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Debunking revolutionary paradigm shifts: evidence of cumulative scientific progress across science

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How can scientific progress be conceived best? Does science mainly undergo revolutionary paradigm shifts? Or is the evolution of science mainly cumulative? Understanding whether science advances through cumulative evolution or through paradigm shifts can influence how we approach scientific research, education and policy. The most influential and cited account of science was put forth in Thomas Kuhn's seminal book *The structure of scientific revolutions*. Kuhn argues that science does not advance cumulatively but goes through fundamental paradigm changes in the theories of a scientific field. There is no consensus yet on this core question of the nature and advancement of science that has since been debated across science. Examining over 750 major scientific discoveries (all Nobel Prize and major non-Nobel Prize discoveries), we systematically test this fundamental question about scientific progress here. We find that three key measures of scientific progress—major discoveries, methods and fields—each demonstrate that science evolves cumulatively. First, we show that no major *scientific methods or instruments* used across fields (such as statistical methods, X-ray methods or chromatography) have been completely abandoned, i.e. subject to paradigm shifts. Second, no major *scientific fields* (such as biomedicine, chemistry or computer science) have been completely abandoned. Rather, they have all continuously expanded over time, often over centuries, accumulating extensive bodies of knowledge. Third, *scientific discoveries* including theoretical discoveries are also predominately cumulative, with only 1% of over

750 major discoveries having been abandoned. The continuity of science is most compellingly evidenced by our methods and instruments, which enable the creation of discoveries and fields. We thus offer here a new perspective and answer to this classic question in science and the philosophy and history of science by utilizing methods from statistics and empirical sciences.

1. Introduction

Scientific discoveries have a tremendous impact on our lives and are commonly viewed as the most exciting aspect of science, for the scientists making the breakthroughs and the scientific community and general public benefitting from them. But we still do not understand well the nature of science and scientific progress [1–10]. What best describes scientific progress: (paradigm-changing) revolution or (cumulative) evolution? Is science thus best conceived as mainly undergoing fundamental changes in scientific paradigms? Or is science mainly a highly cumulative system in which present methods and discoveries connect back to past methods and discoveries and extend forward to enable future methods and discoveries?

Two dominant approaches exist to studying how science evolves and advances. One approach was taken by the historian of science, Thomas Kuhn, who offered the most influential account of science yet. By applying case studies, he studied how theories in a scientific field may go through fundamental changes over time [1,2,11]. The notion of paradigm shifts continues to be widely accepted [2,12,13], with his landmark book continuing to be the most cited account and still receiving thousands of citations each year (over 15 000 citations alone between 2020 and mid−2024 according to Google Scholar). Influential researchers continue to research this view of paradigm shifts and non-cumulative science [12–19]. In public health, researchers found that dominant paradigms in nutrition have shifted through changing dietary guidelines and nutritional standards that reflect large transitions to new ways of thinking about nutrition [18]. In biomedicine, researchers argue that model systems in biology can be viewed as different paradigms, such as alternative models for characterizing viruses [20]. In physics, researchers argue that trends in discoveries over a century exhibit paradigm shifts that can be driven by principles of self-organization [21]. In business, researchers examine paradigm shifts in business management research and argue that new alternative paradigms enable shifts towards better theories and drive scientific progress [19]. In science, more generally, researchers investigate paradigm shifts across fields and argue that paradigm-changing discoveries have led to new fields [22]. In the philosophy of science, different researchers have 'pursued novel research on a number of topics relevant to *Structure's* concerns, such as … the character of scientific progress', as discussed in the edited volume *Kuhn's the structure of scientific revolutions revisited* [13].

Another approach has been taken by scientists adopting big data to study publications and they have argued that scientific articles, on the whole, may be becoming less disruptive (revolutionary) over time [7] and that high-risk innovation papers are becoming rare given an increased focus on established knowledge [23]. They argue that smaller teams are more likely to develop disruptive new ideas than larger teams [24]. They also suggest that the current scientific system that generates vast numbers of publications can overlook new transformative ideas and hinder shifting attention to those ideas [8]. They argue in favour of paradigm shifts by outlining that when leading researchers pass away, fields can more easily advance in new directions [25], that in biological research, published statements can influence the interpretation of later experiments and act as 'microparadigms' similar to established theories [26] and that inflated research can become liable to shift or collapse, like inflated prices in economic markets [27]. These studies adopting a big data approach examine publications and their citations and provide important insights into the dynamics of science [3,5,28]. Tracing science through published literature and citations—the most widely used measure of the impact of discoveries—does not, however, uncover other relevant factors to understanding scientific progress [29,30]: citations are driven in part by path dependency (researchers with limited time often just cite more cited research) [31] and they do not capture the impact of most major discoveries throughout history, as the widespread use of citations only began in the second half of the twentieth century [32]. At the same time, other researchers have suggested that science may have cumulative features by studying select case studies of breakthroughs or using theoretical and conceptual arguments [10,33–36].

Overall, existing studies (using citations or not) have explored a sample of major breakthroughs or publications but have not yet aimed to comprehensively study all major scientific breakthroughs to answer the fundamental question of whether major discoveries, fields and methods (and thus science in general) are overall cumulative or revolutionary. Here we aim to do so and help address the debate with comprehensive data.

