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Analogy in Inflection

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Abstract

Analogy has returned to prominence in the field of inflectional morphology as a basis for new explanations of inflectional productivity. Here we review the rising profile of analogy, identifying key theoretical and methodological developments, areas of success, and priorities for future work. In morphological theory, work within so-called abstractive approaches places analogy at the center of productive processes, though significant conceptual and technical details remain to be settled. The computational modeling of inflectional analogy has a rich and diverse history, and attention is now increasingly directed to understanding inflectional systems through their internal complexity and cross-linguistic diversity. A tension exists between the prima facie promise of analogy to lead to new explanations and its relative lack of theoretical articulation. We bring this to light as we examine questions regarding inflectional defectiveness and whether analogy is reducible to grammar optimization resulting from simplicity biases in learning and language use.

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1. INTRODUCTION

As the twentieth century began, analogy stood at the center of linguistic theories of productivity and the productivity of inflectional wordforms. According to the analogical view, speakers create novel wordforms by comparing existing surface forms and solving inferential problems of proportional analogy as in example 1 (i.e., **a** is to **b** as **c** is to what?):

(1) **a** : **b** :: **c** : **d** = ?

By midcentury, however, analogy had been eclipsed by an alternative view that novel wordforms are composed out of smaller pieces (i.e., morphemes) and that human powers of inflectional productivity follow from the knowledge and deployment of compositional units and associated principles of combination. Yet by the close of the twentieth century, analogy had once again emerged as a serious contender for an explanatory theory of inflectional productivity. Though it would be premature to claim that the pendulum has swung back, the momentum is undeniably in that direction.

In this review, we survey the current state of play for analogy in inflection and the major developments behind it in recent decades. Section 2 reviews analogy in morphological theory, Section 3 reviews analogy in formal models, Section 4 discusses the implications of inflectional defectiveness, and Section 5 addresses the question of whether analogy is the optimization of grammars; we summarize and conclude with future challenges in Section 6. The picture that emerges is one of a theory under construction, characterized by notable diversity in its assumptions and formalization, and still awaiting important details to be fleshed out.

2. ANALOGY IN MORPHOLOGICAL THEORY

In the nineteenth century, Hermann Paul had already laid out the notion of analogy as the main driver behind synchronic productivity (Davies 1978) with diachronic change providing a window into its operation (Paul 1880). Central to this is the notion that forms in a language can enter into analogical proportions, which are then extendable to novel contexts. This concept receded into the background in subsequent periods but has returned in force through a focus on what Blevins (2006) has called abstractive approaches to morphology. Blevins's typology of morphological models distinguishes between abstractive models of inflectional morphology and constructive models. In the constructive approach, inflected wordforms are built up by assembling smaller units. For example, the formation of the plural of *dog* might be described as "take the stem *dog* and add the suffix *-s*." By contrast, an abstractive model starts from a set of fully inflected wordforms. Smaller units are seen as abstractions that emerge from comparisons between the fully inflected wordforms. New wordforms are generated not by assembling smaller units but by analogically extending relationships between known, existing wordforms—for example, "follow the pattern of a word you already know, like *cat*, whose singular is *cat* and plural is *cats*." Consequently, an abstractive model is one in which the productive capacity of inflectional morphology is explicitly built upon analogical inferences (for a detailed exposition, see Blevins 2016).

As Hockett (1967, p. 221) points out, the two approaches cover the same ground: "A correct principal-parts-and-paradigms statement [= abstractive, analogy based model] and a correct morphophoneme-and-rule statement [= constructive model] subsume the same actual facts of alternation, the former more directly, the latter more succinctly. We ought therefore to be free to use the latter, provided we specify that it is to be understood only as convenient shorthand for the former." There is an important difference, though, in terms of what is stored and what is calculated in the two models of morphology. On a constructive approach, a wordform is either composed of smaller pieces each stored separately, or it is a unit without internal divisions and stored as

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a whole (see the discussion below in Section 3.1). An abstractive approach does not entail such a strict alignment between (in)divisibility and storage. For example, the fully inflected form *cats* from the illustration above is a single stored item, yet its participation in the analogical proportion *cat* : *cats* :: *dog* : **x** effectively induces a segmentation into *cat* + *s*. This means that, on the one hand, forms that appear to possess compositional structure can also be stored as undecomposed wholes (Baayen et al. 2003), while on the other hand, forms that apparently lack internal parts may subsequently lend themselves to decomposition when they enter into an appropriate analogical relationship.

Constructive models have long been dominant in morphological theory. With the resurgence of analogical models, one may ask what the respective roles of the models should be. Are they complementary or in competition? Three possibilities seem to emerge.

First, they serve as complementary elements within a single framework. For example, Uchihara & Tiburicio Cano (2020) offer a hybrid analysis of verbal inflection in Tlapanec (Otomanguean, Mexico) in which they argue that tonal formatives are most effectively described in constructive terms, while other aspects of the paradigm are better considered from an abstractive perspective. Stump (2016) explicitly states that the Paradigm Function Morphology model he advances is a hybrid with abstractive elements participating in what is otherwise a constructive model. In particular, syncretism and the "morphomic" distribution of formal similarities through a paradigm (O'Neill 2014) are described in terms of rules of referral or comparable formal devices (Round 2015). These are rules that account for forms not through the direct composition of formatives but obliquely through reference to some other form in the paradigm. While such rules are not typically implemented as analogical proportions, the effect is similar.

Second, the two approaches simply serve different ends, elucidating different aspects of the same data. This strategy can be seen, for example, by contrasting the predominantly constructive model advanced by Stump (2016) with the model of Stump & Finkel (2013), which looks exclusively at paradigmatic relationships in an approach that is at least implicitly analogical. This demonstrates that the same researcher can easily toggle between these two different modes.

Third, analogy-based abstractive models are meant to replace constructive models (Bybee & McClelland 2005, Blevins 2016, Baayen et al. 2019). This view can be seen as a direct counterpoint to the exclusive dominance of constructive models and, in particular, to those theories that explicitly reject the existence of paradigms (Bobaljik 2017) and hence axiomatically exclude any role for analogy in synchronic description. On a purely analogical view, segmented formatives are epiphenomenal. This means that one can still use them in a description, but they have no status as an explanatory mechanism. It means also that there is no need to provide an exhaustive account of the entire system in compositional terms. But basing a model entirely on analogy puts greater weight on establishing what the parameters of an analogical description actually might be. The fact that structure in such a system is not built into the grammatical model itself, but rather can emerge through analogical comparisons, should not prevent us from being able to talk about it.

