

Opinion

Analogy as a Catalyst for Cumulative Cultural Evolution

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Analogies, broadly defined, map novel concepts onto familiar concepts, making them essential for perception, reasoning, and communication. We argue that analogy-building served a critical role in the evolution of cumulative culture by allowing humans to learn and transmit complex behavioural sequences that would otherwise be too cognitively demanding or opaque to acquire. The emergence of a protolanguage consisting of simple labels would have provided early humans with the cognitive tools to build explicit analogies and to communicate them to others. This focus on analogy-building can shed new light on the coevolution of cognition and culture and addresses recent calls for better integration of the field of cultural evolution with cognitive science.

Cultural Evolution and Cognitive Science: Bridging the Gap

Humans, like many other animals, have rich cultural lives in which behavioural variation is extensively acquired via **social learning** (see [Glossary](#)) from conspecifics, rather than via genetic inheritance [1–3]. Yet unlike other species, humans have become one of the most dominant ecological forces on the planet, thriving in diverse ecological niches in a short space of evolutionary time [4]. This ecological domination is often attributed to our uniquely **cumulative culture**, wherein our tools, technologies, and customs ‘ratchet-up’ in complexity in a way that is yet to be unequivocally demonstrated in other species [5–8]. Why only humans exhibit cumulative culture is argued by many cultural evolutionists to be due to our high-fidelity social learning, prosociality, and/or teaching capacity [9–12]. In contrast, cognitive scientists have argued that our capacity for higher-order abstraction is key to explaining the apparent discontinuity between human and non-human minds [13], and that we exceed other species in our ability to combine relations into higher order structures [14].

We believe that there is merit to both these perspectives, and that language and **analogy** crucially underpin both. Language is often acknowledged as essential for cumulative culture due to its role in teaching [15,16], but it is still unclear what it is about language that differentiates mere **culture** from **cumulative cultural evolution**. We argue that language uniquely allows humans to make explicit analogies that aid the social transmission of complex new behaviours.

Analogy has been studied by cognitive scientists and linguists for decades, and a substantial corpus of work has demonstrated the importance of analogies for perception and **categorisation** [17–19], relational reasoning and abstract representation [20–24], learning and reasoning in children [25–27], and language evolution [28–30], as well as the role of language in relational reasoning [14,21,24,31,32] and in structuring our thinking [24,33–35]. Indeed, some argue that analogy is the ‘core of our cognition’ [19,36]. To the extent that cognition is central to cumulative culture [37–42], we suggest that analogy should therefore be considered core to **cultural evolution** too. Our aim here is not to review the aforementioned cognitive science literature in detail, but to point to where we think it is relevant to, and can contribute to, cultural evolution research, which has

Highlights

Analogies map novel concepts onto familiar concepts, aiding the learning and transmission of novel information.

Analogies have been studied in cognitive science for years; here we connect this literature with the theory of cultural evolution.

Cultural evolution provides a framework for understanding how human culture changes over time, but has been criticised for a lack of emphasis on the cognitive and communicative mechanisms that support cultural transmission.

We suggest that a simple protolanguage consisting of labels would have catalysed cumulative cultural evolution by allowing analogy-building to proliferate.

Labelling a novel object or action in relation to a familiar one would be particularly helpful for the transmission of cognitively opaque sequences, on which much of human cumulative culture relies.

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been criticised for placing too much focus on high fidelity cultural transmission and various social learning strategies, and not enough on the cognitive processes or communication mechanisms that support cultural transmission [38,39,41–43]. A focus on **analogy-building** can remedy this and help explain our species' unique capacity for cumulative culture.

What is Analogy-Building?

An analogy is a cognitive device by which a concept is mapped onto another concept based on its perceptual or conceptual similarities. We define analogy-building specifically as labelling novel perceptual or conceptual information on the basis of its relationship to some other previously perceived or conceived category [18,20]. Although in everyday parlance analogies are often viewed as sophisticated linguistic flourishes, we use a broader definition of analogy that does not require complex language, claiming analogy to be a foundational aspect of perception, learning, and categorisation [17,19,35,44–46]. While cognitive scientists typically focus on the computational aspects of producing or parsing analogies, we focus instead on the act of analogy-building to learn and, crucially, to communicate new information. A simple example is instructing a child to 'cup' their hands (hold them in the shape of a cup) to hold water by saying the single word 'cup', rather than dictating the precise arrangement that their fingers and hands must make. A more complex example is the story used to teach how to tie a bowline knot by referring to a rabbit running around a tree (Figure 1). Here, the end of the rope is labelled a 'rabbit' and the loop a 'burrow', to aid memorisation of the sequence. In this way, complex cultural information can be rapidly and effectively communicated.

