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Patchworks and operations

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Abstract
Recent work in the philosophy of scientific concepts has seen the simultaneous revival of operationalism and development of patchwork approaches to scientific concepts. We argue that these two approaches are natural allies. Both recognize an important role for measurement techniques in giving meaning to scientific terms. The association of multiple techniques with a single term, however, raises the threat of proliferating concepts (Hempel, 1966). While contemporary operationalists have developed some resources to address this challenge, these resources are inadequate to account for the full range of complex behaviors of scientific concepts. We adopt show how the patchwork approach's repertoire of inter-patch relations can expand the resources available to the operationalist. We focus on one especially important type of inter-patch relation: sharing a general reasoning strategy. General reasoning strategies serve two important functions: (1) they bind together distinct patches of scientific concepts, and (2) they provide normative guidance for extending concepts to new domains.

Keywords Scientific concepts · Conceptual patchworks · Operationalism · Homology · Cortical column

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1 Introduction

Recent work has seen both the resuscitation of operationalism (Chang, 2017; Feest, 2005, 2010; Vessonen, 2021) and the development of the notion of conceptual patchworks (Bursten, 2018; De Benedetto, 2021; Haueis, 2018, 2021a, b; Haueis & Novick, forthcoming; Novick, 2018; Novick & Doolittle, 2021; Wilson, 2006, 2018). This paper puts these trends in conversation. We argue that the two approaches are natural allies, and that the patchwork approach can help address the problem of concept proliferation.

Operationalism ties the meaning of scientific terms to measurement operations. On the extreme view that operations are wholly constitutive of meaning, the result is widespread proliferation of concepts, since every operation corresponds to a distinct concept (Hempel, 1966, 94). More tempered operationalist views make operations only partially constitutive of meaning. This mitigates the threat of proliferation, but requires some account of how distinct operations can be integrated under a single concept.

While contemporary operationalists have developed responses to this problem (Chang, 2004; Feest, 2020; Vessonen, 2021), patchwork approaches to scientific concepts provide additional resources to show how multiple operations can be integrated. Patchwork concepts consist of (a) specialized uses of concepts (patches) and (b) relations between these uses. Patchwork theorists, like operationalists, view operations as partially constitutive of the meaning of patches. To this, they add a rich account of inter-patch relations. We focus on one such relation: sharing a general reasoning strategy, arguing that distinct operations can be linked to the same concept if they realize the same reasoning strategy. This both allows for retroactively recognizing when distinct operations contribute to the meaning of a single term and provides strategic guidance to researchers looking to extend a concept to a domain where existing operations fail.

2 Operations and patchworks

2.1 Operationalism and the challenge of proliferating concepts

At the core of operationalism is the insight that measurement operations are (at least partially) constitutive of the meaning of scientific terms referring to measurable quantities. This was first articulated by Percy Bridgman, who struggled with the problem of generating and measuring ever more extreme pressures—pressures at which existing techniques for measuring pressure physical broke down. (Chang, 2017). This raised the issue of how one could know that the new techniques measured the same physical quantity (pressure) as the old. Thus, operationalism emerged from attempts to wrangle with a particularly difficult aspect of conceptual development: extending a concept to novel domains. By connecting meaning to measurement operations, operationalists caution scientists not to simply assume that their concept will have the same meaning when they are applied to novel domains (Chang, 2004, 144).

However, connecting meaning to measurement operations raises new issues concerning concept proliferation. If operations are *fully* constitutive of meaning, then each operation defines a new concept, which leaves scientists with an unmanageable mess of distinct concepts. Operationally defined concepts would thus hinder scientists from integrating empirical observations made when performing various operations into a systematic and coherent understanding of phenomena (Hempel, 1966, 94).

Contemporary operationalists address the problem of proliferating concepts in two steps. First, they emphasize that operationalism is not a general theory of meaning but rather an account of how some concepts get their meaning in some cases. For instance, Chang's work on measurement operations in physics shows how operationalism may apply especially well to concepts developed in the absence of well-articulated theorizing. Attempts to measure temperature, for instance, long-predated any well-supported theory of temperature (Chang, 2004). Other scientific concepts may well be introduced in the presence of theory (indeed, Bridgman's work on pressure occurred in the context of a well-developed theory). Likewise, Feest's work on operationalism in psychology (2005) highlights that operational definitions provide researchers with revisable characterizations of phenomena in experimental settings. In other contexts (e.g., modeling), psychological concepts may not be tied to such specific experimental operations. Similarly, Vessonen (2021, 10,618) investigates when concepts in psychology "can and sometimes should be defined in terms of a test operation" without presupposing that all concepts acquire their meaning via operations. By emphasizing locality, contemporary operationalists avoid treating operationalism as a general theory of meaning.

Second, operationalists emphasize the methodological role of operations in scientific practice. Feest (2005, 2020) argues that psychologists use validation methods designed to determine whether two tests measure the same object or two different objects. The idea behind such methods is that operations which produce convergent results measure the same object, whereas those which produce divergent results measure different objects. Multiple operations can be associated with the same concept if these operations provide convergent results about the object of research in question.

Vessonen (2021) goes further, showing how validation helps close the gap between operational and extra-operational elements of a concept's meaning. For example: psychologists operationalize "intelligence" by letting subjects solve various problems, and they validate this measure by correlating test results with school grades. This procedure integrates the operational definition of intelligence as a problem-solving ability with academic achievement, which is an extra-operational element of the meaning of "intelligence". By keeping only those operations which produce consistent results, researchers are able to avoid an unmanageable proliferation of different operational concepts.

Finally, Chang (2004, 2017) discusses operationalism in the context refining measurement standards and proposes two criteria of meaning continuity across multiple operations. First, two measurement operations intended for the same concept must provide convergent numerical results in the overlap region of the operations.