A fully articulated analogical account of an inflectional system remains a task for the future. First, a description is needed of the system that serves as a basis for analogical proportions. Is it a curated list of exemplary paradigms or simply a store of memorized forms? In either case, how is the system represented, organized, and accessed? What does it contain or fail to contain in terms of lexical items (Boyé & Schalchli 2019) and their internal contents (Stump & Finkel 2013)? What is the mechanism used for selecting an appropriate analogical pattern and then applying it to generate new forms (see Section 3.2)? It ought to be knowable what analogical proportions the system licenses—something comparable to the list of rules typically provided by a constructive analysis. But this is not a trivial demand: Despite Hockett's (1967) aforementioned claim that a constructive analysis ("morphophoneme-and-rule") can be understood as convenient shorthand for an abstractive analysis, one of the chief characteristics of an analogical approach is that it licenses multiple competing interpretations; for instance, the correspondence *drink* : *drank* can be compared to "replace /i/ with /a/" or to "replace /ink/ with /ank/," resulting in relations of different scope and thus applicable to different targets (Pirrelli et al. 2020). In the sections to follow, we examine these issues and their current state of development. We find that though significant work has begun on them, their resolution is by no means complete.

3. FORMAL MODELS OF INFLECTIONAL ANALOGY

A central question for analogical theories of inflection is, how exactly does analogy work? To this we may add, to what extent do speakers actually use analogy as opposed to simply retrieving memorized words or parts of words? And how demanding or complex is the task of analogy, given other properties of the system? In the search for precise answers, research has often made use of formal models. Over the past half century, the focus of this research has evolved. In this section we examine three major concerns, following their order of chronological emergence in the literature: the questions of storage versus computation, algorithms for analogy, and analogy and inflectional complexity.

3.1. Storage Versus Computation

Significant early work on the modeling of inflectional analogy was carried out in psychology and psycholinguistics, where a central concern is whether and under what conditions wordforms are stored and/or computed mentally. Since the 1970s a wealth of detailed and often contradictory results has provided support for both the storage and computation of complex wordforms. Using lexical decision tasks, in which subjects classify written forms as real words or not, Taft & Forster (1975) found that nonwords (such as *juvenate*) that are bases of real prefixed words (*rejuvenate*) take longer to classify than nonwords that are not, suggesting that sub-word-level stem constituents are represented and retrievable in the lexicon. Sereno & Jongman (1997) examined English singular and plural nouns and found that response latency is affected by frequency of the whole word, suggesting that even when their internal morphology is transparently derivable, whole words are stored. Baayen et al. (1997) found that response latency for singulars is affected by the sum of the frequencies of both the singular form and its corresponding plural in Dutch. In wug tests (Berko 1958), where subjects are presented with one novel wordform and then must produce or evaluate a related novel form, the degree of productivity of inflectional classes has proven sensitive to the lexical frequency of the class and the phonological substance of the nonalternating bases of words (Bybee & Moder 1983), the phonological neighborhood density of the wug (Dąbrowska 2008), the phonological heterogeneity of bases in the class (Dąbrowska 2004), the frequency of the class in the experimental stimuli (Albright & Hayes 2003, Rácz et al. 2020), and lexical semantics (Ramscar 2002).

3.2. Algorithms for Analogy

Theoretical debates over these findings have been accompanied by formal modeling. The early 1990s saw a burst of activity, which focused empirically on predicting the past tense of English verb forms and included applications of early neural network models. Accompanying these innovations was a robust debate that attempted to extract theoretical insights, often from the shortcomings and obstacles facing competing models (Seidenberg & Plaut 2014). Over time, however, these pivotal obstacles repeatedly dissolved as new technology and implementations arose (Albright & Hayes 2003, Kirov & Cotterell 2018); the present landscape is arguably best characterized as an embarrassment of riches in terms of the sheer diversity of approaches that can achieve reasonably impressive results, suggesting that progress in the next phase may rely as much on asking clearer questions as on demonstrating technical prowess.

The current diversity in algorithmic approaches can be characterized along three dimensions: the tasks that the models are attempting to perform, the calculations that they employ to execute those tasks, and the representations that those calculations manipulate.[1]

At its simplest, analogy is a generative task: Given forms **a**, **b**, and **c**, generate **d**. This top-level task can then be decomposed: First, infer a relation $\mathcal{R}$ that holds between **a** and **b**; then, apply that relation to **c** to obtain **d**. Most computational analogical models, however, begin from larger sets of inputs than this, and many produce larger sets of outputs. Typically, the input to an analogical model is a substantial set of pairs $\{(\mathbf{a}_1, \mathbf{b}_1), (\mathbf{a}_2, \mathbf{b}_2), \ldots, (\mathbf{a}_n, \mathbf{b}_n)\}$ drawn for the lexicon, in addition to the form **c**. For models that attempt it, the task of relation inference can be approached in one of two ways. The first is holistically: Given all of the input pairs $(\mathbf{a}_i, \mathbf{b}_i)$, infer one, general, monolithic relation $\mathcal{G}_0$ that maps from all forms $\mathbf{a}_i$ to the corresponding $\mathbf{b}_i$. The second approach is to break the task of inference into parts: From $\{(\mathbf{a}_1, \mathbf{b}_1), (\mathbf{a}_2, \mathbf{b}_2), \ldots, (\mathbf{a}_n, \mathbf{b}_n)\}$, infer the corresponding set of individual relations $\{\mathcal{R}_1, \mathcal{R}_1, \ldots, \mathcal{R}_n\}$ and then generalize over these to obtain a smaller set of general relations $\{\mathcal{G}_1, \mathcal{G}_1, \ldots, \mathcal{G}_m\}$, each of which maps some of the data. Subsequently, the general relation $\mathcal{G}_0$ or set of relations $\{\mathcal{G}_1, \mathcal{G}_1, \ldots, \mathcal{G}_m\}$ can be applied to the input form **c** to obtain one or more outputs $\{\mathbf{d}_1, \mathbf{d}_2, \ldots\}$. Models that generate multiple outputs typically produce accompanying weights $\{w_1, w_2, \ldots\}$, which can be interpreted in several ways: as probabilities for input to a stochastic sampling process to select a single, final output; as ratings of confidence in the alternative outputs; or for conversion into ranks, to order the outputs by preference. All of these models can be considered generative in that for their output they generate one or more actual forms, $\{\mathbf{d}_1, \mathbf{d}_2, \ldots\}$. **Table 1** shows a selection of generative models of analogy and the subtasks they attempt.

