Computational Theories of Cognition- Part II: Logic-Based Models of Cognition.

Alireza Dehbozorgi
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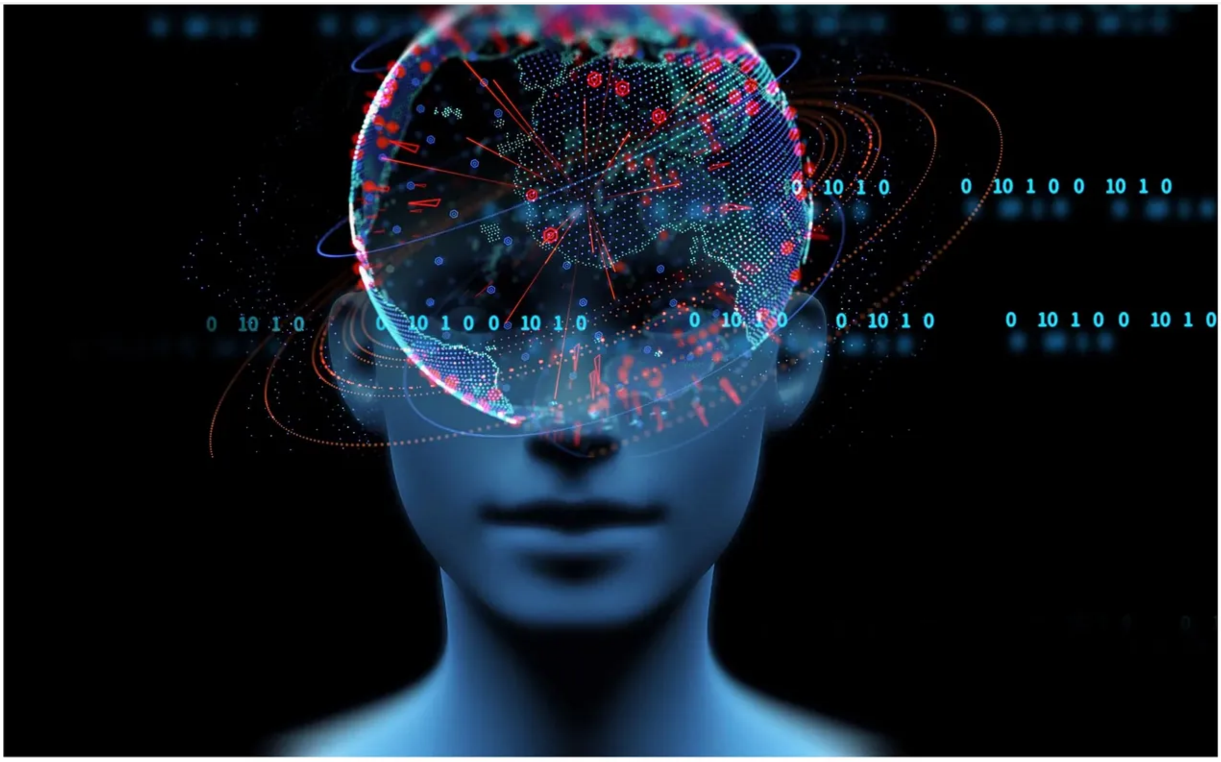

This article explains the approach to reaching the overarching scientific goal of capturing the cognition of persons in computational formal logic. The cognition in question must be coherent, and the person must be at least human-level (i.e., must at least have the cognitive power of a human person).

This snippet shall simply take faute de mieux a person to be a thing that, through time, in an ongoing cycle, perceives, cognizes, and acts (Sun & Bringsjord, 2009). The cognizing, if the overarching goal is to be reached, must be comprised, all and only, of that which can be done in and with computational formal logics. Since it has been proved that Turing-level computation is capturable by elementary reasoning over elementary formulae in an elementary formal logic, any cognition that can be modeled by standard computation is within the reach of the methodology described herein, even with only the simplest logics in the universe. However, it is important to note a concession that stands at the heart of the logicist research program explained herein: viz. that even if this program completely succeeds, the challenge to cognitive science of specifying how it is that logic-based cognition emerges from, and interacts with, sub-logic-based processing in such things as neural networks will remain. Theoretically, in the artificial and alien case, where the underlying physical substrate may not be neural in nature, this challenge can be avoided, but certainly in the human case, as explained long ago by Sun (2002), it cannot: humans are ultimately brain-based cognizers, and have a "duality of mind" that spans from the subsymbolic/neural to the symbolic/abstract.

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- **What is Formal Logic, then?**

It suffices to provide two necessary conditions for something's being a formal logic.

1. One cannot have a formal logic unless one has a formal specification of what counts as a formula, and in the vast majority of cases this specification will be achieved by way of the definition of a formal language $\mathscr{L}$ composed minimally of an alphabet **A** and a grammar ***G***. Without this, one simply does not have a formal logic; with this, one has the ability to determine whether or not a given formal logic is expressive enough to represent some declarative information. Importantly, it is often the case that some natural-language content to be expressed as a formula in some (formal) logic $\mathscr{L}$ cannot be intuitively and quickly expressed correctly by a simple formula in the formal language for $\mathscr{L}$, so that the formula can then be used (for example by a computer program) instead of natural language.

2. Any bona fide logic must have a fully specified system for checkable inference (chains of which are expressed as proofs or arguments, where each link in the chain conforms to an inference schema), and/or a fully specified system for checkable assignments of semantic values (e.g., true, false, probable, probable at value (some number) ***k***, indeterminate, etc.) to formulae and sets thereof.

For more reader-friendly to formal/mathematical logic, see (1), among others.

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- **What is a Computational Formal Logic?**

An easily graspable definition would be that a computational logic is just a logic that can be used to compute, where computing is cast as inference of some sort. Since computing in any form can be conceived of as a process taking inputs to outputs by way of some function that is mechanized in some manner, in the logicist approach to cognition, the mechanization consists in taking inputs to outputs by way of reasoning from these inputs (and perhaps other available content). This is as a matter of fact exactly how logicist programming languages, for instance Prolog, work. Often the inputs are queries, and the outputs are answers, sometimes accompanied by justificatory proofs or arguments. When Newell and Simon presented their system Logic Theorist at the dawn of artificial intelligence (AI) in 1956, at Dartmouth College, this is exactly what the system did. The logic in question was the propositional calculus, the inputs to Logic Theorist were queries as to whether or not certain strings were theorems in this logic, and the outputs were answers with associated proofs. For more details, see the seminal paper of Newell and Simon's (1956); for a recent overview of the history to which we refer, in the context of contemporary AI, see Bringsjord and Govindarajulu (2018) and Russell and Norvig (2020).

