Technological Breakthroughs and the Progress of Science: Evidence from Early Computers (1950-1970)

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Technology as a Driver of Scientific Progress

- What drives scientific progress?
- Large literature on human capital (Jones [2009]; Wuchty et al. [2007]; Waldinger [2016]), institutions (Moser [2005]; Giorcelli and Moser [2020]; Moscona [2021]), and funding (Azoulay et al. [2019]; Myers [2020])
- Technology typically studied as an output of science (Jaffe [1989]; Mansfield [1991]), not as an input
    - Yet tools reshape what can be measured, computed, or inferred (Mokyr [2002]; Rosenberg [1992]; Krauss [2026])
- We study the impact of a general purpose technology — digital computers — on science itself (Bresnahan and Trajtenberg [1995])

This Paper

- Focus on the introduction of digital computers at US universities (1950–1970)
- Study how adoption impacted research direction, quality, and methods
  - Focus on the early and large mainframe computers
  - Computers housed in shared centers, access tied to institutional affiliation
- Construct the first comprehensive database of 2,200 computer installations across 184 universities
- Combine with publication data from OpenAlex and full-text analysis
- Exploit variation in timing of adoption across universities and pre-digital computational intensity across subjects

Related Literature

- Factors Affecting Scientific Direction & Quality (e.g., Nagaraj and Tranchero [2023]; Myers [2020]; Borjas and Doran [2012]; Boudou and Mckeon [2024])
    - Role of **technology itself** as a driver of scientific progress and direction.
    - Study introduction of a **GPT** with **large, discontinuous** jump in compute.

- Technology and Science (e.g., Ahmadpoor and Jones [2017]; Agrawal and Goldfarb [2008]; Gao and Wang [2023], Mokyr [1992, 2002, 2016])
    - Provide **causal evidence** on the reverse direction from technology to science.

- Diffusion of General-Purpose Technologies (e.g., David [1990]; Comin and Hobijn [2010]; Moser and Nicholas [2004]; Bresnahan and Trajtenberg [1995])
    - Trace the **diffusion of a GPT within science** where we can track where, when, and how computers entered the scientific record.

Preview of Results

- Computer-related papers appear immediately after campus installations
- Fields relying on manual calculation before computers adopt them more and earlier
- Computer papers are ∼20% more cited, 35% more likely to be top 1%, and 18–32% more novel
- Triple-difference university-level: computers shift research toward numerically intensive areas
  - Physical Sciences: +15% publications, +22% citations in exposed subfields
  - Social Sciences: +10% publications, +32% citations in exposed subfields
- In the period, computers seem to make science relatively less empirical, shifting research towards simulations and methods
- No quantity-quality trade-off: more papers *and* better papers

Historical Background

> *“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)*

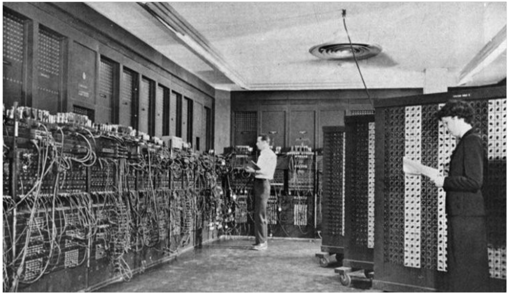
> *“It would appear that we have reached the limits of what is possible to achieve with computer technology, although one should be careful with such statements, as they tend to sound pretty silly in five years.”*
>
> – *John von Neumann (1949)*

Revolution in Scientific Computing

- Pre-1945: Scientific research constrained by computational power
  - Manual computations and mechanical calculators, prone to error
  - Mechanical devices (e.g., differential analyzers) were special-purpose and limited
- Sharp transformation with digital computers (late 1940s) ▸ IAS
  - ENIAC (1946): First programmable computer, 1,000 times faster than predecessors
  - IBM 650 (1953): First widely adopted computer, first model for 27% of our sample
- ∼100,000-fold increase in computations per second between 1945 and 1970 (Nordhaus [2007])

Boom in Computer Innovation: From the ENIAC to IBM

The ENIAC: 1945



IBM 650: 1953

Unlocking Previously Infeasible Ideas

- Many applications were ideas people already had but lacked the computational power to execute
- Numerical Weather Prediction
  - Richardson [1922]: full method laid out in 1922, but infeasible by hand
  - Charney et al. [1950]: first successful numerical forecast on ENIAC (1950)
- Quantum Chemistry
  - Dirac (1929): QM provides the laws, but equations “too complicated to be soluble”
  - Boys (1950): first *ab initio* calculation on EDSAC; Roothaan (1951): matrix formulation for computers
- X-ray Crystallography
  - Fourier syntheses for 3D structures: feasible for small molecules, impossible for proteins by hand
  - Kendrew solved myoglobin on EDSAC (1958) — first 3D protein structure; Nobel Prize 1962 (Kendrew [1963])

Early Digital Computer Adoption by Universities

- High costs of computer installation led to staggered adoption
  - UNIVAC I cost $1.5M in 1951 (∼$15M in 2025 dollars), required 382 sq ft
  - Funding from manufacturer donations, NSF acquisition grants, dedicated fundraisers
- Mostly (50.5%) located in shared computer centers due to high cost and large size

  ▸ Where Installed
  - NSF conditioned funding on university-wide availability (National Research Council [1966])
- Researchers depended on universities for computer access
  - Limited remote access until the late 1960s ▸ Remote Access Example
- First universities got digital computers in 1951 (MIT, GWU)
- By 1969, all research-intensive universities had access to a computer

Data

Computer Installations Database

- First database of computer installations in US higher education, up to 1971
- Information obtained from historical surveys of universities: ▸ All Sources
  - Computers & Automation magazine Rosters of Organizations
  - University of Rochester Computer Center surveys ▸ Snapshot
  - Southern Education Board/NSF surveys by John Hamblen ▸ Snapshot
- In total, 24 survey sources and 82 survey-year pairs, totaling 18,282 computer snapshots ▸ Database Sample ▸ Timeline
- Covers 184 consolidated and verified US universities (2,200 installations)
- Covers all US research-intensive institutions (R1, R2) of the period ▸ List
- For 74% of installations, we have direct documentation of installation dates
- Computer-model mentions in published papers closely track installation dates ▸ Examples

Publication Data

- We retrieve publication and citation metadata from OpenAlex and SciSciNet
  - OpenAlex is widely used in prior work (Priem et al. [2022]; e.g. Azoulay and Greenblatt [2025]; Schmallenbach et al. [2024]; Shvadron et al. [2025])
- For each paper, we collect full metadata (e.g., citations)
- SciSciNet (Lin et al. [2023]) for science-of-science outcomes
- We add n-grams derived from full text via OA and publisher-supplied full text
- OA uses a 4-tier subject classification: domains, fields, subfields, and topics
- Covers 4 domains × 26 fields in Physical, Life, Health, and Social Sciences

▸ Publications over the years

Publication Sample Selection

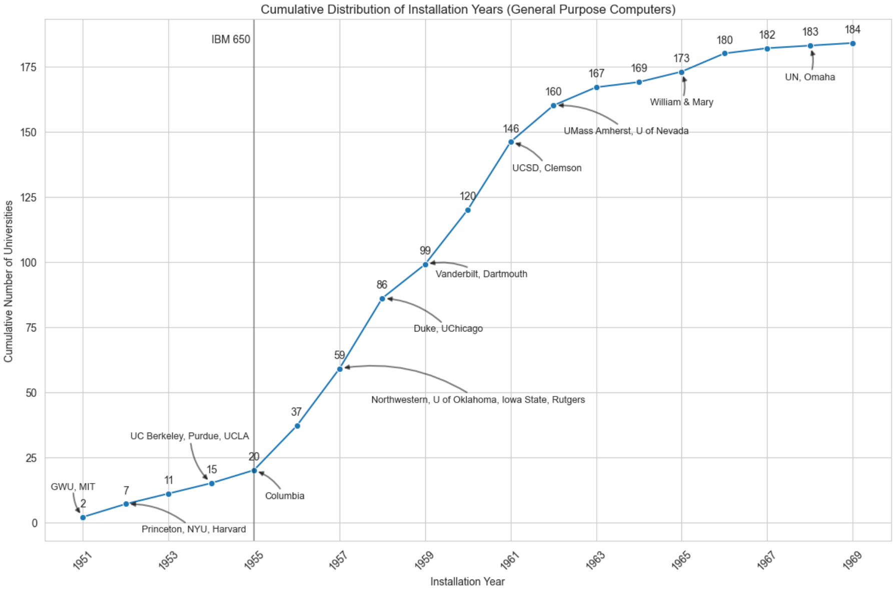
- Restrict all samples to English-language papers published after 1940
- Paper-level descriptives: all OpenAlex papers, with searchable n-grams for roughly 40% of works
  - 8.9M papers before 1970; 16.7M before 1980
- Author- and university-level analyses: papers with at least one affiliation in our university sample (1940–1970)
  - About 650,000 papers; 73% with searchable full text

Identifying Computer Use in Articles

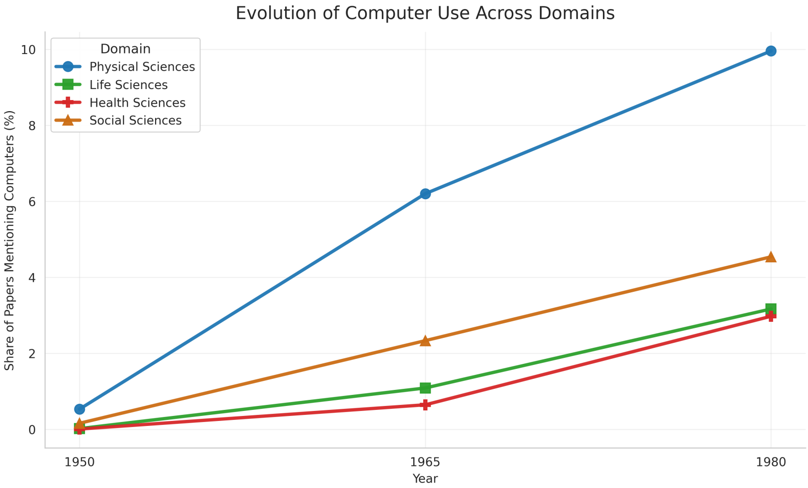
- N-gram search: search full-text for keywords like *digital computer*, *electronic computer*, *high-speed computing device* ▸ Keywords
    - Flags 2.27% of searchable papers (4.86% including "computer")
    - Common for early users to explicitly state use of computers
- LLM classification from full text of 1.3M papers
    - Screen with extended keyword list, then classify with LLMs ▸ Extended List
    - Identifies 3.45% of papers as using/mentioning computers
- Both methods perform well on hand-coded validation of 200 papers ($F_1 = 0.928$ keywords, 0.967 LLMs)

Descriptive Analysis

Digital Computer Adoption by US Universities, 1950–1970 ▸ Stats



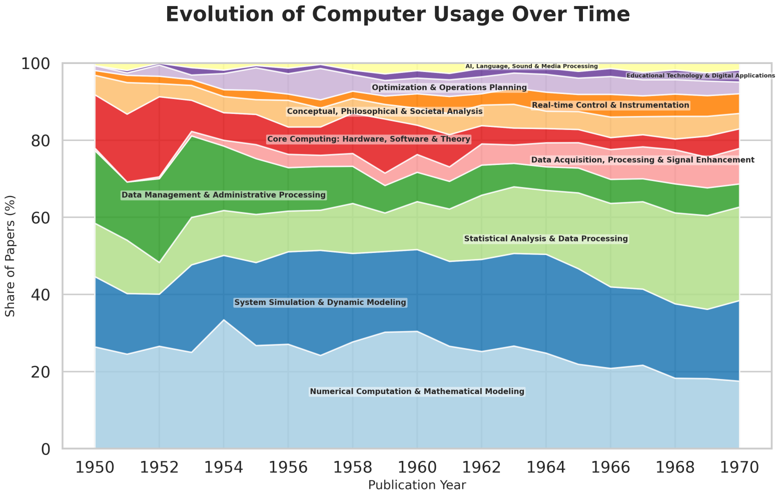
Evolution of Computer Use Across Domains



Taxonomy of Computer Usage in Research

- LLM classification from full text:
  - Computer as a Tool: 62.7%
  - Computer as Object of Study: 2.6%
  - Hardware/Software Papers: 5.5%
  - Other Mentions: 29.2%
- Follow Tamkin et al. [2024] to classify computer usage; data-driven clustering reveals 11 usage categories ▸ Details
- Three categories account for >60% of uses:
  - Numerical Computation: 22.5%
  - System Simulation: 21.3%
  - Statistical Analysis: 19.3%

