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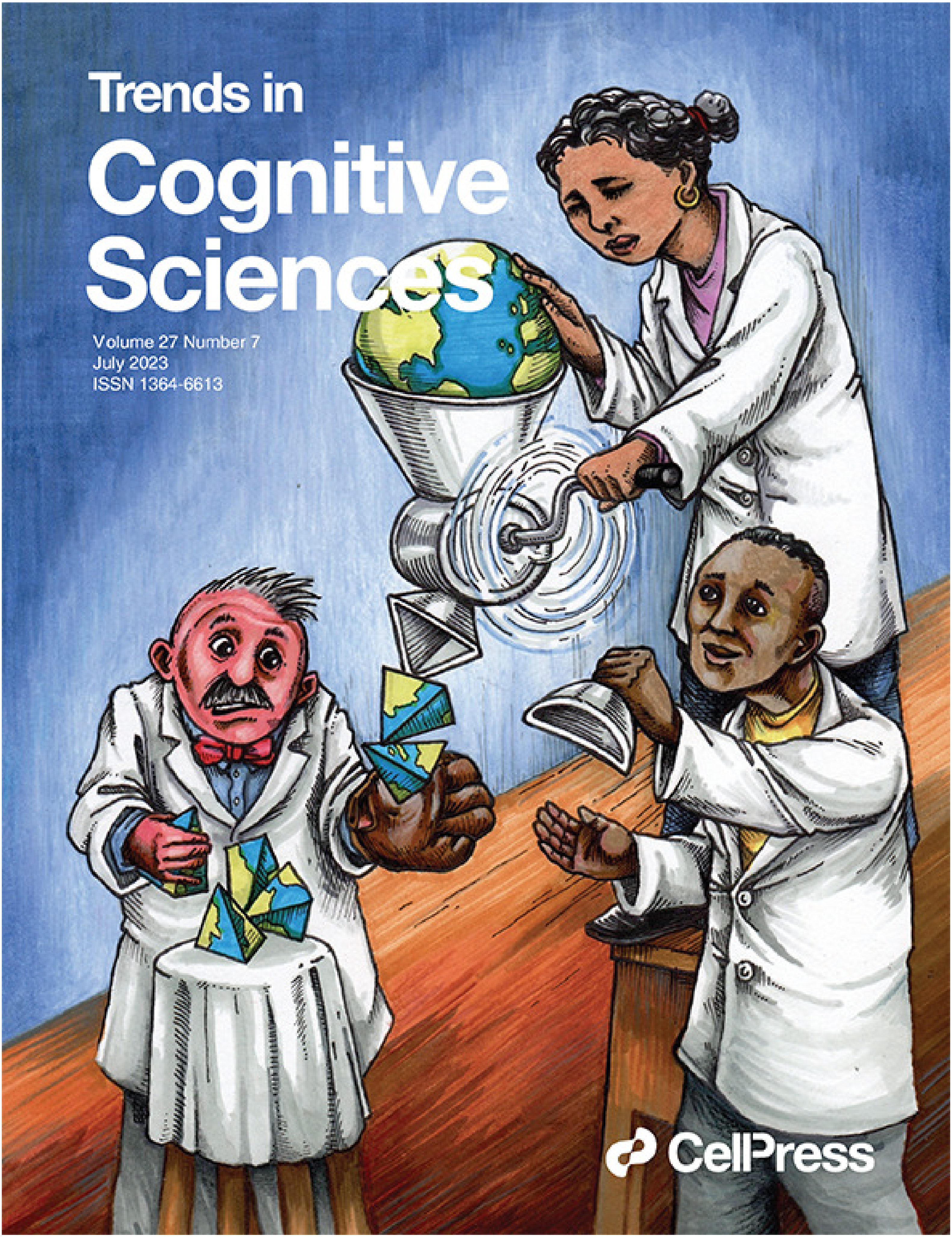

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Trends in Cognitive Sciences

Review

Carving joints into nature: reengineering scientific concepts in light of concept-laden evidence

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A new wave of proposals suggests that scientists must reassess scientific concepts in light of accumulated evidence. However, reengineering scientific concepts in light of data is challenging because scientific concepts affect the evidence itself in multiple ways. Among other possible influences, concepts (i) prime scientists to overemphasize within-concept similarities and between-concept differences; (ii) lead scientists to measure conceptually relevant dimensions more accurately; (iii) serve as units of scientific experimentation, communication, and theory-building; and (iv) affect the phenomena themselves. When looking for improved ways to carve nature at its joints, scholars must take the concept-laden nature of evidence into account to avoid entering a vicious circle of concept-evidence mutual substantiation.

Highlights

Reassessing scientific concepts is essential for scientific progress.

Bottom-up conceptual reengineering agendas across science accommodate previous evidence but ignore how the collection of previous evidence was affected by the concepts being assessed at the time.

Cognitive and philosophical research suggests similarities between conceptual influences on human perception and conceptual influences on scientific evidence.

Specifically, scientific concepts warp the similarity and measurement fidelity of phenomena; serve as units of scientific experimentation, theorizing, and communication; and influence the phenomena themselves.

This challenge calls for new ways of integrating previously collected data and collecting new evidence when reengineering scientific concepts.

Revising scientific concepts: a challenge

Concepts lie at the core of scientific activity [1]. Psychologists investigate, describe, and treat 'schizophrenia' and 'major depressive disorder,' whereas chemists study and manipulate 'calcium,' 'iron,' and 'helium.' Concepts drive disciplinary specification, guide data collection, and serve as the building blocks for theories. Concepts determine how scholars communicate scientific findings and generalize them. 'Schizophrenia' treatments are applied to 'schizophrenia'-diagnosed patients, but not to attention-deficit/hyperactivity disorder ('ADHD')-diagnosed patients. Thus, the quality of scientific concepts within each discipline is closely linked to the success of that discipline. Given the importance of conceptual systems for nearly all scientific processes, scholars and philosophers have argued that they can, and should, be improved (e.g., [2]).

Here, we argue that **concept-dependence of evidence** (see Glossary) is a central challenge when **reengineering** scientific concepts. Building on a rich philosophical literature on the concept-ladenness of scientific observation (see Box 1) and empirical work in cognitive science on the concept-ladenness of human perception, we propose mechanisms by which scientific concepts influence scientific evidence. Following philosophical debates [3–7], we suggest that the concept-dependence of scientific evidence is a double-edged sword. Concepts serve as foundational units of scientific activity and enable scientists to make progress by not being overwhelmed by the blooming, buzzing confusion of the world. However, they can also inappropriately tether scientists to their early ontologies, forming a vicious cycle of concepts **substantiating** themselves via the evidence they affect. We conclude that an essential, but often overlooked, step toward designing better conceptual systems in science is taking the concept-ladenness of evidence seriously.