Many computational models of analogy are not generative, though. These models eschew the task of inferring relations and generating output forms. Instead, they assume that a set of relations $\{\mathcal{G}_1, \mathcal{G}_1, \ldots, \mathcal{G}_m\}$ is given and that one or more of them needs to be selected as appropriate for input **c**. This is a classification task: Given **c**, select index k such that the appropriate relation to apply to **c** is $\mathcal{G}_k$. Classifier models such as this take input pairs $\{(\mathbf{a}_1, i_1), (\mathbf{a}_2, i_2), \ldots, (\mathbf{a}_n, i_n)\}$ containing a form **a** and an index i for a relation $\mathcal{G}_i$—for instance, {(*walk*, class = 1), (*rip*, class = 1), (*sing*, class = 2), (*drink*, class = 2), (*think*, class = 3), …}. Because the task of classification is fundamental in domains well beyond inflectional analogy, inflectional classifiers have often been based on preexisting, more general classification algorithms. A selection of inflectional classifier models is also shown in **Table 1**.

The computational tasks of inference, generation, and classification have been implemented in several ways. In most models, a learning component applies first, during which a generative model learns relations $\mathcal{G}$ and a classifier model learns or fine-tunes a classifier function $\mathcal{C}$, such as by learning weights to be accorded to various features in the input.

In the performance component, the input form **c** is mapped to an output set either of forms $\{\mathbf{d}_1, \mathbf{d}_2, \ldots\}$ or of indices $\{k_1, k_2, \ldots\}$. Here models differ considerably. In many generative models, the relations $\{\mathcal{G}_1, \mathcal{G}_1, \ldots, \mathcal{G}_m\}$ inferred during learning are expressed as rules. During performance, a rule can apply to input **c** to generate output **d** if and only if **c** matches the rule's structural description. Models differ as to whether multiple rules can apply to the same input **c**, generating

[1]We regard a model as analogical if its task is to extend existing relationships among wordforms to novel contexts for the generation of new wordforms. A narrower definition that was common in the earlier literature, but that we do not follow, regards analogical models as those whose calculations lack symbolic rules (correspondingly, some of the models that are analogical by our criteria were not termed "analogical" when they first appeared).

Table 1 Models of analogy: input, output, and subtasks

Model		L98	SPA	Foidl	TP	Qumin	MGL	Gen.NN	AM15	GCM	TiMBL	AML	Cl.NN
Input → output	One **a, b** → one **d**	x											
	Many **a, b** → one **d**		x	x	x				x				
	Many **a, b** → many **d**					x	x	x					
	Many **a**, i → many k									x	x	x	x
Explicit subtasks	Relation inference	x	x	x	x	x	x	x					
	Generalization		x	x	x	x	x						
	Form generation	x	x	x	x	x	x	x	x				
	Classification									x	x	x	x

Generative models listed in the table are L98 (Lepage 1998), SPA (symbolic pattern associator; Ling & Marinov 1993), Foidl (first-order decision lists; Mooney & Califf 1995), TP (tolerance principle; Yang 2016), Qumin (Beniamine 2018, Beniamine et al. 2021), MGL (minimum generalization learner; Albright & Hayes 2002), AM15 (Ackerman & Malouf 2015), and Gen.NN (generative neural networks, e.g., Rumelhart & McClelland 1986, Cotterell et al. 2019).
Classifier models listed in the table are GCM (generalized context model; Nosofsky 1986), TiMBL (Tilburg memory-based learner; Daelemans & van den Bosch 2005), AML (analogical modeling of language; Skousen 1992), and Cl.NN (classifier neural networks, e.g., Plunkett & Marchman 1993, Guzmán Naranjo 2018).

multiple outputs, or only one. Very different are models based on neural networks. Though neural networks are notoriously inscrutable, an approximation of their internal workings can be envisaged through a spatial metaphor in which the set of all possible input forms $\mathbf{a}_i$ is pictured as a "space" **A**, and likewise the set of all possible forms $\mathbf{b}_i$ as a space **B**, and all indices as the space **I**. From their input data, neural networks learn a set of nonlinear distortions that create a projection from space **A** onto either space **B** or **I**. During performance, form **c** is placed in space **A** and then projected to one or more points in **B** or **I**, corresponding to $\{\mathbf{d}_1, \mathbf{d}_2, \ldots\}$ or $\{k_1, k_2, \ldots\}$, the output of the model. Different again are memory-based models. These models make reference to the input data (**a**, i) not only during learning but also during performance. Both **c** and the data (**a**, i) are placed in space **A**, and their relative positions are observed. In "distance-based" variants of these models (Nosofsky 1986, Daelemans 2002), the final output $\{k_1, k_2, \ldots\}$ is based on the indices of **c**'s nearest neighbors in space **A**. In the model of Skousen (1989), space **A** is split into subspaces relative to the position of **c**. The final output is then based on the contents of the resulting subspaces. **Table 2** summarizes these algorithmic approaches for a selection of analogical models.

Models also differ in their representations, though studies typically devote significantly more space to the motivations for their calculations than for their choices of representations. All analogical models of inflection take wordforms in their input. However, relatively few models choose to represent those wordforms as true phonological strings. True strings need to be aligned into order to be compared; for instance, the strings in example 2 should be aligned as example 2a and not example 2b, but string alignment is computationally nontrivial (Beniamine & Guzmán Naranjo 2021):

(2)

a.	*s*	*p*	*l*	*i*	*n*	*g*
			|	|	|	|
			r	*i*	*n*	*g*

b.	*s*	*p*	*l*	*i*	*n*	*g*
	|	|	|	|		
	r	*i*	*n*	*g*		

To avoid needing to compute alignments, strings are routinely converted into sets of features $\{f_1, f_2, \ldots\}$ such that for any two wordforms, f_i in one form always corresponds to f_i in the other. One strategy is to represent words as the contents of a series of slots within a template. The