Evolution of Computer Usage in Research

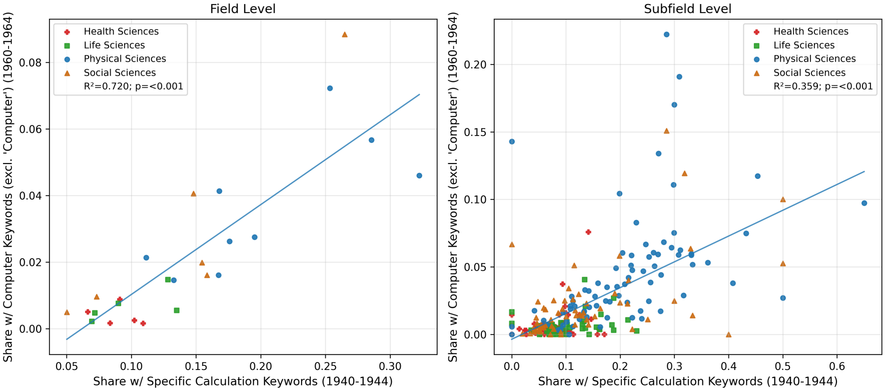


By Domain

Correlates of Computer Diffusion

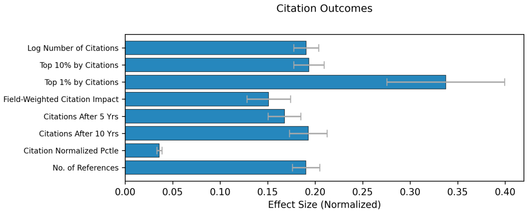
- Pre-1945 reliance on manual/mechanical calculation strongly predicts subsequent computer adoption ▸ Keywords
- $R^2 = 0.720$ at field level; $R^2 = 0.359$ at subfield level ▸ By Domain

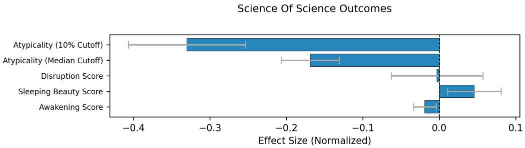
Share w/ Specific Calculation Keywords (1940-1944) vs Share w/ Computer Keywords (excl. 'Computer') (1960-1964)


Field Level

Subfield Level

Citations and Research Impact



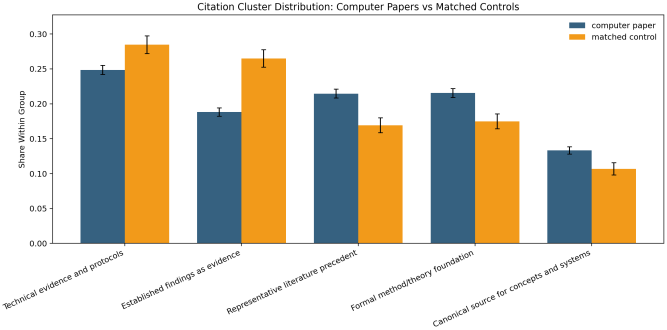


Notes: Weighted paper-author regressions with author, year, university, and topic fixed effects plus controls for number of authors and NSF grants. Searchable-full-text sample with at least one in-sample university affiliation; SciSciNet adds the science-of-science outcomes. $N = 2.2\text{M}–3.8\text{M}$.

- Computer papers are 18-32% more novel by the Uzzi et al. [2013] metric
- Premiums are entirely driven by papers using computers as tools ▸ Usage
- Display higher breadth and novelty as measured by topic combinations ▸ Topics
- But no more likely to be cited by patents ▸ Other

▸ Citations ▸ Cit. Emb. ▸ Sci-of-Sci ▸ SciSci Emb. ▸ Premiums

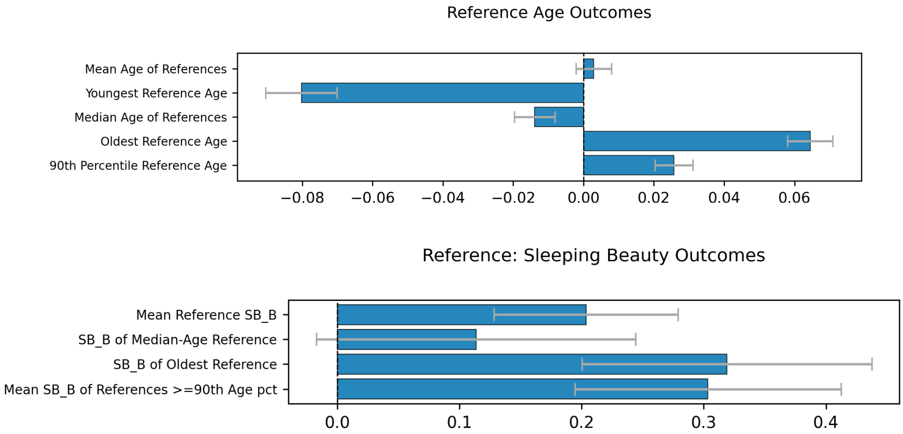
Why Are Computer Papers Cited More?


Citation Cluster Distribution: Computer Papers vs Matched Controls

Notes: Shares of usable citation links by cluster in the 20,910-link sample (16,114 to computer papers; 4,796 to matched controls). Clusters from embeddings of short LLM descriptions of *why* the cited paper is used.

- Composition: computer papers cited more as canonical sources (highest-premium bucket), less as established findings (lowest-premium) ▸ Pipeline ▸ Specs ▸ Examples ▸ Regs
- Accounting: breadth + composition attenuate the FWCI premium by ∼10%; of that, ∼90% is composition, ∼10% excess breadth ▸ Decomposition

Reference Age and Sleeping Beauties



Reference Age Outcomes

Reference: Sleeping Beauty Outcomes

Notes: Bars report normalized treatment effects from pooled paper-level regressions. The regressor is an indicator for computer-related keywords in the paper's full text. Controls: number of authors and NSF grants citing the paper. Fixed effects: author, publication year, university, and primary topic. Standard errors are clustered at the paper level (OpenAlex Work ID). Observations are paper-author pairs weighted by the inverse number of authors. Sample restricted to papers with at least one in-sample university affiliation and searchable full text in OpenAlex. Non-logged outcomes are divided by their sample mean.

▶ Age Table ▶ Age Emb. ▶ SB Table ▶ SB Emb.

Author-Level Patterns

- Comparing authors mentioning computers ("adopters") vs. those who don't
- Computer adopters are positively selected, even after controlling for field, university, and cohort:
  - 4× publications, 4.3× citations, 64% higher H-index ▸ Table
  - Adopters are more experienced ▸ Figure and have 4.5× more top 1% papers ▸ Table
  - Advantages predate university adoption, though gap is smaller ▸ Table
  - Early vs. late adopters look similar within the adopter sample ▸ Table
- Intensive margin: ↑ computer papers → ↑ outcomes ▸ Table

Empirical Strategy

Triple Differences (DDD) Design

- Key idea: Different subjects have different computational demand
  - E.g., Numerical Analysis vs. Arts and Humanities
- Define exposure E_s from the 1940–1944 share of numerically intensive papers; classify subfields above vs. below the median
- DDD regression specification:

$$Y_{ust} = \sum_{k \neq -1} \beta_k \mathbf{1}\{t - G_u = k\} \cdot E_s + \mu_{ut} + \eta_{st} + \delta_{us} + \varepsilon_{ust}$$

- μ_{ut}: university×year FE; η_{st}: subject×year FE; δ_{us}: university×subject FE
- β_k: within-university gap between exposed and unexposed subjects at event time k
- In practice, use mean differences as outcomes on Callaway and Sant'Anna [2021]; de Chaisemartin and D'Haultfoeuille [2020] estimators (Olden and Møen [2022])

Difference-in-Differences Design

- Binary Treatment: Year of first digital computer installation (G_u)
- All institutions in sample had computers by 1969
- University-level DiD:

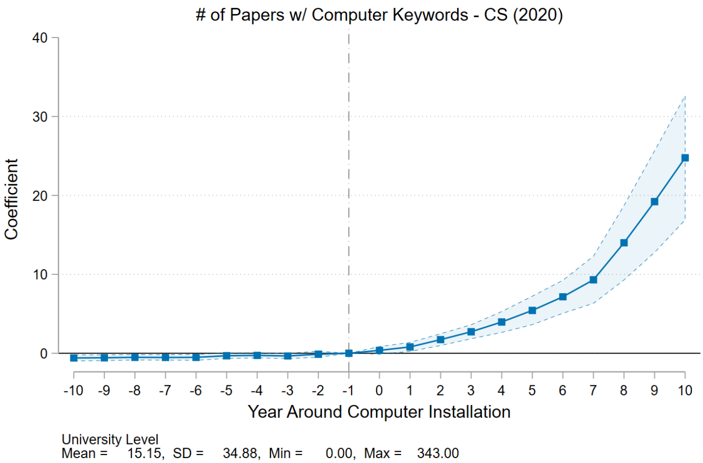
$$Y_{u,t} = \sum_{k \neq -1} \gamma_k \mathbf{1}\{t - G_u = k\} + \alpha_u + \lambda_t + \varepsilon_{ut}$$

  γ_k: effect of adopting computers k years ago on outcome Y

- Methods: Modern staggered-adoption estimators (Callaway and Sant'Anna [2021]; de Chaisemartin and D'Haultfoeuille [2020])
  - Standard TWFE biased with staggered adoption and heterogeneous effects ▸ Plots ▸ Bacon
- Identifying assumptions: Parallel trends, no anticipation, no spillovers
  - Limited remote access supports no spillovers
  - Equipment-specific funding channels support exogeneity

Results

Computer Usage After Installation

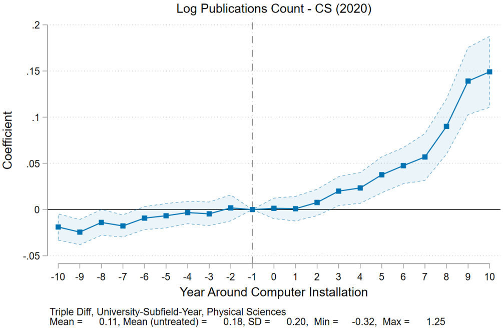


- ∼25 additional computer papers/year by year 10 (∼10% of mean annual output)

TWFE plots Bacon

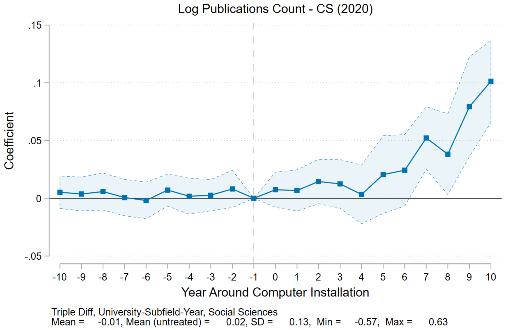
DDD: Direction of Science (Publication Counts)

Physical Sciences



Triple Diff, University-Subfield-Year, Physical Sciences
Mean = 0.11, Mean (untreated) = 0.18, SD = 0.20, Min = -0.32, Max = 1.25

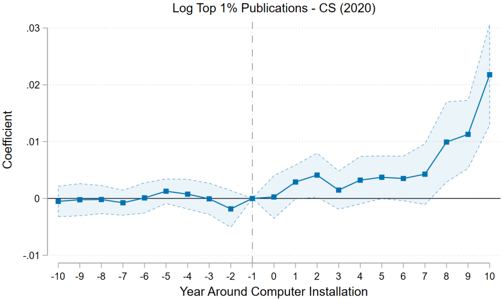
Social Sciences



Triple Diff, University-Subfield-Year, Social Sciences
Mean = -0.01, Mean (untreated) = 0.02, SD = 0.13, Min = -0.57, Max = 0.63

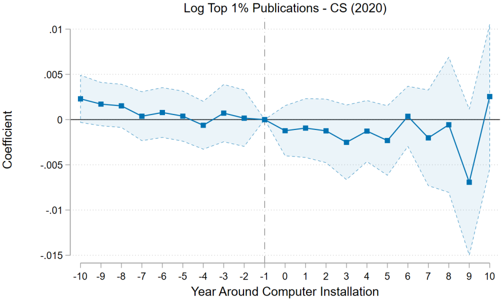
DDD: Quality of Science

Top 1% Papers: Physical Sciences



Triple Diff, University-Subfield-Year, Physical Sciences
Mean = 0.01, Mean (untreated) = 0.02, SD = 0.05, Min = -0.14, Max = 0.66

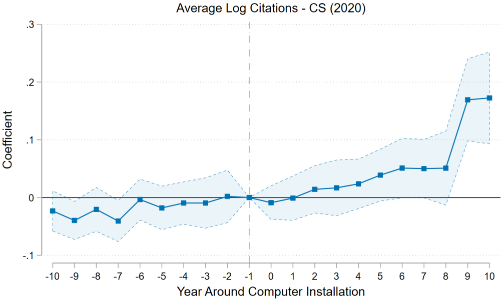
Top 1% Papers: Social Sciences



Triple Diff, University-Subfield-Year, Social Sciences
Mean = -0.00, Mean (untreated) = -0.00, SD = 0.02, Min = -0.24, Max = 0.31

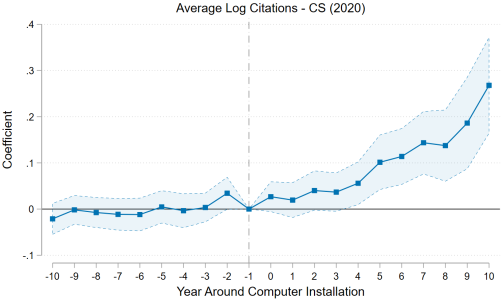
DDD: Quality of Science

Avg Citations: Physical Sciences



Triple Diff, University-Subfield-Year, Physical Sciences
Mean = 0.12, Mean (untreated) = 0.20, SD = 0.29, Min = -1.02, Max = 1.69

