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Miniature Language Acquisition:
A touchstone for cognitive science

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Abstract

Cognitive Science, whose genesis was interdisciplinary, shows signs of reverting to a disjoint collection of fields. This paper presents a compact, theory-free task that inherently requires an integrated solution. The basic problem is learning a subset of an arbitrary natural language from picture-sentence pairs. We describe a very specific instance of this task and show how it presents fundamental (but not impossible) challenges to several areas of cognitive science including vision, language, inference and learning.

1   Introduction

touchstone (tuch' ston'). n. 1. a black siliceous stone used to test the purity of gold and silver by the color of the streak produced on it by rubbing it with either metal. 2. a test or criterion for the qualities of a thing.

—Syn. 2. standard, measure, model, pattern.

Among the things that cognitive science has studied most are visual perception, language, inference, and learning [Posner, 1989]. However, these are often studied as if they were isolated from one another. Studies in visual perception rarely address the questions of how we perceive higher-order spatial relations and what systems of spatial concepts there are in the languages of the world. Computer vision and natural language processing are seen as different and unrelated disciplines. In psychology as well, language and vision are seen as distinct subspecialties, where specialists in one have little or nothing to do with the other.

The study of learning is, for the most part, just as isolated. Learning research often proceeds as if the content of what is learned did not matter. This is especially true of connectionist learning, which studies the learning of correlations among microfeatures, independent of content. One partial exception to this is language acquisition in the generative tradition, where a good deal of innateness is assumed [Pinker, 1989]. But there language acquisition is defined in a very limited way: "language acquisition" usually means just syntax acquisition and research has not attempted to characterize how people learn to describe what they see.

One way to start to unify several branches of cognitive science is to ask the question:

How could we learn to describe what we see?

We believe that addressing this question seriously could change the course of research in several subfields in a healthy way. We believe that these fields need to co-evolve, taking into account one another's constraints.

We realize of course that each of these fields is enormous and complex and largely unknown and that anything like a total integration at present is impossible. However, we believe that it is possible to undertake a small but nonetheless significant portion of that task now, and that doing so will have a sobering and an enriching effect on much of cognitive science.

We are proposing a new touchstone problem for cognitive science, a mini-task that is well-defined, very small relative to the overall job to be done, and yet significant enough so that one can learn a great deal. The Miniature Language Acquisition (MLA) task in its most general formulation is to construct a computer system such that:

The system is given examples of pictures paired with true statements about those pictures in an arbitrary natural language.

The system is to learn the relevant portion of the language well enough so that given a new sentence of that language, it can tell whether or not the sentence is true of the accompanying picture.

There are a number of attractive features in this general task. It is strictly behavioral and theory-free: nothing has been said about the theory or methodology that should be employed in the task. The problem is closed in the sense that one cannot appeal to some forthcoming result in a related domain that will complete the story — the system has to do the whole job. There is no stipulation of how much should be built into the system and how much learned. And the requirement that the same system should work for equivalent fragments of any natural language rules out *ad hoc* solutions. The issue now becomes one of feasibility: whether there is an instance of this task that is currently approachable but still rich enough to meet our programmatic goals.

Of course, the MLA task is not a model of human language acquisition or adult language learning. The semantic and pragmatic context of real human communication is far too complex to use as a basis for a miniature language acquisition task. Even the domain of idealized two-dimensional scenes, which is the simplest we could find, involves considerable complexity as some coming examples will illustrate. In fact, one of the greatest appeals of the MLA task is that deep questions in several areas of cognitive science appear in sharp form, even in the very limited L_0 domain.

2 L_0: a specific formulation

We have been investigating the particular task (which we call L_0) of language acquisition in the domain of simple two-dimensional scenes. In order to define the task precisely, we give a set of rules for L_0 (see Figure 1). These rules have no linguistic significance and, of course, are not available to the learning system. The sentences in the chosen natural language are drawn from a finite corpus capturing (as closely as possible) the meanings of the English descriptions specified by the L_0 grammar. The MLA task requires that the system work for equivalent fragments of any natural language. There may be a question of what would constitute an "equivalent fragment" of another language with a very different structure and a different system of spatial concepts. We (tentatively) characterize an "equivalent fragment" as one that can describe the same range of visual inputs.