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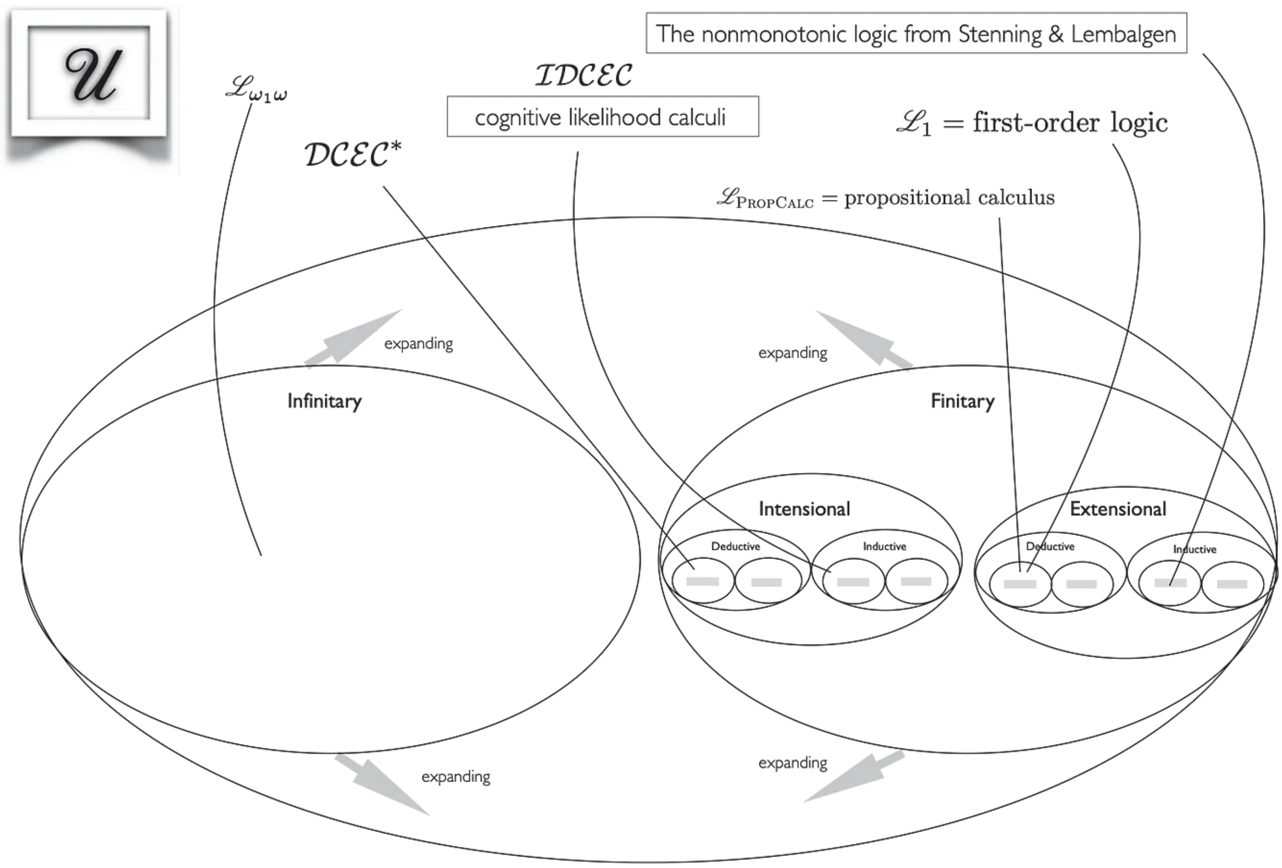
- **What is Cognition?**

Now to the next preliminary to be addressed, which is to answer: What is cognition? And what is it to cognize? Put another way, this pair of questions distill to this question: What is the target for logicist cognitive modeling?

Fortunately, an efficient answer is available: Cognition can be taken to consist in instantiation of the familiar cognitive verbs: *communicating*, *deciding*, *reasoning*, *believing*, *knowing*, *fearing*, *perceiving*, and so on, through all the so-called propositional attitudes (Nelson, 2015). In other, shorter words, whatever cognitive verb is targeted in human-level cognitive psychology, for instance in any major, longstanding textbook for this subfield of cognitive science (e.g., see Ashcraft & Radvansky, 2013), must, if the overall goal of logicist modeling is to be achieved, be captured by what can be done in and with computational formal logics.

But how is it known when logicist cognitive modeling of human-level cognition succeeds? Such modeling succeeds when selected aspects of human-level cognition are captured. But what is it to "capture" part or all of human-level cognition in computational formal logic? After all, is not "capture" operating as a metaphor here, and an imprecise one at that? Actually, the concept of formal logic managing to capture some phenomena is not a metaphor; it's a technical concept, one easily and crucially conveyed here without going into its ins and outs. Some phenomena $\boldsymbol{P}$ is captured by some formal content $\boldsymbol{C_p}$, expressed in a (formal) logic $\boldsymbol{L}$, if and only if all the elements $\boldsymbol{p}$ in $\boldsymbol{P}$ are such that from $\boldsymbol{P}$ one can provably infer in $\boldsymbol{L}$ the formal counterpart $\boldsymbol{C_p}$ that expresses $\boldsymbol{p}$.



The ever-expanding universe of logics. The universe of formal logics can be first divided into those that allow expressions which are infinitely long, and those that do not. Among those that do not, the propositional calculus and first-order logic have been much employed in CogSci and AI. The boxed logics are the ones key to the upcoming analysis and discussion. Note that in the previous section there was crucial use of L_1. (Courtesy of Stenning & Lambalgen (2008))

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- **Quantification and Logic**

From the perspective of those searching to capture human-level cognition via logic, there can be little doubt that quantification is a key, perhaps the key, factor upon which to focus. Some quantification at work has already been seen previously in this chapter, in connection with both the vehicular domain and elementary arithmetic. Hence the reader is now well aware of the fact that "quantification" in the sense of that word operative in logicist computational cognitive modeling (LCCM) has nothing to do with conventional construals of such phrases as "quantitative reasoning." Such phrases usually refer to quantities or magnitudes in some numerical sense. Instead, in formal logic, and in LCCM, quantification refers specifically to the use of of quantifiers such as "all," "some," "many," "a few," "most," "exactly three," and so on. In particular, this chapter has placed and will continue to place emphasis upon the two quantifiers that are used most in at least deductive formal logics, the two quantifiers that (accompanied by some additional machinery) form the basis for most of the formal sciences, including mathematics and theoretical computer science. These two quantifiers are exactly the ones we have already seen in action previously: ∀ (read as "for every" or "for all") and ∃ (read as "there is at least one" or "there exists at least one"). Again, when these two quantifiers are employed, almost invariably they are immediately followed by an object variable, so that the key constructions are $\forall \upsilon$ and $\exists \upsilon$, where, as above, υ is some object variable, for example x, y, or z. These constructions are read, respectively, as "For every thing υ . . . " and "There exists at least one thing υ such that . . .." The ellipses here are stand-ins for formulae in the relevant formal language.

