Papers and patents are becoming less disruptive over time

Michael Park [1] Erin Leahey [2] Russell J. Funk [1]

[1]Carlson School of Management, University of Minnesota

[2]School of Sociology, University of Arizona

Motivation

Background

Innovative activity in science and technology is slowing

- The past century saw unprecedented expansion of scientific and technological knowledge.
- But there is growing concern that innovative activity is slowing.
  - Research productivity is declining in semiconductors, pharmaceuticals, and other fields.
  - Papers, patents, and even grant applications have become less novel and less likely to connect disparate areas of knowledge, both of which are precursors of innovation.

(Jones, 2009; Cowen, 2011; Pammolli et al., 2011; Horgan, 2015; Gordon, 2016; Collison and Nielsen, 2018; Bloom et al., 2020; Packalen and Bhattacharya, 2020; Chu and Evans, 2021)

The problem

While the evidence is compelling, these trends are hard to reconcile with. . .

. . . theories of innovation.

- Innovation is widely viewed as a process of recombination.
- New ideas come from bringing together existing knowledge in new ways.
- The extent of prior knowledge is therefore important for future innovation, enabling the "standing on the shoulders of giants."
- Recent decades have seen explosive growth in scientific and technological knowledge, which should make conditions ripe for advances.

. . . recent breakthroughs in science and technology.

- Measurement of gravity waves.
- Development of deep learning.

To address these tensions, we. . .

- Use a novel, theoretically informed measure to document and characterize long term changes in the nature of discovery and invention, represented in papers and patents.

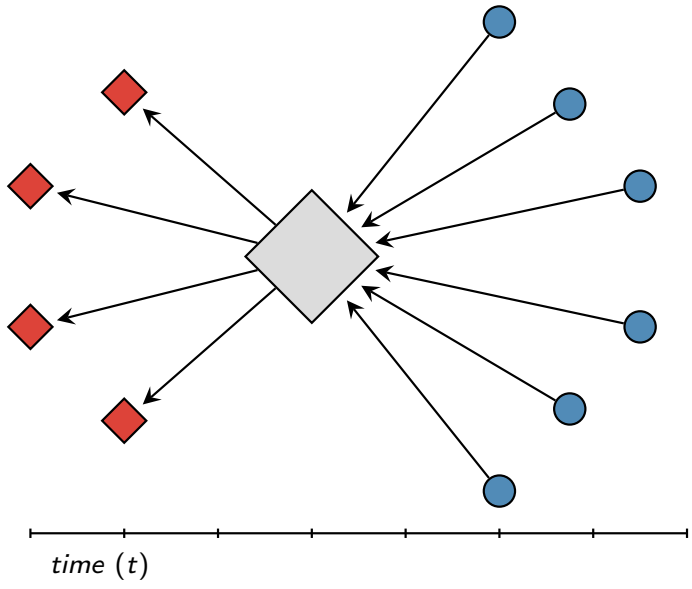
(Schumpeter, 1942; Koyré, 1952; Weitzman, 1998; Fleming, 2001; Fleck, 2012; Popper, 2014; Tria et al., 2014; Acemoglu et al., 2016; Fink et al., 2017)

Measurement

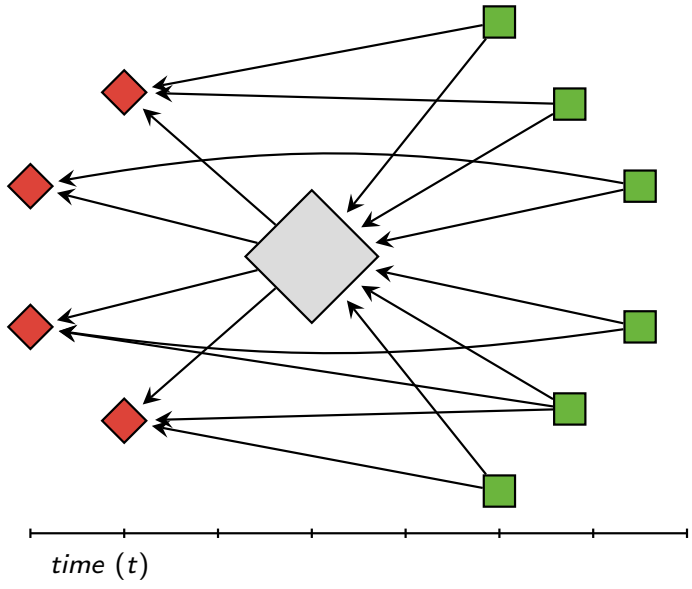
What do we propose?

We use a new indicator of scientific and technological change (Funk and Owen-Smith, 2017).

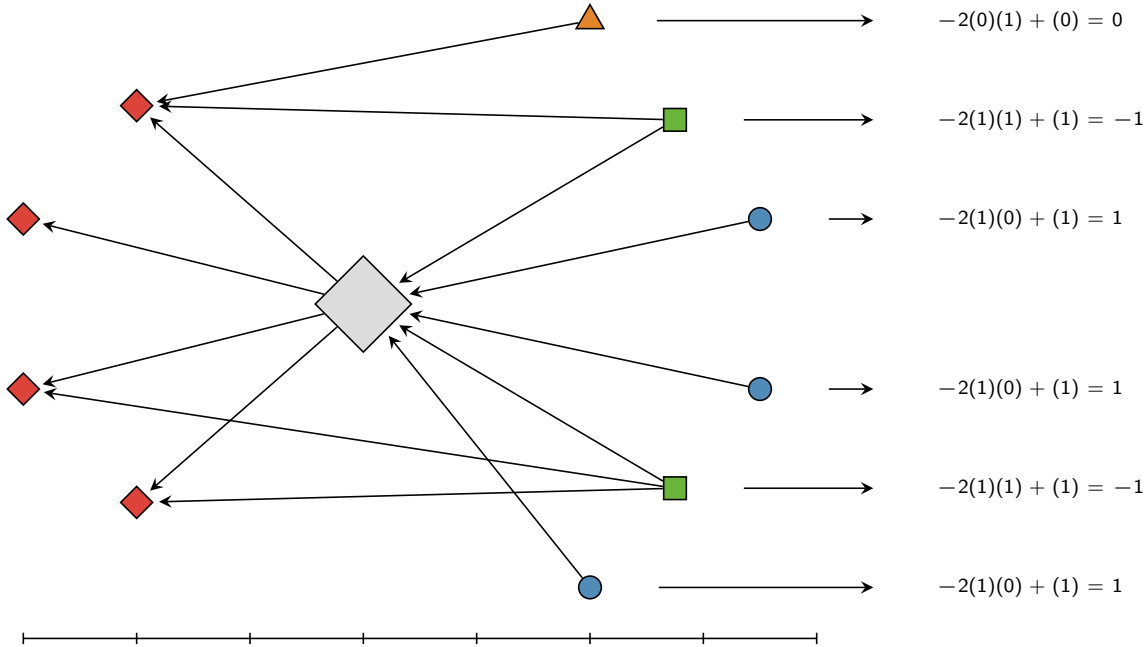
- The idea is that the measure of an intellectual contribution is how it influences the growth of knowledge.
- We consider an intellectual contribution to be. . .
  - **consolidating** when it increases the use of its predecessors.
  - **disruptive** when it decreases the use of its predecessors.