The Role of Analogy in Language Evolution

We argue that the emergence of a simple **protolanguage** in human evolutionary history greatly enhanced our analogy-building capability compared to that of non-human animals, catalysing the process of cumulative cultural evolution in our lineage (Figure 2, Key Figure). Although some **analogical reasoning** can be performed in the absence of language (Box 1), a form of protolanguage capable of simple verbal labels would have allowed early humans to link novel stimuli to familiar stimuli via analogical labels and to communicate this link to others (Figure 2). As highlighted in Figure 2, we are predominantly concerned with a stage of language evolution in which word labels are present, but abstract words such as 'similar/different' need not be. Although comparison terms are clearly important in analogy-making [47], our interest is in the more general property of all words to act as analogies [19]. Iconicity (i.e., a similarity between a



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Figure 1. Bowline Knot Analogy. Images for tying a Bowline knot (adapted from www.animatedknots.com). Tying a Bowline contains multiple steps that must be performed in a specific order that is difficult to infer from the finished product. A commonly used 'rabbit' analogy aids memorisation of the order. (1) Here is the rabbit burrow. (2) The rabbit comes out of the burrow. (3) The rabbit goes around the tree. (4) The rabbit goes back down the burrow. This is typically much easier to remember than 'put the rope end through the loop from underneath, wrap it around the other piece of rope above the loop, then put the same rope end through the same loop from above'. Instead the information gets compressed into a story about a rabbit, which is more easily remembered due to its familiarity. Memory load is reduced to imagining that the rope end represents a rabbit, and the rest follows without having to recall any further information about the rope itself. These analogies are created based on shared perceptual features (e.g., a loop of rope looks like a rabbit burrow).

Glossary

Analogy: A cognitive device by which a stimulus/object/action/concept is labelled or described based on its similarities to a familiar stimulus/object/action/concept. An example is the rabbit analogy used for tying a knot in Figure 1.

Analogy-building: labelling a novel object or action in relation to its perceptual or conceptual similarities to a familiar object or action.

Analogical reasoning: the ability to make inferences about a new situation based on its similarity to an old situation, or the ability to transfer rules learnt in one domain to a new domain.

Categorisation: the compressing and classifying of perceptual information into discrete kinds on the basis of its relationship or similarity to previously perceived information.

Causal understanding: knowledge of the constituents, properties, and physics of a system that allows an individual to explain or predict how antecedent circumstances lead to consequences. May be represented as a story or model.

Culture: information capable of affecting individuals' behaviour that is acquired from conspecifics through teaching, imitation, and other forms of social learning/cultural transmission. This information may be stored in individual brains or in the physical or institutional features that structure individuals' behaviours.

Cultural evolution: the processes by which socially learned cultural variation changes over time; a theoretical framework developed from analogies between genetic and cultural change.

Cumulative culture: behaviours or artefacts that have accumulated innovations over time that increase their functionality or efficiency.

Cumulative cultural evolution: the processes by which a culturally evolving behaviour or artefact accumulates innovations over time that increase its functionality or efficiency.

Protolanguage: a precursor to modern human language that consists of a more basic form of language, perhaps lacking grammar, syntax, or recursion.

Social learning: acquiring new behaviour through observation of, or interaction with, conspecifics.

WEIRD: an acronym designating western, educated, industrialised, rich, and democratic societies. Often used to highlight the overreliance of

sign and its meaning), is likely to have played a crucial role in the origin and evolution of words specifically, perhaps at stage 2 of Figure 2 [48,49]. Metaphor, meanwhile, likely plays a major role in shaping cognition [50,51], but at a later evolutionary stage given that metaphor, as it is often conceived, requires complex linguistic conventions that are unlikely to have been present in protolanguage. Finally, we acknowledge that the process of cumulative cultural evolution contributes to the cultural evolution of language itself [52]. However, our focus here is on the origin of communicative analogy-building and its role in the evolution of human behaviour.

psychological research on participants from these societies, which do not represent the majority of human variation.

