic	Topic

Standard errors are clustered at the affiliation level. Adoption years are calculated weighting by publications in each affiliation of the author.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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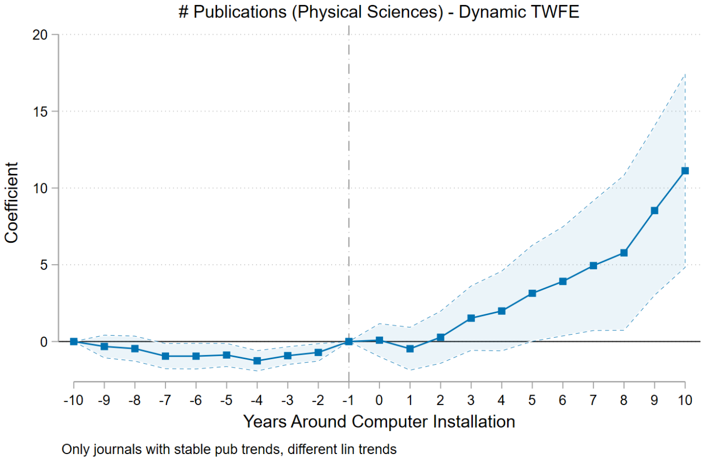
Differences-in-Differences: Number of Publications (Physical Sciences)



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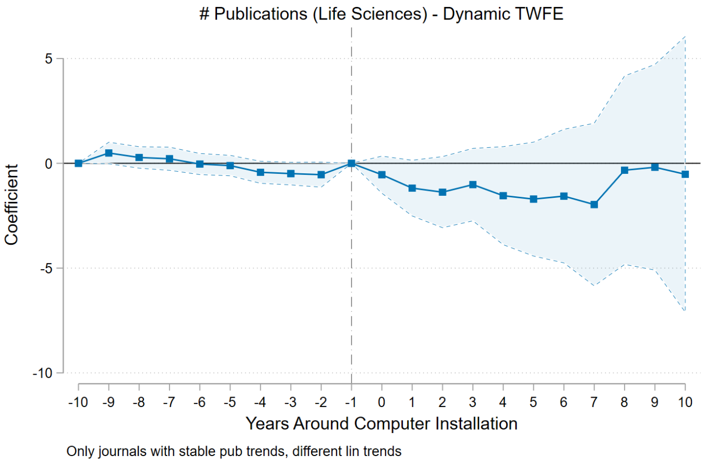
Differences-in-Differences: Number of Publications (Life Sciences)



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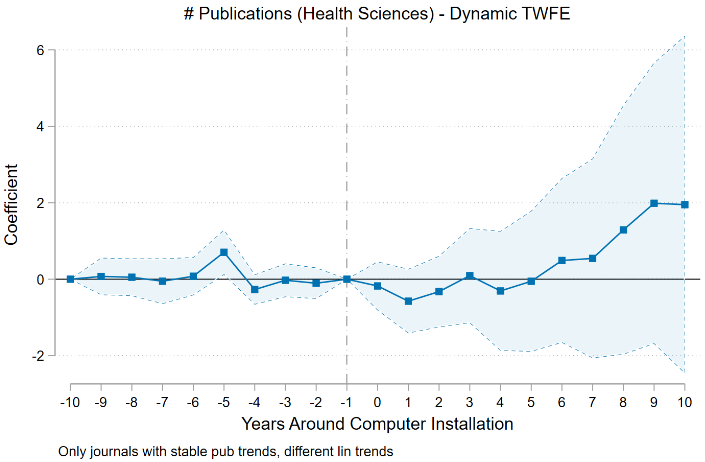
Differences-in-Differences: Number of Publications (Health Sciences)



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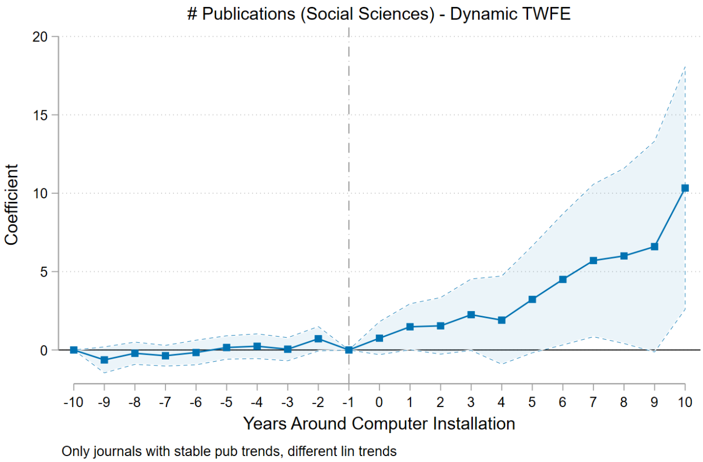
Differences-in-Differences: Number of Publications (Social Sciences)



