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New scientific fields are triggered by powerful new methods

Alexander Krauss [1,2]✉

Scientific fields embody our greatest scientific advances, but we do not yet understand how we give rise to new fields. Explaining empirically and theoretically how we kick-start new fields has the potential to accelerate scientific progress. No comprehensive answer to this fundamental question yet exists. Here we systematically trace the origins of science's major fields including over 350 fields spanning across science. We do this by analysing the methods and tools that enabled sparking the fields and link them to the broader conditions of the scientists who created the fields. This provides a unique opportunity to identify the common mechanism driving new fields. We find that fields consistently emerge by developing a new method or tool – from advanced telescopes to electrophoresis – as they enabled a completely new perspective to the world and without them, the fields would not have been possible. About a quarter of fields are the new method or tool themselves, such as laser physics, computer science, x-ray crystallography, and econometrics, forming entire disciplines around novel techniques. Our extraordinary development of new statistical techniques, x-ray devices, microscopes and spectrometers each made over ten new fields possible. The common link uniting these diverse fields is not specific theories, large teams, more funding or even serendipity – it is that each field relied on the same kind of powerful tool, used in remarkably different domains. The speed at which science expands is not random. The pace of opening new research domains is mainly determined by the pace at which we create new tools: particle detectors launched high-energy physics, microscopy techniques triggered neuroscience and randomised controlled trials kick-started experimental economics. This simple yet powerful principle – if we begin to deliberately develop transformative methods and tools – holds the key to enabling a *tool revolution* in science, changing the way we understand and the speed at which we make scientific progress. This methods-driven mechanism can provide a foundation for the field of *Science of Science*. It also points to the need for a new field targeted to the development of methods: *Methodology of Science*.

[1] Spanish National Research Council, Barcelona, Spain. [2] London School of Economics, London, UK. ✉email: alexander.krauss@iae.csic.es; a.krauss@lse.ac.uk

Introduction

Scientific fields embody our vast scientific, medical and technological advances and bodies of knowledge, but we still do not understand well how we develop new fields. This is a key question because unravelling the mystery would enable us to explore entirely new domains. New fields can seem to arise from discoveries that create a new scientific community and body of knowledge. With a closer look, some new fields seem to grow out of established disciplines as a novel specialised branch, such as molecular biology and developmental psychology. Others seem to arise from the integration of two or more fields, such as biophysics or cognitive science. Some seem to emerge as differing approaches within the same domain, such as theoretical and empirical physics and economics. Still others seem to develop as a result of shifting societal or environmental forces, such as telecommunications and climate science. And these different paths can overlap. But what is the force enabling new fields in the first place, which then reflect greater specialisation, integration, differing approaches and adapting to new external conditions? Given the diverse paths, can we identify a unifying explanation of how we give rise to fields? If we could explain and even help predict their emergence, we would not just be passive observers of scientific growth – we could actively develop new research domains and speed up advances.

The most common explanations for how fields emerge are through paradigm shifts in theories (Kuhn 1962/2012, 2022, 1962a), new research programmes (Lakatos 1970) or splitting or merging scientific communities (Sun et al. 2013). But do they actually explain how new fields come about? A highly influential account, by the historian of science Thomas Kuhn, describes fields arising and evolving through fundamental changes in scientific theories, namely paradigm shifts (Kuhn 1962/2012, 2022, 1962a). But many applied fields do not involve a theory. In fact, no new field emerged as a result of the classic paradigm shift from the Ptolemaic earth-centred theory to the Copernican sun-centred theory, or the shift from the theory of continental drift to the theory of plate tectonics to explain large-scale geologic changes. Another influential account argues that major new research programmes lead to new fields (Lakatos 1970). But many research communities – such as those studying new viruses, astronomical objects and global warming mitigation – have expanded our knowledge without spurring distinct new fields. Another influential account argues that scientific communities split or merge through new collaboration networks that can bring about new fields (Sun et al. 2013). But they are largely a result of new fields as an offshoot after or at the time they arise, rather than its driving force. Sociologists also offer explanations for how social movements and conditions can influence the scientific landscape and some disciplines (Frickel and Gross 2005). Yet, each of the proposed explanations is in fact mainly a consequence of new fields rather than their cause – they generally follow rather than precede their emergence.

While researchers have long attempted to explain new fields, research has mainly centred on scientific outputs, such as new theories (Kuhn 1962/2012, 2022) and citation patterns (Clauset et al. 2017; Wang and Barabási 2021; Fortunato et al. 2018; Chu and Evans 2021; Azoulay et al. 2018; Hu 2016; Zeng et al. 2017). And research has also focused on aspects of fields like collaboration networks and productivity (Wu et al. 2019; Wuchty et al. 2007; Li et al. 2020; Uzzi et al. 2013; Rzhetsky et al. 2015; Shi et al. 2015). But are these the most relevant metrics to focus on? In an article in *Science*, researchers challenge this conventional approach: 'Citations, publication counts, career movements, scholarly prizes, and other generic measures are crude quantities at best … and their ability to predict the emergence of a new field or the possibility of a major discovery may be low' (Clauset et al. 2017; cf. Wang and Barabási 2021; Li et al. 2020; Fortunato et al. 2018; Uzzi et al. 2013; Park et al. 2023; Nature Human Behaviour 2022). Yet explaining and better predicting new fields is a central goal of the field of *science of science* – including scientometrics and the history of science (Clauset et al. 2017; Wang and Barabási 2021; Fortunato et al. 2018). So if these standard metrics fall short in capturing the birth of new disciplines, what does capture them?

Achieving this goal requires us to take a completely new approach. Here we shift our attention from commonly studying outputs (especially article citations and theories) to investigating inputs – especially new scientific methods and instruments that enable entirely new perspectives to studying the world. We thus provide an alternative perspective to the common output-orientated focus in existing studies. The idea that we can study the drivers of new fields to identify successful ways to advance science, but that scientific fields have not yet been systematically analysed and linked to their underlying methods and instruments, may seem ambitious. By tracking the origins of science's major fields, including 373 different fields spanning across science, and the method innovations that enabled them, we show that this alternative approach is attainable – and may be the best strategy we have to understand how we develop new fields and how we can do so faster. Addressing this central question, this is the first study to explain how fields arise by linking them to the methods used to make them, and the broader conditions behind the scientists kick-starting the fields.

A striking pattern emerges: we find that about one hundred new methods and instruments that won a Nobel prize have opened new fields, such as x-ray crystallography, electron microscopy, quantum computing, mass spectrometry, climate modelling, laser spectroscopy, phase-contrast microscopy and econometrics. Each of these is a powerful new method or instrument, each earned a Nobel prize and each is the foundation of the new field it triggered – fundamentally reshaping the way we explore the world. Take the electron microscope, developed in 1933. This pioneering instrument does not just vastly magnify objects, it helped unlock an entirely new domain of biology: modern cell biology. The maser, invented in 1954 as the precursor to the laser, laid the foundation for new fields: laser spectroscopy and quantum electronics. X-ray crystallography methods, created in 1913, gave rise to molecular biology.

Exploring the birth of fields, we find a common pattern across them: whenever a scientific community undergoes a major change in the way it understands the world, it is preceded by a major methodological change in the way we study, measure and theorise about the world that was previously not possible. Yet not every new method innovation triggers new fields. So we also assess the important question: why do some major method discoveries establish new fields while others do not? This requires comparing an experimental and control group that consists of major method discoveries that developed into new fields and others that did not. We do so here with the aim of identifying factors related to major method discoveries that sparked new fields.