As a matter of empirical fact, a focus on quantification in the study of the mind, at least when such study targets human/human-level cognition, has long been established, and is still being very actively pursued. For example, since Aristotle, there has been a sustained attempt to discover and set out a logicbased theory that could account for the cognition of those who, by the production of theorems and the proofs that confirm them, make crucial and deep use of quantification (Glymour, 1992). The first substantial exemplar of such cognition known to us in the twenty-first century remains the remarkable Euclid, whose reasoning Aristotle strove (but failed) to formalize in Organon (McKeon, 1941), and some of whose core results in geometry are still taught in all technologized societies the world over. In fact, it is likely that most readers will at least vaguely remember that they were asked to learn some of Euclid's axioms, and to prove at least simple theorems from them. If this request met with success, the cognition involved included understanding of quantification (over such things as points and lines, reducible therefore to quantification over real numbers).

What about contemporary study of human-level-or-above cognition by way of quantification? Given space restrictions, it is not possible to survey here all the particular research in question; only a few specific examples can be mentioned, before the reader is taken into a deeper understanding of quantification, and from there through a series of aspects of quantification that are important to LCCM. As to the examples of sample quantification-centric research, Kemp (2009), under the umbrella conception that there is a human "language of thought," advances the general idea that this language is that of a logic, one that appears to correspond to a kind of merging of first- and second-order logic (i.e. $\mathscr{L}1$ and $\mathscr{L}2$). He advances as well the specific claim that first-order quantification is easier for the mind to handle than the second-order case. Below, the distinction between first- and second-order quantification is explained, in connection with our vehicular microworld.

As one might expect given how large a role quantification plays in all human natural languages (such as English) as a brute empirical fact (the comma that immediately follows the present parenthetical ends a phrase that has one universal quantifier and one existential one), the connection between linguistic cognition at the human-level and quantification is a deep one. In fact, Partee (2013) argues that quantifiers should be the main pivot around which cognitive linguistics from a formal point of view is pursued. In a particular foray in just this direction, more recently Understanding Quantifiers in Language (2009), Szymanik has explored a connection between different kinds of quantifiers and computational complexity, based in part upon experiments that involve vehicular scenarios of their own (and which in part inspired the somewhat more versatile ones used herein).

It is now time to convey a deeper understanding of quantification, and the nexus between it and cognition at a number of points, starting with higherorder quantification.

- **Quantification in Higher-Order Logic**

One of the interesting, apparently undeniable, and powerful aspects of human-level cognition is that it centrally involves not only use of relations such as "is a bus" or "is a car" (which are of course represented, respectively, by the relation symbols B and C in the vehicular setup), but also relations that can be applied to relations. A body of cognitive-science work indicates this capacity to be present in, and indeed routinely used by, humans (Hummel 2010; Hummel & Holyoak, 2003; Markman & Gentner, 2001). Using resources of LCCM, specifically a logic from ***U*** well-known to practitioners of logic-based modeling, this aspect of human-level cognition is quite easy to express in rigorous terms. More specifically, LCCM has available to it higher-order logics. First-order logic (**FOL**) = *ℒ1*, as has been seen previously, permits only object variables, so named because they refer to objects, not relations (or properties or attributes); the logic *ℒ* does not have relation variables. To make this concrete, *ℒ1* consider vehicular scenario #2 for a minute. Note, upon studying this scenario, that the immediately following declarative sentence holds in it.

Now let's translate the following sentence (from Kemp 2009) into FOL. (2) would be the FOL equivalent counterpart of (1):

1) *There is at least one color property (relation) that holds of every vehicle north of every bus.*

$$\forall x[(\forall y(\boldsymbol{B}(y) \rightarrow \boldsymbol{N}(x,y))) \rightarrow \exists \boldsymbol{X}(\boldsymbol{X}(x) \wedge \boldsymbol{C}(\boldsymbol{X}))]$$

(2) The FOL translation of (1)

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- **Quantification and the Infinite**

As is well-known, human-level cognition routinely involves infinite objects, structures, and systems. This is perhaps most clearly seen when such cognition is engaged in the learning and practice of mathematics, and formal logic itself. All readers will for example recall that even basic high-school geometry invokes at its very outset infinite sets and structures. As to such sets, we have N and R, both introduced previously, these being two specimens that every high-school graduate needs to demonstrate considerable understanding of. And as to structures based upon these two infinite sets, readers will remember as well that for instance two-dimensional Euclidean geometry is based upon the set of all pairs of real numbers. Within this context, it turns out that cognition associated with even some elementary quantification in $\mathscr{L}_1$ instantly and surprisingly provides an opportunity to zero in on cognition that is compelled to range over infinite scenarios; and an excellent way to acquire deeper understanding of LCCM and its resources is to reflect upon why such scenarios are forced to enter the scene. Notice that so far vehicular scenarios have been decidedly finite in size.

In order to reveal the quantification in question, consider the following three straightforward natural-language sentences pertaining to vehicles:

(3) No vehicle honks at itself.

(4) If x honks at y and y honks at z, then x honks at z.

(5) For every vehicle x, there's a vehicle y x honks at.

This trio is quickly represented, respectively, by the following three extremely simple formulae in $\mathscr{L}_1$:

$$\forall x \neg H(x, x)$$
$$\forall x \forall y \forall z [(H(x, y) \land H(y, z)) \to H(x, z)]$$
$$\forall x \exists y H(x, y)$$

Fig. 2- The Logical Translation of 3, 4, 5, respectively

Now here is a question: Can a human understand that the axioms in Fig. 2 , despite their syntactic simplicity, cannot possibly be rendered true by a vehicular scenario that is finite in size? The reader can answer this question by attempting to build a scenario that does in fact do the trick. A sample try is enlightening. For example, consider the vehicular scenario shown in Figure 5.5; for the moment, ignore the use made there repeatedly of the ellipsis. The reader should be able to see that the scenario in fact does not render *Fig. 2* true, and should be able to see why. In order to construct a vehicular scenario that works, the reader will need to understand that an infinite progression of vehicles will need to be used, with an infinite number of honks. It is not difficult to see that the cognition that discovers and writes down such an infinite scenario can itself be modeled using the resources of LCCM.

It is incredibly important to share herein that formal logic is the basis for all of human-known mathematics, and that given this, it seems rather likely that if mathematical cognition of the sort that produced/produces mathematics itself (as archived in the form of proved theorems passed from generation to generation) is to eventually be accurately modeled, LCCM will be the key approach to be employed. But the specific, remarkable, and relevant point to quickly make here is that it is quantification that is the bedrock of mathematics. It is the bedrock because mathematics flows from axiom systems whose power and reach are primarily determined by the modulated use of quantification. 15 To see this, we turn to arithmetic, and to the axiom system known as *'Peano Arithmetic' (PA)*, mentioned b below now to be seen in some detail. PA consists of the following six axioms, plus one axiom schema (which can be instantiated in an infinite number of ways). Here, the function symbol s denotes the function that, when applied to a natural number $n \in N$, yields its successor (so e.g., *s(23)= 24*). Multiplication and addition are symbolized as normal.

