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Quantifying Scientific Performance and Success in the Physics Community

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14. ABSTRACT
The researchers funded under this grant studied the evolution of impact in scientific careers and discovered (i) the presence of 'hot streaks' in careers, (ii) the effect of luck over individual careers. The researchers also investigated the role of interdisciplinarity in science and found that (i) strongly disciplinary work can have an impact across multiple disciplines, (ii) there exists a measurable chaperone effect, and that reputation is one of the main drivers of artistic impact. Finally research was conducted into gender inequality in scientific careers and a systematic gender gap in productivity was discovered between men and women which can explain the gender gap in impact.

The results of this research have been published in 6 published papers in Science, Nature, and Nature Physics journals and the publication of one book. The research has been featured in the Economist, Wall Street Journal, ArtNet, Quartz, Il Corriere Della Sera and Bloomberg.

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Quantifying Scientific Performance and Success in the Physics Community

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1 September 2015 - 31 August 2019

Project Summary

- Keywords: Scientific Careers, Science of Science, Citation Networks, Scientific Impact
- Objective: Our aim is to understand the fundamental patterns that govern creative impact by analyzing the evolution of career paths and the diffusion and success of new ideas, using large data sets containing key information about creative products.
- Annual Progress: We have studied the evolution of impact in scientific careers, discovering (i) the presence of 'hot streaks' of highly cited papers in individual careers, (ii) modeling the effect of luck over individual careers. We investigated the role of interdisciplinarity in science, finding that (i) strongly disciplinary work can have impact across multiple disciplines, (ii) highlighting a Nobel opportunity for interdisciplinary science (iii) studying in depth interdisciplinary careers of physicists across the different physics subdomains. We have also discovered the Chaperone effect, the process according to which junior We have also studied the evolution of individual careers of arts, finding that reputation is one of the main drivers of artistic impact. Finally, we have investigated gender inequality over thousands of scientific careers across disciplines and countries, finding a systematic gender gap in productivity between men and women, and that this gap fully explains gender gap in impact. Finally we have published a review of the emerging field of Science of Science.

Project Summary

- Overall Progress: Performance and success are often used as synonyms to express individual accomplishment. However, from a scientific perspective they cover very different concepts: performance is about individual effort, while success is a collective quantity capturing the community's acknowledgment of effort and performance. Over the last years, we have investigated the quantitative rules that govern both, trying to model their interdependence within the framework of complex systems. From academia to art and the movie industry, we have explored the universal laws that determine the allocation of merit in science and society. Main breakthroughs include (i) the discovery that the timing of the biggest hit is distributed at random across a scientific career, and (ii) the discovery that successful works come in hot streaks, (iii) a novel way to quantify the importance of academic mentorship ('the Chaperone effect') to publish in top-tier journals and in a new scientific discipline, (iv) that reputation is crucial in art, where early access to prestigious central institutions offers life-long access to high-prestige venues. Taken together, our findings help us unveil the key mechanisms that drive success across creative domains, setting the scientific foundations of the emerging fields of the science of science and the science of success

Project Team

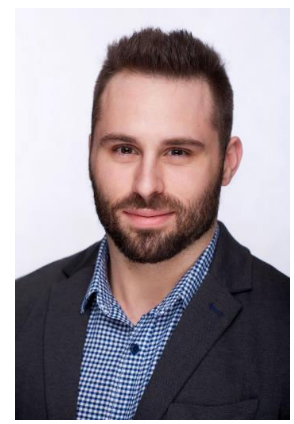
- PI: Albert-László Barabási
- Co-PI: János Kertész, Roberta Sinatra
- Key Researchers: Chulho Choi (postdoc)
- Student: Milán Janosov (PhD candidate)


Albert-László Barabási


János Kertész


Roberta Sinatra


Chulho Choi


Milán Janosov

Activities and Accomplishments: publications and their impact

- 1 paper published in *Science* (2018).
- 1 review paper published in *Science* (2018).
- 1 paper and 1 comment published in *Nature* (2018 and 2019).
- 1 paper published in *PNAS* (2018).
- 1 paper published in *Nature Reviews Physics* (2019).
- 1 paper published in *Nature Physics* (2018).
- 1 manuscript under review on the different evolution of female and male scientific careers in *PNAS*
- 1 manuscript under review in *EPJ Data Science* on the role of luck in scientific careers

- 1 published book: ‘The Formula’, by A.-L. Barabasi.

Activities and Accomplishments: publications and their impact

- In the *Science* paper (Freiberger et al. *Science* 2018), we studied the evolution of artistic careers, and:
    1. Early access to prestigious central institutions offered life-long access to high-prestige venues
    2. We have developed a Markov model that predicts the career trajectory of individual artists and documents the strong path and history dependence of valuation in art
- This research has received considerable attention:
    - It has been featured in more than 20 international venues, including: Economist, Wall Street Journal, ArtNet, Quartz, Il Corriere della Sera, Bloomberg.

