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Towards a Science of Science: findings, challenges, and future directions

Roberta Sinatra

@robysinatra

REVIEW SUMMARY

SCIENCE COMMUNITY

Science of science

Santo Fortunato,* Carl T. Bergstrom, Katy Börner, James A. Evans, Dirk Helbing, Staša Milojević, Alexander M. Petersen, Filippo Radicchi, Roberta Sinatra, Brian Uzzi, Alessandro Vespignani, Ludo Waltman, Dashun Wang, Albert-László Barabási*

BACKGROUND: The increasing availability of digital data on scholarly inputs and outputs—from research funding, productivity, and collaboration to paper citations and scientist mobility—offers unprecedented opportunities to explore the structure and evolution of science. The science of science (SciSci) offers a quantitative understanding of the interactions among scientific agents across diverse geographic and temporal scales: It provides insights into the conditions underlying creativity and the genesis of scientific discovery, with the ultimate goal of developing tools and policies that have the potential to accelerate science. In the past decade, SciSci has benefited from an influx of natural, computational, and social scientists who together have developed big data–based capabilities for empirical analysis and generative modeling that capture the unfolding of science, its institutions, and its workforce. The value proposition of SciSci is that with a deeper understanding of the factors that drive successful science, we can more effectively address environmental, societal, and technological problems.

ADVANCES: Science can be described as a complex, self-organizing, and evolving network of scholars, projects, papers, and ideas. This representation has unveiled patterns characterizing the emergence of new scientific fields through the study of collaboration networks and the path of impactful discoveries through the study of citation networks. Microscopic models have traced the dynamics of citation accumulation, allowing us to predict the future impact of individual papers. SciSci has revealed choices and trade-offs that scientists face as they advance both their own careers and the scientific horizon. For example, measurements indicate that scholars are risk-averse, preferring to study topics related to their current expertise, which constrains the potential of future discoveries. Those willing to break this pattern engage in riskier careers but become more likely to make major breakthroughs. Overall, the highest-impact science is grounded in conventional combinations of prior work but features unusual combinations. Last, as the locus of research is shifting into teams, SciSci is increasingly focused on the impact of team research, finding that small teams tend to disrupt science and technology with new ideas drawing on older and less prevalent ones. In contrast, large teams tend to develop recent, popular ideas, obtaining high, but often short-lived, impact.

OUTLOOK: SciSci offers a deep quantitative understanding of the relational structure between scientists, institutions, and ideas because it facilitates the identification of fundamental mechanisms responsible for scientific discovery. These interdisciplinary data-driven efforts complement contributions from related fields such as scientometrics and the economics and sociology of science. Although SciSci seeks long-standing universal laws and mechanisms that apply across various fields of science, a fundamental challenge going forward is accounting for undeniable differences in culture, habits, and preferences between different fields and countries. This variation makes some cross-domain insights difficult to appreciate and associated science policies difficult to implement. The differences among the questions, data, and skills specific to each discipline suggest that further insights can be gained from domain-specific SciSci studies, which model and identify opportunities adapted to the needs of individual research fields. ■

ON OUR WEBSITE

Read the full article at http://dx.doi.org/10.1126/science.aao0185

The list of author affiliations is available in the full article online.
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Performance


Success

Performance is about you

Success is about us

Why is this important?


SUCCESS
92
93
94
95
96
97
98
99
100
101

Simkin and Roychowdhury, Journal of Mathematical Sociology, 32(2), pp.129-141.(2006)

Salganik, Dodds, Watts, Science, 311, 5762:854-6 (2006)

Watts, Crown Business (2011)

Back in 2013…

Science of Success


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Nitrogen
14,0067

How does success in scientific careers evolve?

Who is going to have an outstanding achievement?

And when?