To provide a comprehensive answer to this question, this study assesses all major scientific discoveries—all Nobel Prize and major non-Nobel Prize discoveries—and the scientific methods used to make them. This novel approach enables going beyond the insights of a handful of theories (for example mainly in physics, as Kuhn studied) [1,2,11], to a systematic analysis of the nature of scientific progress grounded in the major discoveries, methods and fields across science. It allows us to go from a common approach of studying a sample of discoveries or theories often within an individual field [1,37–42] to be able to make general claims about science and progress. It also provides a different perspective from studies that explore revolutionary research by studying a sample of publications and their citations [6–8,23,24,43] to more directly study all major discoveries themselves here. This is a central contribution here that provides an alternative conclusion about the cumulative nature of science's major discoveries [1,2]. In general, a shift from analysis at the individual to the aggregate level (going from a few or small sample of observations to a general analysis) has helped transform our understanding in a number of fields. It is how Boltzmann and Maxwell developed statistical mechanics, and how Austin Bradford Hill created randomized controlled trials that led to meta-analyses of studies which reshaped biomedical, agricultural and behavioural sciences. The other central contribution here is to not just study discoveries but, as a further analysis, shift the focus to include scientific methods and instruments in studying the evolution of science. This also provides an alternative conclusion about the cumulative nature of science, measured with methods and instruments—which have not yet been studied systematically. This is the first study to do so and by adopting this new methodological perspective, we find an extraordinary continuity in the methods and instruments that scientists develop and improve over time and enable us to create new theories, breakthroughs and fields of science. Here we will thus assess all Nobel Prize and major non-Nobel Prize discoveries and apply three different measures of scientific progress: major discoveries, methods and fields. This enables validating the robustness of the findings, and we find that each illustrates the cumulative nature of scientific progress. We then develop a theoretical (conceptual) framework that describes this evidence of the cumulative nature of science.

In doing so, we show how a long series of major advances in genetics could only have been achieved using cumulative methods and tools including continually improved microscopes, X-ray methods and electrophoresis techniques. These led to a set of discoveries, including heredity, DNA sequencing and the human genome, that have continually expanded the field of genetics, improved human health and reduced diseases [44,45]. A collective set of major advances in computer science were only possible using cumulative methods and tools including continually improved mathematical and statistical methods and transistors. These led to a set of discoveries, including the Turing machine, information theory (often called the Magna Carta of the digital age) and microchips, that have collectively made the field of computer science possible including the computers, smartphones and the Internet we use [46]. A sequence of major advances in the field of electricity were only feasible using cumulative methods and tools including continually improved galvanometers, batteries and electric generators. These led to a set of discoveries, including electromagnetism, the theory of electromagnetic radiation and alternating current, that collectively made possible the world of electric motors and electric power plants that we rely on in our daily lives. The story of genes, computers and electricity are each a story of cumulative evolution—they are a story of standing on the shoulders of giants and their methods and they are representative of all major fields across science. New breakthroughs can at times disrupt existing research and science is still overall cumulative. We show here that science is, overall, not characterized by revolutionary paradigm shifts that lead to scientists completely abandoning a discovery or theory—which is rare in science but what Kuhn focused his attention on.

Before proceeding, let us clarify what is meant by revolutionary paradigm shifts in science. The most well-known account of the history of science rejects the view of scientific change as being cumulative [1,2,11]. The history of science can be viewed as a cycle in which established ideas and facts are doubted, new problems and evidence then lead to new revolutionary ideas and facts (and replace the established ones), which eventually over time are also doubted once problems and anomalies associated with them become apparent, and the cycle begins again. In that view, the process of science is not cumulative but reflects revolutionary paradigm shifts, in which a scientific community rejects existing assumptions, concepts and theories and adopts entirely new ones. Researchers like Kuhn argue that a paradigm shift in a major scientific theory 'is far from a cumulative process … Rather it is a reconstruction of the field from new fundamentals' and 'cumulative acquisition of novelty is not only rare in fact but improbable in principle' [1]. 'Scientific revolutions are thus disruptive episodes of fundamental reconfigurations, through which scientific knowledge develops in a noncumulative way' [2]. Revolutionary science is not cumulative because major scientific revolutions (breakthroughs) replace existing assumptions, concepts and theories, according to that view [22]. Here we focus on that central hypothesis and on major breakthroughs (not on everyday, normal science) [1,2,11]. Researchers like Kuhn thus describe science as going through paradigm shifts and state that not just some but '*All significant breakthroughs are break-'withs' old ways of thinking*'—though they often study few theories, such as those in physics up to the early twentieth century, but still make such general claims about all of science [1]. By focusing on the classic examples of changes in the theories of physical reality from Aristotle to Newton and then to Einstein that span over two millennia, such cases may seem to partly support that hypothesis. For researchers like Kuhn, the shift from the Ptolemaic earth-centred theory of the Universe to the Copernican sun-centred theory characterized the classic paradigm change, which he focused much research on [1,2,11]. Yet by assessing the paradigm shift hypothesis for the first time using data on over 750 major discoveries, we show that the shift from Ptolemy's theory (developed in the year 150) to Copernicus' theory (developed in 1543) [47] presents one of the few exceptional cases in which we abandoned a central theory in early science. We show that this process was supported and confirmed with new and improved methods and tools.

2. Data and methods

This study reconstructs the discovery process using data on all major discoveries, which encompasses all 533 Nobel Prize-winning discoveries in science (from the first year of the prize in 1901 to 2022). They also encompass all other major discoveries that were made prior to the Nobel Prize or did not receive the prize; these were identified in all science textbooks providing a list of the greatest 100 scientists and their discoveries and that span across scientific fields and history, with a total of seven textbooks published and incorporated [46,48–53] (with textbooks specific to a field or a time period not included). After excluding all duplicate cases within the seven textbooks, 228 other major discoveries remained. In total, 761 discoveries are thus captured in the study that covers the most influential discoveries in history. If the Nobel Prize had existed earlier, eminent scientists like Galileo, Newton, Hooke, Boyle and Maxwell would almost certainly have also received the prize—and are all included here among the major non-Nobel Prize discoveries. These major non-Nobel Prize discoveries are also used as an independent control and robustness check for validating the results for the Nobel Prize discoveries. We also compare results across fields. The study has thus aimed to be as comprehensive and exhaustive as possible by including all Nobel Prize and other major discoveries across science. These range from the discoveries of cells by Hooke, the theory of evolution by Darwin and Wallace and heredity by Mendel, the theory of electromagnetic radiation by Maxwell, the relativity theory by Einstein and black hole lifespan by Hawking, to the conservation of matter by Lavoisier and the periodic table of elements by Mendeleev. These make up the foundation of the major fields across the physical, biological and social sciences. While there is no clear cut-off for what counts as a small discovery, there is strong consensus among the scientific community on the major discoveries of science, with a vast overlap in the major discoveries between these seven science textbooks and the Nobel Prize discoveries, and between each of the seven different science textbooks. The comprehensive data offer a unique opportunity to assess the fundamental nature of scientific progress and capture science's major theoretical, experimental and methodological breakthroughs—rather than just focusing on select theoretical breakthroughs [1]. The list of discoveries is provided as supplementary material.