RESEARCH

NETWORK SCIENCE

Quantifying reputation and success in art

Samuel P. Fraiberger[1,2], Roberta Sinatra[1,3,4,5], Magnus Resch[6,7], Christoph Riedl[1,2*], Albert-László Barabási[1,3,8,9*]

In areas of human activity where performance is difficult to quantify in an objective fashion, reputation and networks of influence play a key role in determining access to resources and rewards. To understand the role of these factors, we reconstructed the exhibition history of half a million artists, mapping out the coexhibition network that captures the movement of art between institutions. Centrality within this network captured institutional prestige, allowing us to explore the career trajectory of individual artists in terms of access to coveted institutions. Early access to prestigious central institutions offered life-long access to high-prestige venues and reduced dropout rate. By contrast, starting at the network periphery resulted in a high dropout rate, limiting access to central institutions. A Markov model predicts the career trajectory of individual artists and documents the strong path and history dependence of valuation in art.

The Man with the Golden Helmet, an 18th-century painting attributed to Rembrandt, was Berlin's most famous artwork for decades. Once evidence emerged, in the 1980s, that the painting was not by Rembrandt, it lost much of its artistic and economic value, even though the artwork itself had not changed (*1*). Quality in art is elusive; art appeals to individual senses, pleasures, feelings, and emotions. Recognition depends on variables external to the work itself, like its attribution, the artist's body of work, the display venue, and the work's relationship to art history as a whole (*2*, *3*). Recognition and value are shaped by a network of experts, curators, collectors, and art historians whose judgments act as gatekeepers for museums, galleries, and auction houses (*4*). Given the fragmented and often secretive nature of transaction records, quantitative analyses of the art world have been difficult (*5*, *6*). Although artists' reputation is known to affect auction outcomes, our current understanding of these processes is based on small samples spanning short periods and limited to a country or region (*7*–*9*).

Our dataset was collected by Magnus (www.magnus.net) and combines information on artists' tion houses, spanning 143 countries and 36 years (1980 to 2016, fig. S1), allowing us to reconstruct the artistic career of 496,354 artists (see supplementary text S1 for additional description and validation and fig. S1a for an example) (*10*, *11*). The number of exhibitions for an artist followed a fat-tailed distribution; whereas 52% of the artists had one recorded show, a few high-profile artists were exhibited at an exceptional number of venues (fig. S1, c and d). Although half of the auctioned artworks sold for less than $4000, the price for art was as high as $110,500,000 (fig. S1f).

Prestigious institutions have access to well-regarded artists, and influential artists in turn tend to seek out prestigious institutions. Yet, institutional prestige is also highly subjective, determined by factors like history, leadership, resources, and geographic location. Given that major institutions act as art portfolios, we can uncover the slowly changing institutional prestige from frequent artwork exchanges, an approach called "adiabatic approximation" (*12*). For this, we define an order τ coexhibition network, whose nodes are museums and galleries, connected by weighted directed links (i, j) that rep- highly concentrated movement of selected artists between a few prominent institutions. Multiple dense regional communities of institutions in Europe, Asia, South America, and Australia were relatively isolated from the core, indicating that members of these communities share artists mainly among themselves.

A network-based ranking using each institution's eigenvector centrality (*14*) was strongly correlated with known prestige measures (supplementary text S2.4 and fig. S5): (i) $N = 9392$ institutions were independently assigned grades from A to D by a team of experts at Magnus based on criteria including longevity, the artists exhibited, size and quality of exhibition space, and art fair participation. A-rated institutions had high network-based ranking, whereas those rated D were at the bottom half (Fig. 2A). (ii) For each institution, we computed the maximum relative price taken across all the artworks exhibited, observing a high correlation between network-based ranks and economic value of the exhibited artists artworks (Fig. 2B). The top 10–ranked institutions had the highest cumulative sales values (Fig. 2C and fig. S6), indicating that the coexhibition network, though its construction is agnostic to price, identified institutions that have access to highly valued artists. In general, an institution's geographic distance to one of the 10 largest hubs showed no relationship with prestige (fig. S7, a and b). By contrast, the network-based distance of an institution to one of the top 10 institutions was closely linked to its prestige (fig. S7, c and d). Thus, network effects play a defining role in influencing the evolution of an artist's reputation and valuation.

To show that artistic careers can be interpreted within the context of the institutions to which they have access, we grouped artists by the average prestige of their first five exhibits. We assigned an artist a high initial reputation if her work was on average exhibited in the top 20% of institutions as defined by network ranking; an artist had low initial reputation if his work was shown on average in the bottom 40% (supplementary text S3.1). A decade after their fifth exhibit, 39% of the high-initial reputation artists continued to exhibit (Fig. 2D). For low-initial reputation artists, only 14% remained active 10 years later. Next, we selected 31,794

Activities and Accomplishments: publications and their impact

- In the *Nature* paper (Liu et al. *Nature* 2018), we have discovered the 'hot streak' phenomenon in creative careers, that is:
    1. hit works within a career show a high degree of temporal regularity, with each career being characterized by bursts of high-impact works occurring in sequence.
    2. We demonstrate that these observations can be explained by a simple mechanistic hot-streak model, allowing us to probe quantitatively the hot streak phenomenon governing individual careers.
- This research has received considerable attention:
    - It has been featured in more than 30 international venues, including: Daily Mail, The Times, Wired, Quartz, Bloomberg, Spiegel, CNBC, Quartz

LETTER

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Hot streaks in artistic, cultural, and scientific careers

Lu Liu[1,2,3], Yang Wang[1,2], Roberta Sinatra[4,5,6], C. Lee Giles[3,7], Chaoming Song[8] & Dashun Wang[1,2,9]*