Data

Physics

500,000 papers over 110 yrs

3,000 careers

Data

Physics

500,000 papers over 110 yrs

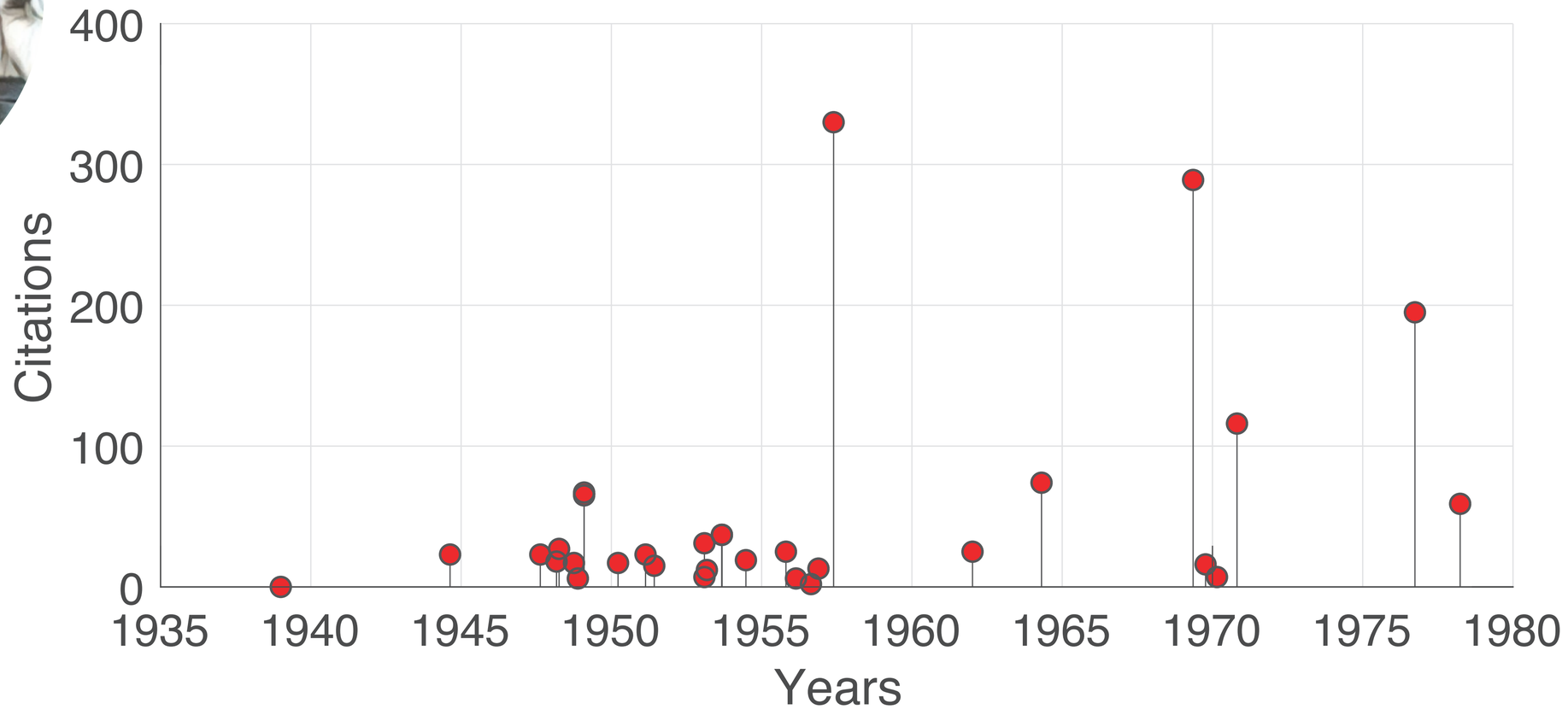
3,000 careers

Six fields

6,500,000 papers over last 30 yrs

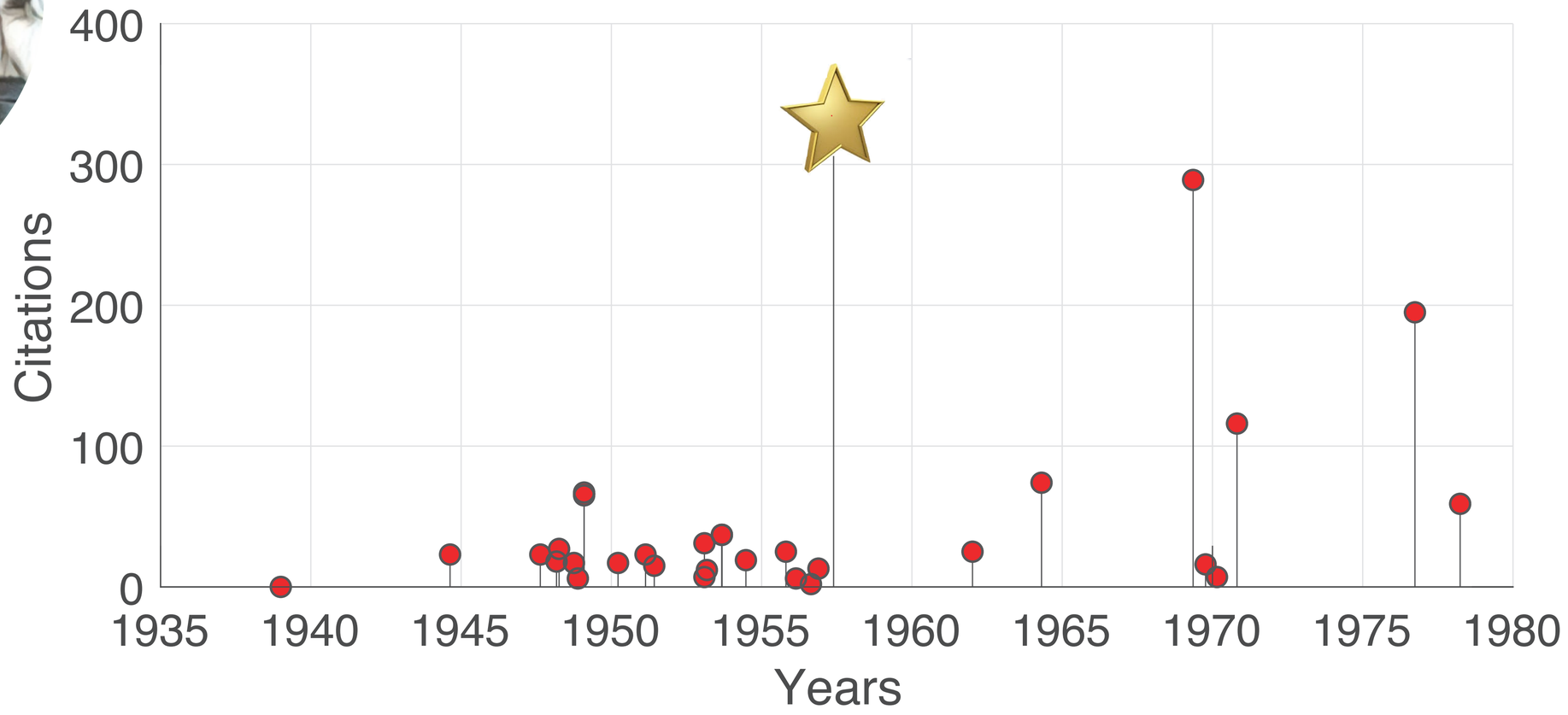
25,000 careers

Career of Richard Feynman



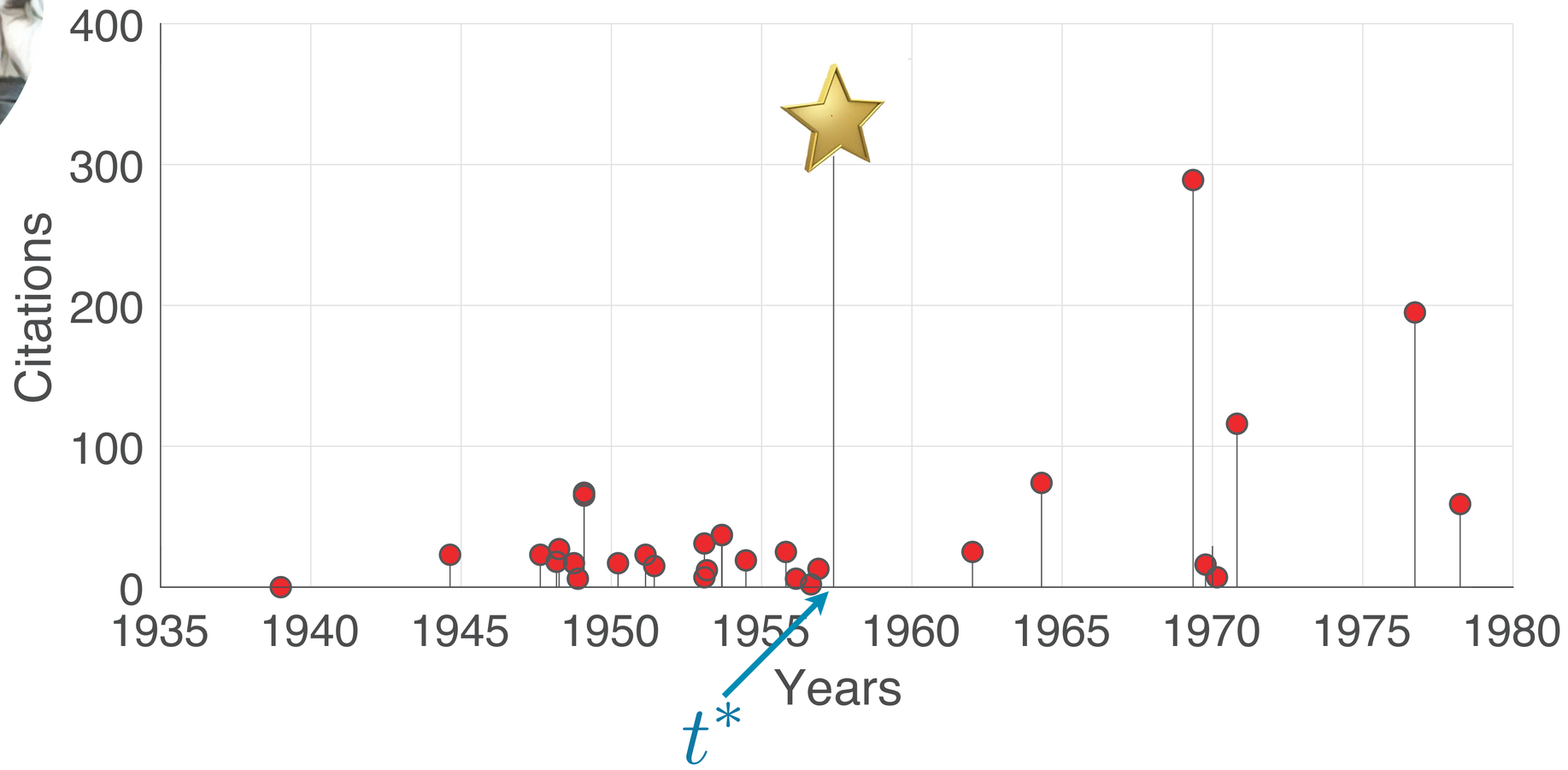
Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)

Career of Richard Feynman



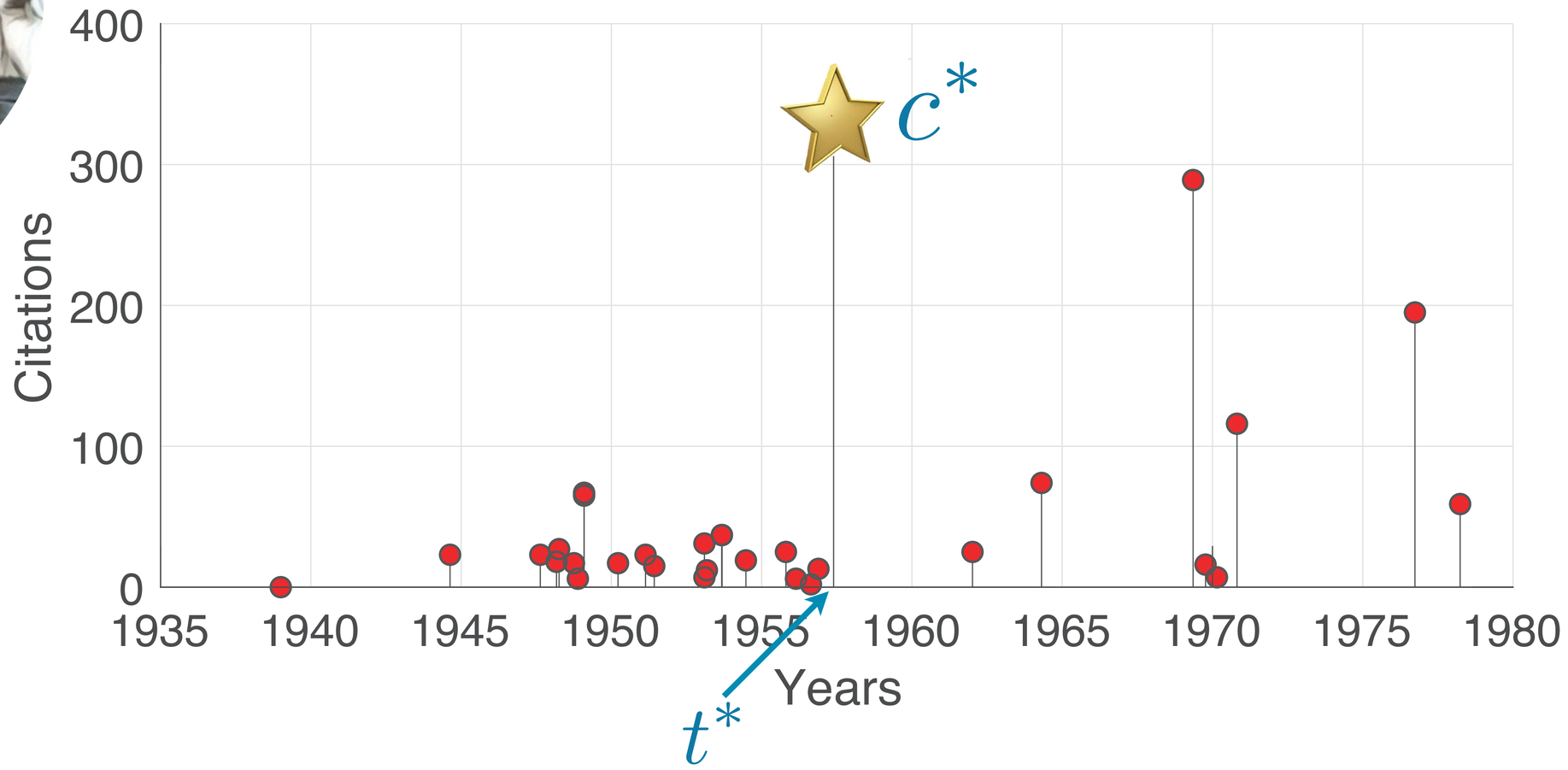
Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)

Career of Richard Feynman



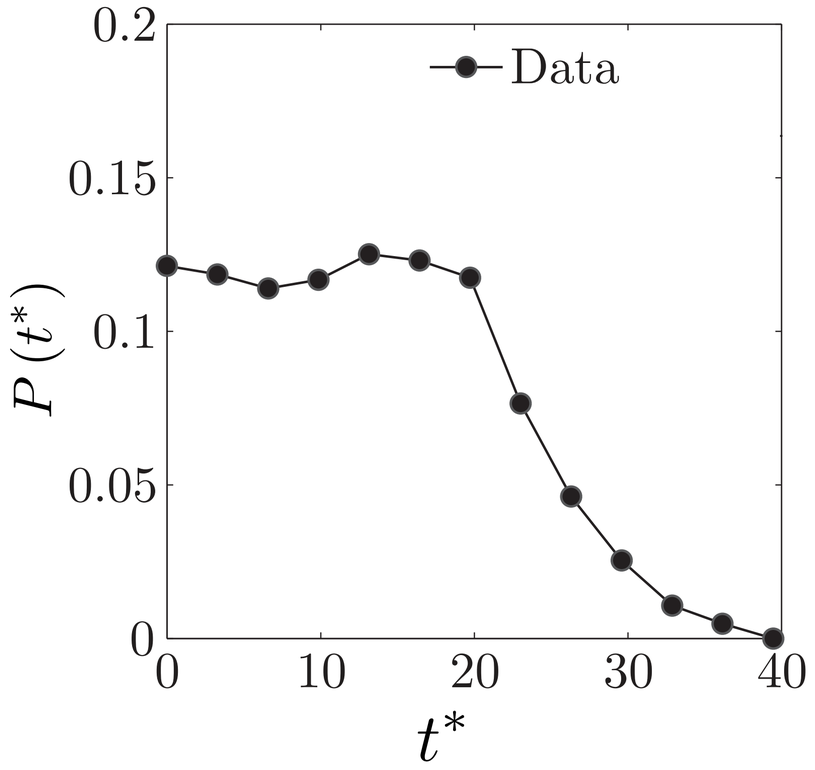
Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)

Career of Richard Feynman



Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)

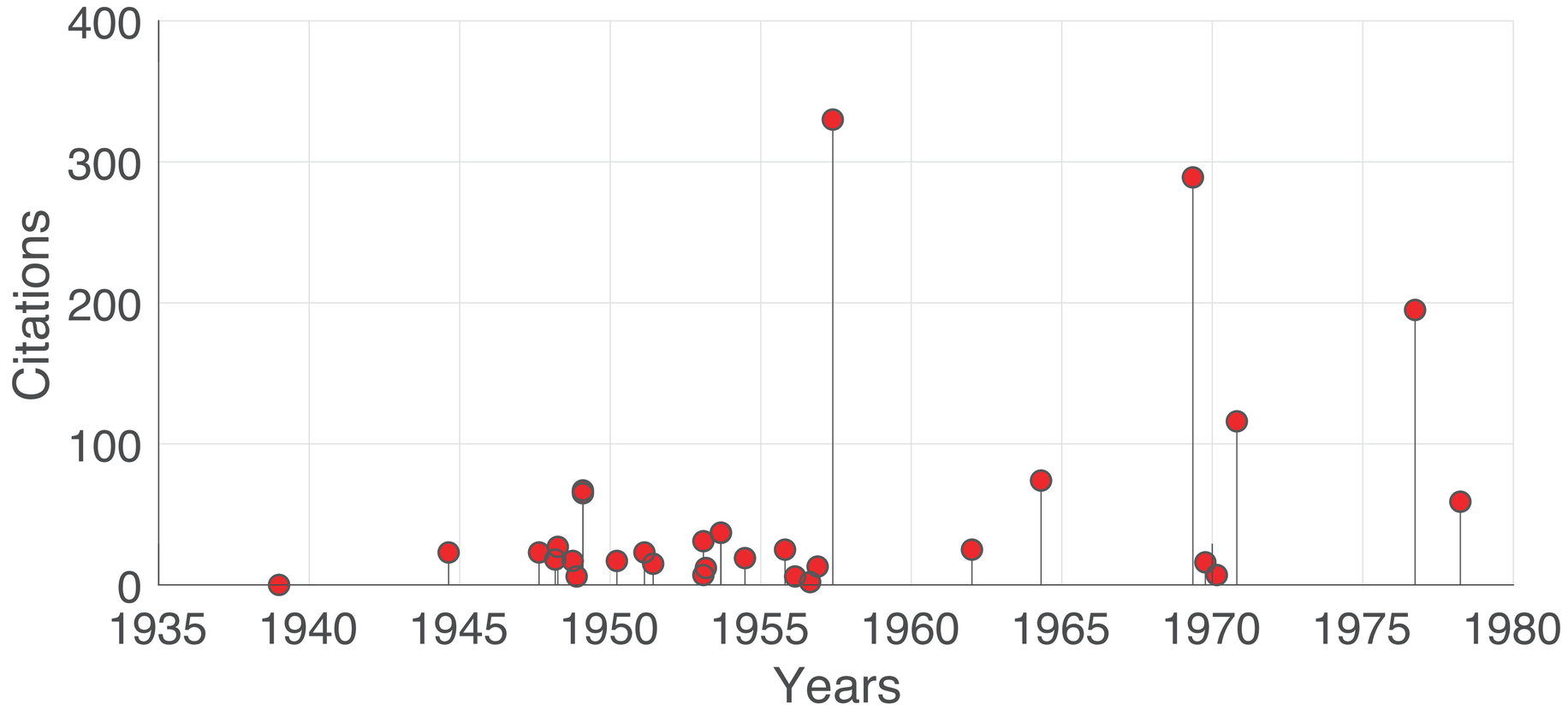
Timing of the hit



Simonton, D. F. (1997). Psychological Review 104, 66.