Table 2 Models of analogy: calculations and representations

Model		L98	SPA	Foidl	TP	Qumin	MGL	Gen.NN	AM15	GCM	TiMBL	AML	Cl.NN
Learning calculations	Relations	x	x	x	x	x	x	x					
	Rule ordering		x	x	x								
	Feature weights									x	x		
Performance calculations	Distances from **c** to (**a**, *i*)								x	x	x		
	(**a**, *i*) in subspaces around **c**											x	
	Projection of **A** onto **B** or **I**							x					x
	Symbolic rule application	x	x	x	x	x	x						
Representations	True strings	x		x	x	x	x	x[a]		x[b]			
	Templatic strings		x					x[c]		x[d]	x[e]	x[f]	x[g]
	Bag of *n*-grams							x[h]					x[i]
	Hand-selected features										x[j]	x[k]	x[l]
	Categorical labels								x				

Examples can be found in the following references, as indicated by the corresponding superscript letters in the table: [a]Cotterell et al. (2019), [b]Albright & Hayes (2003), [c]MacWhinney & Leinbach (1991), [d]Hahn & Nakisa (2000), [e]Daelemans (2002), [f]Wulf (2002), [g]Plunkett & Marchman (1993), [h]Rumelhart & McClelland (1986), [i]Nieder et al. (2022), [j]Eddington (2000), [k]Skousen (1989), [l]Guzmán Naranjo (2018).

definition and granularity of such slots vary, from slots of syllabic prosodic constituents (onsets, nuclei, and codas), to single phonemes or letters, to distinctive features of phonemes (MacWhinney & Leinbach 1991, Plunkett & Marchman 1993, Daelemans et al. 1994). Templates with segmental slots permit a choice of arrangements. For instance, *tas* and *sta* could be placed into a left-justified template C.C.V.C as *t.Ø.a.s* and *s.t.a.Ø* or into a right-justified template C.V.C.V.C as *Ø.Ø.t.a.s* and *s.Ø.t.a.Ø* (MacWhinney & Leinbach 1991, Hahn & Nakisa 2000). A second strategy is to treat words as bags of *n*-grams—for instance, #*cat*# contains the trigrams #*ca*, *cat*, and *at*#—and then for each possible *n*-gram, to code its presence or absence. The internal constituents of the trigrams might be phonemes, letters, or distinctive features (Rumelhart & McClelland 1986, Baayen et al. 2019). A third strategy is to use a heterogeneous set of features that is hand-selected (Skousen 1989, Eddington 2000), granting the researcher considerable freedom, and in which the simplest of representations is a single categorical label per wordform, recording which out of a restricted set of language-specific patterns the form follows (Ackerman & Malouf 2013). **Table 2** summarizes representational decisions in a selection of analogical models. Particularly for non-rule-based models, the variation among representational decisions is largely orthogonal to the choice of model type.

Over three decades, algorithmic studies of analogy have explored a wide range of possibilities, though in a less than systematic manner. Any two studies will typically differ not only on numerous design decisions but also in the data set analyzed, leading to residual unclarity around which factors contribute to the results and how. Representational choices have received relatively little scrutiny, though they are crucial for deciding the content and generalizability of relations, $\mathcal{G}$, and determining which exemplars count as proximal or distal in memory-based models. The problem is exacerbated by the use of hand-selected features, as some researchers report choosing among alternative inputs to obtain satisfying results (Skousen 1989). Classifier studies rarely discuss how the assumed relations $\{\mathcal{G}_1, \mathcal{G}_1, \ldots, \mathcal{G}_m\}$ relate to the classification task itself. For instance, if the relations are rules, then why does the classifier not access the information in their structural descriptions? Is this firewall between the selection of relations versus their content cognitively realistic? As discussed in

Table 3 Forms, endings, and analogical patterns for the singular and plural nominative forms of three Russian nouns

a. Forms		
	SG	PL
ZAKON	/zakón/	/zakóni/
BOLOTO	/bolóto/	/bolóta/
APACHI	/apátɕi/	/apátɕi/

b. Endings		
	SG	PL
ZAKON	—	/-i/
BOLOTO	/-o/	/-a/
APACHI	—	—

c. Analogical patterns	
	SG $\rightleftharpoons$ PL / context
1.	_ϵ $\rightleftharpoons$ _i / XC_
2.	_o $\rightleftharpoons$ _a / XC_
3.	ϵ $\rightleftharpoons$ ϵ / XCi

Note: ϵ is the empty string.

the next subsection, other challenges have arisen in the meantime, suggesting that the program of algorithmic modeling may soon undergo significant revisions in its research questions and scope.

3.3. Analogy and Inflectional Complexity

Algorithmic research in the 1990s and 2000s focused almost exclusively on predicting wordforms in one, fixed paradigm cell based on the contents of just one other, fixed cell. However, as the empirical focus of research broadened beyond the small paradigms of English, it became apparent that this is not the only kind of inflectional analogical inference that speakers might make. In a series of cross-linguistic typological studies, Ackerman et al. (2009) shifted the conversation to a more generalized research agenda, investigating what they termed the Paradigm Cell Filling Problem:

> **Paradigm Cell Filling Problem (PCFP)**: What licenses reliable inferences about the inflected (and derived) surface forms of a lexical item?

Some languages have very large inflectional systems, where memorization of full paradigms seems entirely unlikely; for example, Archi, a Northeast Caucasian language of Dagestan, distinguishes more than a million paradigm cells (Kibrik 2017). One can ask, should we expect the PCFP to be much harder for speakers of these languages? Ackerman & Malouf (2013) propose an analogical model to measure this difficulty across languages. Consider a speaker of Russian who would be familiar with the forms given in **Table 3*a***. If they encounter a new nominative singular form that does not end in /-a/ or /-o/, how difficult is it for them to guess the plural form? The analysis in **Table 3*b*** shows two possibilities: Either apply the same proportional analogy as /apátɕi/:/apátɕi/, where the forms are identical in the singular and plural, or the same as /zakón/:/zakóni/, where the plural adds word-final /-i/. If both alternations were just as frequent, then a speaker would be making a blind guess between two equally likely events and would have a 50% chance of being wrong.