The hot streak—loosely defined as 'winning begets more winnings'—highlights a specific period during which an individual's performance is substantially better than his or her typical performance. Although hot streaks have been widely debated in sports[1,2], gambling[3–5] and financial markets[6,7] over the past several decades, little is known about whether they apply to individual careers. Here, building on rich literature on the lifecycle of creativity[8–22], we collected large-scale career histories of individual artists, film directors and scientists, tracing the artworks, films and scientific publications they produced. We find that, across all three domains, hit works within a career show a high degree of temporal regularity, with each career being characterized by bursts of high-impact works occurring in sequence. We demonstrate that these observations can be explained by a simple hot-streak model, allowing us to probe quantitatively the hot streak phenomenon governing individual careers. We find this phenomemon to be remarkably universal across diverse domains: hot streaks are ubiquitous yet usually unique across different careers. The hot streak emerges randomly within an individual's sequence of works, is temporally localized, and is not associated with any detectable change in productivity. We show that, because works produced during hot streaks garner substantially more impact, the uncovered hot streaks fundamentally drive the collective impact of an individual, and ignoring this leads us to systematically overestimate or underestimate the future impact of a career. These results not only deepen our quantitative understanding of patterns that govern individual ingenuity and success, but also may have implications for identifying and nurturing individuals whose work will have lasting impact.

produced in each career. In a sequence of N works by an individual, we denoted with N^* the position of the highest-impact work within a career, N^{**} the second highest and N^{***} the third. We found that each of the three highest-impact works was randomly distributed among all the works produced by an individual (Extended Data Fig. 1a–c), offering strong endorsement for the random impact rule[10,18,21].

However, as we show next, the randomness in individual creativity is only apparent, because the timing between creative works follows highly predictable patterns. We measured the correlation between the timing of the two biggest hits within a career, and compared it with a null hypothesis in which N^* and N^{**} each occured at random. The normalized joint probability, $\phi(N^*, N^{**}) = P(N^*, N^{**})/(P(N^*)P(N^{**}))$, is substantially overrepresented along the diagonal elements of matrices (Fig. 1a–c), demonstrating that N^* and N^{**} are much more likely to colocate with each other than would be expected from the random impact model across three domains. The diagonal pattern disappears if we shuffle the order of works within each career, thereby breaking the temporal correlations (Extended Data Fig. 1j–r).

To quantify the temporal colocation of hits observed in Fig. 1a–c, we calculated the distance between the two highest-impact works for every individual, measured by the number of works produced in between, $\Delta N = N^* - N^{**}$. We compared $P\left(\frac{\Delta N}{N}\right)$ of real careers with $P_S\left(\frac{\Delta N}{N}\right)$ of shuffled careers by defining $R\left(\frac{\Delta N}{N}\right) = P\left(\frac{\Delta N}{N}\right) / P_S\left(\frac{\Delta N}{N}\right)$. For artists, directors, and scientists, all $R\left(\frac{\Delta N}{N}\right)$ exhibit a clear peak centring around zero and decay quickly as ΔN deviates from zero (Fig. 1d–f). Notably, $R\left(\frac{\Delta N}{N}\right)$ is mostly symmetric around zero (Fig. 1d–f), indicating that the biggest hit is equally likely to arrive before or after the

Activities and Accomplishments: publications and their impact

- In the *Nature* comment (Gates et al. *Nature* 2019), we discovered the 'hot streak' phenomenon in creative careers, that is:
  1. Papers published by Nature are more disciplinary than papers in the general literature. To get into Nature, the paper needs to be grounded in deep expertise. By contrast, the impact of Nature papers has been more interdisciplinary— thanks to the broader readership it attracts.
  2. Cross-disciplinarity emerges when a disciplinary paper impacts other disciplines. In recent decades crossdisciplinarity has declined. As works draw on a broader set of disciplines, there is less scope to influence a set of completely different disciplines.

Nature's reach: narrow work has broad impact

Alexander J. Gates, Qing Ke, Onur Varol and Albert-László Barabási

A scientific paper today is inspired by more disciplines than ever before, shows a new analysis marking the journal's 150th anniversary.

How knowledge informs and alters disciplines is itself an enlightening, and vibrant field[1]. This type of meta research into new findings, insights, conceptual frameworks and techniques is important, among other things, for policymakers who fund research in the hope of tackling society's most pressing challenges, which inevitably span disciplines.

Since its founding in 1869, *Nature* has offered a venue for publishing major advances from many fields. To mark its anniversary, we track here how papers cite and are cited across disciplines, using data on tens of millions of scientific articles indexed in Clarivate

a narrower range of disciplines than does the average paper. Usually, however, *Nature* papers are cited by a broader range of disciplines than average.

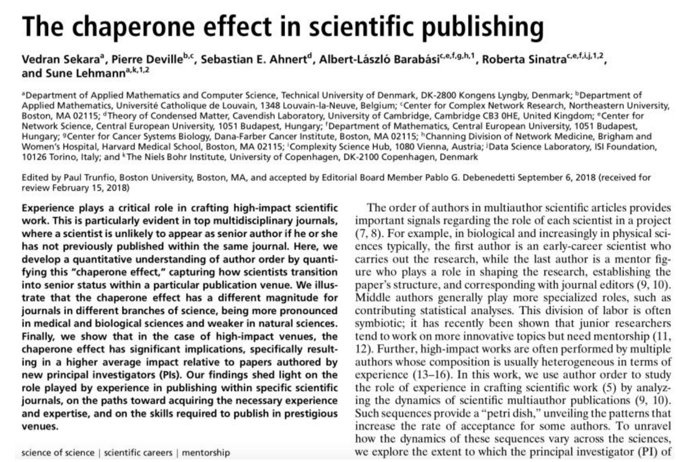
Colossal corpus

We extracted references for papers contained in the WoS publication database from 1900 to 2017, capturing close to 700 million citation relationships. We pinned subsequent analysis to the approximately 19 million articles that had at least one reference and one citation and that were published before 2010 (to give time for citations to accumulate). The resulting corpus integrated the discipline information for 38 million articles.

