 First published Tue Oct 1, 2002; substantive revision Mon Jan 22, 2024 The idea that science is a collective enterprise of researchers in successive generations is characteristic of the Modern Age (Nisbet 1980). Classical empiricists (Francis Bacon) and rationalists (René Descartes) of the seventeenth century urged that the use of proper methods of inquiry guarantees the discovery and justification of new truths. This cumulative view of scientific progress was an important ingredient in the optimism of the eighteenth century Enlightenment, and it was incorporated in the 1830s in Auguste Comte's program of positivism: by accumulating empirically certified truths science also promotes progress in society. Other influential trends in the nineteenth century were the Romantic vision of organic growth in culture, Hegel's dynamical account of historical change, and the theory of evolution. They all inspired epistemological views (e.g., among Marxists and pragmatists) which regarded human knowledge as a process. Philosopher-scientists with an interest in the history of science (William Whewell, Charles Peirce, Ernst Mach, Pierre Duhem) gave interesting analyses of some aspects of scientific change. In the early twentieth century, analytic philosophers of science started to apply modern logic to the study of science. Their main focus was the structure of scientific theories and patterns of inference (Suppe 1977). This "synchronic" investigation of the "finished products" of scientific activities was questioned by philosophers who wished to pay serious attention to the "diachronic" study of scientific change. Among these contributions one can mention N.R. Hanson's Patterns of Discovery (1958), Karl Popper's The Logic of Scientific Discovery (1959) and Conjectures and Refutations (1963), Thomas Kuhn's The Structure of Scientific Revolutions (1962), Paul Feyerabend's incommensurability thesis (Feyerabend 1962), Imre Lakatos' methodology of scientific research programmes (Lakatos and Musgrave 1970), and Larry Laudan's Progress and Its Problems (1977). Darwinist models of evolutionary epistemology were advocated by Popper's Objective Knowledge: An Evolutionary Approach (1972) and Stephen Toulmin's Human Understanding (1972). These works challenged the received view about the development of scientific knowledge and rationality. Popper's falsificationism, Kuhn's account of scientific revolutions, and Feyerabend's thesis of meaning variance shared the view that science does not grow simply by accumulating new established truths upon old ones. Except perhaps during periods of Kuhnian normal science, theory change is not cumulative or continuous: the earlier results of science will be rejected, replaced, and reinterpreted by new theories and conceptual frameworks. Popper and Kuhn differed, however, in their definitions of progress: the former appealed to the idea that successive theories may approach to the truth, while the latter characterized progress in terms of the problem-solving capacity of theories. Since the mid-1970s, a great number of philosophical works have been published on the topics of change, development, and progress in science (Harré 1975; Stegmüller 1976; Howson 1976; Rescher 1978; Radnitzky and Andersson 1978, 1979; Niiniluoto and Tuomela 1979; Dilworth 1981; Smith 1981; Hacking 1981; Schäfer 1983; Niiniluoto 1984; Laudan 1984a; Rescher 1984; Pitt 1985; Radnitzky and Bartley 1987; Callebaut and Pinxten 1987; Balzer et al. 1987; Hull 1988; Gavroglu et al. 1989; Kitcher 1993; Pera 1994; Chang 2004; Maxwell 2017; Shan 2023; Rowbottom 2023). These studies have also led to many important novelties being added to the toolbox of philosophers of science. One of them is the systematic study of inter-theory relations, such as reduction (Balzer et al. 1984; Pearce 1987; Balzer 2000; Jonkisz 2000; Hoyningen-Huene and Sankey 2001), correspondence (Krajewski 1977; Nowak 1980; Pearce and Rantala 1984; Nowakowa and Nowak 2000; Rantala 2002), and belief revision (Gärdenfors, 1988; Aliseda, 2006). A new tool that is employed in many defenses of realist views of scientific progress (Niiniluoto 1980, 2014; Aronson, Harré, and Way 1994; Kuipers 2000, 2019; Garcia-Lapena 2023) is the notion of truthlikeness or verisimilitude (Popper 1963, 1970). Besides individual statements and theories, there is also a need to consider temporally developing units of scientific activity and achievement: Kuhn's paradigm-directed normal science, Lakatos' research programme, Laudan's research tradition, Wolfgang Stegmüller's (1976) dynamic theory evolution, Philip Kitcher's (1993) consensus practice, and Hasok Chang's (2012) systems of practice. Kuhn refined his concept of paradigm to "a disciplinary matrix," which is a constellation of symbolic generalizations, models, values, and exemplary problem solutions. Rachel Ankeny and Sabina Leonelli (2016) define an alternative to Kuhnian paradigms in their concept of "repertoire," understood as a well-aligned assemblage of the skills, behaviors, and material, social, and epistemic components used by a collaborative group of researchers. Nancy Cartwright et al. (2022) argue that, instead of rigorous and objective methods, reliability is guaranteed by the "tangle" of science, i.e., the working together of theories, methods, experiments, instruments, classification schemes, habits of data collection, forms of analysis, and measuring techniques. Likely interest about the development of science promoted close co-operation between historians and philosophers of science. For example, case studies of historical examples (e.g., the replacement of Newton's classical mechanics by quantum theory and theory of relativity) have inspired many philosophical treatments of scientific revolutions. Historical case studies were important for philosophers who started to study scientific discovery (Hanson 1958; Nickles 1980). Historically oriented philosophers have shown how instruments and measurements have promoted the progress of physics and chemistry (Rheinberger 1997; Chang 2004). Experimental psychologists have argued that the strive for broad and simple explanations shapes learning and inference (Lombrozo 2016). Further interesting material for philosophical discussions about scientific progress is provided by quantitative approaches in the study of the growth of scientific publications (de Solla Price 1963; Rescher 1978) and science indicators (Elkana et al. 1978). Sociologists of science have studied the dynamic interaction between the scientific community and other social institutions. With their influence, philosophers have analyzed the role of social and cultural values in the development of science (Longino 2002, Pestre 2003). One of the favorite topics of sociologists has been the emergence of new scientific specialties (Mulkay 1975; Niiniluoto 1995b). Sociologists are also concerned with the pragmatic problem of progress: what is the best way of organizing research activities in order to promote scientific advance. In this way, models of scientific change turn out to be relevant to issues of science policy (Böhme 1977; Schäfer 1983). 2. The Concept of Progress 2.1 Aspects of Scientific Progress Science is a multi-layered complex system involving a community of scientists engaged in research using scientific methods in order to produce new knowledge. Thus, the notion of science may refer to a social institution, the researchers, the research process, the method of inquiry, and scientific knowledge. Accordingly, the concept of progress can be defined relative to each of these aspects of science. Hence, different types of progress can be distinguished relative to science: economical (the increased funding of scientific research), professional (the rising status of the scientists and their academic institutions in the society), educational (the increased skill and expertise of the scientists), methodical (the invention of new methods of research, the refinement of scientific instruments), and cognitive (increase or advancement of scientific knowledge). These types of progress have to be conceptually distinguished from advances in other human activities, even though it may turn out that scientific progress has at least some factual connections with technological progress (increased effectiveness of tools and techniques) and social progress (economic prosperity, quality of life, justice in society). All of these aspects of scientific progress may involve different considerations, so that there is no single concept that would cover all of them. For our purposes, it is appropriate here to concentrate only on cognitive progress, i.e., to give an account of advances of science in terms of its success in knowledge-seeking or truth-seeking. Such progress in modern science presupposes that scientific information is made available in published and peer reviewed articles and monographs, while economical, professional, educational, and methodical advances promote scientific progress but do not constitute cognitive progress (cf. Dellsén 2023). Similarly, technological progress and social progress may be consequences of scientific progress without constituting cognitive progress. 2.2 Progress vs. Development "Progress" is an axiological or a normative concept, which should be distinguished from such neutral descriptive terms as "change" and "development" (Niiniluoto 1995a). In general, to say that a step from stage A to stage B constitutes progress means that B is an improvement over A in some respect, i.e., B is better than A relative to some standards or criteria. In science, it is a normative demand that all contributions to research should yield some cognitive profit, and their success in this respect can be assessed before publication by referees (peer review) and after publication by colleagues. Hence, the theory of scientific progress is not merely a descriptive account of the patterns of developments that science has in fact followed. Rather, it should give a specification of the values or aims that can be used as the constitutive criteria for "good science." The "naturalist" program in science studies suggests that normative questions in the philosophy of science can be reduced to historical and sociological investigations of the actual practice of science. In this spirit, Laudan has defended the project of testing philosophical models of scientific change by the history of science: such models, which are "often couched in normative language," can be recast "into declarative statements about how science does behave" (Laudan et al. 1986; Donovan et al. 1988). It may be the case that most scientific work, at least the best science of each age, is also good science. But it is also evident that scientists often have different opinions about the criteria of good science, and rival researchers and schools make different choices in their preference of theories and research programs. Therefore, it can be argued against the naturalists that progress should not be defined by the actual developments of science: the definition of progress should give us a normative standard for appraising the choices that the scientific communities have made, could have made, are just now making, and will make in the future. The task of finding and defending such standards is a genuinely philosophical one which can be enlightened by history and sociology but which cannot be reduced to empirical studies of science. For the same reason, Mizrahi's (2013) empirical observation that scientists talk about the aim of science in terms of knowledge rather than merely truth cannot settle the philosophical debate about scientific progress (cf. Bird 2007; Niiniluoto 2014). 2.3 Progress, Quality, Impact For many goal-directed activities it is important to distinguish between quality and progress. Quality is primarily an activity-oriented concept, concerning the skill and competence in the performance of some task. Progress is a result-oriented concept, concerning the success of a product relative to some goal. All acceptable work in science has to fulfill certain standards of quality. But it seems that there are no necessary connections between quality and progress in science. Sometimes very well-qualified research projects fail to produce important new results, while less competent but more lucky works lead to success. Nevertheless, the skillful use of the methods of science will make progress highly probable. Hence, the best practical strategy in promoting scientific progress is to support high-quality research. Following the pioneering work of Derek de Solla Price (1963) in "scientometrics," quantitative science indicators have been proposed as measures of scientific activity (Elkana et al. 1978). For example, output measures like publication counts are measures of scholarly achievement, but it is problematic whether such a crude measure is sufficient to indicate quality (cf. Chotkowski La Follette 1982). Another example of a science indicator, citation index, is an indicator for the "impact" of a publication and for the "visibility" of its author within the scientific community. The relative importance and quality of a journal is often measured by its impact factor, defined by the yearly mean number of citations of its published articles in the last two years. Thus, the number of articles in refereed journals with a high impact factor is an indicator of the quality of their author, but it is clear that this indicator cannot yet define what progress means, since publications may contribute different amounts to the advance of scientific knowledge. "Rousseau's Law" proposed by Nicholas Rescher (1978) marks off a certain part (the square root) of the total number of publications as "important", but this is merely an alleged statistical regularity. Martin and Irvine (1983) suggest that the concept of scientific progress should be linked to the notion of impact, i.e., the actual influence of research to the surrounding scientific activities at a given time. It is no doubt correct that one cannot advance scientific knowledge without influencing the epistemic state of the scientific community. But the impact of a publication as such only shows that it has successfully "moved" the scientific community in some direction. If science is goal-directed, then we must acknowledge that movement in the wrong direction does not constitute progress. The failure of science indicators to function as definitions of scientific progress is due to the fact that they do not take into account the semantic content of scientific publications. To determine whether a work W gives a contribution to scientific progress, we have to specify what W says (alternatively: what problems W solves) and then relate this content of W to the knowledge situation of the scientific community at the time of the publication of W. For the same reason, research assessment exercises may use science indicators as tools, but ultimately they have to rely on the judgment of peers who have substantial knowledge in the field. 2.4 Progress and Goals Progress is a goal-relative concept. But even when we consider science as a knowledge-seeking cognitive enterprise, there is no reason to assume that the goal of science is one-dimensional. In contrast, as Isaac Levi's classic Gambling With Truth (1967) argued, the cognitive aim of scientific inquiry has to be defined as a weighted combination of several different, and even conflicting, epistemic utilities. As we shall see in Section 3, alternative theories of scientific progress can be understood as specifications of such epistemic utilities. For example, they might include truth and information (Levi 1967; see also Popper 1959, 1963) or explanatory and predictive power (Hempel 1965). Kuhn's (1977) list of the values of science includes accuracy, consistency, scope, simplicity, and fruitfulness. A goal may be accessible in the sense that it can be reached in a finite number of steps in a finite time. A goal is utopian if it cannot be reached or even approached. Thus, utopian goals cannot be rationally pursued, since no progress can be made in an attempt to reach them. Walking to the moon is a utopian task. Kant's answer to this argument was to regard truth as a regulative principle for science. Charles S. Peirce, the founder of American pragmatism, argued that the access to the truth as the ideal limit of scientific inquiry is "destined" or guaranteed in an "indefinite" community of investigators. Almeder's (1983) interpretation of Peirce's view of scientific progress is that there is only a finite number of scientific problems and they will all be solved in a finite time. However, there does not seem to be any reason to think that truth is generally accessible in this strong sense. Therefore, the crucial question is whether it is possible to make rational appraisals that we have made progress in the direction of the truth (see Section 3.4). A goal should be effectively recognizable if there are routine or mechanical tests for showing that the goal has been reached or approached. If the defining criteria of progress are not recognizable in this strong sense, we have to distinguish true or real progress from our perceptions or estimations of progress. In other words, claims of the form 'The step from stage A to stage B is progressive' have to be distinguished from appraisals of the form 'The step from stage A to stage B seems progressive on the available evidence'. The latter appraisals, as our own judgments, are recognizable, but the former claims may be correct without our knowing it. Characteristics and measures that help us to make such appraisals are then indicators of progress. Laudan requires that a rational goal for science should be accessible and effectively recognizable (Laudan 1977, 1984a). This requirement, which he uses to rule out truth as a goal of science, is very strong. The demands of rationality cannot dictate that a goal has to be given up, if there are reasonable indicators of progress towards it. A goal may be backward-looking or forward-looking: it may refer to the starting point or to the destination point of an activity. If my aim is to travel as far from home as possible, my success is measured by my distance from Helsinki. If I wish to become ever better and better piano player, my improvement can be assessed relative to my earlier stages, not to any ideal Perfect Pianist. But if I want to travel to San Francisco, my progress is a function of my distance from the destination. Only in the special case, when there is one and only one way from A to B, the backward-looking and the forward-looking criteria (i.e., the distance from A and distance to B) determine each other. Kuhn and Stegmüller were advocating backward-looking criteria of progress. In arguing against the view that "the proper measure of scientific achievement is the extent to which it brings us closer to " the ultimate goal of "one full, objective, true account of nature," Kuhn suggested that we should "learn to substitute evolution-from-what-we-know for evolution-toward-what-we-wish-to-know" (Kuhn 1970, p. 171). In the same spirit, Stegmüller (1976) argued that we should reject all variants of "a teleological metaphysics" defining progress in terms of "coming closer and closer to the truth." A compromise between forward-looking and backward-looking criteria can be proposed in the following way. If science is viewed as a knowledge-seeking activity, it is natural to define real progress in forward-looking terms: the cognitive aim of science is to know something that is still unknown, and our real progress depends on our distance from the destination. But, as this goal is unknown to us, our estimates or perceptions of progress have to be based on backward-looking evidential considerations. This kind of view of the aims of science does not presuppose the existence of one unique ultimate goal. To use Levi's words, our goals may be "myopic" rather than "messianic" (Levi 1985): the particular target that we wish to hit in the course of our inquiry has to be redefined "locally," relative to each cognitive problem situation. Furthermore, in addition to the multiplicity of the possible targets, there may be several roads that lead to the same destination. The forward-looking character of the goals of inquiry does not exclude what Stegmüller calls "progress branching." This is analogous to the simple fact that we may approach San Francisco from New York along two different ways—via Chicago or St Louis. 2.5 Progress and Rationality Some philosophers use the concepts of progress and rationality as synonyms: progressive steps in science are precisely those that are based upon the scientists' rational choices. One possible objection is that scientific discoveries are progressive when they introduce novel ideas, even though they cannot be fully explained in rational terms (Popper 1959; cf. Hanson 1958; Kleiner 1993). However, another problem is more relevant here: By whose lights should such steps be evaluated? This question is urgent especially if we acknowledge that standards of good science have changed in history (Laudan 1984a). As we shall see, the main rival philosophical theories of progress propose absolute criteria, such as problem-solving capacity or increasing truthlikeness, that are applicable to all developments of science throughout its history. On the other hand, rationality is a methodological concept which is historically relative: in assessing the rationality of the choices made by the past scientists, we have to study the aims, standards, methods, alternative theories and available evidence accepted within the scientific community at that time (cf. Doppelt 1983, Laudan 1987; Niiniluoto 1999a). If the scientific community SC at a given point of time t accepted the standards V, then the preference of SC for theory T over T' on evidence e was rational just in case the epistemic utility of T relative to V was higher than that of T'. But in a new situation, where the standards were different from V, a different preference might have been rational. 3. Theories of Scientific Progress 3.1 Realism and Instrumentalism A major controversy among philosophers of science is between instrumentalist and realist views of scientific theories (see Leplin 1984; Psillos 1999; Niiniluoto 1999a; Saatsi 2018). The instrumentalists follow Duhem in thinking that theories are merely conceptual tools for classifying, systematizing and predicting observational statements, so that the genuine content of science is not to be found on the level of theories (Duhem 1954). Scientific realists, by contrast, regard theories as attempts to describe reality even beyond the realm of observable things and regularities, so that theories can be regarded as statements having a truth value. Excluding naive realists, most scientists are fallibilists in Peirce's sense: scientific theories are hypothetical and always corrigible in principle. They may happen to be true, but we cannot know this for certain in any particular case. But even when theories are false, they can be cognitively valuable if they are closer to the truth than their rivals (Popper 1963). Theories should be testable by observational evidence, and success in empirical tests gives inductive confirmation (Hintikka 1968; Kuipers 2000) or non-inductive corroboration to the theory (Popper 1959). It might seem natural to expect that the main rival accounts of scientific progress would be based upon the positions of instrumentalism and realism. But this is only partly true. To be sure, naive realists as a rule hold the accumulation-of-truths view of progress, and many philosophers combine the realist view of theories with the axiological thesis that truth is an important goal of scientific inquiry. A non-cumulative version of the realist view of progress can be formulated by using the notion of truthlikeness. But there are also philosophers who accept the possibility of a realist treatment of theories, but still deny that truth is a relevant value of science which could have a function in the characterization of scientific progress. Nancy Cartwright et al. (2022) suggest that truth should be replaced by "reliability" as the ultimate goal of science. Bas van Fraassen's (1980) constructive empiricism takes the desideratum of science to be empirical adequacy: what a theory says about the observable should be true. The acceptance of a theory involves only the claim that it is empirically adequate, not its truth on the theoretical level. Van Fraassen has not developed an account of scientific progress in terms of his constructive empiricism, but presumably such an account would be close to empiricist notions of reduction and Laudan's account of problem-solving ability (see Section 3.2). An instrumentalist who denies that theories have truth values usually defines scientific progress by referring to other virtues theories may have, such as their increasing empirical success. In 1906 Duhem expressed this idea by a simile: scientific progress is like a mounting tide, where waves rise and withdraw, but under this to-and-fro motion there is a slow and constant progress. However, he gave a realist twist to his view by assuming that theories classify experimental laws, and progress means that the proposed classifications approach a "natural classification" (Duhem 1954). Evolutionary epistemology is open to instrumentalist (Toulmin 1972) and realist (Popper 1972) interpretations (Callebaut and Pinxten 1987; Radnitzky and Bartley 1987). A biological approach to human knowledge naturally gives emphasis to the pragmatist view that theories function as instruments of survival. Darwinist evolution in biology is not goal-directed with a fixed forward-looking goal; rather, species adapt themselves to an ever changing environment. In applying this account to the problem of knowledge-seeking, the fitness of a theory can be taken to mean that the theory is accepted by members of the scientific community. But a realist can reinterpret the evolutionary model by taking fitness to mean the truth or truthlikeness of a theory (Niiniluoto 1984). 3.2 Empirical Success and Problem-Solving For a constructive empiricist, it would be natural to think that among empirically adequate theories one theory T_{2} is better than another theory T_{1} if T_{2} entails more true observational statements than T_{1}. Such a comparison makes sense at least if the observation statements entailed by T_{1} are a proper subset of those entailed by T_{2}. Kemeny and Oppenheim (1956) gave a similar condition in their definition of reduction: T_{1} is reducible to T_{2} if and only if T_{2} is at least as well systematized as T_{1} and T_{2} is observationally stronger than T_{1}, i.e., all observational statements explained by T_{1} are also consequences of T_{2}. Variants of such an empirical reduction relation have been given by the structuralist school in terms of set-theoretical structures (Stegmüller 1976; Scheibe 1986; Balzer et al. 1987; Moulines 2000). A similar idea, but applied to cases where the first theory T_{1} has been falsified by some observational evidence, was used by Lakatos in his definition of empirically progressive research programmes: the new superseding theory T_{2} should have corroborated excess content relative to T_{1} and T_{2} should contain all the unrefuted content of T_{1} (Lakatos and Musgrave 1970). The definition of Kuipers (2000) allows that even the new theory T_{2} is empirically refuted: T_{2} should have (in the sense of set-theoretical inclusion) more empirical successes, but fewer empirical counter-examples than T_{1}. Against these cumulative definitions it has been argued that definitions of empirical progress have to take into account an important complication. A new theory often corrects the empirical consequences of the previous one, i.e., T_{2} entails observational statements e_{2} which are in some sense close to the corresponding consequences e_{1} of T_{1}. Various models of approximate explanation and approximate reduction have been introduced to handle these situations. An important special case is the limiting correspondence relation: theory T_{2} approaches theory T_{1} (or the observational consequences of T_{2} approach those of T_{1}) when some parameter in its laws approaches a limit value (e.g., theory of relativity approaches classical mechanics when the velocity of light c grows without limit). Here T_{2} is said to be a concretization or factualization of the idealized theory T_{1} (Nowak 1980; Nowakowa and Nowak 2000; Kuipers 2019). However, these models do not automatically guarantee that the step from an old theory to a new one is progressive. For example, classical mechanics can be related by the correspondence condition to an infinite number of alternative and mutually incompatible theories, and some additional criteria are needed to pick out the best among them. Kuhn's (1962) strategy was to avoid the notion of truth and to understand science as an activity of making accurate predictions and solving problems or "puzzles". Paradigm-based normal science is cumulative in terms of the problems solved, and even paradigm-changes or revolutions are progressive in the sense that "a relatively large part" of the problem-solving capacity of the old theory is preserved in the new paradigm. But, as Kuhn argued, it may happen that some problems solved by the old theory are no longer relevant or meaningful for the new theory. These cases are called "Kuhn-losses". A more systematic account of these ideas is given by Laudan (1977): the problem-solving effectiveness of a theory is defined by the number and importance of solved empirical problems minus the number and importance of the anomalies and conceptual problems that the theory generates. Here the concept of anomaly refers to a problem that a theory fails to solve, but is solved by some of its rivals. For Laudan the solution of a problem by a theory T means that the "statement of the problem" is deduced from T. A good theory is thus empirically adequate, strong in its empirical content, and—Laudan adds—avoids conceptual problems. One difficulty for the problem-solving account is to find a proper framework for identifying and counting problems (Rescher 1984; Kleiner 1993). When Newton's mechanics is applied to determine the orbit of the planet Mars, this can be counted as one problem. But, given an initial position of Mars, the same theory entails a solution to an infinite number of questions concerning the position of Mars at time t. Perhaps the most important philosophical issue is whether one may consistently hold that the notion of problem-solving may be entirely divorced from truth and falsity: the realist may admit that science is a problem-solving activity, if this means the attempt to find true solutions to predictive and explanatory questions (Popper, 1972; Niiniluoto 1984). Bird's (2007) main criticism against the "functional account" of Kuhn and Laudan is its consequence that the cumulation of false solutions from an entirely false theory counts as scientific progress (e.g. someone in the fourteenth century believed that hot goat's blood could split diamonds). According to Shan (2019), "science progresses if more useful research problems and their corresponding solutions are proposed". Progress means that "more useful exemplary practices are proposed", where usefulness requires repeatability in further investigation (Shan 2023). This definition involves both problem-defining and problem-solving, and it is illustrated by the development of early genetics from Darwin to Bateson. Articles in Shan (2023) apply it to economics, seismology, and interdisciplinary sciences. Shan gives up the typical Kuhn-Laudan assumption that the scientific community is able to know whether it makes progress or not, and is open to the introduction of the notions of know-how and perspectival truth, so that his "new functional approach" is a compromise with what Bird (2007) calls the "epistemic view" of progress. Bird (2023) and Dellsén (2023) object that some progressive developments (e.g. the discovery of X-rays, applications of Newtonian mechanics) do not involve the proposal of any new exemplary practices. It can also be argued that improved experimentation and exploration belong to factors which promote but do not constitute progress in science. A different view of problem-solving is involved in those theories which discuss problems of decision and action. A radical pragmatist view treats science as a systematic method of solving such decision problems relative to various kinds of practical utilities. According to the view called behavioralism by the statistician L.J. Savage, science does not produce knowledge, but rather recommendations for actions: to accept a hypothesis is always a decision to act as if that hypothesis were true. Progress in science can then be measured by the achievement of practical utilities of the decision maker. An alternative methodological version of pragmatism is defended by Rescher (1977) who accepts the realist view of theories with some qualifications, but argues that the progress of science has to be understood as "the increasing success of applications in problem-solving and control." Similarly, Douglas (2014), after suggesting that the distinction between pure and applied science should be relinquished, defines progress "in terms of the increased capacity to predict, control, manipulate, and intervene in various contexts." A concrete example of interdisciplinary "frontier science" is given by Nersessian (2022): bioengineering scientists create novel problem-solving methods which help to understand complex dynamical biological systems sufficiently in order to control and intervene in them. Mizrahi (2013) and Shan (2023) count increasing know how as progress in science. But, in this view, the notion of scientific progress is in effect reduced to science-based technological progress (cf. Niiniluoto 1984). 