Ackerman & Malouf (2013) use a probabilistic measure (conditional entropy) to measure the remaining uncertainty when predicting the plural endings, given knowledge of the singular endings. In the small example from **Table 3*b***, the singular forms can be guessed without any doubt from the plurals, and the conditional entropy is thus 0. In the opposite direction, when guessing the plural from the singular, there is some ambiguity: If given a zero ending, the plural could be either /-i/ or a zero ending. Thus, the conditional entropy is higher—in this case, ~0.66. Ackerman & Malouf (2013) compute this value from much larger lexicons, averaging across all pairs of paradigm cells from tables of inflectional endings for 10 languages (Amele, Arapesh, Burmeso, Fur, Greek, Kwerba, Mazatec, Ngiti, Nuer, and Russian), with the number of cells ranging from 3 to 12 and the number of inflectional classes between 2 and 109. They conclude that regardless of the size of the system, it seems always easy for speakers to guess a form if they know another one. They call this the Low Conditional Entropy conjecture. These results are congruent with

Wurzel's (1989, p. 114) observations according to which "inflectional paradigms are…kept together by implications" as well as with Carstairs's (1987) observation that across languages, we always find many fewer inflection classes than what the number of alternative endings makes possible.

Bonami & Boyé (2014), Bonami & Beniamine (2016), and Beniamine (2018) discuss two main issues with Ackerman & Malouf's (2013) model. First, the analysis of the specific analogies relies entirely on preanalyzed tables of endings and realizations, which hides some clues, present in the shape of the stem, while providing extra clues, owing to the differential segmentation of different inflection classes. This leads to both an over- and underestimation of the difficulty of the PCFP. Moreover, while speakers usually do not know full paradigms, they still usually know more than a single form (Bonami & Beniamine 2016, Blevins et al. 2017).

Bonami & Beniamine (2016) describe an implemented method to extract analogical relations automatically from large lexicons of full surface forms without needing the manual segmentation relied on by Ackerman & Malouf (2013). Beniamine (2017) and Beniamine et al. (2021) improve on this methodology to make it applicable to languages with very different morphological systems. **Table 3*c*** shows three of these analogical patterns extracted from our three Russian nouns. Bonami & Boyé (2014) and Bonami & Beniamine (2016) describe how to compute conditional entropy based on these analogies, taking into account conditioning on phonological contexts. They call this measure "implicative entropy." In **Table 3*c***, for the lexemes shown, the choice of a plural is in fact entirely determined by the singular forms: /zakón/ can take pattern 1, but not pattern 2, since it does not end in /-o/, nor pattern 3, the context of which requires ending in /-i/. Similarly, /apátɕi/ cannot take pattern 2, nor pattern 1, which requires ending with a consonant. When predicting in the opposite direction and guessing the singular from the plural, a form ending in /-i/ could take either pattern 1 or pattern 3. In this small example, when taking into account phonological contexts, we find the opposite relation than the one estimated by the method of Ackerman & Malouf (2013). This new measure from Bonami & Beniamine (2016) also allows one to take into account knowledge of several forms to calculate the joint entropy. Studying eight inflectional systems with this methodology (verbs of French, European Portuguese, English, Modern Standard Arabic, Navajo, Zenzontepec Chatino, Yaitepec Chatino, and Russian nouns), Beniamine (2018) confirms that prediction is overall easy even from a single form and shows that this difficulty falls rapidly as more forms are known: Across languages with very different inflectional profiles, it is extremely useful for speakers to rely on analogies based on more than a single form.

A limitation of these models is that they assume a prediction based only on phonological forms, ignoring other information that can provide useful clues when guessing which analogical pattern should be applied. Building on Beniamine's (2018) entropic measures, Pellegrini (2019) shows that the predictability of Latin nouns is greatly improved if gender is known. Using classifiers, Guzmán Naranjo (2018, 2020) shows the utility of information such as stem phonology, gender, animacy, and transitivity in analogical prediction across languages. These combined results show that although inherent grammatical and phonological information does not usually suffice to guess unknown forms categorically, it all contributes useful cues in probabilistic predictions.

The frequency with which speakers encounter forms is another significant factor. Sims-Williams (2022) shows that in the history of Greek, the textual token frequencies of the cells in a paradigm are correlated negatively with the likelihood of a cell undergoing change and positively with its likelihood of serving as an analogical model for change. Boyé & Schalchli (2019) argue that models of inflectional analogy are unrealistic if entropy is computed from complete systems containing a wordform for every paradigm cell; rather, a more faithful model should be able to learn from partial data that contain gaps, similar to what a speaker may have been exposed to. That is, the model should proceed from ecological samples of data. Boyé (2016) sketches a computational model that proceeds from ecological samples and selects reliable analogies by searching for those that lead to sets of mutually predictable forms.

Related advances have been made in the field of natural language processing (NLP), where attempts to create inflected lexicons from corpora also have led to analogical models that need to proceed from more realistic samples. When forms are collected from corpora, their Zipfian distribution leads to very incomplete lexicons, which can be filled in automatically by using analogical relations (Durrett & DeNero 2013; Ahlberg et al. 2014, 2015; Nicolai et al. 2015). Cotterell et al. (2016) formalize this challenge as a shared task, in which models submitted by various research teams are evaluated against the same set of data on a few different analogical prediction tasks. The task most resembling the PCFP, termed a reinflection task, consists of learning to predict the orthographic form of a target paradigm cell, knowing another form and its cell. Neural models (Kann & Schütze 2016) are the most successful, though they do not provide explicit interpretations of <u>how</u> they perform the analogical task. Cotterell et al. (2019) use a neural sequence-to-sequence model to generate all the forms of a paradigm. Rather than model all relations between pairs of forms, they construct a tree of predictive relationships among paradigm cells and then fill each cell by generating it from the form of the parent cell in the tree. They propose a measure of cross-entropy based on this model to evaluate the complexity of the PCFP. They compute this measure for the orthographic paradigms of 33 verbal systems and 18 nominal systems from the UniMorph data sets (Kirov et al. 2016) and find a trade-off between the difficulty of the PCFP and the size of the paradigm, so that smaller paradigms can afford a higher entropy, while larger paradigms display lower entropy.

Finally, Guzmán Naranjo (2020) proposes that to evaluate the difficulty of predicting inflected forms in a language, a better metric than entropy is the accuracy of an analogical classifier model because it is arguably more intuitive and comparable across languages. Guzmán Naranjo shows that the accuracy of his classifier, when restricted to phonological information, is highly correlated with entropy-based measures, but he also argues for input features to include information beyond just the phonological properties of wordforms.

Over 50 years, the terms of the debate have shifted significantly. Questions of cross-linguistic variation have risen to prominence, and the scope of inquiry has expanded to entertain new potential factors in analogical production, asking not only when we use analogy but also the following questions: What information is analogy based on? What types of similarities license analogy? And what resources do speakers have to accomplish analogical inference, in terms of both their exposure to the system and their means of processing that information?