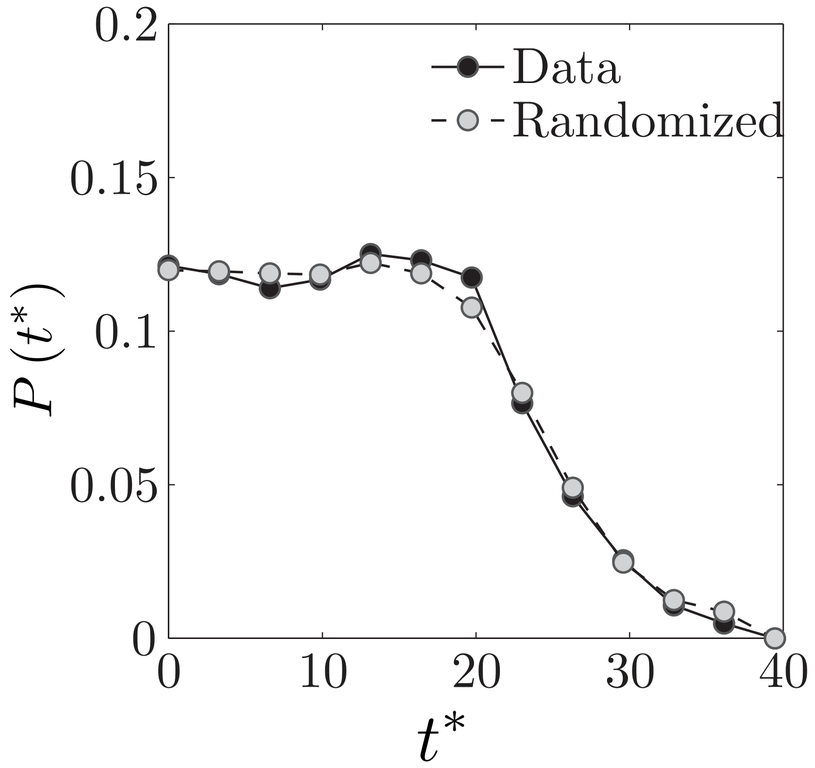
Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)

Randomization: we shuffle the impact of papers



Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)

The hit is random in a scientist's sequence of publications



Simonton, D. F. (1997). Psychological Review 104, 66.

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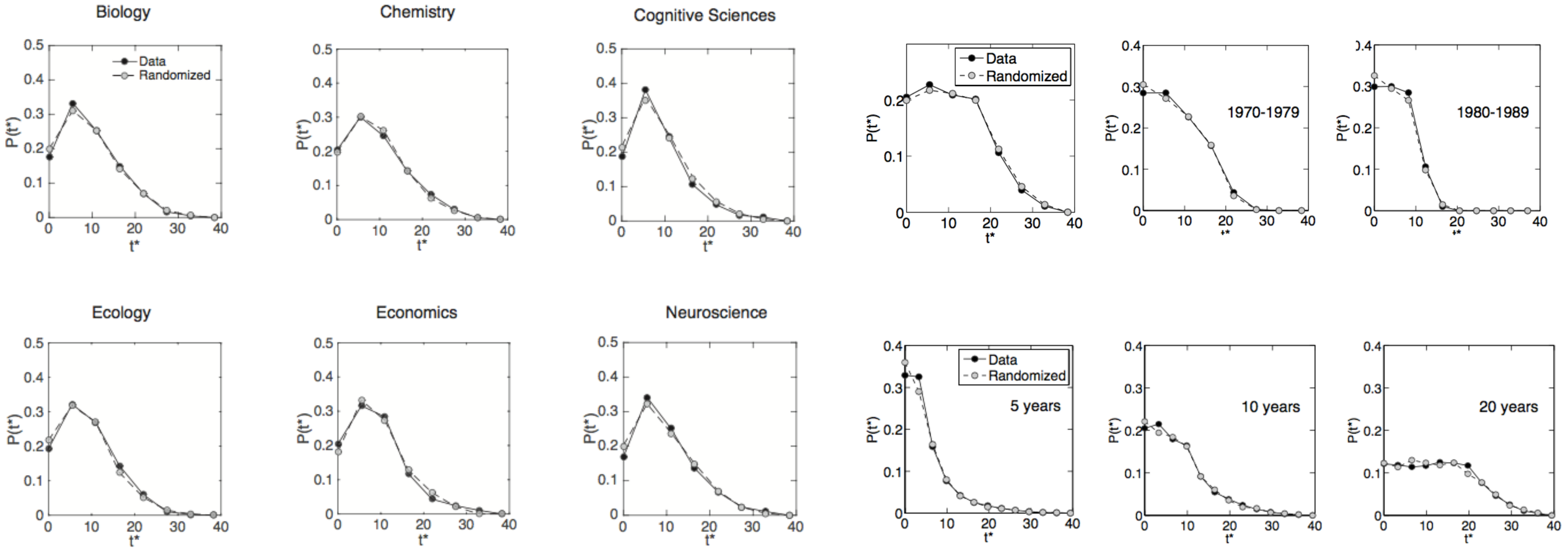
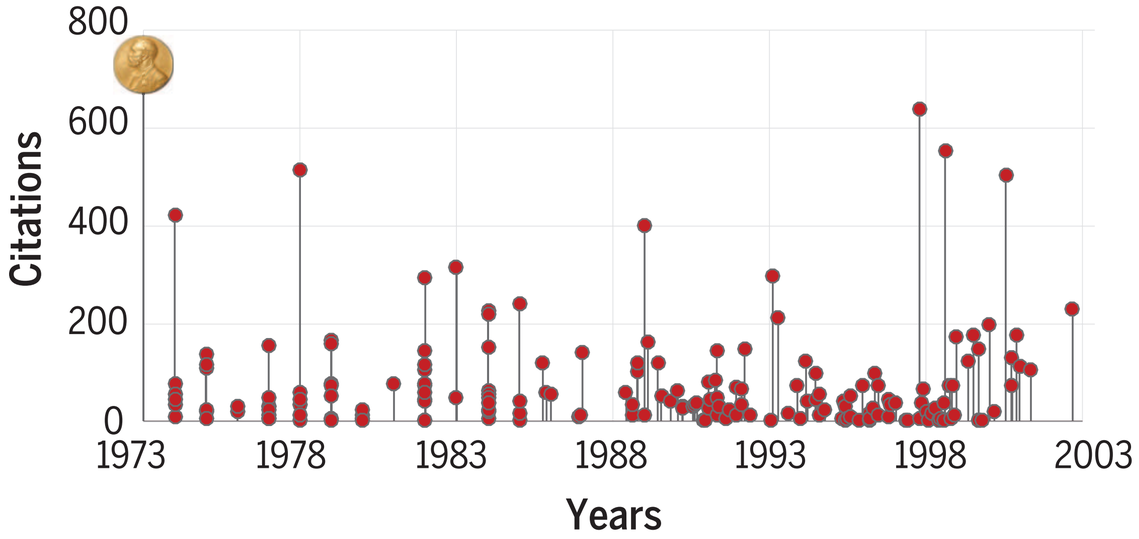
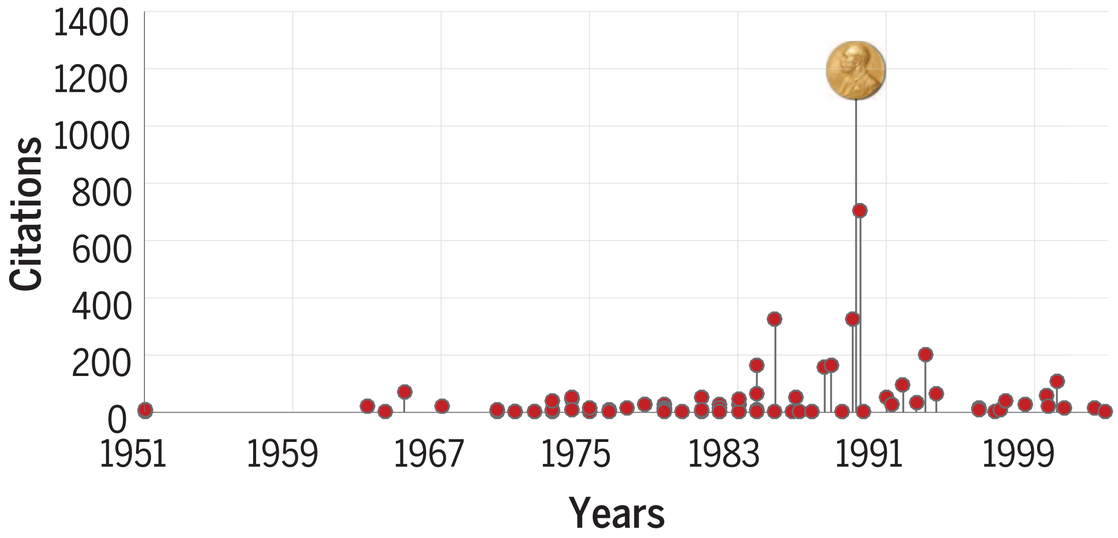


Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)



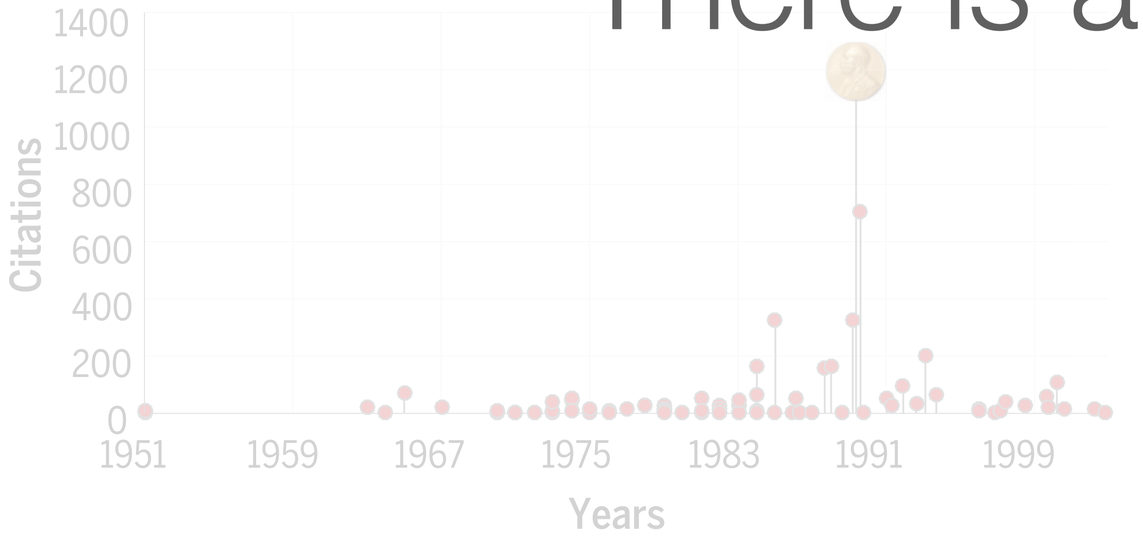
Frank A. Wilczek
Physics Nobel, 2004



John B. Fenn
Chemistry Nobel, 2002

Frank A. Wilczek
Physics Nobel, 2004

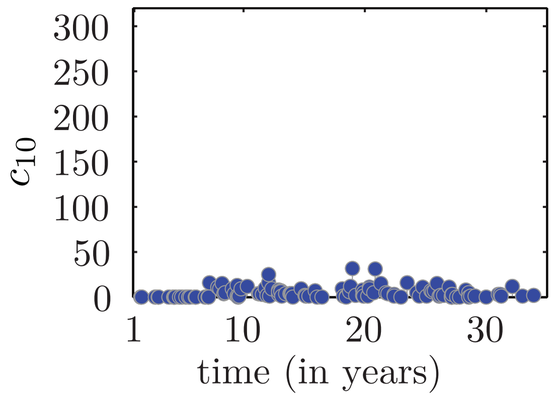
There is always hope!