The main contribution here to the existing literature is identifying the common mechanism that explains how new fields arise that they consistently share in common: a new method or instrument that is applied to make the field possible. Beyond new tools, there are supporting factors that can help influence when a field emerges – such as funding (Stephan 2015), collaborations (Wu et al. 2019; Wang and Barabási 2021), greater productivity (Jones et al. 2014), greater levels of education (Chan and Torgler 2015), paradigm shifts in theories (Kuhn 1962/2012), moments of serendipity (De Rond and Morley 2010; Popper 1959/2005) and developments in other fields – but they cannot directly spark a field on their own. The role of these other factors varies by topic, subject area and researcher. Yet without tools, we cannot generally develop and test theories, and factors like additional funding and collaboration are not directly helpful. It is with new tools – which spark new perspectives – that we can better explain the emergence of new fields that directly follow their development, rather than with existing accounts. Identifying this powerful mechanism is the first step. The second step requires tackling the question of how we can extend our tools of science and create entirely new ones to push the research frontier. Answering this question is the key to more efficiently advance science, and we offer an answer in the final section that outlines the pathways we can take to expand our scientific tools. Providing empirical evidence and a theoretical explanation, we highlight the need for a new field that studies and explains how new methods trigger new scientific advances and how to develop and refine new methods – which we call *Methodology of Science*. A central implication is that to make new fields more rapidly and more predictable, we need to allocate a greater share of existing scientists and existing resources to target the creation of new methods and instruments.

Methods and data

We collect data for the scientists who opened science's major fields, including 373 different fields. We cover science's major fields across the physical, life and social sciences – from physics, chemistry and biology to psychology, economics, anthropology and computer science. We verified that all fields in the paper return via Google Scholar a minimum of 25 results by searching 'field of x' (e.g. 'field of chemistry' or 'field of genetics'), with most generating hundreds or thousands of results. To ensure all fields are recognised fields, we took several steps. First, we included all scientific fields that emerged directly from all nobel-prize-winning research in science – namely, new fields recognised in the prize motivation or opened by scientists who earned the prize (Nobel Prize 2024). These account for 257 fields. The Nobel prize is viewed as the most renowned award in science for the greatest achievements. These fields do not reflect disciplines developed before the Nobel prize was first awarded in 1901 or that did not receive the prize. So secondly, to be as comprehensive as possible, we also included all fields since 1500 pioneered by scientists featured in science textbooks that list the world's 100 greatest scientists and span across disciplines and history, with a total of seven textbooks published and incorporated (Tiner 2022; Salter 2021; Gribbin 2008; Rogers 2009; Simmons 2000; Balchin 2014; Haven 2007). These account for 116 other fields. This adds up to 373 fields and we then verified that the scientists who opened the fields are described in scientific publications as the 'founder', 'father' or 'mother' of the discipline. The data here on major method discoveries that opened fields enables comparing an experimental group (nobel-prize and major non-nobel prize method discoveries that led to new fields) to a control group (the remaining nobel-prize and major non-nobel-prize method discoveries that did not lead to a new field) – from the same data sources.

We cover *fields established at universities* – with each confirmed as a department, institute, centre or school within universities. These account for 213 of the 373 fields (such as cognitive science, astrophysics and microbiology). We focus in the paper on these established fields. As doing so does not include emerging and smaller fields, we conduct an additional analysis that covers *fields not established at universities* but have scientific communities and research programmes and each still returned via Google Scholar a minimum of 25 results by searching 'field of x' (e.g. 'field of porphyrin chemistry' or 'field of phage genetics' as described in the above mentioned publications). Most of these fields also returned hundreds or thousands of results, though younger fields generally return fewer hits. These account for 160 of the 373 fields. In the appendix, we include an additional analysis of these fields not (yet) fully established to broaden the study's scope and provide an additional control group and robustness check for validating the results. We thus cover the natural and social sciences, and not humanities and professions, such as education and public policy. Each discipline is defined as a separate field or subfield – for example, the emergence of modern physics, then particle physics and later laser physics each have their own data point. The complete list of fields is provided in the supplementary material.

What defines a scientific field? A field is commonly defined by shared research topics, methods and tools, a scientific community and at times theoretical models (cf. Schizas 2016). The *first* publication that triggered each field is the main source for compiling the data. The central method or instrument used in opening a field is defined as a major method or instrument applied in that given publication and commonly highlighted by the authors as central to the study – and made the field possible. When a field emerged is established by the year the first article that kick-started the development of the new field was published, and when a central method was developed is also established by the year it was published. Other features of the scientists who opened fields – including their level of education, university, geographic location, gender and age – are collected to test the role of their influence. These data are collected from six encyclopaedias of science (Encyclopaedia Britannica 2023; Daintith 2009; Bunch 2004; Oakes 2007; Simonis 1999; Lerner and Lerner 2004), official Nobel Prize (2024) documentation, and the seven indicated science textbooks. More detail for a given variable is provided when introduced. Methods are defined as systematic techniques (such as statistical methods and controlled experimental methods) and instruments are systematic tools (such as radar telescopes and centrifuges) that are used to study the world and extend our ability to observe, measure and analyse, and are general-purpose (applicable in different contexts). They do not refer to cognitive abilities like observation and hypothesising, or theoretical frameworks.

To assess how new methods and instruments open new fields, we apply descriptive and inferential statistics, and the data are compared across different disciplinary areas and time periods. We analyse the demographic, institutional and geographic features of the scientists who opened new fields, and conduct network analysis and regression analysis. Details of each analysis are provided when introduced.

Results and discussion

The powerful role of new methods and instruments in launching new scientific fields. When we open up and read the papers that kick-started new fields across science, we find that each paper consistently relied on a new method or tool that provided a new lens. So to examine how established fields since 1500 emerged, we first trace the year a new method or tool was created by the year the field arose using it. Each new method or instrument is reflected by a vertical line (|) and each field that emerged using it is reflected by a dot (●). Multiple new fields at times were triggered by a new scientific tool – represented by multiple dots on the same horizontal line. Newly made fields bundle together after we create the needed methods or instruments. Think of for example the development of femtosecond spectroscopy in 1985 (shown as a vertical line |) that led the Egyptian Ahmed Zewail to open the field of femtochemistry in 1988 (shown as a dot ●). This pioneering instrument enables us