Axiom 1 $\forall x(0 \neq s(x))$
Axiom 2 $\forall x \forall y(s(x) = s(y) \rightarrow x = y)$
Axiom 3 $\forall x(+(x, 0) = x)$
Axiom 4 $\forall x \forall y(+(x, s(y)) = s(+(x, y)))$
Axiom 5 $\forall x(\times(x, 0) = 0)$
Axiom 6 $\forall x \forall y(\times(x, s(y)) = +(\times(x, y), x))$
Induction Schema Every formula that results from a suitable instance of the following schema, produced by instantiating ϕ to a formula:

$$[\phi(0) \wedge \forall x(\phi(x) \rightarrow \phi(s(x))] \rightarrow \forall x \phi(x)$$

Fig. 4: Peano's Axioms

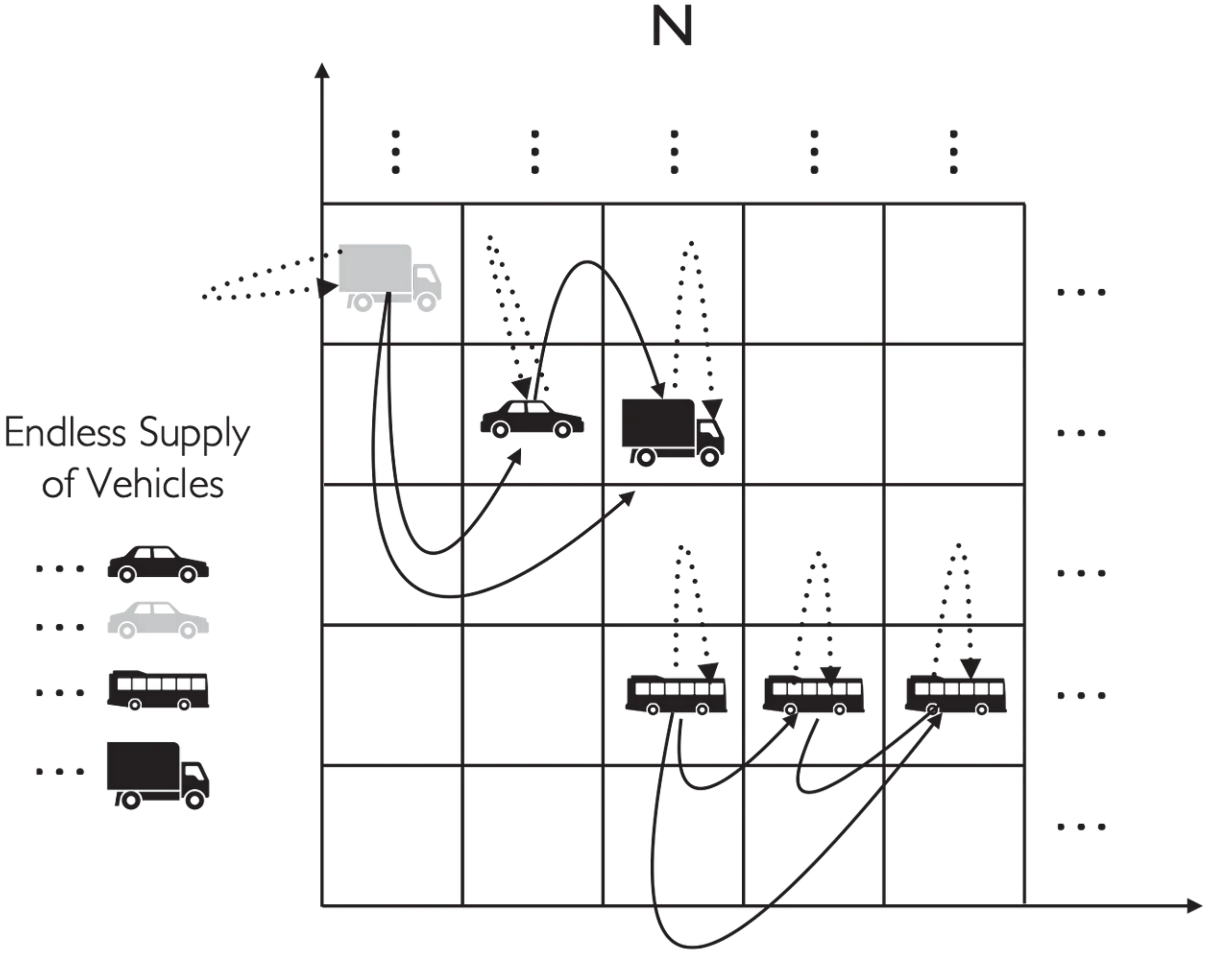

Fig. 5: **A “failing” vehicular scenario. The scenario here fails to model the three rather simple quantified formulas specified in the body of the present chapter. The sedulous reader should ascertain why this failure occurs.**

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- **Defeasible/Nonmonotonic Reasoning**

Deductive reasoning of the sort visited above, in connection with both arithmetic and the vehicular microworld, is monotonic. To put this more precisely, to say that if a formula ϕ in some logic can be deduced from some set Φ of formulae (written $\Phi \vdash$ I, where the subscript I gets assigned to some particular set of inference schemata for precise deductive reasoning), then for any formula $\psi \notin \Phi$, it remains true that $\Phi \cup \{\psi\} \vdash \phi$. In other words, when the reasoning in question is deductive in nature, new knowledge never invalidates prior reasoning. More formally, the closure of Φ under standard deduction (i.e., the set of all formulae that can be deduced from Φ via I), denoted by Φ <sup> I <sup> , is guaranteed to be a subset of $(\Phi \cup \Psi) \vdash$ I‘ , for I all sets of formulas Ψ. Inductive logics within the universe U do not work this way, and that’s a welcome fact, since much of real life does not conform to monotonicity, at least when it comes to the cognition of humans.