Second, common causal assumptions for the behavior of the phenomenon must also hold in the new domain. For example: for temperatures measurable by both mercury and clay thermometers, ordinary processes of heating and cooling increase and decrease, respectively, the temperature measurements. This suggests that the meaning of "temperature" in the domain of extreme heat conforms with the pre-existing meaning of the concept in its original domain. This second criterion ensures that there is at least some degree of *inferential* continuity between new and old uses of a term—an important point of contact between Chang's view and the account we shall give of general reasoning strategies.

Contemporary operationalists emphasize that operations only partially constitute the meaning of some scientific concepts. Despite their differences, all three authors argue that comparing, validating and converging operations help to solve the problem of proliferating concepts. They recognize that the unity of a concept with multiple operations cannot be presupposed: it must be established via empirical research and theorizing. However, these responses do not directly explain how integrating multiple operations does lead to a coherent conceptual understanding of the phenomenon researchers investigate. To provide the resources for such an explanation, we now turn to patchwork approaches to scientific concepts.

2.2 Patchworks

Patchwork analyses of particular concepts recognize that some concepts have a complex internal structure consisting of (a) distinct local patches of use and (b) relations between these patches. Here, we outline the patchwork approach as given in Haueis (2021b), which presents a general picture abstracted from the analyses of particular patchwork concepts offered by Wilson and others (see De Benedetto, 2021 for an alternative systematization). Haueis' framework brings patchwork approaches and operationalism into contact by recognizing that conceptual extension via new operations occurs and is fruitful, while also providing an in-principle account of when such extensions are legitimate.

A *patch* is a particular way of using a term. Patches can be characterized by four elements: scale, technique, property, and domain. Scientific concepts characterize entities and processes instantiated at particular temporal, spatial, and/or energetic length *scales* (Bursten, 2018; Wilson, 2018, Chap. 5). Scientists gain epistemic access to these entities and processes using particular *techniques*, including both physical (e.g., using an instrument) and mental (e.g., calculations) operations. This is the operationalist element of patches. Techniques provide information about some *property* of scientific interest (e.g., a physical quantity). Finally, each patch has a proper *domain* of application: the class of entities for which the associated property assigns members of that class to the extension of the concept.

Consider 'hardness' (Wilson, 2006, Chap. 6; Fig. 1). Patches of 'hardness' mainly differ in their associated techniques, properties, and domains. One patch (Fig. 1, patch 1) involves the Rockwell and Brinell indenter tests (technique), which measure the resistance to macro indentation, a property quantified by *yield strength*. Another patch (Fig. 1, patch 2) involves the use of a durometer (technique), which

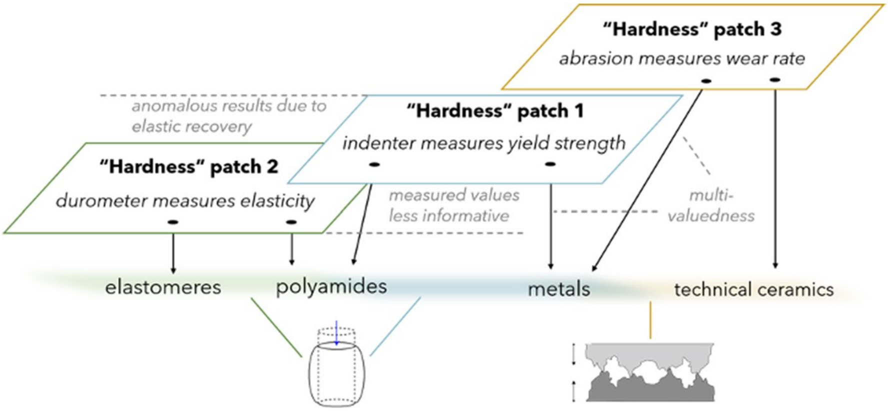

Fig. 1 Simplified representation of the patchwork structure of ”hardness” in materials science (Haueis, 2021b, Fig. 1)

measures resistance to squeezing, a property quantified by *Young’s modulus of elasticity*. The microphysics underlying resistance to macroindentation is not identical to that underlying resistance to squeezing: the first involves plastic, the second elastic deformation (lines below patches 1 and 2). As our everyday notion of ‘hardness’, which spans materials of all kinds, was pressed into greater precision, it “locally settle[d]” on different “fundamental evaluative trait[s]” in different domains, generating a patchwork structure (Wilson, 2006, 336).

What binds the patches together is not the use of the same term, but rather the relations between the patches. Many types of relation can serve this binding function. One type is discussed by operationalist responses to concept proliferation that focus on comparing convergent operations. In our framework, this relation has two aspects: (a) domain *overlap* and (b) technique *coordination*.

In the ‘hardness’ case, both durometers and Rockwell/Brinell tests can measure the hardness of nylon (domain overlap), and they can be calibrated so as to give consistent values (technique coordination), meeting Chang’s first criterion of meaning continuity (Section 2.1). The second criterion is also met. Increased force of indenting and squeezing both lead to a greater deformation of three-dimensional shape (green and blue lines below Fig. 1). Thus, there is a smooth continuation from one patch to the other, enabling meaningful comparison between them. So far, the patchwork and operationalist approaches are in lockstep.

Things get more complicated when we consider other patches. Take the patch defined by the dry sand wear test, which measures resistance to abrasion, quantified as wear rate (Fig. 1, patch 3). This patch’s domain overlaps with the Rockwell/Brinell patch. However, the techniques cannot be coordinated for all values: while they yield the same value for the carbide chrome knife, they yield different values for the knife of tool steel. This is possible because abrasion and indenter tests measure different quantities: different ways materials can resist mechanical intervention. In this case, operationalist strategies of integrating patches via convergent operations are not applicable.

