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# Science's greatest discoverers: a shift towards greater interdisciplinarity, top universities and older age

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What are the unique features and characteristics of the scientists who have made the greatest discoveries in science? To address this question, we assess all major scientific discoverers, defined as all nobel-prize and major non-nobel-prize discoverers, and their demographic, institutional and economic traits. What emerges is a general profile of the scientists who have driven over 750 of science's greatest advances. We find that interdisciplinary scientists who completed two or more degrees in different academic fields by the time of discovery made about half—54%—of all nobel-prize discoveries and 42% of major non-nobel-prize discoveries over the same period; this enables greater interdisciplinary methodological training for making new scientific achievements. Science is also becoming increasingly elitist, with scientists at the top 25 ranked universities accounting for 30% of both all nobel-prize and non-nobel-prize discoveries. Scientists over the age of 50 made only 7% of all nobel-prize discoveries and 15% of non-nobel-prize discoveries and those over the age of 60 made only 1% and 3%, respectively. The gap in years between making nobel-prize discoveries and receiving the award is also increasing over time across scientific fields—illustrating that it is taking longer to recognise and select major breakthroughs. Overall, we find that those who make major discoveries are increasingly interdisciplinary, older and at top universities. We also assess here the role and distribution of factors like geographic location, gender, religious affiliation and country conditions of these leading scientists, and how these factors vary across time and scientific fields. The findings suggest that more discoveries could be made if science agencies and research institutions provide greater incentives for researchers to work against the common trend of narrow specialisation and instead foster interdisciplinary research that combines novel methods across fields.

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## Introduction

Science has fundamentally shaped the course of human history through great advances, but we still do not know well the unique characteristics and traits of the individuals who have made those advances. This question of the particular features of science's great discoverers has intrigued both scientists and the general public. Classic work on scientific discoveries and the traits of discoverers goes back at least to Bolesław Prus (1873), Florian Znaniecki (1923), Galton's (1874) *English men of science: Their nature and nurture* and especially influential has been Zuckerman's (1977) *Scientific Elite: Nobel Laureates in the United States*. Zuckerman, a leading sociologist of science, interviewed Nobel laureates in the US about their backgrounds, family and research. She pioneered the study of the demographic and social characteristics of these prominent scientists, providing insight into the lives of Nobel laureates on attributes like social status, age, gender, religion and ethnicity (Zuckerman 1977). The common approach in existing studies has been to study a sample of discoverers in a given time period, scientific field or country like the US or UK (Li et al., 2020; Chan and Torgler, 2015; Leroy, 2003; Schlagberger et al., 2016; Sherby, 2002; Thompson, 2012; Ye et al., 2013; Breit and Hirsch, 2004; Bjork et al., 2014). Yet this does not allow us to make general claims about science's major discoverers. We thus do not yet have representative data for science's major discoverers and how they differ across countries and time on the broad range of demographic and institutional characteristics. Systematically understanding the characteristics of science's major discoverers in a representative way has not yet been possible, without first compiling comprehensive data on all major discoverers and their features and traits (ibid.).

To address the challenge, this study assesses science's major discoverers by adopting a global scope and evaluating all nobel-prize and major non-nobel-prize discoverers across the history of science. This new data enables compiling a general profile of the scientists who made science's greatest breakthroughs and outlining how their background features relate to their success. Recently, researchers have studied the features of scientists often individually for a sample of scientists; here we instead assess the broad range of demographic features of all nobel-prize and major non-nobel-prize discoverers: age (Wang and Barabási, 2021; Sinatra et al., 2016; Jones et al., 2014; Zuckerman, 1977), education level (Chan and Torgler, 2015; Zuckerman, 1977), interdisciplinary background (Szell et al., 2018), gender (Zeng et al., 2016; Lunnemann et al., 2019), country of residence (Lepori et al., 2019; Danús et al., 2023; King, 2004; Scellato et al., 2017) and religious affiliation (Zuckerman, 1977), but also their institutional features including discoverers' university ranking (Schlagberger et al., 2016; Ioannidis et al., 2007; Krauss et al., 2023) and their broader social and economic features including population size and income per capita of the country in which they lived (King, 2004) at the time of discovery (see also Krauss 2024). Rather than commonly focusing on one factor, we compile data on this broader set of factors and analyse them all to gain a more general understanding of the overall context in which discoverers work. We uncover common patterns in the background features and traits of these eminent discoverers across scientific fields and history. We find that breakthrough science has transformed over the past few decades, with a shift towards greater interdisciplinary education and methodological training, top universities and older age among science's prominent discoverers.

While there are advantages to focusing on a narrow research question in scientific studies, there are also instances when focusing on a broader, more comprehensive research question can be more appropriate. To be able to provide a more comprehensive overview of the features of science's major discoverers in a single study requires assessing the broader range of demographic, institutional and economic features. This enables us to better understand the broader context and identify overarching trends influencing discoverers that a more narrow study cannot. Understanding the features of science's major discoverers is important because it helps identify patterns and key features we can foster, which is useful information for hiring committees, university departments, funding bodies and academic journals.

By identifying the unique traits and features of discoverers, we provide insights into the evolution of the scientific system over time. We observe the degree to which the system is becoming more closed to particular groups. Researchers outside of North America for example made about 35% of major discoveries since 1950 but used to account for the majority, and younger researchers under 33 made less than 20% of major discoveries since 1950 but used to account for almost 35% beforehand. The scientific system also remains highly closed to female researchers, making less than 6% of major discoveries since 1950 (and 4% beforehand). We also provide insights into how we can support future prominent scientists and an inclusive and innovative scientific community that fosters discovery.

## Data and methods

This study compiles data on all major scientific discoveries. These are defined as all 533 nobel-prize-winning discoveries in science (from the first year of the prize in 1901 to 2022) and all other major discoveries that were made prior to or did not receive a Nobel prize; these are derived from all science textbooks (a total of seven) that provide a list of the greatest 100 scientists and their discoveries and that span across scientific fields and history (with textbooks specific to a field or time period not included) (Tiner, 2022; Salter, 2021; Gribbin, 2008; Rogers, 2009; Simmons, 2000; Balchin 2014; Haven, 2007). After excluding duplicate cases within the seven textbooks, 228 other major discoveries remained. A total of 761 major discoveries made by 982 discoverers have thus been included in the study. Results for the major non-nobel-prize discoveries provide an independent control and robustness check for validating results of the nobel-prize discoveries, and we also compare results across fields and over time. These discoveries make up the foundation of the sciences—ranging from microbiology and astrophysics to cognitive science and computer science. Moreover, the science textbooks were published in recent history and thus consider influential discoveries retrospectively using current scientific standards while Nobel Prizes awarded for instance a century ago reflect influential discoveries at the given time but are nearly all also considered influential today. The major non-nobel-prize discoveries include the eminent discoverers of science that did not earn a Nobel prize but helped lay the foundation of science: from Galileo, Newton, Hooke, Boyle and Maxwell to Pasteur, Darwin, Mendeleev and (Rosalind) Franklin.