The visual inputs to an L_0 system are scenes of (up to 4) idealized geometric figures. A candidate system is presented with a picture and with one or more sentences that are grammatical in the given language and are true of that picture. The order and possible repetition of training examples can be whatever the system's designer specifies. We explicitly allow an isolated noun phrase (NP) as a sentence fragment as this should simplify the initial stages of learning. After training on no more than half the examples (and hopefully many fewer) the system is tested by being presented with pairs consisting of a picture and a grammatical sentence which may be true or false about the companion picture. Obviously, the system succeeds to the extent that it produces the right

```
S = NP | NP VP
NP = DET NP1 | DET NP1 and DET NP1
VP = VI PP | VT NP
NP1 = OBJ | SHADE OBJ | SIZE OBJ | SIZE SHADE OBJ
PP = REL NP
VI = is | are
VT = touches | touch
DET = a
OBJ = circle | square | triangle
SHADE = light | dark
SIZE = small | medium | large
REL = REL1 | far REL1
REL1 = above | below | to the left of | to the right of
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Figure 1: A specification of L_0.

answers. It is important to realize that the L_0 grammar is hidden from the system. It is known only to the generator of the training inputs, and the restrictions it embodies (though not these particular rules) must somehow be discovered by the learning system.

From the point of view of linguistics, the task has important attractions. First, there are already enough rich descriptions of spatial systems for various Indo-European and non-Indo-European languages for a start to be made [Rudzhka-Ostyn, 1988; Langacker, 1987; Casad, 1982; Casad and Langacker, 1985; Hershkovits, 1986; Janda, 1986; Talmy, 1983; Talmy, 1972; Talmy, 1985]. Second, the task, even in its simplest form, is demanding enough so that much deeper research on those spatial systems will be required. Third, the task focuses the attention of cognitive science on languages other than English, with special attention to the non-Indo-European languages, where the spatial systems are often very different from what English speakers are used to. Fourth, the task is semantically driven, which will require serious attention to the relation between syntax and semantics.

3 Variants

One advantage of the highly specific formulation of the L_0 task is that it focuses attention on what we consider to be the essence of the problem: acquiring syntactic descriptions of a limited but grounded semantics. The acquisition strategy should of course be extensible to a broader semantic range with the same grounding.

In addition to the base L_0 of Figure 1 we are looking at small variations. A specification that can be derived from Figure 1 by adding up to two words and two grammatical constraints is an acceptable variant of the task. One would not be happy with a system that worked for exactly L_0 but totally broke down for one of these minor variants. We think of a solution as *robust* if its designer can revise it to accommodate any single L_0 variation in one day. We are only interested in robust solutions, namely, those that are easily modifiable for an enormous range of minor variants in any natural language. This should guarantee that any robust solution must be doing quite a

few things right. As we shall see, adding even one minor variation can produce a great deal of complexity.

Note that the task as stated does not explicitly entail that linguistically significant generalizations be learned. We speculate that the robustness condition will guarantee a reasonable level of significant generalization. If a system can be extended simply to deal with any one of a very large number of variants, it would most likely have to have generalized pretty well.