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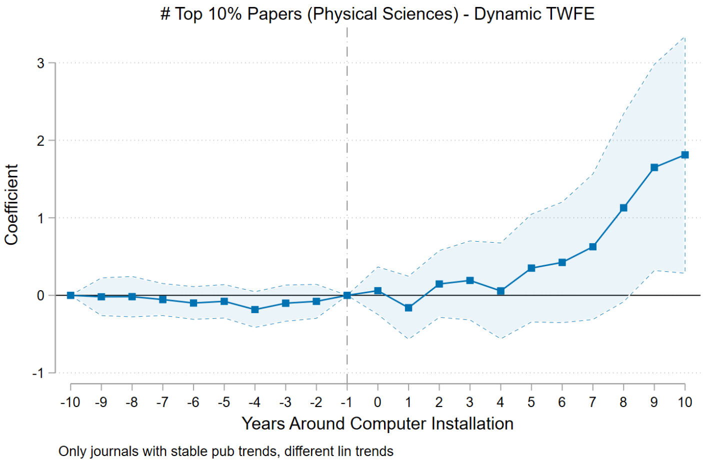
Differences-in-Differences: Number of Top 10% Papers (Physical Sciences)



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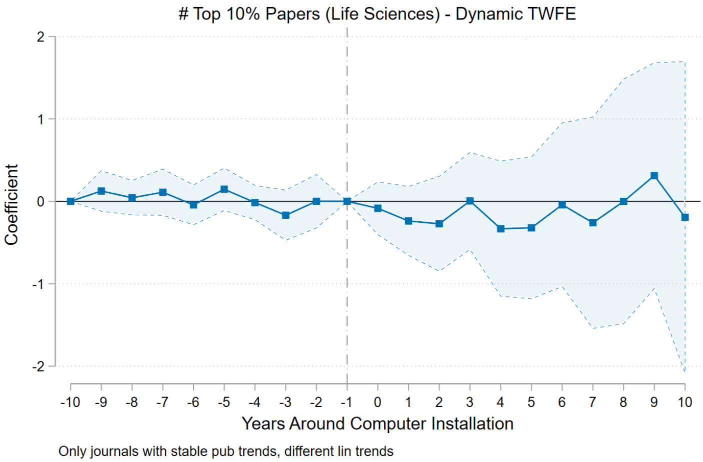
Differences-in-Differences: Number of Top 10% Papers (Life Sciences)



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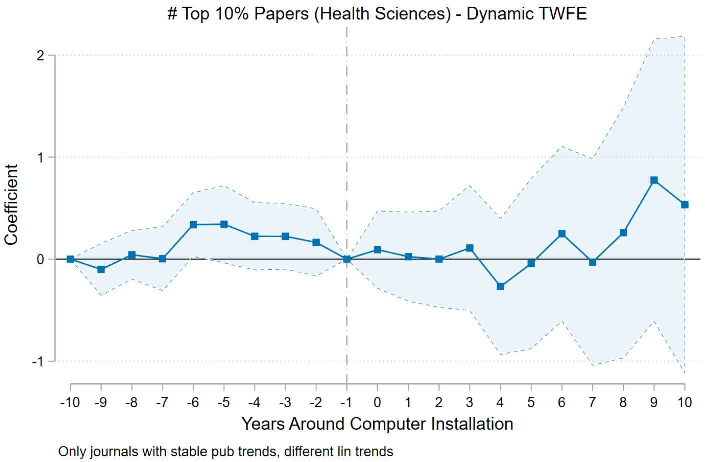
Differences-in-Differences: Number of Top 10% Papers (Health Sciences)



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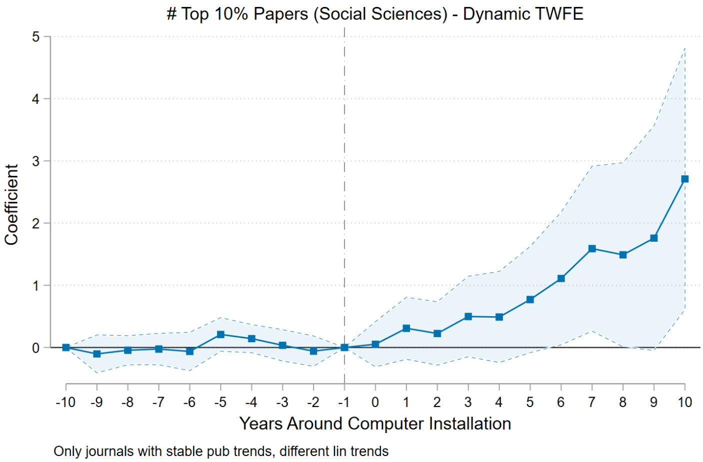
Differences-in-Differences: Number of Top 10% Papers (Social Sciences)