Describing the traits of the discoverers and their broader environment requires linking discoveries to those traits and conditions. To do so, the main sources for compiling the data on discoverers' age, education level, gender, country of birth and residence are Encyclopaedia Britannica (2023) and official Nobel Prize (2023) documentation. After exhausting these sources, the remaining data are derived from five other encyclopaedias of science (Daintith, 2009; Bunch and Hellemans, 2004; Oakes, 2007; Simonis, 1999; Lerner and Lerner, 2004) and the seven indicated science textbooks. Data on discoverers' university ranking are derived from QS World University Rankings (2021), data on the population size and income per capita of the country in which they lived are derived from the Maddison Project Database (2018) and most data on their religious affiliation are derived from Sherby (2002), and otherwise from other scientific publications and contacting living Nobelists via email (see the Supplementary Appendix for more details). All data for relevant variables have been confirmed with encyclopaedic sources. Data on the year of discovery, the university affiliation of the discoverer at the time of the discovery and the methods and instruments used in making the discovery are derived from the discovery-making publication. In total, with over two dozen variables for each of the 761 discoveries, a total of over 20,000 data points have been collected. A fifteen-month period of data collection was required to gather the data for all variables. All data in the study reflect the year the discovery was published—unless explicitly stated that data reflect the year the Nobel prize was awarded. Here the features of discoverers in the year they made the discovery are thus collected and analysed which enables us to describe factors that can influence discoveries—rather than just collecting data for nobel-prize-winning discoverers at the time they receive the award. For the average Nobel laureate receives the prize 21 years after making the discovery and many of their features that influenced their discoveries have changed. Greater detail on the data collected for a given variable is provided when introduced in each section of the results. We apply descriptive statistics to assess the evolution over time and across scientific fields of this range of demographic, institutional and economic features of science's greatest discoverers.

## Results and discussion

**Nearly all discoverers have a PhD and most have an interdisciplinary education that enables greater training in different methods to make breakthroughs**. In assessing the demographic, institutional and economic traits of science's major discoverers, we first explore the role of education as an initial step in scientists' training. We find that 88% of all major discoveries since 1600 (when doctoral awards began to spread) have been made by researchers with a PhD at the time of discovery and the share increases to 96% for all nobel-prize discoveries (awarded since 1901). Most researchers making discoveries are thus highly trained. As science has expanded, the level of complexity we study increases along with the level of sophistication in the methods and instruments we use to be able to study that complexity. Today, to make new discoveries we thus generally require training in advanced methods and instruments—such as electron microscopes and sophisticated statistical methods—and acquiring extensive bodies of knowledge.

In general, two central ways we gain knowledge in science are by assessing how a phenomenon changes over time (historical analysis) and by assessing groups of a population comparatively to identify differences between them (comparative analysis). Studies that just collect data for one group of a population at one point in time provide only a part of the evidence which commonly varies over time and groups. Both analyses together broaden our general understanding—as highlighted in Fig. 1.

Over the history of science, dozens of great discoverers completed at most only secondary schooling, including Faraday, Tesla and Dalton. Yet by acquiring knowledge on their own and with the aid of newly developed instruments like the galvanometer, electric generator and eudiometer, respectively, including mathematics, these scientists were able to make major discoveries. While university education facilitates knowledge and training in methods, it has thus not always been a necessary condition for making discoveries in the past.

Across Europe, universities spread especially since the 14th and 15th century, when most discoverers still had no formal education (Fig. 1a). Since the 18th century, more and more discoverers are likely to have a PhD and to be a professor. Ten nobel-prize discoveries (accounting for 2% of such discoveries) have however been made by researchers with only a Bachelors degree at the time of discovery. These include for example the discoveries by Leo Esaki, Ivar Giaever and Brian Josephson who received the Nobel Prize in physics in 1973 for their work on tunnelling semiconductors, superconductors and supercurrent. Yet we find that all discoveries since 2000 have been made by professors (with a PhD) (Fig. 1a). Medicine is one of the most professionalised and applied fields, with all nobel-prize discoverers completing an MD or PhD but only about 60% being a professor. In contrast, over 75% of nobel-prize discoveries in chemistry, astronomy, and economics and social sciences are made by professors (Fig. 1b)—though they are commonly younger and more recent professors (as illustrated later).

What role does an interdisciplinarily education and training play among science's great discoverers? While it is the norm today for scientists to specialise and work in one field, we find that most nobel-prize discoveries, a total of 54%, have been made by scientists who completed two or more degrees in different academic fields by the time of the discovery—with the share at 42% for major non-nobel-prize discoveries over the same period (as an independent control). In medicine and biology, discoverers are most likely to have received degrees in two or more fields, at 69%. In comparison, in physics the share is 39%, meaning that physicists are much more likely to specialise (Fig. 1d). These large differences between fields can be explained by the historical structure of the scientific system, with physics traditionally organised as a standalone discipline with well-defined subfields while medicine and biology often require greater interdisciplinary training partly due to the interdisciplinary nature of the life sciences and the complexity of living systems. Interdisciplinary education is on the rise, with over 70% of all discoveries since 2000 made by scientists who completed two different degrees. As a comparison, about 25% of US doctorate recipients earned a master's degree in a field different from their doctorate, according to a US census of scientists in 2021 (NSF, 2021). Simply put, Nobel laureates are trained more broadly than their peers.