To identify disciplines, we relied on relatively broad categorizations from WoS. These are necessarily imperfect, but cumulatively reveal patterns of scholarship. Most journals are disciplinary, and so WoS assigns each article to one or more disciplines on the basis of the journal in which it is published. For instance, articles

Activities and Accomplishments: publications and their impact

- In the *PNAS* paper (Sekara et al. *PNAS* 2018), we have discovered the 'Chaperone' effect in scientific publishing, showing the importance of having published with a senior scientists in a top multidisciplinary journal, in order to publish again as senior author in the same venue. In particular, we show that:
  1. the chaperone effect has a different magnitude for journals in different branches of science, being more pronounced in medical and biological sciences and weaker in natural sciences
  2. in the case of high-impact venues, the chaperone effect has significant implications, specifically resulting in a higher average impact relative to papers authored by new principal investigators
- This research has received considerable attention:
  - It has been featured in more than 10 international venues, including: Science Careers, RaiNews



The chaperone effect in scientific publishing

Vedran Sekara[a], Pierre Deville[b,c], Sebastian E. Ahnert[d], Albert-László Barabási[c,e,f,g,h,1], Roberta Sinatra[c,e,f,i,j,1,2], and Sune Lehmann[a,k,1,2]

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Experience plays a critical role in crafting high-impact scientific work. This is particularly evident in top multidisciplinary journals, where a scientist is unlikely to appear as senior author if he or she has not previously published within the same journal. Here, we develop a quantitative understanding of author order by quantifying this "chaperone effect," capturing how scientists transition into senior status within a particular publication venue. We illustrate that the chaperone effect has a different magnitude for journals in different branches of science, being more pronounced in medical and biological sciences and weaker in natural sciences. Finally, we show that in the case of high-impact venues, the chaperone effect has significant implications, specifically resulting in a higher average impact relative to papers authored by new principal investigators (PIs). Our findings shed light on the role played by experience in publishing within specific scientific journals, on the paths toward acquiring the necessary experience and expertise, and on the skills required to publish in prestigious venues.

science of science | scientific careers | mentorship

The order of authors in multiauthor scientific articles provides important signals regarding the role of each scientist in a project (7, 8). For example, in biological and increasingly in physical sciences typically, the first author is an early-career scientist who carries out the research, while the last author is a mentor figure who plays a role in shaping the research, establishing the paper's structure, and corresponding with journal editors (9, 10). Middle authors generally play more specialized roles, such as contributing statistical analyses. This division of labor is often symbiotic; it has recently been shown that junior researchers tend to work on more innovative topics but need mentorship (11, 12). Further, high-impact works are often performed by multiple authors whose composition is usually heterogeneous in terms of experience (13–16). In this work, we use author order to study the role of experience in crafting scientific work (5) by analyzing the dynamics of scientific multiauthor publications (9, 10). Such sequences provide a "petri dish," unveiling the patterns that increase the rate of acceptance for some authors. To unravel how the dynamics of these sequences vary across the sciences, we explore the extent to which the principal investigator (PI) of

Activities and Accomplishments: publications and their impact

- In the *NatRevPhys* paper (Battiston et al. *NatRevPhys* 2019), we take an intellectual census of physics by studying hundreds of thousands physicists' careers on a newly created large-scale dataset. We found that:
    1. the majority of physicists began their careers in only three subfields, branching out to other areas at later career stages, with different rates and transition times.
    2. drastic changes in productivity and impact across fields are attributable to the recent rise of large-scale collaborations, in particular in high-energy physics, and other experimental physics communities.

Taking census of physics

Federico Battiston, Federico Musciotto, Dashun Wang, Albert-László Barabási, Michael Szell and Roberta Sinatra

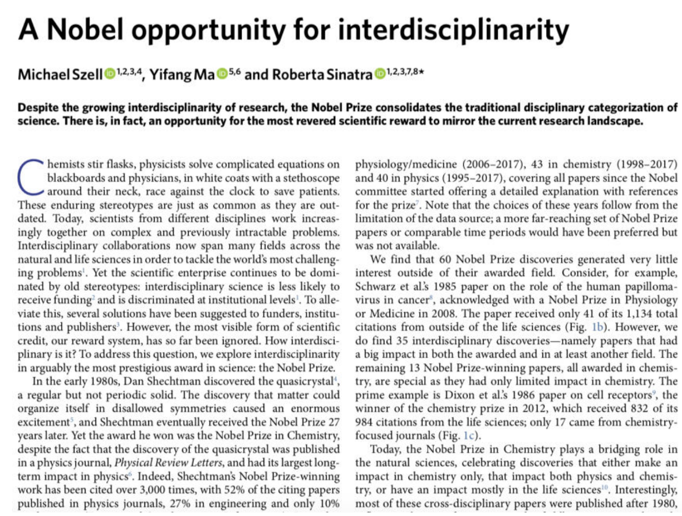
Abstract | Over the past decades, the diversity of areas explored by physicists has exploded, encompassing new topics from biophysics and chemical physics to network science. However, it is unclear how these new subfields emerged from the traditional subject areas and how physicists explore them. To map out the evolution of physics subfields, here, we take an intellectual census of physics by studying physicists' careers. We use a large-scale publication data set, identify the subfields of 135,877 physicists and quantify their heterogeneous birth, growth and migration patterns among research areas. We find that the majority of physicists began their careers in only three subfields, branching out to other areas at later career stages, with different rates and transition times. Furthermore, we analyse the productivity, impact and team sizes across different subfields, finding drastic changes attributable to the recent rise in large-scale collaborations. This detailed, longitudinal census of physics can inform resource allocation policies and provide students, editors and scientists with a broader view of the field's internal dynamics.