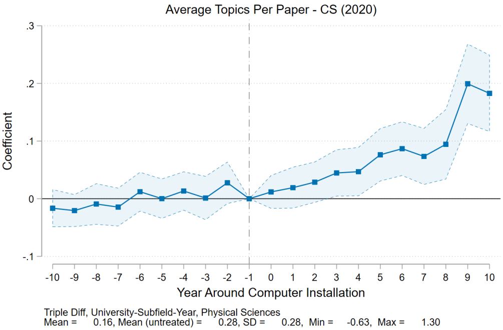
Avg Citations: Social Sciences



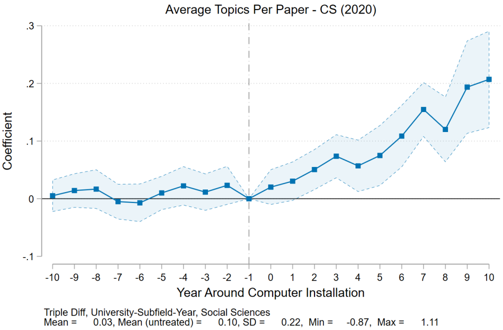
Triple Diff, University-Subfield-Year, Social Sciences
Mean = 0.14, Mean (untreated) = 0.25, SD = 0.28, Min = -1.02, Max = 1.65

DDD: Content of Science

Topics per Paper: Physical Sciences

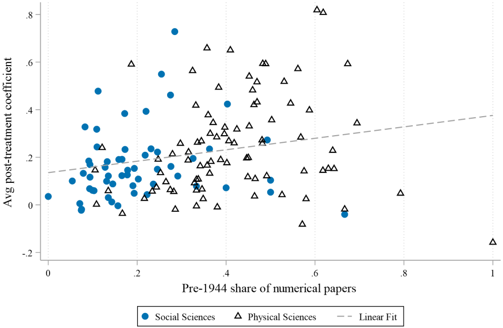


Topics per Paper: Social Sciences

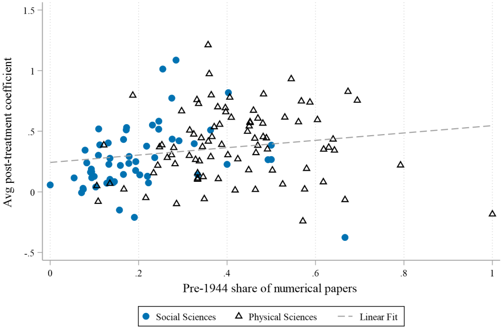


▶ Topic novelty

Effects by Subject Numerical Intensity



Publication counts vs. numerical intensity



Citations per paper vs. numerical intensity

- 90th pctile: +24% publications, +29% citations
- 10th pctile: +10% publications, +12% citations

Classifying Research Methods

- We ask whether research methods shift inside universities after computer installation.
- Each paper is assigned a methodology type: empirical, theory, methods, simulation/computation, or other.
- We first build pseudo ground truth with Gemini 3.0 Flash full-text reads on 177,243 papers.
- We then train a ML gradient-boosted model so we can score papers even when local full text is unavailable.
- Main holdout benchmark: weighted F1 = 0.825 on a 10k full-text test set.

▸ Classifier details ▸ Paper types

What the Classifier Measures

- Each paper is assigned a probability distribution over labels
- For the panels, we aggregate the probability mass to account for uncertainty of the classifier
- 57% of papers are assigned scores in our panel sample

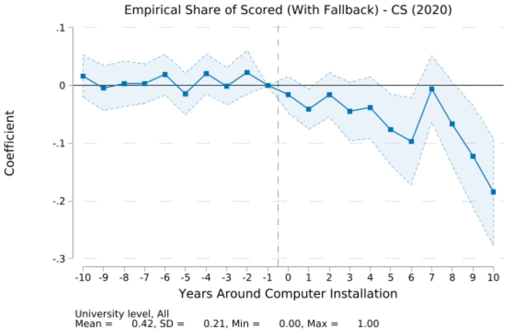
Bucket	Mass share	What it mainly captures
Empirical	48.3%	Data, experiments, field evidence, or observational measurement.
Theory	18.3%	Formal derivations, conceptual models, or theoretical argument.
Methods	11.1%	Algorithms, procedures, software, and measurement techniques.
Simulation	1.1%	Simulation, computational modeling, or numerical experimentation.
Other	21.3%	Reviews, bibliographies, editorials, and reference-type material.

Notes: Percentages are average predicted probability mass across the 268,887 classified papers in the 1951–1969 diagnostic slice, not argmax shares.

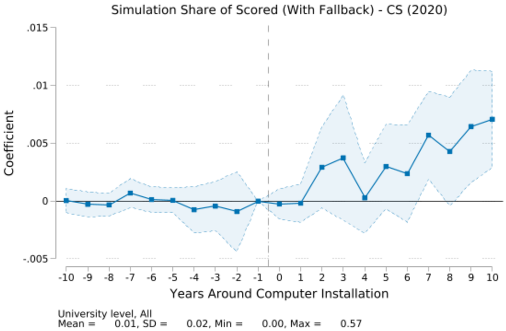
▸ Raw classes

Changes in Research Methodologies

Empirical Share of Scored Papers



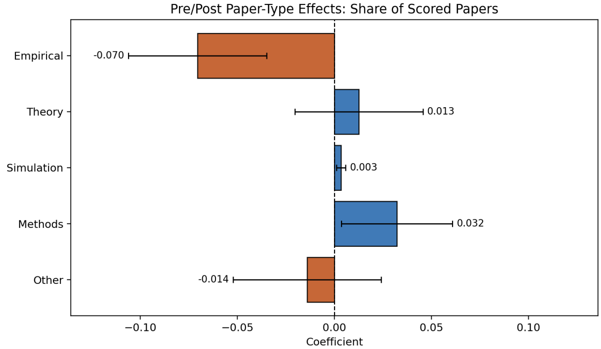
Simulation Share of Scored Papers



Notes: Callaway-Sant'Anna event-study estimates using university-year panel outcomes. Shares are measured among scored papers only ('ptype_shr_wf'), so they track reallocation within the classified subset rather than changes in scoring coverage.

▸ Theory + Methods

Within Scored Papers: Collapsed Pre/Post

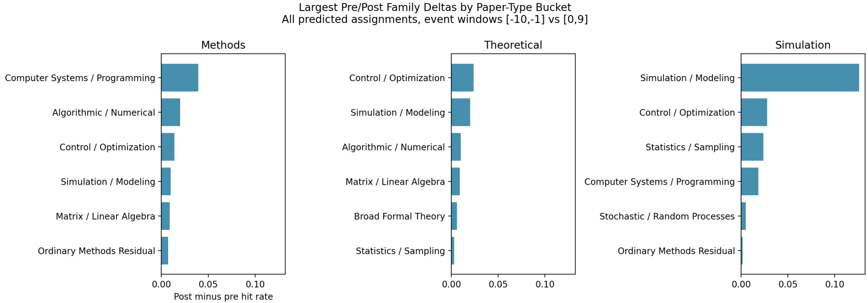


Notes: Bars show collapsed Callaway-Sant'Anna pre/post ATT estimates for shares among scored papers. This is best read as a composition shift: empirical counts rise in raw levels, but theory, methods, and simulation shares rise faster within the scored subset.

▸ Benchmark ▸ Class shares

- Raw empirical counts still increase after installation, so not an absolute collapse of empirical work.
- These bars come from separate CS share regressions, so they are not an exact adding-up decomposition.
- Paper-level regressions confirm computer papers are less likely to be empirical, even relative to theory ones. ▸ Paper-level regs

What Is Rising Inside Theory and Methods?



Notes: Transparent dictionary-hit frequencies, not another classifier. Sample: 270,134 predicted paper × role rows in 1951–1969; pre '[-10,-1]', post '[0,9]'. Lexicons were grounded in 120 manual full-text packets and 3,578 usable snippets.

▸ Families ▸ Title magnitudes ▸ Examples ▸ Keywords DiDs

Conclusion

Conclusion

- Computer usage appears immediately in the scientific record after installation
- Adoption follows pre-digital computational intensity: fields relying on manual calculation adopt first
- Computer papers are more cited, more novel, more broadly topical
- DDD: clear within-university reallocation toward compute-amenable subfields
  - Publication counts, quality, breadth, and novelty all increase
- DiD: strong gradient — effects $\sim 2\times$ larger for 90th vs. 10th percentile of numerical intensity
- Unlike standard GPT narratives: no delayed productivity gains; effects materialize within years
- No quantity-quality trade-off: more papers and better papers simultaneously

Thank you!

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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

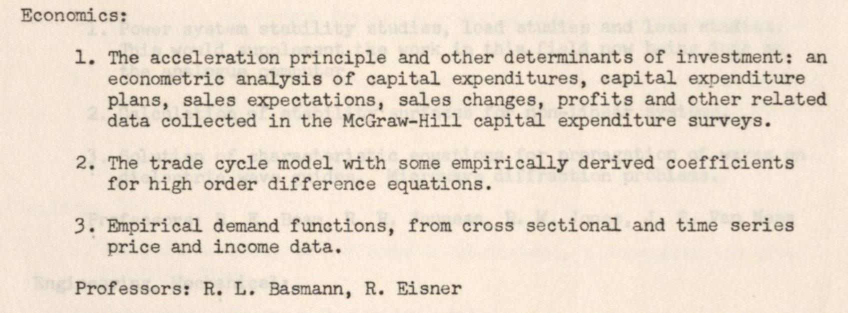
Testing Princeton’s IAS Computer

> *“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

▸ Back



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.

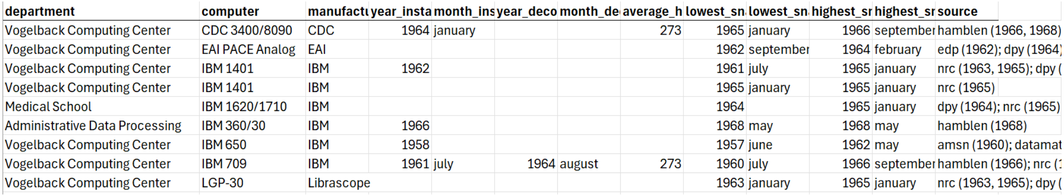
2. The trade cycle model with some empirically derived coefficients for high order difference equations.

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



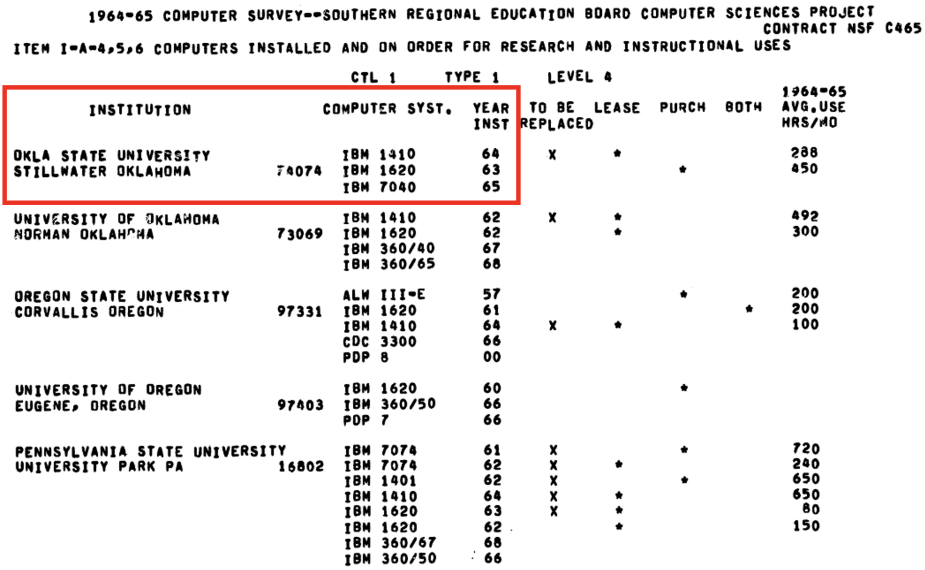
department	computer	manufactu	year_insta	month_ins	year_deco	month_de	average_h	lowest_sn	lowest_sn	highest_sr	highest_sr	source
Vogelback Computing Center	CDC 3400/8090	CDC	1964	january			273	1965	january	1966	septembe	hamblen (1966, 1968)
Vogelback Computing Center	EAI PACE Analog	EAI						1962	septembe	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	septembe	hamblen (1966); nrc (
Vogelback Computing Center	LGP-30	Librascope						1963	january	1965	january	nrc (1963, 1965); dpy (

Figure 1: Installations of Computers at Northwestern University. Some columns removed for readability.