An interdisciplinary education equips researchers with skills in methods and instruments from different fields. Interdisciplinary training puts a wider range of methods in our hands and also enables us to merge methods and develop new integrated methods. Applying a method from one field to another field or combining methods and knowledge from different fields in innovative ways has been central to producing many novel ideas and discoveries. It allows us to bridge the gap between disciplines, integrate perspectives and adopt a completely new approach to address complex questions and generate novel ideas. The physicist Max Delbrück for example turned to biology in the 1930s but used novel methods from physics—the newly developed electron microscope and statistical methods. Using these unconventional methods he was able to address unanswered questions in genetics and show that bacteria develop via mutations. This research helped open the field of molecular genetics. Konrad Bloch completed degrees in chemical engineering and biochemistry that enabled him to apply new isotopic labelling methods to discover the mechanism and regulation of cholesterol. Frederick Sanger studied natural science, biochemistry and medicine, and combined his methodological training to create techniques for sequencing DNA using new gel electrophoresis methods (Sanger et al., 1977). Donna Strickland studied engineering physics and optics and Gérard Mourou studied physics and then worked together applying new laser tools to develop the breakthrough method of ultrashort high-intensity laser pulses. Hermann von Helmholtz received a PhD in medicine and also studied physics and mathematics, allowing him to apply novel mathematical principles and physical analysis which other physiologists did not. This enabled him to make the foundational discovery of the principle of the conservation of energy that

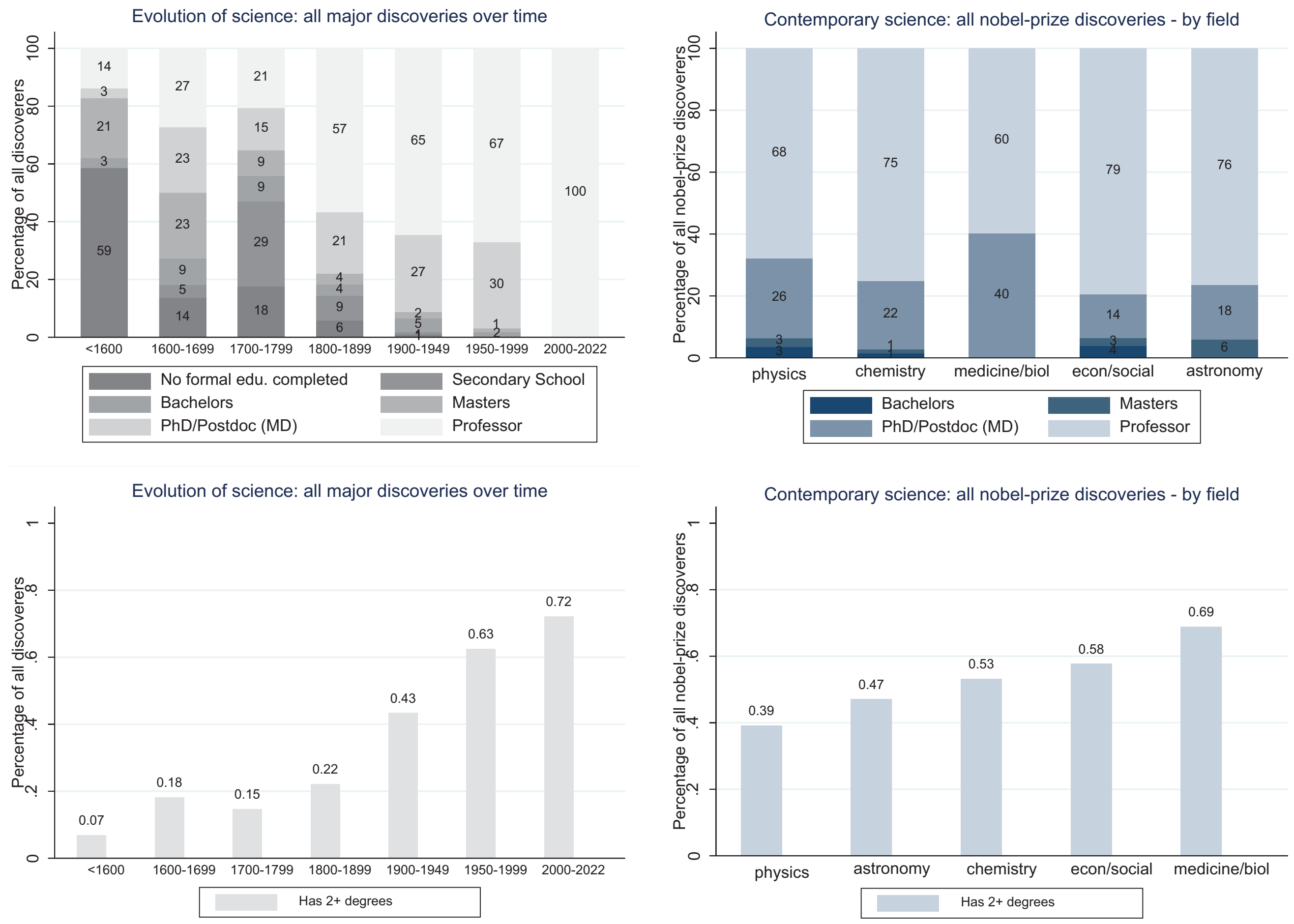


**Fig. 1 A sharp rise in levels of education and interdisciplinary background of discoverers, across time and fields.** Data reflect all 761 major discoveries (including all nobel-prize discoveries) (**a**, **c**), and all 533 nobel-prize discoveries (**b**, **d**). All professors have a PhD. Discoverer has interdisciplinary degrees is defined as having two or more degrees in different disciplinary fields. Universities were founded since the late 14th century and have provided formal education and degrees since then (Hellyer, 2003). Analysis expanding the data in Figure d to include, in addition, the other major discoveries that did not earn a Nobel prize but were made within the same time period (633 discoveries in total) provides a robustness check, illustrating that for example the share of discoverers with two or more degrees are 38%, 58%, 51%, 56% and 65% across these five fields, respectively.

helped transform a part of physiology and physics (Encyclopaedia Britannica, 2023a). Svante Pääbo studied humanities and later medicine, and then did his postdoctoral studies in molecular biology and later became the director of the Max Planck Institute for Evolutionary Anthropology in Leipzig (Encyclopaedia Britannica, 2023b). His interdisciplinary background and interests enabled applying new and improved DNA sequencing methods to discover the Neanderthal genome (Richard et al., 2010). Rosalind Franklin studied physical chemistry and then turned to biological questions to be able to provide the first images of the double-helix structure of DNA using x-ray diffraction methods developed in physics.

In general, there is a trade-off at play. As bodies of knowledge continue to expand over time (Jones, 2009) and the range of methods we use to develop that knowledge, the result has been narrower specialisation among researchers across science. Yet our ability to make novel connections and major discoveries is often directly related to our ability to apply methods and approaches from across scientific domains. While the universal scholar is an ideal of the past, we find that the small share of researchers who make major discoveries and push the research frontier are more likely to have defied the present trend towards specialisation. Science's large body of specialised researchers is more likely to incrementally dent the research frontier little by little. Smaller contributions may seem less spectacular than large interdisciplinary breakthroughs that provide new lenses to the world, but they also contribute to the overall progress of science.

Moreover, we also observe interdisciplinary reasoning in the use of analogies in scientific discoveries, in which a concept from one scientific field is connected to a concept from a distant field. Analogies used by discoverers thus involve at times cross-disciplinary conceptual mapping (see analogy section in the Supplementary Appendix and Supplementary Appendix Table 2).