There was a time when polymaths such as Galileo Galilei knew all the physics that could be known. Over the centuries, however, the body of knowledge spanned by physics has exploded, encompassing topics as diverse as biophysics, chemical physics

quantitative insights relevant to fundamental scientific processes, such as resource allocation to the exchange of knowledge, revealing quantitative footprints not just for physics but also for its intimate relation with the broader scientific community[4,5].

Activities and Accomplishments: publications and their impact

- In the *NatPhys* paper (Szell et al. *NatPhys* 2018), we show that, despite the growing interdisciplinarity of research, Nobel Prizes have so far awarded to work falling in the traditional disciplinary categorization of science. Our results suggest new categories for the most important scientific award might be needed, and highlight a 'Nobel science' opportunity for interdisciplinarity



A Nobel opportunity for interdisciplinarity

Michael Szell[1,2,3,4], Yifang Ma[5,6] and Roberta Sinatra[1,2,3,7,8*]

Despite the growing interdisciplinarity of research, the Nobel Prize consolidates the traditional disciplinary categorization of science. There is, in fact, an opportunity for the most revered scientific reward to mirror the current research landscape.

Chemists stir flasks, physicists solve complicated equations on blackboards and physicians, in white coats with a stethoscope around their neck, race against the clock to save patients. These enduring stereotypes are just as common as they are outdated. Today, scientists from different disciplines work increasingly together on complex and previously intractable problems. Interdisciplinary collaborations now span many fields across the natural and life sciences in order to tackle the world's most challenging problems[1]. Yet the scientific enterprise continues to be dominated by old stereotypes: interdisciplinary science is less likely to receive funding[2] and is discriminated at institutional levels[1]. To alleviate this, several solutions have been suggested to funders, institutions and publishers[3]. However, the most visible form of scientific credit, our reward system, has so far been ignored. How interdisciplinary is it? To address this question, we explore interdisciplinarity in arguably the most prestigious award in science: the Nobel Prize.

In the early 1980s, Dan Shechtman discovered the quasicrystal[4], a regular but not periodic solid. The discovery that matter could organize itself in disallowed symmetries caused an enormous excitement[5], and Shechtman eventually received the Nobel Prize 27 years later. Yet the award he won was the Nobel Prize in Chemistry, despite the fact that the discovery of the quasicrystal was published in a physics journal, *Physical Review Letters*, and had its largest long-term impact in physics[6]. Indeed, Shechtman's Nobel Prize-winning work has been cited over 3,000 times, with 52% of the citing papers published in physics journals, 27% in engineering and only 10%

physiology/medicine (2006–2017), 43 in chemistry (1998–2017) and 40 in physics (1995–2017), covering all papers since the Nobel committee started offering a detailed explanation with references for the prize[7]. Note that the choices of these years follow from the limitation of the data source; a more far-reaching set of Nobel Prize papers or comparable time periods would have been preferred but was not available.

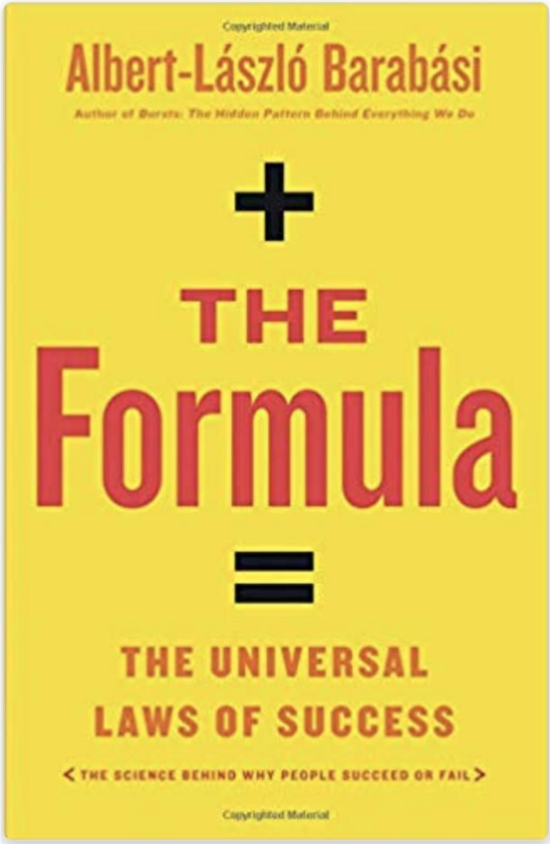
We find that 60 Nobel Prize discoveries generated very little interest outside of their awarded field. Consider, for example, Schwarz et al.'s 1985 paper on the role of the human papillomavirus in cancer[8], acknowledged with a Nobel Prize in Physiology or Medicine in 2008. The paper received only 41 of its 1,134 total citations from outside of the life sciences (Fig. 1b). However, we do find 35 interdisciplinary discoveries—namely papers that had a big impact in both the awarded and in at least another field. The remaining 13 Nobel Prize-winning papers, all awarded in chemistry, are special as they had only limited impact in chemistry. The prime example is Dixon et al.'s 1986 paper on cell receptors[9], the winner of the chemistry prize in 2012, which received 832 of its 984 citations from the life sciences; only 17 came from chemistry-focused journals (Fig. 1c).