Discoveries (including methods/instruments and fields) are classified here into three categories: those that have been *updated* with new evidence, those that have *not been updated* and those that have been entirely *replaced* (abandoned or subject to a paradigm shift)—as illustrated with examples later. A discovery (including a method/instrument or field) is characterized as contributing to cumulative scientific progress if it has not been abandoned and thus been either extended or not extended with evidence in later scientific publications (the first two categories). Discoveries are classified into one of these three categories based on the description of the discovery in one of the following scientific publications, namely in entries within six encyclopaedias of science [54–59], or within Nobel Prize documentation [60] or the seven indicated science textbooks that describe the discoveries. The description for about four-fifths of all discoveries was derived from two sources, namely Nobel Prize documentation (such as prize summaries and press releases) [60] and Encyclopaedia Britannica [54] in which the entries are written as general accepted knowledge by scientific experts (and thus are not self-reported by discoverers). For the few remaining descriptions of discoveries not captured in these sources, we used other encyclopaedias and scientific publications. The most common terms used in these publications to describe whether a discovery has been *updated* are extended/expanded/revised/further developed, whether a discovery has *not been updated* are remains unchallenged, undisputed, valid or unrefuted/has not been extended/expanded/revised/further developed, and whether a discovery has been *replaced* are abandoned/refuted/discarded/undergone a paradigm shift/superseded (for being incorrect).

Using descriptive statistics, the shares for the three categories illustrate reliable trends across time and fields that are compared against each other. Historical and qualitative evidence is provided that supports the quantitative results. To understand the nature of scientific progress, we also collect data on the central scientific *methods*, such as statistical and controlled experimental methods, and *instruments*, such as microscopes and centrifuges (applied in the discovery-making paper and commonly highlighted as such by the authors), which are developed and used to make these discoveries and the fields they opened. The methods and instruments are derived from each of the 761 discovery-making publications (that is, in the case of discoveries earning a Nobel Prize, the prize-winning papers). Methods are systematic techniques and instruments are systematic tools that are used for scientific purposes and are generalizable (applicable in different contexts to do science). They do not refer to methodological abilities like observation and hypothesis testing. Next, we assess the nature of scientific progress using three measures: methods, discoveries and fields.

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3. Results and discussion

(a) One measure of scientific progress: scientific methods and their cumulative nature

We first test the fundamental hypothesis of paradigm shifts in science by assessing scientific methods and instruments. Analysing all Nobel Prize-winning papers, we identify the 10 central methods and instruments most commonly used to make all 533 Nobel Prize discoveries in science: statistical/mathematical methods, spectrometers, microscopes (including electron microscopes), X-ray methods, chromatography, centrifuges, electrophoresis, lasers, particle accelerators and particle detectors. All these tools are constantly extended to increase power, accuracy, precision and efficiency, at times over centuries. We have not abandoned any of these established scientific methods or instruments. We use them in different fields and we continue to improve all of them, which have enabled us to make dozens of new discoveries. Assessing all 149 Nobel Prize-winning methodological discoveries (all major methods and instruments that were awarded the prize), we find that 99% have been updated, 1% have not been updated and none have been abandoned. Basically, all Nobel Prize-winning methodological discoveries, such as the polymerase chain reaction (PCR) method, the electron microscope, the radiocarbon dating method and electrophoresis, have been extended and fine-tuned over time [60]. In fact, no major scientific methods or tools used across fields—from calculus and controlled experimentation to telescopes and thermometers—have been entirely discarded. Rather, we extend them over time. Our central methods and instruments of science are highly cumulative (figure 1*c*).

Advances in microscopes have been highly cumulative over centuries. From the earliest microscopes relying on light and lenses to the more recently created electron microscopes and scanning probe microscopes, we have continuously expanded the field of microscopy and all are widely applied today. Our best light microscopes do not compete today as a different paradigm to the first light microscope developed in 1590 [61]. Our methods of arithmetic today do not compete as a different paradigm with those developed by the Sumerians. As a vast cumulative project, we have extended our major tools of science over time. No major scientific method or instrument that is used across fields goes through competing methodological paradigms. Our best scientific tools are all cumulatively built on. They are the foundation of science and our ability to do science across fields (so that a possible paradigm shift that would abandon them would so fundamentally change how we conceive science that we could likely no longer call what we do science).

Think of statistical methods—they have been developed and expanded over hundreds of years by Gauss, Laplace, Pearson, Fisher and many others [62]. Our cumulative statistical methods make it possible to test most types of hypotheses, analyse vast data and make systematic predictions in fields ranging from physics and biology to economics. Statistics has arguably received most attention in debates on improving how results are reported and published [63–66]. The so-called replication crisis, open science and developments in Bayesian statistics, for example, have all contributed to continually expanding statistical methods. Such reforms have only strengthened the foundational method of statistics. Some scientific tools, such as mercury thermometers and barometers, have been expanded into new tools, such as electronic thermometers and barometers, which improved their accuracy and made them safer to use.

Many particular methods and instruments have each been applied in making five or more discoveries, often across different fields, which highlights the cumulative methodological nature of science, as illustrated in figure 3 (appendix). In fact, we find that major discoveries have only been possible by cumulatively building on and improving our tools over time.