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Box 1. 'Pure' scientific evidence

Philosophers have thoroughly explored the relationship between observation and its context, articulating a variety of positions, from treating scientific observation as theory-free [107] to showing the contingency of scientific observation on its social and historical contexts [7]. By examining cases in the history of science, many scholars have argued that evidence is not a 'view from nowhere' – neutral and value-free information provided by reality. Instead, it is a highly contextualized interpretation of it, passed through cognitive, culture-specific, and method-specific filters [7,8,108]. The theory-ladenness of observations has been convincingly demonstrated for historical cases in microbiology, chemistry, and astronomy, among others [35,36,109]. Some scholars [35,110] have hypothesized that theory-laden effects on observations are the strongest when the data ('bottom-up signal') are weak, ambiguous, or noisy. For others [64,108], the development of more advanced measurements (e.g., photography, x-rays, or high-resolution fMRI) does not allow the data to better 'speak for itself.' Rather, it shifts the interpretive function onto the technical aspects of the instruments, cleaning and analyzing their output, and the final reporting of the results by scientists.

Philosophers have used parallels between human perception and scientific observation to advance our understanding of both [5,36,37,85,111]. For instance, Hanson [37,62] used insights from Gestalt psychology to show how scientific observation is affected by scientists' theories. Humans perceive ambiguous figures (e.g., duck vs. rabbit) as different, mutually incompatible, entities, interpreting their parts in different ways. Similarly, scientific concepts and their associations influence what is noticed, assumed, and predicted even for the same observation [112–115]. The 13th-century astronomer sees the sun as moving around the Earth from dusk to dawn, but the 20th-century astronomer sees the Earth as rotating around the sun. Churchland [5] argued that human perception and scientific observation are both concept-mediated and thus should have equal epistemic status. Estany [83] appealed to the theory of interactive vision to demonstrate how the interaction of top-down (conceptual) and bottom-up (data-driven) influences can result in partial scientific knowledge about the world. Others have, on the contrary, questioned the empirical and theoretical evidence for conceptual influences on perception and its implications for science [48,116,117].

Ontology reengineering across sciences

Most scientific ontologies originate in folk theories and inchoate intuitions of the disciplines' visionaries. Proposals for reconfiguring early ontologies based on newly acquired evidence are common in applied and fundamental disciplines, such as medicine, chemistry, biology, psychology, neuroscience, geology, and others. We provide a brief overview of modern trends to reengineer scientific ontologies, covering three domains of knowledge as examples: (i) cognitive, behavioral, and neural sciences; (ii) medicine and psychiatry; and (iii) chemistry (see Box 2 for reengineering

Box 2. Reengineering ontologies: methods

Scientific concepts can change based on accumulated scientific evidence. One promising approach for revising a scientific ontology is integrating all domain-relevant data and uncovering its underlying structure [118]. Designing concepts based on all available information can, in principle, lead to ontologies that partition phenomena into the most informative or useful units, given the state of the field. Some approaches automatically synthesize published work to find semantic clusters in the fields. For example, topic modeling harnesses co-occurrences of terms in scientific papers to infer research themes that compose together to generate papers [119]. Scientific fields can also be inferred from citation and collaboration patterns [120–122]. The discovered clusters of research can then be used to infer underlying entities that the scientists study.

Some approaches mine patterns of data from published work and then ask scientists to synthesize the gathered information and provide definitions and relationships among the mined concepts. For example, Gene Ontology is an open-ended database of the definitions for biological entities (molecular functions, cellular components, and biological processes) and relationships between them, based on crowdsourced annotations of published records [123]. The database has been progressively developed for over 20 years and now includes over 45 000 terms and over 134 000 relationships between them [124]. Cognitive Atlas [125] is a crowdsourced database of mental constructs that includes their definitions, relationships, and ways to measure them (e.g., psychological tasks). Cognitive Atlas combines both the publication record and the expertise of cognitive scientists, psychologists, and neuroscientists who are tasked with explicating the field's ontology. Similarly, precision medicine harnesses Big Data to reveal patient kinds, disease kinds, treatment kinds, and their relationships to improve diagnosis and treatment [19]. Here, symptoms, patients' features, medical history, and treatment efficacy are clustered according to the available data, and new patients receive individualized treatments based on the cluster of patients to which they are most similar.

Other mechanisms of conceptual reengineering include causal modeling (carving up kinds based on the different causal mechanisms that putatively give rise to them), weighting the dimensions of evidence (deciding which measurements should have priority for categorization: e.g., neural vs. behavioral evidence), lumping concepts together, and splitting them apart.

Glossary

Circular reasoning: a type of reasoning where the proposition is supported by the premises, which are themselves supported only by the proposition.

Concept dependence (concept-ladenness) of scientific evidence: scientific facts are shaped by the concepts scientists use. In this paper, we use 'concept-ladenness' and 'theory-ladenness' interchangeably.

Concept reengineering: assessing and improving conceptual systems.

Conceptual pluralism: openness of the scientific field to different ways to conceptualize the same set of phenomena.

Ontology (computer science): a formal specification of the domain of shared knowledge (often includes entities, their properties, and relationships between them; [131]). For example, an ontology of cognitive processes might include 'attention,' 'memory,' and 'perception' (entities); their properties (e.g., 'perception' is fast and low-level, can be investigated with detection tasks); and their relationships (e.g., information obtained from 'perception' is sent to 'memory' for storage).

Ontology (philosophy): a branch of metaphysics studying what types of things exist and what their properties and relationships are.

Self-substantiating method: evidence obtained from a method is taken as supporting the method itself.

Underdetermination argument: evidence alone is insufficient to determine a unique theory to explain the observed phenomena, as multiple theories can be equally consistent with the available evidence.

methods). In the following section, we articulate the mechanisms that challenge these reengineering agendas.

Neural, psychological, and behavioral sciences

The study of human psychology and behavior in the West is most influenced by folk wisdom and a classification of mental processes that is over a century old ([8]; e.g., [9]). Thus, we typically think of human behavior as driven by latent mental processes, such as sensation, perception, attention, learning, memory, language, motivation, emotion, and subkinds of these processes (e.g., long-term and short-term memory).