There are many different logic-based approaches that have been designed to allow such modeling and simulation, and each approach is associated with a group of logics. Such approaches include: use of default logics (Reiter, 1980), circumscription (McCarthy, 1980), and the approach probably most cognitively plausible: *argument-based defeasible reasoning* (e.g. see for an overview, and an exemplar of the approach, respectively Pollock 1992, Prakken & Vreeswijk, 2001). An excellent survey, one spanning AI, philosophy, and computational cognitive science, the three fields that work in defeasible/nonmonotonic reasoning spans, is also provided in the Stanford Encyclopedia of Philosophy. Because argument-based defeasible reasoning seems to accord best with what humans actually do as they adjust their knowledge through time (e.g., Professor Jones and his students, if queried on the spot immediately after the notification of the tornado's path as to whether Jones' house still stands, will be able to provide arguments for why their confidence that it does has just declined), this section emphasizes the apparent ability of argument-based defeasible reasoning to capture human/human-level defeasible reasoning. It is in fact a rather nice thing about humans and defeasible reasoning that they are often able to explain, and sometimes show, by articulating arguments, why their beliefs have changed through time as new information is known or at least believed, where that new information leads to the defeat of reasoning that they earlier affirmed.

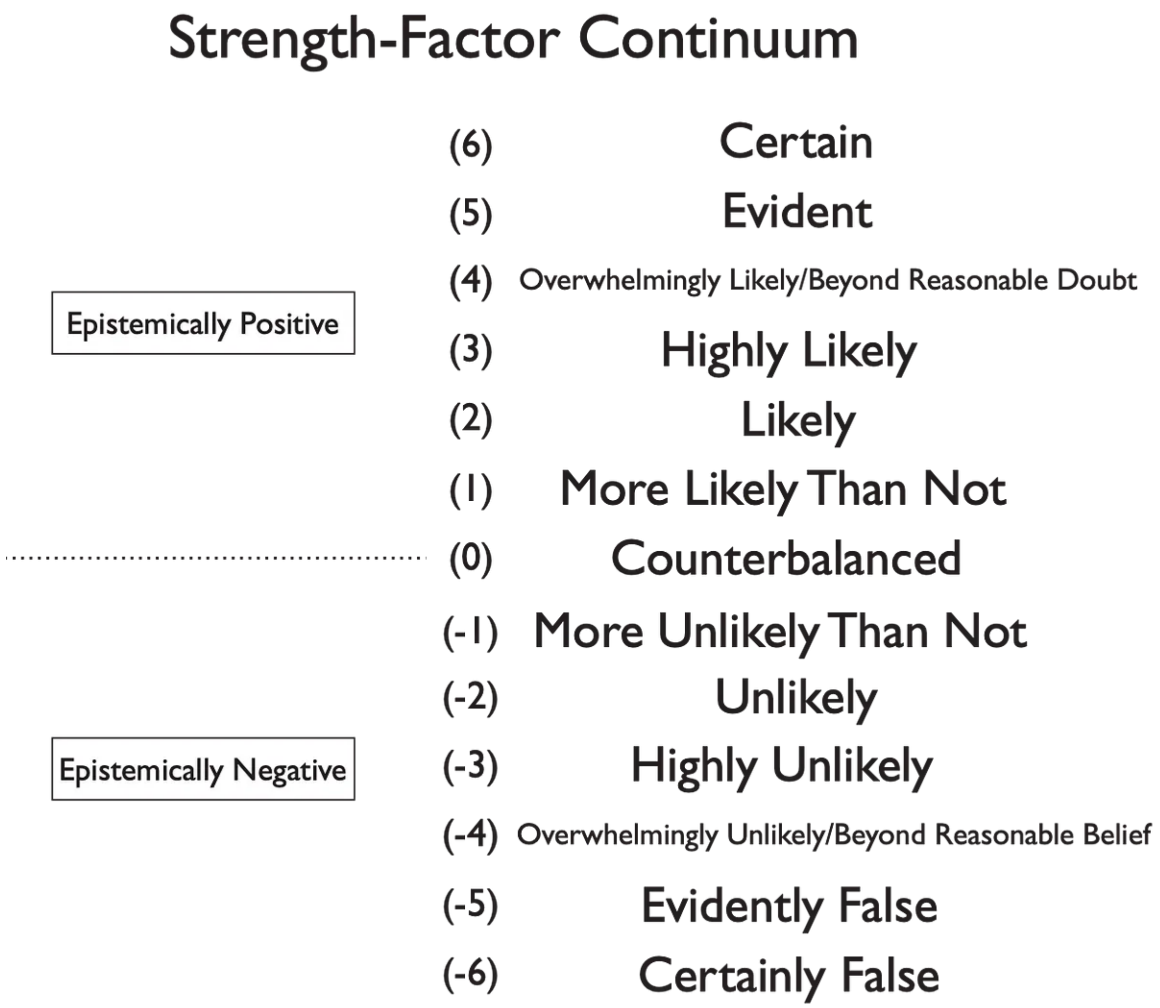

Fig. 6: The current strength factor continuum. The center value, counterbalanced, indicates that there is no evidence for or against belief in the subformula. Increasing positive and negative values indicate increasing and decreasing likelihood of truth in the subformula, respectively.

Stenning and van Lambalgen (S&V) (2008) formalize the concept of what can be called "premise interpretation." They claim that humans, when presented with a set of premises and possible conclusions, first reason toward some rational interpretation of the premises, then from that interpretation to some conclusion. They formalize this process in a Horn-style propositional logic, supplemented with a formalization of the Closed World Assumption (CWA). Given this context, when presented with a set of assumptions and a conclusion to prove, S&V follow this three-step algorithm:

1. Reason to an interpretation.
2. Apply nonmonotonic closed-world reasoning (i.e., apply CWA) to the interpretation produced by (1).
3. Reason from the result of what step (2) produces.

For a the sake of space, I invite the reader to proceed to (4) to gain further information about defeasible reasoning.

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Logic-based/logicist computational cognitive modeling, LCCM as it has been abbreviated, surely seems to be a rather nice fit when the cognition to be modeled is explicit, rational, and intensely inference-centric. But how accurate and informative is such modeling? And how much reach does such an approach to cognitive modeling have, in light of the fact that surely plenty of human-level cognition is neither explicit, nor rational, nor inference-centric? This is not the venue for polemical positions to be expressed in response to such questions. But it is surely worth pointing out that "accuracy" of a cognitive model is itself not exactly the clearest concept in science, and that LCCM tantalizingly offers the opportunity to itself provide the machinery to render this concept precise. The relationship of a model M to a targeted phenomenon P to be modeled, in LCCM, should itself be a relation formalized in some logic in the universe U . If the relation A stands for "accurately models," it can then be declared that what is needed is the completion of the biconditional

$$(\dagger) \quad \mathcal{A}(M, P) \leftrightarrow \boxed{??}.$$

As to the reach of LCCM, some mental phenomena do seem, at least at first glance, to be fundamentally ill-suited to this approach, for instance emotions and emotional states — and yet such mental phenomena conform remarkably well to collections of formulae from relatively simple modal (i.e. intensional) logics in $\mathcal{U}$ (Adam, Herzig, & Longin, 2009).