3.3 Explanatory Power, Unification, and Simplicity Already the ancient philosophers regarded explanation as an important function of science. The status of explanatory theories was interpreted either in an instrumentalist or realist way: Plato's school started the tradition of "saving the appearances" in astronomy, while Aristotle took theories to be necessary truths. Both parties can take explanatory power to be a criterion of a good theory, as shown by van Fraassen's (1980) constructive empiricism and Wilfrid Sellars' scientific realism (Pitt 1981; Tuomela 1985). When it is added that a good theory should also yield true empirical predictions, the notions of explanatory and predictive power can be combined within the notion of systematic power (Hempel 1965). If the demand of systematic power simply means that a theory has many true deductive consequences in the observational language, this concept is essentially equivalent to the notion of empirical success and empirical problem-solving ability discussed in Section 3.2, but normally explanation is taken to include additional structural conditions besides mere deduction (Aliseda 2006). Inductive systematization should also be taken into account (Hempel 1965; Niiniluoto and Tuomela 1973). One important idea regarding systematization is that a good theory should unify empirical data and laws from different domains (Kitcher 1993; Schurz 2015). For Whewell, the paradigm case of such "consilience" was the successful unification of Kepler's laws and Galileo's laws by means of Newton's theory. On the other hand, instead of requiring consensus on a single unifying theory, many philosophers have defended pluralist approaches by arguing that scientific progress needs a variety of conceptual classifications (Dupré 1993; Kitcher 2001; Chang 2012), a non-fundamentalist patchwork of laws for "a dappled world" (Cartwright 1999), and different perspectives and values (Longino 2002). If theories are underdetermined by observational data, then one is often advised to choose the simplest theory compatible with the evidence (Foster and Martin 1966). Simplicity may be an aesthetic criterion of theory choice (Kuipers 2019), but it may also have a cognitive function in helping us in our attempt to understand the world in an "economical" way. Ernst Mach's notion of the economy of thought is related to the demand of manageability, which is important especially in the engineering sciences and other applied sciences: for example, a mathematical equation can be made "simpler" by suitable approximations, so that it can be solved by a computer. Simplicity has also been related to the notion of systematic or unifying power. This is clear in Eino Kaila's concept of relative simplicity, which he defined in 1939 as the ratio between the explanatory power and the structural complexity of a theory (for a translation, see Kaila 2014). According to this conception, progress can be achieved by finding structurally simpler explanations of the same data, or by increasing the scope of explanations without making them more complex. Laudan's formula of solved empirical problems minus generated conceptual problems is a variation of the same idea. After Hempel's pioneering work in 1948, various probabilistic measures of explanatory power have been proposed (Hempel 1965; Hintikka 1968). Most of them demand that the explanatory theory h should be positively relevant to the empirical data e. This is the case also with the particular proposal $$\frac{P(h\mid e) - P(h\mid\neg e)}{P(h\mid e) + P(h\mid\neg e)}$$ defended by Schupbach and Sprenger (2011) as the unique measure which satisfies seven intuitively plausible adequacy conditions. Dellsén's (2016) original version of his noetic account defines progress in terms of increasing explanations and predictions, but he does not apply measures of explanatory or systematic power. While philosophers from Hempel (1965) to Dellsén (2016) have treated explanation and prediction as equally important for scientific advance, some authors have a strong preference for prediction against the "explanationists". Following Akaike's statistical account of model selection, Sober (2008) takes simplicity and predictive accuracy to be the main virtues of a scientific theory. Lakatos emphasized the role of temporally new predictions in his view of progress by research programmes (Lakatos and Musgrave 1970). Leplin (1997) characterizes "novel" predictions by the independence condition, i.e. they were not used in the construction of a theory, and argues that such such novel predictions can be explained only by the truth of the theory (cf. Alai 2014). However, Vickers (2022) argues that evidence provided by novel predictions has been historically unreliable, suggesting that "future-proof science" has to be identified by at least 95 per cent consensus of the scientific community. 3.4 Truth and Information Realist theories of scientific progress take truth to be an important goal of inquiry. This view is built into the classical definition of knowledge as justified true belief: if science is a knowledge-seeking activity, then it is also a truth-seeking activity. However, truth cannot be the only relevant epistemic utility of inquiry. This is shown in a clear way by cognitive decision theory (Levi 1967; Niiniluoto 1987). Let us denote by $B = \{h_{1}, \ldots ,h_{n}\}$ a set of mutually exclusive and jointly exhaustive hypotheses. Here the hypotheses in B may be the most informative descriptions of alternative states of affairs or possible worlds within a conceptual framework L. For example, they may be complete theories expressible in a finite first-order language. If L is interpreted on a domain U, so that each sentence of L has a truth value (true or false), it follows that there is one and only one true hypothesis (say h^*) in B. Our cognitive problem is to identify the target h^* in B. The elements h_{i} of B are the (potential) complete answers to the problem. The set $D(B)$ of partial answers consists of all non-empty disjunctions of complete answers. The trivial partial answer in $D(B)$, corresponding to 'I don't know', is represented by a tautology, i.e., the disjunction of all complete answers. For any g in $D(B)$, we let $u(g, h_{j})$ be the epistemic utility of accepting g if h_{j} is true. We also assume that a rational probability measure P is associated with language L, so that each h_{j} can be assigned with its epistemic probability $P(h_{j}\mid e)$ given evidence e. Then the best hypothesis in $D(B)$ is the one g which maximizes the expected epistemic utility $$U(g\mid e) = \sum_{j=1}^{n} P(h_j \mid e)u(g, h_j) \tag{1}$$ For comparative purposes, we may say that one hypothesis is better than another if it has a higher expected utility than the other by formula (1). If truth is the only relevant epistemic utility, all true answers are equally good and all false answers are equally bad. Then we may take $u(g, h_{j})$ simply to be the truth value of g relative to h_{j}: $$u(g, h_j) = \begin{cases} 1 & \text{ if } h_j \text{ is in } g \\ 0 & \text{ otherwise.} \end{cases}$$ Hence, $u(g, h^*)$ is the real truth value $tv(g)$ of g relative to the domain U. It follows from (1) that the expected utility $U(g\mid e)$ equals the posterior probability $P(g\mid e)$ of g on e. In this sense, we may say that posterior probability equals expected truth value. The rule of maximizing expected utility leads now to an extremely conservative policy: the best hypotheses g on e are those that satisfy $P(g\mid e) = 1$, i.e., are completely certain on e (e.g. e itself, logical consequences of e, and tautologies). On this account, if we are not certain of the truth, then it is always progressive to change an uncertain answer to a logically weaker one. The argument against using high probability as a criterion of theory choice was made already by Popper in 1934 (see Popper 1959). He proposed that good theories should be bold or improbable. This idea has been made precise in the theory of semantic information. Levi (1967) measures the information content $I(g)$ of a partial answer g in $D(B)$ by the number of complete answers it excludes. With a suitable normalization, $I(g) = 1$ if and only if g is one of the complete answers h_{j} in B, and $I(g) = 0$ for a tautology. If we now choose $u(g, h_{j}) = I(g)$, then $U(g\mid e) = I(g)$, so that all the complete answers in B have the same maximal expected utility 1. This measure favors strong hypotheses, but it is unable to discriminate between the strongest ones. For example, the step from a false complete answer to the true one does not count as progress. Therefore, information cannot be the only relevant epistemic utility. Another measure of information content is $cont(g) = 1 - P(g)$ (Hintikka 1968). If we choose $u(g, h_{j}) = cont(g)$, then the expected utility $U(g\mid e) = 1 - P(g)$ is maximized by a contradiction, as the probability of a contradictory sentence is zero. Any false theory can be improved by adding new falsities to it. Again we see that information content alone does not give a good definition of scientific progress. The same remark can be made about explanatory and systematic power. Levi's (1967) proposal for epistemic utility is the weighted combination of the truth value $tv(g)$ of g and the information content $I(g)$ of g: $$aI(g) + (1 - a)tv(g), \tag{2}$$ where $0 \lt a \lt \frac{1}{2}$ is an "index of boldness," indicating how much the scientist is willing to risk error, or to "gamble with truth," in her attempt to be relieved from agnosticism. The expected epistemic utility of g is then $$aI(g) + (1 - a)P(g\mid e). \tag{3}$$ A comparative notion of progress 'g_{1} is better than g_{2}' could be defined by requiring that both $I(g_{1}) \gt I(g_{2})$ and $P(g_{1}\mid e) \gt P(g_{2}\mid e)$, but most hypotheses would be incomparable by this requirement. By using the weight a, formula (3) expresses a balance between two mutually conflicting goals of inquiry. It has the virtue that all partial answers g in $D(B)$ are comparable with each other: g is better than g' if and only if the value of (3) is larger for g than for g'. If epistemic utility is defined by information content cont(g) in a truth-dependent way, so that $$U(g,e) = \begin{cases} cont(g) & \text{ if } g \text{ is true}\\ -cont(\neg g) & \text{ if } g \text{ is false}, \end{cases}$$ (i.e., in accepting hypothesis g, we gain the content of g if g is true, but we lose the content of the true hypothesis $\neg g$ if g is false), then the expected utility $U(g\mid e)$ is equal to $$P(g\mid e) - P(g) \tag{4}$$ This measure combines the criteria of boldness (small prior probability $P(g)$) and high posterior probability $P(g\mid e)$. Similar results can be obtained if $cont(g)$ is replaced by Hempel's (1965) measure of systematic power $syst(g, e) = P(\neg g\mid\neg e)$. For Levi, the best hypothesis in $D(B)$ is the complete true answer. But his utility assignment also makes assumptions that may seem problematic: all false hypotheses (even those that make a very small error) are worse than all truths (even the uninformative tautology); all false complete answers have the same utility (see, however, the modified definition in Levi, 1980); among false hypotheses utility covaries with logical strength (i.e. if h and h' are false and h entails h', then h has greater utility than h'). These features are motivated by Levi's project of using epistemic utility as a basis of acceptance rules. But if such utilities are used for ordering rival theories, then the theory of truthlikeness suggests other kinds of principles. 3.5 Truthlikeness Popper's notion of truthlikeness is also a combination of truth and information (Popper 1963, 1972). For him, verisimilitude represents the idea of "approaching comprehensive truth." Popper's explication used the cumulative idea that the more truthlike theory should have (in the sense of set-theoretical inclusion) more true consequences and less false consequences, but it turned out that this comparison is not applicable to pairs of false theories. An alternative method of defining verisimilitude, initiated in 1974 by Pavel Tichy and Risto Hilpinen, relies essentially on the concept of similarity. In the similarity approach, as developed in Niiniluoto (1987), closeness to the truth is explicated "locally" by means of the distances of partial answers g in $D(B)$ to the target h^* in a cognitive problem B. For this purpose, we need a function d which expresses the distance $d(h_{i}, h_{j}) =: d_{ij}$ between two arbitrary elements of B. By normalization, we may choose $0 \le d_{ij} \le 1$. The choice of d depends on the cognitive problem B, and makes use of the metric structure of B (e.g., if B is a subspace of the real numbers $\Re$) or the syntactic similarity between the statements in B. Then, for a partial answer g, we let $D_{\min}(h_{i}, g)$ be the minimum distance of the disjuncts in g from h_{i}, and $D_{\rm sum}(h_{i}, g)$ the normalized sum of the distances of the disjuncts of g from h_{i}. Then $D_{\min}(h_{i}, g)$ tells how close to h_{i} hypothesis g is, so that the degree of approximate truth of g (relative to the target h^*) is $1 - D_{\min}(h^*, g)$. On the other hand, $D_{\rm sum}(h_{i}, g)$ includes a penalty for all the mistakes that g allows relative to h_{i}. The min-sum measure $$D_{\rm ms}(h_{i},g) = aD_{\min}(h_{i},g) + bD_{\rm sum}(h_{i},g), \tag{5}$$ where $a \gt 0$ and $b \gt 0$, and $(a + b)\le 1$, combines these two aspects. Then the degree of truthlikeness of g is $$Tr(g, h^*) = 1 - D_{\rm ms}(h^*, g). \tag{6}$$ Thus, parameter a indicates our cognitive interest in hitting close to the truth, and parameter b indicates our interest in excluding falsities that are distant from the truth. In many applications, choosing a to be equal to $2b$ gives intuitively reasonable results. If the distance function d on B is trivial, i.e., $d_{ij} = 1$ if and only if $i = j$, and otherwise 0, then $Tr(g, h^*)$ reduces to the variant (2) of Levi's definition of epistemic utility. Obviously $Tr(g, h^*)$ takes its maximum value 1 if and only if g is equivalent to h^*. If g is a tautology, i.e., the disjunction of all elements h_{i} of B, then $Tr(g,h^*) = 1 - b$. If $Tr(g, h^*) \lt 1 - b$, g is misleading in the strong sense that its cognitive value is smaller than that of complete ignorance. Oddie (1986) has continued to favor the average function instead of the min-sum measure (cf. Oddie and Cevolani 2022). An alternative account of truth approximation is given by Kuipers (2019). When h^* is unknown, the degree of truthlikeness (6) cannot be calculated. But the expected degree of verisimilitude of a partial answer g given evidence e is given by $$ver(g\mid e) = \sum_{i=1}^n P(h_i \mid e) Tr(g, h_i) \tag{7}$$ If evidence e entails some h_{j} in B, or makes h_{j} completely certain (i.e., $P(h_{j}\mid e) = 1$), then $ver(g\mid e)$ reduces to $Tr(g,h_{j})$. If all the complete answers h_{i} in B are equally probable on e, then $ver(h_{i}\mid e)$ is also constant for all h_{i}. The truthlikeness function Tr allows us to define an absolute concept of real progress: (RP) Step from g to g' is progressive if and only if $Tr(g, h^*) \lt Tr(g', h^*)$, and the expected truthlikeness function ver gives the relative concept of estimated progress: (EP) Step from g to g' seems progressive on evidence e if and only if $ver(g\mid e) \lt ver(g'\mid e)$. (Cf. Niiniluoto 1980.) According to definition RP, it is meaningful to say that one theory g' satisfies better the cognitive goal of answering problem B than another theory g. This is an absolute standard of scientific progress in the sense of Section 2.5. Definition EP shows how claims of progress can be fallibly evaluated on the basis of evidence: if $ver(g\mid e) \lt ver(g'\mid e)$, it is rational to claim on evidence e that the step from g to g' in fact is progressive. This claim may of course be mistaken, since estimation of progress is relative to two factors: the available evidence e and the probability measure P employed in the definition of ver. Both evidence e and the epistemic probabilities $P(h_{i}\mid e)$ may mislead us. In this sense, the problem of estimating verisimilitude is as difficult as the problem of induction. Rowbottom (2015) argues against RP and EP that scientific progress is possible in the absence of increasing verisimilitude. He asks us to imagine that the scientists in a specific area of physics have found the maximally truthlike theory C*. Yet this general true theory could be used for further predictions and applications. This is indeed the case if we do not make the idealized assumption that the scientists know all the logical consequences of their theories. Then the predictions from C* constitute new cognitive problems. Moreover, in Rowbottom's thought experiment further progress is possible by expanding the conceptual framework in order to consider as a target a deeper truth than C* (Niiniluoto 2017). A similar reply can be given to Dellsén (2023), who argues that Newton's explanation of Kepler's laws of planetary motions does not constitute progress on the truthlikeness account, since the theory and the laws were already accepted before the explanation: Newton was successful in solving the cognitive problem "Which theory would explain Kepler's laws?". The measure of expected truthlikeness can be used for retrospective comparisons of past theories g, if evidence e is taken to include our currently accepted theory T, i.e., the truthlikeness of g is estimated by $ver(g\mid e \& T)$ (Niiniluoto 1984, 171). In the same spirit, Barrett (2008) has proposed that—assuming that science makes progress toward the truth through the elimination of descriptive error—the "probable approximate truth" of Newtonian gravitation can be warranted by its "nesting relations" to the General Theory of Relativity. The definition of progress by RP can be contrasted with the model of belief revision (Gärdenfors 1988). The simplest case of revision is expansion: a theory T is conjoined by an input statement A, so that the new theory is $T \& A$. According to the min-sum measure, if T and A are true, then the expansion $T \& A$ is at least as truthlike as T. But if T is false and A is true, then $T \& A$ may be less truthlike than T. For example, let the false theory T state that the number of planets is 9 or 20, and let A be the true sentence that this number is 8 or 20. Then $T \& A$ states that the number of planets is 20, but this is clearly less truthlike than T itself. Similar examples show that the AGM revision of a false theory by true input need not increase truthlikeness (Niiniluoto 2011). 3.6 Knowledge and Understanding Bird (2007) has defended the epistemic definition of progress (accumulation of knowledge) against the semantic conception (accumulation of true beliefs or succession of theories with increasing verisimilitude) (see also Bird 2022, 2023). Here knowledge is not defined as justified true belief, but still it is taken to entail truth and justification, so that Bird's epistemic view in fact returns to the old cumulative model of progress. According to Bird, an accidentally true or truthlike belief reached by irrational methods without any justification does not constitute progress. This kind of thought experiment may seem artificial, since there is always some sort of justification for any hypothetical theory which is accepted or at least seriously considered by the scientific community. But Bird's argument raises the important question whether justification is merely instrumental for progress (Rowbottom 2008) or necessary for progress (Bird 2008). Another interesting question is whether the rejection of unfounded but accidentally true beliefs is regressive. The truthlikeness approach replies to these problems by distinguishing real progress RP and estimated progress EP: justification is not constitutive of progress in the sense of RP, but claims of real progress can be justified by appealing to expected verisimilitude (Cevolani and Tambolo 2013). On the other hand, the notion of progress explicated by EP (or by the combination of RP and EP) is relative to evidence and justification but at the same time non-cumulative. Bird (2015) can reformulate his initial example by assuming that an accidentally true or truthlike theory H has been obtained by scientific but yet unreliable means, perhaps by derivation from an accepted theory which turns out to be false. Does such application of mistaken reasoning constitute progress? The interplay of RP and EP allows several possibilities here. Later evidence might show that the initial estimate $ver(H\mid e)$ was too high. Or the Tr-value was in fact high but initially the ver-value was low (e.g. Aristarchus on heliocentric system, Wegener on continental drift) and only later it was increased by new evidence. Most accounts of scientific progress would agree that among true theories truthlikeness covaries with logical strength (for an exception, see Oddie 1986). So accumulation of knowledge is a special case of increasing truthlikeness. But it does not cover progress by successive false theories. In his attempt to rehabilitate the cumulative knowledge model of scientific progress, Bird admits that there are historical sequences of theories none of which are "fully true" (e.g. Ptolemy—Copernicus—Kepler or Galileo—Newton—Einstein). As knowledge entails truth, Bird tries to save his epistemic account by reformulating past false theories as true ones. He proposes that if g is approximately true, then the proposition "approximately g" is true (or that "the improving precision of approximations can be an object of knowledge". One problem with this treatment is that scientists typically formulate their theories as exact statements, and at the time of their proposal it is unclear to know how large margins of errors would be needed to transform them into true theories. With reference to Barrett (2008), Saatsi (2019) argues that the approximate truth of Newtonian mechanics can be assessed only from the vantage point of General Theory of Relativity, so that this knowledge was not epistemically accessible to Newton at his time. Further, many past theories were not approximately true or truthlike, but still they could be improved by more truthlike successors. Ptolemy's geocentric theory was superseded in the Copernican revolution, not retained in the form "approximately Ptolemy". Indeed, the progressive step from Ptolemy to Copernicus or from Newton to Einstein are not only matters of improved precision but involve changes in theoretical postulates and laws. A further problem for Bird's proposal is the question whether his approximation propositions are able to distinguish progress and regress in science (Niiniluoto 2014). Dellsén (2016, 2018b) has formulated the noetic account of scientific progress as increasing understanding. Using objectual understanding instead of understanding-why, he characterizes understanding in terms of "grasping how to correctly explain and predict aspects of a given target". Against Bird (2007), who takes understanding to be a species of knowledge of causes, Dellsén argues that understanding does not require the scientists to have justification for, or even belief in, the explanations or predictions they propose. Still, understanding is a matter of degree. Thus, there are increases in scientific understanding without accumulation of scientific knowledge (e.g. Einstein's explanation of Brownian motion in terms of the kinetic theory of heat) and accumulation of scientific knowledge without increases in understanding (e.g. knowledge about random experimental outcomes or spurious statistical correlations). The latter thesis is easy to accept, especially if explanation needs laws, but on the other hand the epistemic and truthlikeness approaches could agree against Dellsén that the collection of new important data may constitute scientific progress. Bird's (2023) example is the activity of cataloguing stars. The possibility of "quasi-factive" understanding by means of idealized theories (a common feature with the verisimilitudinarian approach) is taken to be an advantage of the noetic account. Park (2017) has challenged Dellsén's conclusions against the epistemic definition. He argues that scientific understanding involves belief that the explained phenomena are real and the confirmed predictions are true. He also argues that Wegener's continental drift theory, which was not supported by available evidence, was progressive, since it paved the way for the later theory of plate tectonics in the 1960s. Dellsén (2018a) questions Park's arguments by rejecting the "means-end thesis", i.e., one should draw the crucial distinction between cognitive and non-cognitive scientific progress and likewise distinguish episodes that constitute and promote scientific progress. Dellsén (2023) has restated his noetic account by characterizing understanding in terms of dependency relations (causation, constitution, and grounding). The requirement that a grasped dependency model must be accurate and comprehensive brings his account close to the Popperian notion of truthlikeness as a combination of truth and information (cf. Section 3.5). Bird (2023) objects that the discovery of X-rays in 1895 did not involve dependency relations. Dellsén's (2023) additional proposal to analyze understanding among those for whom scientific progress is made, instead of those by whom progress is made, opens interesting questions about the transmission of public scientific information to non-scientists (such as students, engineers, medical professionals, and policy-makers) is an important consequence of inquiry without constituting scientific progress. The lively debate about four current accounts of scientific progress is continued in Shan (2023): epistemic (Bird), semantic (Niiniluoto), functional (Shan), and noetic (Dellsén) (see also Rowbottom 2023). 4. Is Science Progressive? In Section 3.5., we made a distinction between real and estimated progress. A similar distinction can be made in connection with measures of empirical success. For example, one may distinguish two notions of the problem-solving ability of a theory: the number of problems solved so far, and the number of solvable problems. Real progress could be defined by the latter, while the former gives us an estimate of progress. The scientific realist may continue this line of thought by arguing that all measures of empirical success are in fact best indicators of real cognitive progress, measured in terms of truth or truthlikeness. For example, if T explains e, then it can be shown that e also confirms T, or increases the probability of T (Niiniluoto 1999b). A similar reasoning can be employed to give the so-called "ultimate argument" or "no miracle argument" for scientific realism: theoretical realism is the only assumption that does not make the empirical success of science a miracle (Putnam, 1978; Psillos 1999; Alai 2014; Niiniluoto 2017; Kuipers 2019; cf. criticism in Laudan 1984b). This means that the best explanation of the empirical progress of science is the hypothesis that science is also progressive on the level of theories. The thesis that science is progressive is an overall claim about scientific activities. It does not imply that each particular step in science has in fact been progressive: individual scientists make mistakes, and even the scientific community is fallible in its collective judgments. For this reason, we should not propose such a definition that the thesis about the progressive nature of science becomes a tautology or an analytic truth. This undesirable consequence follows if we define truth as the limit of scientific inquiry (this is sometimes called the consensus theory of truth), since then it is a trivial truth that the limit of scientific research is the truth (Laudan 1984a). But this "trivialization of the self-corrective thesis" cannot be attributed to Peirce who realized that truth and the limit of inquiry coincide at best with probability one (Niiniluoto 1980). The notion of progress also allows us to make sense of the claim that science converges towards the truth. But the characterization of progress as increasing truthlikeness, given in Section 3.5, does not presuppose "teleological metaphysics" (Stegmüller 1976), "convergent realism" (Laudan 1984), or "scientific eschatology" (Moulines 2000), as it does not rely on any assumption about the future behavior of science. The claim about scientific progress can still be questioned by the theses that observations and ontologies are relative to theories. If this is true, the comparison of rival theories appears to be impossible on cognitive or rational grounds. Kuhn (1962) compared paradigm-changes to Gestalt switches (Dilworth 1981). Feyerabend (1984) concluded from his methodological anarchism that the development of science and art resemble each other. Hanson, Popper, Kuhn, and Feyerabend agreed that all observation is theory-laden, so that there is no theory-neutral observational language. Accounts of reduction and progress, which take for granted the preservation of some observational statements within theory-change, thus run into troubles. Even though Laudan's account of progress allows Kuhn-losses, it can be argued that the comparison of the problem-solving capacity of two rival theories presupposes some kind of correlation or translation between the statements of these theories (Pearce 1987). Various replies have been proposed to this issue. One is the movement from language to structures (Stegmüller 1976; Moulines 2000), but it turns out that a reduction on the level structures already guarantees commensurability, since it induces a translation between conceptual frameworks (Pearce 1987). Another has been to point that an evidence statement e may happen to be neutral with respect to rival theories T_1 and T_2, even though it is laden with some other theories. The realist may also point out that the theory-ladenness of observations concern the estimation of progress (EP), but the definition of real progress (RP) as increasing truthlikeness does not mention the notion of observation at all. Even though Popper accepted the theory-ladenness of observations, he rejected the more general thesis about incommensurability as "the myth of the framework" (Lakatos and Musgrave 1970). Popper insisted that the growth of knowledge is always revolutionary in the sense that the new theory contradicts the old one by correcting it, but there is still continuity in theory-change, as the new theory should explain why the old theory was successful to some extent. Kuhn argued against the possibility of finding complete translations between the languages of rival theories, but in his later work he admitted the possibility that a scientist may learn different theoretical languages (Hoyningen-Huene 1993). Kuhn kept insisting that there is "no theory-independent way to reconstruct phrases like 'really there'", i.e., each theory has its own ontology. Convergence to the truth seems to be impossible, if ontologies change with theories. The same idea has been formulated by Putnam (1978) and Laudan (1984a) in the so-called "pessimistic meta-induction": as many past theories in science have turned out to be non-referring, there is all reason to expect that even the future theories fail to refer—and thus also fail to be approximately true or truthlike. But the optimistic reply by comparative realists points out that for all rejected theories in Laudan's list the scientists have been able to find a better, more truthlike alternative (Niiniluoto 2017; Kuipers 2019). The difficulties for realism seem to be reinforced by the observation that measures of truthlikeness are relative to languages. The choice of conceptual frameworks cannot be decided by means of the notion of truthlikeness, but needs additional criteria. In defense of the truthlikeness approach, one may point to the fact that the comparison of theories is relevant only in those cases where they are considered perhaps via a suitable translation) as rival answers to the same cognitive problem. It is then necessary that such rival theories are formulated in the same or different languages, they have to be translated into a common conceptual framework. Another line is to appeal to theories of reference in order to show that rival theories can after all be regarded as speaking about the same entities (Psillos 1999). For example, Thompson, Bohr, and later physicists are talking about the same electrons, even though their theories of the electron differ from each other. This is not possible on the standard descriptive theory of reference: a theory T can only refer to entities about which it gives a true description. Kuhn's and Feyerabend's meaning holism, with devastating consequences for realism, presupposes this account of reference. A similar argument is used by Moulines (2000), who denies that progress could be understood as "knowing more about the same," but his own structuralist reconstruction of progress involves "partial incommensurability" assumes that rival theories share some intended applications. Causal theories of reference allow that reference is preserved even within changes of theories (Kitcher 1993). The same result is obtained if the descriptive account is modified by introducing a Principle of Charity (Putnam 1975; Smith 1981; Niiniluoto 1999a): a theory refers to those entities about which it gives the most truthful description. An alternative account, illustrated by the relation of phlogiston theory and oxygen theory, is given by Schurz (2011) by his notion of structural correspondence. This makes it possible that even false theories are truthlike. Moreover, there can be reference invariance between two successive theories, even though both of them are false; progress means then that the latter theory gives a more truthlike description about their common domain than the old theory. A radically different account of scientific change emerges from Chang's (2022) pluralist ontology. Inspired by classical pragmatists, he advocates a charitable definition of reality and truth in terms of "operational coherence". For example, phlogiston had operational applications, so it has some reality, all along with oxygen. More generally, Chang defends "conservationist pluralism": scientists do not tend to discard concepts from the past, so that scientific progress is largely cumulative. This return to the cumulative model of progress resembles the surprising position that Feyerabend reached from his methodological anarchism without Popperian falsification: "knowledge ... is not a gradual approach to the truth. It is rather an ever increasing ocean of mutually incompatible (and perhaps even incommensurable) alternatives ... Nothing is ever settled, no view can ever be omitted from the comprehensive account" (Feyerabend 1975 [1993], 21). Finally, Rowbottom (2023) has advanced meta-normative relativism to challenge claims about scientific progress: inspired by J. L. Mackie's error-theory in meta-ethics, he argues against the assumption that there are objective or privileged intersubjective aims of science (cf. Section 2.2). Rowbottom allows that individual scientists and groups may have cognitive aims, but doubts attempts to analyze aims on the collective level. His thesis that standards of good science are "ultimately subjective" is in conflict with the fact that science is a social institution, so that the members of the scientific community are jointly committed to methods and values which also characterize standards of scientific progress (Niiniluoto 2020).