▸ Back

Hamblen Survey, 1966

Back



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         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
                                                                                        1964-65
        INSTITUTION                       COMPUTER SYST.   YEAR  TO BE   LEASE  PURCH  BOTH   AVG.USE
                                                           INST REPLACED                       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
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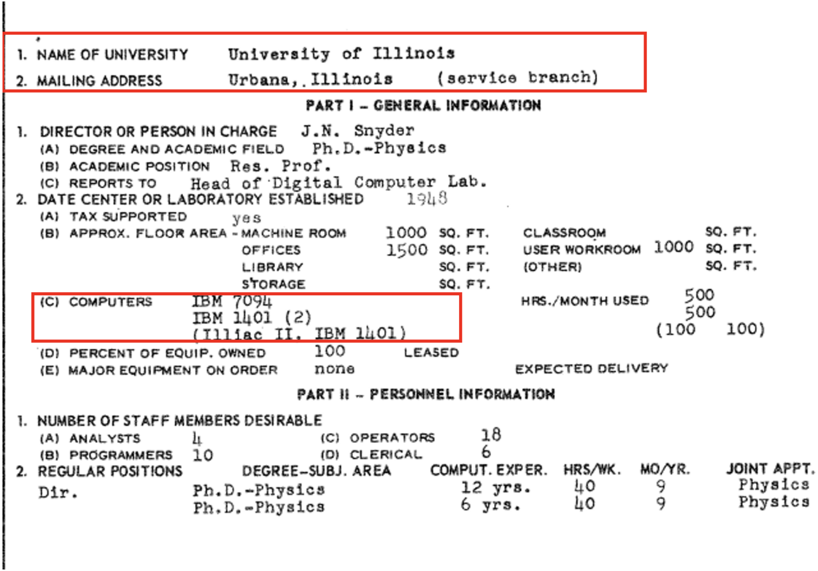
Keenan Survey, 1963

▸ Back



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	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

Survey Sources

1. Computers & Automation Rosters
2. Inventory of Computers in U.S. Higher Education (Hamblen)
3. Rochester annual computing-center survey (Keenan)
4. Digital Needs in Universities and Colleges (Roesser)
5. AMS Notices survey of high-speed computers
6. Datamation university survey
7. Educational Programs and Facilities in Nuclear Science and Engineering
8. Data Processing Yearbooks / Computer Yearbook
9. Business Electronics Reference Guide
10. Hearings on H.R. 4845
11. Hydrologic Computer Programs
12. Digital Computer Newsletter
13. ONR Survey of Automatic Digital Computers
14. BRL Survey of Domestic Electronic Digital Computing Systems (Weik)
15. Florida State University administrative survey
16. IBM 650 installation data (IBM Archives)
17. Mathematics in Education
18. Business Automation university survey
19. Data Processing for Management
20. Research Centers Directory
21. Survey of Numerical Weather Prediction
22. Use of Electronic Data Processing Equipment hearings
23. AEC Authorizing Legislation hearings
24. Datamation installation news

Back

Survey Coverage Timeline

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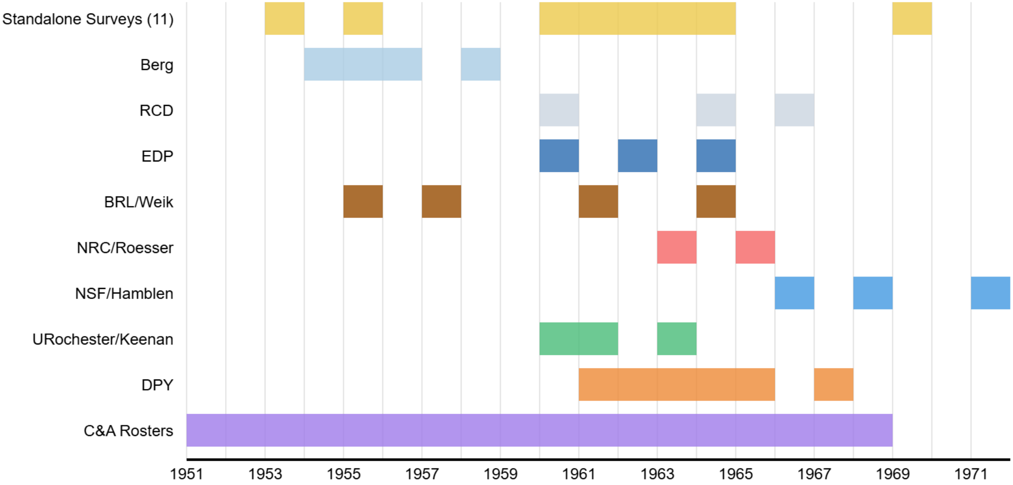


Figure 2: Yearly coverage of survey sources in the database.

Universities In Sample

▶ Back

Abilene Christian College
American University
Arizona State University
Auburn University
Boston College
Boston University
Brandeis University
Brigham Young University
Brown University
Caltech
Carnegie Mellon University
Case Western Reserve
Columbia University
Cornell University
Dartmouth College
Duke University
Emory University
Florida State University
George Washington University
Georgetown University
Georgia Institute Of Technology
Harvard University
Howard University
Illinois Institute Of Technology
Indiana University
Iowa State University
Johns Hopkins University
Kansas State University
Lehigh University
Louisiana State University
MIT
Michigan State University
Mississippi State University
Montana State University
New York University
North Carolina State University
Northwestern University
Ohio State University
Oklahoma State University
Oregon State University
Penn State University
Princeton University
Purdue University
Rensselaer Polytechnic Institute
Rice University
Rutgers University
Stanford University
SUNY Buffalo
Syracuse University
Texas A&M University
Tufts University
Tulane University
UC Berkeley
UC Los Angeles
UC San Diego
University of Chicago
University of Colorado Boulder
University of Florida
University of Illinois UC
University of Iowa
University of Kansas
University of Maryland
University of Michigan
University of Minnesota
University of Missouri
University of Nebraska
University of North Carolina
University of Notre Dame
University of Oklahoma
University of Oregon
University of Pennsylvania
University of Pittsburgh
University of Rochester
University of Southern California
University of Tennessee
University of Texas Austin
University of Utah
University of Virginia
University of Washington
University of Wisconsin Madison
Vanderbilt University
Virginia Tech
Washington University StL
Wayne State University
West Virginia University
Yale University
+ 124 more

Computer Installations Descriptive Statistics ▸ Back

- 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%)
- Computer centers housed 50.5% of all installations ▸ Locations

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

Where Were Computers Installed?

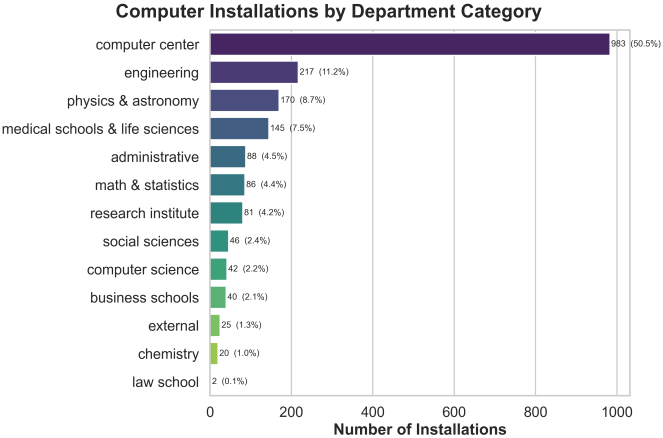


Figure 3: Shared computer centers account for 50.5% of installations with known location.

▸ Adoption ▸ D Stats

Computer Keywords

▸ Back

Core keyword list

- (computer), electronic computer
- digital computer, automatic computer
- high-speed computer, mainframe computer
- high-speed computing device
- electronic brain
- data processing equipment
- computer program
- computer algorithm
- programming language
- FORTRAN, COBOL

Extended LLM screen

- calculator, computing, computational
- punch card, punched card
- Monte Carlo, simulation
- ALGOL, algorithm, program, programming
- electronic machine
- analog computer
- electromechanical computer
- automatic equipment

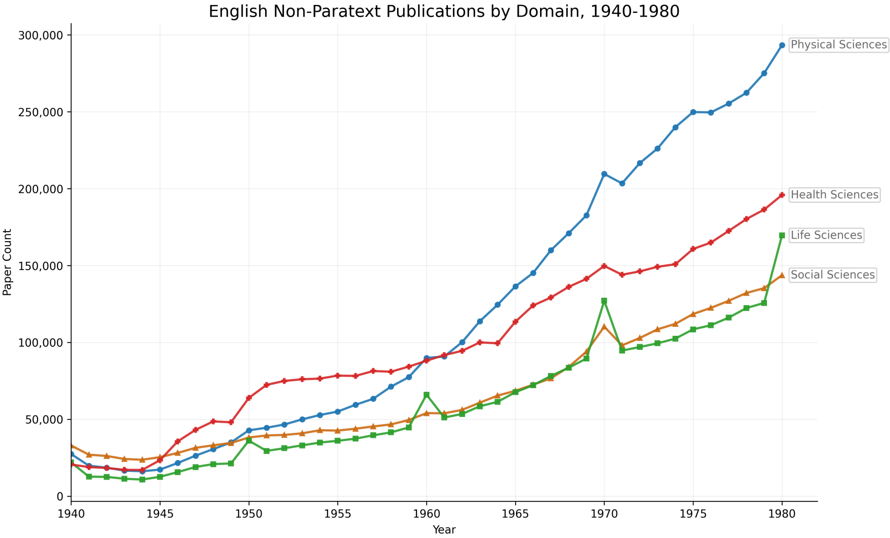
Extended LLM screen (cont.)

- data processing, EDP, ADP
- IBM, UNIVAC, Burroughs

Rates in draft

- Keywords: 2.27% of searchable papers
- 4.86% including “computer”
- LLMs: 3.45% of papers

Publications by Field



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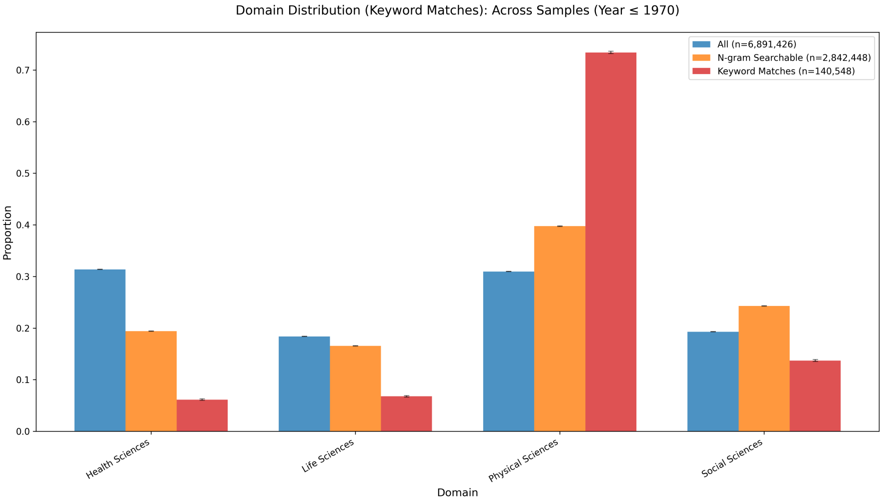
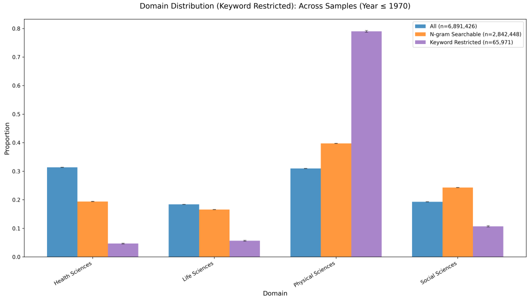
Distribution of Computer Papers Across Domains

▸ Back

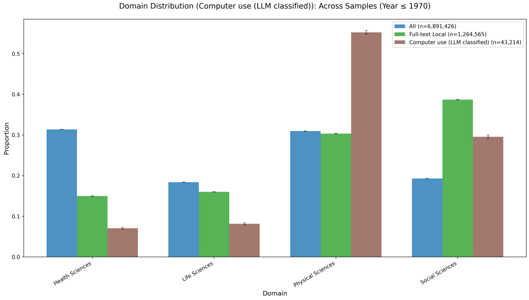


Distribution of Computer Papers: Robustness

▶ Back



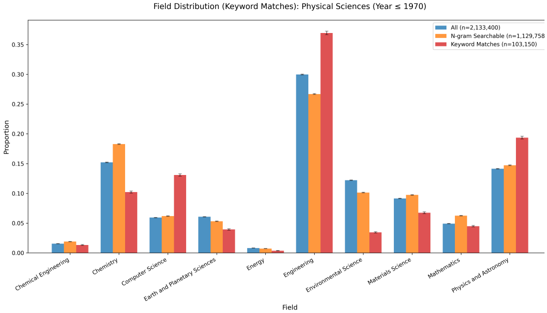
Keywords restricted



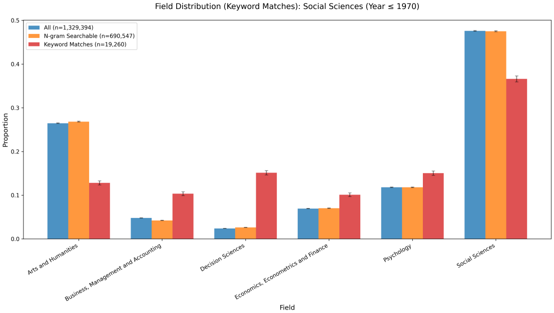
LLM classified

Distribution of Computer Papers in Physical and Social Sciences

▸ Back



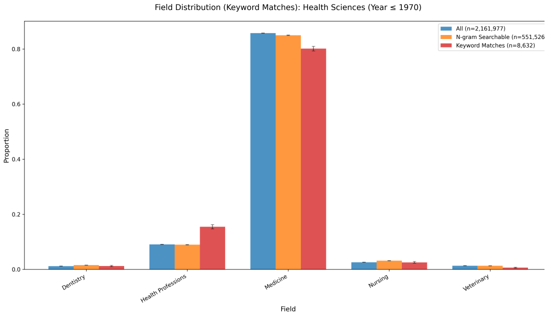
Field Distribution (Keyword Matches): Physical Sciences (Year ≤ 1970)