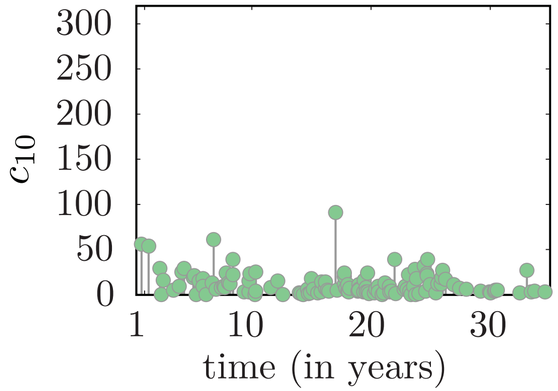


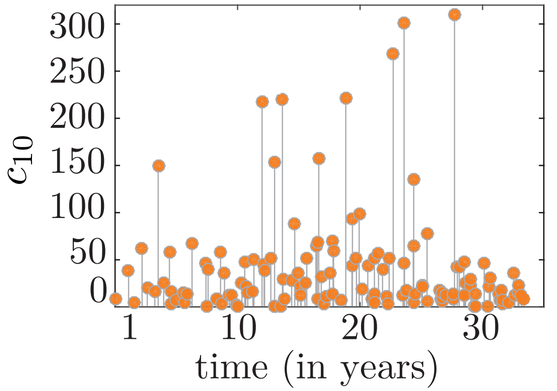
John B. Fenn
Chemistry Nobel, 2002

Impact is random
within a career

Careers differ for systematic impact







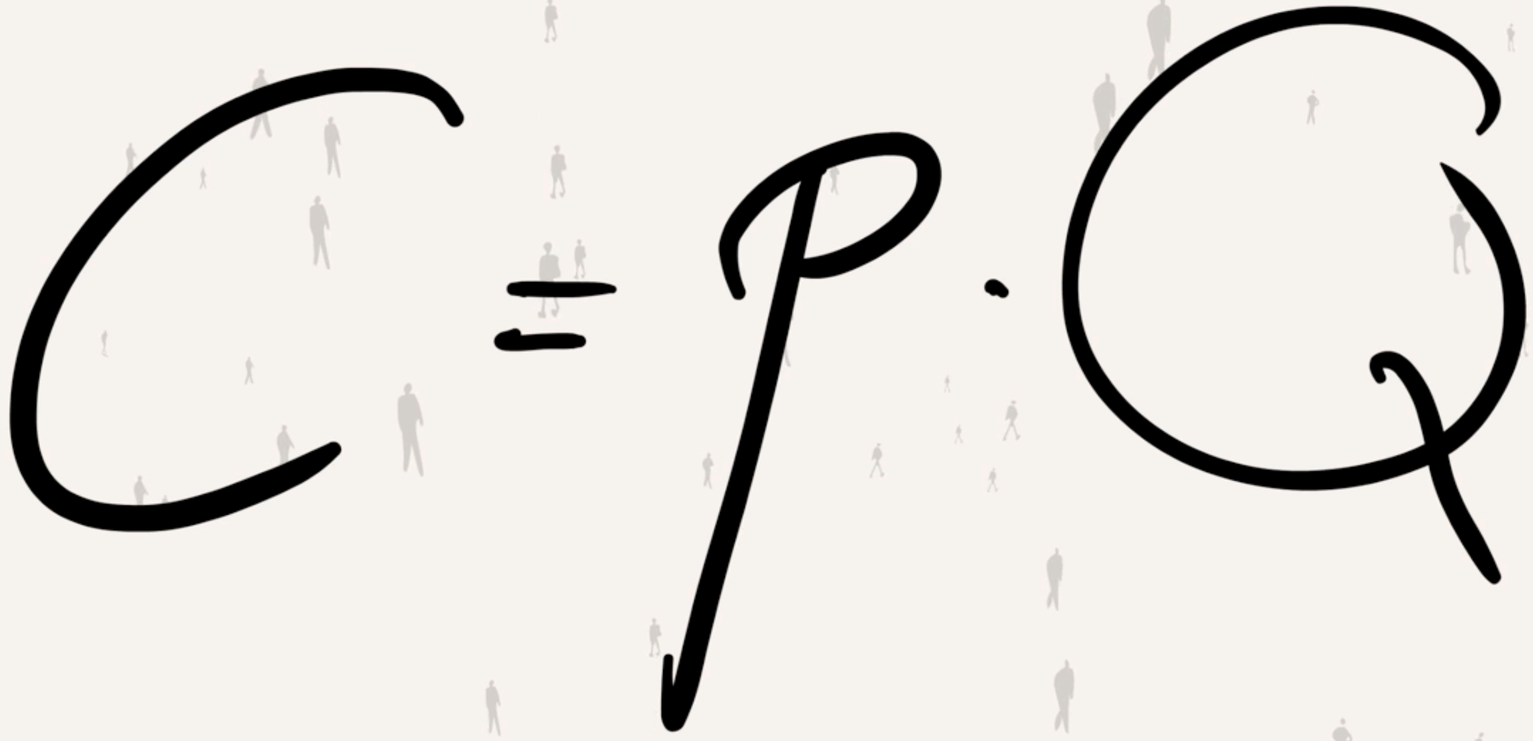
Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)

Modelling individual careers: Q-model

$$c_{j,\alpha} = p_\alpha Q_j$$

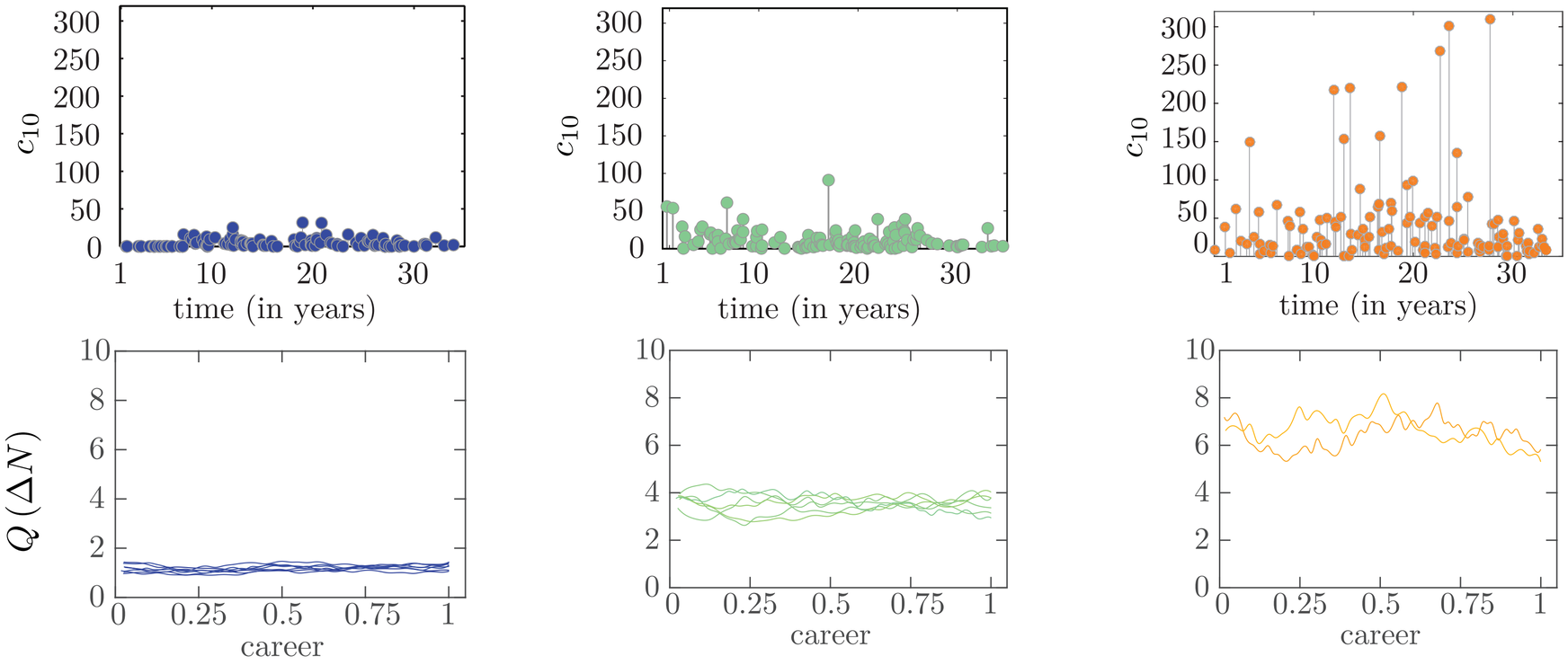
impact of j's paper = luck * researcher Q

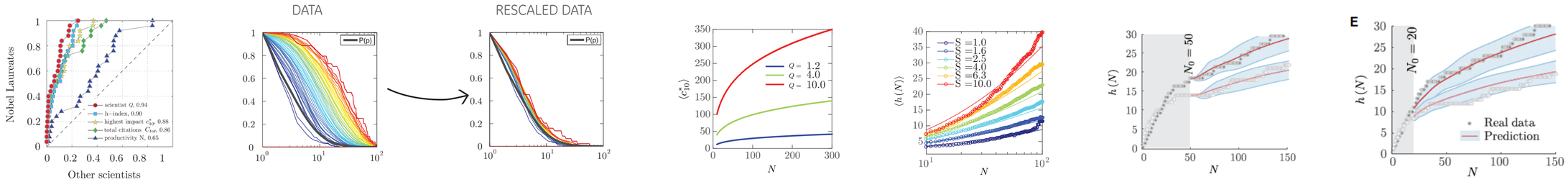
Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)



impact = luck * individual ability

The model provides more testable predictions



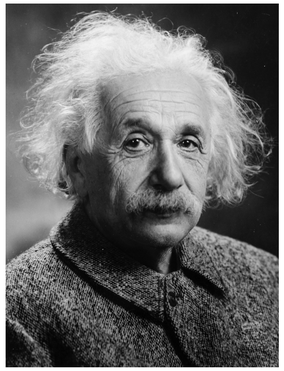


Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)

Hot streaks in artistic, cultural, and scientific careers

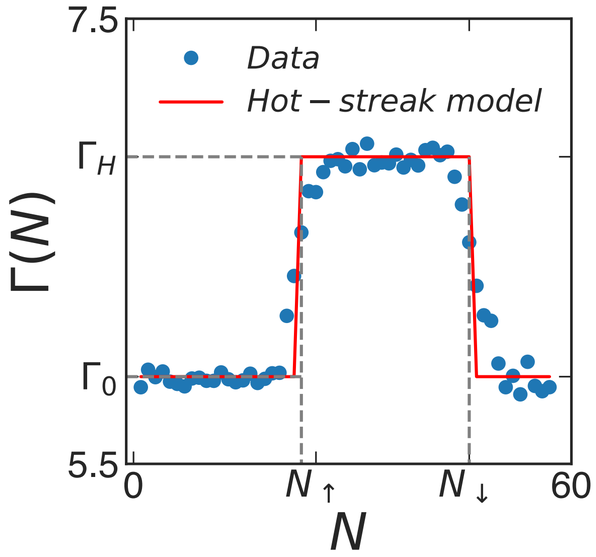
Artists

Movie directors



Scientists

Random Impact Rule
Biggest hit
2nd Biggest
3rd Biggest



Hot Streak model

Liu, Wang, Sinatra, Giles, Song, and Wang, Nature 559, 396–399 (20

Success and luck in creative careers

Music

Movies

Books

Low luck

High luck

Janosov, Battiston, Sinatra, under review, arxiv: 1909:07956

Who is going to have an outstanding achievement?

And when?

Who is going to have an outstanding achievement?

Lucky scientists with high Q,

And when?

Who is going to have an outstanding achievement?

Lucky scientists with high Q,

And when?

Randomly within their career

Video and interactive visualization are online

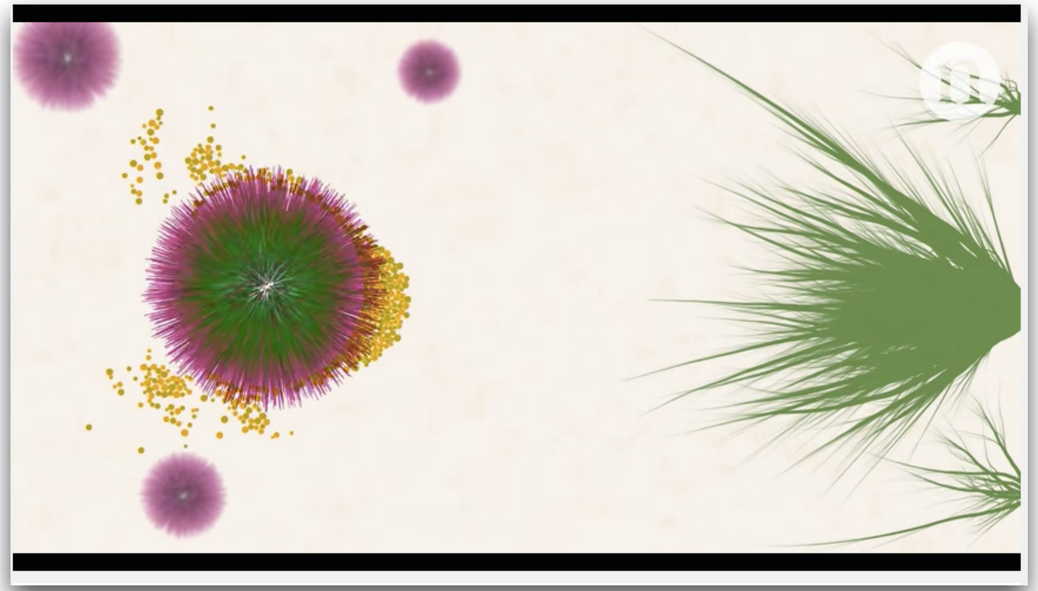

RESEARCH ARTICLE

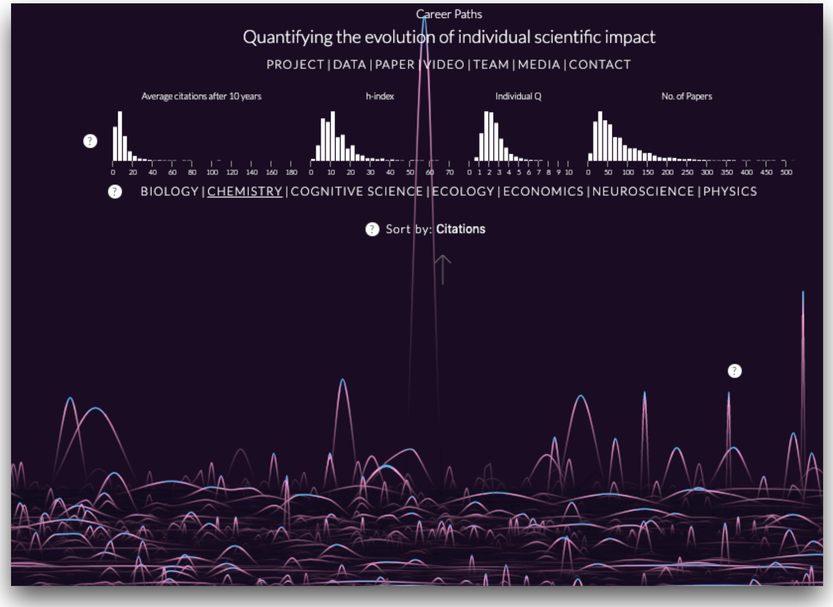
SCIENCE COMMUNITY

Quantifying the evolution of individual scientific impact

Roberta Sinatra,[1,2] Dashun Wang,[3,4] Pierre Deville,[1,5] Chaoming Song,[6] Albert-László Barabási[1,7,8,9]*