Cognitive science has seen a recent rise in proposals to debunk or reconsider the current conceptualizations of mental processes and kinds. Their premise is that psychological kinds ingrained in folk wisdom or Western scholars' early intuitions are unlikely to correspond to the most appropriate joints in the psychological data [10,11], and accumulated data can drive a properly evidence-based method for finding more useful conceptualizations. Recent proposals include integrating neuroevolutionary data to revise psychological categories [12] or using neuroscientific data to develop new concepts for neuroscience [13,14]. Other proposals suggest reconsidering even the format of our scientific concepts: For instance, Barrett [15] concludes that the century-long search for the correlates of the 'core emotions' (e.g., 'fear' and 'anger') has been futile (also, see [16]) and instead recommends exploring other types of representations, such as dimensional spaces (also, see [17]), for describing emotional states.

Precision medicine and psychiatry

Medicine's conceptual systems are anchored in folk concepts from traditional medicine and early insights from Renaissance scholars. A recent reconceptualization in medicine involves explicitly considering macro-level social factors in categorizing pathologies; this approach has been fruitful in explaining why some diseases, such as HIV/AIDS, coronary heart disease, cancer, and others, cluster together in populations under social or environmental stress [18]. Moreover, the recent rise of Big Data, personalized health applications, and machine learning tools has opened up new possibilities to reassess medicine's concepts based on large datasets. Databases that record symptoms and their co-occurrences, genetic information, the efficiency of different types of treatment, and characteristics of individuals (e.g., lifestyle and diet) and their environment offer promise in grounding personalized treatments and future research in empirical patterns rather than early scholars' conceptual intuitions [19–21].

Similarly, the taxonomy of psychiatric disorders, primarily inspired by 19th- and 20th-century scholars such as Kraepelin and Bleuler, is now being revised on the basis of behavioral, phenomenological, and biophysiological data. Two major approaches on this front are RDoC (Research Domain Criteria) and HiTOP (Hierarchical Taxonomy of Psychopathology), which aim to move away from rigid categories and toward dimensional accounts of psychopathology. RDoC is an ongoing effort to reconceptualize psychopathology based on the data accumulated across biological levels (e.g., genetic, neurophysiological, behavioral data) and domains (e.g., social and cognitive processes) [22,23]. HiTOP, however, aims to construct hierarchical mapping of psychopathology based on the empirical associations among reported symptoms, signs, diagnoses, and maladaptive behaviors [24].

Periodic systems in chemistry

Mendeleev's periodic system of elements is perhaps the most elegant and widely accepted scientific **ontology**. Mendeleev is typically famed for having discovered the underlying order in the diverse chemical and physical properties of matter. However, historical evidence traces hundreds of alternative periodic systems that group the elements differently or use different spatial models for reflecting these regularities: helices, circles, pyramids, and others [25,26] (see a web database: https://www.meta-synthesis.com/webbook/35_pt/pt_database.php). In many ways, the choice of Mendeleev's table as the widely accepted ontology might be historically contingent rather than a rational and inevitable choice of the structure that best reflects the available data. After the table was widely recognized and awarded a Nobel Prize, scholars started observing its successful predictions of several new elements. However, it has been argued that Mendeleev's table has made at least as many unsuccessful as successful predictions [26–28]. Moreover, despite the table's universal acceptance and the enormous efforts of scholars to fit everything into it, many elements still do not seem to neatly fit into their current positions in the table [29]. For instance, the International Union of Pure and Applied Chemistry recently assigned a task group exclusively dedicated to finding a more appropriate place for the f-block of elements ('rare earths') in the table [30,31] (https://iupac.org/project/2015-039-2-200/).

Apart from the efforts to fit all available data into the existing table and proposals to reassess the positions of particular elements in it, there have also been arguments in support of completely restructuring the current periodic ontology [32], or reconsidering the entities that constitute its basic units [33]. Moreover, scholars have proposed new element arrangements that would better capture useful regularities for their specific fields, such as the periodic table for earth sciences, which focuses on the similarities of elements according to their geological, rather than chemical, features [34].

Mechanisms underlying concept-laden influences on scientific observation

The idea that scientific ontologies should be continuously reconsidered in light of the available data is not novel. Psychology, for instance, has been attracted by the promise of neuroimaging methods for informing the classification of mental processes for more than 40 years [10]. However, the rise of new technologies and the accumulation of 'big brain' databases have had little effect in diminishing the entrenchment of the traditional Western taxonomy of mental processes. Similarly, in chemistry and physics, the development of new technologies, the collection of new data, and even the synthesis of 'extreme' superheavy elements predominantly just keep showing how correct Mendeleev was. Did the early visionaries, such as James and Mendeleev, and their contemporaries happen to carve nature at its joints in exactly the right way without the benefit of ample data, advanced measurement instruments, or computer technologies that we now have?

Following philosophical work on theory-ladenness of observation [5,35–37], we suggest that the reason ontologies rarely change is not because they perfectly capture all useful distinctions in the studied phenomena from their first iteration. Instead, ontologies, once in place, heavily affect the evidence that serves as a basis for evaluating and potentially reengineering them (Figures 1 and 2 and Box 1). Here, we present candidate mechanisms by which ontologies affect scientific evidence, drawing insights from both scientific practice and cognitive science research showing conceptual influences on human perception.

Concepts warp the similarity space of phenomena

Scientific concepts change how scientists observe similarities and differences among entities in their field of study. If entities are represented as coordinates in a high-dimensional space of their (measurable) properties, then scientific concepts warp these coordinates in several ways.