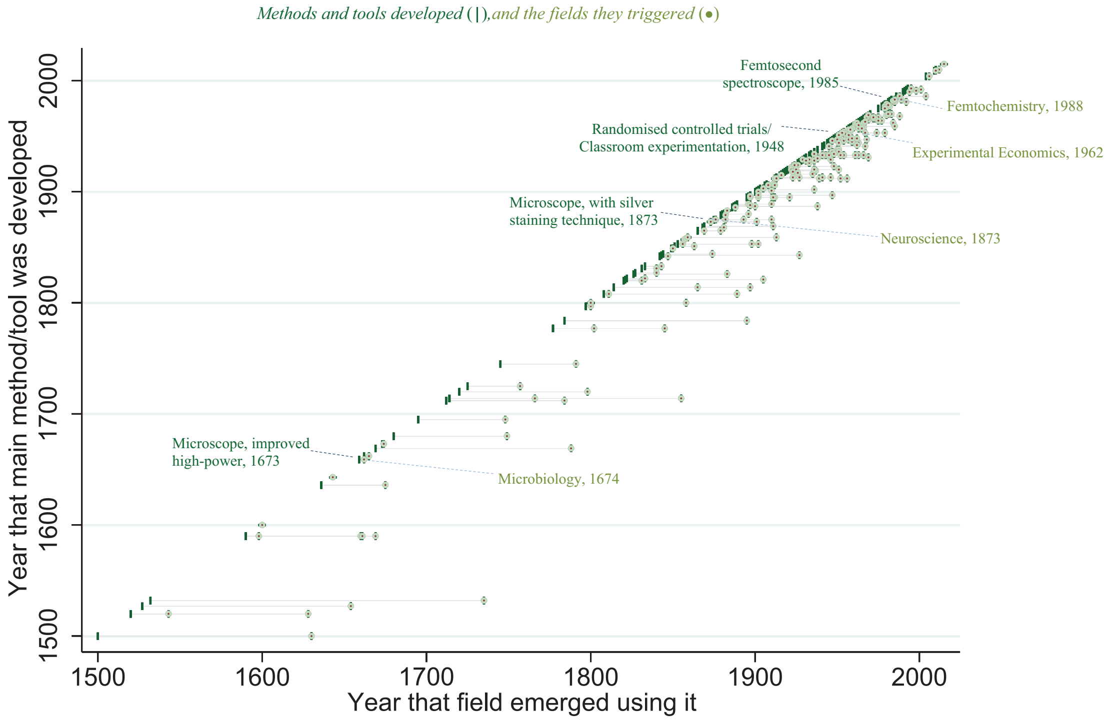

Fig. 1 New scientific fields emerge through newly developed central methods and tools. Data reflect 213 established fields developed since 1500 and the methods and instruments that enabled these fields – with four examples illustrated.

to much better understand chemical reactions on very short timescales – mere quadrillionths of a second – using lasers. Think of the creation of the microscope with the silver staining technique in 1873 that made it possible for the Italian Camillo Golgi and Spaniard Santiago Ramón y Cajal to launch the field of neuroscience that same year. This trailblazing technique revealed the first images of our nerve cells and enabled better understanding the structure of our nervous system. Think of the invention of a new 270-power microscope in 1673 – capable of observing objects just one-millionth of a meter in length – that led the Dutch Anton van Leeuwenhoek to give birth to the field of microbiology in 1674 (as illustrated in Fig. 1). For the first time in history, we could study the invisible world of bacteria. New microscopic techniques, like new spectroscopes and controlled experimental methods, are representative of how new fields arise after creating the necessary scientific tools – and without them, they would not have been possible.

We uncover a strong and direct link between new tools and the birth of new fields: examining the publications that kick-started the 373 new fields shows that each new field – one that studies and measures an unexplored part of the world – consistently begins by adopting a groundbreaking new method that enables studying and measuring the world in a new way. A *new* tool means it is used for the first time ever for a particular problem and provided the new needed lens.[1] Regressing the year the field emerged on the year the particular method was created (without other controls) yields an R-squared of 0.94, among the 213 established fields developed since 1500. That is, the year methods are created is closely correlated with the year subsequent fields emerge (94% of the variation), as seen in Fig. 1.

Some tools spark new fields almost instantly, while others lie dormant for decades before scientists pick up on the tool's potential. This relationship is mapped out here, where the length of each horizontal line reflects the time between the method's invention and the field it enabled. We can observe that there are often longer time lags (Fig. 1). Two striking trends emerge: the lag between the two – new methods leading to new fields – is shrinking over time, and the rise of new fields and bodies of knowledge is not slowing down (Appendix Fig. 1).

We uncover a very strong pattern here. We find that the ten central methods and instruments most commonly used in nobel-prize-winning advances each kick-started five or more fields – in ways their inventors never anticipated: new statistical and mathematical methods gave rise to fields such as experimental economics and empirical finance. Spectrometers launched fields such as molecular spectroscopy and exoplanetary science. Electron microscopes triggered fields such as modern cell biology and electron microscopy. X-ray methods gave birth to fields such as molecular biology and x-ray crystallography. Particle accelerators and detectors paved the way for fields such as high-energy physics and solid-state physics. Chromatography enabled fields such as organocatalysis and signal transduction. Centrifuges kick-started fields such as enzymology and centrifugation. Electrophoresis enabled fields such as DNA sequencing and proteomics. And lasers sparked fields such as laser physics and laser spectroscopy. Beyond these top ten tools, others – such as geiger-müller counters and game theory methods – have also given birth to at least five fields. These powerful, general-purpose tools explain most scientific progress because they each enable us to access a part of the world otherwise out of our scope. *A powerful insight emerges from the fact that each of these tools kick-started multiple fields: what links these diverse fields is not a particular theory, research team, more funding or even serendipity —it is that each relied on the same powerful tool, used in remarkably different domains.*

Surprisingly, none of these major tools was specifically developed to open these fields but they each still sparked multiple fields. They triggered new fields in different disciplinary areas that were not expected or foreseen by the inventors of these tools. For many such fields, establishing that the new method (the independent variable) had no initial relationship to the new field it enabled (the outcome) helps isolate the causal effect of the independent variable in driving the outcome. It also helps reduce alternative explanations – confounding variables such as funding, teams and institutional structures as the key triggers – as the necessary tools were already invented. Using quasi-experimental reasoning, *this lack of an initial relation to the outcome (new fields) is important in understanding the causal effect of method innovations in opening new research domains as they were not intentionally designed for that purpose but still brought about the new fields by providing the new perspective*. The fact that entirely new domains of research emerged from tools designed for other purposes highlights an important insight about scientific progress: new fields commonly come from the unexpected power of new tools. Without them, the new fields would not be possible. This unforeseen link between the two is key to understanding how science unfolds. Expanding our *scientific toolbox* opens new fields by enabling us to perceive and understand the world in entirely new ways, by enabling us to ask and answer completely new questions.

If we focus on outcomes in studying how fields emerge – like major new paradigm shifts in theories, research programmes, splitting or merging scientific communities, or even accumulated citations – we fall short in explaining the birth of disciplines. For these outcomes generally only *arise at or after their emergence*. But new tools, in contrast, can in fact explain and help predict new fields because they must *arise before their emergence* and be applied to kick-start them. This gives us a different way to think about this relationship: we need to track both the baseline (when tools are born) and the endline (when fields are born). Consider how randomised controlled trials designed in 1948 for clinical medicine (BMJ 1948) foreshadowed the eventual (or inevitable) rise of experimental economics. This new branch of economics took shape when Vernon Smith (1962) adopted such experimental methods in economics with his paper *An Experimental Study of Competitive Market Behavior*. It took over a decade to apply such methods as researchers are not generally aware of and trained in methods in related fields. With the creation of modern statistics and biostatistics in 1925 (Fisher 1925), it could be predicted that the field of econometrics (statistical analysis in economics) would eventually emerge which took off in 1933 (Frisch and Waugh 1933). With the invention of the digital electronic computer in the 1940s and 1950s, it could be predicted that computer science would eventually arise which did in the 1950s.

Fields that have emerged from nobel-prize-winning research using the first five of the top ten methods and instruments in science outlined above are shown in Fig. 2. The first particle detector that visualised particle tracks, built in 1911, for example gave birth to high-energy physics. Charles Wilson's groundbreaking 1911 paper *On a method of making visible the paths of ionising particles through a gas* was published in the Proceedings of the Royal Society. The field then rapidly expanded with the creation of more advanced detectors, and also particle accelerators since 1929. These enable us to understand the nature of the particles that make up the building blocks of matter and our physical world. Creating NMR spectroscopy in 1946 launched the fields of MRI and protein NMR spectroscopy. This helps us decode the structure and dynamics of proteins and develop life-saving medical drugs (see Fig. 2) (cf. Nobel Prize 2024).