**The golden age range of high productivity and impact: half of all discoveries are made by scientists aged 35–45 years**. Thomas Kuhn argued that 'Almost always the men who achieve these fundamental inventions of a new paradigm [or major breakthrough] have been either very young or very new to the field whose paradigm they change. … for obviously these are the men who, being little committed by prior practice to the traditional rules of normal science, are particularly likely to see that those rules no longer define a playable game and to conceive another set that can replace them' (Kuhn, 1962/2012). Kuhn developed this hypothesis of the young or new scientist entering a given field in an innovative way based on his study of a small sample of theoretical discoverers largely in physics in the early 1900s such

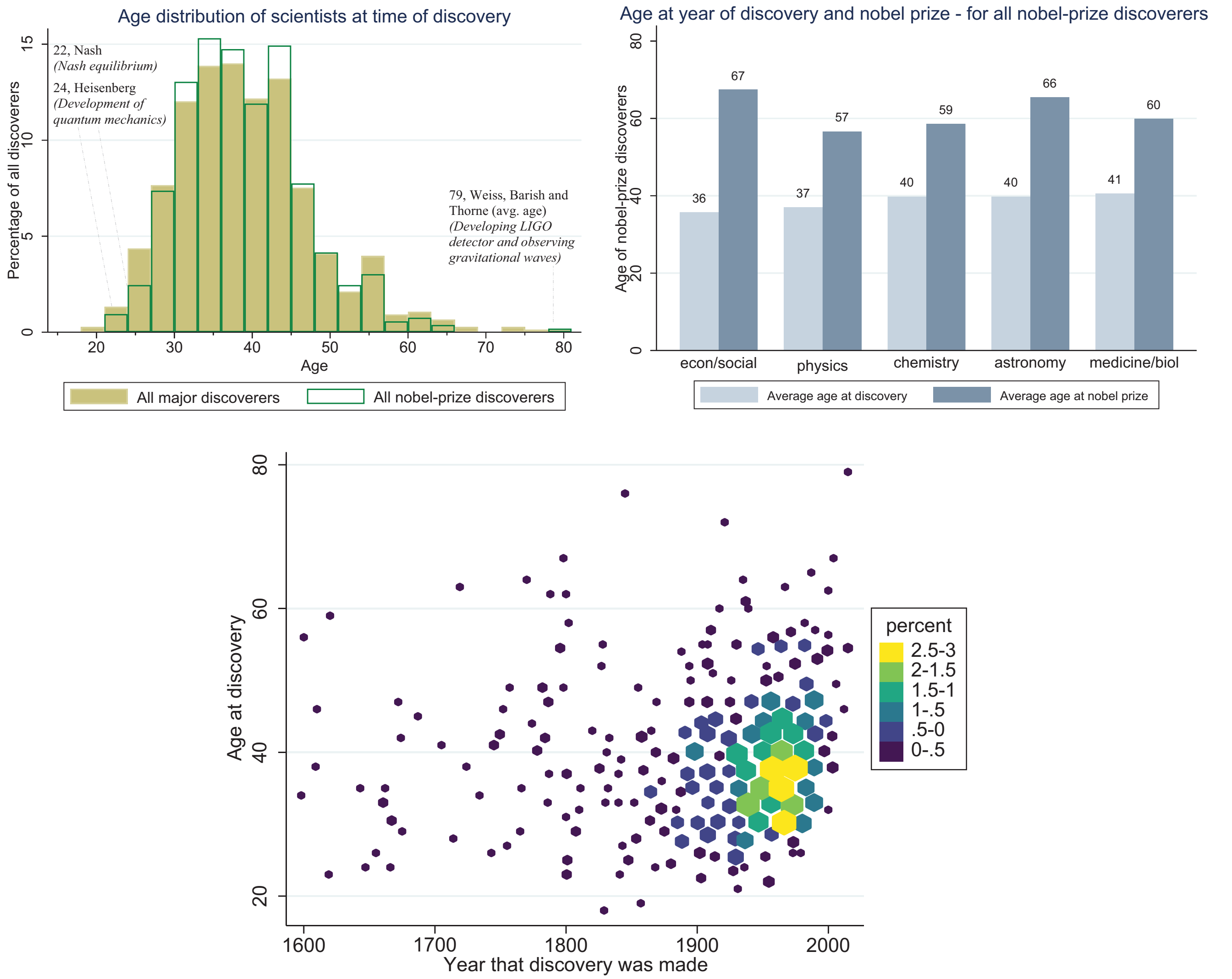


**Fig. 2 The golden age range of high productivity and impact in science is between 35 and 45 years of age.** Data reflect all 761 major discoveries (including all nobel-prize discoveries) (**a**), all 533 nobel-prize discoveries (**a**, **b**) and all 727 major discoveries since 1575 including all nobel-prize discoveries (**c**). In **c**, the size of the hexagons corresponds to the share of discoverers of that age in that year.

as Einstein. We test the hypothesis here using data on all major discoveries. Einstein was indeed only 26 when he published his nobel-prize-winning paper on the law of the photoelectric effect in 1905. As Einstein also claimed, 'A person who has not made his great contribution to science before the age of 30 will never do so' (cf. Rabesandratana, 2014). Yet the conditions in physics at Einstein's time do not reflect science today. We find that the golden age range of high productivity and impact in science is between 35 and 45 years of age. Exactly 50% of all Nobel laureates in science fall into this age range when making their prize-winning discovery, with an average age of 39 years at the time of discovery (median 38). Only 7% of all nobel-prize discoveries and 15% of major non-nobel-prize discoveries over the same period (as an independent control) were made after the age of 50 and only 1% and 3% after the age of 60, respectively. Today, we can thus say that a person who has not made their great contribution to science before the age of 60 is very unlikely to do so (whether a nobel-prize or major non-nobel-prize discovery). At least for nobel-prize discoveries, this can be explained by average life expectancy at present and the average 21-year gap between making the discovery and receiving the prize. Yet on average, Nobel laureates in science are 60 years old when they receive the prize for the discovery (median also 60). These findings are also compatible with the view that younger, untenured researchers may be more motivated to try to make a new discovery than older, tenured researchers with secure positions.

Analysing scientists' age at the time of discovery should be done by examining different time periods separately. This is because scientists in the past did not yet have today's advanced methods and instruments and commonly did not have to build on as much existing knowledge—and they also did not live as long. We find that before 1900, 30% of discoveries were made before age 32, and the share reduced to 23% between 1901 and 2000, but since 2000 it dropped to less than 6%. The average age at the time of discovery rose from 38 for those made between 1901 and 1950, to 40 between 1951 and 2000, and 50 between 2001 and 2022.