Growth rates of modern science: a latent piecewise growth curve approach to model publication numbers from established and new literature databases

Growth of science is a prevalent issue in science of science studies. In recent years, two new bibliographic databases have been introduced, which can be used to study growth processes in science from centuries back: Dimensions from Digital Science and Microsoft Academic. In this study, we used publication data from these new databases and added publication data from two established databases (Web of Science from Clarivate Analytics and Scopus from Elsevier) to investigate scientific growth processes from the beginning of the modern science system until today. We estimated regression models that included simultaneously the publication counts from the four databases. The results of the unrestricted growth of science calculations show that the overall growth rate amounts to 4.10% with a doubling time of 17.3 years. As the comparison of various segmented regression models in the current study revealed, models with four or five segments fit the publication data best. We demonstrated that these segments with different growth rates can be interpreted very well, since they are related to either phases of economic (e.g., industrialization) and/or political developments (e.g., Second World War). In this study, we additionally analyzed scientific growth in two broad fields (Physical and Technical Sciences as well as Life Sciences) and the relationship of scientific and economic growth in UK. The comparison between the two fields revealed only slight differences. The comparison of the British economic and scientific growth rates showed that the economic growth rate is slightly lower than the scientific growth rate. Article Open access 05 October 2021

Growth of science is an ongoing topic in empirical and theoretical studies on science of science. In a recent overview of science of science studies, Fortunato et al. (2018) stated that "early studies discovered an exponential growth in the volume of scientific literature ... a trend that continues with an average doubling period of 15 years". The investigation of growth processes leads to results that can be used to characterize science. For example, if the literature doubles every 15 years, science would be characterized by immediacy: "the bulk of knowledge remains always at the cutting edge" (Wang and Barabási, 2021, p. 163). Results on growth processes can also be used to investigate the validity of theories on the development of science: Does science follow a slow, piecemeal process or a process with normal science interrupted by revolutionary periods with an increased level of activity (Kuhn, 1962; Tabah, 1999)? Popular early studies on growth of science have been published by the theoretician of science, Derek John de Solla Price (1965; 1951, 1961) who can be seen as the pioneer in investigating growth of science processes (see de Bellis, 2009). According to Price (1986), the development of science follows the law of exponential growth: "at any time the rate of growth is proportional to the ... total magnitude already achieved—the bigger a thing is, the faster it grows" (p. 4). Although empirical and theoretical studies in previous decades have confirmed exponential growth, a precise estimation of the growth rate based on reliable and sound publication data has not been done yet. In most of the studies on growth of science published hitherto, bibliometric data have been used to measure growth of science (an alternative measure is the number of researchers, for instance). It is an advantage of using bibliometric data (compared to other data) that large-scale, multi-disciplinary databases are available based on worldwide publication productions. Another advantage is the characteristic of most scientific disciplines that publications are the main outcome: "science would not exist, if scientific results are not communicated. Communication is the driving force of science. That is why scientists have to publish their research results in the open, international scientific literature. Thus, publications are essential" (van Raan, 1999, p. 417). According to Merton (1988), "what we mean by the expression 'scientific contribution': an offering that is accepted, however provisionally, into the common fund of knowledge" (p. 620). In a previous study (Bornmann and Mutz, 2015), two authors of the current study investigated the growth of science based on data from the Web of Science database (Clarivate Analytics; Birkle et al., 2020). Bornmann and Mutz (2015) not only used cited references but also cited references data (see Marx and Bornmann, 2016, for an overview of the use of cited references data for historical studies). They argued that Web of Science data (publication counts) are scarcely suitable to investigate early periods of modern science, since early publications are not sufficiently covered. Cited references may have the advantage of covering these early periods and a wider range of document types, including journal articles, books, book contributions or proceedings, which are still not fully included in the databases. However, cited references data can only serve as a less-than-ideal proxy of publication numbers, because non-cited publications are not considered. In recent years, new bibliographic databases have been introduced: Dimensions (Herzog et al., 2020; Hook et al., 2018) from Digital Science and Microsoft Academic (Wang et al., 2020), which can be used to study growth processes in science from centuries back. Thus, it is the intention of the current study to use data from both databases for investigating these processes and compare the results with those from Web of Science and Scopus (Elsevier; Baas et al., 2020) databases. With Dimensions, Microsoft Academic, Web of Science, and Scopus, we considered in this study (the most) important multi-disciplinary literature databases currently available. The comparison of the empirical results based on the four databases may point to an assessment of growth processes in science that might be interpreted as valid—since the assessments can be made independently of the use of single data sources. We investigated the growth processes not only for all annual publications but also for two broad fields: (1) Physical and Technical Sciences and (2) Life Sciences (including Health Sciences). We selected these broad fields and did not consider further fields such as social sciences and humanities. Only for these two fields, we can be sure that publication data can be used as valid proxy for research activity. In this study, we additionally undertook a comparative analysis of economic and scientific growth processes. According to Price (1986), the theoretical basis for the study of econometrics is similar to that for the study of scientometrics: both follows the law of exponential growth (differences lie in the parameters). Previous scientometrics research revealed that growth of science is related to economic development (Fernald and Jones, 2014; Salter and Martin, 2001). Although a national science system producing high-quality research is—without doubt—an important condition for national wealth, we primarily consider money as necessary input to the science system (and thus, economic growth as independent variable). In principle, national wealth can be achieved without a modern science system (as it has been done for centuries), but (modern) science needs economic input to exist and function. Our comparative analysis of scientometrics and econometrics could not be done based on worldwide data, since long-time series for publication counts and economic growth indices are not available at this level. Following seminal research by May (1997) and King (2004a, 2004b) on the relationship of science and economy, we focus instead on UK for which time series of economic development are available that reach back to the seventeenth century (Thomas et al., 2010). Such historical data are not available for other countries (to the best of our knowledge). Using similar statistical methods as for publication data, we investigated in this study annual growth rates in gross domestic product (GDP) as a measure of economic wealth of a nation similar to the approach by King (2004a, 2004b). We used bibliometric and economic data in this study. The five different databases and datasets are as follows:

Web of Science

The core citation indices of Web of Science (SCI-E, SSCI, and A&HCI) date back until the 1960s when they were founded by Eugene Garfield. The other citation indices were started later on (e.g., CPCI-S and CPCI-SSH). In total, the publications indexed in the Web of Science are divided into 44 different document types (e.g., "Review", "News item", or "Note"). The coverage of the scientific literature dates back to 1900. The Web of Science is more selective with respect to the choice of indexed sources than the other databases used in this study (Visser et al., 2021). We used the advanced search of the Web of Science online interface with the query "py = 1900–2018" in the indices SCI-E, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, and IC (Index Chemicus) (date of search: 30 August 2019). No restriction on document types was imposed. In via the "Analyze Results" function applied to publication years, we were able to conveniently download the number of indexed papers per year. Broad subject categories were defined via the Web of Science subject categories: Physical and Technical Sciences: "Astronomy & Astrophysics", "Chemistry", "Crystallography", "Electrochemistry", "Geochemistry & Geophysics", "Geology", "Mathematics", "Meteorology & Atmospheric Sciences", "Mineralogy", "Mining & Mineral Processing", "Oceanography", "Optics", "Physical Geography", "Physics", "Polymer Science", "Thermodynamics", "Water Resources", "Acoustics", "Automation & Control Systems", "Computer Science", "Construction & Building Technology", "Energy & Fuels", "Engineering", "Imaging Science & Photographic Technology", "Information Science & Library Science", "Instruments & Instrumentation", "Materials Science", "Mechanics", "Metallurgy & Metallurgical Engineering", "Microscopy", "Nuclear Science & Technology", "Operations Research & Management Science", "Remote Sensing", "Robotics", "Science & Technology Other Topics", "Spectroscopy", "Telecommunications", and "Transportation". Life Sciences (including Health Sciences): "Agriculture", "Allergy", "Anatomy & Morphology", "Anesthesiology", "Anthropology", "Audiology & Speech-Language Pathology", "Behavioral Sciences", "Biochemistry & Molecular Biology", "Biodiversity & Conservation", "Biophysics", "Biotechnology & Applied Microbiology", "Cardiovascular System & Cardiology", "Cell Biology", "Critical Care Medicine", "Dentistry, Oral Surgery & Medicine", "Dermatology", "Developmental Biology", "Emergency Medicine", "Endocrinology & Metabolism", "Entomology", "Environmental Sciences & Ecology", "Evolutionary Biology", "Fisheries", "Food Science & Technology", "Forestry", "Gastroenterology & Hepatology", "General & Internal Medicine", "Genetics & Heredity", "Geriatrics & Gerontology", "Health Care Sciences & Services", "Hematology", "Immunology", "Infectious Diseases", "Integrative & Complementary Medicine", "Legal Medicine", "Life Sciences Biomedicine Other Topics", "Marine & Freshwater Biology", "Mathematical & Computational Biology", "Medical Ethics", "Medical Informatics", "Medical Laboratory Technology", "Microbiology", "Mycology", "Neurosciences & Neurology", "Nursing", "Nutrition & Dietetics", "Obstetrics & Gynecology", "Oncology", "Ophthalmology", "Orthopedics", "Otorhinolaryngology", "Paleontology", "Parasitology", "Pathology", "Pediatrics", "Pharmacology & Pharmacy", "Physiology", "Plant Sciences", "Psychiatry", "Public, Environmental & Occupational Health", "Radiology, Nuclear Medicine & Medical Imaging", "Rehabilitation", "Reproductive Biology", "Research & Experimental Medicine", "Respiratory System", "Rheumatology", "Sport Sciences", "Substance Abuse", "Surgery", "Toxicology", "Transplantation", "Tropical Medicine", "Urology & Nephrology", "Veterinary Sciences", "Virology", and "Zoology".

Scopus

Scopus was launched in 2004 by the publisher Elsevier. Coverage of the scientific literature dates back to 1861. The publications indexed in Scopus are divided into 16 different document types. Scopus has a broader coverage than Web of Science, especially in the Social Sciences and Humanities (Visser et al., 2021). We used the advanced search of the Scopus online interface2 with the query "PUBYEAR AFT 1800" for this study (date of search: 30 August 2019). No restriction on document types was imposed. Via the "Analyze Search Results" function applied to publication years, we were able to conveniently download the number of indexed papers per year. Broad subject categories were defined via the Scopus subject areas: Physical and Technical Sciences: "Chemical Engineering", "Chemistry", "Computer Science", "Earth and Planetary Sciences", "Energy", "Engineering", "Environmental Science", "Materials Science", "Mathematics", and "Physics and Astronomy". Life Sciences (including Health Sciences): "Medicine", "Nursing", "Veterinary", "Dentistry", "Health Professions", "Multidisciplinary3", "Agricultural and Biological Sciences", "Biochemistry, Genetics and Molecular Biology", "Immunology and Microbiology", "Neuroscience", and "Pharmacology, Toxicology and Pharmaceutics".