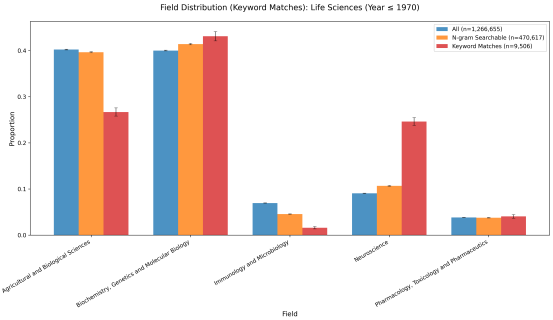


Field Distribution (Keyword Matches): Social Sciences (Year ≤ 1970)

Distribution of Computer Papers in Health and Life Sciences

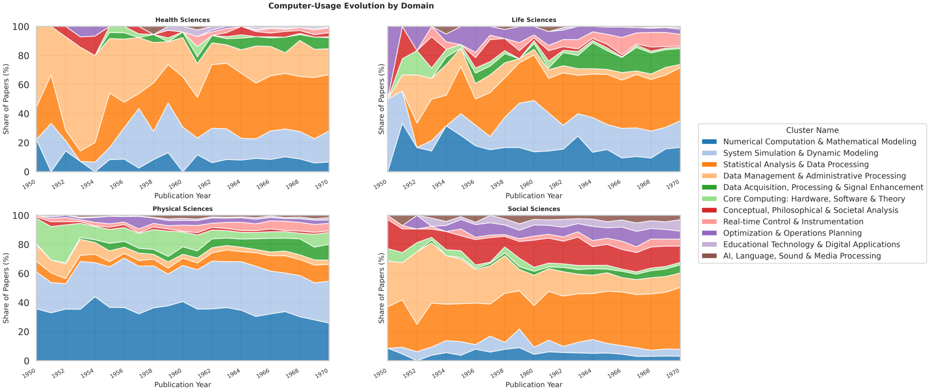
▶ Back


Field Distribution (Keyword Matches): Health Sciences (Year ≤ 1970)


Field Distribution (Keyword Matches): Life Sciences (Year ≤ 1970)

Evolution of Computer Usage by Domain

▸ Back



Calculation-Intensity Keywords ▸ Back

Manual / mechanical calculation

- manual calculation, computed by hand
- hand computation, longhand calculation
- checked by hand
- punched card, Hollerith, keypunch
- desk calculator, mechanical calculator
- adding machine, comptometer
- Friden, Marchant, Brunsviga, Burroughs
- tabulating department, machine accounting

Linear algebra / numerical methods

- matrix inversion, matrix multiplication
- Gaussian elimination, Gauss-Jordan
- normal equations, eigenvalue, eigenvector
- Runge-Kutta, Newton-Raphson
- finite difference, difference equation
- differential equation, simplex method

Analog instruments

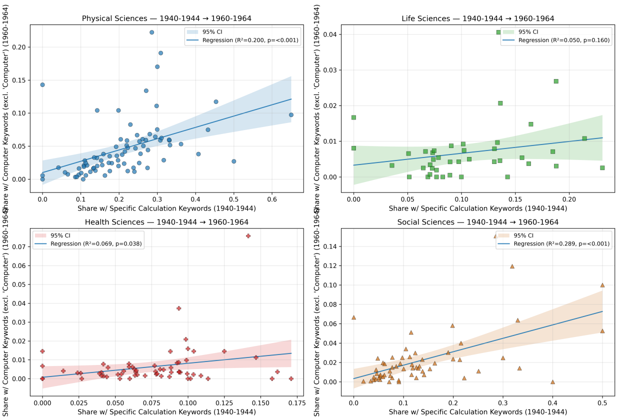
- differential analyzer, network analyzer
- harmonic analyzer, slide rule
- nomogram, integrator
- analog simulator, model board
- patch board, A-C network analyzer

Statistics / new computational uses

- least squares, maximum likelihood
- log-likelihood, regression analysis
- ANOVA, principal component analysis
- probit, logit, sample size, data analysis
- numerical simulation, stochastic simulation
- numerical experiment, random number table
- pseudo-random, Monte Carlo

Computer Diffusion by Domain

▶ Back



Share w/ Specific Calculation Keywords (1940-1944) vs Share w/ Computer Keywords (excl. 'Computer') (1960-1964)

Physical Sciences — 1940-1944 → 1960-1964

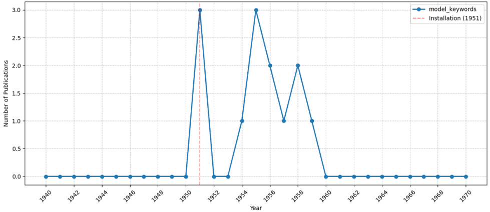
Life Sciences — 1940-1944 → 1960-1964

Health Sciences — 1940-1944 → 1960-1964

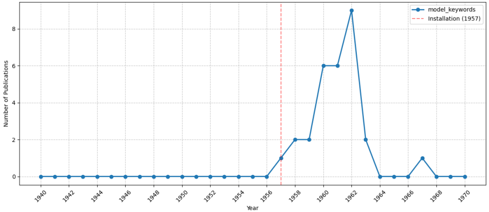
Social Sciences — 1940-1944 → 1960-1964

Computer Model Mentions Across Universities

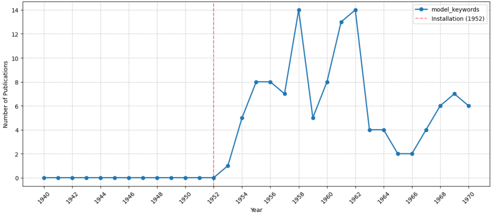
▶ Back



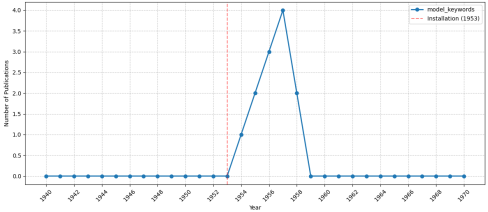
Massachusetts Institute of Technology



Northwestern University



University of Illinois, Urbana-Champaign



University of Michigan, Ann Arbor

Research Impact by Usage Type

▸ Back

	Log Cites	Top 1%	# Cncpts	Cncpt Max Nov	Atp-Z (10%)
Computer as a Tool	0.214***	0.011***	0.072***	0.356***	-10.771***
	(0.015)	(0.002)	(0.025)	(0.093)	(2.581)
Computer as an Object of Study	0.053	0.001	-0.479***	0.410	-28.955
	(0.097)	(0.009)	(0.135)	(0.658)	(27.263)
Computer (Hardware/Software context)	-0.205***	-0.014**	-0.163	-0.725*	24.438
	(0.064)	(0.007)	(0.104)	(0.417)	(18.043)
Mention of Computer (other)	-0.063**	-0.002	-0.211***	0.259	-55.106
	(0.029)	(0.004)	(0.044)	(0.187)	(39.783)
Number of Authors	0.143***	0.005***	0.093***	0.158***	-1.125***
	(0.002)	(0.000)	(0.004)	(0.015)	(0.425)
NSF Grants (paper)	0.473*	0.049	-0.117	0.087	-51.198*
	(0.278)	(0.042)	(0.326)	(1.465)	(26.345)
Observations	642,028	641,989	642,028	642,028	281,706
R^2	0.767	0.471	0.681	0.542	0.650
Mean of Dep Var	1.470	0.022	2.614	10.109	34.091
Author/Year/Univ FE	Yes	Yes	Yes	Yes	Yes
Subject FE	Topic	Topic	Topic	Topic	Topic

Notes: Paper-author observations, weighted by the inverse number of authors. Categories were generated by passing paper full text to an LLM. Sample restricted to papers with at least one in-sample university affiliation and searchable full text in OpenAlex. Standard errors clustered at the author level. Citation and novelty premia are concentrated in papers using computers as tools.

Citation Outcomes

▸ Back

	Log cites	Top 10%	Top 1%	FWCI	C5	Cite pct.
Computer-Keyword Flag	0.191***	0.046***	0.009***	0.409***	1.122***	0.035***
	(0.004)	(0.001)	(0.001)	(0.018)	(0.042)	(0.001)
Number of Authors	0.114***	0.021***	0.002***	0.343***	0.834***	0.021***
	(0.002)	(0.000)	(0.000)	(0.007)	(0.020)	(0.000)
NSF Grants (paper)	0.294***	0.091***	0.007	0.583***	1.001***	0.049***
	(0.026)	(0.012)	(0.005)	(0.100)	(0.213)	(0.004)
Observations	3,903,691	3,903,526	3,903,526	3,902,497	3,903,691	3,903,526
R^2	0.610	0.428	0.291	0.385	0.435	0.612
Mean of Dep Var	1.827	0.191	0.019	1.950	3.880	0.568
Author/Year/Univ FE	Yes	Yes	Yes	Yes	Yes	Yes
Subject FE	Topic	Topic	Topic	Topic	Topic	Topic

Citation Outcomes (Emb.) ▸ Back

	Log cites	Top 10%	Top 1%	FWCI	C5	Cite pct.
Residualized CKW Flag	0.203***	0.035***	0.004***	0.290***	0.457***	0.031***
	(0.004)	(0.001)	(0.001)	(0.017)	(0.034)	(0.001)
Observations	1,883,675	1,883,564	1,883,564	1,882,916	1,883,675	1,883,564
R^2	0.002	0.001	0.000	0.000	0.000	0.001
Mean of Dep Var	-0.035	-0.032	0.005	0.057	-1.107	-0.004

Notes: Second-stage OLS regresses the residualized outcome on the residualized computer-keyword indicator. In the first-stage DML residualization, both treatment and outcome are partialled out on author, publication year, university, and primary-topic fixed effects; controls for number of authors and NSF grants; and concatenated abstract/title embeddings plus SPECTER embeddings. Residuals are estimated with 3-fold cross-fitting and SGD. Second-stage standard errors are clustered at the author level and paper-author observations are weighted by the inverse number of authors. Sample restricted to searchable-full-text observations from 1947–1975.

Science of Science Outcomes

▸ Back

	Atp-Z (10%)	Atp-Z (Med)	Disrupt	SB	Awak
Computer-Keyword Flag	-10.826***	-12.995***	-0.000	0.349***	-0.186***
	(0.733)	(0.830)	(0.000)	(0.109)	(0.040)
# Authors	-1.184***	-1.484***	0.000	-0.007	-0.220***
	(0.112)	(0.131)	(0.000)	(0.020)	(0.008)
NSF grants (paper)	22.339	19.909	0.007	2.403	1.286
	(26.036)	(24.949)	(0.014)	(2.153)	(0.884)
Observations	2,221,852	2,221,852	2,368,555	3,043,443	3,043,443
R^2	0.496	0.519	0.483	0.310	0.472
Mean of Dep Var	41.091	84.676	0.026	11.559	10.700
Author/Year/Univ FE	Yes	Yes	Yes	Yes	Yes
Subject FE	Topic	Topic	Topic	Topic	Topic

Science of Science Outcomes (Emb.) ▸ Back

	Atp-Z (10%)	Atp-Z (Med)	Disrupt	SB	Awak
Residualized CKW Flag	-7.161***	-4.376***	0.005***	0.661	0.281***
	(0.595)	(0.870)	(0.000)	(1.817)	(0.044)
Observations	1,053,142	1,049,893	1,883,675	1,628,800	1,628,800
R^2	0.000	0.000	0.000	0.000	0.000
Mean of Dep Var	-8.904	-6.363	0.009	-8.424	0.118

Notes: Second-stage OLS regresses the residualized outcome on the residualized computer-keyword indicator. In the first-stage DML residualization, both treatment and outcome are partialled out on author, publication year, university, and primary-topic fixed effects; controls for number of authors and NSF grants; and concatenated abstract/title embeddings plus SPECTER embeddings. Residuals are estimated with 3-fold cross-fitting and SGD. Second-stage standard errors are clustered at the author level and paper-author observations are weighted by the inverse number of authors. Sample restricted to searchable-full-text observations from 1947–1975.