Today, the Nobel Prize in Chemistry plays a bridging role in the natural sciences, celebrating discoveries that either make an impact in chemistry only, that impact both physics and chemistry, or have an impact mostly in the life sciences[10]. Interestingly, most of these cross-disciplinary papers were published after 1980,

Activities and Accomplishments: publications and their impact

- In the book *The Formula*, A.-L. Barabási breaks down the secret of success into its main mechanisms and ‘laws’. Barabási approaches the problem of randomness and impact using the state of the art scientific arsenal we have, and uncovers the collective nature of success. Barabási highlights the vital importance of community respect and appreciation when connecting performance to recognition--the elusive link between performance and success. By leveraging the power of big data and historic case studies, Barabási reveals the unspoken rules behind who truly gets ahead and why, and outlines the twelve laws that govern this phenomenon and how we can use them to our own advantage. Unveiling the scientific principles that drive success, the book offers a new understanding of the very foundation of how people excel in today's society.

- The book is available in several languages, and was featured in multiple international venues, including: Bloomberg, Nature, GQ, …



Activities and Accomplishments: publications and their impact

In the *Science review* paper (Fortunato et al. *Science* 2018) we have defined and reviewed the main results of the emerging scientific field of the 'Science of science'

REVIEW

SCIENCE COMMUNITY

Science of science

Santo Fortunato,[1,2]* Carl T. Bergstrom,[3] Katy Börner,[2,4] James A. Evans,[5] Dirk Helbing,[6] Staša Milojević,[1] Alexander M. Petersen,[7] Filippo Radicchi,[1] Roberta Sinatra,[8,9,10] Brian Uzzi,[11,12] Alessandro Vespignani,[10,13,14] Ludo Waltman,[15] Dashun Wang,[11,12] Albert-László Barabási[8,10,16]*

Identifying fundamental drivers of science and developing predictive models to capture its evolution are instrumental for the design of policies that can improve the scientific enterprise—for example, through enhanced career paths for scientists, better performance evaluation for organizations hosting research, discovery of novel effective funding vehicles, and even identification of promising regions along the scientific frontier. The science of science uses large-scale data on the production of science to search for universal and domain-specific patterns. Here, we review recent developments in this transdisciplinary field.

Activities and Accomplishments: Presentations

Several keynotes and plenary presentations on the previously mentioned topics, including:

- Roberta Sinatra: invited talk at Cambridge Network Day, (August 2019, 250 participants), invited talk at the Metascience 2019 Symposium in Stanford (September 2019).
- Laszlo Barabasi (over 50 talks, not tracked)

Technical Highlights: Quantifying the effect of mentorship in scientific publishing