An improved cathode-ray oscillograph developed in 1922 gave birth to the field of neurophysiology, helping unravel how our nervous system functions and diagnose and treat neurological diseases. Game theory methods, initially conceived in 1928 and expanded in 1950 with Nash equilibrium, led to information economics – a field that explains how information impacts our decisions and economy. The transistor, a tiny semiconductor device built in 1947, made the field of microelectronics possible. It was created at Bell Labs by John Bardeen and Walter Brattain and later refined by William Shockley. At the time, they had no idea that the transistor would change the world and kick-start what has become a massive field that shapes our everyday lives through the technologies we use like mobile phones and personal computers (cf. Nobel Prize 2024). Each of these groundbreaking tools earned a Nobel prize. Without new method innovations, these new research domains would not have been possible.

The most important tools to drive new fields across disciplinary areas. What are the most transformative tools across different disciplinary areas? New research domains cluster around key methods that trigger them. We find that the methods and tools that acted as catalysts in opening most established fields within physics-related disciplines are new mathematical techniques, lasers, spectroscopes and cathode-ray oscillographs. Within chemistry-related fields, these groundbreaking methods and tools are new spectroscopic methods, x-ray methods and mathematical techniques. Within medicine- and biology-related fields, these are new optical microscopes and other vision-enhancing tools like x-ray devices, spectroscopes and electron microscopes. Within economics- and social science-related fields, these are new statistical methods and economic modelling methods (Fig. 3). In biology for example, without the microscope several fields could not have emerged, from microanatomy that studies the structure of tissues and organs, to bacteriology that investigates bacteria and their links to disease. Before we change the way we explore and view the world, we first change the tools we design to study the world. Because we can observe these changes in the rise of new disciplinary branches before and after the invention of the key tools, new disciplines do not emerge randomly. We can observe the trends over time and which central methods and instruments have been most important in triggering new fields – with Appendix Fig. 2 highlighting the historical evolution.

Take the field of exoplanetary science. It launched in 1995 with the groundbreaking study published in Nature – *A Jupiter-mass companion to a solar-type star*. The field was made possible by a new echelle spectrograph, invented in 1993 (Mayor and Queloz 1995). New tools expose entirely new realms of exploration, they are indispensable for shedding new light on the known and revealing the unknown. It is those who conceive and refine these tools who amplify our research scope and fields by tackling our cognitive and methodological constraints. In short, expanding our scientific toolbox expands the research frontier. The reason why some methods and instruments are more influential than others is because they much better extend our resolving power and vision, computational strength, statistical power, processing capacity etc. – because they are best at extending the innate limits of our mind and senses.

But our new methods and tools do not just give birth to new fields; we find that for over a quarter of fields, they are the defining feature of the discipline itself (and not phenomena studied using it). Fields like electron microscopy (1933), x-ray crystallography (1913), mass spectrometry (1919) and neutron spectroscopy (1955) emerged with the tool's invention. Such methodological fields are often inherently interdisciplinary as we leverage these tools across the broad domains of chemistry, biology, medicine and physics – with each tool earning a Nobel prize. Reinvention and fusion are also important: dozens of fields have emerged by merging cutting-edge tools from different domains together, like computational chemistry, quantum interferometry and statistical mechanics – with integrating new methodologies and technologies often being key.

Ultimately, we can identify here a general principle of how we give rise to new fields that is grounded in the empirical evidence:

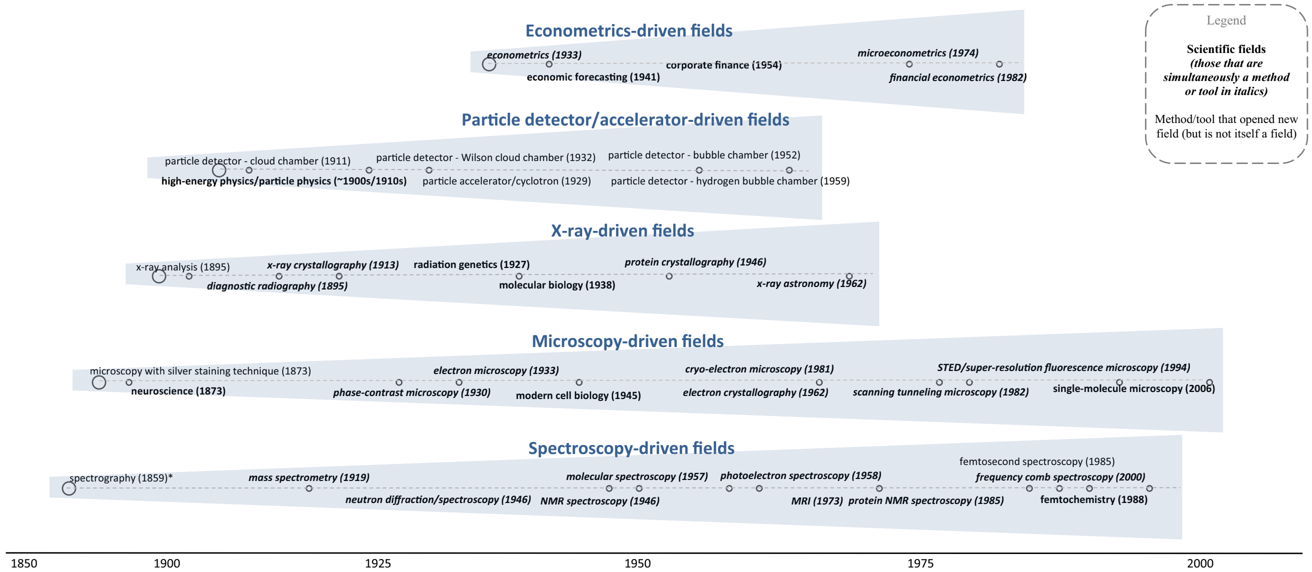

Fig. 2 New central methods and tools kick-start new scientific fields (illustrated with nobel prize-winning methods). High-energy physics is a large and foundational field that has been developed and expanded by multiple particle detectors and accelerators that each won a Nobel prize, and thus that row of data reflects an exception that includes instruments that not only gave rise but also vastly expanded the field. *The first spectrograph, developed in 1859, is the only instrument included in the figure that did not receive a Nobel prize, which was used to open the field of mass spectrometry.

new fields consistently emerge through the development of new methods and instruments that reflect a new way to perceive and understand the world not previously feasible. A new research domain requires a new way to view the world, while most scientists commonly use more conventional methods to study a given problem. The results illustrate that since we must first create and apply new methods and instruments, they are a necessary condition for opening new fields. This new methods-to-fields principle holds across disciplinary areas and time periods (Figs. 1–3).

Most major method discoveries – supported at times by interdisciplinary work – establish new fields. While we find that new fields are consistently driven by method innovations, not every method innovation fuels a new field. This raises a crucial question: why do some major method discoveries establish new fields while others do not? To answer this, we first examine the extent to which major method discoveries (all nobel-prize-winning and major non-nobel-prize method discoveries) trigger new fields. A striking pattern emerges: these major new methods and tools reflect about one in four major discoveries in science, but among them a remarkable 82% opened a new field. These include field-triggering tools like laser cooling launched in 1985 by Steven Chu at Bell Labs; DNA amplification pioneered in 1985 by Kary Mullis at Cetus Corporation; and neutron spectroscopy created in 1955 by Bertram Brockhouse at the Atomic Energy of Canada. This finding – that major method discoveries are much more likely to led to new fields than not – holds across time and disciplinary areas (Appendix Fig. 4). We next test whether broader demographic, institutional and geographic factors can support new fields arising. We can provide further insight into the dynamics of the birth of fields by assessing and comparing a control group of major method discoveries that did not establish new fields with those that did. This enables examining the differences – between the two groups – in factors that can support new disciplines arising.