Must we conclude that we have proliferating ‘hardness’ concepts that do not provide a coherent conceptual understanding of hardness phenomena? For a patchwork theorist, this conclusion is premature: there are conditions under which such multi-valuedness is tolerable (Wilson, 2006, 343). The combination of domain overlap with technique coordination is only one way to bind patches together. In what follows, we focus on a way of binding together patches not recognized by contemporary operationalists: shared general reasoning strategies.

3 Conceptual unity via reasoning strategies

A general reasoning strategy is a set of stepwise instructions that can be realized by different techniques in different domains (Haueis, 2021b). General reasoning strategies are thus highly abstract. They play two important roles in the development of patchwork concepts: (1) they *retrospectively* account for the pragmatic unity of concepts, and (2) they provide *prospective* guidance for extending concepts to new domains. In this section, we present and defend four claims about how general reasoning strategies can bind patchwork concepts together; the next two sections show how these claims can illuminate real cases of conceptual extension.

(GR1) A general reasoning strategy is a set of stepwise instructions that can be realized by different techniques A general reasoning strategy provides criteria for legitimately applying a concept: its instructions must be realized within the relevant domain. For instance, in everyday language, ‘hardness’ is associated with subjective sensations of resistance; the more a material produces such sensations, the harder it is (Wilson, 2006, 335). A general reasoning strategy for everyday uses of ‘hardness’ might thus tell us, when confronted with some new material, to attempt to determine to what extent it produces sensations of resistance.

In scientific contexts, where we wish to avoid such subjectivity, we instead search for objective measures of resistance. Thus, the reasoning strategy tells us (1) to look for some measurable form of resistance to mechanical intervention and (2) to find a way to assign values to this resistance. Here the question arises: resistance to what? This is left unspecified: it varies based on the properties of particular materials. For some materials, what works best is resistance to scratching, for others, resistance to squeezing, and so on.

In describing general reasoning strategies as “stepwise”, we mean that they involve distinct, specifiable steps, but not that these steps must occur in a fixed order. In the case of ‘hardness’ above, identifying a relevant form of resistance to mechanical intervention (1) is necessarily prior to assigning values to it (2). By contrast, in the case of ‘cortical column’ (Section 5.1), the identification of columnar structure (1) and the determination of the functional properties of neurons within that structure (2) can occur in either order. In both cases, however, all steps must be met before the concept can be used in drawing inferences in the new domain.

(GR2) A general reasoning strategy forms a bridge between a concept and a scientific community's epistemic and pragmatic goals Contemporary operationalists treat scientific concepts as tools to achieve certain goals (Chang, 2004, 45; Brigandt, 2010, Feest & Steinle, 2012). A general reasoning strategy helps connect a concept to these ends. For instance, 'homology' plays a central role in the epistemic task of phylogenetic reconstruction (Section 4). Similarly, 'cortical column' served a central role in the neuroscientific quest of finding a basic building block in the neocortex (Section 5). As will be shown in more detail below, the reasoning strategies associated with 'homology' and 'cortical column' ensure that researchers apply these concepts in ways suited to serving these goals.

Concepts also serve pragmatic aims. Measuring the hardness of some material is often essential in manufacturing contexts. Manufacturers of steel, for instance, must be able to quickly determine whether a sample is sufficiently hard, for which a Brinell-type test is used. This test is "both convenient and non-destructive" (Wilson, 2006, 339). By contrast, while applicable to plastics as well, Brinell-type tests are rarely used. This is partly due to differences in their method of manufacture, which make other means of determining resistance to surface damage more useful. Though the epistemic goal (measuring resistance to mechanical intervention) remains the same, the precise manner in which it is realized is subject to different pragmatic constraints in different contexts (see Section 5.1, as well as Brigandt, 2010, 34).

At the same time, most scientific concepts are associated with multiple epistemic goals. For example, 'homology' plays a central role in reconstructing evolutionary history, but it also is used to understand how body parts are individuated (Sections 4.1–4.2). Likewise, some patches of 'cortical column' serve epistemic ends besides searching for building blocks (Section 5.3). In general, whenever a scientific term is shared across multiple subdisciplines, it is liable to come to serve multiple distinct aims. In such cases, attending to reasoning strategies can clarify the relation between these aims. Often, a single reasoning strategy allows scientists to gain epistemic purchase on a quantity that can serve multiple epistemic aims (true for both 'homology' and 'cortical column'). It can also happen that a concept is associated with multiple reasoning strategies that interact in complex ways—'homology' will furnish an example of this (Section 4.2). In either case, however, the reasoning strategies associated with a concept provide general constraints on the techniques that can be associated with them, even as they locally adapt to serve distinct aims.

Aims can also vary diachronically. For example, early uses of 'homology' and allied concepts served morphological ends (as in the work of Goethe and Owen) as well as taxonomic ends (as in Macleay's distinction between 'affinity' and 'analogy'; Novick, 2016). Darwin's evolutionary theory reinterpreted these taxonomic aims in terms of reconstructing evolutionary history, and this aim is central to contemporary uses of 'homology'. Diachronic variation can also lead to researchers giving up the pursuit of an epistemic goal altogether (Section 5.3).

For these reasons, the formation of patchwork structures is historical contingent: no concept is fated to do so. That a general reasoning strategy can be applied to a novel domain does not mean that it will be (Haueis & Novick, forthcoming). It may not serve any epistemic aim recognized by the relevant scientific community. Even if it does serve such an aim, it may not be recognized as doing so, perhaps because the aspects of a phenomenon most obvious at the time of discovery suggest that a different concept is more relevant (Wilson, 1982). And even if an extension is possible and its salience recognized, scientists may nonetheless prefer to use a novel term in the new domain to minimize the risk of confusion (Taylor & Vickers, 2017).