4. IMPLICATIONS OF INFLECTIONAL DEFECTIVENESS

A hallmark of generative theories of inflection, whether analogical or otherwise, is that for a given paradigm cell, they can predict an appropriate wordform. However, in some inflectional systems there exist paradigm cells for which speakers do not produce any form, but rather consistently leave gaps. This phenomenon is known as inflectional defectiveness, which Sims (2015, p. 26) defines as follows:

Inflectional defectiveness:

a. "IF there exists a set of morphosyntactic and/or morphosemantic feature values F that is well-defined and morphologically encoded for at least one lexeme belonging to part of speech C;
b. AND IF there exists a well-formed syntactic structure S that requires F in combination with some lexeme L belonging to C;
c. BUT any form of L_C that is inserted into S produces an ungrammatical construction;
d. THEN the paradigm cell defined by <L_C,[F]> is defective."

For example, in Witsuwit'en (Athabaskan, British Columbia), some verbs only have third-person values, such as /n-wət/ 'walk fast' and /c'-ɬ-tsi/ 'give birth,' with first- and second-person paradigm cells filled by alternative expressions (Hargus 2007). There is no clear form-based or semantic reason for these cases, so the absence of these forms is "simply a stipulated property of these lexemes" (Baerman & Corbett 2010, p. 9). To account for data such as these, the synchronic processes that normally subserve productivity must also be capable of producing no form in defective cells. This is a challenge for all models of morphological productivity including analogy. A comprehensive analogy account must handle the lack of forms in defective cells correctly or else risk overgeneration. In this section, we explore different approaches to defectiveness and discuss their implications for analogical approaches to inflection.

Different accounts of defectiveness exist that solve different aspects of this phenomenon, including item-specific idiosyncrasy, epiphenomenon of rule conflict, morphological indefinition within the paradigm, and defectiveness as a morphological object. No single theory is exhaustive nor necessarily covers every case; instead, these theories shed light on the challenges that defectiveness poses.

One aspect of the challenge is how to flag paradigm cells as defective. Within constructive approaches, one solution is that particular items are lexically specified for defectiveness (Halle 1973, Embick 2000, Spencer 2016), using the same kind of diacritic mechanism proposed to account for phonological irregularities. Under such an analysis, once these specifications have been acquired, synchronic processes need only to recognize them and act upon them. A limitation of this approach is that it predicts that any form could be irregular, and so it is not equipped to account for nonaccidental distributions of defectiveness in the paradigm. Empirically, however, defectiveness often has a distribution throughout a paradigm that matches patterns instantiated in other lexemes by actual forms. This sharing of distributional patterns may be more straightforwardly captured in analogical theories, in which multipart proportional analogies such as the one in example 3 would arguably be unsurprising:

(3)	**a**	:	**a**	:	**b**	:	**b**	:	**b**		Lexeme 1
	c	:	**c**	:	[DEFECTIVE]	:	[DEFECTIVE]	:	[DEFECTIVE]		Lexeme 2

In certain cases, the defectiveness of a cell can be predicted on the basis of other considerations, particularly the existence of conflicting rules or principles in the grammar. For example, in Swedish, nouns with stem-final sibilants lack indefinite genitive forms, but not definite ones, due to a prohibition of sibilant + *s* combinations (*/hus-s/ 'house-GEN' but /hus-en-s/ 'house-DEF-GEN') (Karlsson 2000). Georgian has three words for NOBODY—/nuravin/, /aravin/, and /veravin/—of which only one, /nuravin/, lacks an ergative form. This word is used solely in the scope of the prohibitive negative /nu/, whose use is restricted to the present or future, whereas the Georgian ergative is used only in the past or aorist (Baerman & Corbett 2010). In such cases, defectiveness could be argued to be a well-motivated epiphenomenon, and it is clear why such forms are not produced in analogical formulations.

While the distribution of defective cells in a paradigm may at first consist solely of cases motivated by rule conflict, it is also prone to develop beyond these initial roots, and like any other morphological property, it can spread across lexemes (Sims 2015). Some words can become defective over time, like the Russian /ubeditʲ/ 'to convince,' which is now listed as defective in the first singular form despite displaying (variant) forms in earlier texts (Baerman 2008). New words joining an inflectional class can take on the defective patterns preexisting within that class—such as the verb /pylesositʲ/ 'to vacuum,' which has a defective first-person singular form like other members of its class (Baerman & Corbett 2010). In these developments, new instances of defectiveness emerge not randomly but in specific cells of specific lexemes. Both the fact of the innovations and their details find a straightforward explanation if their causal mechanism is spread via inflectional analogy.

Though defectiveness is often thought of as the complete absence of a form, Sims (2006, 2015) suggests that instead of a strict dichotomy between cells that have forms versus those that lack them, the criterial characteristic of a defective cell is that the token frequency of its wordform is far lower than expected, and actually, it may be attested in a low number of tokens in corpora. This will be challenging to account for using a lexical specification approach if the specification is interpretable only as the deterministic presence versus absence of a form. However, within an analogical analysis, the presence of a few attestations is presumably not problematic since the possibility of some speakers analogically filling a gap is always present, if they attempt to provide a repair for the missing form (Albright 2009) or to produce it for jocular or ironic effect (Baerman 2015).

In some cases of defectiveness, the degree of synchronic motivation is less than obvious, and linguistic analyses of it can differ. Albright (2003) suggests that defectiveness in Spanish verbal paradigms corresponds to situations in which allomorphic alternations are expected but the two options—raising or diphthongization—are equally possible and verbs have a frequency too low for speakers to decide what to do. The key here is not that the regular constraints of the grammar would categorically rule out a form for the defective paradigm cell but rather that it is unclear which form precisely they should predict. However, while this proposal can account for some of the lexemes in question, such as the verb /abolir/ lacking the first singular form */abolo/, it cannot cover all defective cases. Other verbs like /blandir/ 'brandish' have the same defectiveness pattern but lack the ambiguous structural condition for diphthongization/raising, which on Albright's account should give rise to defectiveness (Sims 2015). Maiden & O'Neill (2010, p. 108) propose an alternative account that is less synchronic than diachronic, noting that the defective verbs in question are late loans from Latin or French, and even their nondefective paradigm cells are "downright aberrant," lacking the usually expected stem alternations. As such, both the defective gaps and the nondefective, nonalternating stems can be viewed as responses to the incongruity of these borrowed lexemes in comparison to the native Spanish patterns. These two different analyses of the motivations for defectiveness have different implications for the role of analogy. In Albright's account, defectiveness might be construed as a failure of productive analogy to choose between two competing synchronic patterns. In Maiden and O'Neill's account, the active role of analogy is more historical.