Maximally disruptive



Maximally consolidating



Step 1

Compute the numerator of the CD_t index equation for each forward citation.

$$\sum -2f_i b_i + f_i = (0) + (-1) + (1) + (1) + (-1) + (1) = 1$$

Step 2

Sum the values from Step 1 to obtain the numerator.

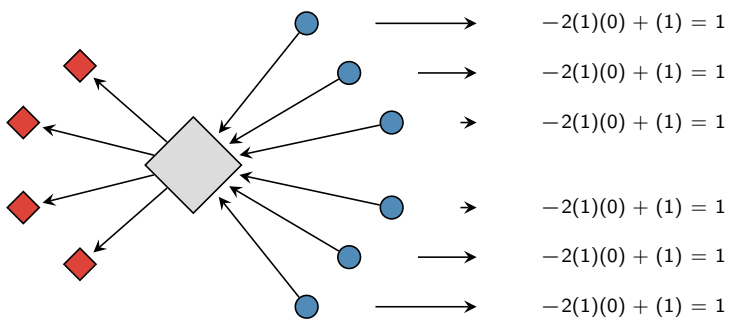
Key

- Cites focal document (type $f = 1$)
- Cites predecessors (type $b = 1$)
- Cites focal document and predecessors (type $f = 1$, $b = 1$)

$$\frac{1}{6} = 0.17$$

Step 3

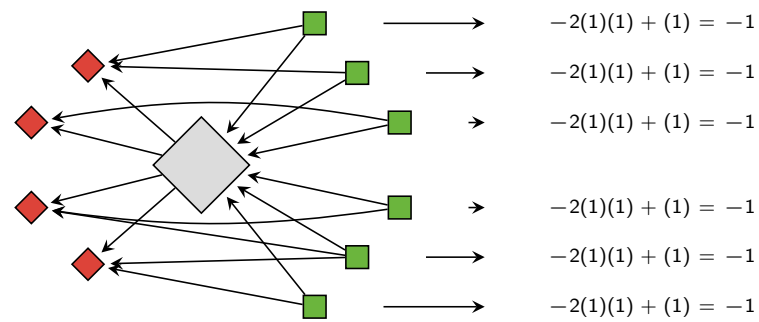
Divide the value from Step 2 by the total number of forward citations, n, to obtain the CD_t index.