(b) A second measure of scientific progress: scientific discoveries and their cumulative nature

We next test the fundamental hypothesis of paradigm shifts in science by assessing scientific discoveries. Analysing over 750 major discoveries in science, we find that about 83% have been extended using new methods and evidence, about 16% have not been extended, whereas only in a few exceptional cases—1%—has a discovery been abandoned. What were once viewed as the leading discoveries of the time have generally been built on and updated by new methods and more accurate evidence, accounting thus for over four in five discoveries. The discovery of DNA sequencing in 1977 was, for example, extended with improved electrophoresis methods and sequencing machines [44]. The discovery of the nature of isotopes in 1913 was updated once the neutron was discovered using the new particle detector [46]. The discovery of hormonal treatment for prostatic cancer in 1940 was expanded with new methods and types of hormone treatments [60]. Each of these Nobel Prize-winning discoveries has been updated by new methods and later discoveries.

We find that about one in six discoveries has thus stood the test of time and has not (yet) been extended but remains largely unchanged. The Nobel Prize-winning discoveries of the first planet discovered outside our solar system, the detection of the neutrino and the isolation of fluorine are examples. Often these are one-off breakthroughs that establish the existence of a new phenomenon. Other examples are discoveries such as the electron and the double helix structure of the DNA molecule that are foundational breakthroughs in the sense that other breakthroughs build on them but do not directly revise them.

We find that only 1% of all discoveries have been entirely replaced by new methods and evidence, accounting for only eight discoveries that have been superseded among all 761 major discoveries. Three of them were awarded a Nobel Prize but have since been abandoned. One is Johannes Fibiger's initial findings in 1913 that ingesting a roundworm caused cancer in rats. Yet, later created methods and research found that a lack of vitamin A was actually the cause of the cancer and that the worm larvae only led to tissue damage where the cancer could then begin developing [67]. Another is Egas Moniz's development of leucotomy as a treatment for mental illnesses in 1935. Yet, this surgical technique, involving an incision into the brain's prefrontal lobe, also could cause major personality changes and was abandoned as new methods and medications for treating mental illness were developed in the 1950s [68]. The third is Harry Markowitz's economic theory of portfolio management in 1952. Yet, he later 'warns the reader that the 1952 piece should be considered only a historical document—not a reflection of my current views about portfolio theory', since he soon discarded his initial theory due to methodological errors and changes in his views about mean and variance [69]. Even in these eight exceptional cases, the discoveries, theories and methods applied were used as a reference point to be able to build on and supersede them (see table 1). So even in the few exceptional cases, scientific progress can still be conceived as being cumulative, as mismeasurements and mistakes also contribute to the overall picture by triggering correction. A revolutionary paradigm shift requires replacing an existing major theory or breakthrough, and revolutionary leaps that represent a complete rupture from preceding knowledge are thus rare in science—unless we search for exceptional differences over millennia such as in the most commonly cited example of a paradigm shift from Ptolemy to Copernicus [1,47]. The last step or discovery often seems to be the most impressive or revolutionary. But it is only possible by building on previous methods and resulting discoveries.

Comparison across fields provides insight into the evolutionary nature of science. Astronomy has the highest share of Nobel Prize discoveries that have not been updated, accounting for about four out of 10 discoveries in the field (figure 1*b*). Pulsars (neutron stars) and the accelerating expansion of the Universe, for example, once discovered, have not been updated given the nature of such discoveries. Nearly all discoveries in economics and social sciences, by contrast, have been further expanded over time. Importantly, discoveries that are updated

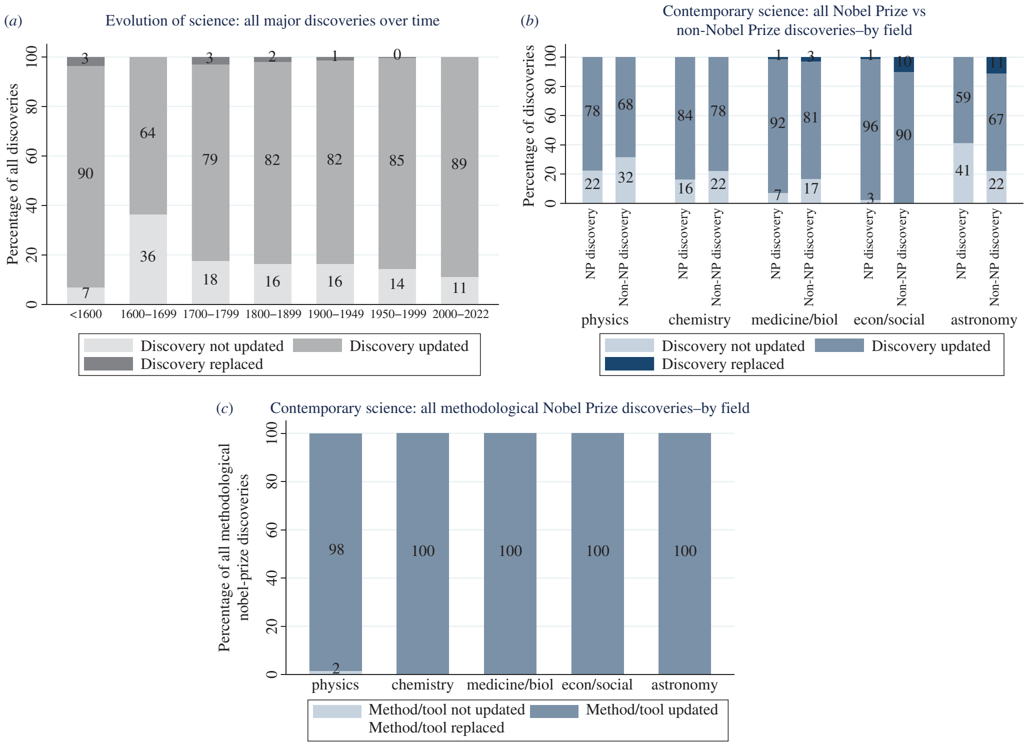

Figure 1. Discoveries are most likely to have been cumulatively updated, across time and fields. Data reflect all 761 major discoveries (including all Nobel Prize discoveries) (*a*), all 533 Nobel Prize discoveries compared with 100 major non-Nobel Prize discoveries that were made within the same time period (*b*) and all 149 Nobel Prize-winning methodological discoveries only (*c*). NP stands for Nobel Prize. An analysis that combines all Nobel Prize and major non-Nobel Prize discoveries across these five fields in (*b*) illustrates that the aggregate shares of replaced discoveries are 0%, 0%, 2%, 2% and 4%, respectively.