Although there is considerable debate as to when the first protolanguages emerged and whether they were predominantly lexical, gestural, musical, or holistic, our theory fits with recent evidence that a protolanguage capable of providing verbal labels likely emerged sometime between *Homo habilis* and *Homo sapiens*, with *Homo erectus* a likely candidate [53–57]. This timing is consistent with evidence suggesting that the manufacture of sophisticated stone tools likely relied on some form of protolanguage, with Oldowan tools potentially providing a selective gradient for the evolution of verbal teaching in early *Homo* [58], and Acheulean tools almost certainly requiring a form of verbal protolanguage [54]. The social learning of tool use and production is often touted as a key selection pressure for the evolution of language and teaching [16,59]. Evidence for a ‘cognitive coupling’ theory of language evolution linking tool use and protolanguage comes

Key Figure

Stages of Protolanguage Relevant to Analogy-Building

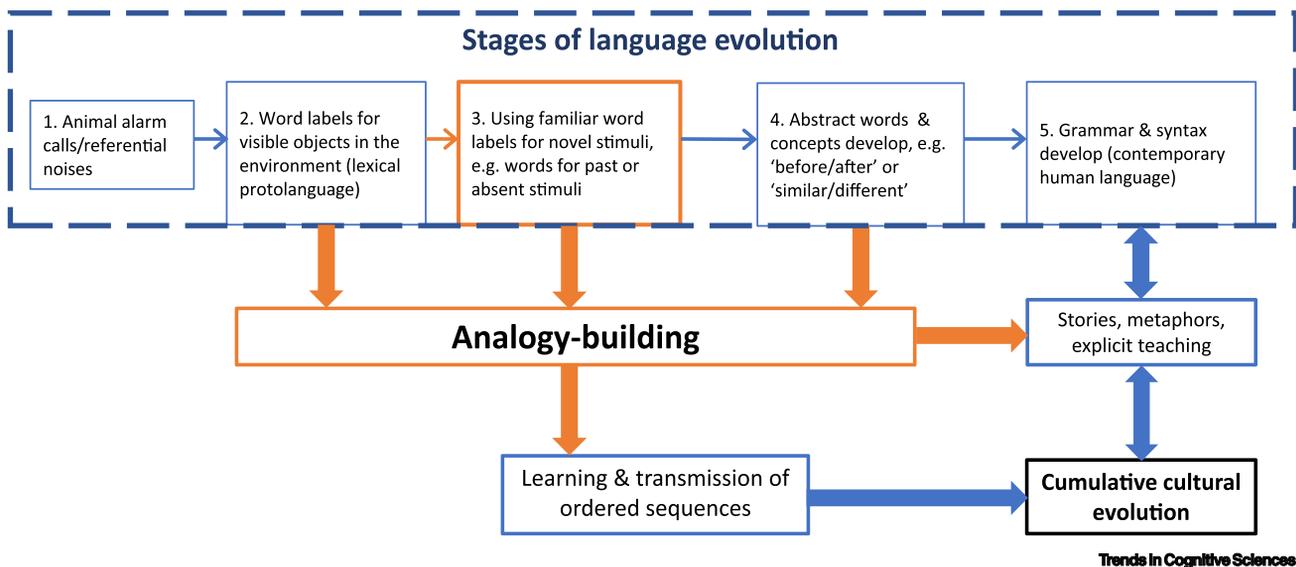


Figure 2. Proposed stages of protolanguage leading to analogy-building and cumulative cultural evolution. The thin arrows represent a step in language evolution, and the thick arrows represent a contribution to a process. The orange arrows represent the particular steps and processes that we are focussing on in this paper, and that we believe bring important insights to the study of cultural evolution. A form of protolanguage in which familiar words are used to label novel stimuli would allow for analogy-building (Stage 3), for example by labelling a new object or action as a past/absent object or action (e.g., labelling a new tool as a ‘tooth’ due to its functional and perceptual similarities: sharp, pointed, used to cut through meat). Being able to label and link multiple actions via an analogy would enhance the learning and transmission of ordered sequences, necessary for the cumulative cultural evolution of complex technology. Once human language evolved to its contemporary form (including complex grammar and syntax), then stories, metaphors, and explicit teaching contribute to the process of cumulative cultural evolution as well, a process which feeds back into the cultural evolution of stories, metaphors, and language itself, represented by the bidirectional arrows. We suggest that iconicity is likely to have been involved in stage 2, and that metaphor would not be possible until Stage 5. It is Stage 3 that we are focussing on in this paper.

Box 1. Is Analogy-Building Unique to Humans?