(GR3): A general reasoning strategy can explain why a concept that has been extended to a novel domain settles on a particular property in that domain Patchwork approaches to concepts share externalist sympathies with causal theories of reference: the world plays a role in fixing the reference of our terms, even when we cannot accurately describe the referent (Stanford & Kitcher, 2000; Nimtz, 2021). When a term is extended to a new domain, however, its reference may not be fixed at baptism: there may be multiple properties (or none) in the area to which it might attach. For example: having a workable notion of 'hardness' for metals does not suffice to fix the term's behavior when applied to plastics—that must be worked out over time.

The reasoning strategy driving a conceptual extension can help the term settle on an appropriate property in the new domain. When applying 'hardness' to plastics, the reasoning strategy tells researchers to look for a measurable form of resistance to mechanical intervention. This is then further subject to pragmatic constraints based on the needs of plastics manufacturers. As an appropriate test is developed, 'hardness' settles on the underlying property measured by the test—in this case, Young's modulus of elasticity.

The reasoning strategy thus guides and constrains the process of reference-fixation: the term settles on a property that allows for the realization of the reasoning strategy. Reasoning strategies therefore go beyond operationalist approaches which only specify meaning continuity when different operations have the same referent (e.g., different thermometers measuring temperature, cf. Chang, 2004). By contrast, patchwork concepts can partially refer to more than one thing because different operations settle on different properties to realize the reasoning strategy in a novel domain (Haueis, 2021b).

(GR4) The association of a general reasoning strategy with a term makes certain extensions possible, but it does not by itself accomplish them This is due to the process of reference-fixation just described. A general reasoning strategy provides guidance for conceptual extensions, but successful extension requires developing means of applying a term in informative ways. It may be an objective feature of the world that a given reasoning strategy *can* be realized by using a technique in a particular domain, but the realization must accomplished for the term to apply.

For example, 'homology' can, in principle, be applied to any kind of character for which ancestor-descendent relations can be identified (genes, body parts, etc.). However, getting such applications to fruitfully serve biologists' epistemic aims is a non-trivial task, as the history of blood serum diagnostics shows (Section 4.1). Furthermore, what *counts* as a successful realization of a reasoning strategy is not a given but is itself as a potential locus of scientific controversy. Such controversies played important roles in the extension of 'homology' to molecules (Section 4.3) and of 'cortical column' to structures in the primary somatosensory cortex (Section 5.2).

Three points are important here. First, because of the contingency of such extensions, the fact that a term is *applicable* to a new domain does not suffice to fix how it should be applied. Second, even if a reasoning strategy can be realized in a new domain, that doesn't mean that extending the concept will serve the relevant epistemic aim sufficiently well for the extension to be worth pursuing. Third, because there is room for controversy about what counts as realizing a reasoning strategy "sufficiently well", the prospective guidance that reasoning strategies offer is itself a locus for debate among scientists.

Coda Together, (GR1-4) show how general reasoning strategies allow the integration of multiple patches, even when the resulting conceptual structure is rather baroque. As concepts are extended to new domains, different techniques are required to make the new applications precise and meaningful. This can involve significant property dragging, in which attempts to realize a reasoning strategy in a new domain lead a term to pick out a different property than in the original domain—the referent of the term is "dragged" (by the imperative to realize the reasoning strategy) from one property to another (Wilson, 2006, 159). Moreover, while in some cases measured values can be coordinated where techniques overlap, multi-valuedness is occasionally an inescapable consequence of this complexity. In such cases, operationalist criteria of meaning continuity fail.

This may seem to justify the operationalist's worst fears. When a concept is associated with multiple measurement techniques, how do we ensure that each technique measures the same thing? Frequently, not only can we not ensure this, we *know* that the various techniques do not all measure the same thing. Worse still, it is not clear that they *could* do so: there is no reasonable prospect of associating 'hardness' with a single physical property in all domains. At this point, the threat of conceptual confusion rears its head: what seems like a perfectly unproblematic extension of a concept may lead to a situation where multiple concepts are being conflated (Taylor & Vickers, 2017).

Allowing for a shared reasoning strategy to bind distinct patches mitigates this threat: it captures a core motivation driving particular extensions. Shared reasoning strategies provide normative guidance for conceptual extensions and explain why property dragging frequently attends such extensions. As concepts are extended to new domains, they naturally settle into local patches of use; this settling occurs under the auspices of a reasoning strategy. Thus, shared reasoning strategies can do a great deal of work in binding together complex concepts, even in the presence of property dragging and multi-valuedness. Moreover, they can do this while still respecting the operationalist insight that measurement techniques are partially constitutive of the meanings of scientific concepts.

4 Case study #1: 'homology'

This section shows how the foregoing account of reasoning strategies illuminates the structure and history of 'homology'. The first two subsections consider synchronic structure; the third illustrates the normative role of reasoning strategies in guiding potential extensions of the concept. The analysis provided here follows Novick (2018) and (Haueis & Novick, forthcoming).

4.1 The fine structure of 'homology'

Homology is a correspondence relationship between the parts of organisms (Ghiselin, 2005). A dugong's fin, a mole's digging forelimb, and a bat's wing, despite differing in form and function, are corresponding parts (Owen, [1849] 2007). Though originally a pre-Darwinian morphological notion, homology is now understood as sameness due to shared ancestry. It plays a central role in phylogenetic reconstruction: biologists determine ancestry by analyzing the states of homologous characters. This occurs within the research tradition of phylogenetic systematics, stemming from the work of Willi Hennig ([1966] 2000). Despite significant methodological advances since 1966, Hennig's basic conceptual framework remains largely intact. More generally, homology judgments underwrite all comparative biology (Hall, 1994; Currie, 2021).