or replaced are commonly done so by using a new scientific method or instrument that provides a new perspective and evidence. We thus compare results here between all Nobel Prize discoveries and major non-Nobel Prize discoveries within the same time period—as a replication analysis to test and validate results (figure 1*b*). Overall, we find that less than 1% of Nobel Prize discoveries have been abandoned and the share is slightly higher at 2% for major non-Nobel Prize discoveries across history, illustrating comparable results across the two groups of discoveries. This provides evidence against the hypothesis that revolutionary paradigm shifts dominate science [1].

Let us take a closer look at the classic and most discussed paradigm shift: the shift in theories of our Universe from Ptolemy to Copernicus [1]. Ptolemy's geocentric theory proposed that the Earth was the centre of our Universe, with the Sun revolving around it. Copernicus' heliocentric theory proposed the opposite: that the Sun is the centre of our Universe, around which the Earth orbits [47]. Copernicus used systematic observational data and mathematical calculations that enabled predictive accuracy, and the shift from Ptolemy's theory to Copernicus' theory occurred gradually as more evidence backed by new methods, particularly the new telescope, supported the heliocentric theory. Galileo refined and confirmed Copernicus' theory through new discoveries by applying the newly invented telescope that played a crucial role. Galileo's discovery of the moons of Jupiter demonstrated that celestial bodies could orbit something other than Earth. Copernicus' heliocentric theory was only accepted once hypotheses could be tested rigorously using standards of contemporary science including predictive accuracy and new methods and tools were developed such as the telescope [70]. Once they were developed, we could better disprove such incorrect theories.

Table 1. Discoveries updated, not updated or replaced (examples of discoveries).

Field of discovery	*cumulative science*		*non-cumulative science*
	discovery updated	**discovery not updated**	**discovery replaced**
physics	structure of atoms based on quantum theory, 1913	electron, 1897	Ptolemaic geocentric theory, 150*
	electron microscope, 1933	detection of neutrino, 1953	animal electricity theory, 1791*
	electroweak theory, 1964	first exoplanet, 1995	steady-state theory of Universe, 1948*
chemistry	method of electrophoresis and adsorption analysis, 1930	isolation of fluorine, 1886	—
	sandwich compounds, 1952	conductive polymers, 1977	—
	computational methods in quantum chemistry, 1969	fullerenes, 1985	—
medicine	acquired immunological tolerance, 1949	double helix structure of DNA molecule, 1953	biogenetic law, 1866*
	radioimmunoassays (RIA) technique (for peptide hormones), 1959	reversible protein phosphorylation, 1956	Spiroptera carcinoma causes cancer in rats, 1913
	RNA interference, 1998	regulation of neurotransmitter release, 1990	leucotomy as treatment for mental illnesses, 1935
economics/ social sciences	econometrics, 1933	importance of exchange rate regime, 1963	hereditary genius ability, 1869*
	economic models of causes of poverty, 1954	expectations-augmented Phillips curve, 1967	theory of portfolio management, 1952
	integrated assessment model of climate change, 1994	—	—
share of all major discoveries (%)	*83*	*16*	*1*
share of all Nobel Prize discoveries (%)	*85*	*14*	*1*

Three examples are provided per category for each field based on 761 major discoveries, with all examples provided being Nobel Prize discoveries except for five of the eight 'replaced' discoveries in the last column marked with an asterisk (*) given that only three Nobel Prize discoveries have been replaced. No major discovery has been replaced in chemistry. In economics, only two Nobel Prize discoveries have not been updated. Years reflect when the discovery was published.

The older an abandoned theory is, the less likely it was developed and confirmed using sophisticated scientific methods and instruments that cumulatively build on each other over time. What appears to be a new, radical idea is generally made possible by being able to measure and observe the world with new and improved tools that enable new perspectives and increasingly greater precision. *What are called paradigm shifts are generally driven by new and better methods and instruments that enable studying and understanding the world in new ways.*

(c) A third measure of scientific progress: scientific fields and their cumulative nature

We now test the fundamental hypothesis of paradigm shifts in science by assessing scientific fields, such as genetics, computer science and electricity. In the development of electricity, for example, Franklin's discovery of the nature of electricity in 1752 was a critical first step that was made by using Leyden jars invented in 1745. Galvani, also using Leyden jars, then developed an animal electricity theory in 1791. Building on this theory and outlining its limitations, Volta created the first electric battery in 1800. The newly created battery was used by Ørsted who in 1820 discovered that an electric current creates a magnetic field. Building on the work of Volta, Ørsted and Faraday and using a magnetic conductor he created in 1822, Ampère was able to develop the law of electromagnetism in 1827. In the same year, using a galvanometer Georg Ohm introduced the mathematical concept of electrical resistance, establishing Ohm's Law. Faraday was then able to create a generator using electromagnetic induction in 1831. Through Faraday's work and using mathematical methods, Maxwell could then combine what was known about electricity and magnetism into a theory of electromagnetic radiation in 1864. These collective methods and knowledge enabled Tesla to develop alternating current (an induction motor) in 1883 [51]. Building on the accumulated tools and evidence, Thomson ultimately discovered the electron, the first subatomic particle, in 1897 by applying a cathode ray tube he designed the previous year. These scientists had an expanding methodological toolbox at their disposal. Importantly, all of them since 1820 used the newly developed galvanometer, battery and/or electric generator, which were continually improved to be able to make their discoveries. The fact that major discoveries could not be made without first generating these needed tools and building on resulting discoveries provides strong evidence of the highly cumulative nature of science (table 2).