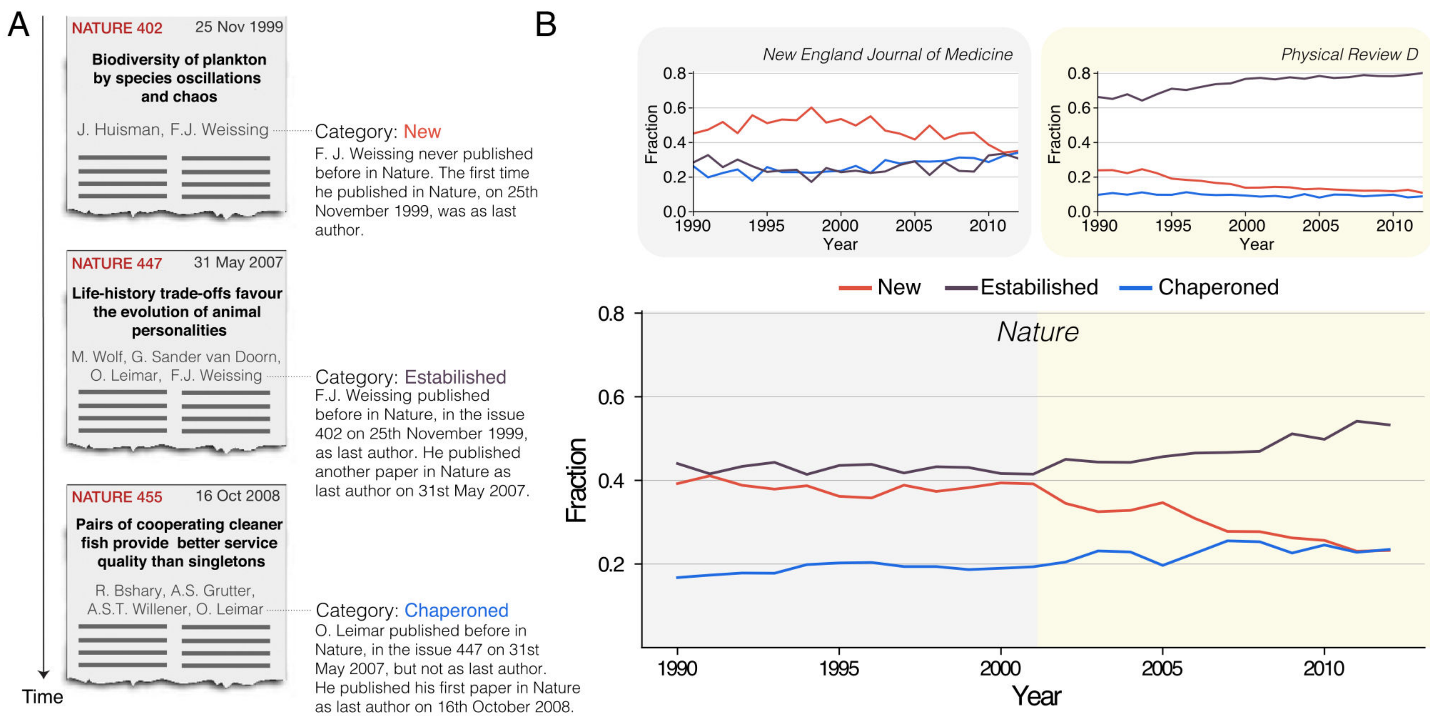


Fig. 1. Probability of being listed as PI in *Nature* given previous publication history. (*A*) Terminology of authors. The last authors of all papers published each year in *Nature* are divided into three categories: new authors that have never published in *Nature* before, chaperoned authors that have published in *Nature* before only at junior level, and established authors that have already previously published as last authors. (*B*) Change in author fractions over time for three journals, displaying different trends over time. While in the *New England Journal of Medicine* (*NEJM*) the proportion of different PIs tends to be equally balanced over time, in *Physical Review D* this proportion tends to become more unbalanced, with the fraction of established PIs increasing.

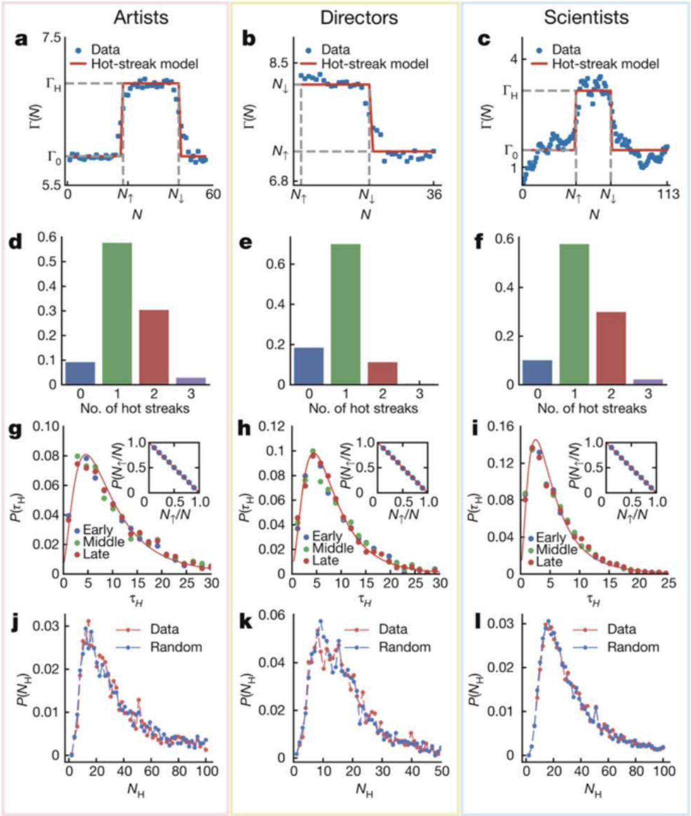
Discovery of the Chaperone effect

Sekara, Deville, Ahnert, Barabási, Sinatra, Lehmann
PNAS, 50 (115), 12603-12607 (2018)