Topic and Concept Outcomes

▸ Back

	Topics			Concepts		
	# Tpks	Tpk HHI	Pair Avg Nov	# Cncpts	Cncpt HHI	Pair Avg Nov
Computer-Keyword Flag	0.022***	-0.004***	0.064***	0.086***	-0.007***	0.203***
	(0.002)	(0.001)	(0.014)	(0.008)	(0.000)	(0.016)
Number of Authors	0.023***	-0.005***	0.097***	0.072***	-0.002***	0.060***
	(0.001)	(0.000)	(0.004)	(0.002)	(0.000)	(0.004)
NSF Grants (paper)	0.108***	-0.028***	0.429***	0.565***	-0.016***	0.448***
	(0.015)	(0.004)	(0.081)	(0.062)	(0.002)	(0.087)
Observations	3,903,691	3,903,691	3,903,691	3,903,691	3,903,691	3,903,691
R^2	0.593	0.519	0.506	0.510	0.507	0.462
Mean of Dep Var	2.095	0.491	7.392	3.485	0.197	9.168
Author/Year/Univ FE	Yes	Yes	Yes	Yes	Yes	Yes
Subject FE	Topic	Topic	Topic	Topic	Topic	Topic

Other Outcomes

▸ Back

	# Patent Cites	# Countries	# Institutions	# Refs
Computer-Keyword Flag	0.244	0.003***	0.013***	1.967***
	(0.197)	(0.001)	(0.002)	(0.042)
# Authors	0.013	0.039***	0.140***	0.080***
	(0.012)	(0.001)	(0.002)	(0.010)
NSF grants (paper)	-0.084	-0.006	0.009	4.132***
	(0.154)	(0.004)	(0.013)	(0.297)
Observations	3,903,691	3,903,691	3,903,691	3,903,691
R^2	0.289	0.490	0.537	0.454
Mean of Dep Var	0.259	0.605	0.643	5.492
Author/Year/Univ FE	Yes	Yes	Yes	Yes
Subject FE	Topic	Topic	Topic	Topic

Reference Age Outcomes

▸ Back

	Mean	Min	Median	Max	P90
Computer-Keyword Flag	0.025	-0.217***	-0.099***	1.300***	0.383***
	(0.022)	(0.014)	(0.021)	(0.066)	(0.041)
Number of Authors	-0.188***	-0.100***	-0.186***	-0.314***	-0.254***
	(0.005)	(0.003)	(0.005)	(0.015)	(0.009)
NSF Grants (paper)	0.450**	-0.261**	0.190	2.944***	1.374***
	(0.202)	(0.114)	(0.206)	(0.703)	(0.443)
Observations	2,912,619	2,912,619	2,912,619	2,912,619	2,912,619
R^2	0.564	0.545	0.551	0.490	0.528
Mean of Dep Var	8.554	2.705	7.134	20.159	14.865
Author/Year/Univ FE	Yes	Yes	Yes	Yes	Yes
Subject FE	Topic	Topic	Topic	Topic	Topic

Notes: Paper-author observations, weighted by the inverse number of authors. Treatment indicates computer-related keywords in the paper's full text. Controls: number of authors and NSF grants citing the work. Fixed effects: author, publication year, university, and primary topic. Standard errors clustered at the paper level (OpenAlex Work ID). Sample restricted to papers with at least one in-sample university affiliation and searchable full text in OpenAlex. Outcomes summarize cited-reference ages.

Reference Age Outcomes (Emb.)

▸ Back

	Mean	Min	Median	Max	P90
Residualized CKW Flag	0.090***	-0.146***	-0.108***	0.758***	0.378***
	(0.021)	(0.014)	(0.021)	(0.060)	(0.039)
Observations	1,268,013	1,268,013	1,268,013	1,268,013	1,268,013
R^2	0.000	0.000	0.000	0.000	0.000
Mean of Dep Var	0.554	0.060	-0.280	-0.021	-0.537

Notes: Second-stage OLS regresses the residualized outcome on the residualized computer-keyword indicator. In the first-stage DML residualization, both treatment and outcome are partialled out on author, publication year, university, and primary-topic fixed effects; controls for number of authors and NSF grants; and concatenated abstract/title embeddings plus SPECTER embeddings. Residuals are estimated with 3-fold cross-fitting and SGD. Second-stage standard errors are clustered at the author level and paper-author observations are weighted by the inverse number of authors. Sample restricted to searchable-full-text observations from 1947–1975.

Reference: Sleeping Beauty Outcomes

▸ Back

	Mean	Median Ref.	Oldest	Age90 Mean
Computer-Keyword Flag	14748.189***	5949.303*	47497.033***	42901.972***
	(2791.209)	(3497.185)	(9005.499)	(7858.461)
Number of Authors	-91.527	-308.707	1448.036	2225.190*
	(425.293)	(548.370)	(1454.504)	(1194.364)
NSF Grants (paper)	-10498.526	-45371.170**	-59951.894	-38000.606
	(15767.920)	(22087.269)	(42935.123)	(36637.594)
Observations	2,911,144	2,900,333	2,905,141	2,906,534
R^2	0.519	0.468	0.423	0.440
Mean of Dep Var	72464.983	52424.594	148906.728	141450.568
Author/Year/Univ FE	Yes	Yes	Yes	Yes
Subject FE	Topic	Topic	Topic	Topic

Notes: Paper-author observations, weighted by the inverse number of authors. Treatment indicates computer-related keywords in the paper's full text. Controls: number of authors and NSF grants citing the work. Fixed effects: author, publication year, university, and primary topic. Standard errors clustered at the paper level (OpenAlex Work ID). Sample restricted to papers with at least one in-sample university affiliation and searchable full text in OpenAlex. Outcomes report the mean cited-reference Sleeping Beauty score *B*, the *B* score of the median-age cited reference, the *B* score of the oldest cited reference, and the mean *B* score among references in the oldest-age decile, following Ke et al. [2015].

Reference: Sleeping Beauty Outcomes (Emb.)

▸ Back

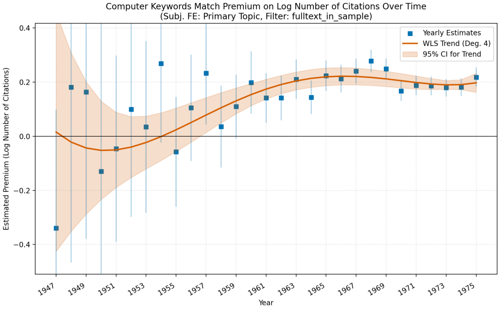
	Mean	Oldest	Age90 Mean
Residualized CKW Flag	15855.266***	43691.935***	33356.432***
	(2755.396)	(8380.273)	(7349.512)
Observations	1,267,251	1,263,720	1,264,821
R^2	0.000	0.000	0.000
Mean of Dep Var	-11093.575	-54844.167	-41587.824

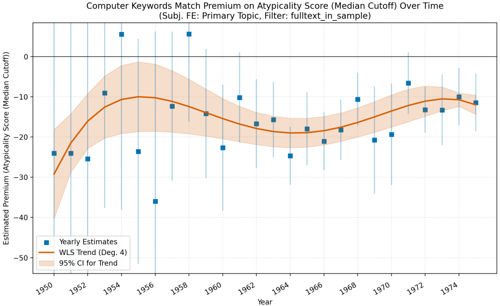
Notes: Second-stage OLS regresses the residualized outcome on the residualized computer-keyword indicator. In the first-stage DML residualization, both treatment and outcome are partialled out on author, publication year, university, and primary-topic fixed effects; controls for number of authors and NSF grants; and concatenated abstract/title embeddings plus SPECTER embeddings. Residuals are estimated with 3-fold cross-fitting and SGD. Second-stage standard errors are clustered at the author level and paper-author observations are weighted by the inverse number of authors. Sample restricted to searchable-full-text observations from 1947–1975.

Available outcomes: mean cited-reference SB$_B$, SB$_B$ of the oldest cited reference, and mean SB$_B$ among references in the oldest-age decile. The median-age-reference outcome is unavailable in the embeddings run.

Extended Computer Premiums Over Time

▶ Back


Computer Keywords Match Premium on Log Number of Citations Over Time
(Subj. FE: Primary Topic, Filter: fulltext_in_sample)


Computer Keywords Match Premium on Atypicality Score (Median Cutoff) Over Time
(Subj. FE: Primary Topic, Filter: fulltext_in_sample)

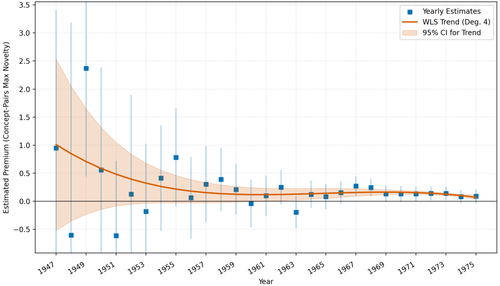
Data: fulltext_in_sample sample.
Stage 1 FE: Institution RoR ID, OpenAlex Author ID, Year, Primary Topic. Trend: WLS (Poly. Deg. 4) weighted by 1/SE^2.
Controls: Number of Authors. Cluster: OpenAlex Author ID.
Linear term slope (WLS): 19.549 (p-val: 0.013)

Notes: Yearly coefficients from regressing each outcome on computer-keyword × year dummies, controlling for university, author, and primary-topic fixed effects and number of authors. Shaded bands show 95% confidence intervals. ▶ Next

Extended Computer Premiums Over Time (II)

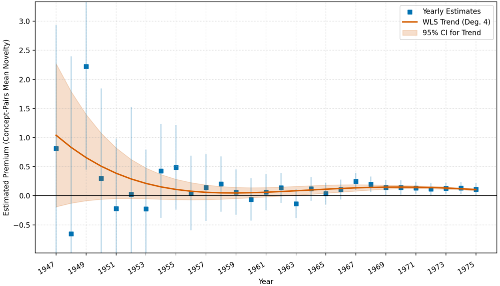
▶ Back

Computer Keywords Match Premium on Concept-Pairs Max Novelty Over Time
(Subj. FE: Primary Topic, Filter: fulltext_in_sample)



Data: fulltext_in_sample sample.
Stage 1 FE: Institution RoR ID, OpenAlex Author ID, Year, Primary Topic. Trend: WLS (Poly. Deg. 4) weighted by 1/SE^2.
Controls: Number of Authors. Cluster: OpenAlex Author ID.
Linear term slope (WLS): -0.173 (p-val: 0.372)

Computer Keywords Match Premium on Concept-Pairs Mean Novelty Over Time
(Subj. FE: Primary Topic, Filter: fulltext_in_sample)



Data: fulltext_in_sample sample.
Stage 1 FE: Institution RoR ID, OpenAlex Author ID, Year, Primary Topic. Trend: WLS (Poly. Deg. 4) weighted by 1/SE^2.
Controls: Number of Authors. Cluster: OpenAlex Author ID.
Linear term slope (WLS): -0.225 (p-val: 0.159)

Notes: Yearly coefficients from regressing each outcome on computer-keyword × year dummies, controlling for university, author, and primary-topic fixed effects and number of authors. Shaded bands show 95% confidence intervals. ▶ Previous

Computer Usage Clustering

▸ Back ▸ Citation Links

- Start from papers flagged as using or mentioning computers via keywords and LLM screening
- First-pass LLM classification separates four broad roles: tool, object of study, hardware/software, and other mentions
- Restrict to research articles using computers, then follow Tamkin et al. [2024]: Gemini 2.5 Flash descriptions, `gemini-embedding-001` embeddings, and K-means with $K = 61$
- Label lower-level clusters with Gemini 2.5 Pro using centroid and neighboring examples, then manually aggregate them into 11 high-level usage categories

Citation-Function Pipeline

▸ Back

- Start from computer papers and matched controls built with embedding-based nearest neighbors under tight year/domain restrictions
- Download open-content citing papers from OpenAlex
- Recover inline citation context with GROBID-style tags or string/pattern matches
- Follow the usage-taxonomy workflow to write, embed, and cluster short descriptions of *why* the cited paper is used
- Current sample: 98,051 citation-context descriptions; 20,910 usable clustered links; 16,114 links to computer papers; 4,796 links to matched controls; 16,120 cited papers in the paper-level panel

▸ Tamkin-style clustering

Citation-Function Examples ▸ Back

- Precedent = “people have talked about this before”;
- Established findings = “this paper shows the fact I’m invoking”
- Technical protocols = “this paper tells me how to do/measure it”;
- Formal method = “this paper gives the framework I’m using”;
- Canonical source = “this paper is the recognized origin of the concept/system”

Computer-paper example Matched-control example

- **Technical evidence / protocols**: “as previously described” means the cited paper supplies a lab protocol or benchmark input; Close and Kidd (1969) plays the same empirical-benchmark role for a control paper.
- **Established findings as evidence**: Waterman and Horch (1966) or Daley et al. (1971) are cited as accepted evidence or factual support the new paper relies on.
- **Representative precedent**: Siegel (1974) or Posner, Nissen, and Klein (1976) appear as one example in a list showing the phenomenon or debate already existed in the literature.
- **Formal method / theory foundation**: Eisenthal and Cornish-Bowden (1974) or Wilkinson (1961) are cited as the estimator, derivation, or framework the analysis actually uses.
- **Canonical source for concepts / systems**: Hoare on monitors or the TAXIS data model are cited for provenance: the original concept, system, or language being invoked.
- Full brief with centroid-nearest inside examples, nearby outside examples, and matched computer-vs-control comparisons is in the outputs folder.