Although the explicit analogy-building we refer to here relies on a basic protolanguage, a more fundamental capacity for analogical reasoning likely exists in many non-human animals, at least in the sense that non-human animals are capable of categorisation [85–87].

Analogical reasoning can be defined as applying learnt rules from one context to another. The extent to which non-human animals can perform analogical-reasoning tasks is debated. Evidence of analogical reasoning in rats was provided by Murphy and colleagues [88], in an experiment in which rats learnt to differentiate sequences of stimuli based on simple rules, and then applied these learnt rules to novel stimuli sequences. However, a carefully controlled version of this experiment found that neither rats nor pigeons could generalise based on learnt rules, but that rats and pigeons instead appeared to generalise based on perceptual features [89]. For example, when learning that stimuli combination 'AB' predicts a different outcome to either stimulus 'A' or 'B' humans were able to infer that 'CD' predicted a different outcome to 'C' and 'D'. By contrast, rats and pigeons incorrectly predicted the same outcome for the compound stimulus based on the perceptual overlap of CD with its component parts C and D.

The best evidence so far of analogical reasoning in non-human animals comes from relational match-to-sample tasks in language- or symbol-trained apes [90–93]. These experiments involve matching sequences of stimuli as described previously. The likely difficulty that non-human animals have with such tasks is overcoming memory constraints, particularly for ordered sequences of stimuli [61]. One solution to the problem of memory constraints is to chunk information by providing a shorthand for subsections of sequences. Arbitrary symbols allow such chunking, which could explain why those best able to perform these tasks are symbol- or language-trained apes.

Although non-human animals may be capable of analogical reasoning, evidence of their analogy use in communication is almost non-existent. Tantalising examples come from the language-trained parrot Alex [94], and a sign-language trained chimpanzee Washoe [95], in which the animals combined learned words to describe a novel stimulus, such as 'water bird' for 'swan'. Evidence so far suggests a non-human animal 'can make its analogical knowledge explicit only if it is first provided with a symbol system by which propositional representations can be encoded and manipulated' [92]. This reliance on a symbol system supports our theory that a form of lexical protolanguage would have enabled early humans to explicitly build analogies between concepts, and crucially to communicate these with others.

from the observed coupling of the neural communication system with circuits related to complex motor sequence processing and action planning [59]. We agree that the capacity for language likely coevolved with cognitive mechanisms for sequence processing in the context of tool production, and suggest that this coupling occurred as a result of analogy-based protolanguage scaffolding the learning of complex sequences and motor actions by chunking ordered sequences into compressed, more memorable, and thus more communicable information (see 'ordered sequence learning' later).

Our theory of analogy-building resolves a common critique of lexical protolanguage: how vocal learning could have arisen to provide the flexible use of words in the first place [53]. The need to vocally learn many words would be drastically reduced if analogy-building was the core mechanism, because analogies reduce the number of words or phonemes that need to be flexibly controlled. If an individual only has five distinct sounds in their repertoire, these five sounds can be mapped onto many more than five stimuli using perceptual or conceptual similarities [60]. Thus, when using an already learnt utterance to refer to a novel stimulus, learning a novel utterance is not necessary. For example, imagine a prehistoric group with a lexical protolanguage including a word for 'tooth' but no words for knife/tool. An individual from this group might call a novel, sharp, and pointed item a 'tooth' when first encountering it, with no need to vocally learn a new label. Eventually these sounds can be combined, shortened, or moderated to provide distinct utterances once new categories are further developed and established in the population. For example, 'tooth' may drift into 'toother' or 'otooth' to distinguish reference to the tooth-like tool, or eventually 'hand tooth'. This hypothetical example demonstrates that if utterances for 'hand' and 'tooth' are already present in the protolanguage, analogy-building allows for more communicative flexibility without any increase in vocal flexibility per se.

Analogies Aid the Acquisition of Complex Information

Ordered Sequence Learning

Analogies help individuals learn complex ordered sequences, which is a core requirement of cumulative cultural evolution. For example, tool-making often involves many cognitively opaque steps that must be followed in a specific order to successfully construct even the ‘simplest’ of tools such as handaxes. Language enables us to chunk information into relevant analogies, by which ordered sequences can be more efficiently learnt and transmitted. This fits evidence that sequence learning represents a key difference between humans and other species [61]. A review of 108 experiments on sequence discrimination in 14 bird and mammal species found that non-human animals display a limited capacity for discriminating arbitrary sequences of stimuli, with some species needing thousands of trials to learn to discriminate a sequence of just two stimuli [61]. In contrast, humans typically learn arbitrary sequences of five to ten stimuli when presented just once or twice [61]. Non-human animals’ difficulty in discriminating ordered sequences is likely related to memory constraints, and language may help humans to overcome these constraints. Further evidence comes from a comparative study finding that human children are able to learn arbitrary spatial and item-based sequences through observation, whereas orangutans could only learn these via individual trial-and-error learning [62].