We find that most method discoverers who have triggered new fields have worked interdisciplinarily at 65% while the share is 39% for those who have not triggered a field (see Fig. 4a). Yet it is not just about combining two scientific communities through new collaboration networks (Sun et al. 2013); rather, new fields are more likely to arise when we fuse methods across disciplines – either integrating methodological approaches from different domains or applying methods in completely new domains. Working interdisciplinarily – in more than one field – enables us to apply methods and evidence from one discipline in another and has been important for generating many novel ideas and breakthroughs (Uzzi et al. 2013; National Research Council 2007). It allows us to adopt new perspectives and make novel connections. The physicist Max Delbrück for example turned to genetics in the 1930s but used cutting-edge tools from physics – the new electron microscope and statistics – to address unanswered questions. With these new methods, he was able to show that bacteria develop via mutations. His breakthrough 1943 paper *Mutations of bacteria from virus sensitivity to virus resistance* helped open the field of molecular genetics. Hermann von Helmholtz worked in both medicine and physics and his synthesising scientific approach helped trigger the field of biophysics by applying novel mathematical principles and physical analysis which other physiologists did not (Krauss 2024; Encyclopaedia Britannica 2023a).

Other factors, such as discoverers' level of education, gender and age at the time of their major advance, show little to no difference between the established-field and no-field groups (Fig. 4a). Such factors seem less important behind fields emerging. Method discoverers who sparked new fields were more likely to work at a top 50 ranked university worldwide and be based in North America, but as we observe below these factors are not statistically significant when controlling for the range of demographic factors. We also conduct the same analysis but only for nobel prize discoveries (Fig. 4b). Other factors, such as levels of income per capita and population size, illustrate no significant differences between the two groups.

We next explore what helps predict whether major method discoveries establish new fields or do not (the dependent variable). To do this, we use logistic regression to analyse these demographic, institutional and geographic characteristics of these discoverers (as independent variables). The regression results illustrate that a method discoverer working interdisciplinarily is the only statistically significant factor of a new field emerging, while controlling

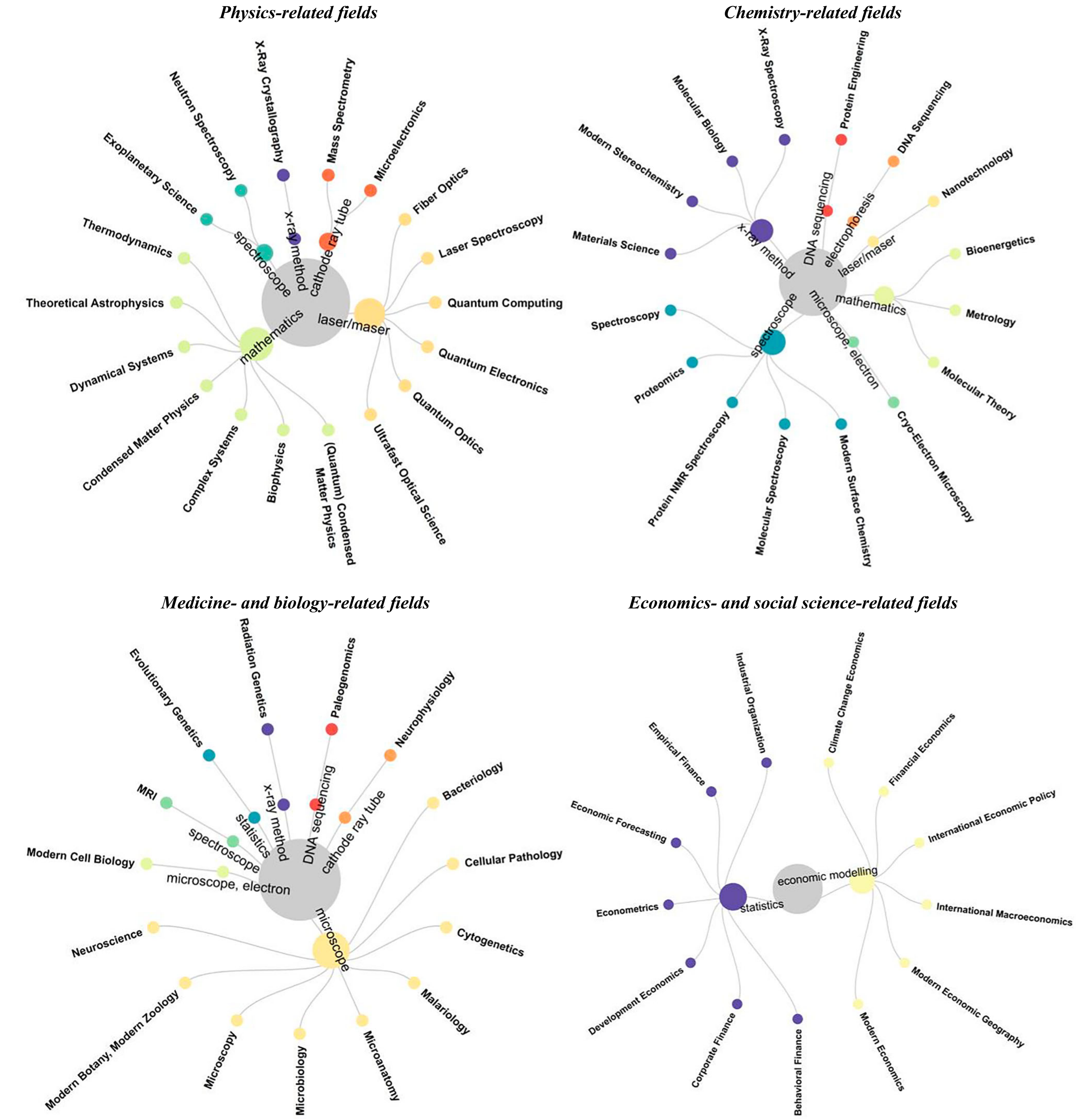

Fig. 3 Mapping the central methods and tools that open new fields – a network analysis. Data reflect the central methods and instruments used in opening established fields since 1600, reflecting 18, 16, 15 and 13 fields, respectively. Each method or instrument was used in developing at least three fields – within any disciplinary areas.

for these other features of the researchers that are not statistically significant – and considering the small sample of less than a hundred major method discoveries (Appendix Fig. 3).

As a final robustness check, all results are robust when testing them with a threshold for a scientific field at a minimum of 10 or 100 hits via Google Scholar instead of 25, and the conclusions remain the same.