Evidence conforming to conceptual distinctions is emphasized, and contradicting evidence is neglected. Concepts warp human perception of objects and events, often making the entities that belong to the same concept appear more similar to each other and entities from

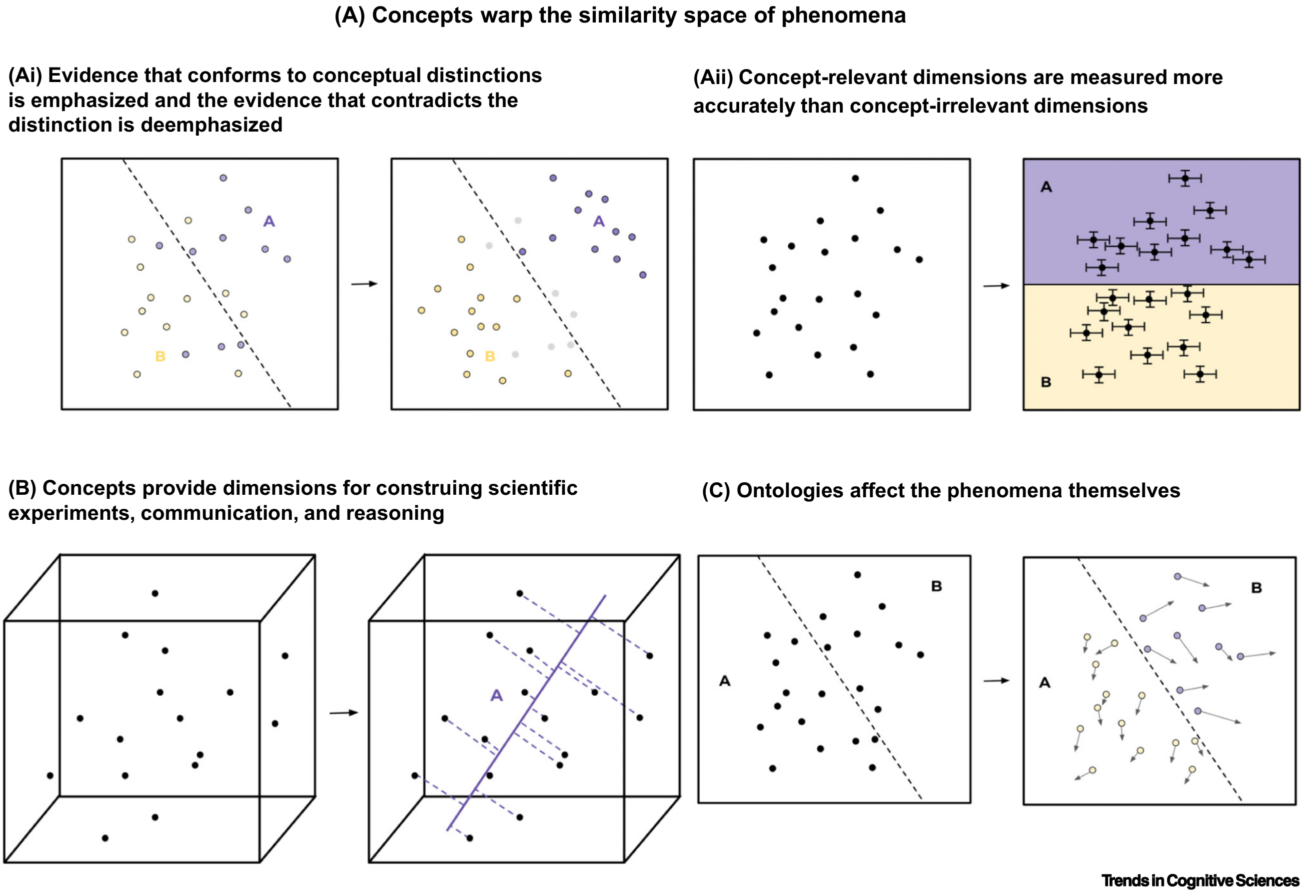

Figure 1. Functionally different mechanisms of conceptual influences on scientific observations. (Ai) Over time, the within-concept phenomena (As or Bs) become more similar to each other, and between-concept phenomena (A vs. B) become more different, due to biases in measuring, analyzing, communicating, and applying scientific results. One mechanism underlying such change is selective neglect of the observations that contradict conceptual distinction. (Aii) When a conceptual distinction is made between As and Bs, then phenomena are more accurately measured along the dimensions that distinguish As from Bs (here, the vertical dimension is conceptually important). (B) Once a concept enters a scientific ontology, it becomes a dimension onto which individual observations are projected for experimentation, communication, and theorizing purposes. The observations (dots) become represented in terms of their positions along a conceptually relevant axis (A). (C) Phenomena change in response to the introduced conceptual distinction. For instance, once categorized into As and Bs, the A exemplars (yellow dots) change their properties to move away from the B exemplars, and vice versa.

different concepts appear more different than they would without possession of the concepts [38]. For example, professional musicians are more likely than novices to notice a difference between major and minor intervals than they are to notice a physically equated difference between two intervals that are both major or both minor [39]. Similarly, human perception and memory of perceptual attributes of objects that belong to a category tend to assimilate to the category [40–44]. Participants' perceptual estimation of items and their features is also often biased away from the boundary that distinguishes one concept from another. For example, perception of an exemplar of one type of fish will be moved away from the features characterizing another fish category to prevent erroneous misclassification [45].

In science, ontologies influence data collection, reporting, communication, and field specialization in ways that make the phenomena that belong to the same class in the ontology more similar to each other and phenomena from two different classes more different (Figure 1Ai). First, studies are rarely conducted to explore potential differences in items or events that belong to the same