Analogy-building helps to explain this difference between human and non-human sequence discrimination. Recall the example of tying a bowline knot (Figure 1). Looking at the finished knot does not reveal how it was tied; the process involves multiple steps that must be performed in a specific order that is difficult to infer from the finished product. A commonly used analogy or ‘story’ aids memorisation of the order: ‘the rabbit comes out of the burrow, goes around the tree, and goes back down into the burrow’. This is easier to remember than ‘put the rope end through the loop from underneath, wrap it around the other piece of rope above the loop, then put the same rope end through the same loop from above’. The story about the rabbit uses familiar elements and schemas that are easily encoded; going in and out of burrows is typical rabbit behaviour. Moreover, it does not require encoding new information about either ropes or knots, as the analogy can be recalled and applied each time the knot is tied. Thus, the constraint of memory is overcome by chunking sections of the sequence into a shorthand, via analogy. Shared cultural information like that of rabbits and burrows is crucial for communicating relevant analogies that can be understood by others, as discussed later.

Labels, Categorisation, and Conceptualisation

Analogies aid in the categorisation of novel objects and concepts [14,31,61–63]. Indeed, some scholars have taken the strong position that the act of categorisation is primarily an exercise in analogy-building [17–19,36]. Even without taking this strong stance, it is clear that much of our ability to perform cognitive computations stems from the compression of information into categories, and this is further aided by the ability to explicitly assign a categorical label to an object [23,32,61,63]. Experimental evidence suggests that the ability to assign even previously meaningless labels to novel objects aids categorisation of, and memory for, those objects [61–63]. When familiar words or utterances can be used as labels for novel stimuli based on perceptual or relational similarities, analogies can be drawn between the properties of the label’s referent and properties of the novel stimulus, further aiding categorisation and reducing memory load. Here analogy-building not only reduces the cognitive load of novel information by anchoring it to already learnt information, but takes an abstract category from inside the individual’s mind and gives it an external, audible utterance that allows it to be manipulated and communicated.

Relating a novel action to a familiar concept makes the cultural transmission of sequences and behaviours considerably easier. If a group has a verbal label for ‘cup’, then asking a child to

'cup' their hands by simply using the word 'cup' is more effective than accurately describing the arrangement and movement that their fingers must make to achieve the same function. The difficulty of the latter is exacerbated if precise words for those actions and movements are not yet present in the lexicon. Considerable work in cognitive science has demonstrated the utility of characterising knowledge as a structured network of semantic and causal relationships, and analogies as mappings between the structural and perceptual relationships in different domains [17,20,29,45,64]. Analogy-building allows categories to become canalised into abstract concepts that can be manipulated cognitively, but crucially, it also allows those abstract concepts to be communicated effectively. Manipulation underlies all reasoning, whether about technical or social information [19,44]. The ability to manipulate concepts both individually and communicatively leads to explicit causal reasoning and eventually to technical understanding.

Causal Reasoning and Understanding

The ability to build and communicate analogies underpins **causal understanding** of complex concepts and technologies, which in turn facilitates the cumulative cultural evolution of those concepts and technologies. Analogy-building is a form of categorisation, and as categories are used more regularly they become canalised into readily-accessible labels. Those labels can be used to build and communicate analogies to others, allowing communities to converge on folk theories of processes based on their similarities to other already-understood processes. These folk theories may be over simplistic by scientific standards, while still allowing for practical application. An example is the complex process used to make Samurai swords in pre-industrial times [65,66]. A rich understanding of the physico-chemical processes involved in making the swords both strong and sharp was not achieved until the 20th century, and indeed the physics and chemistry underpinning the process continues to be updated. Instead, samurai sword making was surrounded by mythology and folk beliefs [67]. These beliefs allowed for high fidelity transmission of complex procedures based on analogies to other shared concepts and stories. Causal explanations that rely on analogies, even flawed analogies, are still causal explanations.