In order to serve the epistemic aim of phylogenetic reconstruction, two criteria must be met. First, it must be possible to distinguish between characters and character states. A character is a feature of an organism that can be described using at least one parameter capable of taking multiple values; in this respect, characters are abstractions. A character state is the value that one particular such parameter takes in a given kind of organism. For instance, the vertebrate forelimb is a character (shared by moles and bats), while having webbing between the fingers is a character state (possessed by bats only). This criterion is essential to determining the likeliest sequence of character state transitions over evolutionary time.

Second, offspring must inherit these characters from their parents. For the vertebrate forelimb to be shared by bats, moles, and dugongs, they must have inherited that forelimb from a common ancestor. That requires that individual bats (etc.) inherit their wings from its parents. If this criterion cannot be met, one is not dealing with a genuine character.

Thus we have the central genealogical reasoning strategy associated with 'homology': (1) search for parts of organisms that can stand in ancestor-descendant relations, or *characters*, and (2) find a way to assign values to the different states of these characters. For example, the vertebrate forelimb is a character, and instances of the character come in different states. The bat forelimb, for instance, has webbing between the digits; the human forelimb, by contrast, does not. While there are other reasoning strategies associated with 'homology', the genealogical reasoning strategy alone plays a central role in unifying the concept, including explaining *why* other reasoning strategies become attached to it (see below, Section 4.2).

This reasoning strategy is permissive: any feature that can meet these criteria is a potential homolog. While 'homology' began as a morphological notion (Goethe, [1790] 2009; Owen, [1849] 2007), it is now applied well beyond morphology (e.g., to genes and behaviors). In each domain, biologists homologize those features of organisms for which they can realize this reasoning strategy. This may require developing new techniques, which is thus is an essential part of the process of extending 'homology' to new domains (cf. Section 4.3). For example, homologizing genes relies on sequence alignment techniques. Body parts, by contrast, are generally homologized using Remane's rules, which identify similarities (position relative to other features, structure, and the existence of transitional forms) of especial relevance (Laubichler, 2000). The same reasoning strategy is realized differently in the two domains, which is why 'gene homology' and 'body part homology' are distinct patches of 'homology' (cf. Novick & Doolittle, 2021, sec. 3).

In this case, there is a necessary order to the steps: it must be established (at least provisionally) that characters can stand in ancestor-descendant relations (step 1) before it makes sense to compare different character states (step 2), since such comparison involves attributing those character states to distinct tokens of the same character type. For instance, the use of sequence alignment to identify putatively homologous genes is sensible only after it has been determined that sequence similarity is at least potentially the result of shared ancestry.

Once characters are identified, they can be used to reconstruct phylogeny. Knowledge of phylogeny can then ground research into the processes underlying particular instances of evolutionary change. Allowing researchers to make such inferences is the epistemic aim served by using 'homology' within a domain. Thus, to realize the genealogical reasoning strategy within a domain, it is not enough to carry out both steps—rather, they must be carried out *in a way that suitably serves that epistemic aim.*

Hennig's ([1966] 2000, 101–7) critique of blood serum diagnostics illustrates this point. In considering attempts to determine ancestry using chemical characters, Hennig ([1966] 2000, 102) explicitly required that the genealogical reasoning strategy be realized for them, insisting that such methods "can be used for disclosing phylogenetic relationships only if series of transformations… can be recognized among them." As with the extension of 'homology' to genes, realizing the genealogical reasoning strategy for chemical characters required the development of novel techniques. Hennig's critique of blood serum diagnostics focused on these techniques, which he thought had significant limitations: serum diagnostics suffered from low resolution (e.g., an inability to distinguish goats and sheep) and from inconsistency between the parts of organisms (e.g., rye pollen serum reacts with wheat seeds, but not with other organs). The root issue was not that the genealogical reasoning strategy could not be realized *at all* for chemical characters, but that it could not be realized *in a way that rendered serum diagnostics useful for drawing phylogenetic inferences* (**GR4**, Section 3).

4.2 Multiple reasoning strategies: 'special homology' and 'serial homology'

The genealogical reasoning strategy is powerful because it is abstract, allowing diverse organismal features can all be homologized. However, the requirement that characters be inherited complicates things: different kinds of characters are inherited in different ways. For instance, genes are inherited by direct replication, whereas morphological parts develop anew each generation.

Because of this, determining what counts as a morphological character is a difficult problem. One recent view ties character identity to the operation of gene regulatory networks known as "character identity networks", or ChINs (Wagner, 2014; cf. DiFrisco et al., 2020; DiFrisco et al., 2022). On this view, I inherited my vertebrae from my parents because I inherited the relevant ChIN from them. ChIN inheritance rests in turn on the inheritance of the underlying DNA sequences. This can be extended back to ancestors deeper in the phylogenetic tree, accounting for special homology.

The first step of the genealogical reasoning strategy thus becomes associated with a second, developmental reasoning strategy within the morphological domain: identify parts individuated by a ChIN (the second step remains the same). The details for how to do this do not concern us here, but, in brief, they involve attending to both the ways in which parts vary as well as (where possible) directly identifying the ChIN (see Wagner, 2014).

The genealogical and developmental reasoning strategies relate in complex ways. In the case of special homologs, the developmental reasoning strategy can be understood as a domain-specific way of realizing the genealogical reasoning strategy. When comparing morphological parts in different organisms, satisfying the demands of the developmental reasoning strategy *just is* satisfying the demands of the genealogical reasoning strategy. If Wagner's account is correct, sharing a ChIN is just what it *is* for (some) morphological parts in two distinct organisms to share ancestry.

However, realizing the developmental reasoning strategy does not guarantee realizing the genealogical reasoning strategy. Failure occurs in the case of serial homology, when the same part is repeated within a single organism (e.g., the repetition of vertebrae). For Wagner, this is due to the same ChIN being activated in multiple regions of the developing embryo. Serial homologs do not stand in ancestor-descendant relationships, so the genealogical reasoning strategy is not realizable for them, and they do not play a role in reconstructing ancestry (Novick, 2018).