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One final point regarding the assessment of LCCM, a point that follows from the above definition of what it is for logicist computational cognitive modeling to capture some aspect or part of human-level cognition. The point is simply this: whether or not some attempt to cognitively model (in the LCCM approach) some phenomenon succeeds or not can be settled formally, by proof/disproof. The ultimate strong suit of LCCM is indeed formal verifiability of capture. The cognitive scientist can know that some phenomenon has been captured, period, because outright proof is available. Unfortunately, carrying this out in practice in a wide way would require the formalization of ?? so that † can be employed in the manner described above.

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- **Conclusion**

It should be clear to the reader that formal computational logic is plausibly up to the challenge of modeling and simulating both quantificationcentric reasoning and defeasible (nonmonotonic) reasoning at the human level and in the human case, even when this challenge is required to be substantively based upon arguments of the sort that human agents routinely form as they adjust their belief and knowledge through time. But for the overarching program of LCCM, is the ambitious long-term goal of capturing all rational human cognition in computational logic reasonable? And if it is, what is to be done next?

While the present chapter extends the rather narrow deduction-focused overview of LCCM given earlier (Bringsjord, 2008) into the important realms of quantification and dynamic defeasible reasoning in the human sphere, certainly humans reason and cognize in many additional ways, effectively. These additional ways range from the familiar and everyday, to the rarefied heights of cutting-edge formal science. In the former case, prominently, there is reasoning that makes crucial use of pictorial elements, and hence is reasoning that simply cannot be captured by the kind of symbolic structures we have hitherto brought to bear. The universe $\mathcal{U}$ depicted in Figure 7 does include logics that offer machinery for representing and reasoning over diagrams and images. For a simple but relevant example, consider the question as to whether

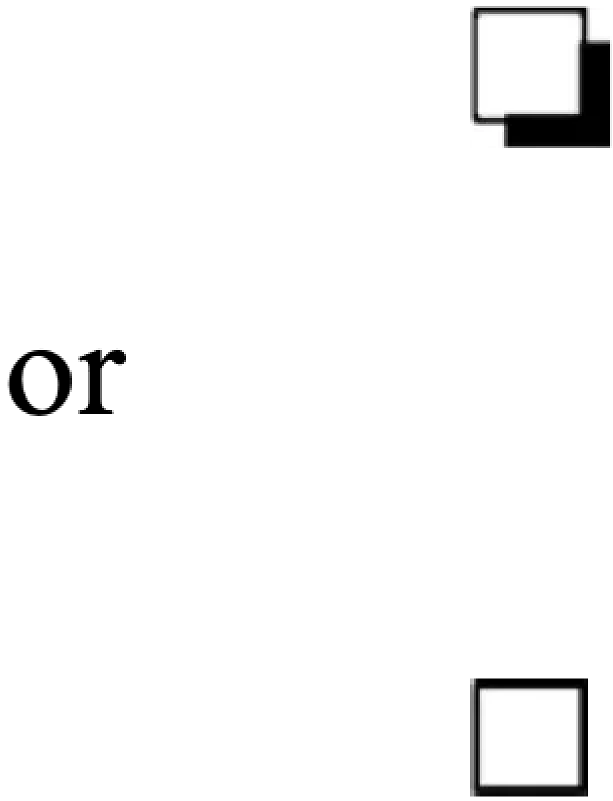

Fig. 7

is more likely to have in front of it and shining upon it a light. Here, the two things centered just above are not symbols; they are diagrams, and as such denote not as symbols do, but — to use the apt terminology of Sloman (1971) and Barwise & Etchemendy (1995), respectively — in a manner that is *analogical* or *homomorphic*. Clearly, humans do routinely reason with diagrams — and yet the logics that have been employed above from U have no diagrams. Therefore further work in LCCM is clearly in order. This work must bring to bear the spaces of pictorial logics indicated in the universe $\mathcal{U}$.

Finally, what about the latter challenge, that of applying LCCM to rarefied reasoning in the formal sciences? Here a key fact must be confronted: viz., that reasoning in logic and mathematics often makes use of expressions and structures that are infinitary in nature. For example, there can be very good reason to make use of formulae that are infinitely long, such as a disjunction like

$$\delta := \exists^{=1} xRx \vee \exists^{=2} xRx \vee \ldots,$$

which — using a variation on the existential quantifier used repeatedly above says that there is exactly one thing that is an R, or exactly two things each of which is an R, or exactly three things each of which is an R, and so on ad infinitum. It turns out that however exotic δ may seem, this is about the only way to express that there exist a finite number of Rs; but this way is utterly beyond the reach of first-order logic = $\mathscr{L}1$. And yet there has been no discussion above of logics that allow for infinitely long disjunctions to be constructed; what are classified as "infinitary logics" in the universe $\mathcal{U}$, which are the logics needed, have been untouched in the foregoing discussion. Of course, as the reader will rationally suspect, the need for formulae of this nature, given the infinitary expressions presented even in textbooks devoted to bringing human students into serious cognizing about (say) analysis (e.g. see Heil, 2019), is undeniable. So again, it would seem that if the general program of logic-based cognitive modeling is to succeed in capturing human reasoning and human-level reasoning across the board, additional effort of a different nature than has so far been carried out will be required of relevant researchers. This effort will need to tap other logics in $\mathcal{U}$, which as the reader can now note by returning to that figure, does indeed refer to the space of infinitary logics.

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Thank you so much for reading! Comments are highly welcome!

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Linguistics Semantics Artificial Intelligence Formal Logic Computation

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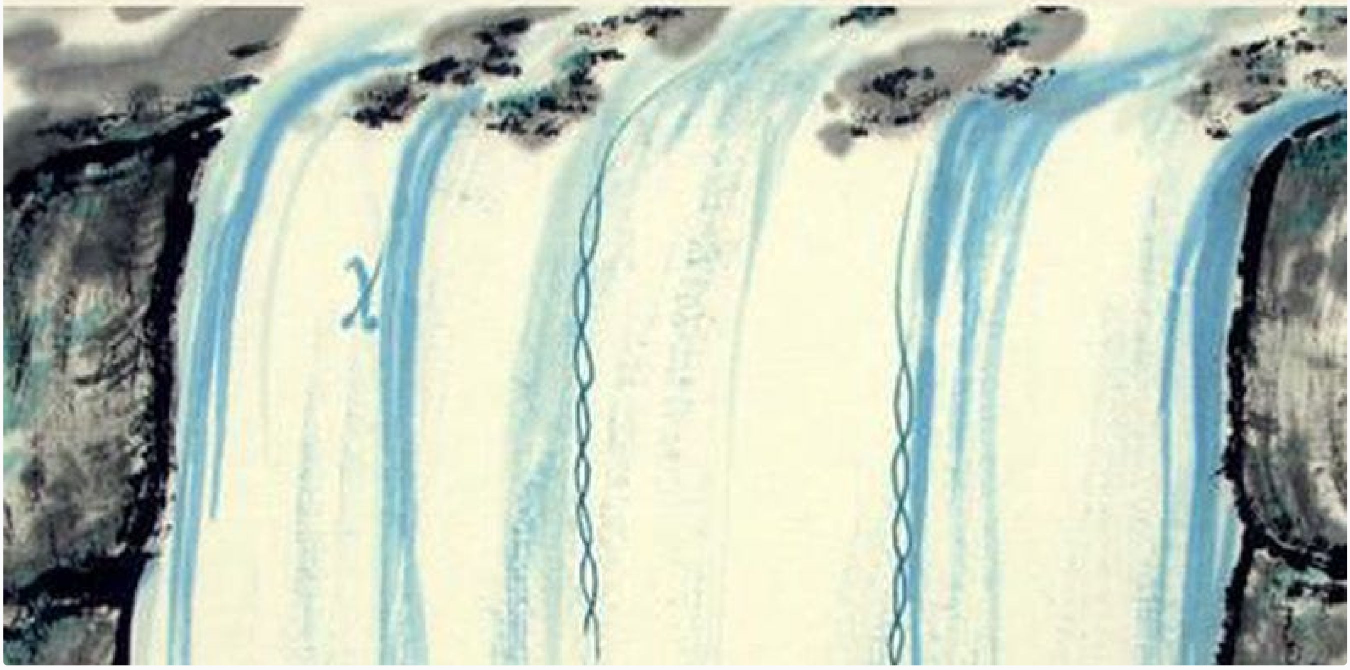