Citation Regressions ▸ Back Reg Results

- **Unit of analysis:** cited paper. Main ‘FWCI‘ sample: $N = 15{,}938$ cited papers with at least one classified citation.
- **Overall bucket premium scores** (right panel on “Why Are Computer Papers Cited?”):

$$FWCI_p = \alpha + X_p'\gamma + \lambda_{\text{year}(p)} + \delta_{\text{domain}(p)} + \sum_{k=1}^{4} \theta_k s_{pk} + u_p$$

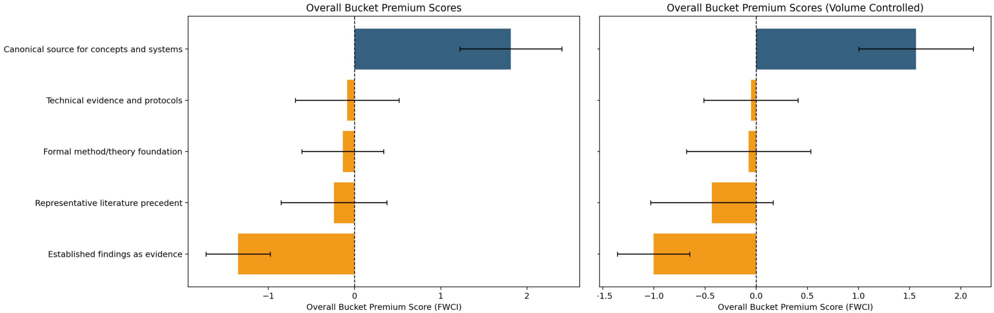
- Here s_{pk} is the share of paper p’s classified incoming citations in cluster k. We omit cluster 0 in estimation, then re-center the fitted cluster coefficients so the five reported bucket scores average to zero.
- **Premium decomposition regression** (“Does Citation Function Help Explain the Premium?”):

$$FWCI_p = \alpha + \beta T_p + X_p'\gamma + \lambda_{\text{year}(p)} + \delta_{\text{domain}(p)} + B_p^* + \sum_{k=1}^{4} \theta_k s_{pk} + u_p$$

- T_p is the computer-paper indicator. B_p^* is excess breadth: residual effective clusters after partialling out classified-citation-count bins, controls, and fixed effects.
- The attenuation logic is: compare the baseline treated coefficient to the treated coefficient after adding B_p^* and the cluster-share block. That difference is the part of the computer-paper premium accounted for by citation-function structure.

Bucket Premium Scores

▶ Back



Notes: Left: cited-paper regression of FWCI on cluster shares, controlling for number of authors, NSF grants, cited-paper year FEs, and domain FEs; the treated dummy is omitted so plotted coefficients summarize the overall association of each bucket with citation impact. Scores re-centered so all five buckets are directly comparable; whiskers are 95% CIs. Right: same specification adding $\log(1 + \text{classified citation count})$ to partial out citation volume. Ranking is stable across both specifications: canonical source remains the highest-premium bucket, established findings the lowest.

Citation Premium Decomposition

▸ Back

Outcome: FWCI

Spec	Treat. coef.	Atten.	p-value
Baseline	1.193	–	0.000
+ Excess breadth	1.179	1.2%	0.000
+ Composition	1.086	9.0%	0.000
+ Breadth + composition	1.077	9.8%	0.000
+ Volume (robustness)	0.773	35.2%	0.000
+ Volume + breadth + composition	0.657	45.0%	0.001

Notes: Unit = cited paper ($N = 15{,}938$ with at least one classified citation). Left panel: FWCI regressed on the computer-paper indicator, number of authors, NSF grants, cited-paper year FEs, and domain FEs. Rows add excess breadth, composition (cluster shares), or both. Composition controls are citation-cluster shares: the fraction of a paper's classified incoming citation links falling in each of the five function clusters. Excess breadth is constructed in two steps: (1) regress the number of effective clusters (i.e. the inverse Herfindahl across citation-function categories) on flexible classified-citation-count bins, the baseline controls, and fixed effects; (2) take the residual as the excess-breadth measure and enter it as an additional control. This isolates breadth of citation reasons beyond what is mechanically explained by having more classified citations. Right panel: Shapley decomposition splits the explained attenuation (0.117) into shares attributable to each block, averaging across both orderings (breadth-then-composition and composition-then-breadth).

- Baseline premium: $\hat{\beta}_0 = 1.193$
- After breadth + composition: $\hat{\beta}_{B*+C} = 1.077$
- Explained part: $1.193 - 1.077 = 0.117$
- Shapley decomposition of explained part:
  - Composition (mix of citation reasons): $\sim$90%
  - Excess breadth: $\sim$10%
- Excess breadth = residual effective clusters after partialling out citation-count bins, controls, and FEs
- Caveat: breadth and citations jointly determined — descriptive accounting, not causal mediation

Author-Level Patterns

▸ Back

	(1)	(2)	(3)	(4)	(5)
	Log Works	Log Cites	H-Index	# Topics	# 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)
Observations	316,970	316,970	316,970	316,970	316,970
R^2	0.309	0.437	0.533	0.292	0.327
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
Subject FE	Topic	Topic	Topic	Topic	Topic

Notes: Standard errors clustered at the affiliation level. Outcomes are measured over the author's entire career. Cohort is defined by the year of an author's first publication in the dataset. Affiliation is the modal one across the author's publications. Field (area) is the modal topic across the author's publications. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Author Patterns: Early vs. Late Adopters

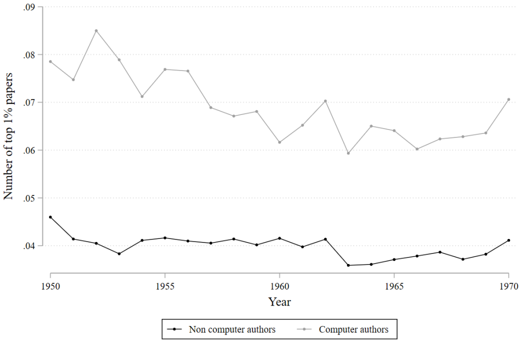
▸ Back

	(1)	(2)	(3)	(4)	(5)
	Log Works	Log Cites	H-Index	# Topics	# 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)
Observations	6,141	6,141	6,141	6,141	6,141
R^2	0.373	0.601	0.759	0.341	0.524
Mean of Dep Var	4.358	7.271	23.65	24.01	6.636
Affiliation/Cohort/Topic FE	Yes	Yes	Yes	Yes	Yes

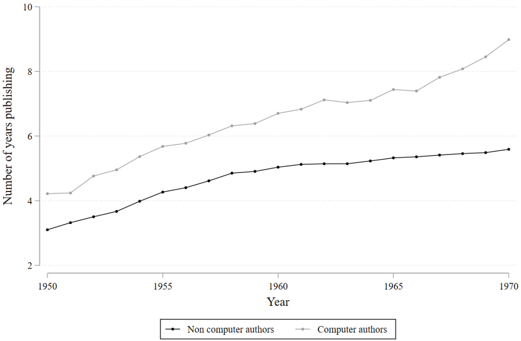
SE clustered at affiliation level. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Author-Level Patterns: Top Citations & Experience

▸ Back



More Top 1% Cited Papers



Longer Publishing Careers (Experience)

Author Patterns: Outcomes at University Computer Adoption Year

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	(1)	(2)	(3)	(4)	(5)
	Log Works	Log Cites	H-Index	Top 1%	Top 10%
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)
Observations	122,159	134,521	134,521	122,159	122,159
R^2	0.344	0.251	0.246	0.169	0.0964
Mean of Dep Var	1.530	3.460	4.438	2.581	0.267
Affiliation/Cohort/Topic FE	Yes	Yes	Yes	Yes	Yes

SE clustered at affiliation level. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

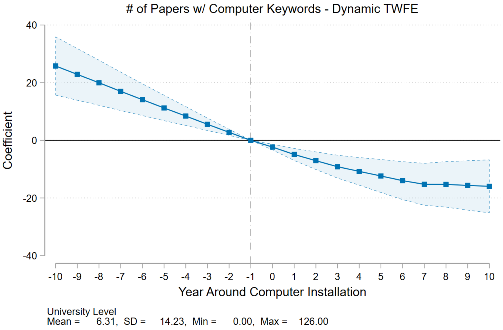
Author Patterns: Intensive Margin

▸ Back

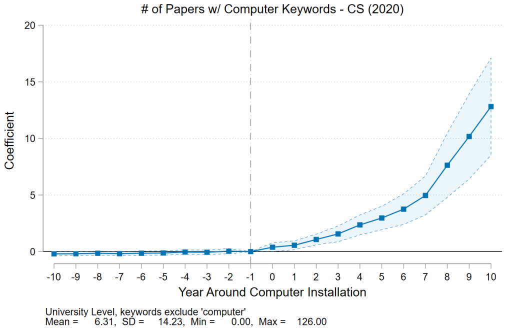
	(1)	(2)	(3)	(4)	(5)
	Log Works	Log Cites	H-Index	Topics	Affiliations
Computer Paper Count	0.188***	0.181***	1.166***	0.553***	0.258***
	(0.00790)	(0.0256)	(0.250)	(0.0639)	(0.0294)
Number of Works		0.00553**	0.0582**	0.0128**	0.00631**
		(0.00185)	(0.0189)	(0.00435)	(0.00208)
Observations	316,970	316,970	316,970	316,970	316,970
R^2	0.280	0.417	0.524	0.269	0.317
Mean of Dep Var	2.732	5.158	12.16	16.77	3.525
Affiliation/Cohort/Topic FE	Yes	Yes	Yes	Yes	Yes

SE clustered at affiliation level. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Why TWFE Fails



TWFE event study

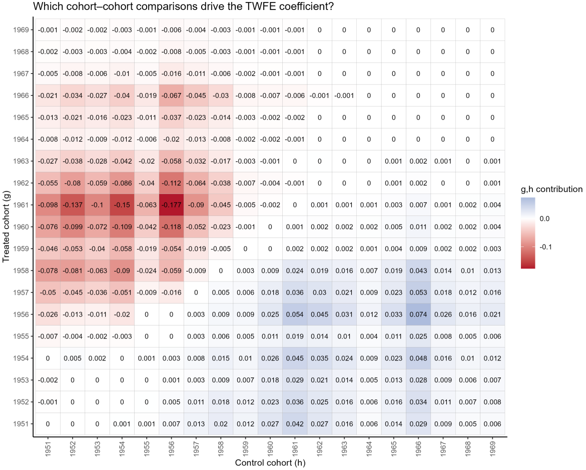


Callaway-Sant’Anna event study

Same sample and treatment definition; TWFE flips the sign because staggered timing and heterogeneous effects induce forbidden comparisons.

Back to design | Back to usage | Bacon

Why TWFE Fails: Bacon Decomposition



Which cohort–cohort comparisons drive the TWFE coefficient?

	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
1969	-0.001	-0.002	-0.002	-0.003	-0.001	-0.006	-0.004	-0.003	-0.001	-0.001	-0.001	0	0	0	0	0	0	0	0
1968	-0.002	-0.003	-0.003	-0.004	-0.002	-0.008	-0.005	-0.003	-0.001	-0.001	-0.001	0	0	0	0	0	0	0	0
1967	-0.005	-0.008	-0.006	-0.01	-0.005	-0.016	-0.011	-0.006	-0.002	-0.001	-0.001	0	0	0	0	0	0	0	0
1966	-0.021	-0.034	-0.027	-0.04	-0.019	-0.067	-0.045	-0.03	-0.008	-0.007	-0.006	-0.001	-0.001	0	0	0	0	0	0
1965	-0.013	-0.021	-0.016	-0.023	-0.011	-0.037	-0.023	-0.014	-0.003	-0.002	-0.002	0	0	0	0	0	0	0	0
1964	-0.008	-0.012	-0.009	-0.012	-0.006	-0.02	-0.013	-0.008	-0.002	-0.002	-0.001	0	0	0	0	0	0	0	0
1963	-0.027	-0.038	-0.028	-0.042	-0.02	-0.058	-0.032	-0.017	-0.003	-0.001	0	0	0	0	0.001	0.002	0.001	0	0.001
1962	-0.055	-0.08	-0.059	-0.086	-0.04	-0.112	-0.064	-0.038	-0.007	-0.004	-0.001	0	0	0	0.001	0.002	0	0	0.001
1961	-0.098	-0.137	-0.1	-0.15	-0.063	-0.177	-0.09	-0.045	-0.005	-0.002	0	0.001	0.001	0.001	0.003	0.007	0.001	0.002	0.004
1960	-0.076	-0.099	-0.072	-0.109	-0.042	-0.118	-0.052	-0.023	-0.001	0	0.001	0.002	0.002	0.002	0.005	0.011	0.002	0.002	0.004
1959	-0.046	-0.053	-0.04	-0.058	-0.019	-0.054	-0.019	-0.005	0	0	0.002	0.002	0.002	0.001	0.004	0.009	0.002	0.002	0.003
1958	-0.078	-0.081	-0.063	-0.09	-0.024	-0.059	-0.009	0	0.003	0.009	0.024	0.019	0.016	0.007	0.019	0.043	0.014	0.01	0.013
1957	-0.05	-0.045	-0.036	-0.051	-0.009	-0.016	0	0.005	0.006	0.018	0.036	0.03	0.021	0.009	0.023	0.053	0.018	0.012	0.016
1956	-0.026	-0.013	-0.011	-0.02	0	0	0.003	0.009	0.009	0.025	0.054	0.045	0.031	0.012	0.033	0.074	0.026	0.016	0.021
1955	-0.007	-0.004	-0.002	-0.003	0	0	0.003	0.006	0.005	0.011	0.019	0.014	0.01	0.004	0.011	0.025	0.008	0.005	0.006
1954	0	0.005	0.002	0	0.001	0.003	0.008	0.015	0.01	0.026	0.045	0.035	0.024	0.009	0.023	0.048	0.016	0.01	0.012
1953	-0.002	0	0	0	0	0.001	0.003	0.009	0.007	0.018	0.029	0.021	0.014	0.005	0.013	0.028	0.009	0.006	0.007
1952	-0.001	0	0	0	0	0.005	0.011	0.018	0.012	0.023	0.036	0.025	0.016	0.006	0.016	0.034	0.011	0.007	0.008
1951	0	0	0	0.001	0.001	0.007	0.013	0.02	0.012	0.027	0.042	0.027	0.016	0.006	0.014	0.029	0.009	0.005	0.006

Goodman-Bacon decomposition of a simple pre/post TWFE

Model	Estimate	SE	p-value	N
TWFE	-2.036	0.489	0.000	5 704
Callaway-Sant'Anna (2021)	5.417	0.716	0.000	-
de Chaisemartin-D'Haultfoeuille (2020)	5.417	0.663	0.000	3 312

Simple pre/post DiD: TWFE flips the sign, while modern estimators remain positive.