Sims (2006, 2015) finds that gaps often occur in paradigms of lexemes that are characterized by a low cohesion within the inflectional system—for instance, due to being a loanword or having low frequency. In time, however, gaps become integrated into the system and then can extend to other words with a resemblance to the originally defective form, such as other loanwords. This accounts for the clustering of defectiveness within inflectional classes or among forms with similar phonology. For example, Boyé & Hofherr (2010) and Maiden & O'Neill (2010) note that Spanish /abolir/ has defective cells that are not affected by the rule conflict conditions posited by Albright (2003). Rather, the defectiveness has been extended from cells that do have a rule conflict to cells that should share the same form.

We have seen that analogy and defectiveness interact at multiple points. Defectiveness may initially be motivated in certain lexemes but spread analogically to others. Its distributional pattern in a paradigm may resemble patterns instantiated in other lexemes by actual wordforms. The nonzero frequency of attestation of forms for defective cells can be explained by the availability of analogy to productively fill them.

On the other hand, it is less clear what should prevent productive analogy from quickly supplying novel forms in defective cells that are synchronically unmotivated. A convincing answer would appear to require an unambiguous account of which other cells, in which other paradigms, speakers attend to when choosing whether to generate a novel inflected wordform—an account that theories of analogy are yet to furnish.

5. IS ANALOGY GRAMMAR OPTIMIZATION?

Can analogy itself be explained by a more fundamental process or principle? A frequent outcome of analogical generalization is the elimination of irregularities and exceptions, which nudges languages in the direction of greater structural coherence and regularity. The effect can be seen both in language change and in first- and second-language acquisition, and it has inspired attempts to motivate analogy, either explicitly or implicitly, by appealing to innate constraints or biases on learning. Since these constraints and biases, acting cumulatively over repeated cycles of intergenerational transmission and use, are also seen as mechanisms for the optimization of grammar, the question has also been framed as follows: Is analogy grammar optimization?

In the 1960s and 1970s, one line of work in generative linguistics argued that the traditional notion of analogical change used in historical linguistics should be replaced with that of grammar simplification (Kiparsky 1968, King 1969). Under this view, analogical leveling corresponded to simplification of the output of a generative rule and extension to simplification of its environment or target. This was attributed to a constraint within Universal Grammar that learning should favor simplicity, where simplicity was originally conceived in terms of minimum description length (Kiparsky 1970). Diachronic simplification was then hypothesized to follow from the way the learner's evaluation measure decides between possible grammars that are equally consistent with primary linguistic data. One manifestation of that simplification, so the argument went, was what had previously been termed analogy.

Alternatively, in the field of language evolution, the linguistic manifestation of a domain-general learning bias for simplicity (Culbertson & Kirby 2016) is held responsible for both the original emergence of linguistic structure and the maintenance of structure in subsequent language change (Newmeyer 2002). In iterated learning models of language evolution, simplification is seen as the inevitable result of interaction of a domain-general simplicity bias combined with the poverty of the stimulus, which prevents the learner from being directly exposed to all possible projections of the previous generation's underlying grammar (e.g., Smith et al. 2003). Although explaining analogical changes is not the explicit concern of these theories, the implicit analysis of analogical formations (such as those produced by participants in artificial language learning experiments, e.g., Kirby et al. 2008, 2015) is broadly similar to the generative one characterized above, except that the learning bias is conceived of as probabilistic rather than deterministic, and domain-general rather than language-specific, and therefore is expressed and modeled in more abstract and theory-neutral terms.

In earlier iterated learning models (Kirby 2000, 2001), this learning bias was implemented via processes of grammar induction and extension. Agents exposed to an utterance as an expression of a particular meaning first acquire a holistic rule linking the two, then gradually merge it with other rules in their grammar in such a way that it is eventually expressed in the most general form compatible with the data. An invention algorithm supplies new expressions not produced by any existing rule; this preserves and extends existing structure without introducing new structure. These processes of grammar induction and invention correspond loosely to what historical linguists would call reanalysis and extension. More recent iterated learning models take a Bayesian approach: Agents attempt to arrive at a grammar that maximizes the likelihood of the language data they have been exposed to, with a simplicity bias explicitly built in as part of the prior that represents speakers' preexisting expectations about languages (e.g., Kirby et al. 2015). In this type of model, the creation of analogical forms would appear to be located entirely in grammar

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induction, with analogical innovations being the visible projections of novel grammars subsequently manifested and transmitted in usage, as in the generative analysis. However, neither the Bayesian nor the earlier iterated learning models are intended to be psychologically realistic at this fine-grained level. Instead it is assumed that speakers' learning biases are implemented psychologically by some heuristic, without committing to any particular standpoint on what that heuristic is [cf., for example, Batali's (2002) model of the emergence of linguistic structure, which relies on an explicitly analogical mechanism to generalize from memory, based on general models of analogical reasoning in cognitive science; see, e.g., Gentner & Forbus 2011, Gentner & Maravilla 2018].

While the work discussed so far has located analogical processes in acquisition, usage-based explanations of analogical change have also been proposed (e.g., Hooper 1976, Bybee 2006). Beckner & Wedel (2009) explicitly attribute regularization to analogy; using a memory-based model where memorized exemplars are constantly deteriorating in the adult grammar unless reinforced by exposure, they demonstrate that a correlation between frequency and irregularity can equally arise from either usage or acquisition. Usage-based accounts are compatible with analogical changes being introduced by adults instead of or in addition to child learners (for arguments in favor of this view, see, e.g., Slobin 2004, section 2; Bybee & Slobin 1982). They are nonetheless similar to the acquisition-based accounts in that a paucity of linguistic data makes some mechanism for generalization necessary, and generalization is biased in favor of regularization or simplification.