Making discoveries at a very young age has thus become rare because acquiring the needed methodological training and comprehensive knowledge to be able to discover something new takes longer. For our methods have become much more complex and our bodies of knowledge more vast. There is thus more training and research to get through before reaching the research frontier, which continuously gets redrawn with newly developed methods and knowledge. This helps explain in part why *low-hanging-fruit* discoveries have largely been picked. Younger researchers, particularly those who have just completed their university education and are just entering a field, can have more recent and up-to-date training in the latest methods and technologies. They can also have a fresh perspective on existing problems, without accepting established assumptions, and be more open to exploring new approaches and techniques (though they may not have as deep an understanding of their field).

We find that nobel-prize-winning economists are the youngest group when making their discovery at an average age of 36 (see Fig. 2b). It is the youngest field (with less knowledge) and has the largest share of theoretical breakthroughs which can require less work to build on. But economists wait the longest to be awarded the Nobel prize, an average of 31 years. The age distribution of discoverers is illustrated in Fig. 2a.

In the past, some researchers made a major breakthrough very early in their careers. Chandrasekhar described the physical processes of the evolution of stars at age 21—which makes him the youngest scientist who made a nobel-prize-winning discovery. He was closely followed by Josephson who discovered tunnelling supercurrents at 22. Nash created the concept of Nash equilibrium at 22. Arrhenius developed the electrolytic theory of dissociation at 24. Heisenberg, Dirac and Bohr made their major contributions to quantum mechanics at 24, 26 and 28, respectively. All received a Nobel prize for these breakthroughs. A few centuries ago, some researchers also had no formal education when making the discovery such as Joule who discovered Joule's law at age 23, Pascal who developed Pascal's law at 24 and Germain who discovered Germain's theorem at 25. Today, it is extremely difficult to make a major discovery at such a young age. The increasing age of researchers at the time of discovery is illustrated in the heatmap in Fig. 2c.

Moreover, the gap in years between the nobel-prize discovery and award is also increasing over time across all fields—see Supplementary Appendix Figs. 1 and 2. This could be explained by the fact that the bigger the discovery the quicker it becomes awarded, and the vast importance of many major discoveries in the early 20th century was quickly realised and awarded. We find that discoveries awarded with a Nobel prize within five years of being made include for example DNA sequencing, the neutron, superconductivity, quarks and X-ray diffraction.

**Only about a third of discoverers since 1950 worked at top 25 universities which can help provide greater access to resources and sophisticated instruments for making discoveries**. After exploring the role of university education among researchers and their age, we next analyse whether researchers at top universities are more likely to make breakthroughs. We find that 30% of all nobel-prize discoverers are at a top 25 ranked university in the world. The share is also 30% among major non-nobel-prize discoverers over the same period (as an independent control), illustrating robust results between the two groups. Globally however, less than 1% of all researchers worldwide—an estimated 0.6%—are based at one of the top 25 universities (Supplementary Appendix for calculations of global estimate). Expanding the scope to the top 50 universities we observe that 38% of all nobel-prize discoverers and 34% of major non-nobel-prize discoverers were at such a university when making their discovery. Some of the world's largest and most sophisticated particle accelerators, radio telescopes, electron microscopes, laser interferometers and advanced x-ray methods used for making discoveries are concentrated at the best universities in the world. Though many of our most common scientific methods and instruments used to make major discoveries are inexpensive, such as statistical and mathematical methods, light microscopes, electrophoresis, assay techniques, chromatography methods and centrifuges. Being at a top university can nonetheless provide researchers with a comparative advantage in accessing sophisticated laboratory facilities. It can also provide greater access to resources, funding and networks of leading researchers, as well as higher salaries (which are among the highest worldwide at these institutions).

We observe that most discoverers in astronomy, and economics and social sciences were at a top 50 university. In these fields, there was moreover about a 15% increase in moving to a top 50 university after making the discovery, with about three-fourths of discoverers at such universities when receiving the Nobel prize (Fig. 3b). With only one-quarter of discoverers thus not at a top 50 university at that time, we can observe the high premium that academic institutions place on attracting world-leading researchers. Yet it is important to note that those who select to go to top universities are also often the most dedicated and ambitious. More generally in terms of mobility, most nobel-prize discoveries (55%) were made by scientists at a different academic institution in the year of discovery than in the year they received the prize.

Scientists at five elite universities at the time of discovery—Cambridge, Harvard, Berkeley, Chicago and Columbia (in that order)—account for 16% of all nobel-prize discoveries (84 discoveries in total). Scientists at just ten universities account for 25% of all nobel-prize discoveries.

**The very low share of female discoverers and the role of collaborations in discoveries**. We next assess gender disparities and find that breakthrough science remains heavily biased towards males. We find that women account for only 5% of all scientists who made a major discovery and only 3% of all Nobel laureates. The rewarding of scientific breakthroughs remains rigidly male-dominated across all fields: in physics, only 2% of nobel-prize discoveries have been made by women, while the share is 6% in astronomy and 7% in medicine (Supplementary Appendix Fig. 3). Women who have made groundbreaking contributions to various fields include Marie Curie's discovery of radium and polonium, Ada Lovelace's work on early computer programming, and Donna Strickland's research on developing high-intensity, ultra-short laser pulses that are used in surgeries.

A number of major discoveries have been in large part made by women who did not receive credit or a Nobel prize for their work. One classic example is Rosalind Franklin who applied the method of x-ray diffraction to be able to make one of the greatest discoveries of the 20th century, identifying DNA's double-helix structure. Crick, Watson and Wilkins received the Nobel Prize for the work that builds on her research directly after she passed away. A central explanation for the very low levels of female Nobel laureates is that women have been systematically discriminated in accessing education and science throughout history. Women have been underrepresented in many fields and faced barriers to accessing opportunities for research, especially in science, technology, engineering and mathematics (STEM) fields. The unfavourable norms about the role of women in science have begun to improve since the second half of the 20th century and especially in the 21st century (Zeng et al., 2016). Consequently, we find a positive trend, with more than half of all female Nobelists ever awarded the prize receiving it since 2000.