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Classifier Details

- LightGBM is a gradient-boosting model that combines many small decision trees by training new trees on the residuals of the ensemble prediction.
- It is useful here because it can learn nonlinear interactions between titles, metadata, and embeddings without us hand-coding them.
- The output is a probability vector over paper types, which we can aggregate into university-year methodology shares.

Benchmark	Accuracy	Weighted F1	Macro F1
Main LightGBM (validation)	0.752	0.749	0.657
10k full-text benchmark	0.824	0.825	0.760
Fallback no-lexicon model	0.814	0.814	0.751

Universe	N
Unique papers in 1951–1969 panel slice	470,395
Classified unique papers	268,887
Keyword-matched computer papers in panel slice	25,665
Keyword-matched computer papers among classified	17,667
Classified papers with local full text	100,378
Already in Gemini first-pass set	56,650

Notes: The main production model is LightGBM. The appendix keeps only the benchmark numbers we actually need here: the rebuilt validation score, the 10k full-text benchmark, and the no-lexicon fallback.

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Raw 7-Class Taxonomy

Raw class	Mass share	Maps to
Quantitative empirical	31.1%	Empirical
Qualitative empirical	17.2%	Empirical
Formal theoretical	12.9%	Theory
Discursive theoretical	5.4%	Theory
Methods	11.1%	Methods
Computational	1.1%	Simulation bucket
Other	21.3%	Other

Notes: Shares are average predicted mass across the 268,887 classified papers in the 1951–1969 panel slice. Raw labels collapse into the five panel buckets in the main text. Computational papers are rare in this period; other is mostly reviews, bibliographies, editorials, and similar reference material rather than a generic model-failure bucket.

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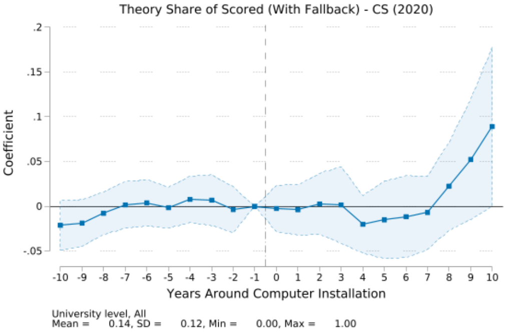
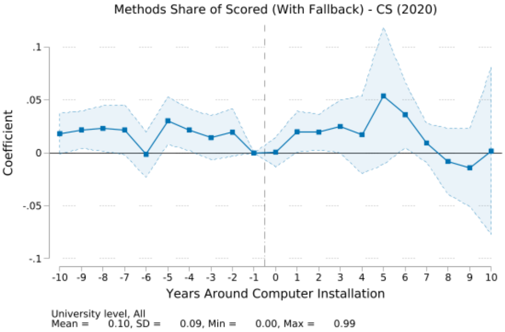
Changes in Research Methodologies: Theory and Methods

Theory Share of Scored Papers



Methods Share of Scored Papers



Notes: These are the same ‘ptype_shr_wf‘ event-study objects as in the main text, shown here for the two categories that appear to absorb most of the reallocation inside the scored subset.

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Paper-Level Method Regressions ▸ Back

	Empirical	Theory	Simulation	Methods	log(Emp./Theory)
Computer-Keyword Flag	-0.043***	-0.018***	0.028***	0.036***	-0.034***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
# Authors	0.028***	-0.015***	0.000	0.000	0.049***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)
NSF grants (paper)	0.029***	-0.005*	0.001	-0.006*	0.038***
	(0.005)	(0.002)	(0.001)	(0.003)	(0.007)
Observations	2,128,533	2,128,533	2,128,533	2,128,533	2,128,533
R^2	0.798	0.816	0.572	0.667	0.841
Mean of Dep Var	0.466	0.146	0.009	0.124	0.375
Author/Year/Univ FE	Yes	Yes	Yes	Yes	Yes
Subject FE	Topic	Topic	Topic	Topic	Topic

Notes: Paper-author observations, weighted by the inverse number of authors. Treatment indicates computer-related keywords in the paper's full text. Controls: number of authors and NSF grants citing the work. Fixed effects: author, publication year, university, and primary topic. Standard errors clustered at the paper level (OpenAlex Work ID). Sample restricted to papers with at least one in-sample university affiliation and searchable full text in OpenAlex. Negative values in log(Emp./Theory) indicate relatively more theoretical than empirical mass.

Transparent Family Dictionaries

Family	Definition and example language
Computer systems / programming	Explicit computer, compiler, programming-language, assembler, time-sharing, or computer-center language. Example terms: computer, compiler, ALGOL, program, time-sharing.
Algorithmic / numerical	Algorithms, numerical procedures, matrix computation, finite-difference, and finite-element schemes. Example terms: algorithm, numerical, matrix, finite element.
Simulation / modeling	Simulation, simulation models, numerical forecasting, or model-based experimentation. Example terms: simulation, model, modeling, dynamics.
Control / optimization	Feedback, control, queueing, encoding, and related systems or optimization problems. Example terms: control, optimal, feedback, queueing, encoding.
Statistics / sampling	Statistical inference, regression, variance analysis, or survey/sampling design. Example terms: statistical, regression, sampling, inference.
Differential equations	PDE/ODE and boundary-value or continuum-model problems. Example terms: differential equation, boundary value, PDE, ODE.

Notes: These families were built from manual full-text reading of methods, theory, and simulation papers. They are used only as transparent dictionaries for descriptive frequency comparisons, not as a replacement classifier.

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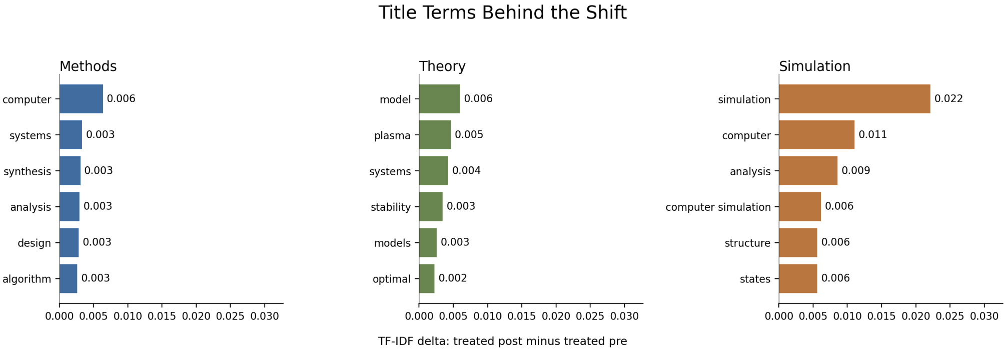
Title Terms Behind the Shift



Notes: Terms come from TF-IDF contrasts on predicted paper-university rows in the 1951–1969 slice, comparing treated-post with treated-pre. The bars show the magnitude of the post-minus-pre TF-IDF delta within each bucket.

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Examples Behind the Labels

Methods

- *The structure of yet another ALGOL compiler* (W2050572856): compiler architecture and implementation.
- *Programming Technique: An improved hash code for scatter storage* (W2003248512): programming-method paper on data storage and retrieval.
- *The simplex method of linear programming using LU decomposition* (W2071877138): numerical optimization method built for computation.

Computer-adjacent theory

- *Feedback Queueing Models for Time-Shared Systems* (W2074065133): queueing/control theory aimed at time-sharing computer systems.
- *Levels of computer systems* (W1983161084): formal systems-theory discussion explicitly about computer architecture.
- *Source encoding in the presence of random disturbance* (W1584278176): information/encoding theory that sits on the computation-communications interface.

Simulation

- *The simulation of time sharing systems* (W2113442017): explicit simulation of computer-system performance.

Notes: These examples come from manual full-text packet reads. The key point is that the most convincing post-treatment theory cases are not theory in general; they are a narrower slice of queueing, encoding, control, and computer-systems work.

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DDD: Content of Science, Topic Novelty

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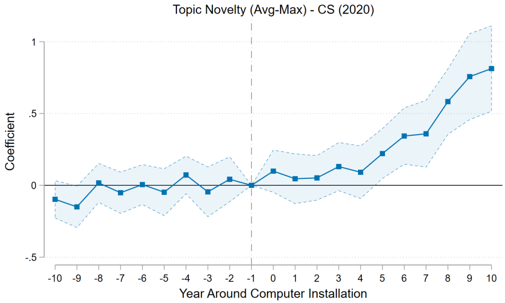
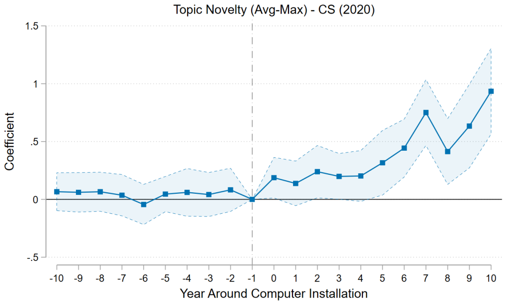
Topic Novelty: Physical Sciences



Triple Diff, University-Subfield-Year, Physical Sciences
Mean = 0.45, Mean (untreated) = 0.77, SD = 0.96, Min = -2.91, Max = 5.39

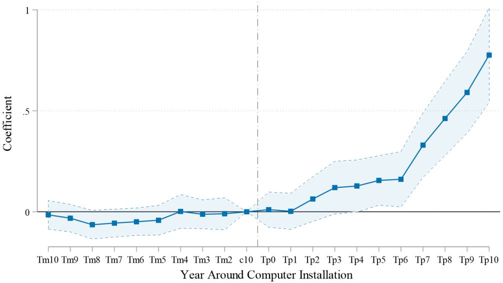
Topic Novelty: Social Sciences



Triple Diff, University-Subfield-Year, Social Sciences
Mean = 0.05, Mean (untreated) = 0.24, SD = 0.96, Min = -4.22, Max = 5.00

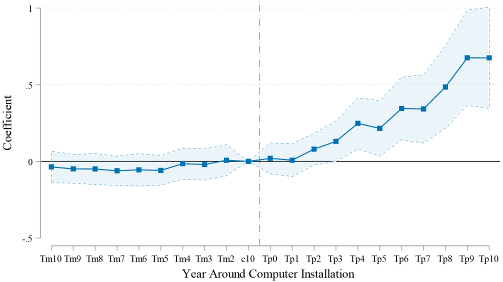
Keywords DiDs (I)

Random Sampling



University level.
Mean: .21, SD: .51, Min: 0, Max: 3.3

Numerical Simulation



University level.
Mean: .36, SD: .6900000000000001, Min: 0, Max: 3.85

Notes: Legacy keyword-based DiD results for two tangible content buckets. These are robustness objects from the earlier word-bucket exercise, not the new classifier-based panel.

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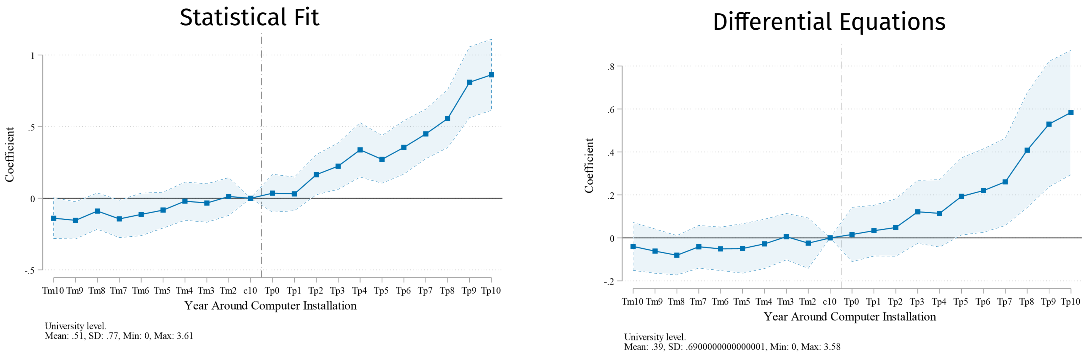
Keywords DiDs (II)



Statistical Fit

University level.
Mean: .51, SD: .77, Min: 0, Max: 3.61

Differential Equations

University level.
Mean: .39, SD: .6900000000000001, Min: 0, Max: 3.58

Notes: Additional legacy keyword-based DiD results. These help show that the strongest new classifier-based family shifts are not simply mirroring broad rises in all quantitative language.

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