Microsoft Academic

Microsoft Academic was first released in 2016. It can be considered an unconventional bibliographic database because its content is not delivered by the publishers but found by the search engine Bing on the publisher's websites. This implies that especially the data from Microsoft Academic might have a bias towards publications with a digital footprint. However, many publishers provide websites for their older publications, too. Microsoft Academic offers a basic search interface4 and bulk data access via the Azure platform5. Microsoft Academic has a broader coverage than Web of Science and Scopus (Visser et al., 2021). We downloaded a snapshot of the Microsoft Academic data from the Azure platform (last update: 11 January 2019). The raw Microsoft Academic data were imported and processed in a locally maintained PostgreSQL database at the Max Planck Institute for Solid State Research. Our current snapshot of the Microsoft Academic database contains bibliographic data of 212,209,775 publications, such as title, publication year, and document type. Content coverage dates back to 1800. The publications indexed in Microsoft Academic are divided into five document types ("Journal", "Patent", "Conference", "BookChapter", and "Book"). Unfortunately, 77,227,143 indexed items are not assigned to any document type. Via SQL commands, we produced items per publication year statistics for all items with known document type in the Microsoft Academic database excluding the document type patent but included the items without document type for a separate analysis. Microsoft Academic offers a subject classification on different hierarchical levels. There are 19 different fields on the highest level. Broad subject categories were defined via that highest level: Physical and Technical Sciences: "Geology", "Chemistry", "Materials science", "Mathematics", "Engineering", "Environmental science", "Physics", "Geography", and "Computer science". Life Sciences (including Health Sciences): "Biology" and "Medicine".

Dimensions

Dimensions is the most recent database used in this study. It was launched in 2018 by Digital Science and contains meta-information about grants, publications, clinical trials, and patents. Like Web of Science and Scopus, Dimensions receives publication information from the publishers but pursues a different indexing strategy. Dimensions tries to cover as many publications and publication types as possible. Dimensions is accessible via an online search interface6, an API, Google BigQuery, and additionally, Digital Science shares the raw data without cost for research purposes7. The raw Dimensions data (last update: 26 September 2019) were downloaded, imported and processed in a locally maintained PostgreSQL database at the Max Planck Institute for Solid State Research. The raw data of the Dimensions database are provided as separate sub-databases: "Grants", "Publications", "Clinical trials", and "Patents". In the following, by using the term "Dimensions" in the text, we refer only to the Dimensions sub-database "Publications". The indexed publications therein are divided into six different publication types ("Article", "Chapter", "Proceeding", "Preprint", "Monograph", and "Book"). Dimensions offers the second largest coverage of the literature in this study (Visser et al., 2021). Dimensions offers a much larger coverage of books and book chapters than Web of Science or Scopus (Clarivate, 2020; Elsevier, 2020; Taylor, 2020). Via simple SQLs, we produced publications per publication year statistics without restrictions on publication types or other items. Dimensions offers many different classification schemes, some of them are focused on specific disciplines or topics like Sustainable Development Goals (SDGs). For the purposes of our study, we have made use of the Dimensions implementation of the Australian and New Zealand Standard Research Classification (ANZSRC) Fields of Research (FOR) codes, as per the 2008 field definitions.8 The ANZSRC codes are delivered at three levels, the two least granular levels of which have been implemented in Dimensions. There are 22 fields of the highest level. Broad subject categories were defined in this study via that higher level: Physical and Technical Sciences: "Mathematical Sciences", "Physical Sciences", "Chemical Sciences", "Earth Sciences", "Environmental Sciences", "Information and Computing Sciences", "Engineering", "Technology", and "Built Environment and Design". Life Sciences (including Health Sciences): "Biological Sciences", "Agricultural and Veterinary Sciences", and "Medical and Health Sciences".

Federal Reserve Bank of St. Louis (FRED)

The economic research department of the FRED offers a series of datasets for economic analyses and for analyses of the historical development of the economy (e.g., GDP). A time series from 1770 to 2016 of the annual "Nominal Gross Domestic Product at Market Prices in the UK, Millions of British Pounds, Annual, Not Seasonally Adjusted" (NGDPMPUKA) for UK was downloaded as an Excel table.9 We use in the following the term "gross domestic product" or GDP instead of NGDPMPUKA to facilitate the reading of the results. Since the values are nominal values, GDP is not adjusted for inflation. Publication counts for UK were retrieved from Dimensions for the years 1788 until 2016.

Growth Analyses

The data retrieved from the different databases is the number of publications published in 1 year. For the growth analysis, however, the cumulative number of publications is used. If, for example, up to a year x, 1000 publications were published, and in the year x 100, the accumulated number of publications in the year x is 1100 publications. The difference to year x – 1 is exactly the absolute growth in year x, i.e., 100 publications, the number of publications published in year x. For simplification, "Number of Publications" is used below instead of "Cumulative Number of Publications".

Statistical Analyses

Scientific growth processes do not necessarily run homogeneously over time, especially when a long-time horizon is chosen, for example, from the beginning of modern science in the sixteenth/seventeenth century until today. Therefore, modern growth analysis has to simultaneously address three different problems: (1) Science can grow according to different growth functions, which provide hypotheses about the nature of growth processes (e.g., unrestricted exponential). (2) It can be assumed that science grows at different rates at different time periods or segments, i.e., growth rates vary over time. (3) Growth functions might vary across different databases such as Scopus or Web of Science covering different time horizons. In the following sections, solutions to the three problems are presented, which refer to growth functions (unrestricted and restricted exponential growth), segmented regression, and latent growth curve models.

Growth functions

The simplest growth function is that of unrestricted growth in the form of an exponential function, where the growth of science in each year is proportional to the volume of publications available in the previous year. An equal percentage of the volume grows every year. For example, if we assume an annual growth rate of 10% and 100 publications in a certain year, then there are 100 + 0.10*100 = 110 publications in the following year. One year later, there are 110 + 0.10*110 = 121 publications (and so on). Another growth function assumed by Price (1963) is that of restricted growth: Science would run exponentially at the beginning, but with time the growth process approaches an upper capacity limit with constantly decreasing growth rates (s-shaped course). In view of the limited capacities of human and investment capital for research (and other sections of society), the latter thesis by Price (1963) seems to be more plausible than the simplest growth function: Since resources (human resources, capital) are limited, growth cannot be limitless either. These considerations make it necessary to choose a statistical analysis strategy in which different growth rates apply and different growth functions are possible as well. The time segments themselves are not known in advance and have to be estimated. Such an opportunity is offered by the "Segmented Regression" or "Piecewise Regression" analyses, which start from different intervals of a dependent variable (in this case: time). These regression analyses apply different functional relationships and simultaneously make it possible to estimate time segments and parameters of the growth functions (Gallant and Fuller, 1973; McZgee and Carleton, 1970; Schwarz, 2015; Toms and Lesperance, 2003; Valsamis et al., 2019; Wagner et al., 2002). In this study, we assume a time series y_t of the number of publications y_t available per year, where t denotes the index of the time series, and t = 0 the starting year of the time series (e.g., for the year 1665: t = year-1665). We thus consider two growth functions (see above): Unrestricted exponential growth The functional relationship for exponential growth assumes that the derivative of the function is proportional to the function itself: f(t) = b1 f(t). The resolution of this differential equation leads to a functional relationship, which can be represented in the following statistical model:

$$\begin{array}{*{20}{c}} {y_t = {e^{b_0}}{e^{b_1 t}} + \varepsilon_t; \varepsilon_t \sim N\left({0,\sigma ^2{{\mathbf{CORR}}}_{\varepsilon_t\varepsilon_{t-1}}} \right)} \end{array},$$

where e^{b_0} represents the initial volume of publications at the starting point of the time series (t = 0), b_1 the growth constant, and ε_t the residual with the variance σ2 as well as the correlation matrix $({\mathbf{CORR}})_{\varepsilon_t\varepsilon_{t-1}}$. The latter is equated here with the identity matrix I, which means that the residuals do not (auto-)correlate. After the model estimation, we checked whether the residuals of the estimated model are actually auto-correlated or not. In the simplest case of an autoregressive process of first order (AR(1)), the residuals at time t are (auto-)correlated with the residuals at time t - 1. If Eq. (1) is logarithmically transformed, a simple linear regression function can be obtained:

$$\begin{array}{*{20}{c}} {\ln \left({y_t} \right) = b_0 + b_1 t + \varepsilon_t; \varepsilon_t \sim N\left({0,\sigma^2{{\mathbf{CORR}}}_{\varepsilon_t\varepsilon_{t-1}}} \right)} \end{array}$$

The doubling time is the time the growth process needs to double the population size at a given time point t: $\ln(2)/\ln(1 + g)$ with $g = e^{b_1}-1$, where b_1 is the estimated regression coefficient and g the annual growth rate. The annual growth rate g as the percentage change between two time points is given by $e^{b_1}-1$ for Eq. (1). For b1 = 0.05, for example, g amounts to 0.051 or 5.1%.

Restricted growth (Verhulst-Pearl)

For the growth of science as a special case of a logistic growth model with a capacity limit C, the derivation of the function is proportional to the following function: f(t) = b1 f(t) (1 - f(t)/C). The resolution of this differential equation leads to a functional relationship, which can be represented in the following statistical model (Tsoularis and Wallace, 2002, p. 28f.):

$$\begin{array}{*{20}{c}} {y_t = f\left(t \right) = \frac{ {e^{K}} {e^{b_0}} }{ \left({e^K - {e^{b_0}}} \right){e^{-b_1 t}} + {e^{b_0}} } + \varepsilon_t; \varepsilon_t \sim N\left({0,\sigma^2{{\mathbf{CORR}}}_{\varepsilon_t\varepsilon_{t-1}}} \right)} \end{array}$$

It can be seen in Eq. 4 that if t→∞, the exponential expression in the denominator, $e^{-b_1 t}$, goes towards zero and the function approaches the capacity limit C = eK. At time t = 0, the start of the time series, the exponential expression in the denominator is 1, and the function corresponds to the initial value of the publications e^{b_0} (1). A limited growth in the sense of the S-curve would have to be described as limited growth for the first segment to rule out or not the de Solla Price hypothesis of growth in science. The combination of s-shaped segments over time seem to be implausible in light of the empirical results on the growth of science reported by Bornmann and Mutz (2015). If Eq. 4 is logarithmically transformed, the following linear regression function results:

$$\begin{array}{*{20}{c}} {\ln \left({y_t} \right) = K + b_0 - \ln \left({\left({e^K - e^{b_0}} \right)e^{-b_1 t} + e^{b_0}} \right) + \varepsilon_t; \varepsilon_t \sim N\left({0,\sigma^2{{\mathbf{CORR}}}_{\varepsilon_t\varepsilon_{t-1}}} \right)} \end{array}$$

In the following, we will call the "restricted growth model (Verhulst-Pearl)" the "logistic growth model".

Segmented regression

Following the literature on the development of science over time (e.g., de Solla Price, 1963), we consider the process of development in science as one of repeated changes in growth rates (Heyer, 2008). We used segmented regression that defines the regression models for the respective segments of time and can be represented in the form of nested IF-THEN clauses for each segment j, the following overall model applies with y_t as the starting year of the time series (e.g., 1665):

IF t ≤ α1 THEN $$\log \left({y_t} \right) = b_0 + b_1 t + \varepsilon_t$$

ELSE IF t ≤ α2 THEN $$\log \left({y_t} \right) = b_0 + b_1\left({a_1 - t_0} \right) + b_2\left({t - a_1} \right) + \varepsilon_t$$

ELSE IF t ≤ α3 THEN $$\log \left({y_t} \right) = b_0 + b_1\left({a_1 - t_0} \right) + b_2\left({a_2 - a_1} \right) + b_3\left({t - a_2} \right) + \varepsilon_t$$

ELSE IF t ≤ αj THEN $$\begin{array}{*{20}{c}} {\log \left({y_t} \right) = b_0 + \left({j \ge 2} \right)\mathop {\sum}\limits_{k = 1}^{j - 1} b_k\left({a_k - a_{k-1}} \right) + b_j\left({t - a_{j-1}} \right) + \varepsilon_t; \varepsilon_t \sim N\left({0,\sigma^2{{\mathbf{CORR}}}_{\varepsilon_t\varepsilon_{t-1}}} \right)} \end{array}$$

where aj denotes the year at which the jth time segment ends, and where a0 = t0 = the starting year of the time series. In addition to the parameters of the growth function, the year parameters a1 to aj-1 are estimated. The same distribution of residuals is assumed for each segment. Publication counts is a count variable. The variable includes positive integer values with zero. This implies that the values are distributed, for example, according to a Poisson distribution (Hilbe, 2014, p. 2). In this study, however, a logarithmic transformation (log-linear regression) of the publication data was favored over a Poisson model for the following reasons: (1) with regard to growth rates of science, unrestricted growth or exponential growth is assumed, in which the logarithmic transformation leads to a simple linear regression function. The parameters of the function can be interpreted in terms of the original non-transformed growth function (Panik, 2014, p. 33). (2) If it can be demonstrated that the growth of publication data are very well explained by the function (because of low-residual variance), then neither the distribution function nor the transformation play a major role. (3) Owing to the smaller scale of the values resulting from log-transformation, there is a greater chance that complex statistical models converge in the estimation process.

Piecewise latent growth curve model with missing imputation

In this study, we used data from several bibliographic databases. Therefore, we needed to find an answer to the question of how the various datasets reflecting the same information (scientific output) should be analyzed statistically. It was one option to conduct the analyses for each database separately. However, this approach has the risk of obtaining four different results that might reflect specific aspects of a database. Another option was to model the data from the different databases within one statistical model. This solution would still need solutions to the following problems: (1) The time intervals at which publication data are available vary from database to database. The largest time interval (from 1665 to 2018) is available from Dimensions. To analyze only the time interval for which all databases provide complete data would significantly limit the period of investigation of the development of science. (2) The publication data vary greatly in volume between the databases. Dimensions, for example, has the highest volume of publications when the entire time series is considered, whereas Web of Science has the comparatively lowest volume. Here, the question arises whether some form of data weighting according to volume is necessary. The solution for these problems that we favored in this study was the application of the so-called "Latent Piecewise Growth Curve Model". This model can be run in conjunction with an approach based on completed time series, i.e., incomplete time series are treated statistically as missing-value problem. Another possible solution for the problems would be to refer only to those years for which all time series have information. This solution would limit the horizon of the analysis (elimination of epochs). Furthermore, the possibility of looking further into the past would get lost with the consequence of missing data. The problem of missing values in the data by which the incomplete time series of different databases are handled becomes relevant when the years before the turn into the twentieth century are considered. There are established methods available to deal with missing values (Little and Rubin, 2019). The most important are two types of procedures: "Maximum Likelihood" and "Imputation". Maximum Likelihood methods can be used to identify different patterns of missing values and then efficiently estimate the parameters in the estimation procedure using all available information across the patterns, so-called "Full Information Maximum Likelihood" (FIML). In imputation procedures, missing values are replaced by estimated values, for example by the mean value of a variable. In the "Multiple Imputation Procedure" several predicted values from a stochastic regression on variables with full information (here time series) are used for a missing value, representing the uncertainty in the estimate. The different assumptions about the missing-value process are crucial for both procedures. In the case of "Missing Completely at Random" (MCAR), it is assumed that the missing-value process is completely random, i.e., the missing values do not depend on observed values of other variables or the unobserved values of the variable under investigation itself. The missing-value process can be ignored. A case-wise deletion would be appropriate in this case. "Missing at Random" (MAR) assumes that the missing-value process depends on observed values of other variables, but not on the unobserved values of the variable under investigation itself. "Missing not at Random" (MNAR) assumes that the missing-value process depends not only on observed values of other variables in the data but also on unobserved values of the variable under investigation itself. Imagine, for example, database providers would exclude papers of specific publication years, because only a small set of documents were published. An MNAR assumption is not very plausible in this case. Database providers did not make any selections of publication years on the basis of the number of publications in 1 year. The database providers replicate the same growth process with high correlations (>0.90) among the time series, the MCAR assumption cannot hold either, leaving the assumption of "Missing at Random". Our data from Web of Science, for example, cover the range from 1900 to 2018, and our data from Dimensions cover the range from 1670 to 2018. MAR requires that the missing values of Web of Science between 1670 and 1899 are not the results of intended actions by the database provider, Clarivate Analytics. In the case of intended actions, for example, the company would systematically (completely) leave out publication years with low publications counts. Owing to the fact that the missing-value process is not observable, we unfortunately, MAR cannot be verified. We opt for a multiple imputation procedure. In contrast to FIML, the procedure allows to make imputed values visible in order to check for possible biases. The problem of missing values becomes relevant in this study when we go back in time before 1900. The assumed inaccuracy of the overall model estimation by missing imputation reflects the uncertainty of the historical perspective: the further the empirical analyses goes back in history, the more uncertain the results become. In the first step of the imputation procedure in this study, based on the complete information across all four time series/databases, the missing values of a time series are imputed with estimated values. To take into account the inaccuracy of values in the estimation (when imputed values are used), five imputed values are estimated for each missing value, which should represent a random sample of missing values. Graham et al. (2007) recommend >5 imputed values. The relative efficiency of an imputation estimator as measure of how well the true parameters in the population are estimated was very high (above .99). The statistical estimation of one imputation was too time-consuming to allow for more imputations. A Markov-Chain Monte Carlo (MCMC) procedure was used to impute the missing values from the available time series with full information. In the second step of the imputation procedure in this study, for each of the five complete datasets with imputed values, a segmented regression model was estimated and then synthesized to an overall result considering the inaccuracy of the missing imputation in the calculation of standard errors. The point estimate of the overall segmented regression model parameter is the average of the parameters of the five complete-data estimates. The point estimate of the predicted value (missing or not) for each time point and database is the average of the corresponding estimates of the five complete-data estimates. The standard error of the overall segmented regression model parameter consists of two estimates: the average of the standard errors of the regression parameter estimated for each of the five imputed datasets (within variance) and the variability of the regression parameter across the five imputed datasets (between variance). The main challenge in the analyses was to obtain convergence of the estimation algorithm across all models and all imputations. Especially for models with many segments, convergence problems occurred due to the differential scaling of the variance components (high variability in the intercept and decreasing variability in the slopes with increasing number of segments). Therefore, random effects were partly scaled (e.g., multiplied by 100 or 0.01) to establish convergence. The statistical analyses in this study were done within the statistical software package SAS and the procedures PROC NLMIXED, PROC NLIN, PROC MI, and PROC MIANALYZE (SAS Institute Inc., 2015). In this section, the results of the model estimations are presented. The first 5 years of each time series were excluded to reflect only a pseudo segment or artifact without any empirical meaning. Therefore, the actual starting years were 1670 for Dimensions, 1805 for Microsoft Academic, 1905 for Web of Science, and 1866 for Scopus. Each time series ran until the year 2018.

Model comparison

Statistical model comparisons make it possible to rule out unrealistic models with poor model fit in order to get the model with the relatively best fit to the data. The model formulation is associated with certain assumptions about segmented growth (see Table 1): (1) A model with unconstrained exponential growth can be distinguished from a model with a logistic growth (S-shaped curve). (2) One can distinguish whether the models based on different bibliographic databases come to similar or different results (e.g., are there mixed-effects or not?). (3) If there are significant differences between the results based on the databases, the following question would arise: Do the databases with a comparable high (low) volume of publications in the beginning of the time series show a high (low) increase in the later publication count? If so, the covariance or correlation between starting volume of publications and slope across the databases would be high (is there covariance or not?). (4) The models can provide different answers to the question of how many segments exist in the growth of science (how many segments can be distinguished?).

Table 1 Model comparison using Schwarz's Bayesian information criterion (BIC) for publication data from different bibliographic databases, All publications, Life Sciences publications, and Physical and Technical Sciences publications.

Model M1 "Exponential Growth" (see Table 1), for example, includes three parameters: intercept, slope and residual variance. If intercepts and slopes are allowed to vary across the four databases, two variance components were additionally estimated with overall five parameters. In M3, the covariance of intercept and slope only for the first segment was added as a further parameter. Instead of statistical significance testing, model comparison is undertaken in this study based on Schwarz's Bayesian information criterion (BIC). The smaller the BIC, the better the model fits the data (see Table 1). Models represent very different hypotheses about the nature of growth (e.g., exponential). The BIC is corrected for the number of parameters. A selection of models (e.g., number of segments) was made that were useful to estimate given the number of parameters and that still showed model improvement in terms of BIC. Comparing model 1 and model 2, it becomes clear that a simple fixed-effects model (M1) does not fit the data well. The differences between the growth curves based on the various databases are too large, so that a mixed-effects model (M2) can be assumed, which results in a significantly smaller BIC. The hypothesis of logistic growth can be rejected as well since the exponential model fits better. Among the models in Table 1, model M9 with five segments and a covariance of intercept and slope in the first segment fits best for "Physical and Technical Sciences", model M8 with four segments fits best for "All Publications" and "Life Sciences" with a negligible improvement for "All Publications" with five segments (period of 2nd World War). This result applies to all datasets (databases) considered in this study that refer to (1) "All Publications", (2) "Physical and Technical Sciences", and (3) "Life Sciences" publications. Since the explained variance—measured in terms of the coefficient of determination (R2)—exceeds 0.99, any autocorrelation among residuals or possible heterogeneity of residual variances can be neglected (Eqs. 2 to 5). The covariance matrix of the residuals, $({\mathbf{CORR}})_{\varepsilon_t\varepsilon_{t-1}}$, is assumed to be an identity matrix I. The model comparison in Table 1 demonstrates that the assumption of constant scientific growth over time is not realistic; hence, we can start with the premise that growth rates vary. The covariance of the intercepts and slopes (as in the first segment) for example, the history of the twentieth century is characterized by two World Wars with drastic consequences for the science system worldwide. As the results by Bornmann and Mutz (2015) based on cited references data have shown, the negative effects of the World Wars on scientific growth are also clearly visible for the estimated parameters of the segmented growth (see Table S1 in the Supplementary Information). Comparing model M3 with model M2 and model M6 with model M5, BIC improves in both cases. There is a covariance across all databases between the intercept and the slope in the first segment that is negative in all models. The higher the initial time series level of a database, the more the time series slope in the first segment is below the average slope of all databases and vice versa. With respect to the single time series of the GDP, a model with seven segments fits the data best (see Table 2). For publication counts, a model with eight segments fits the data best (see Table S2 in the Supplementary Information). We additionally compared the models using the mean square error (MSE) and the BIC derived from the MSE to select certain models (Kim and Kim, 2016) (see Table S2 in the Supplementary Information).

