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Is science getting less disruptive — and does it matter?

A finding that papers and patents that change the course of science are becoming less dominant is prompting soul-searching on the nature of the modern scientific enterprise.

The influential twentieth-century physicist and philosopher Thomas Kuhn was instrumental in formulating the term 'paradigm shift' to characterize how unexpected evidence can set research fields off in new directions. A paper published in *Nature* last month by the social scientists Michael Park, Erin Leahey and Russell Funk has prompted lively debate by suggesting that the proportion of disruptive papers and patents has been decreasing over time[1].

By analysing more than 60 years of data from bibliometric and patent databases, the authors conclude that it is less likely now than in the mid-twentieth century that any one paper or patent will be 'highly disruptive' — that is, that it will change the course of an entire scientific field. Although the number of new papers and patents the researchers classified as disruptive stayed broadly the same over the period they studied — from 1945 to 2010 — the explosion in research articles, patents and funding in that time means that disruptive science's share of publishing and patenting has been dropping.

Much of the reaction has involved soul-searching about the implications for science if innovation is slowing down, as well as questions about the nature of the modern scientific enterprise itself. This, in turn, is prompting more questions that could become the subject of further analysis.

The study uses a number of measures of disruptiveness. The one that has attracted perhaps the most attention is called the CD index, which is based on citations. As the authors write, "if a paper or patent is disruptive, the subsequent work that cites it is less likely to also cite its predecessors", whereas "if a paper or patent is consolidating, subsequent work that cites it is also more likely to cite its predecessors". In other words, with more consolidation, the same previously disruptive papers continue to be cited.

Single papers do have the potential to disrupt or create fields. One of the best-known examples is James Watson and Francis Crick's model of DNA from 1953, created with the help of Rosalind Franklin's groundbreaking X-ray crystallography work[2,3]. Another is the 1995 discovery by Michel Mayor and Didier Queloz of a planet orbiting a Sun-like star[4] that launched the field of searching for exoplanets.

But new directions also arise from many studies reporting long-running research efforts. Gravitational waves are one example. Much as the paper from the LIGO collaboration reporting the first direct detection of a gravitational wave[5] is itself highly cited, subsequent work has continued to cite work that led up to it. Researchers cite studies for different reasons, and not only to acknowledge previously important work that is being built on. Park and his colleagues do control for some of these things, to better compare disruptiveness today with that several decades ago.

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For this Editorial, *Nature* spoke to a number of scholars who study science and innovation. The paper by Park and his colleagues[1], they say, builds on a pattern identified elsewhere in the specialist literature[6,7], and some are worried by the findings' implications. Science and innovation are drivers of both growth and productivity, and declining disruptiveness could be linked to the sluggish productivity and economic growth being seen in many parts of the world.

Others argue that a decline in the fraction of disruptive science shouldn't cause concern if the absolute number of disruptive studies has remained relatively constant over time. If a greater proportion of publications are consolidating, that could just reflect the current situation: in many disciplines, the fundamentals are agreed on, so most further advances will be incremental, rather than disruptive. No doubt scholars will analyse the importance of these findings using qualitative approaches, such as interviews and observations that capture researchers' own experiences in individual fields, as the sociologist Harry Collins has done from within the LIGO team.

Another reason that the study by Park and his colleagues has created such resonance is that it plays into wider concerns about how science is organized. One of these is whether the division of science into ever-narrower units of knowledge is detrimental to the discovery of new paths. Critics also point to publication incentives and metrics-driven research evaluations, which steer scientific study away from risk-taking as funders, researchers and institutions take the safe option to keep the grant–publication–citation wheel turning. This periodically leads to calls to incentivize more high-risk, high-reward research, and initiatives such as the United Kingdom's Advanced Research and Invention Agency. This is modelled on the US Defense Advanced Research Projects Agency (founded in 1958), so the search for disruptive innovation is not new.

But it is also possible that science's knowledge and publication overload is not specifically a research problem. The lack of space to think in the face of an information deluge is apparent across many sectors of society. Some in innovation studies think that artificial intelligence could help, by sifting and sorting information in meaningful and beneficial ways, aiding researchers in summarizing cutting-edge knowledge in a discipline[8], for example, or identifying which research projects have the potential for breakthroughs[9]. If used appropriately, such technological disruption has the potential to free up more time for scientists to progress their fields — disruptively or otherwise.