Next, what role do collaborations play in science? Science is a collective effort. No nobel-prize-winning discovery in science has actually been made or could have been made by a single scientist in isolation without building on the methods and work of others. But surprisingly most nobel-prize discoveries feature a single scientist. How is that possible? There is a discrepancy between how science is conducted and how it is awarded and taught in education systems. Textbooks on the greatest scientists and discoveries are also generally

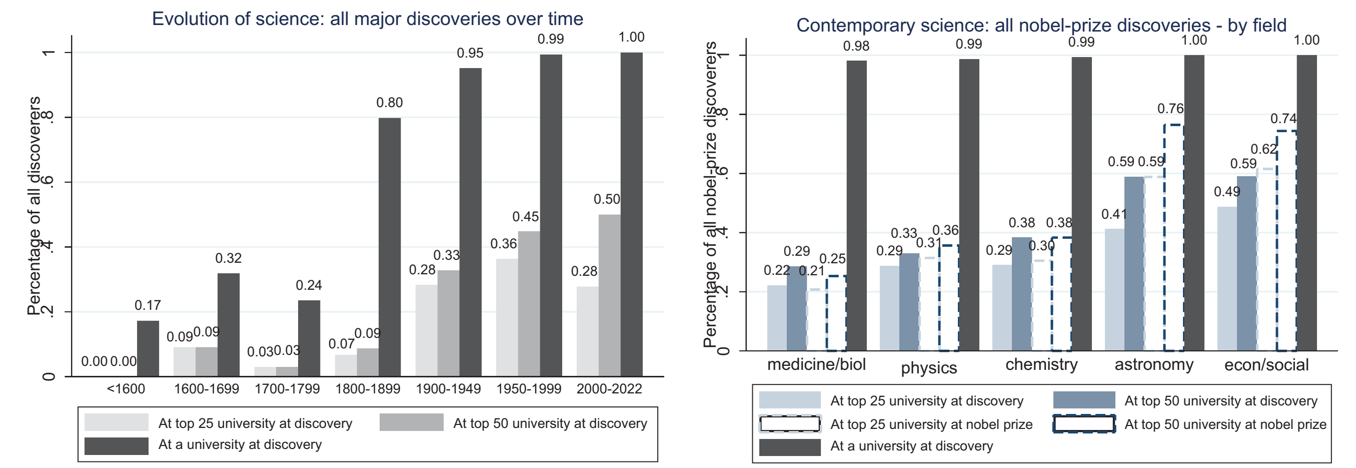


**Fig. 3 An increase in discoverers at the top 25 and 50 universities worldwide, across time and fields.** Data reflect all 761 major discoveries (including all nobel-prize discoveries) (**a**), and all 533 nobel-prize discoveries (**b**). Data represent the discoverers' university affiliation at the time of discovery, using the university ranking in 2021 as a common reference point for all discoverers. Most top universities have remained among the top universities over time (for years with available data), though data on ranking are not available for earlier centuries. The data for earlier centuries should be interpreted with caution: while the majority of discoverers lived at the time the top 50 universities today existed, some top 50 universities today did not exist for some discoverers in the 1500s to 1800s (**a**). Using data from QS World University Rankings 2021, university ranking is measured by output metrics like citations and academic reputation. Analysis expanding the data in **b** to include, in addition, the other major discoveries that did not earn a Nobel prize but were made within the same time period (633 discoveries in total) illustrates nearly identical results and serves as a robustness check, with for example the share of discoverers at a top 25 university at the time of discovery at 22%, 28%, 29%, 42% and 48% across these five fields, respectively.

structured in such a way to highlight the most influential scientist, or the last scientist, in the process of making a discovery, who generally receives all the credit (Tiner, 2022; Salter, 2021; Gribbin, 2008; Rogers, 2009; Simmons, 2000; Balchin, 2014; Haven, 2007). Sometimes recognition is expanded to encompass a few scientists.

The average number of researchers awarded a Nobel prize for making a given discovery is 1.4 individuals (which does not reflect the number who shared the prize at times for different discoveries) (Supplementary Appendix Fig. 3). A major discovery is however often achieved by a community of researchers, working in cooperation and competition. Researchers within a community require building on existing tools and research that account for important contributions towards the discovery. Returning to the example of DNA's double-helix structure, the theory was not just developed by Watson and Crick. But it was enabled by the pivotal x-ray work produced by Franklin as outlined above and her student Gosling, without which producing the image of the double helix would not have been possible that required applying x-ray diffraction methods developed by von Laue (who used x-radiation identified by Röntgen), and was built on initial work by Miescher and supported by parallel work on DNA structure by Wilkins and his group of colleagues, among many others (Watson, 1969). The Nobel prize in chemistry in 1962 was awarded to Perutz and Kendrew for discovering the structures of globular proteins, but in Perutz's nobel-prize speech he gives credit to 21 researchers for their essential methodological, experimental and theoretical contributions needed to be able to make the discovery in the first place (Nobel Prize, 1962). In general, some scientists create the needed methods and instruments to be able to carry out the research, others may then make the observational and experimental findings, and others may finally develop a theoretical explanation for those findings. Taken together, a discovery is commonly made possible by the less known but equally important researchers who develop the needed tools and the smaller advancements that are cumulatively built on towards the larger discovery—or last breakthrough in a set of interconnected breakthroughs.

Discovering the Higgs boson and the multiple mechanisms driving evolution for instance have required the collective effort of hundreds of researchers working together. In general, larger teams are becoming more common in science, and generally improve the quality and impact of research (Xu et al., 2022; Wuchty et al., 2007; Wu et al., 2019; Danús et al., 2023). For larger teams are better able to apply different methodologies and combine them, integrate more expertise and develop new combinations of ideas—with multiplier effects among interdisciplinary collaborations. Larger teams enable pooling resources for more advanced and cutting-edge instruments, and generally have greater access to different technologies and laboratory equipment. They also provide a built-in peer review process as team members can review and critique each other's work. Overall, focusing on a few scientific superstars neglects the important scientists who lay the foundation before them and make the last step towards discovery possible.

The traditional structure of the Nobel prize that only allows up to a maximum of three winners per field each year and often allocates credit for a discovery, for simplicity, to an individual researcher does not reflect actual scientific practice. It instead institutes a winner-takes-all mentality and endorses a 'lone genius' stereotype in science. It is simpler for science textbooks, teaching science, awarding prizes and the media to associate a discovery with a single name rather than with the community of scholars who developed the discovery. And this is part of the reason why they do so. But simplicity comes at a cost: it distorts the image of science, how the scientific and discovery process works and how to leverage new major advances. We need to thus reform the structure of the Nobel prize to reward not just individuals but also research teams, as well as the triangle of researchers who make the methodological, experimental and theoretical discoveries.