$$(1) + (1) + (1) + (1) + (1) + (1) = 6$$

Maximally disruptive

$$\frac{6}{6} = 1$$



$$(-1) + (-1) + (-1) + (-1) + (-1) + (-1) = -6$$

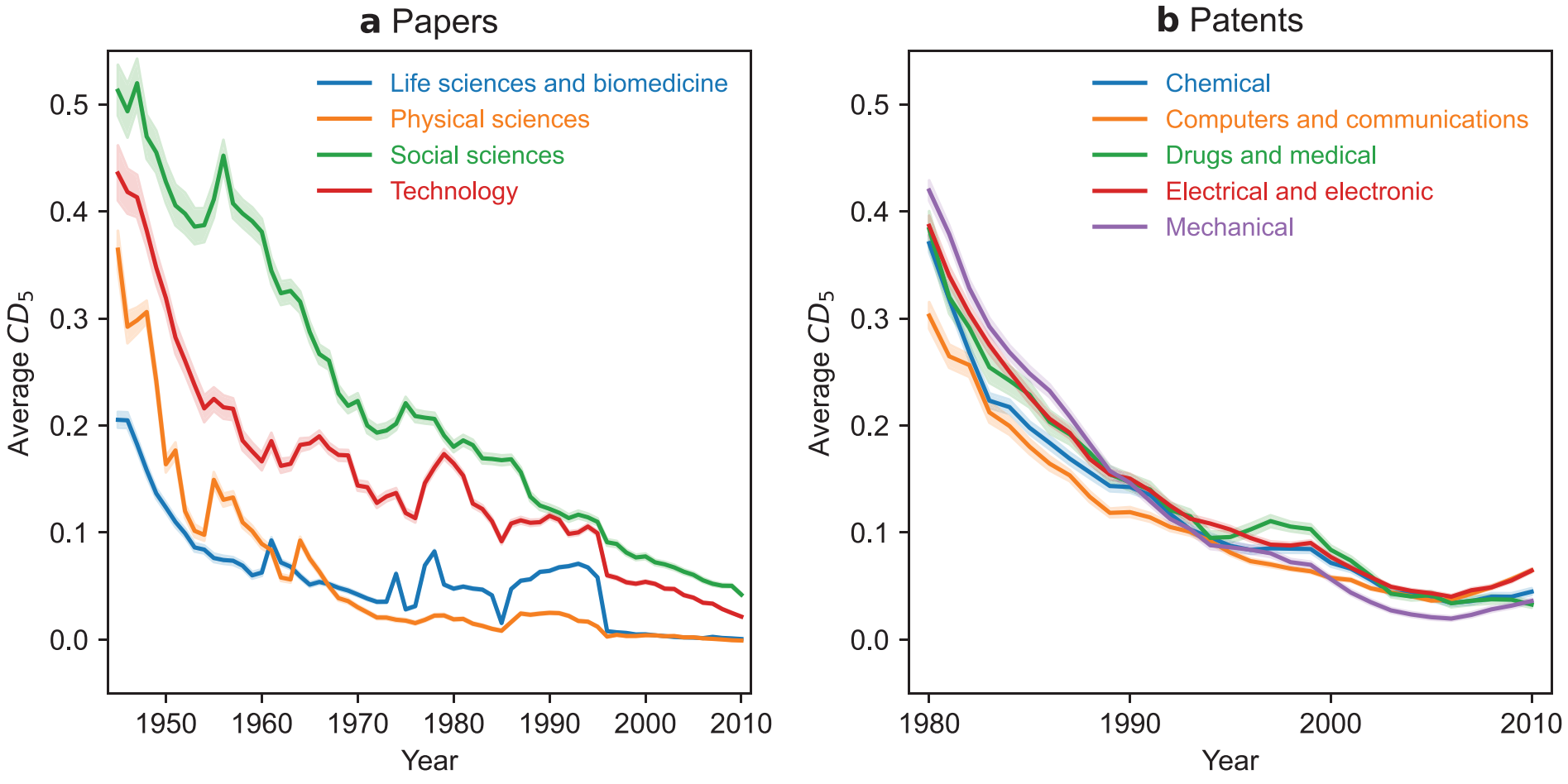
Maximally consolidating

$$\frac{-6}{6} = -1$$

Results: The decline of disruptive science and technology

The decline of disruptive papers and papers

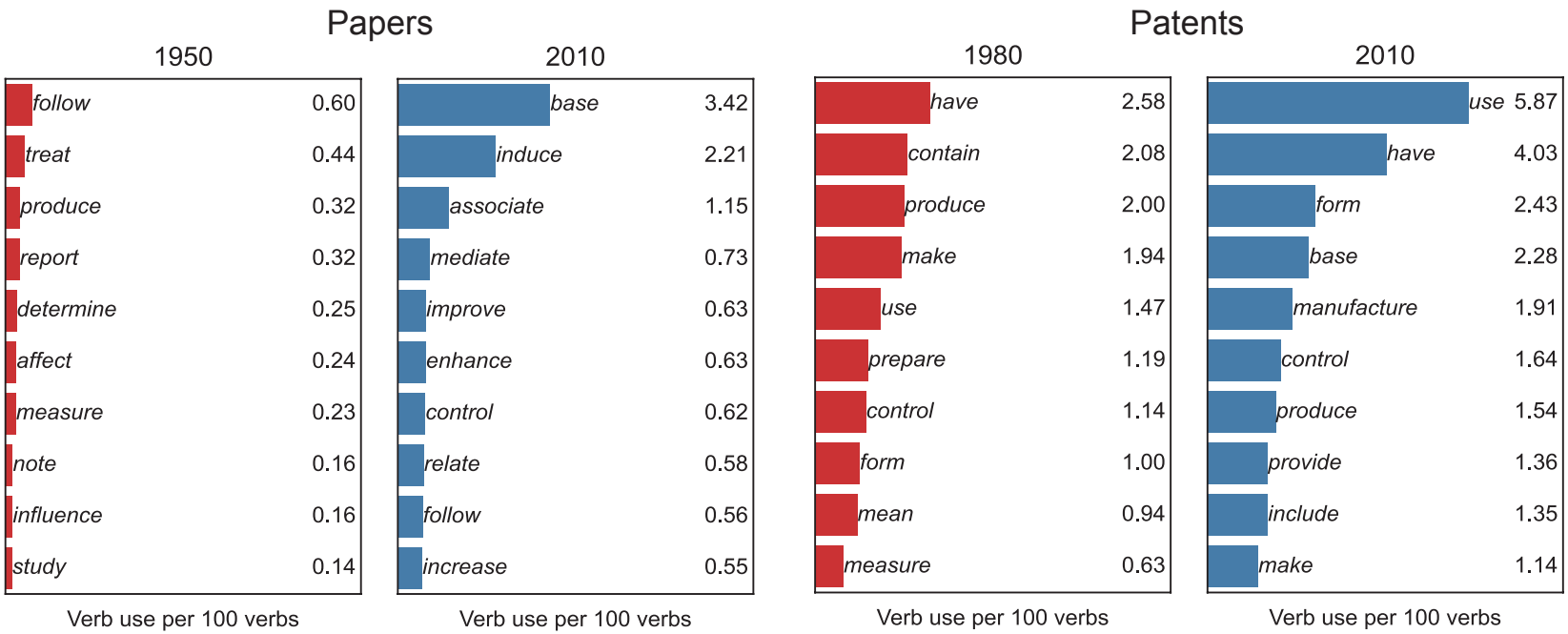
We see similar trends across science and technology



Consistent with claims of slowing innovative activity, we observe declining CD index values over time, across fields, for both papers and patents; over time, papers and patents are doing less to stimulate breaks from the status quo.

The decline is also reflected in changing word use

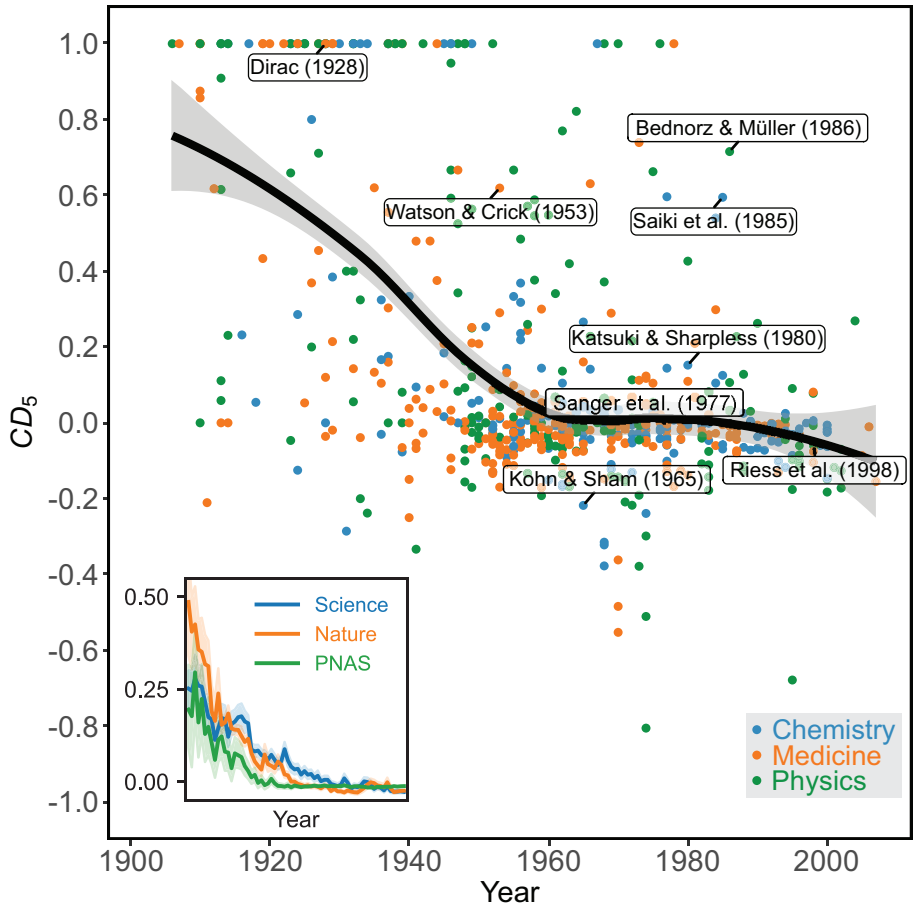
- If disruptiveness is declining, then verbs alluding to the creation, discovery, or perception of new things ("disruptive" words) should be used less over time.
- Verbs alluding to the improvement, application, or assessment of existing things ("consolidating" words) may be used more frequently.