Some of the L_0 variants that we have found useful to work with are:

1. Synonyms: e.g., have 'big' and 'large' used interchangeably.

2. Abstraction: add 'thing' to the definition of OBJ. This shows that one cannot simply identify an object with its shape.

3. Predicate negation: add "is not" and "are not" to the definition of VI. Negative sentences say much less about a picture, e.g. "A dark circle is not touching a square".

4. Sentence inversion: Add "PP VI NP" to the definition of S, e.g. "Above a circle is a small square". This forces the system to use grammatical cues in figuring out role assignment, rather than merely using relative position.

5. Plurals: add 'circles' and 'triangles' to the definition of OBJ, e.g. "A circle and a square are below large triangles".

6. Verb conjuncts: add "VT 'and' VI PP" to the definitions of VP, e.g. "A circle touches and is above a square". This makes explicit the requirement of allowing multiple references to a given object, e.g. "A circle touches a square and *the same circle* is above *the same square*".

7. Conjunctive attributes: add "REL1 'and' REL1" to the definition of REL. Conjunction can be subtle. For example, the sentence "A circle is above and to the left of a square" does not require that the circle be either 'above' or 'to the left of' the square.

8. Relative sizes: Add 'larger' and 'smaller' to definition of SIZE, e.g. "A circle is above a larger square". Expanding the scope of relational properties to comparatives highlights the necessity of adopting a visual representation that can handle abstract shape features and relations. One candidate is Ullman's [1984] visual routines. As Ullman points out, shape properties (e.g. connectedness) and relations (e.g. inside) can be computed by routines but are very hard to capture in a propositional semantics. Another L_0 example of this is the modifier 'far'.

9. Definite article: add 'the' to the definition of DET. Compare Figure 3 (c) with "The smaller circle is above the larger square".

10. Over and Under: add 'over' and 'under' to the definition of REL1. This is a far from trivial extension, since the term 'over' has dozens of related spatial senses [Lakoff, 1987]. For example, in Figure 2 (a), the circle is over (above) the square, while it is not in the topologically identical situation shown in Figure 2 (b). Another interesting asymmetry between 'under' and 'over' is depicted in Figure 3 (c).

11. Quantifiers: add 'every' and 'no' to the definition of DET, e.g. in Figure 2 (a), "No square is under a circle".
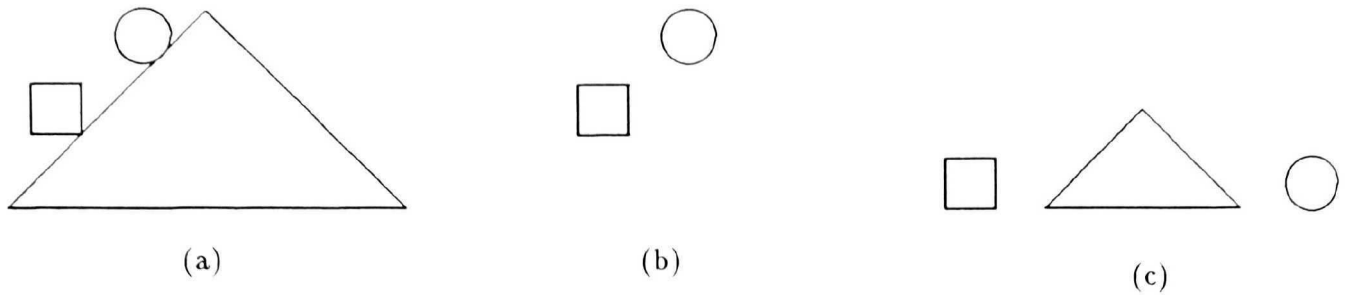
Figure 2: An interesting situation that highlights the complexity of the L_0 domain. (a) with the triangle as a frame of reference, the circle is seen to be 'over' the square; (b) without the apparent support of the triangle, the circle is no longer 'over' the square. Dialects differ on this. (c) The circle is over the triangle from the square.

Another possible set of variants involve motion and time and entail a whole range of new sentences and representations and inference issues. The six variants listed below should provide some of the flavor of the additional considerations.

1. Single object motion: add 'moved' to the definition of VT,

   and/or add "is now" to the definition of VI,

   and/or add 'was' to the definition of VI.

   Temporal variants raise the issue of object identity. It seems reasonable to assume that the system is given the inter-scene object correspondences.

2. Single object change: add "turned into" to the definition of VT.

3. Single object contact: add "bumped into" to the definition of VT.

4. Temporal non-change: add 'remains' to the definition of VI.

5. Pronoun: add 'it' to the definition of NP, eg. "It is now above it". Multiple scenes permit pronominal reference.

6. Trajectories: add "went between" to the definition of VT.