**Country-level, historical and cultural factors: the scientific system is becoming more closed to researchers outside North America who no longer account for most discoverers**. We next analyse differences across countries that help shape access to

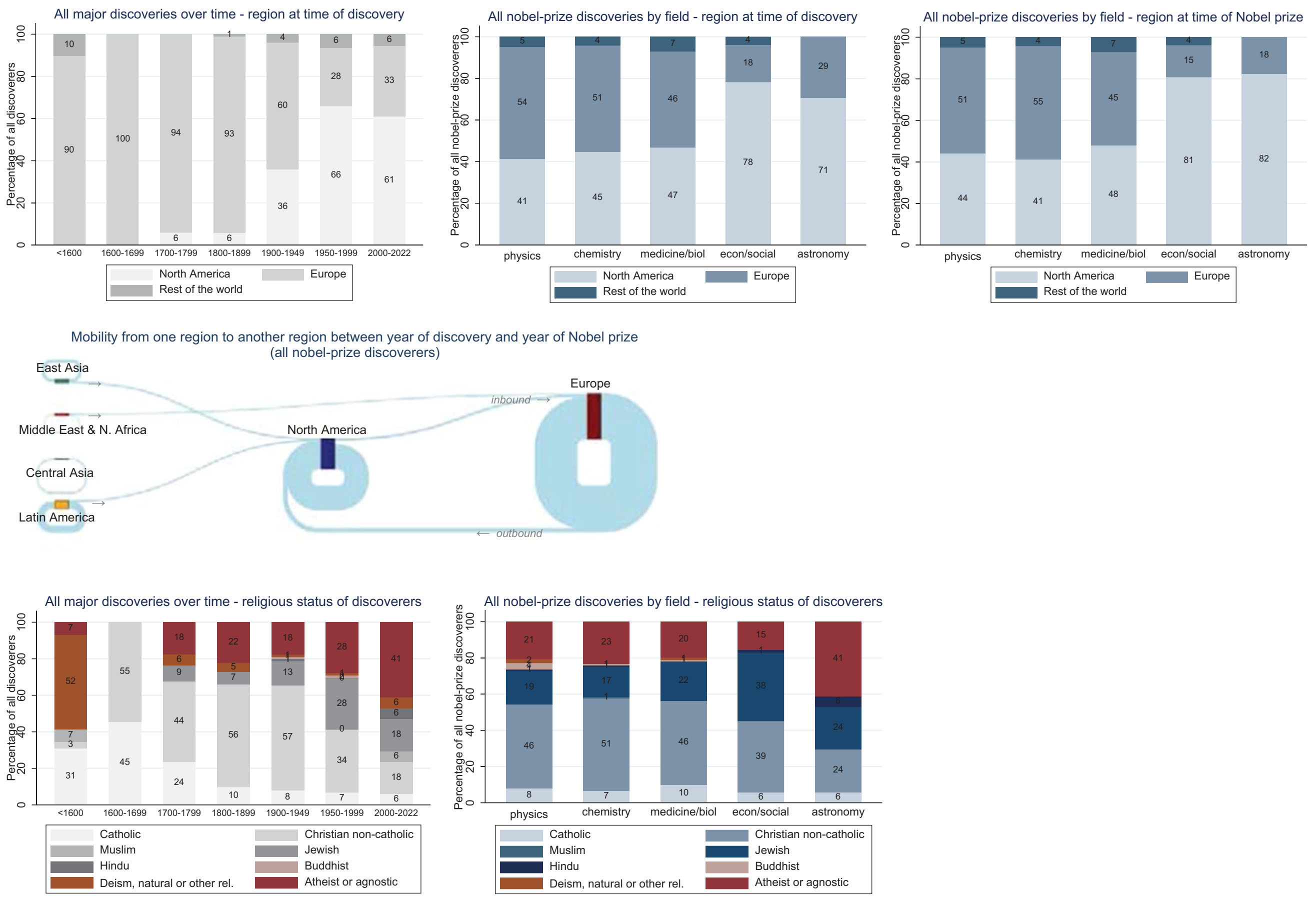


**Fig. 4 Shifts in geographic location and religious status of discoverers, across time and fields.** Data reflect all 761 major discoveries (including all nobel-prize discoveries) (**a**, **e**), and all 533 nobel-prize discoveries (**b**, **c**, **d**, **f**).

resources and attitudes to science, and are linked to the location and concentration of top universities in the world (Schlagberger et al., 2016). We find that over 90% of discoveries up to 1900 were made by scientists living in Europe at the time of their discovery, but the share dropped to 41% over the period 1900 and 1999, reaching about one-third between 2000 and 2022. East Asia is on the rise, accounting for about 6% of discoverers since 2000. In physics and chemistry, most nobel-prize discoverers (1901–2022) lived in Europe when making their discovery. Economics is the field with the highest concentration in North America (Fig. 4b). Historically, German scientists led the world in nobel-prize discoveries, measured in both absolute and relative terms, compared to scientists from any other country. They accounted for about one-quarter of all nobel-prize discoveries up to 1930 at 24%, with British scientists falling in second place who accounted for 16% of discoveries. Fascism in Germany and World War II however led to a shift. World-leading scientists, top journals and institutions moved from Germany to the US and UK. The shift reflects the unintentional effect of fascism on the rise of anglophone science. Tracing all nobel-prize discoverers over their lives—from their country of birth to the country at the time of their discovery and then country at the time of receiving the Nobel prize—illustrates this geographic mobility to the US (Supplementary Appendix Table 1).

Country residence plays a similar role as university affiliation but at a more aggregate level. The country in which researchers reside can affect their access to different scientific instruments, funding availability, infrastructure and government support. Countries with stronger economies and public support often have more specialised laboratories and more advanced technological and computing facilities that can be needed for making some discoveries. Researchers in poor economies can have a disadvantage in fields that require certain cutting-edge technologies.

Research institutions in countries with greater facilities, prestige, salary and technologies thus attract the best researchers and foster discoveries. We find that between 2000 and 2022, 61% of all discoveries were made by scientists living in North America but over half of all discoveries over this period were made by scientists born outside North America, most of whom coming from continental Europe. This highlights the extent of academic migration.

Among all nobel-prize discoveries, North American research institutions received a larger influx of researchers who first made their prize-winning discoveries in Europe, Latin America and East Asia, and later moved to North America where they resided when receiving the Nobel prize. European research institutions in turn received researchers from North America and the Middle East and Northern Africa after making their prize-winning discoveries (Fig. 4d) (Scellato et al., 2017).

In terms of religion, we observe that religion and science are inversely correlated: religion has declined as science has expanded. Religious beliefs in different countries can influence individual beliefs (attitudes towards scientific inquiry), governmental support (limited research on stem cells, gene editing and evolution) and cultural norms (emphasis on certain types of education) (Zuckerman, 1977).