Results: Alternative explanations

The trends are not driven by changes in publication quality

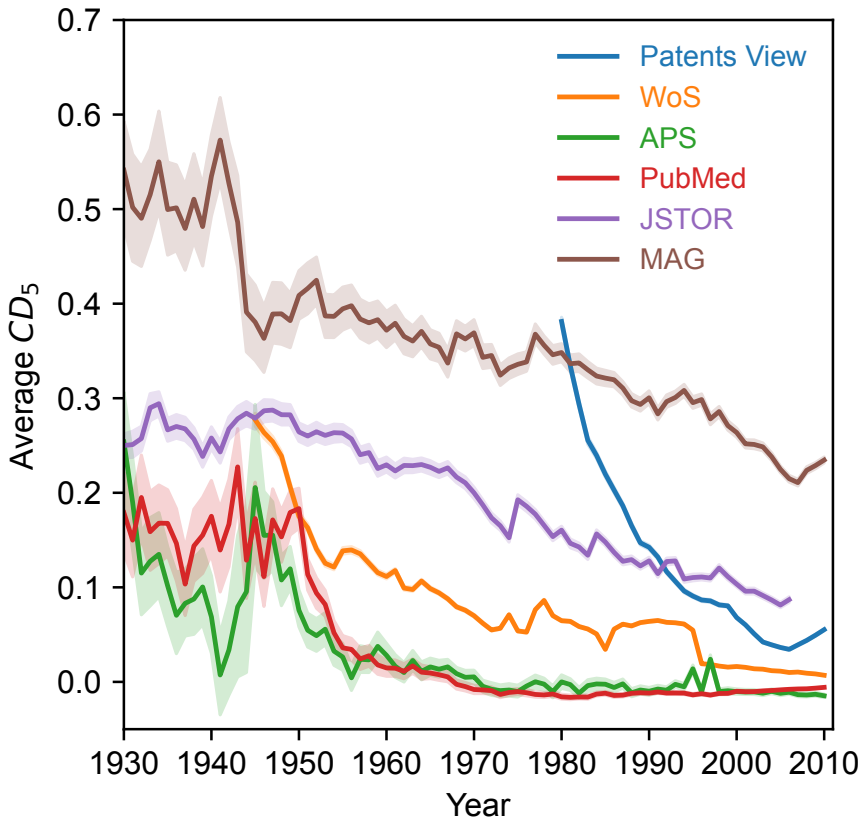
- One concern with our results is that they may be driven by changes in the quality of published science.
- We therefore looked for consistent patterns in recognized "high quality" journals.
- We also looked at papers associated with Nobel Prize winning discoveries.



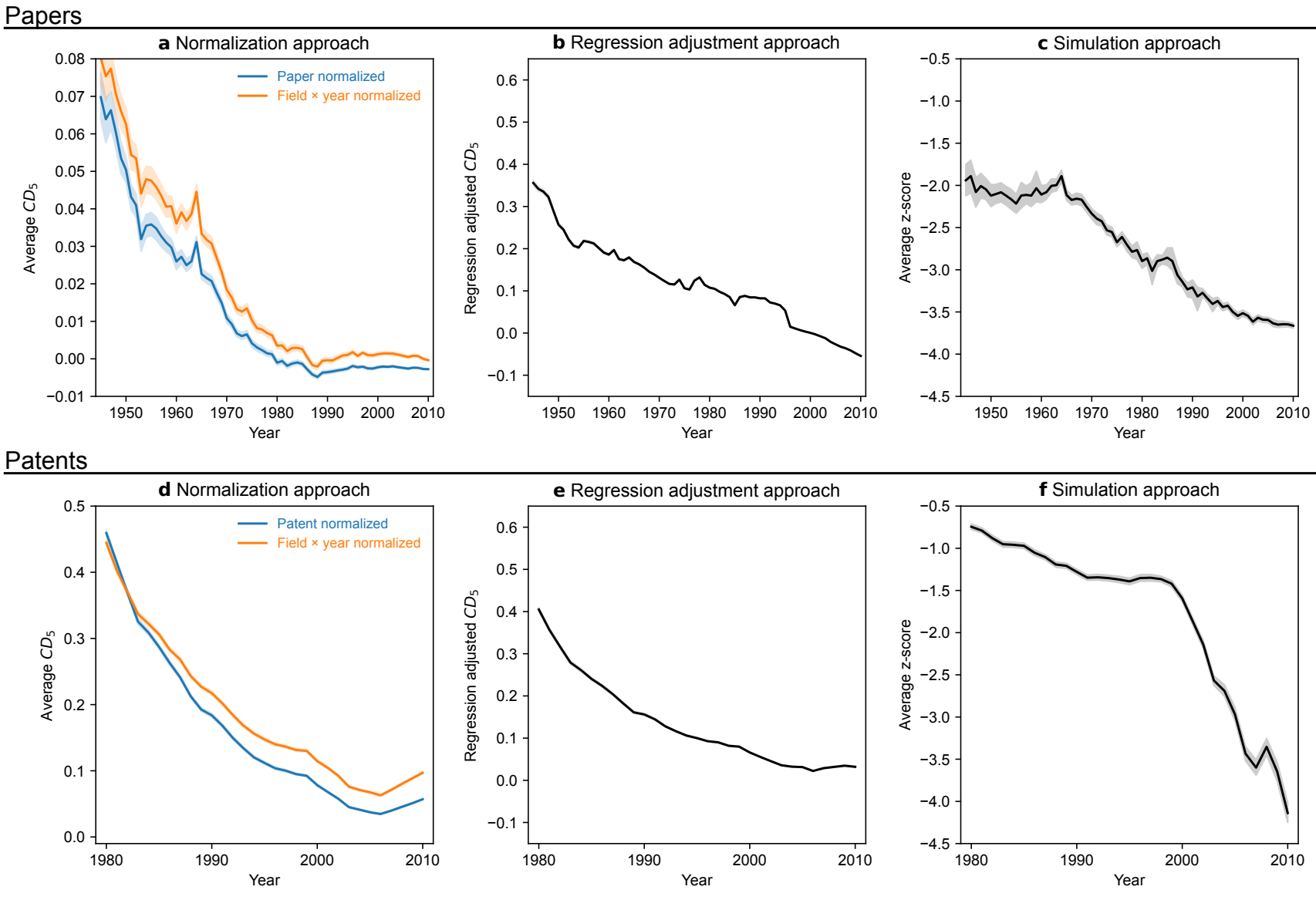
Dirac (1928): Discovery of the Dirac equation of relativistic quantum theory
Watson & Crick (1953): Discovery of the structure of the DNA
Kohn & Sham (1965): Development of a new method for calculating electronic structure
Sanger et al. (1977): Development of a new method for mapping the order of nucleotides
Katsuki & Sharpless (1980): Development of asymmetric epoxidation
Saiki et al. (1985): Discovery of polymerase chain reaction
Bednorz & Müller (1986): Discovery of superconductivity in cermaic materials
Riess et al. (1998): Discovery of the accelerating expansion of the universe

Nor are they due to the particularities of our data sources

- While we find consistent patterns across papers and patents, it is possible that the results we observe may be due to the particularities of our data sources.
- We therefore replicated our analyses across four additional databases.
  - American Physical Society (mostly physics papers, N=636,294)
  - JSTOR (mostly humanities and social science papers, N=1,787,348)
  - PubMed (mostly biomedical papers, N=22,759,312)
  - Microsoft Academic Graph (N=250,613,378)
- Across all data sources, we continue to observe a decline in disruptiveness.