Despite this, the developmental reasoning strategy—which, in the case of special homologs, explains why the genealogical reasoning strategy is realizable at all—is realizable both within individual organisms and between species. The same mechanism that allows offspring to inherit parts from their parents allows individuals to have multiple copies of a single part. As a result, 'homology' naturally covers both serial and special homology.

A shared reasoning strategy need not span all patches of a concept (Fig. 2). In this case, schematically, Patch 1 (orthology) and Patch 2 (special homology) are linked by Reasoning Strategy 1 (genealogical). In Patch 2, realizing Reasoning Strategy 1 involves realizing Reasoning Strategy 2 (developmental). Realizing Reasoning

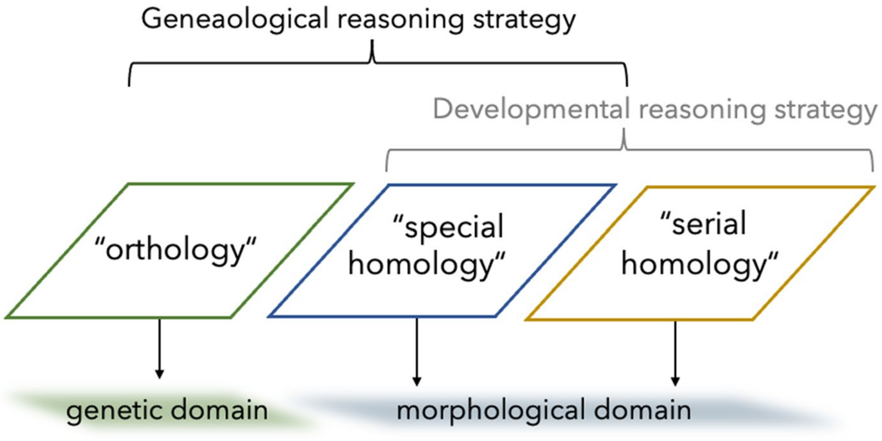

Fig. 2 Relations between the genealogical and developmental reasoning strategies associated with 'homology'

Strategy 2 can then be realized in Patch 3 (serial homology). Thus, Patches 1 and 2 are connected by a shared reasoning strategy, as are Patches 2 and 3, though no single reasoning strategy connects all three patches.

4.3 Dynamics of meeting a reasoning strategy: the case of 'sequence homology'

The case of 'sequence homology' illustrates the contextual nature of meeting a reasoning strategy (Haueis & Novick, forthcoming). Originating in the late 1960s (Neurath et al., 1967; Britten, 1967), 'sequence homology' referred to the degree of similarity between molecular sequences (nucleotide or amino acid). For two decades, it played an important role in phylogenetic research, including the pathbreaking work of Carl Woese establishing the archaebacteria (as they were then known) as a third domain of life (Woese & Fox, 1977), until a deliberate and largely successful effort was made to eliminate it (Reeck et al., 1987).

Interestingly, the *arguments* for and against the legitimacy of 'sequence homology' barely changed between 1967 and 1987. From the start, those who thought it illegitimate argued that, unlike standard morphological uses of 'homology', 'sequence homology' was a pure similarity metric, and so was "deviant" (Nolan & Margoliash, 1968; Fitch, 1970). For them, 'homology' was meant to refer to correspondences that allow for divergence (as between the bat wing and dugong fin); this is obviously flatly incompatible with being a pure similar metric. They worried that using the same term for such different relations would cause undue confusion.

The core explicit defense of the extension of 'homology' to molecular sequences turned on (a) the desire to use molecular data for phylogenetic ends and (b) the claim that sequence similarity made this possible. Defenders of the usage acknowledged its "deviance", but argued that this was necessary: available techniques did not allow for better (Winter et al., 1968). Without sequencing technology, little was available beyond measures of overall similarity (see Britten, 1967). Defenders thus argued that ‘sequence homology’ was the best that could be done to realize the genealogical reasoning strategy for molecules, despite its imperfections.

The new usage caught on, and was not displaced until 1987, when eleven eminent scientists published a critique in *Cell* (Reeck et al., 1987). Their criticisms were the same as in the late 60s (see Haueis & Novick, forthcoming, sec. 4 for documentation). What changed? The technology. With the rise of sequencing technology and PCR in the late 70s and early 80s, less deviant applications of ‘homology’ to molecules became available, not just conceptually but technically (Sapp, 2009, Chaps. 10, 17–18). This allowed biologists to more accurately reconstruct ancestry using molecular data.

Realizing a reasoning strategy thus depends, not only on intrinsic conceptual content, but also on the surrounding context. When technological limitations make estimates of overall similarity the best way to compare molecular sequences for the sake of determining ancestry, it may be reasonable to use ‘homology’ to refer to sequence similarity, despite the differences between this usage and the term’s morphological patch. Once techniques become available that allow for the identification of *dissimilar* corresponding sequences, however, the differences between the morphological and molecular patches become salient. Without becoming *intrinsically* any worse, ‘sequence homology’ ceased to adequately realize the genealogical reasoning strategy.

Thus, whether or not a particular technique allows one to realize a reasoning strategy within a domain is contextual: it depends on features of the broader epistemic situation, beyond the nature of the technique itself (GR2).

5 Case study #2: ‘cortical column’

This section generalizes our account by considering the development of the neuroscientific concept ‘cortical column’ (for historical details, see Haueis, 2016, 2021a). The case also highlights how the interplay of reasoning strategies and epistemic aims accounts for conceptual extension and failures of conceptual integration.