The examples involving motion and time suggest the need for an extended range of semantic primitives. For a variety of reasons [Feldman, 1988], we postulate that explicit trajectories will be an important primitive. It turns out that the trajectories are also useful in understanding some static scenes such as Figure 2 (c).

4 Conclusions

In order to succeed at the L_0 task, a program would have to be able to learn the grammars of at least small, simple fragments of any of the world's languages. It would have to be able to learn the
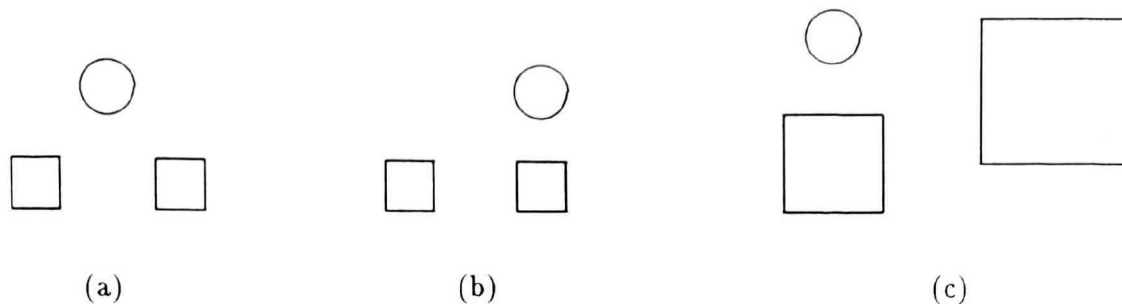
Figure 3: (a) the circle is 'over' the two squares, but the two squares are *not* 'under' the circle. (b) the circle is not over two squares (it is only over one of them). (c) The effect of context: "A smaller circle is above a larger square" is an acceptable description only with the indefinite article.

semantics of space for any of the world's languages. It would have to be able to learn to link that semantics of space to visual input. And it would have to be able to learn to do a range of spatial inferences for any of the spatial systems in the world's languages.

One question that would obviously arise immediately is just how much and what kind of innate structure would have to be built in. Building in too much would make it impossible to learn the task for some range of languages. Building in too little would most likely make the task intractable. Thus, if one has opinions about innate structure or the lack of it, this is a good task to test them on.

Miniature Language Acquisition, even at the L_0 level, is a cognitive science task that requires that very serious attention be paid to the enormous variety in syntax and semantics across the world's languages. The system will have to deal, for example, with classifier systems, which are common in the world's languages. It will have to deal with systems like Mixtec, where there are no prepositions, postpositions, or cases, but where spatial relations are characterized in terms of body-part projections and an elaborate spatial deixis system. And it will have to deal with languages like Cora, where there is an extensive deictic locative system which is based on image-superimposition [Langacker, 1987; Casad, 1982; Casad and Langacker, 1985]. This task will help cognitive science confront the fact that there is much more to human cognition than the concepts one finds in English or in familiar European languages.

Since the L_0 task is at the intersection of vision, language, inference, and learning studies, it encourages researchers in each of those fields to take the other fields seriously. It encourages linguists to take vision seriously and to ask how we can describe what we see. It encourages developmental psycholinguists to look beyond mere syntax acquisition and ask how we learn to describe what we see. It encourages vision researchers to focus on higher level systems of spatial relations of the sort that exist in the languages of the world. It encourages learning theorists to focus on content-specific learning.

Touchstone problems, which are easy to state but beyond current science, play an important role in many fields. Some examples are the "P=NP?" question in computability theory and the "copy demo" problem in robotics, and linguistic universals. We believe that the L_0 task can play such a role in contemporary cognitive science. Cognitive science is by nature interdisciplinary, but, unfortunately, it has developed subdisciplines that are going off in different directions without

paying enough attention to where they intersect and constrain each other. The adoption of the L_0 task as a touchstone would force these disciplines to pay attention to one another and, in the course of that, we think, change the disciplines in a healthy way.

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