Nor are they driven by changing authorship, publication, or citation practices

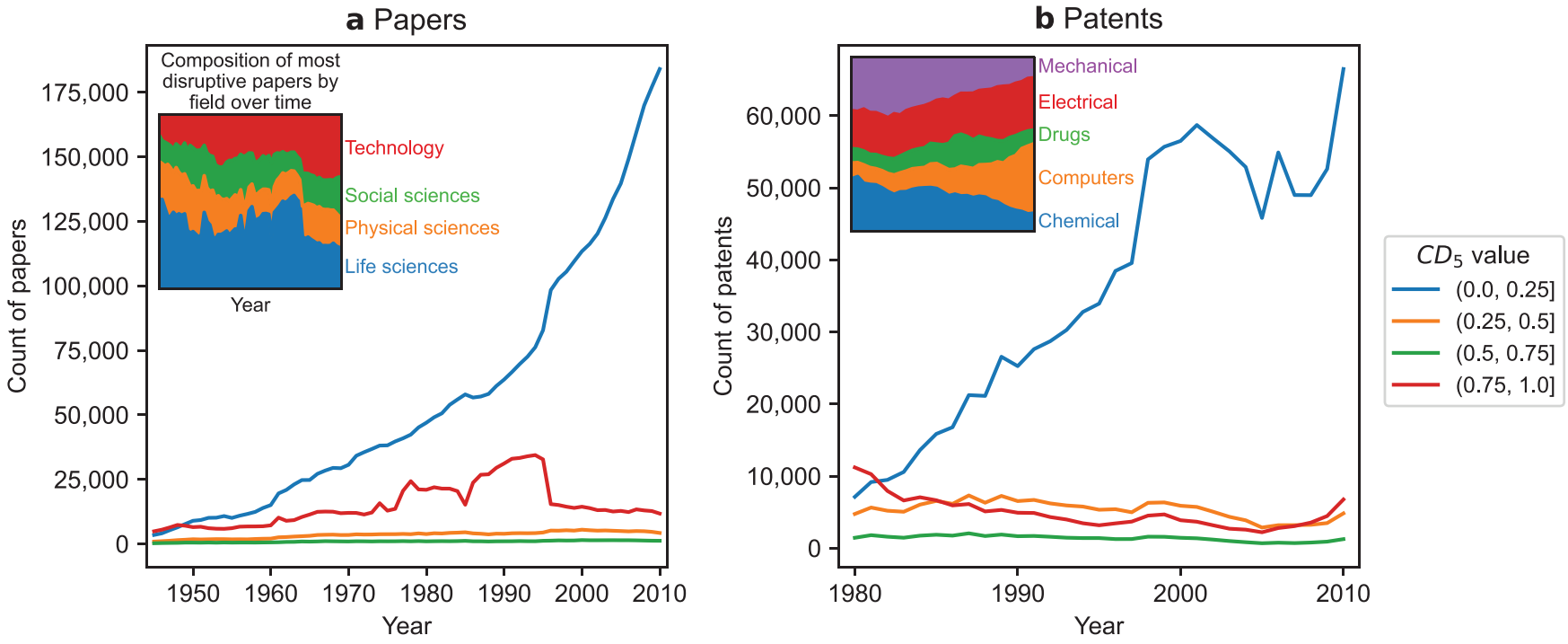


Results: Conservation of highly disruptive work

Conservation of highly disruptive work

Reconciling slowing innovative activity with continued breakthroughs

Despite huge increases in the number of papers and patents published each year, the number of highly disruptive publications is remarkably constant.



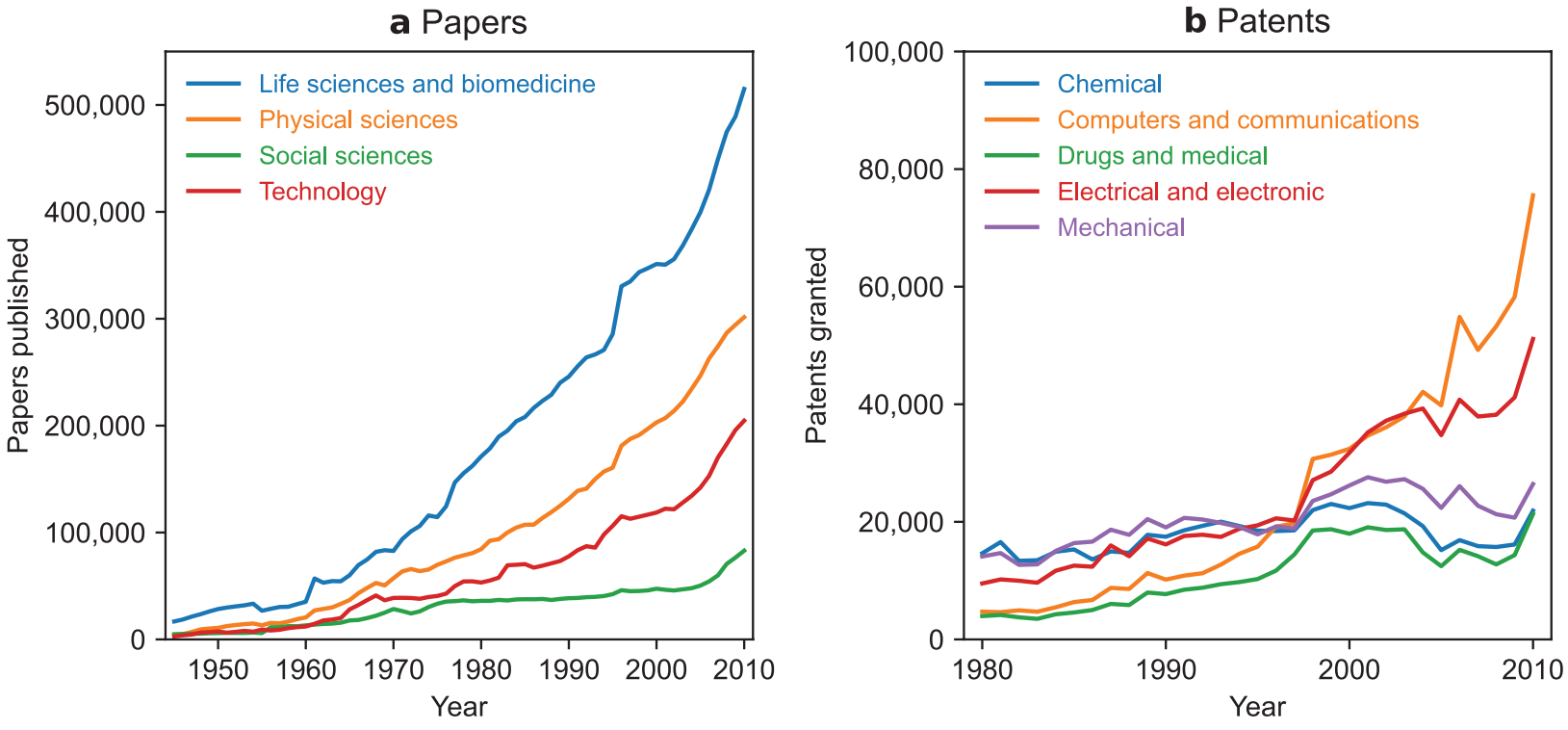
This pattern may help explain how and why we still see examples of major innovations while also observing slowdowns in more macro indicators.

But also note that not all breakthroughs are disruptive!