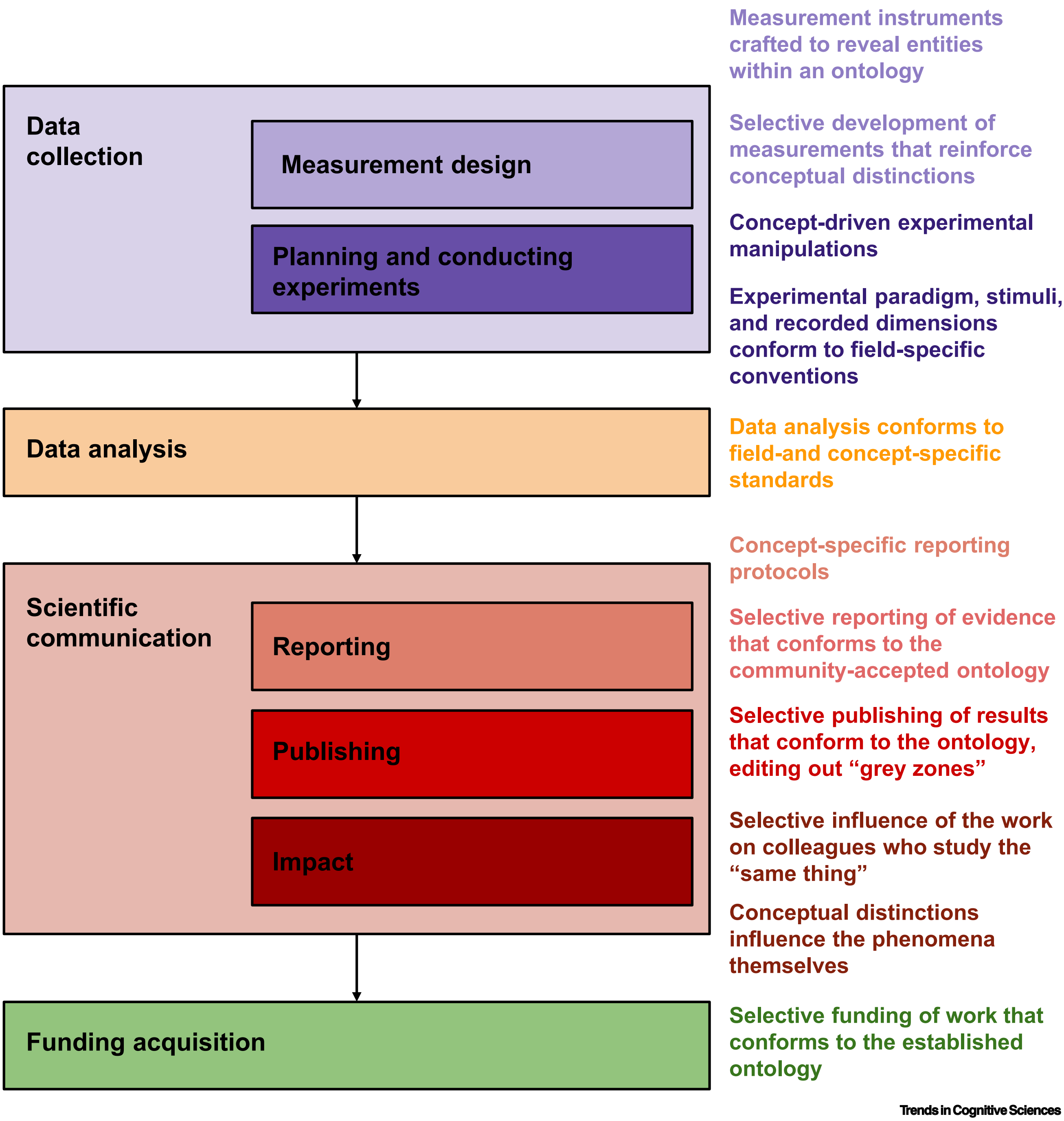

Figure 2. Examples of specific concept-laden biases at different stages of the scientific process. These practices cumulatively contribute to the functional changes in scientific evidence, which include warping of the similarity space of phenomena; reinforcement of existing concepts as units of experimentation, communication, and theorizing; and effects on the studied phenomena themselves.

category in the ontology [46,47]. For instance, psychological studies typically take a modular approach – they study only one putative mental process (e.g., 'perception') while aiming to completely isolate influences from 'other processes' (e.g., 'attention' or 'memory'; see [48] for a defense of such approach). Second, limited information exchange between scholars who specialize in studying different elements of an ontology (e.g., attention and decision making; schizophrenia and ADHD) diminishes their influence on each other's research in terms of experimental design, data analysis, reporting, and interpretation. The content-based filtering exhibited by many paper recommendation systems (e.g., Google Scholar) can further isolate already compartmentalized scientific communities [49,50]. These differences can superficially exacerbate the disparities in the evidence that scholars from different areas obtain. Finally, studies that do not clearly fall into the tradition of studying one or another conceptually delineated entity frequently fail to find a place in academic discourse. For instance, science has a long history of resisting work that requires major reconceptualization, which famously characterizes the Copernican revolution, the transition from the corpuscular to wave theory of light, and the adoption of Mendel's theory of independent inheritance of different traits [51]. This dynamic can create a published record of evidence that edits the ambiguous or undesirable zones out of the body of evidence, leading to the mistaken impression that already existing concepts aptly describe the full range of a field's phenomena.

These ontology-driven effects are potentially exacerbated by the lack of feedback when applying scientific knowledge to practice. For instance, oncologists have noticed that the overarching concept of 'cancer' potentially hides the inter- and intratumor heterogeneity that determines disease causes, progression, and treatment outcomes. Considering 'breast cancer' as a category that unifies its variants primes scientists and doctors to apply the same treatments to all 'breast cancer' cases, ignoring the variability that has recently been found to be crucial for treatment effectiveness [52]. Similarly, treating 'tumor' as a unitary entity may prime scientists and practitioners to ignore the heterogeneity of cells within a tumor, which, again, has recently been implicated as essential for cancer diagnosis and treatment [53]. Similar arguments have been emerging in psychiatry. For instance, researchers have argued that the poorly developed autism spectrum disorder (ASD) diagnosis clumps multiple diverse subgroups together, thus making it difficult to assess whether within-ASD heterogeneity is potentially meaningful [54]. Similarly, different major depressive disorder (MDD) scales have been used interchangeably in different studies and by practitioners, putting the results in the same 'MDD' basket. Only recently has it been noted that these scales have very little overlap in what they measure (e.g., only 12% of symptoms are shared among several scales). Their interchangeable use as 'MDD scales' could have partially hidden potential heterogeneity in the phenomena they end up capturing [55].

Concept-relevant dimensions are measured more accurately than concept-irrelevant dimensions. Human perceptual systems (e.g., vision) have limited resources; thus, they must tune to the perceptual features that are most relevant for our cognitive demands, such as categorization and communication, at the expense of other features [38,40]. For instance, when human participants are trained with new categories, they become perceptually attuned to the dimensions that are diagnostic for categorization. As a result, humans perceive, reconstruct, and encode these features more accurately [45,56–61] than nondiagnostic features. Real-life examples of this effect include radiologists becoming perceptually tuned to the features that distinguish malignant from benign tumors.

Similarly, scientific concepts determine which aspects of a phenomenon scientists record, pay attention to, and share with others (Figure 1Aii). The dimensions characterizing a conceptual system prime scientists to attend to some aspects of the data at the expense of other aspects. For instance, the geometrical thinking of early physicists (e.g., Descartes) may have led to their neglecting the temporal aspect of moving bodies, which was later found to be crucial for developing successful theories of object motion [62]. Atemporal conceptualization of diseases, such as tuberculosis, may have turned medical scientists' and practitioners' attention away from patterns in the pathology's progression that are crucial for its treatment [63]. Concepts influence what is recorded and analyzed in neuroscience: For example, neuroimaging studies tend to focus on 'conceptually relevant' parts of the brain while markedly deemphasizing the rest [64]. Thus, fear studies may only causally manipulate or analyze the neural activity in amygdala as a region of interest – a practice that has recently been challenged by network neuroscience [65].