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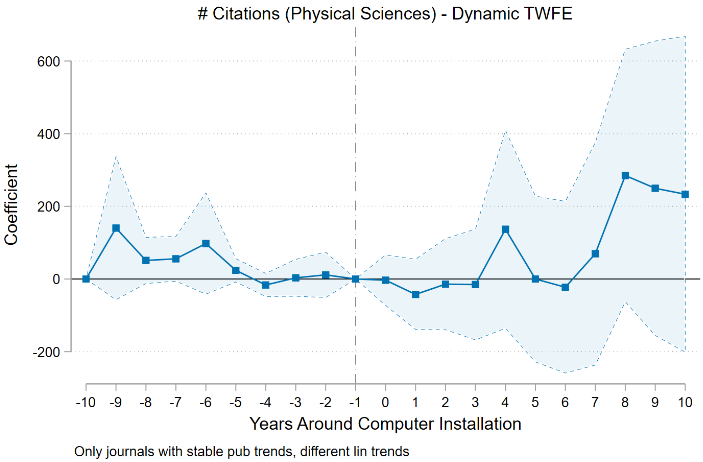
Differences-in-Differences: Number of Citations (Physical Sciences)



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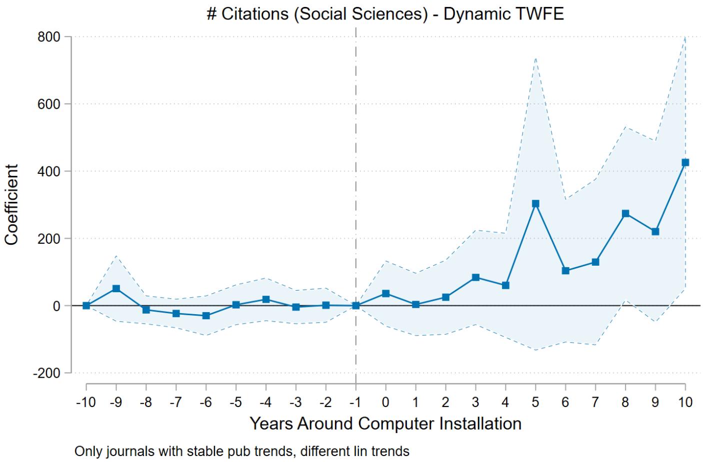
Differences-in-Differences: Number of Citations (Social Sciences)



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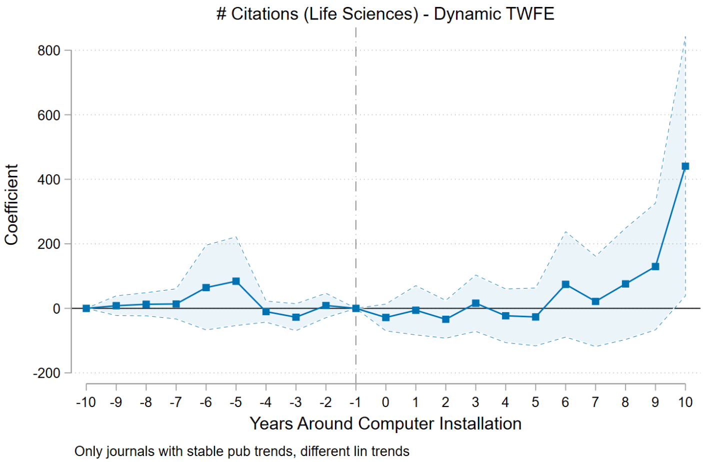
Differences-in-Differences: Number of Citations (Life Sciences)



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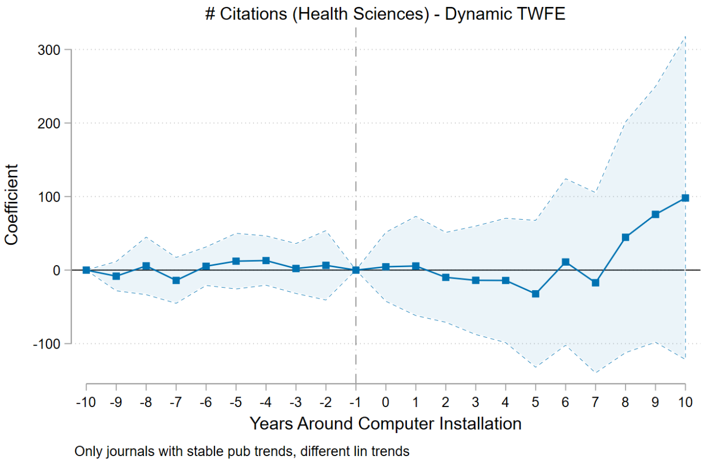
Differences-in-Differences: Number of Citations (Health Sciences)