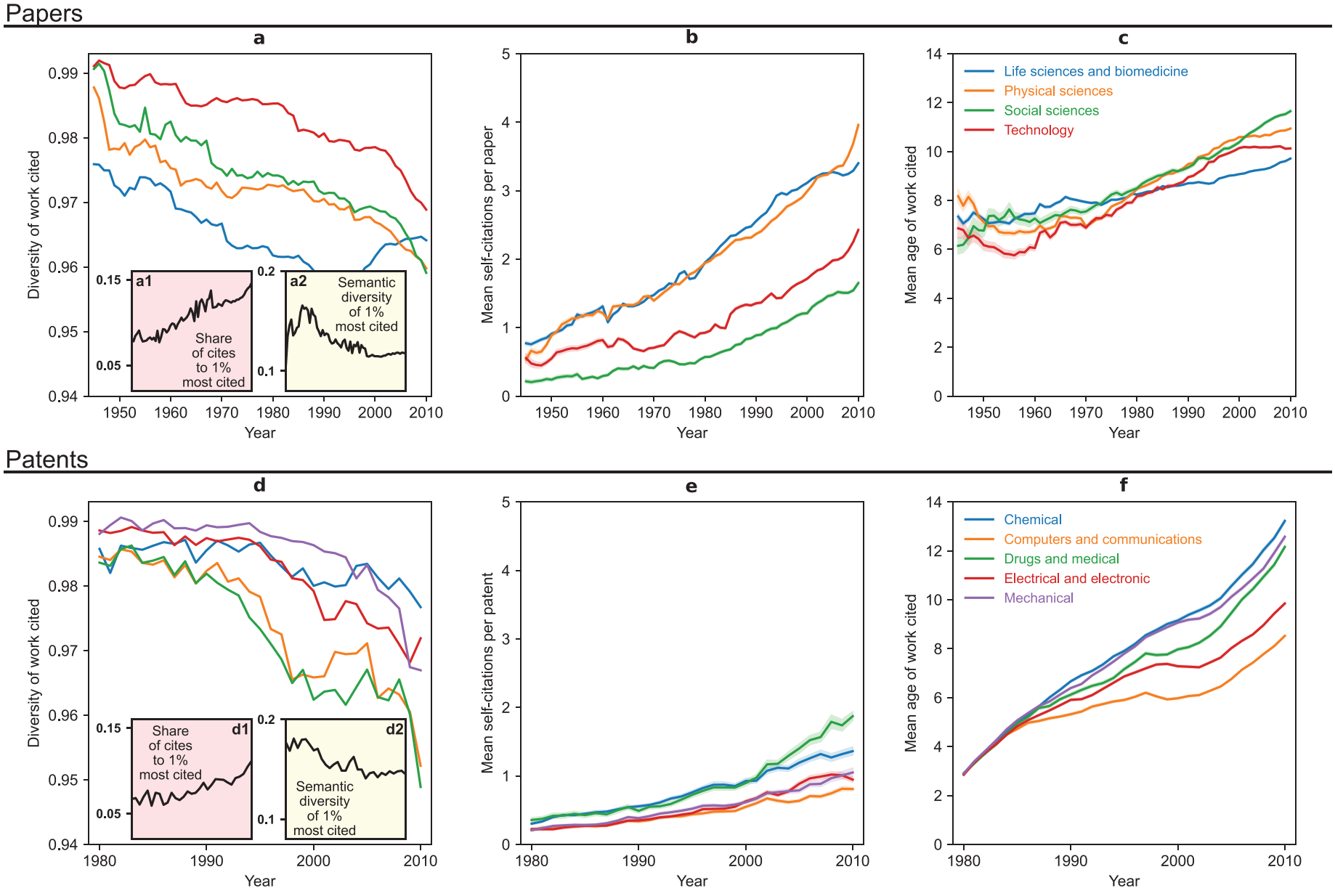
Results: Growth of knowledge and disruptiveness

The volume of science and technology has increased dramatically

Reconciling slowing innovative activity with the growth of knowledge



But utilization seems to be decreasing



Reception and reactions

Article

Papers and patents are becoming less disruptive over time

https://doi.org/10.1038/s41586-022-05543-x

Received: 14 February 2022

Accepted: 8 November 2022

Published online: 4 January 2023

Check for updates

Michael Park[1], Erin Leahey[2] & Russell J. Funk[1]✉

Theories of scientific and technological change view discovery and invention as endogenous processes[1,2], wherein previous accumulated knowledge enables future progress by allowing researchers to, in Newton's words, 'stand on the shoulders of giants'[3–7]. Recent decades have witnessed exponential growth in the volume of new scientific and technological knowledge, thereby creating conditions that should be ripe for major advances[8,9]. Yet contrary to this view, studies suggest that progress is slowing in several major fields[10,11]. Here, we analyse these claims at scale across six decades, using data on 45 million papers and 3.9 million patents from six large-scale datasets, together with a new quantitative metric—the CD index[12]—that characterizes how papers and patents change networks of citations in science and technology. We find that papers and patents are increasingly less likely to break with the past in ways that push science and technology in new directions. This pattern holds universally across fields and is robust across multiple different citation- and text-based metrics[1,13–17]. Subsequently, we link this decline in disruptiveness to a narrowing in the use of previous knowledge, allowing us to reconcile the patterns we observe with the 'shoulders of giants' view. We find that the observed declines are unlikely to be driven by changes in the quality of published science, citation practices or field-specific factors. Overall, our results suggest that slowing rates of disruption may reflect a fundamental shift in the nature of science and technology.

Although the past century witnessed an unprecedented expansion of scientific and technological knowledge, there are concerns that innovative activity is slowing[18–20]. Studies document declining research productivity in semiconductors, pharmaceuticals and other fields[10,11]. Papers, patents and even grant applications have become less novel relative to prior work and less likely to connect disparate areas of knowledge, both of which are precursors of innovation[21,22]. The gap between the year of discovery and the awarding of a Nobel Prize has also increased[23,24], suggesting that today's contributions do not measure up to the past. These trends have attracted increasing attention from policymakers, as they pose substantial threats to economic growth, human health and wellbeing, and national security, along with global efforts to combat grand challenges such as climate change[25,26].