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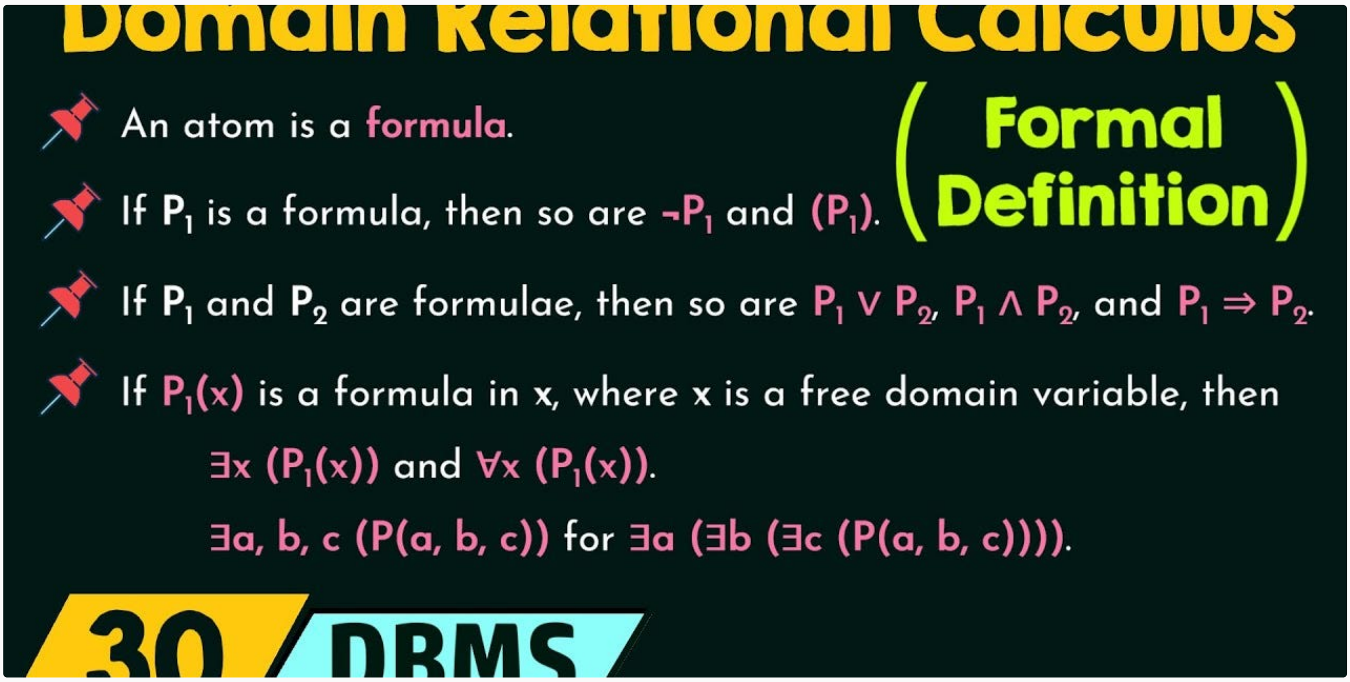

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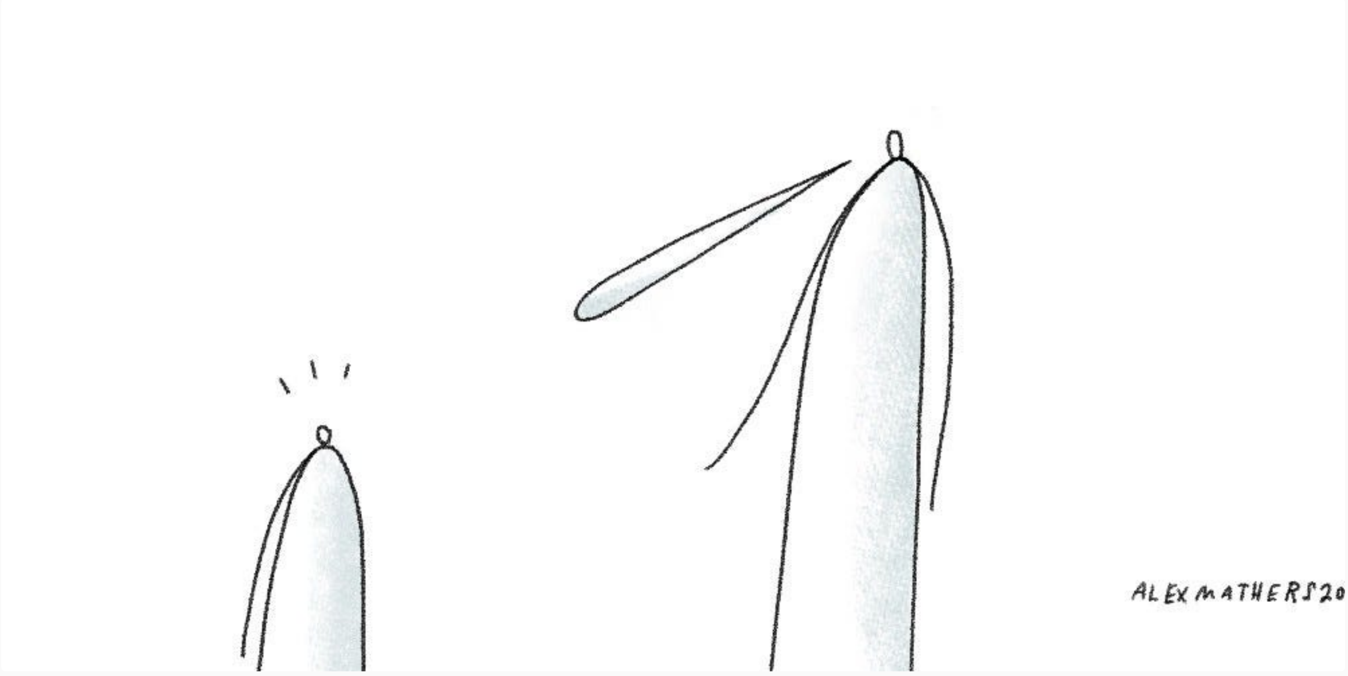