It is sometimes suggested that many products of cumulative cultural evolution can be successfully learnt and transmitted without causal understanding of how they are produced or why they are effective, and that causal reasoning or understanding often occurs post hoc [7]. However, causal understanding is not binary; rather, groups are constantly updating their theories of how systems work. Causal understanding and reasoning about a process may be scaffolded by (often flawed) analogies during learning and transmission. Although many anecdotal and ethnographic examples have been offered [7], and experiments show that improvements in some tasks can occur in the absence of causal understanding [68], no experimental investigation to date has demonstrated that complex, opaque technology can cumulatively evolve in the absence of causal understanding. In one recent study [68], participants found increasingly efficient solutions to a task, in which weights had to be placed on a wheel to make it descend a ramp as quickly as possible. Performance improved equally when causal theories could be transmitted alongside wheel designs as when designs were transmitted without causal theories. However, this task did not involve an ordered sequence of causally opaque steps, perhaps limiting the potential of causal understanding to improve solutions. Moreover, participants typically displayed some level of causal understanding, rather than none at all. In fact, a small number of participants spontaneously used analogies in their written accounts of the task, even though this was not intended to convey understanding to others. Participants compared the wheel task to ice-skating, Formula 1 driving, and being on a swing [e.g., 'the wheel covers the distance faster when the weights are close to the centre, just as if you stretch your legs on a swing that is spinning, it slows down', and 'one could compare the wheel to a Formula 1 car, which needs a low centre of gravity' (Derex, pers comm 2020)]. We hypothesise that individuals rely on folk theories

for the majority of systems we interact with day to day, and that these folk theories are underpinned by analogy.

Analogies Aid the Communication of Complex Information

Communication and Teaching

Human cumulative cultural evolution likely relies on teaching to ensure sufficiently high fidelity cultural transmission [16,69]. Some definitions of teaching require that the teacher adjusts their behaviour based on what the student does or does not know, leading to debates around whether theory of mind (i.e., understanding another's knowledge or belief state) is necessary for effective teaching [70]. Analogy-based teaching involves describing the elements of the new domain by analogy to another previously-learned domain, and aids learning in children [71,72]. The evolutionary burden of theory of mind in the context of teaching is reduced with a protolanguage that can reference already-shared concepts via analogy. Referencing similarities to shared concepts automatically creates a shared perspective between teacher and student that does not require the ability to explicitly represent another's mental state. What is required is shared developmental and cultural information between the teacher and learner. As such, intense sociality is a prerequisite for analogy-based protolanguage.

For example, imagine a group who frequently hunt a 'Nattoo' bird with a large, fan-shaped crest (like a cockatoo). This group has a hand gesture that represents the Nattoo, holding four fingers splayed with thumb tucked-in. Now imagine this same hand position is required for a novel action sequence, because a strand of rope must be weaved between the splayed fingers whilst held in position by the thumb. A teacher could use the 'Nattoo' utterance to instruct a student to hold their fingers splayed in such a way. This utterance would not be helpful to a member of another group who does not know the bird or does not associate the 'Nattoo' utterance with this gesture. The use of the 'Nattoo' utterance does not require an explicit theory of mind, only the knowledge that using this utterance is likely to cause an individual who hears it to use the gesture. In this way, analogy-based protolanguage creates a stepping stone between instances of teaching without explicit theory of mind [73] and a teaching system relying on fully-fledged theory of mind like those present in contemporary human societies.

Are Analogies Too WEIRD?

It is sometimes claimed that teaching in pre-industrialised, small-scale societies does not take the explicit, verbal pedagogical form that it does in most western, educated, industrialised, rich, and democratic (**WEIRD**) or post-industrialised societies [74]. If explicit verbal teaching is only an artefact of contemporary WEIRD societies, this would undermine our argument that label-based protolanguage and explicit analogies coevolved to support cumulative cultural evolution. However, recent reviews of teaching in hunter-gatherers find that, although direct verbal instruction is relatively rare, it frequently occurs in domains of complex ecological knowledge or subsistence skill [74–77]. Evidence from seafaring navigators using traditional techniques in the Marshall Islands finds that the islanders conceptualise different wave patterns as resembling various tools used in their culture [78]. For example, one term used to describe a wave pattern is the same term as the pole that they traditionally use to harvest fruit from a breadfruit tree, with the V-shaped fork at the end resembling the pattern of the waves. Another term literally means 'pit for bird fighting' and refers to the small cage traditionally used to capture birds, with the intersecting bars of the cage resembling the intersecting waves [78]. This kind of analogical labelling, where a familiar term is used to label a complex pattern or concept based on perceptual similarities, is the exact type of communication that our theory predicts. A similar example of analogous labelling comes from the Pirahã, who famously do not have fixed colour terms in their language, but instead refer to items as 'looking like blood' to designate red [79]. This reflects a type of experience-based

communication that analogy-building relies upon, and that we predict would have been present in a hypothetical protolanguage. Indeed, this type of reference-based terminology is common in the world's languages across sensory modalities, particularly for the smell modality (e.g., in English, 'smells fishy/eggy') [80].