Causal link between new tools and new fields. Because each publication that opened science's over 350 fields used a new method (or tool) – and the study, including often experiments, could only be conducted with that method – we find that new fields consistently emerge through new methods. Because they enable novel insights and testing those insights that would not have been possible before. Scanning these field-triggering publications, we observe that significant shares of these advances are made by scientists who can be in small or large teams, low or high funded, young or old, at lower or top ranked universities, interdisciplinary or not; but the key factor common among new fields is that they consistently apply a new method to be able to break new ground and provide a new perspective that grounds the new

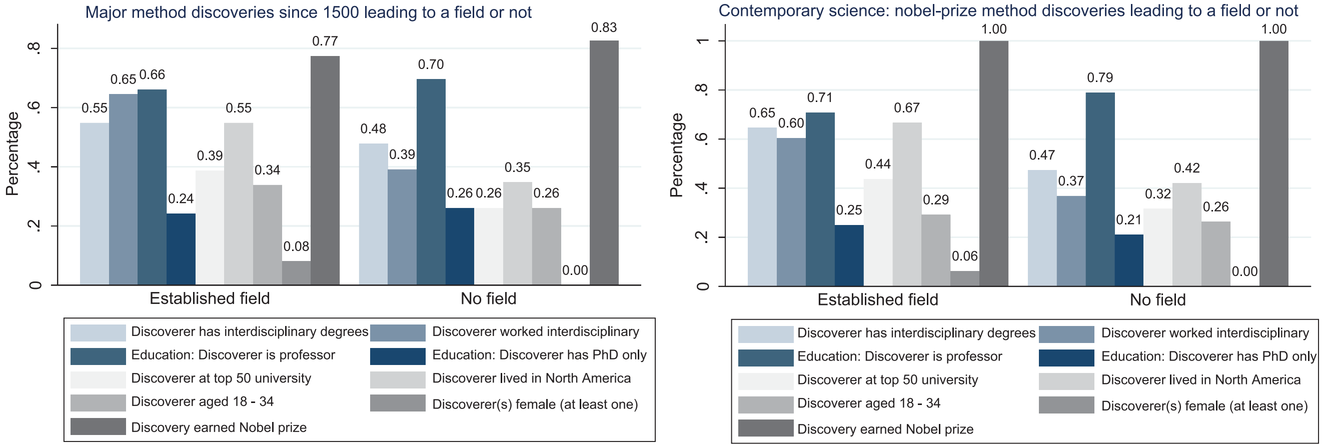

Fig. 4 Major method discoveries leading to new established fields compared to those that did not, by features at the time the discovery/field emerged. Data reflect a total of 85 major method discoveries since 1500, with 62 leading to established fields and 23 not leading to a new field (figure a) (derived from nobel-prize-winning research in science and the seven indicated science textbooks). And the data represent a total of 67 nobel-prize-winning method discoveries, with 48 and 19 discoveries in the two groups, respectively (figure b) (derived only from nobel-prize-winning research in science). Discoverer has interdisciplinary degrees is defined as having two or more degrees in different fields. Discoverer worked interdisciplinarily is defined as working, or having worked, in more than one field – in different academic departments or professions. Discoverer at a top 50 university is based on whether they were at a top 50 ranked university worldwide according to QS World University Rankings (2021). Universities were founded since the late 14th century and have provided formal education and degrees since then (Hellyer 2003). For earlier centuries, we should view data on university ranking with caution: while most discoveries have been made while today's top 50 universities existed, some did not yet exist before the 1800s (figure a).

field. New tools enable new insights that were previously not possible without them, underscoring that the tool does not just facilitate but fundamentally drives the field – from laser physics and computer science to x-ray crystallography and econometrics. High-energy physics would likewise not have been possible without particle detectors, experimental economics without randomised controlled trials, and the like.

The ten central methods and instruments most commonly used in science were not invented with the set of scientific fields in mind that they made possible. Ernst Ruska's electron microscope, Max von Laue's x-ray diffraction, Charles Townes' maser/laser etc. were not specifically developed with a field in mind that later emerged by applying these new tools. Yet these powerful, general-purpose scientific tools gave rise to many new fields (see Fig. 3). They were created in one disciplinary area, like physics, and then applied to make fields in different disciplinary areas, like medicine, chemistry or biology, that were not foreseen by the inventors of these tools (Fig. 3). One of the strongest pieces of causal evidence is that researchers in unconnected disciplinary areas pick up and apply the new methods to spark new fields. Using quasi-experimental reasoning, this lack of an initial relation to the outcome (no intention as tools to develop different fields) helps identify a causal relationship between the new tools and the new fields they were not even designed for. These methods and tools were not specifically designed and funded to make the different fields that they still triggered, commonly in different disciplinary domains.

Designing advanced microscopes for example gave rise to new fields that were not predicted, such as bacteriology and neuroscience. Inventing x-ray crystallography brought about new fields that were not foreseen, such as molecular biology and organometallic chemistry. The probability of developing many fields is 0 before the needed tools are created, and the probability then jumps when such tools are designed, which have often led to multiple new fields.

There are also researchers' salaries and recurring costs of laboratories and tools, at least in some fields with more expensive tools such as particle accelerators and space telescopes. Yet a number of the most commonly used central methods and instruments driving science are low cost, including statistical and mathematical methods, light microscopes, electrophoresis, thermometers, chromatography methods and centrifuges, which today we can acquire new for less than a thousand or even few hundred dollars (Krauss 2024). Assessing the publications that kick-started the fields, we see that hundreds of fields have emerged without the need for additional funding or collaborations but by leveraging recently developed tools – already available – that provided the entirely novel insights. Methods and tools can directly trigger a major advance by providing the new perspective needed to open a field, and without them supporting factors like more money (Stephan 2015), collaborations (Wu et al. 2019; Wang and Barabási 2021) and education (Chan and Torgler 2015) are not enough and theories cannot generally be created and tested.

Some influential fields are seen as emerging *theoretically*. An example is the field of quantum mechanics. Yet Plack (1900), who laid the critical first step, developed his famous quantum hypothesis by building on blackbody radiation experiments that applied spectrometers and bolometers to measure emitted spectra. Einstein's (1905) photoelectric effect further contributed and was rooted in experiments using electroscopes and cathode ray tubes to observe how light liberated electrons from metal surfaces. Then came Bohr's (1913) quantum model that relied on spectroscopes, using prisms to identify spectral lines that pointed to quantized energy levels. Each of these scientists also relied on advanced mathematical methods (Nobel Prize 2024; Encyclopaedia Britannica 2023). Another example is the field of evolutionary biology. Yet Darwin, who launched the field, relied on his advanced microscopes that enabled him to study barnacles, corals and plant structures that shaped his ideas on variation and adaptation (Jardine 2016). He also conducted breeding experiments with plants and pigeons, providing him direct evidence of how artificial (human) selection could drive changes in species over generations. These experiments enabled him to draw the analogy for natural selection. He also applied comparative anatomy methods to study finches, dissected animals and used fossil discoveries that provided him further evolutionary evidence, including Malthus's views on population growth (Darwin 1859). Far from being just an abstract creation, fields like quantum mechanics and evolutionary biology are only possible by relying heavily on scientific tools. These provided the necessary empirical

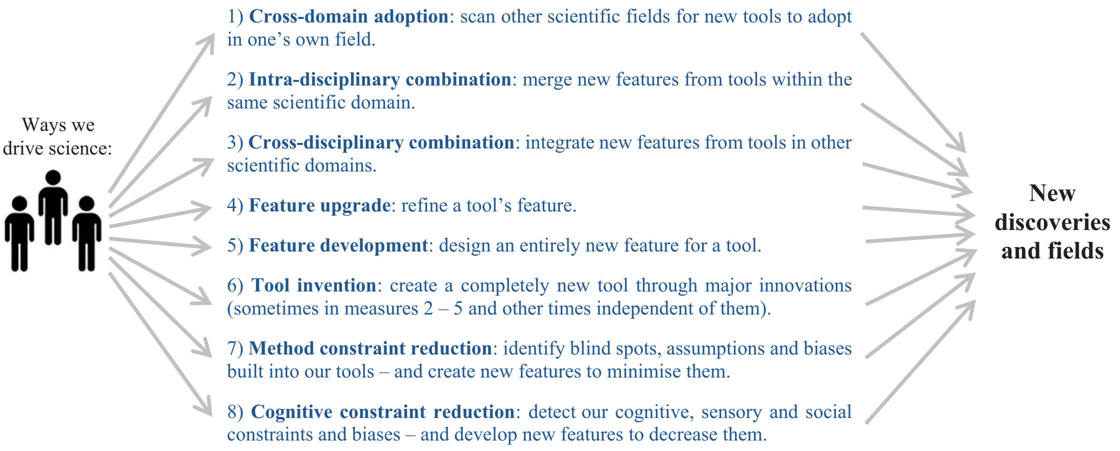

Fig. 5 Practical guidelines for how we extend our methods and tools: Eight pathways.

foundation on which they could then develop theoretical explanations for what they observed.