For major events in the world we could not observe and explain, such as the origin of life and the universe, leading scholars around the 17th century often relied on supernatural

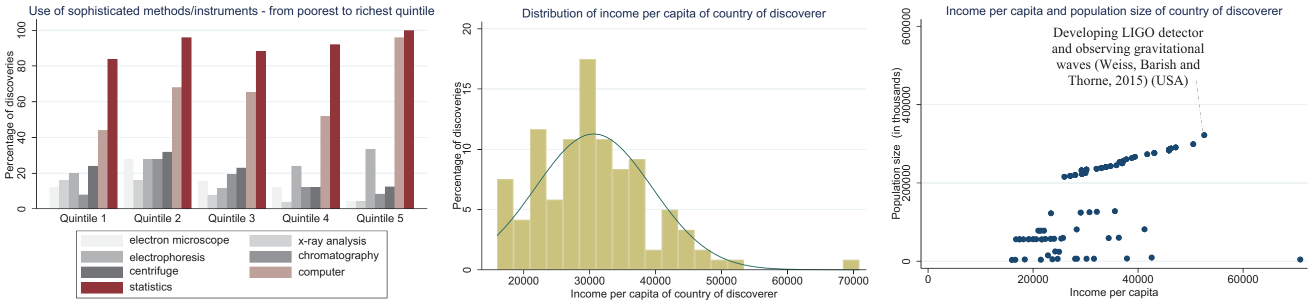


**Fig. 5 Comparable access and use of sophisticated methods/tools in poorer and wealthier countries, and distribution of discoveries by income per capita and population size of the country of the discoverer, for nobel-prize discoveries from 1975 to 2022.** Data reflect all 125 major discoveries including all nobel-prize discoveries since 1975 (**a**, **b**, **c**). In **a**, all methods and instruments were first developed by 1950 and in wide use by 1975, and income quintiles (using per capita 2011 US$ as the benchmark) are generated using only the set of countries in which nobel-prize discoverers resided from 1975 to 2022. Data on income are adjusted for inflation. Data on income and population size are also analysed here from 1975 to 2022 to control for larger variations over time.

explanations, such as Copernicus, Kepler, Galileo and Newton who self-identified as Christians. We find that the share of discoverers who are religious dropped from 100% in the 1600s to 72% in the second half of the 20th century, and then to 59% for the period 2000 to 2022 (Fig. 4e). The distribution of the religious affiliations of researchers is consistent across fields, with the exception of astronomy. Discoverers in astronomy are about twice as likely to be atheists or agnostic and may be explained by being faced with the minute role of our species in the universe (Fig. 4f). Darwin's *On the Origin of Species* in 1859 and Hubble's discovery of the expanding universe in 1926 have been two important contributions to understanding human life, the universe and our minute place in it. Such discoveries, by providing explanations supported by empirical evidence, may help explain part of the decline in the use of religious explanations of such phenomena, together with factors such as citizens depending less on religious institutions than on governments and welfare states.

**The role of economic and demographic factors**. Finally, what role do broader economic and demographic factors play? While we must directly apply methods and instruments to make new discoveries, greater income per capita (and thus resources) and greater population size (and thus more researchers) can foster the basic conditions of science. For wealthier and larger societies can facilitate more sophisticated instruments and laboratory equipment. Though, expensive instruments are often not needed and a number of our most commonly used methods and instruments of science are low-cost, as outlined earlier. Among all nobel-prize discoveries since 1975, we observe that the discoverers residing in countries in the bottom two quintiles (the poorest 40%) do not systematically have less access and use of common instruments and methods of science (including computers, centrifuges, electrophoresis and electron microscopes) compared to those in richer quintiles (Fig. 5a). Discoveries made using some of these more sophisticated scientific instruments are thus not just concentrated in the richest countries. Using methods like statistics and electrophoresis does not vary much across income quintiles as they are relatively cheap and easily accessible. Once a minimal threshold of income is met, scientists in contexts with less resources do not appear to face substantially greater constraints in making scientific breakthroughs (Fig. 5b).

## Conclusion

We have aimed to uncover the particular features and characteristics of the scientists who have made the greatest breakthroughs in science, enabling us to provide a general profile of science's great discoverers and better understand their broader context. We found that breakthrough science has transformed vastly over the last decades, shifting towards greater interdisciplinary education and methodological training, top universities and older age among science's major discoverers. We found that about half of all nobel-prize discoveries have been made by scientists with at least two degrees in different fields. This enables greater interdisciplinary methodological training and novel methodological connections and perspectives across fields that can spark new scientific advances. Science is also becoming increasingly elitist, with scientists at the top 25 universities making up almost one-third of both all nobel-prize and non-nobel-prize discoveries. Only few nobel-prize discoveries and non-nobel-prize discoveries were made after the age of 50 (7% and 15%) and very few after the age of 60 (1% and 3%, respectively). Science institutions need to consider whether some types of grants aimed at innovation should be targeted especially to those between 35 and 45 years of age (as they account for 50% of all nobel-prize discoverers). Overall, factors such as levels of education, interdisciplinary education and institutional environment can support researchers in accessing the latest methods, facilities and resources to make discoveries.

Although breakthrough research is often interdisciplinary, the structure of universities, academic journals and scientific awards like the Nobel Prize embodies the traditional disciplinary borders between fields (Szell et al., 2018). To foster discoveries, we need to rethink disciplinary divisions and how interdisciplinary research can be fostered and awarded, including the Nobel Prize. We need to reward the best research, independent of disciplines. Overall, a constraint here is the lack of data to also assess the possible role of psychological traits of the discoverers like levels of motivation and drive. These cannot be easily collected and tested as most discoverers have passed away.

We observed the evolution of the scientific system over time and the degree to which the system is increasingly closed to particular groups. Researchers outside of North America for example account for about 35% of major discoveries since 1950 but used to account for the majority, and younger researchers under 33 account for less than 20% of major discoveries since 1950 but used to account for almost 35% beforehand. The scientific system also remains highly closed to female researchers who account for less than 6% of major discoveries since 1950 (and 4% beforehand). Providing incentives for researchers in such groups will be important to foster a more inclusive and more global scientific system. We need to reform the structure of the Nobel prize to reward also research teams (not just up to three individuals per field each year) as it distorts the image of how the discovery process works and how to trigger new major advances. Other features of science's major discoveries are outlined in a series of forthcoming papers, including the particular drivers of new discoveries and fields. Ultimately, to support future prominent scientists, the findings here also suggest that more discoveries could be made if science agencies and research institutions provide greater incentives for researchers to work against the common trend of narrow specialisation and instead foster interdisciplinary research that combines novel methods across fields.

## Data availability

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

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## Author contributions

Alexander Krauss is the sole author.

## Competing interests

The author declares no competing interests.

## Ethical approval

The study involves data compiled from the nobel-prize-winning papers (Nobel Prize 2023), the publications of the discoveries indicated in the seven science textbooks, six encyclopaedias of science, etc. that are publicly available (see Methods section). All data in the study are anonymized, 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/s41599-024-02781-4.

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