Table 2 Model comparison using Schwarz's Bayesian information criterion (BIC) for publication data and gross domestic product (GDP) of UK.

Growth rates of science

Growth analyses in scientometrics: Although publication counts are frequently used as an indicator of research productivity in scientometrics, in investigating growth processes in science using publication data, we follow typical assumptions such as those formulated by Long and Fox (1995): "while research productivity is not strictly equivalent to publication productivity, publication is generally taken as an indication of research" (p. 51). Figure 1 shows the result of the unrestricted growth (M1) and segmented unrestricted growth (M9) models based on the data from four different bibliographic databases: Dimensions, Microsoft Academic, Scopus, and Web of Science. The graphs in the figure present the annual logarithmized number of publications and cumulated number of publications (y-axis) over time. The gray dots represent the missing imputed values (or the observed values (the raw data from the databases), and the black solid line (with the two black dashed lines) the predicted values from the regression analyses (with 95% prediction intervals). As the results of the unrestricted growth model (M1) in Fig. 1a show, the overall growth rate amounts to 4.10% with a doubling time of 17.3 years.

Fig. 1: Plots for scientific growth based on the number of publications from four databases.

Shown are the results for the unrestricted growth (M1) in Fig. 1a and for the segmented unrestricted growth (M9) in Fig. 1b. The colored dashed lines show the predicted values of the segmented regression model, and the black solid line the overall regression for the whole data (across all databases). The symbols represent single values, either observed (colored symbols) or imputed (gray dots). The results are shown in the figure—with the exception of the results based on the Scopus data for the first segment—that the predicted values from the regression (dashed lines) cover the observed values (points) very well (high amount of explained variance) in both broad fields (see Figs. 2b and 3b). The four segments in Fig. 1b seem to represent separate historical epochs in the modern history of science: These segments with different growth rates are oriented towards either phases of economic (e.g., industrialization) and / or political developments (e.g., World Wars), 1. Phase: Emergence of modern physics and pre-industrialization (1675–1809). The phase up to the end of the Napoleonic wars is characterized by a moderate annual growth of 2.87% and a doubling time of 24.5 years, i.e., during 24.5 years the volume of publications doubles. This early phase of science is characterized by major discoveries in physics by Isaac Newton (1643–1727) and the development of the steam engine (James Watt, from 1769). 2. Phase: Industrial Revolution (1810–1882). In this phase of industrial revolution, science grew strongly with an annual growth rate of 5.62% and a doubling time of 12.6 years. 3. Phase: Economic crises and World Wars and Post-war period (1881–1952): The development of science flattened out with an annual growth rate of 3.78% and a doubling time of 18.7 years. In this period, two economic depressions and two World Wars took place. The "long depression" is a period that started in 1873 and ended in 1896. The period is mainly characterized by a deflation in the USA and Europe (Capie and Wood, 1997). The "long depression" can be distinguished from the "Great Depression" that ranged from 1929 until the beginning of the Second World War. 4. Phase: Post-war period (after 1952 until today): Since 1952, science has grown exponentially without restrictions with an annual growth rate of 5.08% and a doubling time of 14.0 years. In the analyses of Microsoft Academic data, we considered all publications with known document types except patents, i.e., we excluded the publications with unknown document type. Microsoft Academic publications without document type but with DOI, we identified book chapters and journal publications as well as conference papers and technical reports. We also found summaries of the events of conference papers. Since not all publications can be seen as scientific contributions to scientific progress, we analyzed the influence of document type on the results (see the results in the Supplementary Information, Fig. S6). The differences between the results including all documents and only those documents with known document types are small. For all documents a further segment could be identified, which represents the period of Second World War (1940–1945).

Growth rates of science for Life Sciences and Physical and Technical Sciences

In addition to the analyses including all publications, we have also conducted analyses for two broad fields: Life Sciences and Physical and Technical Sciences. The estimated parameters of the models are reported in Table S1 in the Supplementary Information. The results are visualized in Figs. 2 and 3. With the comparison of two broad fields, we wanted to find out whether different fields are characterized by similar or different growth rates in their historical developments. As the results in Fig. 2a show, the overall annual growth rate for Life Sciences amounts to 5.07% with a doubling time of 14.0 years.

Fig. 2: Plots for scientific growth based on the number of publications in Life Sciences.

Shown are the unrestricted growth (M1) and the segmented unrestricted growth (M9).

Fig. 3: Plots for scientific growth based on the number of publications in Physical and Technical Sciences.

Shown are the unrestricted growth (M1) and the segmented unrestricted growth (M9). In agreement with the results for all publications in Fig. 1b, the predicted values of the segmented regression model (dashed lines) cover the observed values (points) very well (high amount of explained variance) in both broad fields (see Figs. 2b and 3b). In both figures, we can observe trends that—although not completely congruent with the trends based on all publications—roughly illustrate the four central stages in the development of science and society: pre-industrialization (until 1793/1808), Industrial Revolution (till 1810 /1848), Second World War (1936–1943) only for Physical and Technical Science with a decline in the volume of publications, and the post-World War period. In the segment reflecting the period after 1945 with an annual growth rate of 5.99% and a doubling time of 11.9 years, the growth in the Physical and Technical Sciences is higher than the growth rate in the Life Sciences. In the Life Sciences the growth rate is 4.79% with a doubling time of 14.8 years. The growth rate in the Physical and Technical Sciences is also slightly higher than the growth rate that we calculated based on all publications in this segment (see Fig. 1b): 5.08%.

Comparative analysis of growth rates of gross domestic product in UK

For a comparative analysis of economic and scientific growth (using similar statistical methods), we used data from UK as explained in the "Introduction" section. We analyzed logarithmic transformed cumulative publication data to estimate the different segments of growth and the respective growth rates. For the comparative analysis, only the publication counts of Dimensions are used since the data from this database reach far back into the history of science. Only in this way, the growth rates of science and economy can be directly compared. The publication counts were obtained by the Dimensions database. The average annual growth rate of science in UK since 1780 is 4.97% (see Fig. 4a). This corresponds to a doubling time of 14.3 years. This annual growth rate is slightly higher than the average worldwide growth rate of 4.10% (see Fig. 1a). The statistical analysis revealed eight segments with different growth rates (see Fig. 4b). The growth is, therefore, more differentiated than the overall growth with five segments (see Fig. 1a). Between 1780 and 1805 (pre-industrialization) as well as 1805 and 1844 (early industrialization), a strong growth of 7.73% and 5.33%, respectively, can be observed. The strong growth weakens to 3.70% in the phase of industrialization from 1848 and the First World War as well as in the 1920s.

Fig. 4: Plots for growth of science based on the number of publications from UK.

Shown are the results for the unrestricted growth (M1) and segmented unrestricted growth (M9) (using Dimensions data). Comparable to the worldwide results (see Fig. 1b), a significant slowdown in scientific growth with an annual growth rate of 2.62% is apparent around the Second World War (between 1940 and 1948). While the overall analysis demonstrated an unrestricted exponential growth after 1945 (see Fig. 4b), the exponential growth of science in UK took place in three stages: a strong growth of 6.80% until 1959, which intensified between 1959 and 1983 (8.65%), and slowed down to 6.42% in the years after 1983. The growth rates in these three segments are even higher than the worldwide growth rate of 5.28% in the corresponding time segment (between 1945 and 2018). At the beginning of the 1980s, Margaret Thatcher was Prime Minister of UK and with her party, the Conservative Party, having won the majority in the House of Commons for the second time in 1983. Figure 5 shows the annual GDP growth rate between 1700 and 2018 for comparison with the publication growth. The figure is based on the logarithmized annual GDP, presented as raw data and predicted values from the regression model. Previous studies investigating the relationship between economic and scientific growth have demonstrated positive relationships (e.g., Halpenny et al., 2010; Hart and Sommerfeld, 1998; Ntuli et al., 2015). The results in Fig. 5a reveal an annual GDP growth rate of 3.05% and doubling time of 23.1 years, which is lower than the growth rate based on publication counts of 4.97% (see Fig. 4a).

Fig. 5: Plots for economic growth based on gross domestic product (GDP) data from UK.

Shown are the results for the unrestricted growth (M1) and the segmented growth (M8) (source: FRED Economic Research). At first glance, economic growth and scientific growth do not seem to be coupled. A more detailed view shows, however, that both growth rates are parallel at certain points over time (see Figs. 4b and 5b). For example, science and economy grew from 1780 to the beginning of the nineteenth century (1810, 1805), i.e., in the phase of pre-industrialization at a comparable rate: whereas the economy grew by 4.29%, science grew by 5.93%. Furthermore, there is a coupling of economic and scientific development at the beginning of industrialization in the 1840s (1843, 1844) with a moderate annual growth rate of 2.37% in economy and 3.70% in science. A last temporal coupling can be observed in the years after the Second World War (1948, 1945) with a moderate growth rate of 6.74% as well as 6.80%. At the beginning of the 1980s, science grew again with a strong economic growth, especially from 1969 to 1987 of 14.45%. Three years later, in 1990, Margaret Thatcher resigned as Prime Minister. While the slowdown in the economy continued, science grew at a rate of only 6.42% as early as 1983. Margaret Thatcher's economic policy, based on the privatization of state enterprises, was not being until after 1987, science began to grow at a faster rate, probably due to a more knowledge-producing institutions and processes (Gieryn, 1982).

Conclusion

Current research is a method of "systematically exploring the unknown to acquire knowledge and understanding. Efficient research requires awareness of all prior research and technology that could impact the research topic of interest, and builds upon these past advances to create discovery and new advances" (Kostoff and Shlesinger, 2005, p. 199). Society expects a steady increase in scientific growth since only considerable growth processes would lead to growth in other sectors of society such as economics and health. Since (public) investments in science are frequently justified on the basis of growth of science and science contribution to national economic growth (Wagner et al., 2015), measurements of scientific growth processes are highly topical. These measurements are usually based on numbers of publications, since many publications are thought to contribute to scientific progress. "In academic institutions, publications constitute in all scientific-scholarly subject fields an important form of academic output" (Moed, 2017, p. 63). The research by Digital Science (2016) show that especially the journal article becomes increasingly popular as a medium for presenting scientific results. The popularity of journal articles could also be the consequence of the higher than average growth in disciplines using journal articles. The motivation by researchers for publishing their research (in journal articles) is especially fostered by the specificity of the scientific reward system: "Publications have another function as well [besides the open availability of research results]: The principal way for a scholar to be rewarded for his contribution to the advancement of knowledge is through recognition by peers. In order to receive such an award, scholars publish their findings openly, so that these can be used and acknowledged by their colleagues" (Moed, 2017, p. 62). Although the publication of findings is so basic in science, researchers also process their findings in other forms of output (e.g., patents or presentations). An overview of indicators for measuring productivity based on these other forms can be found in Godin (2009). The problem of most of these indicators for measuring productivity or scientific growth, however, is that they are not available for such a long time period as the science system until today. In accordance with the law of exponential growth in science by Price, we found that the overall growth rate amounts to 4.10% with a doubling time of 17.3 years. The result is slightly lower than the growth rate (over the various databases) of 2.96% reported in Bornmann and Mutz (2015), since we considered in the current study a significantly longer time period than Bornmann and Mutz (2015): from 1900 until 2018 in this study (119 years) versus from 1980 until 2012 (33 years) in Bornmann and Mutz (2015). As the comparison of various segmented regression models in the current study revealed, the model with five segments fits the data best. We demonstrated that these segments with different growth rates can be interpreted very well, since they are related to either phases of economic (e.g., industrialization) and/or political developments (e.g., World Wars). Obviously, the war efforts (allocation of funds) led to a visible decline in research (by output measure of publication) but research went on nevertheless, possibly with even more vigor. However, that research was not being made available openly for security reasons (and researchers pulled in for the sake of war efforts from physics to languages, material science to mathematics/emerging computer science)—and arguably the research by results of war-time research triggered post-war discoveries, too. We additionally undertook two further analyses focusing on (1) growth in two broad fields (Life Sciences and Physical and Technical Sciences) as well as (2) relationship between scientific and economic growth. (1) The comparison between the two broad fields revealed only slight differences. Thus, these differences are not so great that they can be denoted as fundamental. For example, whereas the overall annual average growth rate for Life Science is 5.07% with a doubling time of 14.0 years, the overall annual growth rate for Physical and Technical Science is 5.51% with a doubling time of 12.9 years. (2) In the investigation of the relationship of scientific and economic growth, we focused on UK—one of the few countries with comparatively available (historical) data. The results showed that the growth rate of scientific growth of UK's number of publications (4.97%) is slightly higher than the average worldwide growth rate (4.10%). Furthermore, the results revealed that the growth of UK's number of publications is more differentiated (with eight segments) than the worldwide growth (with five segments). The comparison of the British economic and scientific growth rates revealed that the GDP growth rate is lower than the scientific growth rate (3.05% versus 4.97%). Since GDP is not corrected for inflation in this study, results on the comparison of growth rates of science and economy should be interpreted with caution. There are two possible interpretations: The interpretation of the scientific growth rates that we reported in this study could be cautious. In the literature on growth of science, two interpretations are possible: Either the scientific growth can be traced back to an increase in the number of researchers. The study by Fanelli and Larivière (2016) targeted this question. Their results pointed to the second interpretation being more plausible. Fanelli and Larivière (2016) analyzed "individual publication profiles of over 40,000 scientists whose first recorded paper appeared in the Web of Science database between the years 1900 and 1998, and who published two or more papers within the first 15 years of activity—an 'early-career' phase in which pressures to publish are believed to be high. As expected, the total number of papers published by scientists has increased over the past decades. However, the average number of collaborators has also increased, and this factor should be taken into account when estimating publication rates. Adjusted for co-authorship, the publication rate of scientists in all disciplines has not increased overall, and has actually mostly declined" (Fanelli and Larivière, 2016). Two limitations mentioned by Bornmann and Mutz (2015) are still valid for the current study and should be considered in the interpretation of the results: The first limitation refers to the use of publication counts to measure growth processes. According to Tabah (1999), there are advantages and disadvantages in using these numbers "although counting publications is simple and relatively straightforward, interpretation of the data can create difficulties that have in the past led to severe criticisms of bibliometric methodology ... The main problems concern the least publishable unit (LPU), disciplinary variance, variance in quality of work, and variance in output per researcher" (p. 264). The second limitation concerns the interpretation of "growth" as an "increase in numbers". According to Bornmann and Mutz (2015), "it is not clear whether an "increase in numbers" is directly related to an "increase of actionable knowledge", for example for reducing needs, extending our knowledge about nature in some lasting way or some other "higher purposes" (p. 2221). Both limitations might be targeted in future studies on growth processes of science. The results of our study show that an exponential growth explains quite well the data and there is different speed in different growth periods. For example, we show that a regression with four segments have different growth speeds. However, we did not empirically investigate these differences: How can we explain, e.g., that between 1660 and 1793 the growth rate is 3.23%, while between 1793 and 1810 it is 25.41% (Technical Sciences)? Therefore, future studies should try to explore empirically the reasons for different growth processes over time. This study is based on multi-disciplinary databases only. Future studies that focus on growth processes in various (broad) fields—as we did it in section "Growth rates of science for Life Sciences and Physical and Technical Sciences" could use data from mono-disciplinary databases such as Chemical Abstracts (see) or Medline (see). The datasets analysed during the current study are available in the Edmond data repository: and . These datasets were derived from the following public domain resources: The Microsoft Academic and Dimensions data used in this paper are from a locally maintained database at the Max Planck Institute for Solid State Research derived from the snapshots provided by Microsoft and Digital Science, respectively. Web of Science and Scopus data were retrieved using the corresponding web-interfaces: and .