Although analogy-building per se has not been explicitly studied in small-scale societies, story-telling in some form appears to be universal in human communication and often accompanies complex cultural behaviours (Box 2). For example, sand drawing in Vanuatu, in which intricate sequences of geometric shapes and symbols are traced in sand without lifting a finger from the ground, is often accompanied by a verbal story or song that communicates valuable cultural knowledge to others [81]. With over 300 different designs, the patterns seem too complex to learn via imitation alone, and although this has not been formally tested, it is reasonable to assume that story-telling or singing aids the learning of the sequence. Further evidence from contemporary foraging groups suggests that analogy is commonly used for identifying safe versus poisonous mushrooms, for example by describing certain mushrooms as wearing hats or stockings [82]. These examples are consistent with our theory that verbal analogy use is necessary for communicating information that has a heavy memory load or involves learning a large number of complex patterns or associations.

Concluding Remarks

All Analogies Are Wrong, but Some Are Cumulative

Our theory of the role of analogy in the evolution of human cumulative culture is based on a consideration of the problem of communicating new information to naïve individuals. Analogies allow individuals to effectively communicate while avoiding the memory requirements of new jargon, enabling the linking of steps in an ordered sequence, and anchoring new information onto already-learned concepts for easier encoding and future retrieval. As individuals become more familiar with a concept, it becomes more solidified in memory, and the scaffolding of the analogy can be shed or updated. Furthermore, once one becomes a specialist, relevant information is learnt, condensed, and chunked differently, allowing one to build qualitatively different analogies that link different, or differently organised, aspects of the system [36]. This is how jargon emerges in

Box 2. Story-Telling

Stories provide shared knowledge of a set of situations that are likely to be useful to people in those societies. Thus, they shape the analogies that people have available and hence the ways in which they characterise the world, similarly to how formal models can provide mental models for scientists [96]. Humans have been characterised as 'the storytelling animal', with evidence put forward for the centrality of stories in human life as well as their universality in human societies [97]. Shared stories function as a communal analogy pool, in that the whole community is guaranteed a set of shared parables, myths, and legends, to support teaching of not only practical but also moral, religious, and spiritual information. Having these ready-made shared concepts means not all concepts have to come from direct experience, but can be communicated within the group with reference to the story. This transmission of valuable cultural knowledge via story-telling has been particularly well documented as part of Aboriginal 'dreamtime' culture and is common to many small-scale societies all over the world [74,75,98].

In WEIRD societies, story-telling is becoming a popular strategy for science communication initiatives [99]. Evidence suggests that putting the usually abstract and unfamiliar process of scientific discovery in the context of a story makes the information more accessible and digestible, and memorable analogies are an acknowledged form of science communication [100,101]. Analogies themselves are abundant in the history of science, whether for describing the structure of an atom as planets orbiting the solar system, enzyme receptor systems as a lock and key, or carbon dioxide as a glass pane in a greenhouse. Studies have found that metaphors and analogies are helpful for transmitting complex scientific concepts, whether for specific concepts such as thermodynamics and algorithms [102,103], or for science education in general [104,105]. The use of metaphor and story-telling requires contemporary language, including some form of grammar, syntax, and recursion, and thus involves a more complex type of analogy-building than we are focussing on in this paper. Nevertheless, evidence suggests the ongoing use of analogies and metaphors today facilitates the ongoing cumulative cultural evolution of complex concepts and technology.

Outstanding Questions

Do analogies aid the learning and transmission of cognitively opaque ordered sequences?

Does labelling novel objects and actions with familiar labels aid the learning and transmission of these objects and actions?

Do hunter-gatherer communities use analogies to aid the transmission of complex tools and artefacts?

Is analogy-building a human universal?

Are there systematic cultural differences in the way analogies are used for thinking and communication?

Do analogies aid the transmission and persistence of complex, counter-intuitive concepts?

Does analogy-building explain the difference between human and non-human animal cultural evolution and cognition?