Despite the frequent use of numerous quantitative indicators to gauge the professional impact of a scientist, little is known about how scientific impact emerges and evolves in time. Here, we quantify the changes in impact and productivity throughout a career in science, finding that impact, as measured by influential publications, is distributed randomly within a scientist's sequence of publications. This random-impact rule allows us to formulate a stochastic model that uncouples the effects of productivity, individual ability, and luck and unveils the existence of universal patterns governing the emergence of scientific success. The model assigns a unique individual parameter Q to each scientist, which is stable during a career, and it accurately predicts the evolution of a scientist's impact, from the h-index to cumulative citations, and independent recognitions, such as prizes.





Nature video:
Is a scientific career predictable?

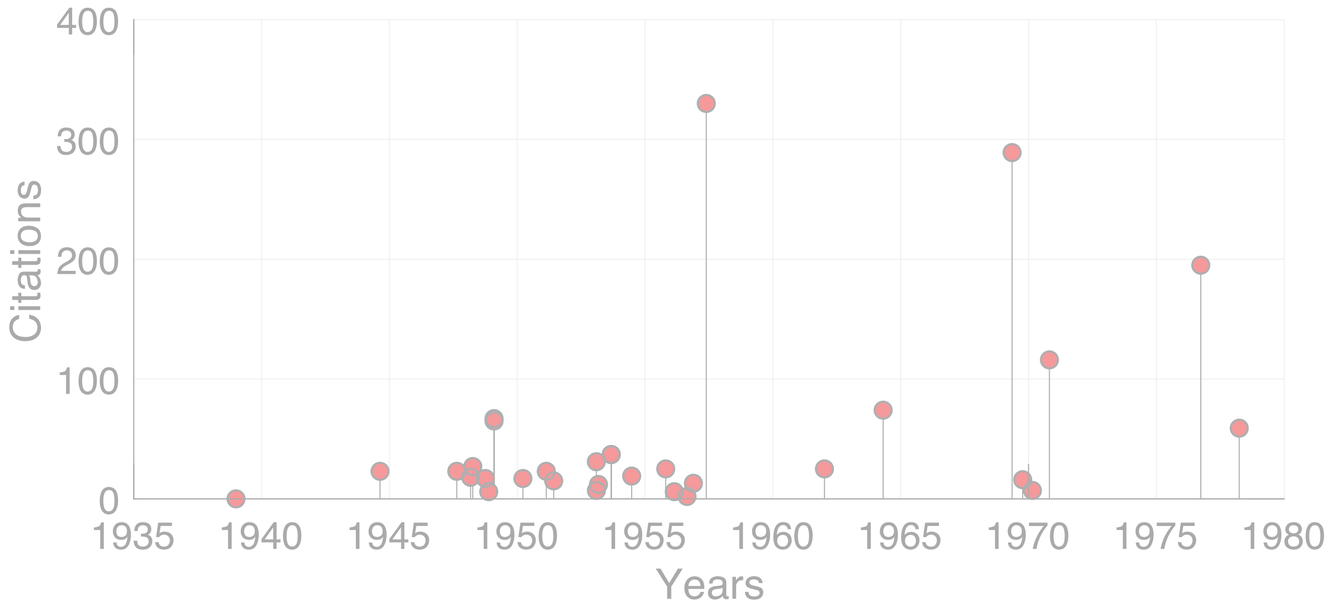
http://sciencepaths.kimalbrecht.com/

Sinatra, Wang, Deville, Song, Barabási, Science, 354, 6312, aaf5239 (2016)

2 Challenges

1

“Career”?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Citations
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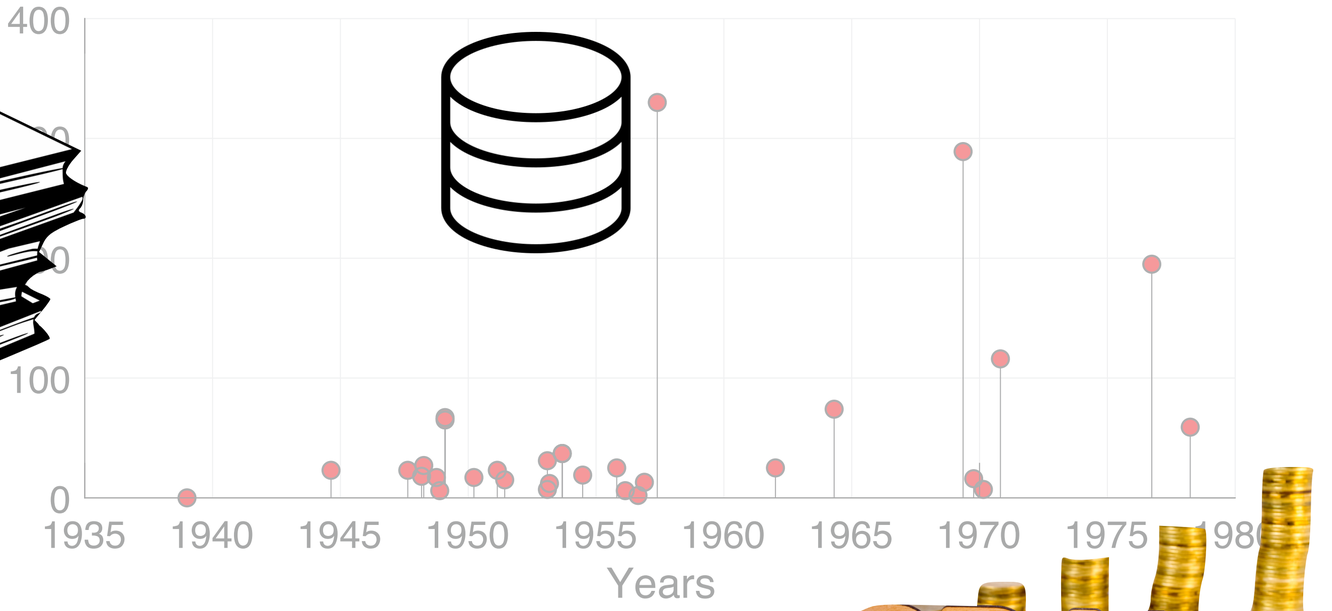
1940
1945
1950
1955
1960
1965
1970
1975
1980
Years

1

“Career”?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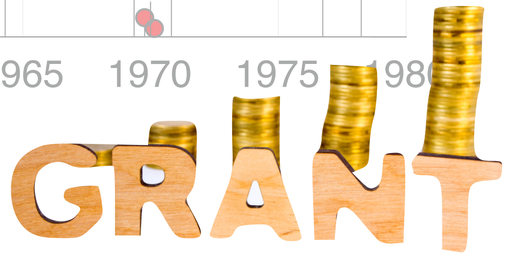
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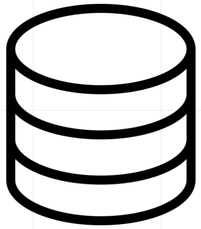
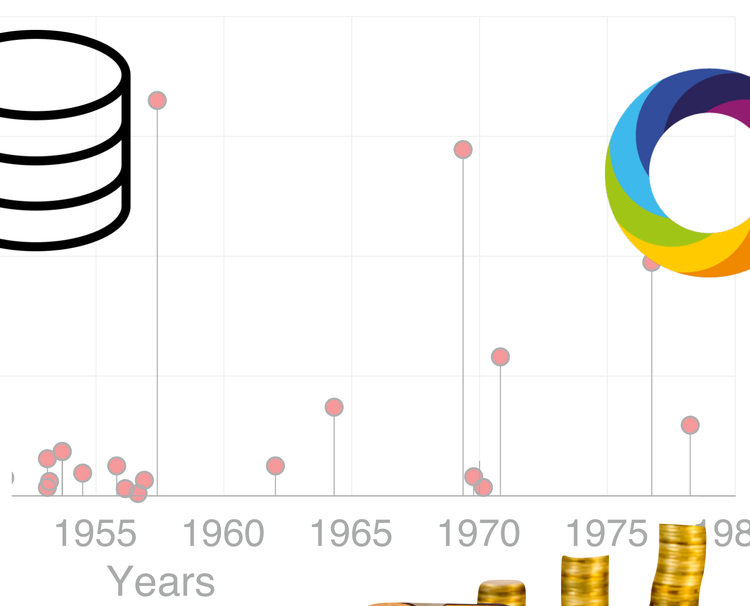
1

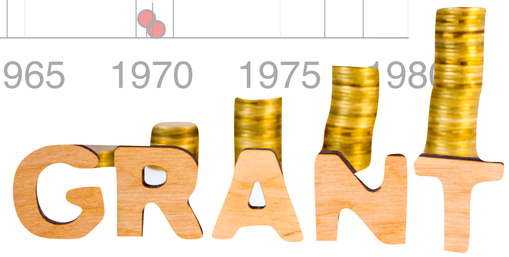
“Career”?





Altmetric

GitHub



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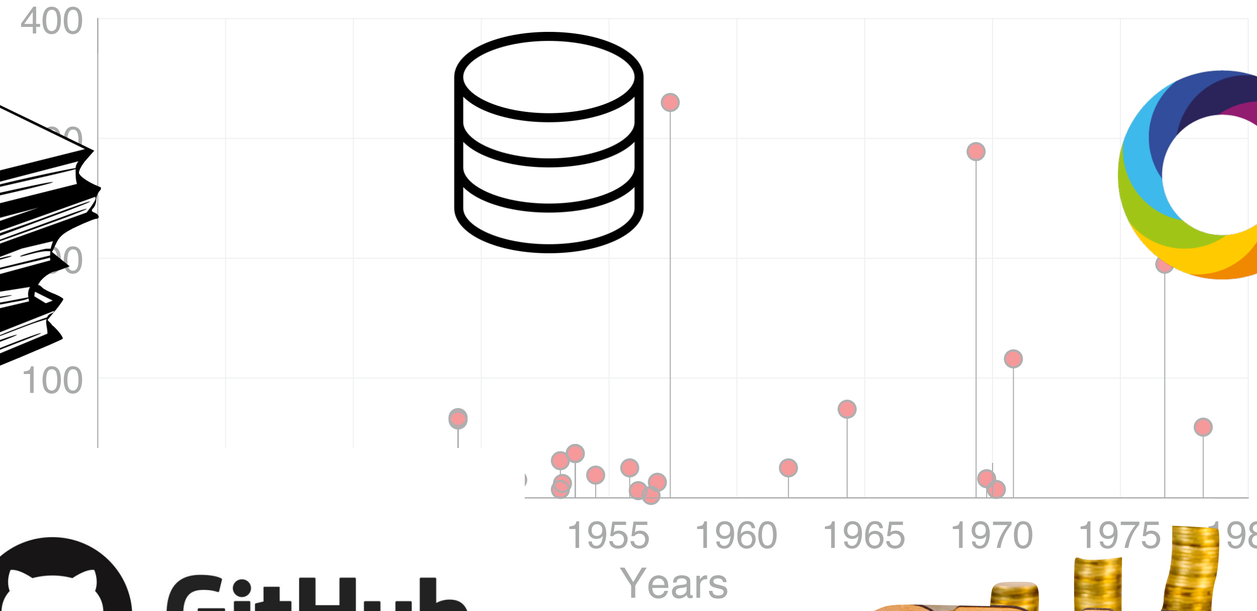
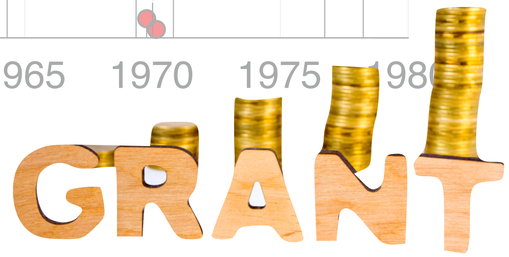
“Career”?