More broadly in physics, Einstein was then able to make several breakthroughs by combining mathematical methods, Maxwell's equations and Michelson's measurements of the speed of light using the newly developed interferometer in 1881. In doing so, he formulated the special theory of relativity in 1905 and the related equation $E = mc^2$ that reshaped the field of physics. Moreover, particle detectors such as the cloud chamber were built in 1911 by Wilson, then the bubble chamber in 1952 by Glaser and subsequently the hydrogen bubble chamber in 1959 by Alvarez that built on each other and revolutionized our ability to study electrically charged particles and the subatomic world [51].

Like the field of electricity, genetics and computer science demonstrate that our knowledge of complex phenomena can only be developed through a highly interlinked set of methods, instruments and resulting discoveries that build on each other over time, and often span over more than a century—as outlined in table 2. The history of electricity, genes and computers is representative of how we use interconnected methods and tools to make interconnected discoveries over time in fields across the physical, biological and social sciences. In fact, no major scientific fields—such as biology, nuclear physics, medicine or mechanical engineering—have been entirely discarded. Our highly connected system of science is the outcome of these collective feedbacks.

In chemistry, fitting the pieces together of the periodic table of elements has been one enormous collaborative and cumulative project over time that makes up the foundation of the field. In biology, most knowledge builds on the theory of evolution and the mechanisms of evolution that provide the foundation for the field. Yet, it would be odd if we did not observe a larger change in theory in the classic example provided between Ptolemy and Copernicus, or between Aristotle's, Newton's and Einstein's view of physical reality spanning two millennia. Scholars in the sixteenth and seventeenth centuries like Copernicus and Newton turned to Ptolemy's geocentric astronomy and Aristotle's laws of motion [71], which provided them with the theories they tested, disproved and built

Table 2. Cumulative nature of science and scientific fields: central discoveries and the methods used to develop them build on each other over time. Data based on all 761 major discoveries. Years reflect when the central methods and discoveries were published. A number of other discoveries have also played an important role in these fields.

	discoveries in the field of genetics	**heredity (Mendel 1865)**	**composition of nucleic acids (Kossel 1897)**	**role of genetics in evolution (Dobzhansky 1937)**	**genes regulate definite chemical events (Beadle and Tatum 1941)**	**bacteria develop via mutations (Delbrück and Luria 1943)**	**mobile genetic elements (McClintock 1951)**	**DNA as bearer of genetic information (Hershey 1952)**	**structure of DNA molecule (Franklin, Crick and Watson 1953)**	**interpretation of genetic code (Holley, Khorana and Nirenberg 1961)**	**DNA sequencing (Gilbert and Sanger 1977)**	**genes causing genetic diseases (Collins 1989)**	**RNA interference (fire and Mello 1998)**	**human genome (Watson and Venter 2004)**	**method for genome editing—CRISPR (Charpentier and Doudna 2012)**
	central method/ instrument used to make the discovery	statistics, probability (1814)	hydrolysis (1888)	statistics, improved (1919)	X-ray analysis, improved (1913)	electron microscope (1933)	microscope, improved (1940)	isotopic labelling (1923)	X-ray diffraction (1912)	paper electrophoresis (1948)	electrophoresis, PAGE (1964)	chromosome jumping technique (1987)	microinjection, improved (1991)	genome mapping, improved (2001)	RNA sequencing, improved (2010)

	discoveries in the field of computer science	**computing machine/mechanical computer (Babbage 1833)**	**computer programming (Lovelace 1843)**	**incompleteness theorem (Gödel 1931)**	**Turing machine (Turing 1936)**	**transistor (Shockley, Bardeen and Brattain 1947)**	**information theory (Shannon 1948)**	**compiler for developing computer codes (Hopper 1951)**	**integrated circuit/microchip (Kilby 1959)**	**World Wide Web (Berners-Lee 1989)**
	central method/ instrument used to make the discovery	mathematics (automated logarithm tables) 1822	computing machine (Babbage 1833)	mathematics, improved logic (Hilbert 1928)	mathematics, improved logic (Hilbert 1928)	cathode-ray oscilloscope (1897)	statistics/probability theory, improved (1923)	computer, Mark I (1944)	transistor (1947)	computer network (Internet) (1983)

	discoveries in the field of electricity	**nature of electricity (Franklin 1752)**	**animal electricity theory (Galvani 1791)**	**electric battery (Volta 1800)**	**electromagnetism (Oersted 1820)**	**law of electromagnetism (Ampere 1827)**	**Ohm's Law (Ohm 1827)**	**electromagnetic induction (generator) (Faraday 1831)**	**Self-inductance—principle of electricity (Henry 1832)**	**Theory of electromagnetic radiation (Maxwell 1865)**	**Alternating current (induction motor) (Tesla 1883)**	**Evidence of electromagnetic radiation (Hertz 1887)**	**Electron (Thomson 1897)**
	central method / instrument used to make the discovery	Leyden jar (1745)	Leyden jar (1745)	alternating disks (zinc and silver) (1800)	electric battery (1800)	magnetic conductor (Ampère 1822)	galvanometer (Oersted 1820)	galvanometer (Oersted 1820)	electromagnet, improved (1831)	mathematics, electromagnetic theory of light (1846)	electric generator/ dynamo (Faraday 1831)	induction coil (1836)	cathode ray tube, improved (1896)

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on [72]. Einstein then turned to Newton's laws of motion and theory of gravity as a point of reference to build on, with classical mechanics still useful today for describing everyday, macroscopic objects. Even the rare historical cases of abandoned discoveries also involve elements of cumulative knowledge that were used to go beyond them. In studying discoveries systematically, we can overcome what appears to be a discontinuity in some select theories in the past, especially about physical reality. Major discoveries and fields in contemporary science are always developed by building on our cumulative tools.