5.1 The patchwork and pragmatic unity of ‘cortical column’

In 1955, Vernon Mountcastle inserted glass microelectrodes vertically into primary somatosensory cortex (S1) of cats. Near the electrode, neurons responded to the same kind of tactile stimulus (Fig. 3, left). Mountcastle inferred that the responses arose from vertical columns of cells, which he speculated to be an “elementary unit of cortical organization” (Mountcastle, 1957, 130). These early experiments were exploratory and were not driven by a theory of cortical processing (Haueis, 2016).

Mountcastle’s experiments operationally defined “cortical column” by uniform neuronal responses to the same kind of sensory stimulus measured in a vertical electrode recording. To infer an anatomical structure from such a recording, researchers have to reconstruct the location of the electrode tracks in histological brain sections.

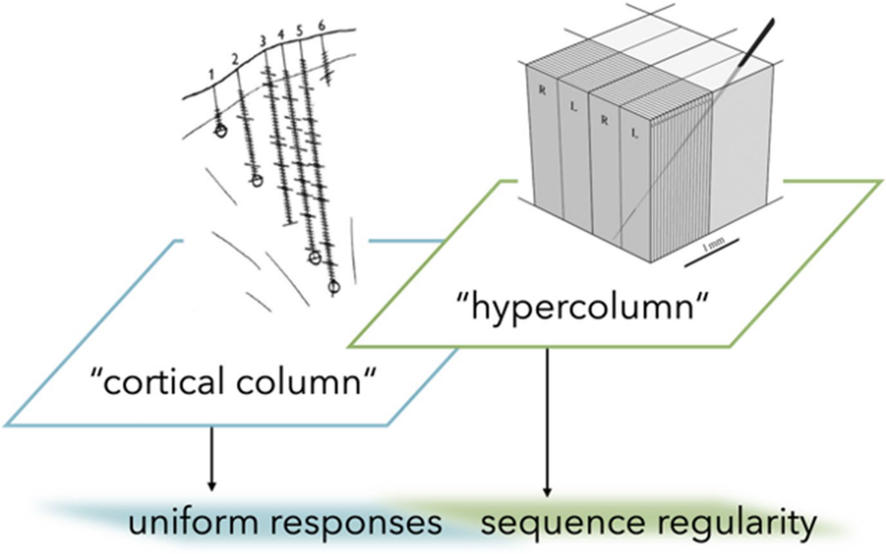

Fig. 3 Simplified patchwork structure of 'cortical column'

Thus, the general reasoning strategy associated with 'cortical column' instructs researchers to (1) search for a vertical structure in the cortex and (2) establish that neurons in this structure have relevantly similar functional properties.

Researchers can fulfil the steps of the columnar reasoning strategy in either order (see Mountcastle & Powell 1959 and Woosley & Van der Loos, 1970 for examples). Yet it is crucial that researchers fulfil both steps if they want to achieve the central epistemic goal of using "cortical column" to describe a unit of brain organization. If only (1) is realized, researchers do not know whether the detected structure is of functional significance. If only (2) is realized, they are uncertain if the pattern in the functional data corresponds to an anatomical entity. On its own, neither step is sufficient to describe a basic unit of brain organization (Horton & Adams, 2005).

The columnar reasoning strategy can be realized in multiple ways because it can be applied to vertical structures at various scales, as well as to other sensory modalities. These applications frequently involve the use of different techniques. The column case thus illustrates one way in which two techniques share the same reasoning strategy, namely when researchers use them to achieve the same epistemic goal (Section 2.1).

Consider Hubel and Wiesel (1977), who applied the columnar reasoning strategy to primary visual cortex (V1) and discovered that functional responses to visual stimuli are arranged into *orientation columns* and *ocular dominance columns*. Recording at tangential angles they also discovered that regular shifts in responses to oriented line segments. This property of s*equence regularity* measured by tangential recordings operationally defines the term "hypercolumn". In V1, this term characterizes a set of orientation columns covering all orientation angles and two ocular dominance columns (Fig. 2 right). Hubel and Wiesel's (1977, 17) use of tangential electrode recordings pursues the same epistemic goal as Mountcastle's use of vertical recordings, because they argued that hypercolumns constitute a 1-2 mm large "basic building block of visual perception".

As the columnar reasoning strategy was applied to various sensory areas and scales, 'cortical column' developed a complex patchwork structure (Fig. 3; see Haueis 2021a, Fig. 6 for further detail). The two patches displayed are distinguished by vertical and tangential electrode recordings, targeting functional properties of vertical structures at distinct scales. Their domains overlap in some areas (V1) and diverge in others (see below).

In the column case, operationalism captures well that the domains of the column and hypercolumn patches *overlap* and techniques can be *coordinated* in cortical areas where uniform functional responses and sequence regularity co-occur (e.g. in V1). Additionally, patchwork approaches reveal that tangential recordings also realize the columnar reasoning strategy, because they (a) record from adjacent vertical structures and (b) detect regular shifts in the uniform responses to sensory stimuli. This realization of the reasoning strategy allowed researchers to extend 'cortical column' to areas where sequence regularity occurs without discrete boundaries between individual columns (e.g., middle temporal area or inferotemporal cortex; Haueis 2021a, 4–6). Together with the reuse of techniques and overlap of domains, the general reasoning strategy accounts for the way in which 'cortical column' is integrated even though the concept is associated with multiple operations.

5.2 The interplay of reasoning strategies and epistemic goals: the case of cortical barrels

So far, the column case illustrates how reasoning strategies can be realized by multiple techniques (GR1) and how applying the strategy to a new domain centered 'cortical column' on a novel property (GR3). We now turn to (GR2) and (GR4) by looking a more contentious proposal of extending 'cortical column'.