Altmetric

GitHub

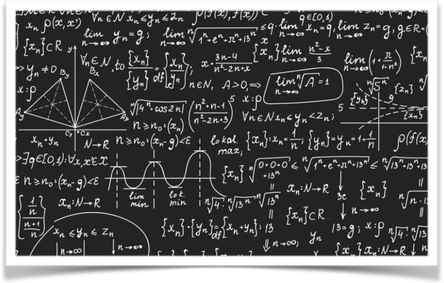


publons

Community service

1 Potential issues

Combining different datasets is hard



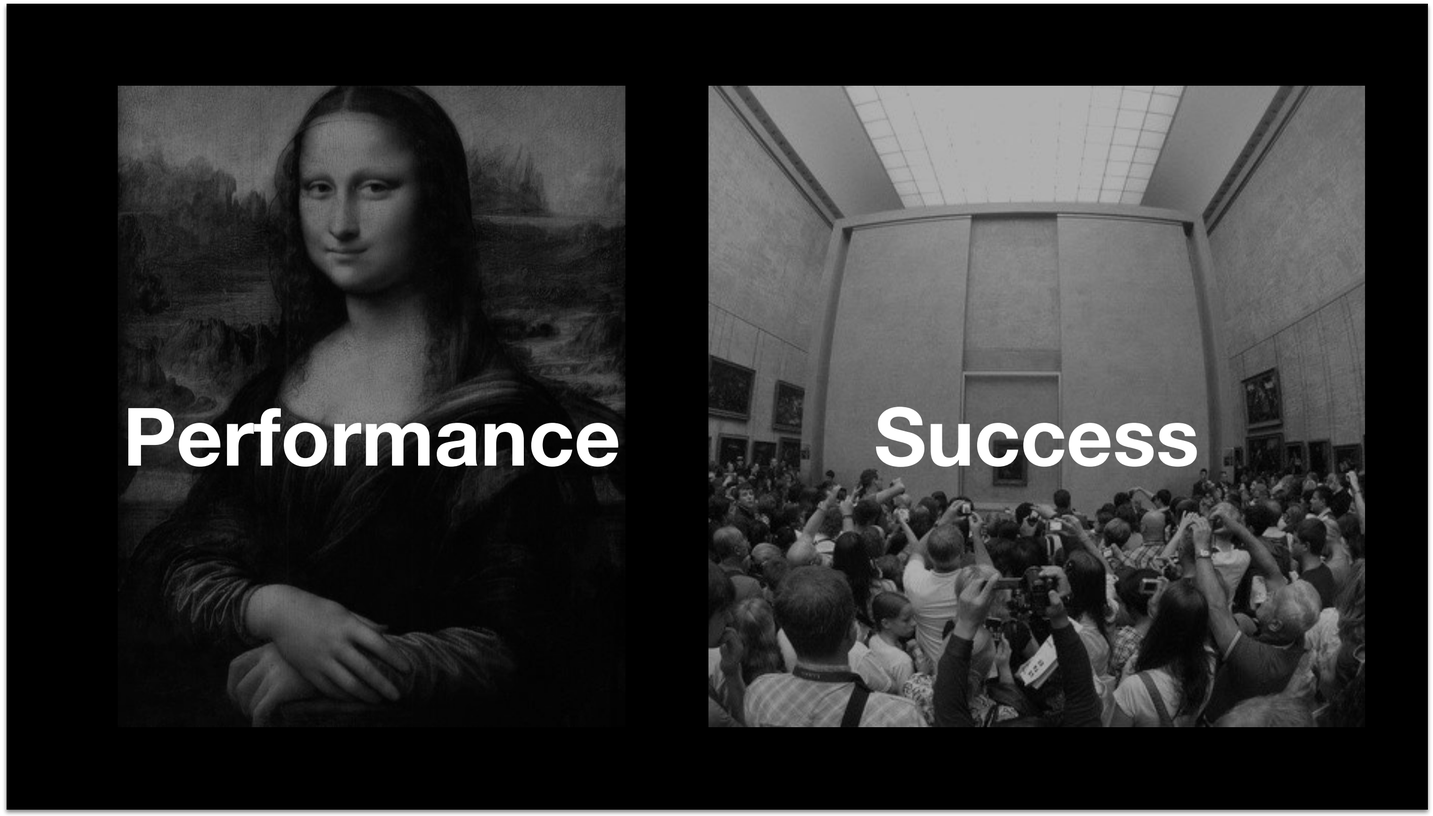
Developing new quantitative methods is complex

2

Do performance and success in science differ?

2

Do performance and success in science differ?



Citations

Altmetrics

Publons

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How scientists perceive performance

DEMOGRAPHICS
Participant ID #: 149
Name: Jennifer
Gender: Female
Ethnic Background: Caucasian
Age: 22
Degree: Bachelors of Science, obtained May 2011 from University

BACKGROUND
GPA: 3.2
GRE score: 650 verbal, 780 quant
Awards/honors: President's Service Award, Rotary Club College Scholarship
Previous research experience: 2 years as a research assistant working with 2 different faculty mentors
Academic standing: appears from Jennifer's transcript that she was in good standing upon graduation, but withdrew from 1 class prior to final
Letters of recommendation: 3 (2 from former faculty research supervisors, 1 from an intro science course professor), all supportive
Future plans: apply to doctoral programs
Extracurricular activities: student government, college learning center tutor
Position sought: Lab Manager
Position duration: 2 years, with possibility of renewal pending satisfactory performance

STATEMENTS/LETTERS
Excerpt from student statement: "I am a motivated student and would make the most of the opportunity to serve as your lab manager. After spending a semester working in Dr. lab and another year doing research with Dr. have gained valuable technical skills, co-authored a journal article, and am now committed to an academic research career…as someone focused on improving my standing and enhancing my research experience, this lab manager position would provide the perfect opportunity to hone the necessary skills to make me competitive for graduate school applications… additionally, the fascinating research taking place in your lab is directly in line with my interests and experiences…in short, I am focused, motivated, organized and dedicated to improving my research skills. I am enthusiastic about the opportunity to fill the lab manager position and collaborate with you on future research."

Excerpt from faculty recommendation letter: "…although Jennifer admittedly took a bit longer than some students to get serious about her studies early in college, she has impressed me by improving over the last two years of her science coursework and has made every effort to make up for lost ground…she has been a strong research assistant in my lab, and I know she is capable of serving as a dedicated lab manager."

Moss-Racusin et al., PNAS, 109 (41), 2012.

How scientists perceive performance

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DEMOGRAPHICS
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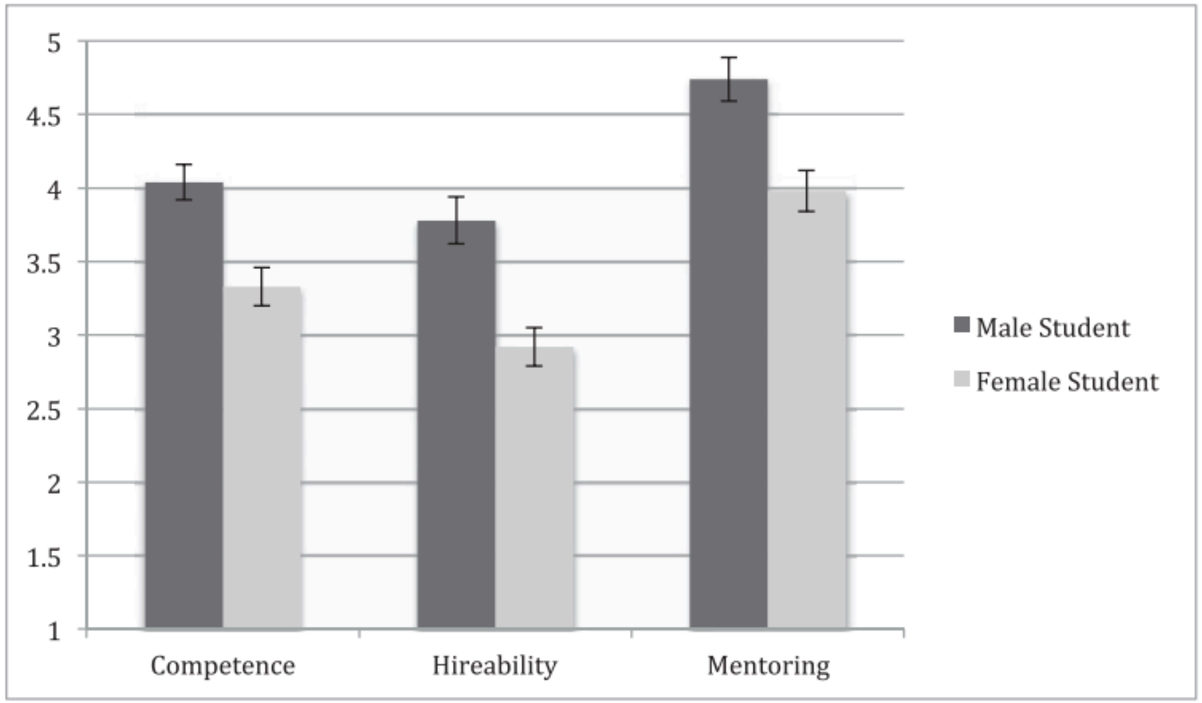
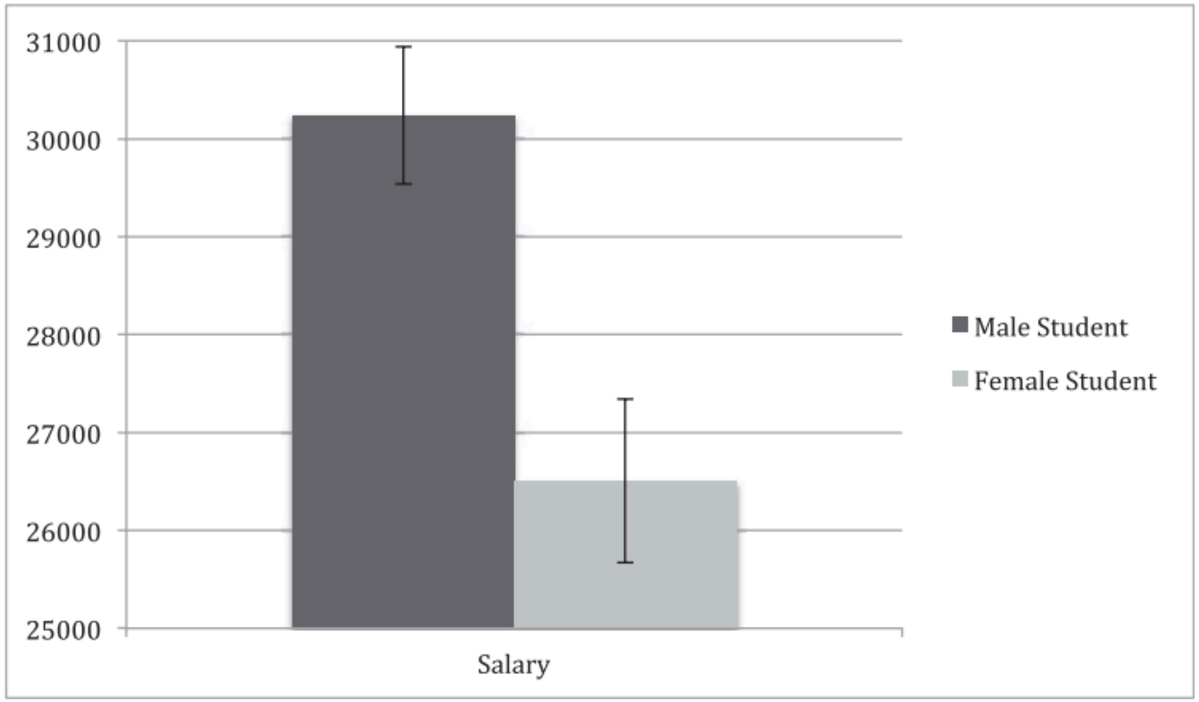
Name: John
Gender: Male
Ethnic Background: Caucasian
Age: 22
Degree: Bachelors of Science, obtained May 2011 from

Moss-Racusin et al., PNAS, 109 (41), 2012.