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Quan Sci Stud 1(1):396–413. � Google Scholar Download referencesWe thank members of the Digital Science team for providing us with feedback on an earlier version of our manuscript.Open Access funding enabled and organized by Projekt DEAL. The authors declare no competing interests. BMC Veterinary Research (2025) npj Climate Action (2025) Scientific Reports (2025) Scientific Data (2025) Climatic Change (2025) Solids, liquids and gases Perceived increase in the rate of technological change throughout history This article has multiple issues. Please help improve it or discuss these issues on the talk page. (Learn how and when to remove these messages) This article includes a list of general references, but it lacks sufficient corresponding inline citations. Please help to improve this article by introducing more precise citations. (September 2020) (Learn how and when to remove this message) This article needs additional citations for verification. Please help improve this article by adding citations to reliable sources. Unsourced material may be challenged and removed.Find sources: "Accelerating change" – news · newspapers · books · scholar · JSTOR (March 2023) (Learn how and when to remove this message) (Learn how and when to remove this message) Futures studies Concepts Accelerating change Cashless society Global catastrophic risk Future Earth Mathematics Race Climate Space exploration Universe Historical materialism Kondratiev wave Kardashev scale Moore's law Peak oil Population cycle Resource depletion Singularity Swanson's law Techniques Backcasting Causal layered analysis Chain-linked model Consensus forecast Cross impact analysis Delphi Real-time Delphi Foresight Future-proof Futures wheel Future workshop Horizon scanning Reference class forecasting Scenario planning Systems analysis Threatcasting Trend analysis Technology assessment and forecasting Critical design Design fiction Exploratory engineering FTA Hype cycle Science fiction prototyping Speculative design TRL Technology scouting Related topics Futarchy Transhumanism v.t.e In futures studies and the history of technology, accelerating change is the observed exponential nature of the rate of technological change in recent history, which may suggest faster and more profound change in the future and may or may not be accompanied by equally profound social and cultural change. Writing in 1904, Henry Brooks Adams outlined a "law of acceleration." Progress is accelerating including military progress. As coal-output of the world doubles every ten years, so will be the world output of bombs both in force and number. The bomb passage follows the "revolutionary" discovery of radium--an ore of uranium--and states that power leaps from every atom. Resistance to the law of acceleration is futile and progress might outpace the mind. "If science were to go on doubling or quadrupling its complexities every ten years, even mathematics would soon succumb. An average mind had succumbed already in 1850; it could no longer understand the problem in 1900." But Adams remains optimistic because "bombs educate vigorously". Thus far in history, states his bottom line, the mind had successfully reacted and can keep this way, but it "would need to jump". In 1910, during the town planning conference of London, Daniel Burnham noted, "But it is not merely in the number of facts or sorts of knowledge that progress lies: it is still more in the geometric ratio of sophistication, in the geometric widening of the sphere of knowledge, which every year is taking in a larger percentage of people as time goes on."[1] And later on, "It is the argument with which I began, that a mighty change having come about in fifty years, and our pace of development having immensely accelerated, our sons and grandsons are going to demand and get results that would stagger us."[1] In 1938, Buckminster Fuller introduced the word ephemeralization to describe the trends of "doing more with less" in chemistry, health and other areas of industrial development.[2] In 1946, Fuller published a chart of the discoveries of the chemical elements over time to highlight the development of accelerating acceleration in human knowledge acquisition.[3] By mid-century, for Arnold J. Toynbee it was "not an article of faith" but "a datum of observation and experience history" that history was accelerating, and "at an accelerating rate".[4] In 1958, Stanisław Ulam wrote in reference to a conversation with John von Neumann: One conversation centered on the ever accelerating progress of technology and changes in the mode of human life, which gives the appearance of approaching some essential singularity in the history of the race beyond which human affairs, as we know them, could not continue.[5] In a series of published articles from 1974 to 1979, and then in his 1988 book Mind Children, computer scientist and futurist Hans Moravec generalizes Moore's law to make predictions about the future of artificial life. Moore's law describes an exponential growth pattern in the complexity of integrated semiconductor circuits. Moravec extends this to include technologies from long before the integrated circuit to future forms of technology. Moravec outlines a timeline and a scenario[6][7] in which robots will evolve into a new series of artificial species, starting around 2030–2040.[8] In Robot: Mere Machine to Transcendent Mind, published in 1998, Moravec further considers the implications of evolving robot intelligence, generalizing Moore's law to technologies predating the integrated circuit, and also plotting the exponentially increasing computational power of the brains of animals in evolutionary history. Extrapolating these trends, he speculates about a coming "mind fire" of rapidly expanding superintelligence similar to the explosion of intelligence predicted by Vinge. Main article: Connections (British TV series) In his TV series Connections (1978)—and sequels Connections2 (1994) and Connections3 (1997)—James Burke explores an "Alternative View of Change" (the subtitle of the series) that rejects the conventional linear and teleological view of historical progress. Burke contends that one cannot consider the development of any particular piece of the modern world in isolation. Rather, the entire gestalt of the modern world is the result of a web of interconnected events, each one consisting of a person or group acting for reasons of their own motivations (e.g., profit, curiosity, religious) with no concept of the final, modern result to which the actions of either them or their contemporaries would lead. The interplay of the results of these isolated events is what drives history and innovation, and is also the main focus of the series and its sequels. Burke also explores three corollaries to his initial thesis. The first is that, if history is driven by individuals who act only on what they know at the time, and not because of any idea as to where their actions will eventually lead, then predicting the future course of technological progress is merely conjecture. Therefore, if we are astonished by the connections Burke is able to weave among past events, then we will be equally surprised to what the events of today eventually will lead, especially events we were not even aware of at the time. The second and third corollaries are explored most in the introductory and concluding episodes, and they represent the downside of an interconnected history. If history progresses because of the synergistic interaction of past events and innovations, then as history does progress, the number of these events and innovations increases. This increase in possible connections causes the process of innovation to not only continue, but to accelerate. Burke poses the question of what happens when this rate of innovation, or more importantly change itself, becomes too much for the average person to handle, and what this means for individual power, liberty, and privacy.[9] In his book Mindsteps to the Cosmos (HarperCollins, August 1983), Gerald S. Hawkins elucidated his notion of mindsteps, dramatic and irreversible changes to paradigms or world views. He identified five distinct mindsteps in human history, and the technology that accompanied these "new world views": the invention of imagery, writing, mathematics, printing, the telescope, rocket, radio, TV, computer... "Each one takes the collective mind closer to reality, one stage further along in its understanding of the relation of humans to the cosmos." He noted: "The waiting period between the mindsteps is getting shorter. One can't help noticing the acceleration." Hawkins' empirical 'mindstep equation' quantified this, and gave dates for (to him) future mindsteps. The date of the next mindstep (5; the series begins at 0) he cited as 2021, with two further, successively closer mindsteps in 2045 and 2051, until the limit of the series in 2053. His speculations ventured beyond the technological: The mindsteps... appear to have certain things in common—a new and unfolding human perspective, related inventions in the area of memes and communications, and a long formulative waiting period before the next mindstep comes along. None of the mindsteps can be said to have been truly anticipated, and most were resisted at the early stages. In looking to the future we may equally be caught unawares. We may have to grapple with the presently inconceivable, with mind-stretching discoveries and concepts. Mass use of inventions: Years until use by a quarter of US population The mathematician Vernor Vinge popularized his ideas about exponentially accelerating technological change in the science fiction novel Marooned in Realtime (1986), set in a world of rapidly accelerating progress leading to the emergence of more and more sophisticated technologies separated by shorter and shorter time intervals, until a point beyond human comprehension is reached. His subsequent Hugo Award-winning novel A Fire Upon the Deep (1992) starts with an imaginative description of the evolution of a superintelligence passing through exponentially accelerating developmental stages ending in a transcendent, almost omnipotent power unfathomable by mere humans. His already mentioned influential 1993 paper on the technological singularity compactly summarizes the basic ideas. In his 1999 book The Age of Spiritual Machines, Ray Kurzweil proposed "The Law of Accelerating Returns", according to which the rate of change in a wide variety of evolutionary systems (including but not limited to the growth of technologies) tends to increase exponentially.[10] He gave further focus to this issue in a 2001 essay entitled "The Law of Accelerating Returns".[11] In it, Kurzweil, after Moravec, argued for extending Moore's Law to describe exponential growth of diverse forms of technological progress. Whenever a technology approaches some kind of a barrier, according to Kurzweil, a new technology will be invented to allow us to cross that barrier. He cites numerous past examples of this to substantiate his assertions. He predicts that such paradigm shifts have and will continue to become increasingly common, leading to "technological change so rapid and profound it represents a rupture in the fabric of human history". He believes the Law of Accelerating Returns implies that a technological singularity will occur before the end of the 21st century, around 2045. The essay begins: An analysis of the history of technology shows that technological change is exponential, contrary to the common-sense 'intuitive linear' view. So we won't experience 100 years of progress in the 21st century—it will be more like 20,000 years of progress (at today's rate). The 'returns,' such as chip speed and cost-effectiveness, also increase exponentially. There's even exponential growth in the rate of exponential growth. Within a few decades, machine intelligence will surpass human intelligence, leading to the Singularity—technological change so rapid and profound it represents a rupture in the fabric of human history. The implications include the merger of biological and nonbiological intelligence, immortal software-based humans, and ultra-high levels of intelligence that expand outward in the universe at the speed of light. Moore's Law expanded to other technologiesAn updated version of Moore's Law over 120 years (based on Kurzweil's graph). The seven most recent data points are all Nvidia GPUs. The Law of Accelerating Returns has in many ways altered public perception of Moore's law. [citation needed] It is a common (but mistaken) belief that Moore's law makes predictions regarding all forms of technology,[citation needed] when really it only concerns semiconductor circuits. Many futurists still use the term "Moore's law" to describe ideas like those put forth by Moravec, Kurzweil and others. Computer power grows exponentially. Exponential growth in supercomputer power According to Kurzweil, since the beginning of evolution, more complex life forms have been evolving exponentially faster, with shorter and shorter intervals between the emergence of radically new life forms, such as human beings, who have the capacity to engineer (i.e. intentionally design with efficiency) a new trait which replaces relatively blind evolutionary mechanisms of selection for efficiency. By extension, the rate of technical progress amongst humans has also been exponentially increasing: as we discover more effective ways to do things, we also discover more effective ways to learn, e.g. language, numbers, written language, philosophy, scientific method, instruments of observation, tallying devices, mechanical calculators, computers; each of these major advances in our ability to account for information occurs increasingly close to the previous. Already within the past sixty years, life in the industrialized world has changed almost beyond recognition except for living memories from the first half of the 20th century. This pattern will culminate in unimaginable technological progress in the 21st century, leading to a singularity. Kurzweil elaborates on his views in his books The Age of Spiritual Machines and The Singularity Is Near. In the natural sciences, it is typical that processes characterized by exponential acceleration in their initial stages go into the saturation phase. This clearly makes it possible to realize that if an increase with acceleration is observed over a certain period of time, this does not mean an endless continuation of this process. On the contrary, in many cases this means an early exit to the plateau of speed. The processes occurring in natural science allow us to suggest that the observed picture of accelerating scientific and technological progress, after some time (in physical processes, as a rule, is short) will be replaced by a slowdown and a complete stop. Despite the possible termination / attenuation of the acceleration of the progress of science and technology in the foreseeable future, progress itself, and as a result, social transformations, will not stop or even slow down - it will continue with the achieved (possibly huge) speed, which has become constant.[12] Accelerating change may not be restricted to the Anthropocene Epoch,[13] but a general and predictable developmental feature of the universe.[14] The physical processes that generate an acceleration such as Moore's law are positive feedback loops giving rise to exponential or superexponential technological change.[15] These dynamics lead to increasingly efficient and dense configurations of Space, Time, Energy, and Matter (STEM efficiency and density, or STEM "compression").[16] At the physical limit, this developmental process of accelerating change leads to black hole density organizations, a conclusion also reached by studies of the ultimate physical limits of computation in the universe.[17][18] Applying this vision to the search for extraterrestrial intelligence leads to the idea that advanced intelligent life reconfigures itself into a black hole. Such advanced life forms would be interested in inner space, rather than outer space and interstellar expansion.[19] They would thus in some way transcend reality, not be observable and it would be a solution to Fermi's paradox called the "transcension hypothesis".[20][14][16] Another solution is that the black holes we observe could actually be interpreted as intelligent super-civilizations feeding on stars, or "stellivores".[21][22] This dynamics of evolution and development is an invitation to study the universe itself as evolving, developing.[23] If the universe is a kind of superorganism, it may possibly tend to reproduce, naturally[24] or artificially, with intelligent life playing a role.[25][26][27][28][29] Dramatic changes in the rate of economic growth have occurred in the past because of some technological advancement. Based on population growth, the economy doubled every 250,000 years from the Paleolithic era until the Neolithic Revolution. The new agricultural economy doubled every 900 years, a remarkable increase. In the current era, beginning with the Industrial Revolution, the world's economic output doubles every fifteen years, sixty times faster than during the agricultural era. If the rise of superhuman intelligence causes a similar revolution, argues Robin Hanson, then one would expect the economy to double at least quarterly and possibly on a weekly basis.[30] In his 1981 book Critical Path, futurist and inventor R. Buckminster Fuller estimated that if we took all the knowledge that mankind had accumulated and transmitted by the year One CE as equal to one unit of information, it probably took about 1500 years (or until the sixteenth century) for that amount of knowledge to double. The next doubling of knowledge from two to four "knowledge units" took only 250 years, until about 1750 CE. By 1900, one hundred and fifty years later, knowledge had doubled again to 8 units. The observed speed at which information doubled was getting faster and faster.[31] In modern times, exponential knowledge progressions therefore change at an ever-increasing rate. Depending on the progression, this tends to lead toward explosive growth at some point. A simple exponential curve that represents this accelerating change phenomenon could be modeled by a doubling function. This fast rate of knowledge doubling leads up to the basic proposed hypothesis of the technological singularity: the rate at which technology progression surpasses human biological evolution. Both Theodore Modis and Jonathan Huebner have argued—each from different perspectives—that the rate of technological innovation has not only ceased to rise, but is actually now declining.[32] Accelerando - 2005 science fiction novel by Charles Stross Accelerationism - Ideologies of change via capitalism and technology Diminishing returns – Economic theory Future Shock - 1970 book by Alvin Toffler Logarithmic timeline Novelty theory – American ethnobotanist and mystic (1946–2000)Pages displaying short descriptions of redirect targets Simulated reality – Concept of a false version of reality Zimmerman's law - Concept of Pretty Good Privacy (PGP)Pages displaying short descriptions of redirect targets ^ a b Town Planning Conference (1910 : London, England); Royal Institute of British Architects (8 July 2018). Transactions. London : Royal Institute of British Architects – via Internet Archive.{{cite book}}: CS1 maint: numeric names: authors list (link) CS1 maint: publisher location (link) ^ R. Buckminster Fuller, Nine Chains to the Moon, Southern Illinois University Press [1938] 1963 pp. 276–79. ^ R. Buckminster Fuller, Synergetics (Fuller), ^ Fettweis, Christopher J. (2010). Dangerous Times? The International Politics of Great Power Peace. (Washington, DC: Georgetown University Press), p 215-216, ^ Ulam, Stanislaw (May 1958). "Tribute to John von Neumann". Bulletin of the American Mathematical Society. 64, nr 3, part 2: 5. ^ Moravec, Hans (1998). "When will computer hardware match the human brain?". Journal of Evolution and Technology. 1. Archived from the original on 15 June 2006. Retrieved 2006-06-23. ^ Moravec, Hans (June 1993). "The Age of Robots". Archived from the original on 15 June 2006. Retrieved 2006-06-23. ^ Moravec, Hans (April 2004). "Robot Predictions Evolution". 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Again? by Juergen Schmidhuber: singularity predictions as a side-effect of memory compression? Secular Cycles and Millennial Trends The Royal Mail Coach: Metaphor for a Changing World Retrieved from " Millions of scientific papers are published globally every year. These papers in science, technology, engineering, mathematics and medicine present discoveries that range from the mundane to the profound.Since 1900, the number of published scientific articles has doubled about every 10 to 15 years; since 1980, about 8 percent to 9 percent annually. This acceleration reflects the immense and ever-growing scope of research across countless topics, from the farthest reaches of the cosmos to the intricacies of life on Earth and human nature.Yet, this extraordinary expansion was once thought to be unsustainable. In his influential 1963 book, Little Science, Big Science... And Beyond, the founder of scientometrics – or data informatics related to scientific publications – Derek de Solla Price famously predicted limits to scientific growth.He warned that the world would soon deplete its resources and talent pool for research. He imagined this would lead to a decline in new discoveries and potential crises in medicine, technology and the economy. At the time, scholars widely accepted his prediction of an impending slowdown in scientific progress.Faulty predictionsIn fact, science has spectacularly defied Price's dire forecast. Instead of stagnation, the world now experiences "global mega-science" – a vast, ever-growing network of scientific discovery. This explosion of scientific production made Price's prediction of collapse perhaps the most stunningly incorrect forecast in the study of science.Unfortunately, Price died in 1983, too early to realize his mistake.So, what explains the world's sustained and dramatically increasing capacity for scientific research?We are sociologists who study higher education and science. Our new book, Global Mega-Science: Universities, Research Collaborations, and Knowledge Production, published on the 60th anniversary of Price's fateful prediction, offers explanations for this rapid and sustained scientific growth. It traces the history of scientific discovery globally.Factors such as economic growth, warfare, space races and geopolitical competition have undoubtedly spurred research capacity. But these factors alone cannot account for the immense scale of today's scientific enterprise.The education revolution: Science's secret engineIn many ways, the world's scientific capacity has been built upon the educational aspirations of young adults pursuing higher education.Over the past 125 years, increasing demand for and access to higher education has sparked a global education revolution. Now, more than two-fifths of the world's young people ages 19-23, although with huge regional differences, are enrolled in higher education. This revolution is the engine driving scientific research capacity.Today, more than 38,000 universities and other higher-education institutions worldwide play a crucial role in scientific discovery. The educational mission, both publicly and privately funded, subsidizes the research mission, with a big part of students' tuition money going toward supporting faculty.These faculty scientists balance their teaching with conducting extensive research. University-based scientists contribute 80 percent to 90 percent of the discoveries published each year in millions of papers.External research funding is still essential for specialized equipment, supplies and additional support for research time. But the day-to-day research capacity of universities, especially academics working in teams, forms the foundation of global scientific progress.Even the most generous national science and commercial research and development budgets cannot fully sustain the basic infrastructure and staffing needed for ongoing scientific discovery.Likewise, government labs and independent research institutes, such as the US National Institutes of Health or Germany's Max Planck Institutes, could not replace the production capacity that universities provide.Collaboration benefits science and societyThe past few decades have also seen a surge in global scientific collaborations. These arrangements leverage diverse talent from around the world to enhance the quality of research.International collaborations have led to millions of co-authored papers. International research partnerships were relatively rare before 1980, accounting for just over 7,000 papers, or about 2 percent of the global output that year.But by 2010 that number had surged to 440,000 papers, meaning 22 percent of the world's scientific publications resulted from international collaborations.This growth, building on the "collaboration dividend," continues today and has been shown to produce the highest-impact research.Universities tend to share academic goals with other universities and have wide networks and a culture of openness, which makes these collaborations relatively easy.Today, universities also play a key role in international supercollaborations involving teams of hundreds or even thousands of scientists. In these huge collaborations, researchers can tackle major questions they wouldn't be able to in smaller groups with fewer resources.Supercollaborations have facilitated breakthroughs in understanding the intricate physics of the universe and the synthesis of evolution and genetics that scientists in a single country could never achieve alone.The IceCube collaboration, a prime example of a global megacollaboration, has made big strides in understanding neutrinos, which are ghostly particles from space that pass through Earth. (Martin Wolf, IceCube/NSF)The role of global hubsHubs made up of universities from around the world have made scientific research thoroughly global. The first of these global hubs, consisting of dozens of North American research universities, began in the 1970s. They expanded to Europe in the 1980s and most recently to Southeast Asia.These regional hubs and alliances of universities link scientists from hundreds of universities to pursue collaborative research projects.Scientists at these universities have often transcended geopolitical boundaries, with Iranian researchers publishing papers with Americans, Germans collaborating with Russians and Ukrainians, and Chinese scientists working with their Japanese and Korean counterparts.The COVID-19 pandemic clearly demonstrated the immense scale of international collaboration in global megascience. Within just six months of the start of the pandemic, the world's scientists had already published 23,000 scientific studies on the virus. These studies contributed to the rapid development of effective vaccines.With universities' expanding global networks, the collaborations can spread through key research hubs to every part of the world.Is global megascience sustainable?But despite the impressive growth of scientific output, this brand of highly collaborative and transnational megascience does face challenges.On the one hand, birthrates in many countries that produce a lot of science are declining. On the other, many youth around the world, particularly those in low-income countries, have less access to higher education, although there is some recent progress in the Global South.Sustaining these global collaborations and this high rate of scientific output will mean expanding access to higher education. That's because the funds from higher education subsidize research costs, and higher education trains the next generation of scientists.De Solla Price couldn't have predicted how integral universities would be to driving global science. For better or worse, the future of scientific production is linked to the future of these institutions.David P. Baker, Professor of Sociology, Education and Demography, Penn State and Justin J.W. Powell, Professor of Sociology of Education, University of LuxembourgThis article is republished from The Conversation under a Creative Commons license. Read the original article. Collaboration and communication are important in science because they increase the likelihood of a successful outcome. More people contributing to a research project means more ideas, more hands, and more opportunities to test. expansion. [ik-span′shən] An increase in the volume of a substance while its mass remains the same. Expansion is usually due to heating. When substances are heated, the molecular bonds between their particles are weakened, and the particles move faster, causing the substance to expand. What is expansion and contraction in physics? Thermal Expansion and Contraction. THERMAL EXPANSION AND CONTRACTION. Materials expand or contract when subjected to changes in temperature. Most materials expand when they are heated, and contract when they are cooled. When free to deform, concrete will expand or contract due to fluctuations in temperature. What is Thermal Expansion. Thermal expansion is the phenomenon observed in solids, liquids, and gases. In this process, an object or body expands on the application of heat (temperature). Thermal expansion defines the tendency of an object to change its dimension either in length, density, area, or volume due to heat. See also What is a positive velocity? What does expansion mean in thermodynamics? Thermal expansion is the tendency of matter to change its shape, area, volume, and density in response to a change in temperature, usually not including phase transitions. What is expansion Short answer? Expansion is the process of becoming greater in size, number, or amount. Definitions of expansion. the act of increasing (something) in size or volume or quantity or scope. synonyms: enlargement. What is expansion with example? Expansion is defined as the act of getting bigger or something added onto something else. An example of an expansion is an extra three rooms built onto a house. noun. 2. What is expansion and contraction with examples? Examples of expansion and contraction: If we hold a very hot glass tumbler under cold water. it cracks. This is because the outer surface of the glass comes in direct contact with cold water and contracts more as compared to the inner surface. Water expands on heating try this with the help of an adult. Answer: The increase in the size of an object on heating is called expansion whereas, the decrease in size of an object on cooling is called contraction. What are the types of expansion in physics? There are three types of thermal expansion depending on the dimension that undergo change and that are linear expansion, areal expansion and volumetric volume. How does expansion occur? Thermal expansion is caused by heating solids, liquids or gases, which makes the particles move faster or vibrate more (for solids). This means that the particles take up more space and so the substance expands. See also Why is it called gas switch? The expansion (or contraction) of any material is due to the kinetic energy of its atoms. When a material is heated, the increase in energy causes the atoms and molecules to move more and to take up more space— that is, to expand. This is true of even a solid such as a metal. What is expansion in heat energy? According to the molecular theory of matter, objects absorbing thermal energy have molecules with increasing kinetic energy. This causes the object to expand. All three states of matter undergo thermal expansion. What is free expansion in physics? The Joule expansion (also called free expansion) is an irreversible process in thermodynamics in which a volume of gas is kept in one side of a thermally isolated container (via a small partition), with the other side of the container being evacuated. The expansion of a gas occurs whenever it is heated. Heating a gas increases the kinetic energy of the particles, causing the gas to expand. How do you write an expansion? 5 Tips to Expand an Idea. Here are just a few ways to expand your idea State and deny the contrarian view to your idea. Provide examples that illustrate your idea. Quote someone else. Use metaphor, imagery, or other literary devices. Apply the idea. What is a different word for expansion? In this page you can discover 33 synonyms, antonyms, idiomatic expressions, and related words for expansion, like: spread, increase, enlargement, augmentation, extension, growth, restructuring, widening, elaboration, diversification and rationalisation. What is expand and extension? Although extend and expand can be used interchangeably in some contexts, extend applies to things that are being stretched out, while expand applies to things that are spread out. One implies length; the other area. If you extend your arm, for example, you stretch it out, making it longer. See also What is equilibrant in science? The three types of thermal expansions are Linear expansion , Superficial expansion and Cubical expansion. Is stretch and expansion the same? If you extend your arm, for example, you stretch it out, making it longer. If your waist expands, it's getting larger. As a business expands, or gets larger, it may extend its opening hours. What is the difference between expansion and dilation? A dilation that creates a larger image is called an enlargement (or expansion). A dilation that creates a smaller image is called a reduction (or contraction). A dilation is NOT a rigid transformation. When more quantity is supplied at the same price, it is called an increase in supply. Expansion of supply takes place only due to a rise in the price of a commodity. The other factors remain constant. What is the law of expansion? by Meaning Ring on 2014/07/27. The only way to increase your capacity intentionally is to change the way you approach personal growth. Learning more information isn't enough. You must change how you think and you must change your actions. What happens in expansion? Expansion is the phase of the business cycle where real gross domestic product (GDP) grows for two or more consecutive quarters, moving from a trough to a peak. Expansion is typically accompanied by a rise in employment, consumer confidence, and equity markets and is also referred to as an economic recovery. As the temperature of the matter increases, the average kinetic energy of the atoms increases and they start to vibrate faster. Due to this the matter expands. So, temperature is the factor which cause expansion. Page 2expansion. [ik-span′shən] An increase in the volume of a substance while its mass remains the same. Expansion is usually due to heating. When substances are heated, the molecular bonds between their particles are weakened, and the particles move faster, causing the substance to expand. What is expansion and contraction in physics? Thermal Expansion and Contraction. THERMAL EXPANSION AND CONTRACTION. Materials expand or contract when subjected to changes in temperature. Most materials expand when they are heated, and contract when they are cooled. When free to deform, concrete will expand or contract due to fluctuations in temperature. What is Thermal Expansion. Thermal expansion is the phenomenon observed in solids, liquids, and gases. In this process, an object or body expands on the application of heat (temperature). Thermal expansion defines the tendency of an object to change its dimension either in length, density, area, or volume due to heat. See also What do you mean by open and closed pipes?What does expansion mean in thermodynamics? Thermal expansion is the tendency of matter to change its shape, area, volume, and density in response to a change in temperature, usually not including phase transitions. What is expansion Short answer? Expansion is the process of becoming greater in size, number, or amount. Definitions of expansion. the act of increasing (something) in size or volume or quantity or scope. synonyms: enlargement. What is expansion with example? Expansion is defined as the act of getting bigger or something added onto something else. An example of an expansion is an extra three rooms built onto a house. noun. 2. What is expansion and contraction with examples? Examples of expansion and contraction: If we hold a very hot glass tumbler under cold water. it cracks. This is because the outer surface of the glass comes in direct contact with cold water and contracts more as compared to the inner surface. Water expands on heating try this with the help of an adult. Answer: The increase in the size of an object on heating is called expansion whereas, the decrease in size of an object on cooling is called contraction. What are the types of expansion in physics? There are three types of thermal expansion depending on the dimension that undergo change and that are linear expansion, areal expansion and volumetric volume. How does expansion occur? Thermal expansion is caused by heating solids, liquids or gases, which makes the particles move faster or vibrate more (for solids). This means that the particles take up more space and so the substance expands. See also What is gravity and its unit? The expansion (or contraction) of any material is due to the kinetic energy of its atoms. When a material is heated, the increase in energy causes the atoms and molecules to move more and to take up more space— that is, to expand. This is true of even a solid such as a metal. What is expansion in heat energy? According to the molecular theory of matter, objects absorbing thermal energy have molecules with increasing kinetic energy. This causes the object to expand. All three states of matter undergo thermal expansion. What is free expansion in physics? 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Increases are important in science because they can help us to understand how things work. For example, if we know that the amount of water in a glass increases when we add more water, we can use this information to predict how much water will be in the glass after we add a certain amount of water. Your browser does not support the audio element. The population of the world is increasing at an alarming rate. Noun: an increase is the act of making something bigger. It can also refer to the amount by which something is made bigger or greater. Verb: To increase is to make something bigger or greater. Adjective: Increasing means becoming bigger or greater. Adverb: Increasingly means more and more. Your browser does not support the audio element. The word "increase" comes from the Latin word "incrementum", which means "growth" or "addition". This is a very accurate description of the meaning of the word "increase", as it refers to the act of making something bigger or greater. Your browser does not support the audio element. How do scientific theories, concepts and methods change over time? Answers to this question have historical parts and philosophical parts. There can be descriptive accounts of the recorded differences over time of particular theories, concepts, and methods—what might be called the shape of scientific change. Many stories of scientific change attempt to give more than statements of what, where and when change took place. Why this change then, and toward what end? By what processes did they take place? What is the nature of scientific change? This article gives a brief overview of the most influential views on the shape and nature of change in science. Important thematic questions are: How gradual or rapid is scientific change? Is science really revolutionary? How radical is the change? Are periods in science incommensurable, or is there continuity between the first and latest scientific ideas? Is science getting closer to some final form, or merely moving away from a contingent, non-determining past? What role do the factors of community, society, gender or technology play in facilitating or mitigating scientific change? Are there general laws of scientific change, and if so, what are they? Table of Contents Introduction The Shape of Scientific Change The Nature of Scientific Change Other Issues in Scientific Change References and Further Reading Introduction Scientific change is a ubiquitous feature of science. When we speak of scientific change it should be recognized that it is only a fairly contextualized level of description of the practices of scientists at rather specific times and places that anything substantial can be said. Nonetheless, scientific change is connected with many other key issues in philosophy of science and broader epistemology, such as realism, rationality and relativism. The present article does not attempt to address them all. Higher-order debates regarding the methods of historiography or the disciplinary differences between History and Philosophy, while important and interesting, represent an iteration of reflection on top of scientific change itself, and go beyond the article's scope. Table of Contents 1. If Science Changes, What is Scientific Change? We begin with some organizing remarks. It is interesting to note at the outset the reflexive nature of the topic of scientific change. A main concern of science is understanding physical change, whether it be motion, growth, causal relations, or the creation of the universe or the causes of change of identity, particularly among living organisms. Scientists view science as a description of the world as it evolved over time, whether in identity, particularly among living organisms. Scientific views of change have influenced philosophical views of change and identity, particularly among living organisms. These philosophical views are then reflected back, through the history and philosophy of science, as images of how science itself changed, of how its theories are created, evolve and die. Models of change from science—evolutionary, mechanical, revolutionary—often serve as models of change in science. This makes it difficult to disentangle the study of scientific change from our philosophical expectations about it. And that historiography and the philosophy of science do not always live together comfortably. Historians balk at the evaluative, forward-looking, and often reconstructive accounts of philosophers. Philosophers, for their part, have argued that details of the history of science matter little to a proper theory of scientific change, and that a distinction can and should be made between how scientific ideas are discovered and how they are justified. Beneath the ranging, messy, and contingent happenings which led to our current scientific outlook, there lies a progressive, systematically evolving activity waiting to be rationally reconstructed. Clearly, to tell any story of 'science changing' means looking beneath the surface of those changes in order to find something that remains constant, the thing which makes the changes changes in science. Put another way, what part of human history is to be identified with science? Where does science start and where does it end? The breadth of science has a dimension across concurrent events as well as across the past and future. That is, it has both synchronic (at a time) and diachronic (over time) dimensions. Science will consist of a range of contemporary events which need to be demarcated. But likewise, science has a temporal breadth: a beginning, or possibly several beginnings, and possibly several ends. The synchronic dimension of science is one way in which views of scientific change can be distinguished. On one hand there are logical or positivistic accounts, in which scientific activity can be reduced to a collection of objective, rational decisions of a number of individual scientists. On this latter view, the most significant changes in science can be described through the logically-reconstructable actions and words of one historical figure, or at most a very few. According to many of the more recent views, however, an adequate picture of science cannot be formed with anything less than the full context of social and technological activity which makes up the scientific practice, including the actions of great men. And further, historical, institutional and cultural relations scientists are a part. We look at some of these broader sociological views in the section on social process of change. Finally, some views of scientific change have wanted also to "broaden" science diachronically, to historicize its content, such that the justifications of science, or even its meanings, cannot be divorced from their past. We will begin with the most important figure in the history and philosophy of science in North America in the last half-century: Thomas Kuhn. Kuhn's work in the middle of the last century was primarily a reaction to the then prevalent, philosophical views of science, as being dominated by the logical and progressive accumulation of knowledge. We will follow with a discussion of the most influential philosophical accounts of change, and some of the philosophical accounts that was developed in the previous paragraph. Along with Kuhn, we describe the closely related views of Imre Lakatos and Larry Laudan. For an introduction to the most influential philosophical accounts of the diachronic development of science, see Losee 2004. When Kuhn and the others advanced their new views on the development of science into Anglo-Saxon philosophy of science, history and sociology were already an important part of the landscape of Continental history and philosophy of science. A discussion of these views can be found as part of the sociology of science section as well. The article concludes with more recent naturalized approaches to scientific change, which turn to cognitive science for accounts of scientific understanding and how that understanding is formed and changed, as well as suggestions for further reading. Science itself, at least in a form recognizable to us, is a twentieth century phenomenon. Although a matter of debate, the canonical view of the history of scientific change is that its seminal event is the one tellingly labeled the Scientific Revolution. It is usually dated to the 16th and 17th centuries. The first historiographies of science—that is, of how the history of science is and should be written—were not far behind, coming in the eighteenth century (and even earlier, for example in the work of Bacon). Professionalization of the history of science, characterized by reflections on the telling of the history of science, followed later. We begin our story there. 