(d) A conceptual framework of the cumulative nature of science

While a hypothesis or theory put forth by a scientist can be tested by others and be more easily abandoned, the methods and fields of science encompass our extensive bodies of knowledge consolidated over time. We have not abandoned our major methods used across fields nor our major fields, while we do abandon many of our ideas and hypotheses and some of our theories—as depicted in figure 2. Testing the paradigm shift hypothesis with over 750 major discoveries that include science's major theories (theoretical discoveries), we found that the few abandoned discoveries were mostly theoretical in nature—not experimental or methodological. These discoveries were often not grounded in rigorous empirical evidence (table 1). Contrary to this hypothesis, the history of science tells a cumulative and unified story. And the story is driven by the cumulative methodological and instrumental advances we make to trigger our discoveries and fields. Researchers, however, have not studied all discoveries nor the essential role of methods and instruments in driving them, and instead focus on grand changes in particular theories and discoveries but still make general claims about 'all significant breakthroughs' and scientific progress [1]. Shifting our attention from individual hypotheses and select theoretical discoveries to all major scientific discoveries, methods and fields is a more systematic way to measure and assess the cumulative nature of science. For they make up the foundation of science and how we conduct science, and they encompass our bodies of knowledge. Cumulative knowledge is thus commonly on a spectrum: from unestablished ideas and hypotheses, then experimental findings and theories (experimental and theoretical discoveries) and finally to established methods and fields (figure 2).

The title of Kuhn's best-selling book, *The structure of scientific revolutions*, portrays the notion of vast scientific changes resembling vast political changes or revolutions. A more accurate title, given his select case studies, could have been *An account of theory change mainly in early physics*, as he did not identify an underlying structure across such shifts and they are generally slow, collective processes rather than revolutions. A more accurate account of science could be described as *An account of cumulative scientific progress embodied in scientific methods and fields*.

In general, we rework the details of our knowledge continuously as we develop new methods and collect new evidence. Evidence and explanations are works in progress that are valid until we update them using better methods and instruments that provide better evidence and explanations. Science is about creating new tools that enable revising our best theories and explanations of the world in light of new evidence. This is the nature of science. Science and scientific methods are an iterative and bootstrapped process of continual improvement. Quantum theory and the mechanisms of evolution, statistics and microscopes, chemistry and computer science are all continually refined over time as we come across new methods, problems and constraints.

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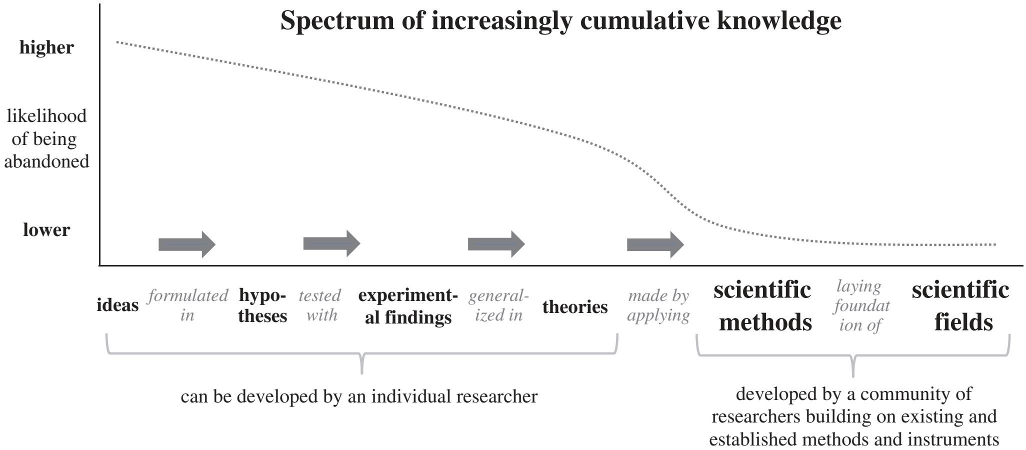

Figure 2. The cumulative nature of science: decreasing likelihood of abandoning ideas, hypotheses, experimental findings, theories, methods and fields.

4. Conclusion: evolution over revolution in science

Studying the evolution of science over history is at times viewed as not scientific because we cannot conduct controlled experiments in the past. But by applying scientific methods to systematically study major discoveries, methods and fields, we can conduct a systematic historical analysis and gain a greater understanding of science and how science advances. We observe the cumulative nature of scientific progress by assessing all Nobel Prize discoveries and major non-Nobel Prize discoveries and using three different measures of scientific progress (major discoveries, methods and fields). We observe that scientific methods and resulting discoveries are highly cumulative across fields and time. In fact, no complex scientific methods or instruments (such as mathematics, lasers and particle accelerators) and no complex scientific fields (such as biomedicine, earth sciences and atomic physics) would even be possible if they were not highly cumulative. Though, if we instead scan the history of science and focus on select theories (as some historians and philosophers of science like Kuhn have) or focus on a random sample using publications and citations (as some scientists using big data have), we can find what looks like discontinuity between those individual or select cases. Testing this fundamental question here with evidence from all major discoveries and methods across fields provides a different, cumulative answer. We find that the hypothesis of grand paradigm shifts, which govern science and replace central theories with entirely new theories, applies to only about 1% of major theoretical, experimental and methodological breakthroughs. *New and continually improved methods and tools of science better explain scientific progress than new revolutionary, paradigm-changing ideas and theories that result from those improved methods and tools.*

Scientific progress is fundamentally brought about by the methods and instruments we develop to do science and make discoveries—not just by *theory-driven* changes. The common focus on theoretical shifts reflects a final output but does not consider the methodological process we take to create, replicate and refine the output. Traditionally, discoveries and theories have been viewed as the centre of science. Methods have been viewed as constituting a temporary bridge that, once we develop the given discoveries and theories, no longer receives our attention. *We need to also place methods at the centre of science, with the discoveries and theories we develop using methods viewed as the temporary output of science, until we update them with new evidence collected using our continually expanded and cumulative methods*. This explanation of *methods-driven science* provides an alternative to the notion of winner-takes-all paradigm shifts. It better reflects scientific practice and enables us to better understand and foster scientific progress.