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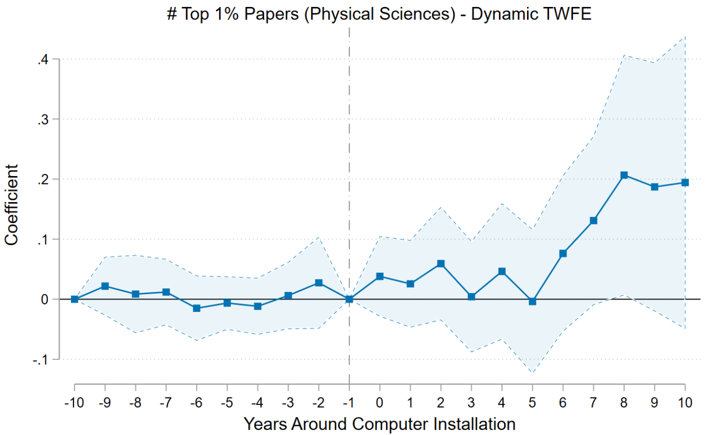
Differences-in-Differences: Number of Top 1% Papers (Physical Sciences)



Only journals with stable pub trends, different lin trends

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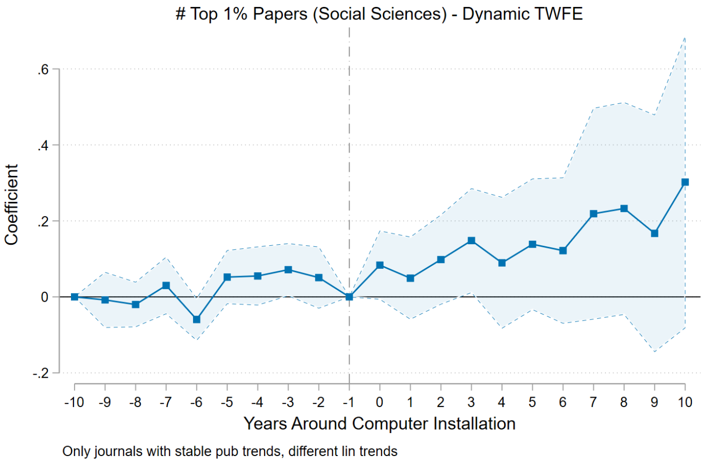
Differences-in-Differences: Number of Top 1% Papers (Social Sciences)



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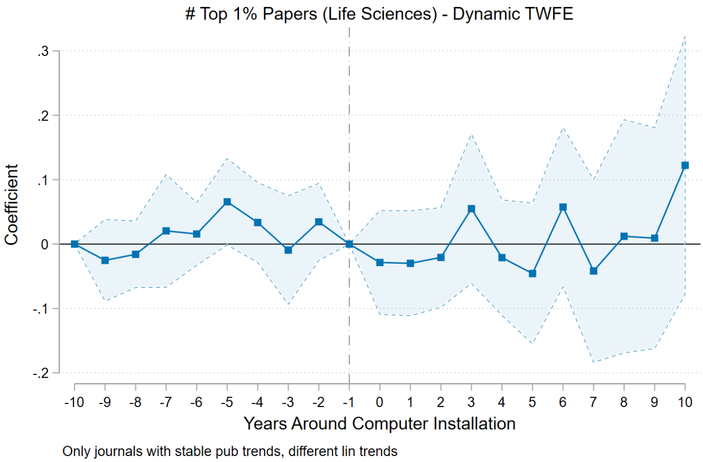
Differences-in-Differences: Number of Top 1% Papers (Life Sciences)



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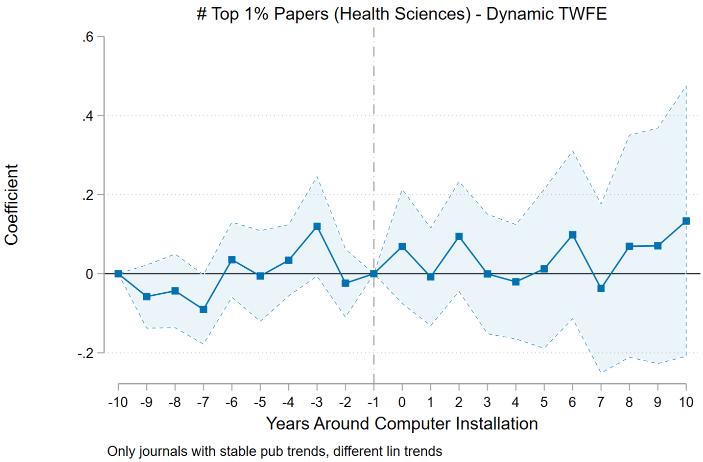
Differences-in-Differences: Number of Top 1% Papers (Health Sciences)



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