2. History of Science and Scientific Change As history of science professionalized, becoming a separate academic discipline in the twentieth century, scientific change was seen early on as an important theme within the discipline. Admittedly, the idea of radical change was not a key notion for early practitioners of the field such as George Sarton (1884-1956), the father of history of science in the United States, but with the work of historians of science such as Alexandre Koyré (1892-1964), Herbert Butterfield (1900-1979) and A. Rupert Hall (1920-2009), radical conceptual transformations came to play a much more important role. One of the early examples of this is the influential work on scientific change is found in the Oxford Symposium on Scientific Change (Crombie, 1963) in which historians of science covering the span of science from the ancient to modern periods, all investigated the conditions for scientific change by examining cases from a multitude of periods, societies, and scientific disciplines. The introduction to Crombie's volume presented a large number of questions regarding scientific change that remained key issues in both history and philosophy of science for several decades: What were the essential changes in scientific thought and what brought them about? What was the part played in the initiation of change by mutations in fundamental ideas leading to new questions being asked, new problems being seen, new criteria of satisfactory explanation replacing the old? What was the part played by new technical inventions in mathematics and experimental apparatus; by developments in pure mathematics; by the refinements of measurement; by the transference of ideas, methods and information from one field of study to another? What significance can be given to the description and use of scientific methods and concepts in advance of scientific discovery? How have methods and concepts of explanation differed in different sciences? How has language changed in changing scientific contexts? What parts have chance and personal idiosyncrasy played in discovery? How have scientific changes been located in the context of general ideas and intellectual motives, and how far have extra-scientific beliefs given theories their power to convince? ... How have scientific and technical changes been located in the social context of motives and opportunities? What value has been put on scientific activity by society at large, by the needs of industry, commerce, war, medicine and the arts, by governmental and private investment, by religion, by different social systems? To what external social, economic and political pressures have science, technology and medicine been exposed? Are money and opportunity all that is needed to create scientific and technical progress in modern society? (Crombie, 1963, p. 10) Of particular interest among historians of science have been the changes associated with scientific revolutions and especially the period often referred to as the Scientific Revolution, seen as the sum of achievements in science from Copernicus to Newton (Cohen 1985; Hall 1954; Koyré 1965). The word 'revolution' had started being applied in the eighteenth century to the developments in astronomy and physics as well as the change in chemical theory which emerged with the work of Lavoisier in the 1770s, or the change in biology which was initiated by Darwin's work in the mid-nineteenth century. These were fundamental changes that overturned not only the reigning theories but also carried with them significant consequences outside their respective scientific disciplines. In most of the early work in history of science, however, the word 'revolution' was something which happened only rarely. This view was changed by the historian and philosopher of science Thomas S. Kuhn whose 1962 monograph The Structure of Scientific Revolutions (1970) came to influence philosophy of science for decades. Kuhn raised the point in his monograph to argue for a change in the philosophical conceptions of science and its development, but based on historical case studies. The notion of revolutions that he used in Structure included not only fundamental changes of theory that had a significant influence on the overall world view of both scientists and non-scientists, but also changes of theory whose consequences remained solely within the scientific discipline in which the change had taken place. This considerably widened the notion of scientific revolutions compared to earlier historians and initiated discussions among both historians and philosophers on the balance between continuity and change in the development of science. 3. Philosophical Views on Change and Progress in Science In the British and North American schools of philosophy of science, scientific change did not become a major topic until the 1960s onwards when historically inclined philosophers of science, including Thomas S. Kuhn (1922-1996), Paul K. Feyerabend (1924-1994), N. Russell Hanson (1924-1967), Michael Polanyi (1891-1971), Stephen Toulmin (1922-2009) and Mary Hesse (*1924) started questioning the assumptions of logical positivism, arguing that philosophy of science should be concerned with the historical structure of science rather than with an ahistorical logical structure that they took to be a chimera. The occupation with history led naturally to a focus on how scientific theories and methods change, and opened up the question of whether science progresses incrementally or through changes which represent some kind of discontinuity. Similar questions had also been discussed among Continental scholars. The development of the theory of relativity and of quantum mechanics in the beginning of the twentieth century suggested that empirical science could overturn deeply held intuitions and introduce counter-intuitive new concepts and ideas; and several European philosophers, among them the German neo-Kantian philosopher Ernst Cassirer (1874-1945), directed their work towards rejecting Kant's absolute categories in favor of categories that may change over time. In France, the historian and philosopher of science Gaston Bachelard (1884-1962) also noted that what Kant had taken to be absolute preconditions for knowledge had turned out wrong in the light of modern physics. To Bachelard's view, what had seemed to be absolute preconditions for knowledge had turned out to be wrong. Science, Bachelard concluded, a full account of scientific reasoning could only be derived from reflections upon its historical conditions and development. Based on the analysis of the historical development of science, Bachelard advanced a model of scientific change according to which the conceptions of nature are from time to time replaced by radical new conceptions – what Bachelard called epistemological breaks. Bachelard's view was later developed and modified by the historian and philosopher of science, and student of Bachelard, George Canguilhem (1904-1995) and by the philosopher and social historian, and student of Canguilhem, Michel Foucault (1926-1984). Beyond the teacher-student connections – there are other commonalities which unify this tradition. In North America and England, among those who wanted to make philosophy more like science, or to import into philosophical practice lessons from the success of science, the exemplar was almost always physics. The most striking and profound advances in science seemed to be, after all, physics, namely the quantum and relativity revolutions. But on the Continent, model sciences were just as often linguistics or sociology, biology or anthropology, and not limited to those. Canguilhem's interest in changing notions of the normal versus the pathological, for example, coming from an interest in medicine, typified the more human-centered theorising of the tradition. What is more relevant to our topic is the way that, in it, what we know, how we know it, and how we successfully achieve our aims, are often seen as inseparable from the rest of the human condition of situatedness. Foucault described his project as archaeology of the history of human thought and its conditions. He compared his project to Kant's critique of reason, but with the difference that Foucault's interest was in a historical a priori; that is, with what seem to be for a given period the necessary conditions governing reason, and how these constraints have a contingent historical origin. Hence, in his analysis of the development of the human sciences from the Renaissance to the present, Foucault described various so-called epistemes that determined the conditions for all knowledge of their time, and he argued that the transition from one episteme to the next happens as a break that entails radical changes in the conception of knowledge. Michael Friedman's work on the relativized and dynamic a priori can be seen as continuation of this thread (Friedman 2001). For a detailed account of the work of Bachelard, Canguilhem and Foucault, see Gutting (1989). With the advent of Kuhn's Structure, "non-Continental" philosophy of science also started focusing in its own way on the historical development of science, often apparently unaware of the earlier tradition, and in the decades to follow alternative models were developed to describe how theories supersede their successors, and whether progress in science is gradual and incremental or whether it is discontinuous. Among the key contributions to this discussion, besides Kuhn's famous paradigm-shift model, were Imre Lakatos' (1922-1974) model of progressing and degenerating research programs and Larry Laudan's (*1941) model of successive research traditions. a. Kuhn, Paradigms and Revolutions One of the key contributions that provoked interest in scientific change among philosophers of science was Thomas S. Kuhn's seminal monograph The Structure of Scientific Revolutions from 1962. The aim of this monograph was to question the view that science is cumulative and progressive, and Kuhn opened with: "History, if viewed as a repository for more than anecdote or chronology, could produce a decisive transformation in the image of science by which we are now possessed" (p. 1). History was expected to do more than just chronicle the successive increments of, or impediments to, our progress towards the present. Instead, historians and philosophers should focus on the historical integrity of science at a particular time in its development, and should analyze science as it developed. Kuhn expected a new image of science would emerge from this diachronic historiography. In the rest of Structure he used historical examples to question the view of science as a cumulative development in which scientists gradually add new pieces to the ever-growing aggregate of scientific knowledge, and instead he described how science develops through successive periods of tradition-preserving normal science and tradition-shattering revolutions. For introductions to Kuhn's philosophy of science, see for example Andersen 2001, Bird 2000, and Hoyningen-Huene 1993. i. Key Concepts in Kuhn's Account of Scientific Change On Kuhn's model, science proceeds in key phases. The predominant phase is normal science which, while progressing successfully in its aims, inherently generates what Kuhn calls anomalies. In brief, anomalies lead to crisis and extraordinary science, followed by revolution, and finally a new phase of normal science. Normal science is characterized by a consensus which exists throughout the scientific community as to (a) the concepts used in communication among scientists, (b) the problems which can meaningfully be formulated as relevant research problems, and (c) a set of exemplary problem solutions that serve as models in solving new problems. Kuhn first introduced the notion 'paradigm' to denote these shared communal aspects, and the tools used by that community for solving its research problems. Because so much was apparently captured by the term 'paradigm', Kuhn was criticized for using the term in ambiguous ways (see especially Masterman 1970). He later offered the alternative notion 'disciplinary matrix', covering (a) symbolic generalizations, or laws in their most fundamental forms, (b) beliefs about which objects and phenomena that exist in the world, (c) values by which the quality of research can be evaluated, and (d) exemplary problems and problem situations. In normal science, scientists draw on the tools provided by the disciplinary matrix, and they expect the solutions of new problems to be in consonance with the descriptions and solutions of the problems that they have previously examined. But sometimes these expectations are violated. Problems may turn out not to be solvable in an acceptable way, and then instead they represent anomalies for the reigning theories. Not all anomalies are equally severe. Some discrepancy can always be found between theoretical predictions and experimental findings, and this does not necessarily challenge the foundations of normal science. Hence, some anomalies can be neglected, at least for some time. Others may find a solution within the reigning theoretical framework. Only a small number will be so severe and so persistent that it is suggested that the tools provided by the accepted theories must be given up, or at least be seriously modified. Science has then entered the crisis phase of Kuhn's model. Even in crisis, a new paradigm may not be immediately forthcoming. Scientists may "agree" that no solution is likely to be found in the present state of their field and simply set the problems aside for future scientists to solve with more developed tools, while they return to normal science in its present form. More often, when crisis has become severe enough for questioning the foundation, and the anomalies may be solved by a new theory, that theory gradually receives acceptance until eventually a new consensus is established among members of the scientific community regarding the new theory. Only in this case has a scientific revolution occurred. Importantly though, even severe anomalies are not simply falsifying instances. Severe anomalies cause scientists to question the accepted theories, but the anomalies do not lead the scientists to abandon the paradigm without an alternative to replace it. This raises a crucial question regarding scientific change on Kuhn's model: where do new theories come from? Kuhn said little about this creative aspect of scientific change; a topic that later became central to cognitively inclined philosophers of science working on scientific change (see the section on Cognitive Views below). Kuhn described merely how severe anomalies would become the focal point for further research, while attempts to solve them might gradually diverge more and more from the solution hitherto accepted as exemplary. Until, in the course of this development, embryonic forms of alternative theories were born. ii. Incommensurability as the Result of Radical Scientific Change For Kuhn the relation between normal science traditions separated by a scientific revolution cannot be described as incorporation of one into the other, or as incremental growth. To describe the relation, Kuhn adopted the term 'incommensurability' from mathematics, claiming that the new normal-scientific tradition which emerges from a scientific revolution is not only incompatible but often actually incommensurable with that which has gone before. Kuhn's notion of incommensurability covered three different aspects of the relation between the pre- and post-revolutionary normal science traditions: (1) a change in the set of scientific problems and the way in which they are attacked, (2) conceptual changes, and (3) a change, in some sense, in the world of the scientists' research. This latter, "world-changing" aspect is the most fundamental aspect of incommensurability. However, it is a matter of great debate exactly how strongly we should take Kuhn's meaning, for instance when he stated that "though the world does not change with a change of paradigm, the scientist afterwards works in a different world" (p. 121). To make sense of these claims it is necessary to distinguish between two different senses of the term 'world': the world as the independent object which scientists investigate and the world as the perceived world in which scientists practice their trade. In Structure, Kuhn argued for incommensurability in perceptual terms. Drawing on results from psychological experiments showing that subjects' perceptions of various objects were dependent on their training and experience, Kuhn suspected that something like a paradigm was prerequisite to perception itself and that, therefore, different normal science traditions would cause scientists to perceive differently. But when it comes to visual gestalt-switch images, one has recourse to the actual lines drawn on the paper. Contrary to this possibility of employing an 'external standard', Kuhn claimed that scientists can have no recourse above or beyond what they see with their eyes and instruments. For Kuhn, the change in perception cannot be reduced to a change in the interpretation of stable data, simply because stable data do not exist. Kuhn thus strongly attacked the idea of a neutral observation-language; an attack similarly launched by other scholars during the late 1950s and early 1960s, most notably Hanson (Hanson 1958). These aspects of incommensurability have important consequences for the communication between proponents of competing normal science traditions and for the choice between such traditions. Recognizing different problems and adopting different standards and concepts, scientists may talk past each other when debating the relative merits of their respective paradigms. But if they do not agree on the list of problems that must be solved or on what constitutes an acceptable solution, there can be no point-by-point comparison of competing theories. Instead, Kuhn claimed that the role of paradigms in theory choice was necessarily circular in the sense that the proponents of each would use their own paradigm to argue in that paradigm's defense. Paradigm choice is a conversion that cannot be forced by logic and neutral experience. This view has led many critics of Kuhn to the misunderstanding that he saw paradigm choice as devoid of rational elements. However, Kuhn did emphasize that although paradigm choice cannot be justified by proof, this does not mean that arguments are not relevant or that scientists are not rationally persuaded to change their minds. In contrast, Kuhn argued that, "Individual scientists embrace a new paradigm for all sorts of reasons and usually for several at once." (Kuhn 1996. p. 152) According to Kuhn, such arguments are, first of all, about whether the new paradigm can solve the problems that have led the old paradigm to a crisis, whether it displays a quantitative precision strikingly better than its older competitor, and whether in the new paradigm or with the new theory there are predictions of phenomena that had been entirely unsuspected while the old one prevailed. Aesthetic arguments, based on simplicity for example, may enter as well. Another common misunderstanding of Kuhn's notion of incommensurability is that it should be taken to imply a total discontinuity between the normal science traditions separated by a scientific revolution. Kuhn emphasized, rather, that a new paradigm often incorporates much of the vocabulary and apparatus, both conceptual and manipulative, of its predecessor. Paradigm shifts may be "non-cumulative developmental episodes ...," but the former paradigm can be replaced "... in whole or in part ..." (Ibid. p. 2). In this way, parts of the achievements of a normal scientific tradition will turn out to be permanent, even across a revolution. "[P]ostrevolutionary science invariably includes many of the same manipulations, performed with the same instruments and described in the same terms ..." (Ibid. p 129-130). Incommensurability is a relation that holds only between minor parts of the object domains of two competing theories. b. Lakatos and Progressing and Degenerating Research Programs Lakatos agreed with Kuhn's insistence on the tenacity of some scientific theories and the rejection of naïve falsification, but he was opposed to Kuhn's account of the process of change, which he saw as "a matter for mob psychology" (Lakatos, 1970, p. 178). Lakatos therefore sought to improve upon Kuhn's account by providing a more satisfactory methodology of scientific change, along with a meta-methodological justification of the rationality of that method, both of which were seen to be either lacking or significantly undeveloped in Kuhn's early writings. On Lakatos' account, a scientific research program consists of a central core that is taken to be inviolable by scientists working within the research program, and a collection of auxiliary hypotheses that are continuously developing as the core is applied. In this way, the methodological rules of a research program divide into two different kinds: a negative heuristic that tells the scientists which paths of research to avoid, and a positive heuristic that tells the scientists which paths to pursue. On this view, all tests are necessarily directed at the auxiliary hypotheses which come to form a protective belt around the hard core of the research program. Lakatos aims to reconstruct changes in science as occurring within research programs. A research program is constituted by the series of theories resulting from adjustments to the protective belt but all of which share a hard core. As adjustments are made in response to problems, new problems arise, and over a series of theories there will be a collective problem-shift. Any series of theories is theoretically progressive, or constitutes a theoretically progressive problem-shift, if and only if there is at least one theory in the series which has some excess empirical content over its predecessor. In the case if this excess empirical content is also corroborated the series of theories is empirically progressive. A problem-shift is progressive, then, if it is both theoretically and empirically progressive, otherwise it is degenerate. A research program is successful if it leads to progressive problem-shifts and unsuccessful if it leads to degenerating problem-shifts. The further aim of Lakatos' account, in other words, is to discover, through reconstruction in terms of research programs, where progress is made in scientific change. The rationally reconstructive aspect of Lakatos' account is the target of criticism. The notion of empirical content, for instance, is carrying a pretty heavy burden in the account. In order to assess the progressiveness of a program, one would seem to need a measure of the empirical content of theories in order to judge when there is excess content. Without some such measure, Lakatos' methodology is dangerously close to being vacuous or ad hoc. We can instead take the increase in empirical content to be a meta-methodological principle, one which dictates an aim for scientists (that is, to increase empirical knowledge), while cashing this out at the methodological level by identifying progress in research programs with making novel predictions. The importance of novel predictions, in other words, can be justified by their leading to an increase in the empirical content of the research program. A problem-shift which results in novel predictions can be taken to entail an increase in empirical content. It remains a worry, however, whether such an inference is warranted, since it seems to simply assume novelty and cumulativity go together unproblematically. That they might not was precisely Kuhn's point. A second objection is that Lakatos' reconstruction of scientific change through appeal to a unified method runs counter to the prevailing attitude among philosophers of science from the second half of the twentieth century on, according to which there is no unified method for all of science. At best, anything they all have in common methodologically will be so general as to be unhelpful or uninteresting. At any rate, Lakatos does offer us a positive heuristic for the description and even explanation of scientific change. For him, change in science is a difficult and delicate thing, requiring balance and persistence. "Purely negative, destructive criticism, like 'refutation' or demonstration of an inconsistency does not eliminate a program. Criticism of a program is a long and often frustrating process and one must treat budding programs leniently. One may, of course, whop up on [criticize] the degeneration of a research program, but it is only constructive criticism which, with the help of rival research programs, can achieve real successes; and dramatic spectacular results become visible only with hindsight and rational reconstruction" (Lakatos, 1970, p. 179). c. Laudan and Research Traditions In his Progress and Its Problems: Towards a Theory of Scientific Growth (1977), Laudan defined a research tradition as a set of general assumptions about the entities and processes in a given domain and about the appropriate methods to be used for investigating the problems and constructing the theories in that domain. Such research traditions should be seen as historical entities created and articulated within a particular intellectual environment, and as historical entities they would "wax and wane" (p. 95). On Laudan's view, it is important to consider scientific change both as changes that may appear within a research tradition and as changes of the research tradition itself. The key engine driving scientific change for Laudan is problem solving. Changes within a research tradition may be minor modifications of subordinate, specific theories, such as modifications of boundary conditions, revisions of constants, refinements of terminology, or expansion of a theory's classificatory network to encompass new discoveries. Such changes solve empirical problems, essentially those problems Kuhn conceives of as anomalies. But, contrary to Kuhn's normal science and to Lakatos' research programs, Laudan held that changes within a research tradition might also involve changes to its most basic core elements. Severe anomalies that are not solvable merely by modification of specific theories within the tradition may be seen as symptoms of a deeper conceptual problem. In such cases scientists may instead explore what sorts of (minimal) adjustments could be made in the deep-level methodology or ontology of that research tradition (p. 98). When Laudan looked at the history of science, he saw Aristotelians who had abandoned the Aristotelian doctrine that motion in a void is impossible, and Newtonians who had abandoned the Newtonian demand that all matter has inertial mass, and he saw no reason to claim that they were no longer working within those research traditions. Solutions to conceptual problems may even result in a theory with less empirical support and still count as progress since it is overall problem solving effectiveness (not all problems are empirical ones) which is the measure of success of a research tradition (Laudan 1996). Most importantly for Laudan, if there are what can be called revolutions in science, they reflect different kinds of problems, not a different sort of activity. David Pearce calls this Laudan's methodological monism (see Pearce 1984). For Kuhn and Lakatos, identification of a research tradition (or program or paradigm) could be made at the level of specific invariant, non-rejectable elements. For Laudan, there is no such class of sacrosanct elements within a research tradition—everything is open to change over time. For example, while absolute time and space were seen as part of the unrejectable core of Newtonian physics in the eighteenth century, they were no longer seen as such a century later. This leaves a dilemma for Laudan's view. If research traditions undergo deep-level transformations of their problem solving apparatus this would seem to constitute a significant change to the problem solving activity that may warrant considering the change the basis of a new research tradition. On the other hand, if the activity of problem solving is strong enough to provide the identity conditions of a tradition across changes, consistency might force us to identify all problem solving activity as part of one research tradition, blurring distinctions between science and non-science. Distinguishing between a change within a research tradition and the replacement of a research tradition with another seems both arbitrary and open-ended. One way of solving this problem is by turning from just internal characteristics of science to external factors of social and historical context. 4. The Social Processes of Change Science is not just a body of facts or sets of sentences. However one characterizes its content, that content must be embodied in institutions and practices comprised of scientists themselves. An important question then, with respect to scientific change, regards how "science" is constructed out of scientists, and which unit of analysis – the individual scientist or the community—is the proper one for understanding the dynamic of scientific change? Popper's falsificationism was very much a matter of personal responsibility and reflection. Kuhn, on the other hand, saw scientific change as a change of community and generations. While Structure may have been largely responsible for making North American philosophers aware of the importance of historical and social context in shaping scientific change, Kuhn was certainly not the first to theorize about it. Kuhn himself recognized his views in the earlier work of Ludwik Fleck (See for example Brorson and Andersen 2001, Babich 2007 and Mössner 2011 for comparisons between the views of Kuhn and Fleck). a. Fleck As early as the mid-1930s, Ludwik Fleck (1896-1961) gave an account of how thoughts and ideas change through their circulation within the social strata of a thought-collective (Denkkollektiv) and how this thought-traffic contributes to the process of verification. Drawing on a case study from medicine on the development of a diagnostic test for syphilis, Ludwik Fleck argued in his 1935 monograph Genesis and the Development of a Scientific Fact that a thought collective is a functional unit in which people who interact intellectually are tied together through a particular 'thought style' that forces narrow constraints upon the thinking of the individual. The thought-style is dogmatically transmitted from one generation to the next, by initiation, training, education or other devices whose aim is introduction into the collective. Most people participate in numerous thought-collectives, and any individual therefore possesses several overlapping thought-styles and may become carriers of influence between the various thought-collectives in which they participate. This traffic of thoughts outside the collective is linked to the most outstanding alterations in thought-content. The ensuing modification and assimilation according to the foreign thought-style is a significant source of divergent thinking. According to Fleck, any circulation of thoughts therefore also causes transformation of the circulated thought. In Kuhn's Structure, the distinction between the individual scientist and the community as the agent of change was not quite clear, and Kuhn later regretted having used the notion of a gestalt switch to characterize changes in a community because "communities do not have experiences, much less gestalt switches." Consequently, he realized that "to speak, as I repeatedly have, of a community's undergoing a gestalt switch is to compress an extended process of change into an instant, leaving no room for the microprocesses by which the change is achieved" (Kuhn 1989, p. 50). Rather than helping himself to an unexamined notion of communal change, Fleck, on the other hand, made the process by which individual interacted with collective central to his account of scientific development and the joint construction of scientific thought. What the accounts have in common is a view that the social plays a role in scientific change through the social shaping of science content. It is not a relation between scientist and physical world which is constitutive of scientific knowledge, but a relation between the scientists and the discipline to which they belong. That relation can be restrictive of change in science. It can also provide the dynamics for change. b. Hull's Evolutionary Account of Scientific Change Several philosophers of science have held the view that the dynamics of scientific change can be seen as an evolutionary process in which some kind of selection plays a central role. One of the most detailed evolutionary accounts of scientific change has been provided by David Hull (1935-2010). On Hull's account of scientific change, the development of science is a function of the interplay between cooperation and competition for credit among scientists. Hence, selection in the form of citations plays a central role in this account. The basic structure of Hull's account is that, for the content element of science—problems and their solutions, accumulated data, but also beliefs about the goals of science, proper ways to realize these goals, and so forth—to survive in science they must be transmitted more or less intact through history. That is, they must be seen as replicators that pass on their structure in successive replication. Hence, conceptual replication is a matter of information being transmitted largely intact by different vehicles. These vehicles of transmission may be media such as books or journals, but also scientists themselves. Whereas books and journals are passive vehicles, scientists are active in testing and changing the transmitted ideas. They are therefore not only vehicles of transmission but also interactors, interacting with their environment in a way that causes replication to be differential and hence enabling of scientific change. Hull did not elaborate much on the inner structure of differential replication, apart from arguing that the underdetermination of theory by observation made it possible. Instead, the focus of his account is on the selection mechanism that can cause some lineages of scientific ideas to cease and others to continue. First, scientists tend to behave in ways that increase their conceptual fitness. Scientists want their work to be accepted, which requires that they gain support from other scientists. One kind of support is to show that their work rests on preceding research. But that is at the same time a decrease in originality. There is a trade-off between credit and support. Scientists whose support is worth having are likely to be cited more frequently. Second, this social process is highly structured. Scientists tend to organize into tightly knit research groups in order to develop and disseminate a particular set of views. Few scientists have all the skills and knowledge necessary to solve the problems that they confront; they therefore tend to form research groups of varying degrees of cohesiveness. Cooperating scientists may often share ideas that are identical in descent, and transmission of their contributions can be viewed as similar to kin selection. In the wider scientific community, scientists may form a deme in the sense that they use the ideas of each other much more frequently than the ideas of scientists outside the community. Initially, criticism and evaluation come from within a research group. Scientists expose their work to severe tests prior to publication, but some things are taken so much for granted that it never occurs to them to question it. After publication, it shifts to scientists outside the group, especially opponents who are likely to have different—though equally unnoticed—presuppositions. The self-correction of science depends on other scientists having different perspectives and different career interests—scientists' career interests are not damaged by refuting the views of their opponents. 5. Cognitive Views on Scientific Change Scientific change received new interest during the 1980s and 1990s with the emergence of cognitive science; a field that draws on cognitive psychology, cognitive anthropology, linguistics, philosophy, artificial intelligence and neuroscience. Historians and philosophers of science adapted results from this interdisciplinary work to develop new approaches to their field. Among the approaches are Paul Churchland's (*1942) neurocomputational perspective (Churchland, 1989; Churchland, 1992), Ronald Giere's (*1938) work on cognitive models of science (Giere, 1988), Nancy Nersessian's (*1947) cognitive history of science (Nersessian, 1984; Nersessian, 1992; Nersessian, 1995a; 1995b), and Paul Thagard's (*1950) computational philosophy of science (Thagard, 1988; Thagard, 1992). Rather than explaining scientific change in terms of a priori principles, these new approaches aim at being naturalized by drawing on cognitive science to provide insights on how humans generally construct and develop conceptual systems and how they use these insights in analyses of scientific change as conceptual change. (For an overview of research in conceptual change, see (Vosniadou, 2008).) a. Cognitive History of Science Much of the early work on conceptual change emphasized the discontinuous character of major changes by using metaphors like 'gestalt switch', indicating that such major changes happen all at once. This idea had originally been introduced by Kuhn, but in his later writings he admitted that his use of the gestalt switch metaphor had its origin in his experience as a historian working backwards in time and that, consequently, it was not necessarily suitable for describing the experience of the scientists taking part in scientific development. Instead of dramatic gestalt shifts, it is equally plausible that for the historical actors there exist micro-processes in their conceptual development. The development of science may happen stepwise with minor changes and yet still sum up over time to something that appears revolutionary to the historian looking backward and comparing the original conceptual structures to the end product of subsequent changes. Kuhn realized this, but also saw that his own work did not offer any details on how such micro-processes would work, though it did leave room for their exploration (Kuhn 1989). Exploration of conceptual microstructures has been one of the main issues within the cognitive history and philosophy of science. Historical case studies of conceptual change have been carried out by many scholars, including Nersessian, Thagard, the Andersen-Barker-Chen groupThat (see for example Nersessian, 1984; Thagard, 1992; Andersen, Barker, and Chen, 2006). Some of the early work in cognitive history and philosophy of science focused on mapping conceptual structures at different stages during scientific change (see for example Thagard, 1990; Thagard and Nowak, 1990; Nersessian and Resnick, 1989) and developing typologies of conceptual change in terms of their degree of severeness (Thagard, 1992). These approaches are useful for comparing between different stages of scientific change and for discussing such issues as incommensurability. However, they do not provide much detail on the creative process through which changes are created. Other lines of research have focused on the reasoning processes that are used in creating new concepts during scientific change. One of the early contributions to this line of work was Shapere who argued that, as concepts evolve, chains of reasoning connect the successive versions of a concept. These chains of reasoning therefore also establish continuity in scientific change, and this continuity can only be fully understood by analysis of the reasons that motivated each step in the chain of changes (Shapere 1987a;1987b). Over the last two decades, this approach has been extended and substantiated by Nersessian (2008a; 2008b) whose work has focused on the nature of the practices employed by scientists in creating, communicating and replacing scientific representations within a given scientific domain. She argues that conceptual change is a problem-solving process. Model-based reasoning processes, especially, are used to facilitate and constrain abstraction and information from multiple sources during this process. b. Scientific Change and Science Education Aiming at insights into general mechanisms of conceptual development, some of the cognitive approaches have been directed toward investigating not only the development of science, but also how sciences are learned. During the 1980s and early 1990s, several scholars argued that conceptual divides of the same kind as described by Kuhn's incommensurability thesis might exist in science education between teacher and student. Science teaching should, therefore, address these misconceptions in an attempt to facilitate conceptual change in students. Part of this research incorporated the (controversial) thesis that the development of ideas in students mirrors the development of ideas in the history of science—that cognitive ontogeny recapitulates scientific phylogeny. For the field of mechanics in particular, research was done to show that children's naïve beliefs parallel early scientific beliefs, like impetus theories, for example. (Champagne, Klopfer, and Anderson, 1980; Clement, 1983; McClosky, 1983). However, most research went beyond the search for analogies between students' naïve views and historically held beliefs. Instead, they carried out material investigations of the cognitive processes employed by scientists in constructing scientific concepts and theories more generally, through the available historical records, focussing on the kinds of reasoning strategies communicated in those records (see Nersessian, 1992; Nersessian, 1995a). Thus, this work still assumed that the cognitive activities of scientists in their construction of new scientific concepts was relevant to learning, but it marked a return to a view of the relevance of the history of science as a repository of case studies demonstrating how scientific concepts are constructed and changed. In assuming a conceptual continuity between scientific understanding "then and now," the cognitive approach had moved away from the Kuhnian emphasis on incommensurability and gestalt shift conceptual change. 6. Further Reading and References It is impossible to disentangle entirely the history and philosophy of scientific change from a great number of other issues and disciplines. We have not addressed here the epistemology of science, the role of experiments in science (or of thought experiments), for instance. The question of whether science, or knowledge in general, is approaching truth, or tracking truth, or approximating to truth, are debates taken up in epistemology. For more on those issues one should consult the relevant references. Whether science progresses (and not just changes) is a question which supports its own literature as well. Many iterations of interpretations, criticism and replies to challenges of incommensurability, non-cumulativity, and irrationality of science have been given. Beliefs in scientific progress founded on a naïve realism, according to which science is getting ever closer to a literally true picture of the world, have been criticized soundly. A simple version of the criticism is the pessimistic meta-induction: every scientific image of reality in the past has been proven wrong, therefore all future scientific images will be wrong (see Putnam 1978; Laudan 1984). In response to challenges to realism, much attention has been paid to structural realism, an attempt to describe some underlying mathematical structure which is preserved even across major theory changes. Past theories were not entirely wrong, on this view, and not entirely discarded, because they had some of the structure correct, albeit wrongly interpreted or embedded in a mistaken ontology or broader world view which has been since abandoned. On the question of unity of science, on whether the methods of science are universal or plural, and whether they are rational, see the references given for Cartwright (2007), Feyerabend (1974), Mitchell (2000;2003); Kellert, et al (2006). For feminist criticisms and alternatives to traditional philosophy and history of science the interested reader should consult Longino (1990;2002); Gary, et al (1996); Keller, et al (1996); Ruetsche (2004). Clough (2004) puts forward a program combining feminism and naturalism. Among twenty-first century approaches to the historicity of science there are Friedman's dynamic a priori approach (Friedman 2001), the evolving subject-object relation of McGuire and Tuchanska (2000), and complementary science of Hasok Chang (2004). Finally, on the topic of the Scientific Revolution, there are the standard Cohen (1985), Hall (1954) and Koyré (1965); but for subsequent discussion of the appropriateness of revolution as a metaphor in the historiography of science we recommend the collection Rethinking the Scientific Revolution, edited by Osler (2000).