Methodology of Science: Evidence and theory for a new field. What if we treated the design of scientific tools across science—not just as technical supports—but as a field of research in itself that speeds up scientific advances? Most scientists do not commonly focus on studying and extending the very methods that enable them to do research. After identifying the powerful role of new research methods and instruments in opening research domains, the next step requires answering the question of how we can create and extend methods and instruments to develop new scientific advances. In this section we outline the main pathways we can take to expand our scientific toolbox.

The central implication is that to make new advances and fields more rapidly, we need to allocate a greater share of existing scientists and existing resources to foster new method innovations. We need to begin strategically planning, structuring and targeting efforts for developing new methods and instruments to push the research frontier. There are two main ways to accelerate the pace at which we trigger new advances and open new fields. The most common strategy is to extend our tools, re-combine them in novel ways or invent entirely new tools – with capacities never before achieved that enable opening new research domains presently out of our scope. Just as we run experiments in science, we need to run method and tool experiments. We need to begin developing research programmes and shifting existing funding schemes to promote experimenting with new methods and instruments and combining them to create new ways for doing science. The other strategy is to scan other fields for tools that we can tap into to solve problems in one's own field and open new lines of research. This requires rapidly disseminating knowledge about newly developed methods and tools across fields as soon as we create them. We can achieve this through leading publication sources, both disciplinary and interdisciplinary, that incentivise researchers to make and publish method advances. For tools in some fields often lay unused in other fields for decades (such as randomised controlled trials and certain spectrometric methods) – or are not yet applied.

We now dig deeper and analyse the concrete pathways we can take to make new method innovations. We observe that there are general steps we can take to increase the chances of making a groundbreaking advance or new field (Fig. 5). There are countless ways we can expand nearly all existing tools given the vast range of possible combinations of features from tools within one's own field and within other fields. The potential method and tool combinations are enormous given the sheer number of techniques we can adopt across for instance the experimental, statistical and computational sciences. Any path we take requires shifting our focus to leveraging methods or instruments in new ways that open new avenues of exploration. Any student or established researcher can use these practical strategies as a roadmap to advance their research agenda.

Because our methodological limits determine our experimental and theoretical limits makes it so important to find ways to tackle our methodological constraints more efficiently. But existing research to improve a method or tool – such as statistical techniques or microscopy – has been domain-specific and fragmented (Fisher 1925; Mertz 2019). It is surprising that, despite centuries of scientific expansion, no field has emerged that systematically studies tool development from all angles and perspectives across science – building the very methods and tools that make new advances and fields possible. Combining the empirical evidence with a theoretical framework, there is a need for a new field that studies and explains how new methods trigger new scientific advances and how to develop and expand new methods – which we call *Methodology of Science*. Making major new scientific advances and fields ultimately involves reducing our existing cognitive and methodological constraints. Like some areas of basic research, research on expanding methods and tools has not yet been appealing for researchers, since scientific incentives – institutions, journals, awards – continue to revolve around final outputs (experimental findings and theories) and not foundational inputs (method innovations) that enable them. No field yet exists that aims to advance tools across science; we propose such a field here and outline what it can look like:

The *Methodology of Science* is a field dedicated to understanding and designing the scientific methods and tools that enable better ways to discover, measure and explain the world. It studies the foundations, limitations and advancement of our tools: from observational and experimental to statistical and computational tools. The field does not view methods and tools as technical supports, but places them at the centre of scientific progress – because how we investigate determines what we can discover. It identifies the constraints, assumptions and biases facing tools and develops ways to tackle them. The field continually scans across disciplines for new method combinations and maps how new tools shape knowledge production and redefine disciplines. It builds systems for interdisciplinary method-building, offers a platform for rapidly disseminating promising tools across fields and trains researchers how to adapt and invent new tools of discovery. Ultimately, the field offers a framework for how to make method innovations – not just to conduct science, but to build science and advances themselves.

The field would represent a new domain of basic research. It would serve as a cross-disciplinary bridge, bringing together toolmakers, methodologists, experimentalists, computational scientists, engineers and field-specific researchers in a culture of innovation. The field could address many important questions at the core of scientific progress: How can we redistribute current resources to pioneer new tools that push the research frontier? How can we best incentivise *methods projects* and not just *science projects*? How can we target current resources to tackle the bottlenecks of our current tools? Which research networks and grant schemes can we restructure to incentivise method innovations and researchers at different stages of their career? How can we best support interdisciplinary teams that combine both methodologists and scientists collaborating together? Allocating more funding, just like training more scientists or promoting larger teams, without addressing such questions and identifying the strategic areas for advancing science, makes science more likely to be driven by chance. It slows the pace of scientific advancement. To understand the foundations of science, we need to understand the foundations of the methods and tools we create to spark new knowledge. To understand our current limits of science and how to advance science, we need to understand the current limits of our methods and tools and identify ways to extend them – with Appendix Table 1 outlining examples for common methods and instruments. Yet scientists do not commonly focus on studying and extending the methods that enable them to do their research.

The vision is to reframe tools not as background instruments, but as evolving systems of perception, reasoning, exploration, imagination and innovation. The hope is that developing more sophisticated telescopes, computational methods and x-ray techniques would no longer be seen as less important than opening new fields – that these very tools make possible.

This methods-driven mechanism here can provide a foundation for such a field. The best test for evaluating a new field is how useful it is in addressing unsolved problems, offering ways to solve new problems, revealing systemic blind spots to progress and advancing new lines of research. On these measures, *Methodology of Science* could have a significant impact, since tackling our past methodological constraints has had an enormous impact on scientific progress throughout history and given the range of constraints and untapped opportunities of today's leading tools.

Ultimately, we observe that new tools contribute most significantly to new advances when they address a critical methodological bottleneck enabling us to better observe or measure phenomena or they significantly improve efficiency or precision of our methods, unlocking new perspectives and research areas. Inventing the electron microscope for example vastly broadened our world of microorganisms, molecules and nanoparticles. New tools also contribute most significantly when they can be applied and scaled across subject areas – such as machine learning that has transformative effects in fostering innovation at the intersection of disciplines, from materials science to astrophysics and healthcare.

Finally, many initial methods may not be useful enough or too limited in scope to survive to make advances. Just like experimental results and theories, we only see methods that directly trigger advances, not those that do not make it into publications. There is often a trial-and-error process in making methodological and scientific innovations. (So a research design that aims to collect data on unsuccessful methods faces constraints as such methods do not generally appear in publications but some may appear in conference presentations, preprints and lab notebooks.)