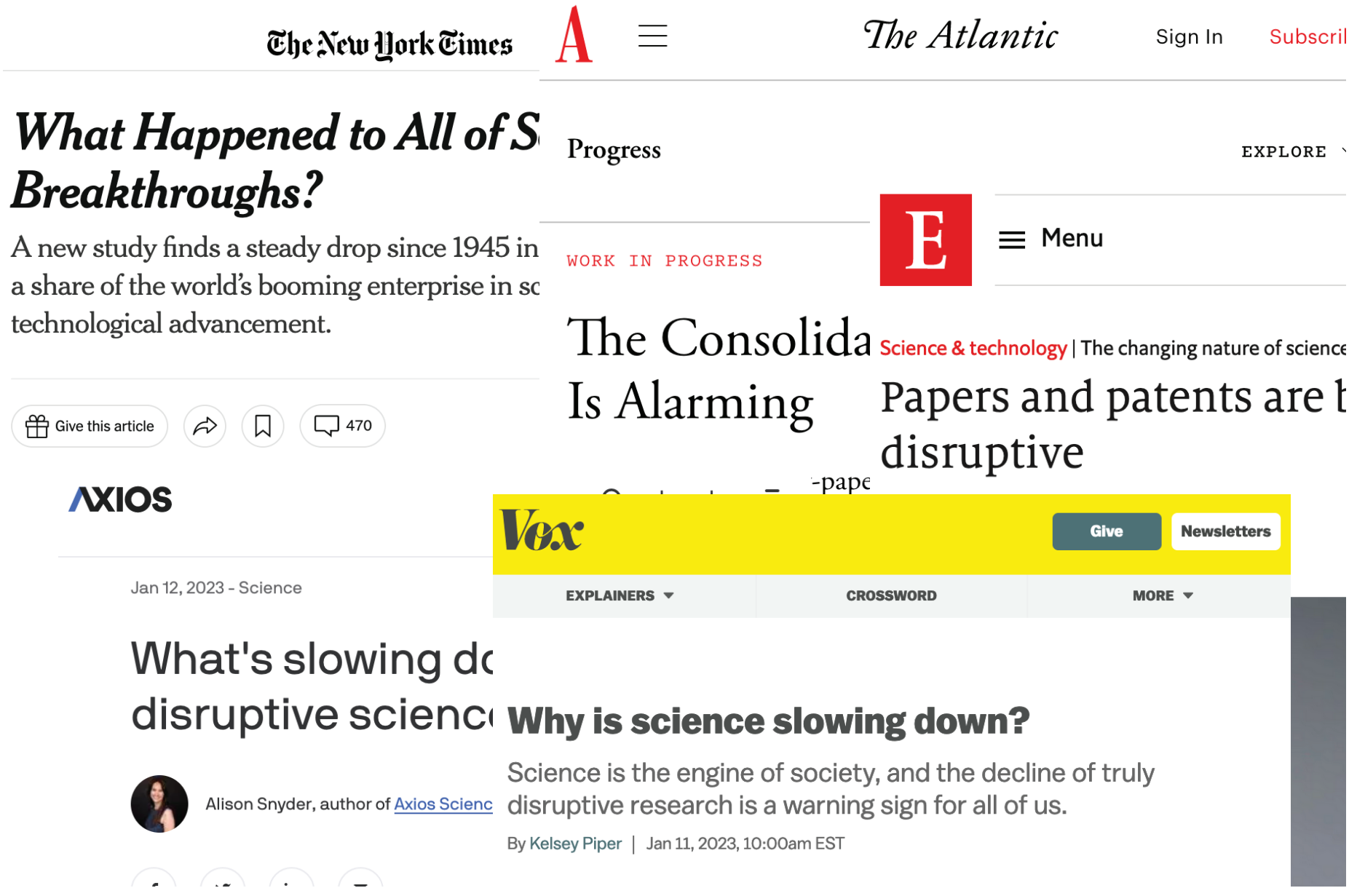
Numerous explanations for this slowdown have been proposed. Some point to a dearth of 'low-hanging fruit' as the readily available productivity-enhancing innovations have already been made[19,27]. Others emphasize the increasing burden of knowledge; scientists and inventors require ever more training to reach the frontiers of their fields, leaving less time to push those frontiers forward[18,28]. Yet much remains unknown, not merely about the causes of slowing innovative activity, but also the depth and breadth of the phenomenon. The decline is difficult to reconcile with centuries of observation by philosophers of science, who characterize the growth of knowledge as an endogenous process, wherein previous knowledge enables future discovery, a view captured famously in Newton's observation that if he had seen further, it was by 'standing on the shoulders of giants'[3]. Moreover, to date, the evidence pointing to a slowdown is based on studies of particular fields, using disparate and domain-specific metrics[10,11], making it difficult to know whether the changes are happening at similar rates across areas of science and technology. Little is also known about whether the patterns seen in aggregate indicators mask differences in the degree to which individual works push the frontier.

We address these gaps in understanding by analysing 25 million papers (1945–2010) in the Web of Science (WoS) (Methods) and 3.9 million patents (1976–2010) in the United States Patent and Trademark Office's (USPTO) Patents View database (Methods). The WoS data include 390 million citations, 25 million paper titles and 13 million abstracts. The Patents View data include 35 million citations, 3.9 million patent titles and 3.9 million abstracts. Subsequently, we replicate our core findings on four additional datasets—JSTOR, the American Physical Society corpus, Microsoft Academic Graph and PubMed—encompassing 20 million papers. Using these data, we join a new citation-based measure[12] with textual analyses of titles and abstracts to understand whether papers and patents forge new directions over time and across fields.

Measurement of disruptiveness

To characterize the nature of innovation, we draw on foundational theories of scientific and technological change[2,29,30], which distinguish between two types of breakthroughs. First, some contributions improve existing streams of knowledge, and therefore consolidate the status

[1]Carlson School of Management, University of Minnesota, Minneapolis, MN, USA. [2]School of Sociology, University of Arizona, Tucson, AZ, USA. ✉e-mail: rfunk@umn.edu


The New York Times
What Happened to All of S
Breakthroughs?
A new study finds a steady drop since 1945 in
a share of the world's booming enterprise in sc
technological advancement.
Give this article
470
The Atlantic
Sign In
Subscril
Progress
EXPLORE
WORK IN PROGRESS
The Consolida
Is Alarming
Menu
Science & technology | The changing nature of science
Papers and patents are l
disruptive
-pape
AXIOS
Jan 12, 2023 - Science
What's slowing dc
disruptive scienc
Alison Snyder, author of Axios Scienc
Vox
Give
Newsletters
EXPLAINERS
CROSSWORD
MORE
Why is science slowing down?
Science is the engine of society, and the decline of truly disruptive research is a warning sign for all of us.
By Kelsey Piper | Jan 11, 2023, 10:00am EST

Altmetric Details Page

About this Attention Score

In the top 5% of all research outputs scored by Altmetric

MORE...

Mentioned by

- **139** news outlets
- **22** blogs
- **7357** tweeters
- **8** Facebook pages
- **6** Wikipedia pages
- **12** Redditors
- **1** research highlight platform
- **4** video uploaders

Citations

- **29** Dimensions

SUMMARY | News | Blogs | Twitter | Facebook | Wikipedia | Reddit | More...

Title	Papers and patents are becoming less disruptive over time
Published in	Nature, January 2023
DOI	10.1038/s41586-022-05543-x
Pubmed ID	36600070
Authors	Michael Park, Erin Leahey, Russell J. Funk

View on publisher site

Alert me about new mentions

TWITTER DEMOGRAPHICS | MENDELEY READERS | ATTENTION SCORE IN CONTEXT

This research output has an **Altmetric Attention Score** of **4018**. This is our high-level measure of the quality and quantity of online attention that it has received. This Attention Score, as well as the ranking and number of research outputs shown below, was calculated when the research output was last mentioned on **24 April 2023**.

ALL RESEARCH OUTPUTS	OUTPUTS FROM NATURE	OUTPUTS OF SIMILAR AGE	OUTPUTS OF SIMILAR AGE FROM NATURE
#1,118	#111	#35	#5
of 23,585,652 outputs	of 92,703 outputs	of 438,588 outputs	of 958 outputs

Altmetric has tracked 23,585,652 research outputs across all sources so far. Compared to these this one has done particularly well and is in the 99th percentile: it's **in the top 5% of all research outputs ever tracked** by Altmetric.

Nature paper

Reception and reactions

The paper has stimulated significant discussion on many different issues. . .

What's causing the decline?

- Innovative work is difficult to get through peer review.
- Funders tend to pick lower risk projects.
- Grant proposal requirements limit opportunities for serendipity.
- Scientific evaluation emphasizes quantitative metrics like numbers of papers and citations.
- All the low hanging fruit is gone.
- The "burden of knowledge" has become too great.

How do we measure scientific progress?