In 1970, Woolsey and van der Loos (1970) reported barrel-shaped structures in the primary somatosensory cortex (S1) of the mouse. The shape, position and number of barrel subfields suggested that each barrel unit corresponds to one mystacial vibrissa hair on the muzzle of the mouse (Woolsey & Van der Loos, 1970, 229). The use of cell staining in this study realizes step (1) of the columnar reasoning strategy by identifying a vertical structure: the cortical barrel. Regarding step (2), previous electrophysiological studies showed that S1 responses to stimuli of the same mystacial vibrissa hair correspond in size to cortical barrels (Woolsey & Van der Loos, 1970, 235). The authors thus inferred that cortical barrels are the morphological manifestation of "*functional columns defined by electrophysiological means*" (Woolsey & Van der Loos, 1970, 236).

While the columnar reasoning strategy certainly guided the researchers, it could not itself justify this extension of 'cortical column'—the realization had to be shown to serve a relevant epistemic goal. The response to mystacial hair is an instance of *sensory topography*, i.e. the mapping of the sensory surface onto the cortical surface. Mountcastle (1978, 19–20) accepted this as a functional property of columns. By contrast, Hubel and Wiesel (1974, 289) argued that "topography itself forms the system upon which columns are engrafted". In their view, columns map additional stimulus features in the vertical dimension. Many neuroscientists accepted Mountcastle's interpretation because it linked the columnar reasoning strategy to the epistemic goal of identifying a basic building block in the neocortex (Mountcastle, 1978). The discovery of cortical barrels supported researchers' beliefs that this building block has discrete anatomical boundaries and is invariantly present across mammalian species (Haueis, 2021a). The decision to extend 'cortical column' to barrels in rodents was justified because it contributed to the epistemic goal of finding a species-invariant building block. The barrel example thus illustrates how a general reasoning strategy links a concept to the epistemic goal of the scientific community, and how an interpretation of the reasoning strategy in light of that goal justifies its application to a novel case.

5.3 Reasoning strategies and failed conceptual development

As mentioned above (Section 2.1), operationalists claim that by introducing measurement procedures and extending them to novel circumstances, researchers bring the phenomena that the operationally defined concept refers to into clearer focus (Chang, 2004, Chap. 4; Feest, 2011, 403; 2017, 1170). Yet operationalists also insist that this process can fail: there may not one object or even a coherent set of phenomena that binds the different uses of the concept together. Operationalism thus cautions against simply assuming conceptual unity whenever we find that extending an operation is possible, or two operations converge in an overlapping domain (Chang, 2017).

Amending operationalism with the generalized patchwork approach refines this insight by emphasizing that conceptual integration depends on epistemic goals. Depending on the particular goal, researchers may try to apply a general reasoning strategy and the techniques realizing it more narrowly or more broadly to the overall domain of inquiry. If the reasoning strategy and its realizing techniques are less widely applicable than required, then the concept—at least in its current form—may fail to contribute to the pursuit of that goal.

For example, using 'cortical column' to identify a basic building block requires that the columnar reasoning strategy is applicable to all cortical areas in all mammalian species. Neuroscientists soon realized the limits of that strategy. Although neocortical neurons are organized in vertical rows, no discernable boundaries separate these rows into columnar or hypercolumnar structures (Horton & Adams, 2005). Moreover, in many areas vertical electrode recordings do not reveal uniform functional responses because those areas are not organized in a columnar fashion. These discoveries suggest that 'cortical column' does not refer to a basic building block, but to different *kinds* of scale-dependent and domain-specific columnar structures (Haueis, 2021a).

This suggested that different realizations of the columnar reasoning strategy do not reveal a single kind of object (the building block) which could unify the different patches of 'cortical column'. This failure also altered the significance of extending the concept to barrels. Cross-species comparisons revealed that cortical structures map sensory topography in an isomorphic fashion, leading researchers to favor Hubel and Wiesel's (1974) position, which excludes sensory topography as a relevant "functional property" of vertical structures (Horton & Adams, 2005, 852). Cortical barrels thus aligned more closely with features of the contrast class "cortical isomorph", refining researcher's understanding of the conceptual structure of 'cortical column' (cf. Bloch-Mullins, 2020, 17). At the same time, there are technique involving uses of 'cortical column' that pursue other epistemic or practical goals (e.g. studying brain development or calibrating instruments) and which do not integrate different patches in light of identifying a basic building block of the neocortex (Haueis, 2021a, 11).

The column case underlines the operationalist view that the unity of scientific concepts cannot be presupposed but needs to be determined over the course of inquiry (Chang, 2004). Operationalists also rightly stress that this process proceeds in part by using multiple operations to explore novel domains to discover further aspects of the object of research (Feest, 2017). Yet a focus on operations alone cannot account for the conceptual dynamics in practice discussed in the previous two sections. Integrating concepts with multiple operations in scientific practice also depends on how researchers interpret the results of applying measurement operations in light of their epistemic goals. These interpretations in turn affect whether they view a general reasoning strategy as narrowly or widely applicable to a domain of inquiry. The generalized patchwork approach thus amends operationalism with a pragmatic view of unity that is the product of an interplay of operations, epistemic goals and the structure of the world (Haueis, 2021b).

6 Conclusion

We have argued that operationalist and patchwork approaches to concepts are natural allies. Operationalists begin from the important insight that measurement techniques are partially constitutive of the meanings of scientific terms, but this raises the threat of concept proliferation, with each technique being associated with an isolated concept. Operationalists have some resources for addressing this problem, but these are inadequate to deal with the full range of complex behaviors that scientific concepts show. The patchwork approach, with its focus on inter-patch relations, provides a wealth of resources for addressing this issue. Here, we have focused on one such resource: general reasoning strategies. General reasoning strategies both bind together (synchronically) distinct patches of scientific concepts, as well as provide normative guidance for the (diachronic) extension of concepts to new domains.

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