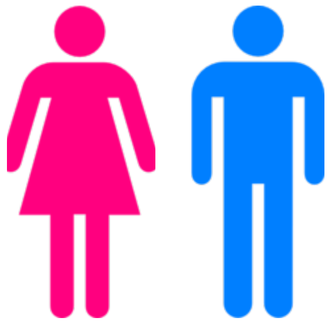
How scientists perceive performance

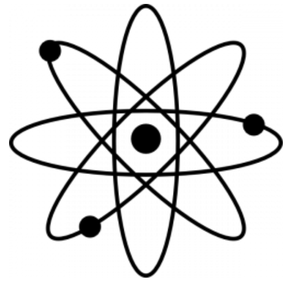




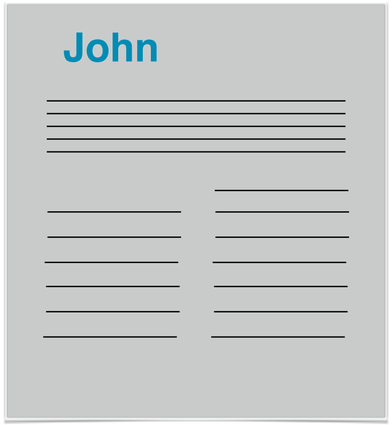
Moss-Racusin et al., PNAS, 109 (41), 2012.

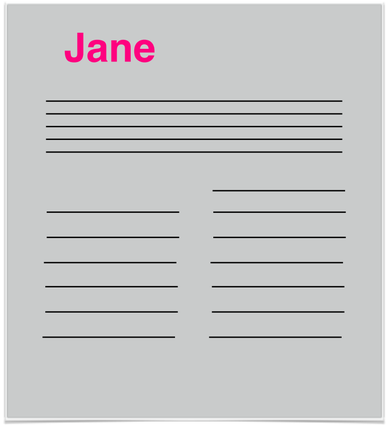
Many biases have been documented

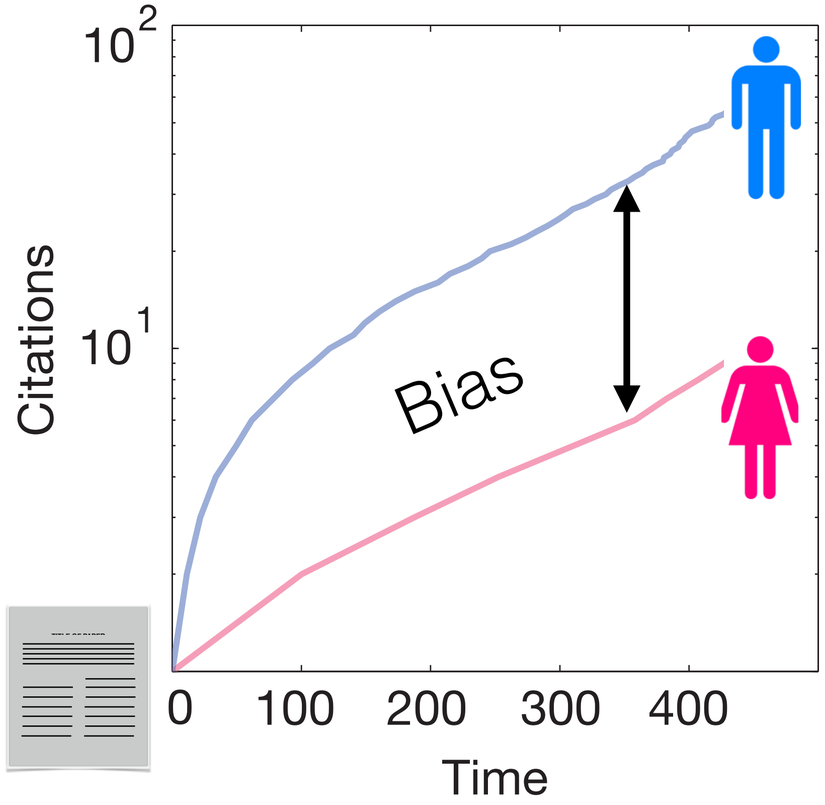




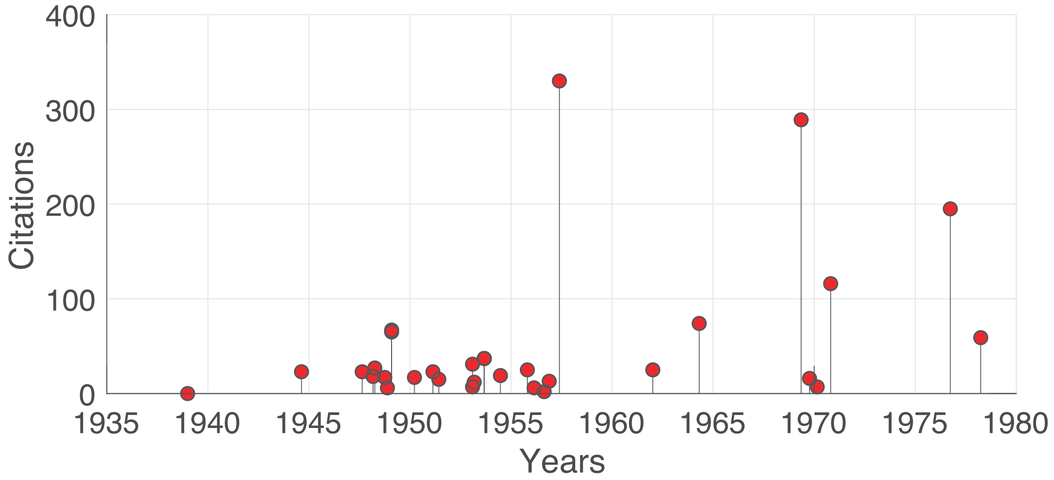
What is the role of bias in success measures?





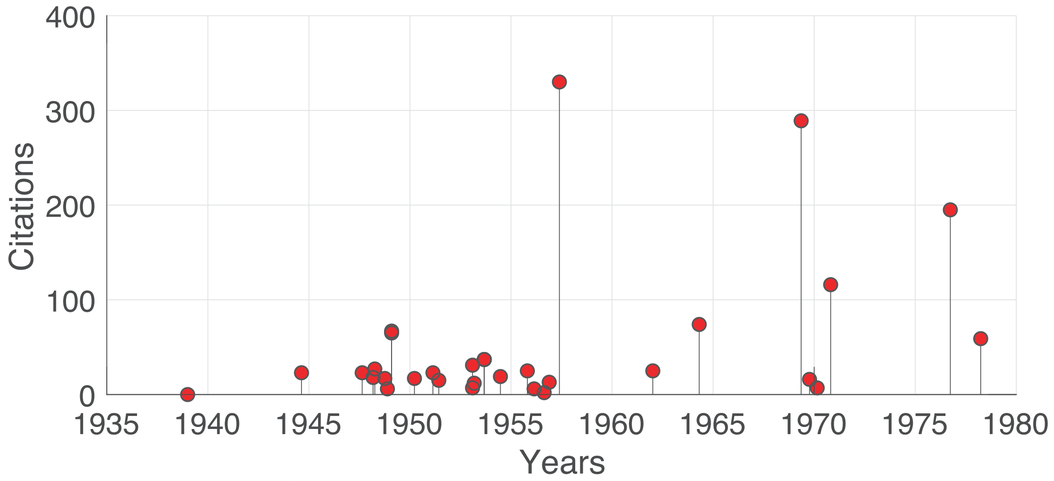


Scientific careers and gender



Huang, Gates, Sinatra, Barabasi, arxiv:1907.04103, *PNAS* 117 (2020)

Scientific careers and gender



Jennifer
Alice
Marta
Roberta
...

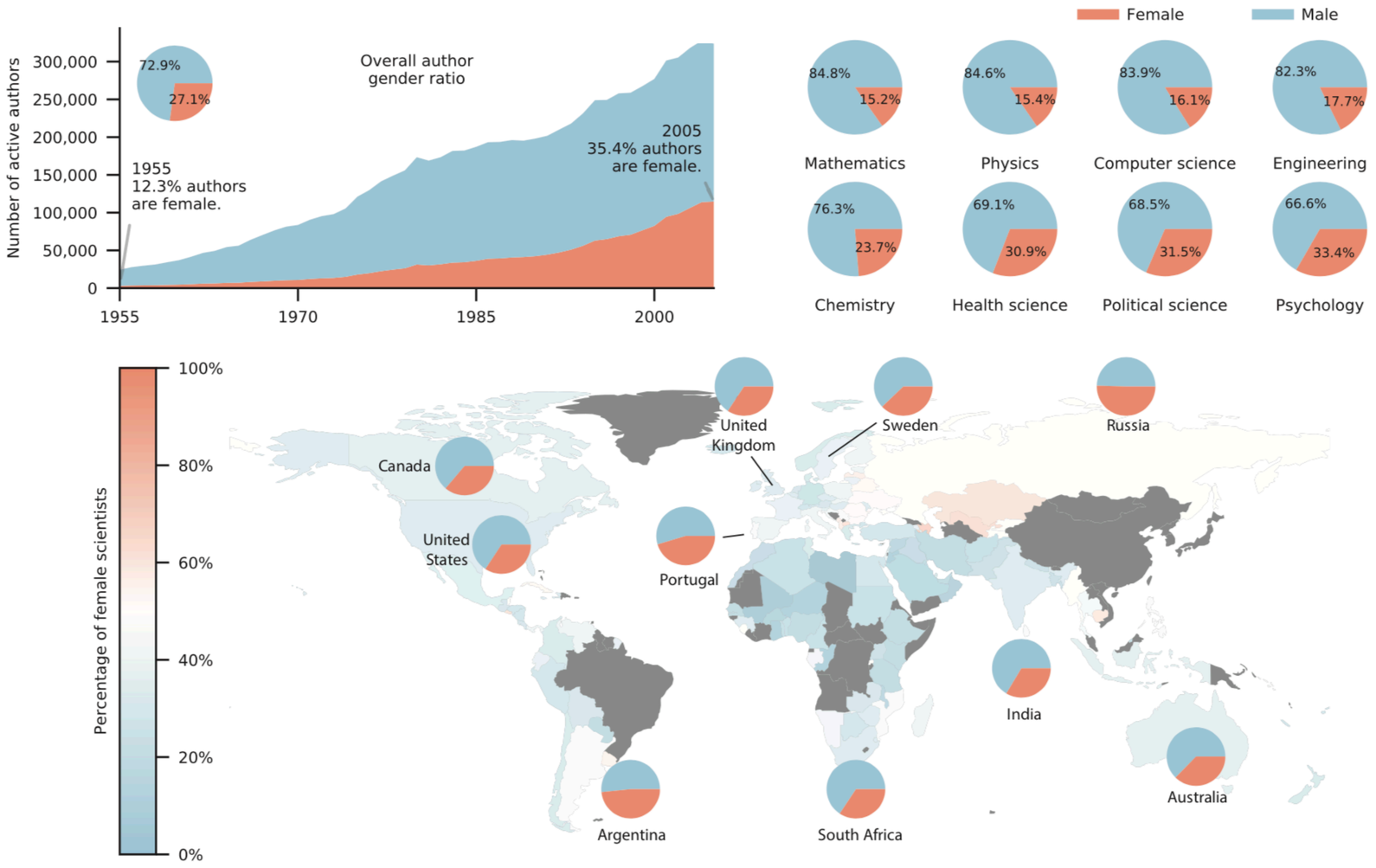
John
Bob
Christian
Matthew
...

Huang, Gates, Sinatra, Barabasi, arxiv:1907.04103, *PNAS* 117 (2020)

How does productivity differ between female and male scientists?