Conceptually distinct phenomena prime scientists to use different measurement instruments for their study. For example, the creation of the *virus* concept helped scientists to develop new measurements for its study, instead of reusing previously developed technology for studying bacteria [66]. Cognitive scientists exploring different mental processes employ different tasks. For example, perception studies often use simple signal detection paradigms, whereas overt attention research often employs eye movement paradigms (e.g., visual search). These effects make the data obtained by researchers studying different entities within an ontology incompatible, which presents a challenge for resynthesizing the data when coming up with new conceptual distinctions that cut across previous categories. In this manner, tailoring experimental methods to specific constructs serves to reinforce existing conceptual distinctions.

Concepts provide dimensions for construing scientific experiments, communication, and reasoning

Concepts serve as mental units for our perception, cognition, and action. 'Llama' is a useful concept because once we know that something is a llama, many properties can be inferred (these associations also lead to expectation-based effects when scientists are working with the evidence: Box 3). Once a concept has been formed, it can be combined with other concepts to intervene on the world around us [67–69]. Here, concepts are essential for reasoning because most properties of individual exemplars (e.g., llama 1 and llama 2) can be ignored – ideally, the concept serves as a reasonable proxy for communicating about, thinking about, and deciding how to behave around a llama.

Similarly, scientific concepts serve as interactive units for experimentation. Chemists add 'sodium' to 'chlorine,' while educational psychologists manipulate students' 'attention load' and 'motivation' when attempting to improve students' math learning. Here, concepts determine

Box 3. Expectation-based effects: perceiving what is not there and missing what is there

Cognitive scientists have shown that humans often completely miss an unexpected and unattended stimulus (e.g., large gorilla) even when it is present in their plain sight [126–128]. Similarly, concept-driven expectations often make scholars miss the patterns that are present in data. For instance, mitochondria were only discovered relatively late in biology, in 1857, by Albert van Kolliker, a long time after microscopy was invented by van Leeuwenhoek in the 1670s. Even when there was clear evidence for mitochondria, given the decent optics of microscopes in the 1700s, scientists ignored them, with justifications such as 'there is a smudge on the cover slip' or 'part of the cell is damaged' [129].

Conversely, scientific concepts can lead scientists to see things that are not present in the data. Ontologies do not only discretize observations on the basis of some criteria – concepts also serve as efficient compressions of all their theoretical and data-driven associations. These associations lead scientists to perceive ambiguous or hidden properties in the data. In some cases, concept-driven associations lead scholars to consistently perceive evidence that was completely absent in the data. For example, in the 20th century, a subdiscipline in French physics was devoted to studying a new physical phenomenon, N-rays. After unsuccessful attempts to replicate these studies in other countries and further investigation, it turned out that the N-rays were simply in the eyes of the experimenters. When the proposed 'necessary conditions' for eliciting N-rays were secretly switched off, French scientists still 'detected' N-rays in the data [35,110]. Similarly, many famous results in psychology and social sciences have failed replication tests. Replication crises have also been identified in other disciplines, such as biology, medicine, and computer science. As many as 40% of published psychological studies report effects that do not capture any real regularity [130] – this phenomenon has been partially linked to concept-laden expectations influencing scientists' data analysis, reporting, and publishing decisions.

what kinds of interventions are even considered by scientists and which interventions are treated as equivalent. Before the widespread recognition of the importance of isotopes – elements sharing their position in the periodic table but characterized by different numbers of neutrons in their nuclei –in the 1940s, chemists were indifferent to which isotope of an element they used in a chemical reaction [70]. Likewise, a psychologist working with the concept of 'attention load' may treat its different experimental manipulations as equivalent.

Concepts serve as compact compressions of the rich evidence associated with them for scientists' communication and reasoning (Figure 1B). When we plan new studies on 'attention' or discuss 'schizophrenia' we operate with rich associations (e.g., accumulated evidence, relationships to other concepts) as compressed into discrete labels (or projected onto conceptual dimensions: [71]). Such compressions can be combined when conceiving of new experimental designs, making predictions, and developing new theories [72]. In these ways, conceptual systems determine what is remembered and what is forgotten by the scientific record, as well as which possibilities are considered for future exploration [73].

Ontologies affect the phenomena themselves

In some cases, ontological distinctions affect the categorized phenomena themselves (Figure 1C). Social, medical, and psychological sciences can 'make up people,' creating new ways for them to be, such as a patient with 'multiple personality disorder.' Ontologies loop people into new types of interactions with other people and institutions [74,75]. Once 'autism' was isolated as a diagnostic term, new institutional procedures and recommendations for families and schools were created [76]. Some effects, such as stereotyping, can cause humans to conform to the conceptual distinctions imposed on them. Alternatively, categorization can create resistance or other reactive responses in humans being categorized [77]. The stigmatization of psychiatric disorders in society affects people who have been diagnosed with them in various ways [78].

Overall, human science ontologies can have nonlinear and nuanced influences on their subjects [79,80]. For instance, 'hysteria'-diagnosed patients used to see the same doctors, receive the same treatments, and learn from each other what 'hysteria' was. As 'hysteria' was gradually broken down into 'epilepsy,' 'infertility,' and 'personality disorders,' among other categories, 'hysteria' patients became separately treated by science, society, the medical establishment, and themselves [74,81]. Bowker and Star [63] analyze ways in which being diagnosed with 'tuberculosis' used to influence one's life, which includes being isolated with other 'tuberculosis' patients for a long time, being stigmatized or romanticized by the rest of the society, adapting to the 'tuberculosis' sanatorium lifestyle, and sometimes resisting return to a mainstream life after recovery.

Humans are moving, rather than stationary, targets for classification. After being classified by experts, they change in response to the ontologies imposed on them. Similarly, phenomena from nonsocial domains (e.g., chemistry) can also change in response to a conceptual system through its influences on human scientists and engineers. For example, the periodic table establishes the building blocks for the application of chemical knowledge. This influences the abundance of certain chemical compounds and elements on Earth, most dramatically exemplified by the very existence of laboratory-created superheavy elements [82]. These completely new, although short-living, elemental building blocks of matter exist because an ontology has led scientists to create them.