Can cumulative cultural evolution occur in the absence of language?

Can cumulative cultural evolution occur in the absence of any causal understanding?

communities of experts. Experts no longer need the original anchors to remember or process information in their domain of expertise, and may find that the originally-learned analogies miss complexities and details that have since been discovered or understood. In these cases, an analogy learned early on may become a hindrance, an oversimplification that misses nuance. This may explain why many experts, scientists included, are often poor communicators in their domain of expertise; they are unwilling to oversimplify the nuances of their work for the goal of easing a novice into a new topic.

Analogies create value by highlighting similarities between two or more objects, events, or systems, similarities that exist in some particular contextual framing. A teddy bear is like a real bear by virtue of its shape and appearance, but this analogy does not provide us with useful information about the teddy bear's interior or whether we should approach a real bear for a cuddle. No analogy is perfect, because the whole point of an analogy is to draw connections between different things. Analogies often rely on complex linguistic structuring and will inevitably break down as more details of a system come to light. The limitations of analogies impinge on the history of science, as models of phenomena are replaced with new models that serve as increasingly generalisable analogies, what Kuhn [83] called 'paradigm shifts'. Examples of widespread analogies in the history of science include the characterisation of light as a wave or of the brain as a computer. These analogies, once learned, become fodder for future analogies. For example, if the brain is a computer, then perhaps a society is a supercomputer [84]. This accumulation of analogies is part of what facilitates cumulative culture. In the 1930s, when Alan Turing's original papers on computability were written, it would have been near impossible to explain to someone what a digital computer is and how it works; the underlying mechanics and mathematics were too dense to be easily accessible or understood. Now, after years of analogy to ease our familiarity ('desktops', 'folders', and 'documents'), we have useful concepts about how computers work, and so we have a new analogy for the brain, an analogy that wouldn't have been possible a century ago and one that provides new ways to conceptualise parts of the brain and how it works.

Analogy-Building as the Core of Cumulative Cultural Evolution?

Hofstadter argues that analogies are the core of cognition [36]. We argue further that analogy-building was a catalyst for cumulative cultural evolution. Our hypothesis is that once a protolanguage consisting of simple labels evolved, our capacity for analogy-building snowballed, allowing for the acquisition and transmission of complex ordered sequences that are the bedrock of cumulative cultural evolution. Although theories of cumulative cultural evolution provide a plausible explanation of human ecological success [7, 10], they have so far left individual cognition in a black box. These theories therefore provide little satisfactory explanation for the underlying computational and neurological underpinnings of human cultural transmission, nor our subjective cognitive experiences. Furthermore, our seemingly unique capacity for language has often been left in the wings, hailed as an effective sidekick for high-fidelity transmission, rather than being allowed centre stage in the story of how cultural innovations accumulate. Our focus on analogy-building shows why language should be in the limelight. As the roles of cognition and language are taken more seriously, insights from both cognitive science and cultural evolution can recombine to produce an improved understanding of the coevolution of cognition and culture.

Building on the ideas put forward in this paper, we propose a research programme in which the role of analogy in cumulative cultural evolution is investigated (see Outstanding Questions). Firstly, it should be possible to test using formal modelling when the benefits of an analogy-based communicative system can off-set some of the biological costs of developing a high-fidelity teaching mechanism that is needed for cumulative culture. We also predict that experimental transmission chains in which analogical labels (e.g., familiar labels from a different context) are used would

allow for better transmission of novel behavioural sequences than chains which use non-analogical labels (e.g., nonsense words lacking any context). This type of experiment would differentiate between the effects of labelling with and without analogy-building. We further predict that the transmission of complex or counter-intuitive concepts are better transmitted via analogy than through purely literal argumentation. We hypothesise that participants in teaching conditions of cumulative culture transmission chain experiments (e.g., [58,69]) who use analogical language will better transmit the technology at hand than those who use non-analogical language. These experimental set-ups could be expanded to include conditions that allow for analogical language, or simple analogical labelling of apparatus, to investigate if, when, and how, analogy-making improves the transmission of novel behavioural sequences or novel concepts.

To summarise our argument, analogy-building allows an individual to learn a novel behaviour or concept by anchoring it to a familiar behaviour or concept. Once an individual could externalise this mapping as a verbal label, the analogy could be communicated to others, facilitating the spread of novel behaviours and concepts through communities, and ultimately catalysing cumulative cultural evolution.

Declaration of Interests

The authors have no interests to declare.

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