The findings of the highly cumulative nature of science also highlight the important role of long-term research projects, large-scale collaborations and meta-analyses in building cumulative knowledge. Meta-analyses, for example, systematically synthesize the findings of many independent studies to provide general aggregate knowledge about a body of research. They are often viewed as the most robust form of cumulative evidence in medicine as they establish knowledge in the field by providing more rigorous evidence than in any individual study. Making meta-analyses also the norm in most other related fields would push science forward towards greater overall rigour.

In terms of constraints of the study, some discoveries may be less likely to be recognized, such as in mathematics and some interdisciplinary fields (which may be under-represented from receiving the Nobel Prize) [23,73,74]. Future research could explore different time periods and aim to study even longer time frames—given that for example Nobel Prizes are awarded to living scientists and the increasing average lag between discovery and award [75–77]. Other features of the dynamics of science, discoveries, fields and scientific methodology (beyond their cumulative nature) are outlined in a series of related studies [77–80] and a forthcoming book, *The motor of scientific discovery* [81].

Because science has cumulatively expanded independent of how we theoretically conceive of scientific change, our scientific advances have not been affected by the philosophical debate on whether some exceptional theories may evolve via paradigm shifts. Given our vast bodies of cumulative methods and knowledge connected across science and the vast technologies made using them, the debate on some scientific theories evolving via paradigm shifts can be, for many empirical scientists, largely a negligible or non-existent problem. Though, researchers like Kuhn would insist that scientists are not progressing towards the truth, in the philosophical sense—for example from Ptolemy to Copernicus. Yet importantly, we can in fact speed up the pace of cumulative scientific progress by shifting our focus and conception of scientific change, namely to extending our collective methods and tools. By standing on the shoulders of giants and cumulatively expanding our *methodological toolbox*, we will continue to see further and develop new discoveries, life-saving medicines and technologies.

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

Declaration of AI use. I have not used AI-assisted technologies in creating this article.

Authors’ contributions. A.K.: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing—original draft, writing—review and editing.

Conflict of interest declaration. I declare I have no competing interests.

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Appendix

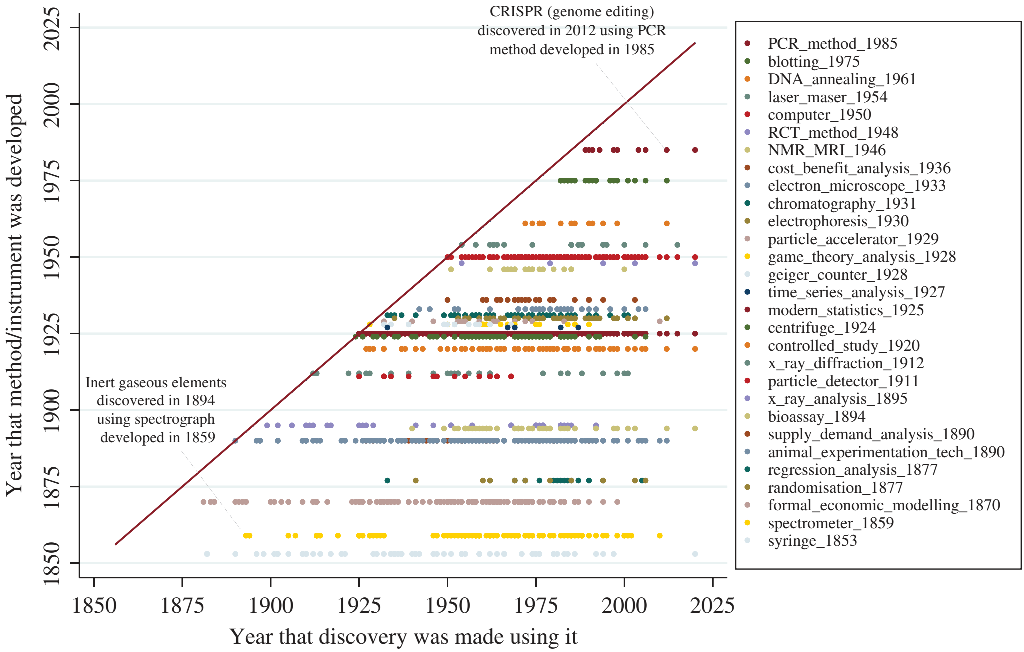

Figure 3. The cumulative use of methods and instruments commonly applied in making science's major discoveries, from 1875 to 2022. Data reflect all 620 discoveries made since 1875, including all nobel-prize discoveries, using common methods and instruments developed since 1850 that have each been applied in making five or more discoveries. Each discovery that applies multiple methods is reflected by multiple dots in the figure. That is, each row reflects all the discoveries that used the given method. The year reflects when the method or instrument was first developed. The year 1925 is applied here as the year modern statistics was developed, as this is when Ronald Fisher, commonly viewed as the father of the field, published 'Statistical Methods for Research Workers', which marked the first full-length book on statistical methods and was critical in establishing and spreading modern statistics. (62) The standardised use of controlled studies became more commonly applied around 1920. Animal experimentation techniques became standardised and widespread since around 1890, including the production and preparation of animals for experimental purposes.

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