Technical Highlights: Quantifying the evolution of creative careers

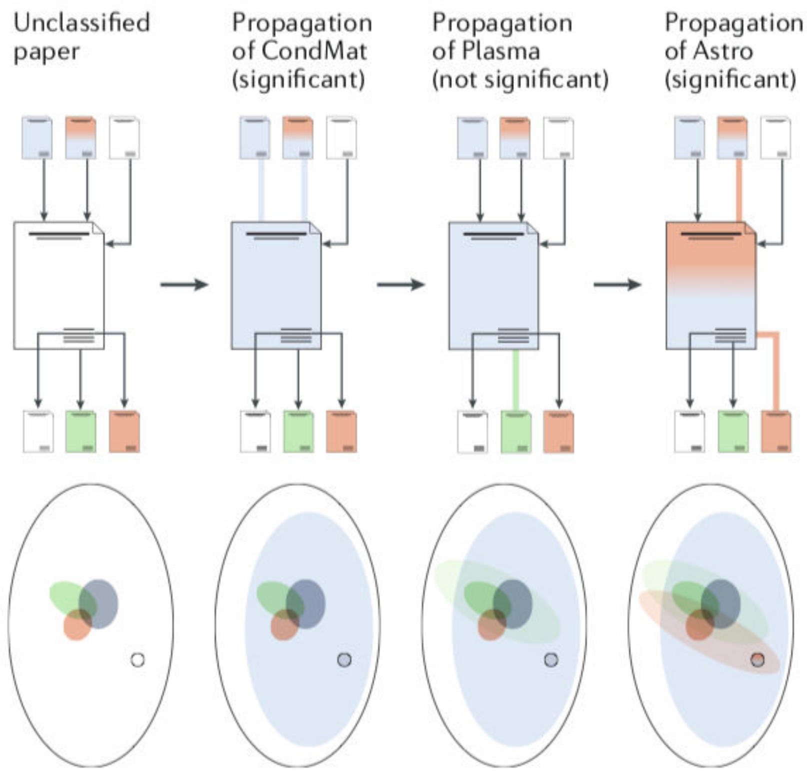
Discovery of the Hot-Streak phenomenon

The hot streak emerges randomly within an individual's sequence of works, is temporally localized, and is not associated with any detectable change in productivity. They can be described with a simple mechanistic model



Liu, Wang, Sinatra, Giles, Song, Wang Nature, 559, (7714), 396 (2018)

echnical i hli ht Buildin the lar e t data et of phy ic career



Identifying subfields

We classify papers into nine subfields on the basis of the 1-digit Physics and Astronomy Classification Scheme (PACS) by the American Institute of Physics[7]:

- General: Mathematical Methods, Quantum Mechanics, Relativity, Nonlinear Dynamics and Metrology
- HEP (high-energy physics): Physics of Elementary Particles and Fields
- Nuclear: Nuclear Structure and Reactions
- AMO: Atomic and Molecular Physics
- Classical: Electromagnetism, Optics, Acoustics, Heat Transfer, Classical Mechanics and Fluid Dynamics
- Plasma: Physics of Gases, Plasmas and Electric Discharges
- CondMat (condensed matter physics): Structural, Mechanical and Thermal Properties, Electronic Structure and Electrical, Magnetic and Optical Properties
- Interdisc: Interdisciplinary Physics and Related Areas of Science and Technology
- Astro: Astrophysics, Astronomy and Geophysics

PACS codes were consistently used in 435,772 papers published in the journals of the American Physical Society (APS) between 1985 and 2015 (Supplementary Section 2). Using an algorithm that evaluates the patterns of citations and references among papers, we propagate subfield labels from APS papers to other papers: if the fraction of references and citations between a given paper and papers in a particular subfield is larger than expected by the null model, the paper is assigned to that subfield. A paper may be assigned to multiple subfields, in line with APS papers reporting multiple PACS codes. As a hypothetical example, we consider a paper that references papers in CondMat, Plasma and Astro and that is cited by CondMat, Astro and another publication still lacking a PACS code (see the figure, part **a**). The publication is first assigned to CondMat and then to Astro but not to Plasma, because it lacks statistically significant links to the subfield. The algorithm is run iteratively until convergence for each subfield, helping us associate at least one subfield to 1,137,670 papers

Battiston, Musciotto, Wang, Barabasi, Szell, Sinatra, Nature Reviews Physics, (1) 1 89-97 (2019)

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Publications

1. Science of Science
   S. Fortunato et al. (including R. Sinatra and A.-L. Barabá i)
   Science, **359**, (6379), eaao0185 (2018)
2. Hot streaks in artistic, cultural, and scientific car rs
   L. Liu et al. (including R. Sinatra)
   Nature, **559**, (7714), 396 (2018)
3. A Nobel Opportunity for Interdisciplinarity
   M. Szell, Y. Ma and R. Sinatra,
   Nature Physics, **14** (11), 1075-1078 (2018)
4. Quantifying reputation and success in art
   S.P. Fraiberger, R. Sinatra, M. Resch, C. Riedl, A.L. Barabási
   Science, **362**, (6416), 825-829 (2018)
5. The chaperone effect in scientific publishing
   V. Sekara et al. (including R. Sinatra and A.-L. Barabási)
   PNAS, **115**, (50), 12603-12607 (2018)
6. Taking census of physics
   F. Battiston et al. (including R. Sinatra and A.-L. Barabási)
   NatRevPhys, **1**, (1), 89-97 (2019)
7. Nature's reach: narrow work has broad impact
   A.J. Gates, Q. Ke, O. Varol, A.L. Barabási
   Nature, **575**, (7781), 32-34 (2019)
8. Historical comparison of gender inequality in scientific careers acro countrie an discipline
   J. Huang, A.J. Gates, R. Sinatra, A.L. Barabási
   preprint (2019)
9. The fate of research fields: Statistical analysis of co-citation networks
   C. Choi and J. Kertész
   preprint (2019)
10. Success and luck in creative careers
    M. Janosov, F. Battiston, R. Sinatra
    preprint (2019)

Other Topics/Issues

- Have you met, collaborated, or discussed your research with anyone from the U.S. (academic, military, or government)?
  - With multiple individuals, including Prof. Dashun Wang (Northwestern University, Chicago), Prof. Brian Uzzi (Northwestern University, Chicago), Prof. Santo Fortunato (Indiana University, Bloomington), Prof. Alessandro Vespignani (Northeastern University, Boston)
- Do you have ideas for future research?
  - We are continuing towards understanding better the gender bias in academic settings, and plan to submit an application for funding to AFOSR early in 2020 to support this work. We are also working on research related to the emergence of high impact works across disciplines.