Beyond simplicity in itself, cases of analogical paradigm leveling have led some to propose learning constraints favoring uniform linguistic expression of meaning. This principle has sometimes been summed up as "one meaning, one form" (Humboldt's universal). Depending on theory-internal considerations (e.g., the abstractness of underlying forms that generative rules work with), it may or may not be necessary to understand this as a separate principle from simplicity (see Kiparsky 1974). The principle has been formalized in various ways—for instance, as output–output correspondence constraints in Optimality Theory (Burzio 1994, Kenstowicz 1996) or as the paradigm condition of Kiparsky (1971), which was one of several new constraints on the learner's evaluation measure beyond simplicity per se, favoring uniform realization of lexical meaning within paradigms. Ultimately this was supposed to facilitate learning by making the task of perception easier. Models of the cultural transmission of language also have to build in antisynonymy constraints in some way. In the model of Kirby (2000, 2001), agents are capable of learning synonymous expressions but will always produce a single expression per meaning in production because the algorithm responsible for production is deterministic. In Bayesian models, grammars with less synonymy will be more diachronically stable, all other things being equal, because expressions with fewer synonyms will be better represented in the primary linguistic data and thus less likely to be lost during intergenerational transmission (e.g., Frank et al. 2009).

Despite the virtual certainty that simplicity constraints upon learning exist, and that simplicity can arise in the course of language change, attempts to motivate analogy in terms of grammar optimization need to contend with cases where analogy appears to complicate grammatical structure rather than simplify it.

While regularization may be the usual direction of change, irregularization also occurs; for instance, the replacement of *dived* by *dove* in some English varieties creates an additional exception to a regular rule. In many cases, analogy would lead to simplification only if it were allowed to follow through to a completion point, but cannot be seen as simplification in intermediate stages. For example, Thomason (1976) discusses a case where analogical change could be regarded as simplifying grammar only if it were to proceed through the whole lexicon, but has not done so. Similarly, it is not hard to find examples where analogical mergers between inflection classes only affect a subset of paradigm forms, so that analogy effectively creates new unpredictable hybrid classes (Vincent 1974, Sims-Williams & Enger 2021). The analogical extension of morphomic distribution of stem variants (Maiden 2018) is a problem for optimization-based accounts of analogy because it often involves the replacement of morphosyntactically motivated patterns of distribution within paradigms with morphosyntactically unmotivated ones. Likewise, attempts to motivate leveling in terms of a one-to-one meaning–form correspondence principle must also explain why analogical change can extend alternations as well, especially since leveling and the extension of alternations can be accounted for by the same mechanisms (Garrett 2008; Sims-Williams 2016; Round et al. 2021, 2023).

These problems mean that if analogy is guided by a learning bias for simplicity, the bias cannot be operating at a global level since analogical change does not necessarily simplify with respect to the whole grammar. This pushes the question back one step: Can analogy still be viewed as grammar optimization, but operating within some other scope?

Kiparsky (1978) proposes that while analogy does not necessarily simplify with respect to adult grammar, it is still grounded in simplification with respect to the "working hypothesis" grammar of child learners. Analogical innovations that survive into adult grammar are the remnants of optimal (i.e., maximally simple) analyses of incomplete linguistic data at some point during acquisition. However, if we consider that adult grammars are also incomplete, in the sense that even the experience of an adult speaker contains extensive paradigm gaps (Section 3), then we have to concede that adult speakers will also not have the "whole" grammar in view when performing the comparisons that underpin analogical innovations (Joseph 2011).

Drawing these threads together, some weak form of simplicity bias is undoubtedly at play when speakers generalize both in acquisition and in production; for instance, we only infer exceptions or conditions to regularities when there is positive evidence for them. Yet if speakers generalize from only a subset of possible wordforms, then this weak simplicity bias should operate at only a "local" level and therefore produce outcomes that could be nonsimplifying at the global level, which is consistent with the empirical evidence. Under this view, analogy should be expected to tend toward regularization in the long term—because higher type frequency (and therefore more predictable) patterns will be better attested in the language data that speakers generalize from—but not necessarily in every individual case. To predict the effect of analogical generalization at a more fine-grained level, we would need a better understanding of how exactly speakers select the data to generalize from. This emphasizes, once again, the centrality of the question of just what speakers take into account when performing analogy—the same central question that this review has repeatedly led to.

6. CONCLUSION

After an extended dormancy, analogy has returned as a serious contender on the field of inflectional theories. Analogy appears well suited to explaining a wealth of empirical facts that have emerged over the past half century (Sections 3 and 4) and likewise appears to fit naturally with a notion of simplicity biases in learning and emergent simplification during language use (Section 5). Nonetheless, in many crucial regards, analogy as a theory remains underdeveloped and imprecise. Almost paradoxically, this is true despite analogy having been repeatedly implemented in formal models (Section 3). The paradox is resolved, though, by noting that many models sidestep the actual generation of novel forms and that the models themselves are highly diverse, suggesting that the theory at present is so underspecified that it readily invites divergent interpretations. Relatedly, the same lack of precision leaves open questions about how an abstractive theory of inflection that relies upon analogy should fit with, or vie against, constructive theories (Section 2).

During the long ascendancy of constructive morphological theory, proponents of analogy had no choice but to argue vigorously that analogy deserved attention at all. In our view, that case has been made sufficiently. To complete the transition to a fully viable theory, the emphasis in analogy research must now shift away from polemics and onto the detailed work of articulating a comprehensive theory underpinned by precision, cognitive plausibility, and cross-linguistic validity.

SUMMARY POINTS

1. Abstractive theories of inflection, which depend on analogy to account for both synchronic and diachronic productivity, have reemerged as an alternative to the constructive theories dominant since midcentury.
2. A strong tradition of computational modeling is now addressing wider cross-linguistic questions, organized around the Paradigm Cell Filling Problem in theoretical linguistics and the reinflection task in natural language processing.
3. An analogical theory of inflection appears to account well for inflectional defectiveness, though gaps remain owing to impreciseness of the theory, especially on the question of what information speakers rely on during analogy.
4. Analogical theories of inflection appear compatible with modern notions of cognitive simplicity biases, but likewise, a full evaluation requires greater precision about the information that speakers rely on during analogy.

FUTURE ISSUES

1. It remains to be determined how abstractive and constructive theories relate: as competitors, one of which is incorrect; as complementary subtheories; or as equally valid alternatives.
2. Current computational models are diverse. For greater interpretability of results, research will benefit from more systematic exploration of modeling options.
3. A greater understanding is necessary of what information speakers access during analogy, both in terms of which items and what information about them.
4. A greater understanding is necessary of how speakers process information during analogy. Currently, a highly diverse range of formal models perform well, indicating that new questions and sharper means of evaluation are needed.

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