Before closing, we consider one last point: think of major fields that have stagnated and those that have recently grown rapidly. Now think of how tool development relates to these differences. It is applied fields across science – like experimental physics, economics and biology – that are largely thriving. In contrast, theoretical fields – like theoretical physics, economics and biology – have mostly stagnated, at times locked in long-standing debates. Applied research thrives because of new, frontier-opening tools, methods and data they produce. Consider the James Webb space telescope exploring the early universe, the LIGO interferometer detecting gravitational waves, and sequencing and high-throughput tools decoding the entire human genome.

Can method innovation explain this vast divide? Indeed, the main driver of a field's growth or stagnation is commonly the power and novelty of its tools and methods. The fields that expand most rapidly commonly apply the most powerful new tools – think of the field of AI that is driven by new machine learning methods, to genomics powered by DNA sequencing methods, and genetic engineering driven by the CRISPR gene-editing method. So when do fields actually grow fastest? We find here four pathways: one, through such method inventions that allow asking questions not possible before. Two, through upgrading – or three, integrating – computational, statistical and experimental tools that enable researchers to analyse such previously intractable problems with massive, complex data. Four, through cross-disciplinary borrowing that can involve fields also combining tools – like neuroscience merging tools from biology, computing and cognitive science, and behavioural economics mixing methods from psychology and economics. And when do fields stagnate? Not because we run out of ideas or papers, but because we run out of ways to explore, test and generate new findings – using new methods. The key insight is simple: fields that begin treating tool-building and method-design as central – not auxiliary – will be the ones generally unlocking the vast new frontiers of research.

Conclusion

Scientists like Galileo, Newton, Mendeleev, Hooke and Mendel were pioneers in testing new methods and evidence. Yet they could not foresee whether and how their individual contributions would fit the construction of an immense system of knowledge. What they were contributing – eventually leading to the fields of physics, chemistry and biology – became clearer over the centuries. Today, we have a far clearer view of the evolving edifice of science and its ever expanding structure and complexity. While we are not fully aware of the immensity of what is beyond our planet, we have amassed vast bodies of complex knowledge, from laser physics and genetics to climate science, that were incomprehensible just a few generations ago. A key goal of the science of science is to understand how these bodies of knowledge grow – from the 17th century to the cutting-edge developments of today. A general explanation has not been possible without first comprehensively assessing scientific fields and the methods and instruments used to be able to develop those fields.

Through the new tools we design, we can trace what new fields fundamentally rely on: new microscopes leading to microbiology, computers launching computer science and radio telescopes giving rise to radio astronomy. For these tools allow us to observe phenomena that are otherwise too small, too vast, too fast, too far beyond our mind's capacities to imagine and study. The history of science is ultimately a history of expanding our human senses – crafting new ways to detect, measure and understand our world that open new domains of knowledge. Here we identify the general mechanism that fields share in common: we consistently kick-start new fields through newly invented methods and instruments that reflect a new way to perceive the world not previously feasible.

Science's most powerful tools are rarely confined to their discipline of origin; instead, most spill over into other disciplinary areas to unexpectedly trigger new fields that their inventors never anticipated. This underscores the causal link of new fields driven by new tools that would not have been possible without them. This new *methods-to-fields* principle holds across history and disciplinary areas and helps redefine the predictability of new fields emerging after and where we make new method advances. We found that most major method discoveries (nobel-prize and major non-nobelprize method discoveries) do not just open a new field but often multiple new fields. We also found that method discoverers are more likely to conduct interdisciplinary work to create and apply those new methods.

Ultimately, this principle embodies the incredible power of expanding our scientific toolbox that enables developing new research domains. Unlike traditional explanations – including paradigm shifts in theories, evolving research programmes, splitting or merging scientific communities, or even accumulated citations – this principle does not focus on just outputs but on what precedes and causes new fields in the first place. Beyond new tools, there are supporting factors that can help influence when a field emerges – like funding (Stephan 2015), collaborations (Wu et al. 2019; Wang and Barabási 2021) and developments in other fields – but they cannot directly start a field on their own.

This methodological principle highlights the need for us to redirect much greater attention to improving our methods and instruments. Yet getting funding, hired and promoted in science is overwhelmingly tied to the number of citations that scientists' articles receive. Scientists do not commonly cite and reference the discovery of the methods and instruments they apply, but primarily just cite other scientific studies. The most important method-making articles in history – from Ruska's article on the invention of the electron microscope (Knoll and Ruska 1932) and Tiselius' (1930) electrophoresis method, to Martin and Synge's (1941) partition chromatography method and Bloch and Purcell's NMR spectroscopy (Bloch et al. 1946) – have only received between a few hundred and a few thousand citations, but each are mentioned in millions of publications via Google Scholar. They are so foundational to science that they are thus largely taken as given, without the need to even cite them. If citation practices accounted well for tools, then inferential statistics, x-ray crystallography, computational methods, randomised controlled experimentation and lasers for example would each have received millions of citations. This far surpasses the most-cited scientific studies of all time that rarely give (citation) credit to the discovery of the methods and instruments they use. A rethinking is needed away from using common ex-post indicators like citations (Wang and Barabási 2021; Fortunato et al. 2018; Clauset et al. 2017; Chu and Evans 2021; Sugimoto 2021; Nature Human Behaviour 2022), towards ex-ante indicators – the process of science – that recognise tool innovations.

By prioritising the development of new methodologies and technologies, we can create an environment for accelerating scientific advances and new fields. This in turn can depend on researchers taking risks, exploring new ideas and receiving a greater share of existing resources. In terms of constraints of the study, future work could apply longitudinal research designs to assess the evolution of fields and the methods they use which can provide broader insight into how they change over time. Future research can also study methodological bottlenecks – those critical points where existing tools limit progress – and develop ways to overcome them.

Extending our tools is where the frontier of research lies, yet we still do not give sufficient attention to this research. A guiding principle for scientists seeking to break new ground is: when we hit upon an interesting problem facing a method or tool we are using or come across an idea of how to tackle that problem, we should drop everything and pursue it – because history shows that this is generally how new scientific advances and fields are born. The most promising thing to hear in science is often not just 'I have a new idea' but rather 'I have a new method that I can apply.' Shifting our research focus to this powerful principle of method innovation would speed up how we spur new advances and the pace at which we can enter unmapped terrain at the borders of science. Such a shift would mark a method revolution in science. After identifying the powerful role of our new methods and tools in driving new fields, a new question then emerges of what steps we need to take to generate new methods and tools – and we addressed this question in the previous section. Other related research on science's major discoveries is outlined in a series of companion studies – on discoverers' broader demographic traits, serendipity, paradigm shifts, the scientific method and the causal role of new tools (Krauss 2024, 2024a, 2024b, 2024c, 2024d) – and in a larger forthcoming book, *The Engine of Scientific Discovery* (Krauss 2025). Ultimately tomorrow's great scientists – those best equipped to tackle society's pressing challenges – are generally those who are best at developing new tools or who take advantage of powerful new tools.

Data availability

Data used for the analysis are available online from these sources outlined in the Methods section.

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Note

1 A new tool not only needs to be developed but also applied – innovation comes from invention and application. While most tools have been created within a few years before the field emerged since 1975, some tools have been developed several decades or more ago but their novel application for the first time ever to a question is what enables the novel insights and triggering fields.

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Author contributions

Alexander Krauss is the sole author.

Competing interests

The author declares no competing interests.

Ethical approval

Scientific fields are analysed that directly emerged from all nobel prize-winning research and that were developed by leading scientists listed in the mentioned science textbooks (see Methods section). No human experiments were conducted and no ethical approval was required.

Informed consent

No informed consent was required.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1057/s41599-025-05797-6.

Correspondence and requests for materials should be addressed to Alexander Krauss.

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