Asking questions about the nature of science and reflecting on the answers can only be a good thing. The work by Park and his colleagues must continue to be built on, using both quantitative and qualitative methods, down to the level of individual fields. This will help us to understand in

nature

more detail how and why science is changing, and where we want it to lead. The end result could be disruption or consolidation — or even a paradigm shift.

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We have nothing to fear from the decolonization of mathematics

Maths made the modern world — and everyone stands to gain from the acknowledgment that the world made maths.

What's the point of decolonizing mathematics? This is one of the questions being asked in response to the international decolonizing movement, through which university faculty members and students are exploring the contributions that people from many cultures have made to the story of different research fields.

Such questions have long been central to the study of science's history, but not its teaching. Efforts to address them include works such as maths historian George Joseph's book *The Crest of the Peacock: Non-European Roots of Mathematics* (1991) and the ongoing encyclopaedic series Science Across Cultures, edited by Helaine Selin. But there's been pushback, too, as interest in decolonization has mushroomed in many parts of the world. The debate on decolonizing mathematics is explored in the latest instalment of our series on decolonizing science (see page 183).

Some researchers are concerned that the decolonization movement politicizes universities and restricts academic freedom. One common argument is that decolonization is irrelevant to the practice of mathematics: the solution to a quadratic equation doesn't, after all, depend on a mathematician's identity or protected characteristics.

In fact, such questions reprise aspects of an older, more academically focused debate on whether — or to what extent — scientific knowledge is socially constructed. What is known as pure mathematics is a case in point. Algebra, the method of representing problems in mathematical form, is often taught as a collection of rules to memorize and practise, described using abstract symbols such as *x* and *y*. But it was not always so.

> "Algebra is often described using abstract symbols such as *x* and *y*. But it was not always so."

The word 'algebra' is a contraction of the name of a ninth-century Arabic text, *al-Kitāb al-mukhtaṣar fī ḥisāb al-jabr wa'l-muqābala* (The Compendious Book on Calculation by Completion and Balancing), written by Muḥammad ibn Mūsā al-Khwārizmī, who was born in about AD 780. Al-Khwārizmī was an astronomer, cartographer and mathematician working in Baghdad, in what is now Iraq, during Islam's imperial era. He wrote the book as a kind of public service, to help people work out everyday problems, such as what they were entitled to in inheritance or how much they owed in tax. The text includes worked examples and uses words instead of symbols, along with visual and geometric techniques to make solving problems easier.

Mathematicians from Europe, particularly Fibonacci (born in Italy in around 1170), came across these ideas while travelling in Arabic-speaking countries and helped to extend their geographical reach by presenting them in Latin. Chief among the concepts Fibonacci helped to introduce to Europe was the Indo-Arabic system of numerals we use today. Because many original Arabic texts (including Al-Khwārizmī's algebra book) were later lost, many ideas that originated in the Middle East later found their way back to the region through translations of these Latin texts.

Al-Khwārizmī refers to Indian numerals to acknowledge earlier sources for his methods. The only surviving example of a potential source of this type is the Bakhshali manuscript, a collection of some 70 'pages' of mathematics written on birch-tree bark in a form of Sanskrit. The manuscript has been dated to as early as the third or fourth century AD and is now stored at the Bodleian Libraries at the University of Oxford, UK. It is regarded as the oldest surviving text that uses the concept of zero (represented by a dot). Even today, numbers written in Arabic use a dot to denote zero.

This manuscript also contains descriptions of what would have been everyday mathematical problems at the time, and rules for how to solve them. Among these are linear equations, quadratic equations and means of finding the square roots of numbers. Like Al-Khwārizmī, the unknown writer describes equations using words.

So, to answer the question: what's the point of decolonizing mathematics? It is so we can get a more accurate picture of the subject's origins and development, and the variety of problems it helps to solve. Decolonization shows that the roots of discovery and invention are shared between many world cultures, which can be particularly empowering for people from historically marginalized groups. Decolonizing science is the antidote to exceptionalism, the idea that any single culture or civilization possessed special abilities in advancing science.

The last words must go to the guest editors of *Nature*'s special issue on racism, published in October. "It is so important for science curricula, research and academic spaces to go through decolonization processes. These are not political or ideological acts, but part of science itself — an example of science's self-correcting mechanism in the pursuit of truth."