Mutual interactions of ontologies and evidence

Scientific evidence and concept engineering are in a closed-loop interaction with each other [83]. Not only is scientific observation concept-laden, but also the concepts are **underdetermined** by observations [84]. The mutually reinforcing interactions of scientific concepts and evidence can take two possible dynamics [85]. They can form a vicious circle, by which scientific ontologies and evidence reinforce each other, resulting in no progressive change. Alternatively, bootstrapping may occur, by which the concept-ladenness of observation enables scientists to create new, more productive systems of knowledge. A recent study on perceptual learning demonstrates these two possibilities: When learning to discriminate or estimate the motion direction of stimuli without feedback, adults improve at the categorical discrimination (clockwise vs. counter-clockwise) at the expense of having an exacerbated (categorically induced) bias in estimating the actual direction of motion [61]. Figure 3 (Key figure) demonstrates two putative ways of viewing empirical and theoretical developments in chemistry as a vicious or benign interaction of concepts and evidence. From one perspective, the periodic table can be viewed as an ontology that hindered scientists' recognition of practically and theoretically important empirical phenomena such as isotopes (within-element heterogeneity in physical and chemical properties) and noble gases (a class of elements not originally included in the table), and directed scientists toward potentially fruitless paths, such as synthesizing practically useless superheavy elements to fill in empty cells in the table. Alternatively, one can view theoretical development in chemistry as a progressive bootstrapping by which concepts and empirical evidence inform each other – the periodic table directed scientists toward experimental designs that enabled them to discover

Key Figure

Illustration of vicious and benign interactions between concepts and evidence

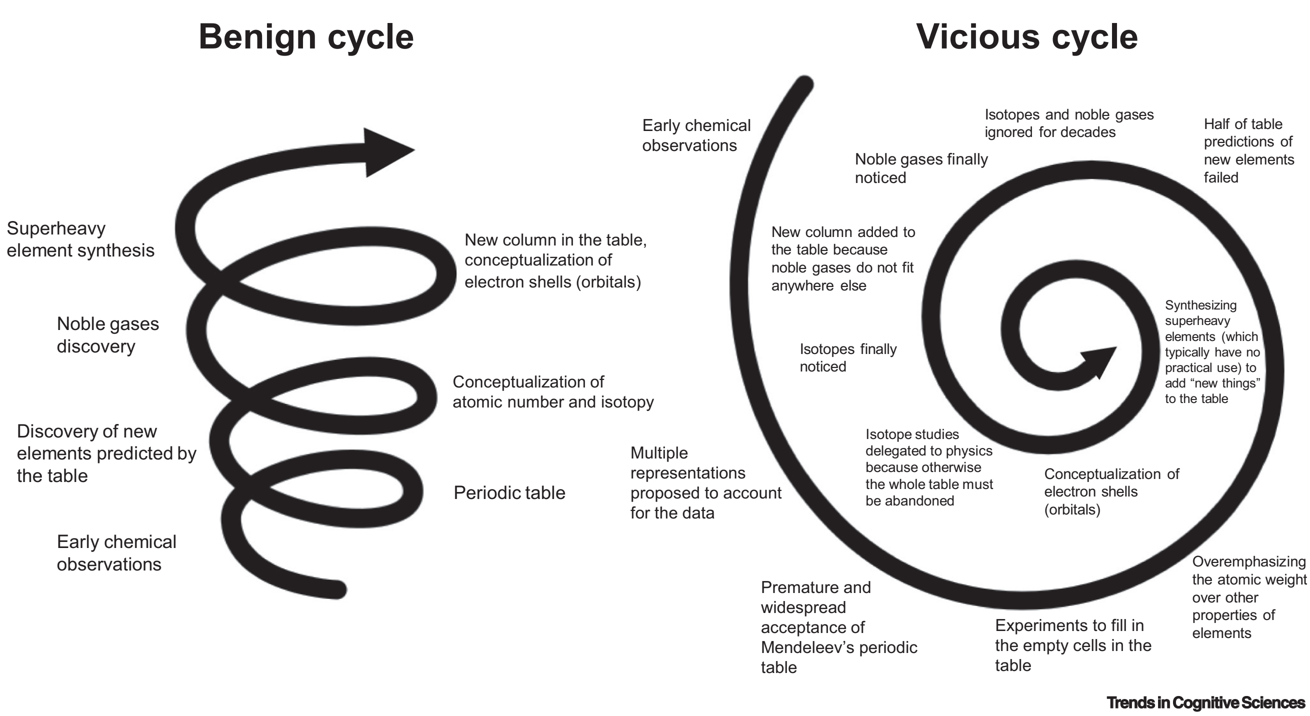

Figure 3. Benign cycle represents a case when conceptual and empirical developments affect each other in a way that facilitates scientific progress. Vicious cycle corresponds to cases when concepts and evidence reinforce each other, resisting progressive change. Note that for historical scientific cases, we typically cannot know whether the concepts and evidence interact in productive (benign) or unproductive (vicious) ways, except in hindsight; therefore, it is crucial to consider both possibilities.

isotopes and noble gases, which then served as reasons to revise the chemical theories and the table itself. The perspective outlined in this section aims to help scientists consider both harmful and benign interactions of concepts and evidence in their disciplines.

Why ontologies rarely change: vicious circles

Even the most ambitious conceptual reengineering agendas ignore the dependence of evidence on the ontological context. 'Episodic memory' and 'attention' have been studied by different groups of scholars who rarely talk to each other; use different, often incompatible, methods; and focus on different properties in the data (e.g., retrieval contents vs. accuracy). 'ADHD' and 'schizophrenia' are studied by different scholars who often look at data from different brain areas and use different behavioral tests, whose patients receive different treatments and might conform to their diagnoses (see a similar discussion in [86]). The periodic table, which emphasizes the atomic number and the properties that co-occur with it, may have led to more data recorded, communicated, and noticed about these properties and their predicted co-occurrences and less data on the less 'essential' properties as deemed by Mendeleev's table. Thus, scientists may inadvertently enact the structures that the ontologies postulate as existing in the world (this possibility has been discussed in the philosophy and sociology of knowledge: e.g., [87]).

Taking evidence at its face value when reengineering scientific concepts risks reinforcing a vicious cycle of self-fulfilling prophecies. Scientists reengineer an ontology based on evidence that has been crucially shaped by their preexisting concepts, find that these concepts fit the structure observed in the data, and become increasingly convinced in the aptness of the original ontology, letting it affect subsequent evidence collection even more.