- Could the decline of disruption be good if it means greater cumulation of knowledge?
- Is there an optimal level of disruptive science and technology?
- Should all science aim to be disruptive?

Stepping back
Thoughts on implications and next steps

Implications and next steps

Convening stakeholders

- Support efforts (like this roundtable!) to understand the changing nature of discovery and invention.
- The declines we observe are consistent across both science and technology.
- Similar trends are also evident elsewhere (e.g., film)
- Government has an opportunity to convene stakeholders (e.g., academia, industry) to identify common challenges and opportunities.

Implications and next steps

Incentivizing research

- Many scientists are evaluated based on quantitative benchmarks (e.g., publication/patents, invention disclosures, citation counts).
- These have important benefits, including supporting transparency and objectivity.
- But they may also incentivize behaviors that result in less disruptive work.
- For example, work that is more developmental is likely to be easier for evaluators to understand and therefore more rewarded (e.g., publishable).
- Similarly, work that develops existing conversations or product lines is likely more useable (e.g., "citeable") in the short run.

Implications and next steps

Funding research

Grant review

- Funders want to be sure they are supporting projects that are likely to be successful.
- But disruptive work is likely harder to evaluate ex ante than developmental research.
- Moreover, opportunities for disruption seem likely to come from serendipitous discoveries, which may be unforeseen at the time of proposal submission.
- There is an opportunity for funders to consider ways of supporting freedom and flexibility while also maintaining accountability.

Grant programs

- There may also be opportunities for new types of grant programs.
- Our results (and reactions to our paper) suggest scientists are struggling to keep up with the literature.
- Programs that allow unstructured time (e.g., through teaching releases) may be helpful.
- Smaller seed grants, with faster proposal processes, may also promote exploration.

Implications and next steps

Supporting the Science of Science

- More (public) data on the products of R&D are also needed.
- For patents, the USPTO's Patents View has democratized access to quality data.
- But there's no analogue for papers, software, and so on, which are often proprietary.

Additional resources

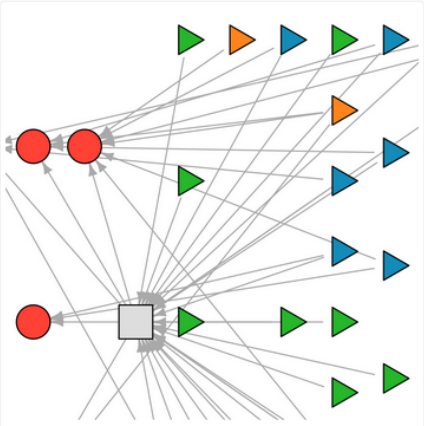
Website

http://www.cdindex.info

Measuring dynamic networks

The CD index is a new approach to finding important points in evolving networks. When applied to large-scale data sets like U.S. patent citations, the index is useful for identifying influential innovations and other features of technological change.

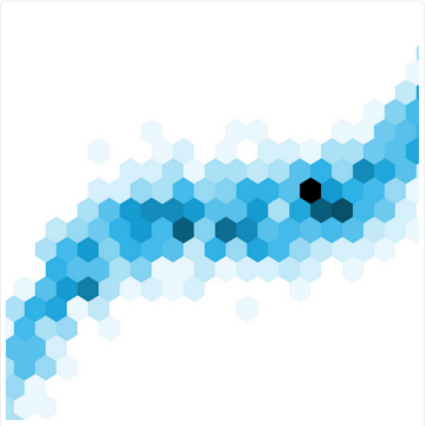
LEARN MORE »



Data

Download the CD index computed for U.S. patents.

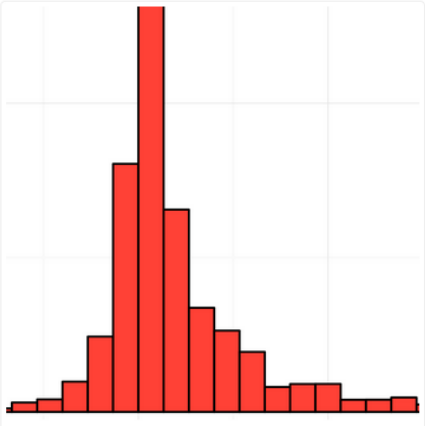
GO »



Code

Access software libraries for computing the CD index.

GO »



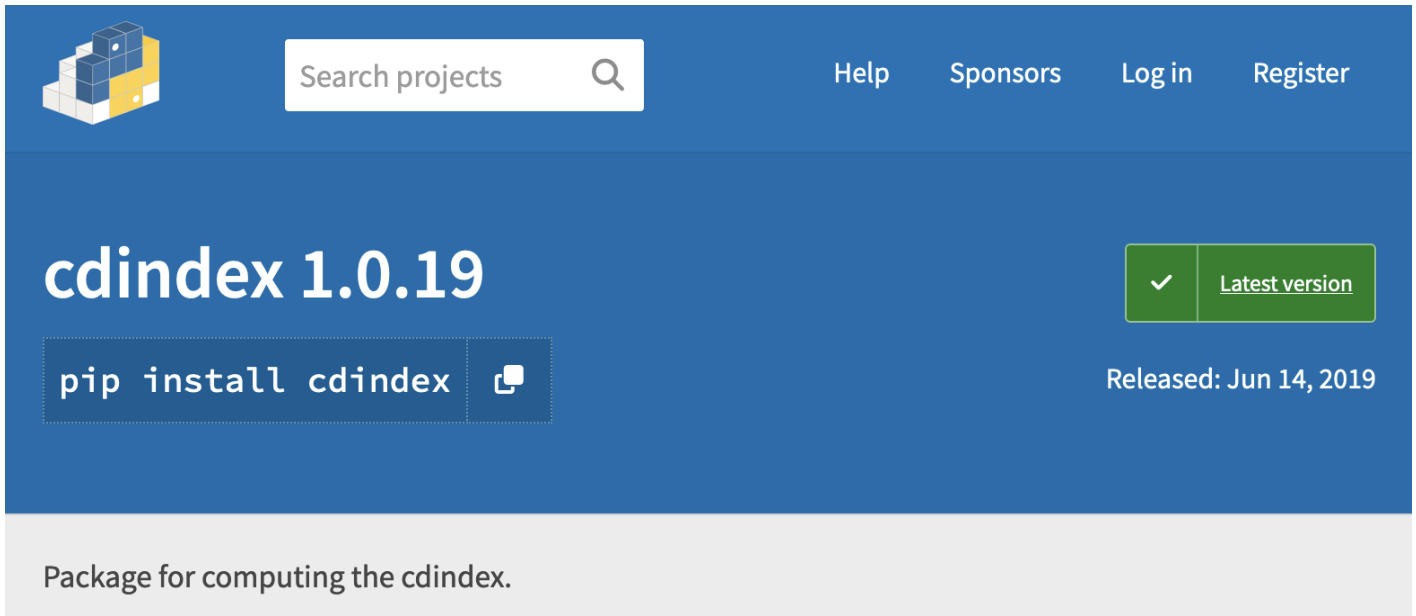
Publications

Learn more about the CD index.

GO »

PyPI

https://pypi.org/project/cdindex/



GitHub

https://github.com/russellfunk/cdindex