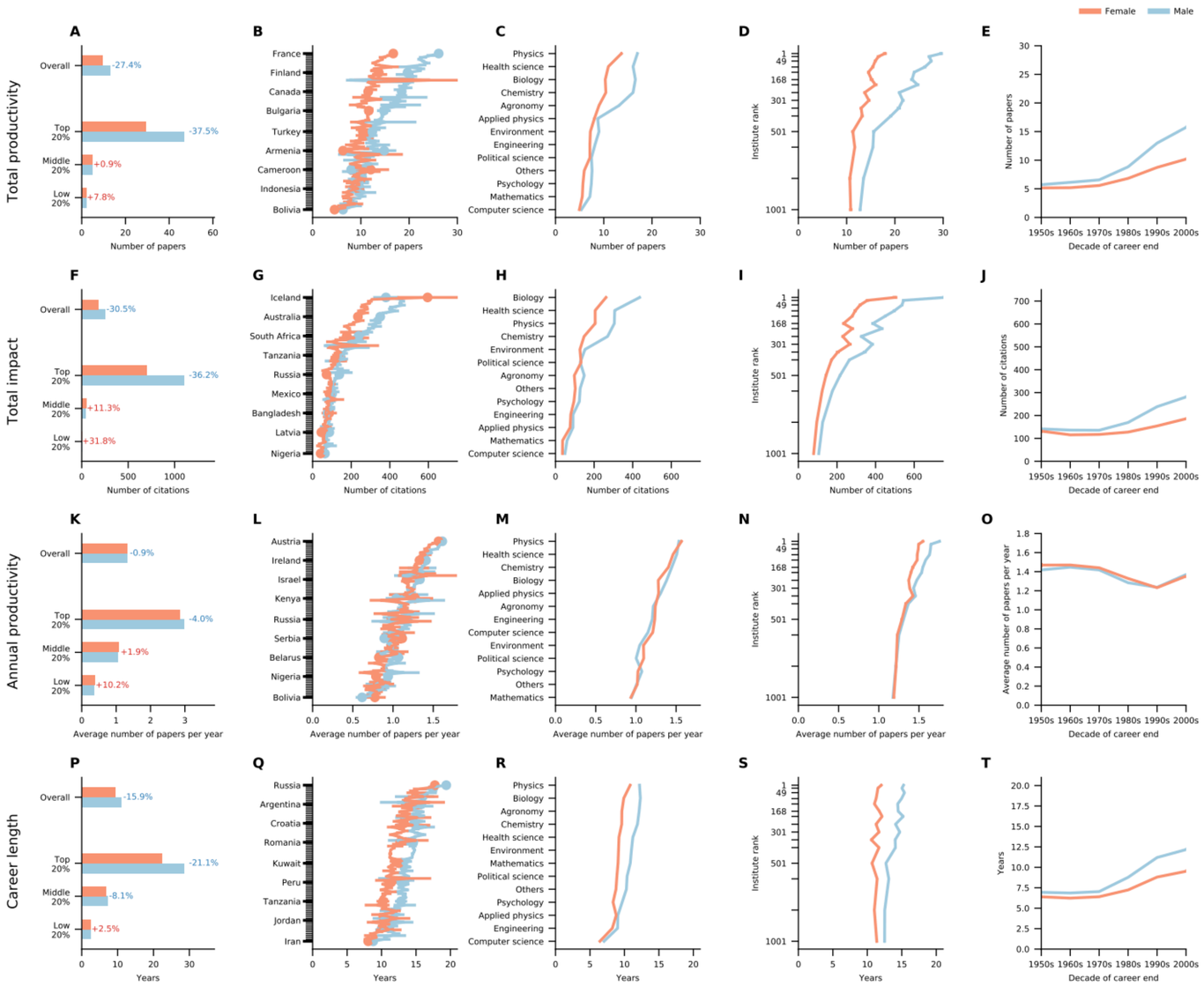
How does impact differ between female and male scientists?

We study careers by gender through time, disciplines and countries



Huang, Gates, Sinatra, Barabasi, *PNAS* 117 (2020)

We found differences for everything!



Huang, Gates, Sinatra, Barabasi, *PNAS* 117 (2020)

Scientific careers and gender

Confounding factors!

Huang, Gates, Sinatra, Barabasi, *PNAS* 117 (2020)

We use a matched sample approach to simulate controlled experiments

25,033 female authors

Maria
American physicist with a career of 10 years,
mostly working at an institute ranked 200th ~ 250th

Angela
Italian mathematician with a career of 15 years,
mostly working at a top-20 institute

Christiana
German psychologist with a career of 30 years,
mostly working at an institute ranked 50th ~ 90th
...

25,033 male authors

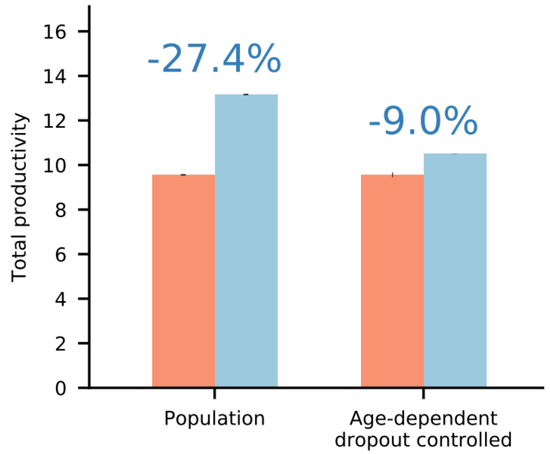
Mario
American physicist with a career of 10 years,
mostly working at an institute ranked 200th ~ 250th

Angelo
Italian mathematician with a career of 15 years,
mostly working at a top-20 institute

Christopher
German psychologist with a career of 30 years,
mostly working at an institute ranked 50th ~ 90th
...

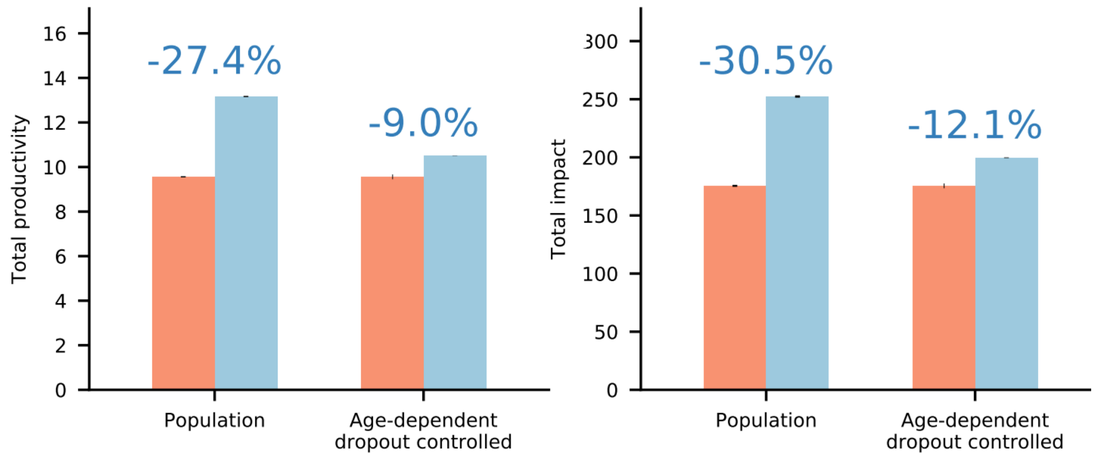
Huang, Gates, Sinatra, Barabasi, *PNAS* 117 (2020)

Gender affects dropout rate, productivity and impact



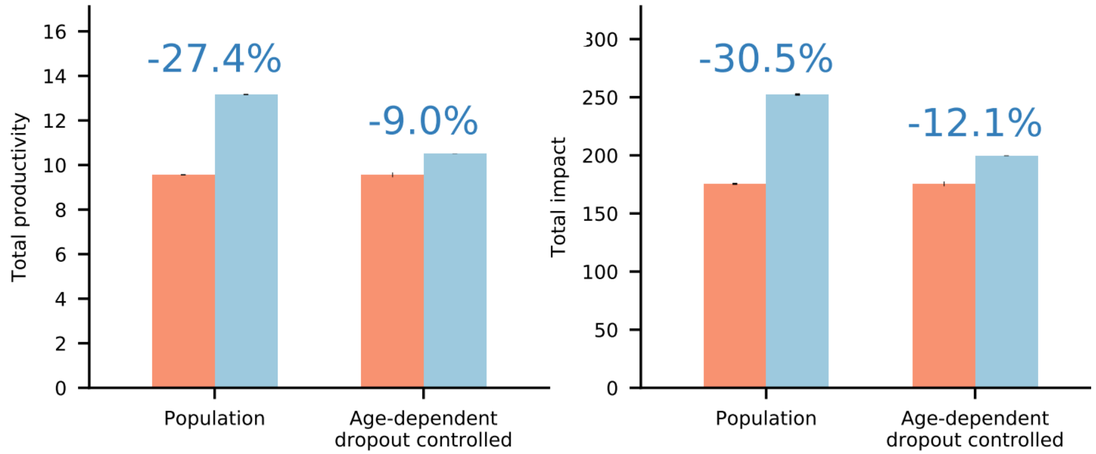
Huang, Gates, Sinatra, Barabasi, *PNAS* 117 (2020)

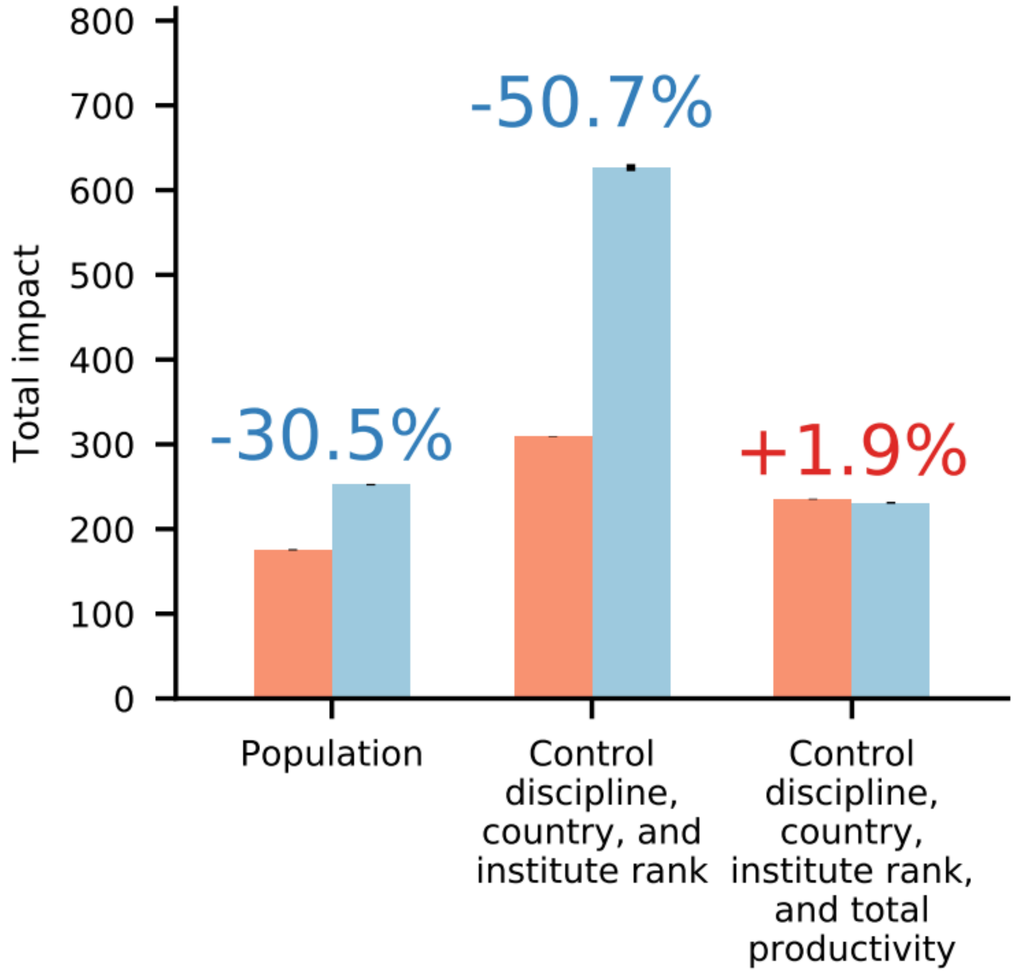
Gender affects dropout rate, productivity and impact



Huang, Gates, Sinatra, Barabasi, *PNAS* 117 (2020)

Gender affects dropout rate, productivity and impact





Huang, Gates, Sinatra, Barabasi, *PNAS* 117 (2020)

How does productivity differ between female and male scientists?

How does impact differ between female and male scientists?

How does productivity differ between female and male scientists?

Only by 9% if we take into account dropout rate

How does impact differ between female and male scientists?

How does productivity differ between female and male scientists?

Only by 9% if we take into account dropout rate

How does impact differ between female and male scientists?

Almost no difference if we take into account confounding factors

Do performance and success in science differ?

Do performance and success in science differ?

They do.

Future direction

Improve the coverage of “the systems”

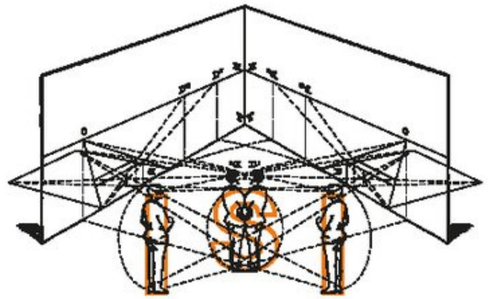
Unbiased data


SUCCESS
92
93
94
95
96
97
98
99
100
101


Performance


Success

IT UNIVERSITY OF COPENHAGEN



Fondazione ISI
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Thank you

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