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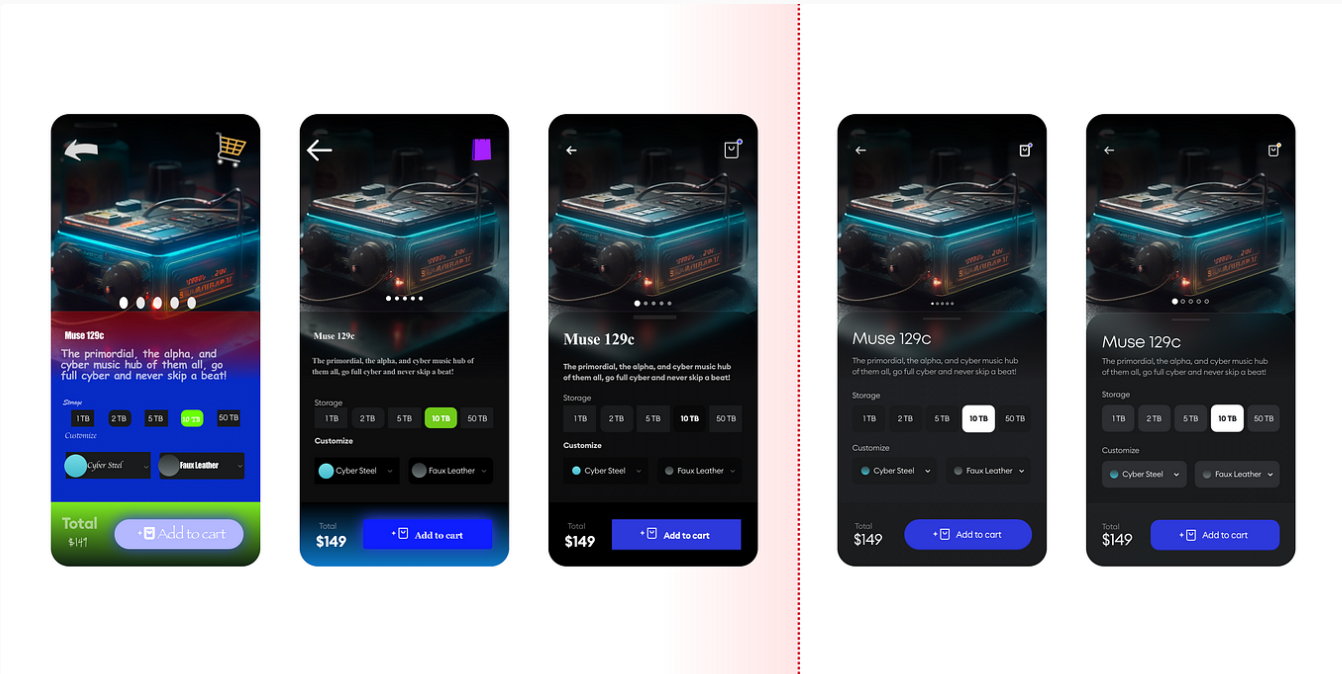

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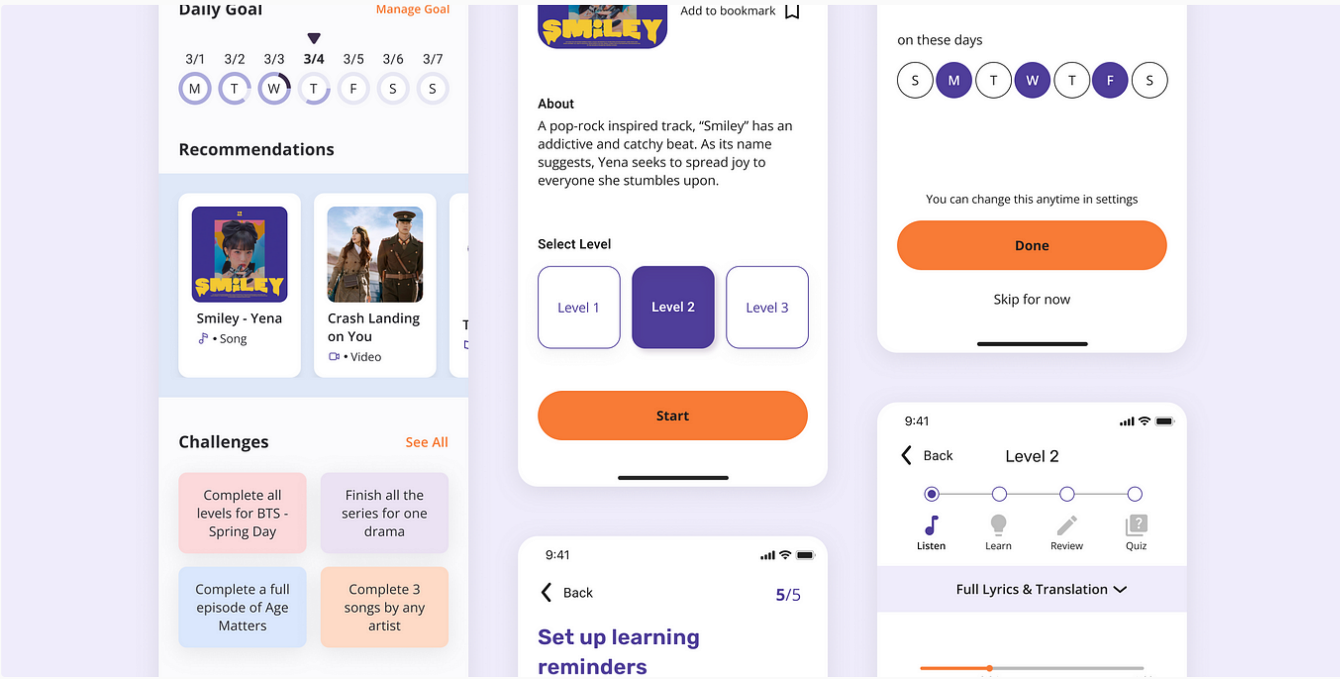

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