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Social Dimensions of Scientific Knowledge. South Bend: Notre Dame University Press. Ruetsche, Laura, 2004, "Virtue and Contingent History: Possibilities for Feminist Epistemology", Hypatia, 19.1: 73–101 Solomon, Miriam. (2001). Social Empiricism. Cambridge: Massachusetts Institute of Technology Press. iii. The Scientific Revolution Cohen, I. B., (1985). Revolution in Science, Cambridge: Harvard University Press. Koyré, A. (1965). Newtonian Studies. Chicago: The University of Chicago Press. Osler, Margaret (2000). Rethinking the Scientific Revolution. Cambridge: Cambridge University Press. Author Information Hanne Andersen Email: hanne.andersen@ivs.au.dk University of Aarhus Denmark Science and technology feed off of one another, propelling both forward. Scientific knowledge allows us to build new technologies, which often allow us to make new observations about the world, which, in turn, allow us to build even more scientific knowledge, which then inspires another technology … and so on. As an example, we'll start with a single scientific idea and trace its applications and impact through several different fields of science and technology, from the discovery of electrons in the 1800s to modern forensics and DNA fingerprinting… From cathodes to crystallography A cathode ray tube from the early 1900s. Photo credit: The Cathode Ray Tube site. We pick up our story in the late 1800s with a bit of technology that no one much understood at the time, but which was poised to change the face of science: the cathode ray tube (node A in the diagram below and pictured above). This was a sealed glass tube emptied of almost all air — but when an electric current was passed through the tube, it no longer seemed empty. Rays of eerie light shot across the tube. In 1897, physicists would discover that these cathode rays were actually streams of electrons (B). The discovery of the electron would, in turn, lead to the discovery of the atomic nucleus in 1910 (C). On the technological front, the cathode ray tube would slowly evolve into the television (which is constructed from a cathode ray tube with the electron beam deflected in ways that produce an image on a screen) and, eventually, into many sorts of image monitors (D and E). But that's not all… In 1895, the German physicist Wilhem Roentgen noticed that his cathode ray tube seemed to be producing some other sort of ray in addition to the lights inside the tube. These new rays were invisible but caused a screen in his laboratory to light up. He tried to block the rays, but they passed right through paper, copper, and aluminum, but not lead. And not bone. Roentgen noticed that the rays revealed the faint shadow of the bones in his hand! Roentgen had discovered X-rays, a form of electromagnetic radiation (F). This discovery would, of course, shortly lead to the invention of the X-ray machine (G), which would in turn, evolve into the CT scan machine (H) — both of which would become essential to non-invasive medical diagnoses. And the CT scanner itself would soon be adopted by other branches of science — for neurological research, archaeology, and paleontology, in which CT scans are used to study the interiors of fossils (I). Additionally, the discovery of X-rays would eventually lead to the development of X-ray telescopes to detect radiation emitted by objects in deep space (J). And these telescopes would, in turn, shed light on black holes, supernovas, and the origins of the universe (K). But that's not all… The discovery of X-rays also pointed William and William Bragg (a father-son team) in 1913 and 1914 to the idea that X-rays could be used to figure out the arrangements of atoms in a crystal (L). This works a bit like trying to figure out the size and shape of a building based on the shadow it casts: you can work backwards from the shape of the shadow to make a guess at the building's dimensions. When X-rays are passed through a crystal, some of the X-rays are bent or spread out (i.e., diffracted) by the atoms in the crystal. You can then extrapolate backwards from the locations of the deflected X-rays to figure out the relative locations of the crystal's atoms. This technique is known as X-ray crystallography, and it has profoundly influenced the course of science by providing snapshots of molecular structures. Perhaps most notably, Rosalind Franklin used X-ray crystallography to help uncover the structure of the key molecule of life: DNA. In 1952, Franklin, like James Watson and Francis Crick, was working on the structure of DNA — but from a different angle. Franklin was painstakingly producing diffracted images of DNA, while Watson and Crick were trying out different structures using tinker-toy models of the component molecules. In fact, Franklin had already proposed a double helical form for the molecule when, in 1953, a colleague showed Franklin's most telling image to Watson. That picture convinced Watson and Crick that the molecule was a double helix and pointed to the arrangement of atoms within that helix. Over the next few weeks, the famous pair would use their models to correctly work out the chemical details of DNA (M). The impact of the discovery of DNA's structure on scientific research, medicine, agriculture, conservation, and other social issues has been wide-ranging — so much so, that it is difficult to pick out which threads of influence to follow. To choose just one, understanding the structure of DNA (along with many other inputs) eventually allowed biologists to develop a quick and easy method for copying very small amounts of DNA, known as PCR — the polymerase chain reaction (N). This technique (developed in the 1980s), in turn, allowed the development of DNA fingerprinting technologies, which have become an important part of modern criminal investigations (O). As shown by the flowchart above, scientific knowledge (like the discovery of X-rays) and technologies (like the invention of PCR) are deeply interwoven and feed off one another. In this case, tracing the influence of a single technology, the cathode ray tube, over the course of a century has taken us on a journey spanning ancient fossils, supernovas, the invention of television, the atomic nucleus, and DNA fingerprinting. And even this complex network is incomplete. Understanding DNA's structure, for example, led to many more advances besides just the development of PCR. And similarly, the invention of the CT scanner relied on much more scientific knowledge than just an understanding of how X-ray machines work. Scientific knowledge and technology form a maze of connections in which every idea is connected to every other idea through a winding path. Previous Fueling technology Next Making strides in medicine