When ontologies change: bootstrapping

A progressive change in scientific ontologies is possible. Philosophers have argued that scientific concepts can come closer to capturing inductively powerful aspects of the world despite the theory-ladenness of scientific observation and the **underdetermination** of concepts by the evidence [4]. For instance, Kuhn used the paradigmatic shift from the Ptolemaic to Copernican view in astronomy as an example of such progress. He suggests that this paradigm shift was enabled by the gradual accumulation of evidence that did not fit into the Ptolemaic paradigm, as well as the development of more advanced mathematical tools and telescopes that enabled more precise predictions to be made and tested based on the two theories [36]. Recent discussions in the philosophy of science have more thoroughly investigated the conditions for such progress, arguing for the importance of taking multiple paths in making sense of the world **(conceptual pluralism)** and therefore receiving diverse feedback from it [8,33,88], endorsing multiple perspectives and looking for points of converging evidence across them [6], and using strict scientific consensus criteria for identifying robust knowledge obtained by a diverse scientific community [89].

The permeation of scientific observation by concepts is not necessarily harmful. Mutual influences of concepts and evidence lay at the core of constructing sophisticated conceptual systems and successful scientific programs in the first place. For instance, measurement design and concept formation mutually guided each other in the history of thermometry [3]. The early attempts to design a scale that could measure 'true temperature' always ended with a realization that there is no standard temperature measurement that the measurement-to-be-designed could be validated against. However, bottom-up explorations of different temperature scales and their desirable properties (e.g., stable calibration points) coupled with the parallel theoretic development of thermodynamics eventually resolved part of this issue by the two pursuits mutually informing each other. Here, neither the concepts nor the evidence independently stand on their own. Working in concert, both of them are responsible for the temperature scale we currently use.

Concepts enable scientific progress by opening up new modes for learning and discovery (e.g., analogy and mental simulation [90,91]). Moreover, conceptual influences on perception often do not prevent, but rather facilitate, genuine conceptual change. A prominent series of studies on conceptual change in children's understanding of physics [92] and case studies of scientists undergoing conceptual change [4,36,90] show how empirical evidence can motivate and guide a new, more apt conceptualization, even though it is filtered through a less apt conceptualization. Here, symbols (concepts) enable analogical mapping and mental simulation as cognitive mechanisms for comparing conceptual systems to the evidence and to each other, noting discrepancies, which can eventually lead to a transformative transition between conceptual systems.

Human cognition can provide insights into how an adaptive system of perceptually grounded concepts and conceptually laden perception can learn and successfully function. Conceptual influences on perception, when gradually acquired as an individual learns about the environment, allow humans to excel across domains from simple tasks to intellectual, creative problems [91,93–96]. In contrast, scientific practice has only existed for an exceedingly brief period of time, evolutionarily speaking. For this reason, it might not have benefited from the independent selection of the mechanisms that actually work well. Conceptual influences on evidence in science are often neither carefully timed, nor weighted according to how well studied the concepts are, nor governed by the particular mechanisms that have proved over eons to be successful and robust. Accordingly, we have less reason to expect that the mutually constraining processes that connect scientific concepts and evidence will give rise to successful ontologies. This shows a promising direction for future work – bringing mechanistic insights from human perception and learned expertise to explore ways to make concept-laden influences on scientific evidence benign rather than vicious.

Concluding remarks

Conceptual reengineering in science operates on evidence already affected by the concepts to be revised. The challenge of concept-laden scientific evidence calls for new approaches to conceptual engineering that do not just take evidence at its face value when developing new ontologies for sciences. Cognitive research on perceptual and category learning could provide some initial insights for developing these new approaches. For instance, one validated approach to teaching Japanese speakers the tricky phonetic distinction between /r/ and /l/, which cuts across phonetic categories that they have previously learned, is by constructing stimuli that highlight the subtle distinction by eliminating most other sources of variation [97]. Perhaps laboratory-contrived contexts and strategic, simplifying idealizations can also be fruitful in helping scientists explore new concept-measurement pairs for their fields. Moreover, humans often acquire concepts particularly effectively from caricatures – representations that systematically exaggerate a concept in a direction opposite to other similar concepts, and think of concepts in terms of caricatures when they are learning interrelated conceptual systems [98,99]. Given that many scientific concepts occur within rich systems of interrelated concepts (e.g., periodic system of elements), scientists might consider refining their conceptualizations by looking at extreme, not just typical, cases.

Although more research is needed to explore and validate the methods that promote scientists' progression through a benign, rather than vicious, interplay between concepts and evidence (see Outstanding questions), here we offer some preliminary suggestions aimed at scientists, editors, reviewers, ontologists, and funders: (i) recognizing the contingent nature of scientific concepts (scientists) – being open to evidence that requires major reconceptualization, and being more exploratory when choosing dimensions to measure; (ii) recognizing the contingent nature of scientific concepts (editors, reviewers, funders) – not dismissing evidence that does not neatly fit into

Outstanding questions

What mechanisms can capture conceptual influences on scientific evidence?

What factors determine the vicious versus benign nature of the concept-evidence interaction? Empirical and historical research can help develop methods for detecting benign or vicious concept-evidence dynamics in scientific fields.

How should scientists balance the trade-off between conceptual pluralism (openness to different ontologies for the same set of phenomena) and standardization of concepts for scientific communication?

Which types of representations are best suited for capturing phenomena in different scientific fields (e.g., categorical vs. dimensional, hierarchical vs. lattice, structure- vs. process-based)?

Which kinds of tools (e.g., software) could help scientists explore alternative conceptual systems for their disciplines?

contemporary conceptual schemes, and encouraging diversity in conceptualizations [100]; (iii) encouraging integrative data collection efforts intended to broaden the scope of data available to scientists [101–103] (scientists, funders); (iv) encouraging continuous reassessment of ontologies [104,105] and exploration of alternative representation formats (e.g., process-based, rather than static entities-based, ontologies [106]) (scientists, funders); (v) keeping the potentially **circular concept-evidence** loop in check through other functions of science (scientists, funders) – evaluating the quality of concepts and evidence by external measures of progress such as the success of medical treatment, effective algorithms for applied problems, and connection to results in other fields; (vi) correcting for concept-dependent aspects of evidence when reengineering (ontologists) – adding uncertainty around concept-laden features and similarities when looking for new ways to partition evidence; and (vii) explicitly trying to reengineer concepts (scientists, funders) – pursue projects that are explicitly aimed at critically examining and potentially replacing current ontologies. These efforts will involve evidence obtained from studies outside of a field's current conceptualization, systematic inquiry into accidental and 'stumbled upon' results, and exploration of conceptualizations from other fields.

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Declaration of interests

The authors have no interests to declare.

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