
What is incremental interpretation?

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Abstract

Experimental evidence demonstrates that understanding begins before the end of a sentence. This presumably means that some proposition based on what is heard is integrated with contextually relevant propositions drawn from general knowledge. However, formal treatments of the semantics of natural language do not typically give fragments a propositional interpretation. We call this *The Paradox of Incremental Interpretation*. We argue against two potential solutions to this paradox, one where reasoning can take place over non-propositions, the other where sentence fragments are actually given propositional interpretations. In this second case, the processor would either have to draw extremely weak conclusions, or have to incorporate large amounts of syntactic information to allow for wholesale retraction. In contrast, we propose a two-level account, in which the processor constructs a standard logical form representation at an *input level*, which is not normally propositional, and a derived propositional representation at a *knowledge level*. We consider reasoning, recovery from misanalysis and modularity in terms of this account.¹

1 Introduction

This paper discusses a problem in the explanation of language comprehension. Experimental evidence has demonstrated that understanding an utterance takes place as it is encountered, before the end of the sentence. But this should only be possible if the interpretation of a sentence fragment is a proposition, and, according to standard formal semantics, this is typically not the case. We call this the paradox of incremental interpretation. This section discusses experimental evidence and formal semantics, and shows how they lead to the paradox. The next section considers and rejects two “one-level” solutions to the paradox in which the role of the logical form is altered. Instead, we propose a “two-level” solution in which there is a separation between a generally non-propositional logical form and a derived propositional representation which serves as the basis for understanding. We discuss reasoning, recovery from misanalysis and modularity in terms of this account.

1.1 Incremental Understanding

People can obviously think about utterances that they hear (or read) for as long as they like. But understanding begins when the meaning of what is heard is integrated with general knowledge (i.e. beliefs). At this point, the perceiver becomes aware of the plausibility of what has been heard: it is plausible if it is compatible with general knowledge, and implausible if it is not. After this, the perceiver will be able to conduct more extensive reasoning with what

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has been heard, in combination with relevant general knowledge. This paper is concerned with the initial process of understanding.

The following processes do not constitute understanding an utterance: performing lexical access on individual words; resolving referring expressions; building syntactic representations. They are prerequisites of understanding, but not understanding itself. However, all of these processes may be affected by "top-down" processes dependent on understanding. For instance, ambiguous pronouns are often resolved on the basis of the meaning of a utterance in relation to background knowledge. In other words, general knowledge can be used in resolving anaphors, but understanding an utterance involves more than resolving anaphors.

Incremental processing occurs when a stimulus is analysed piece-by-piece as it is encountered. Sentence processing is incremental if the processor analyses each part of the sentence as that part is reached. *Fine-Grained Incremental Interpretation* occurs if the processor analyses each small portion of a sentence, such as each word or morpheme, immediately it is encountered. In contrast, *Coarse-Grained Incremental Interpretation* occurs if the processor waits until larger chunks of a sentence are encountered.

Some aspects of sentence processing certainly involve very fine-grained incremental processing. Word recognition normally occurs extremely quickly (e.g. Ehrlich & Rayner, 1981; Tyler & Marslen-Wilson, 1980). Resolution of pronouns can occur very rapidly (e.g. Nicol, 1988; Shillcock, 1982). The existence of garden-path phenomena indicate that syntactic analysis takes place over sentence fragments (e.g. Bever, 1970; Frazier, 1979; Frazier & Rayner, 1982). The resolution of a NP with respect to a discourse context can occur quickly and appears able to have rapid effects on choice of syntactic analysis under certain circumstances (Altmann, Garnham, & Dennis, 1992; Altmann, Garnham, & Henstra, 1994; Altmann & Steedman, 1988; Britt, Perfetti, Garrod, & Rayner, 1992; Britt, 1994; Spivey-Knowlton, Trueswell, & Tanenhaus, 1993).

Intuitively, understanding is also incremental, beginning well before the end of the sentence. For instance, a hearer can often complete a speaker's sentence. Off-line, it is possible to judge the implausibility of sentence fragments like *the book devours, singing silently or the rich beggar*. More convincingly, evidence from language processing experiments suggests that sentence fragments can be incrementally understood, in a fairly fine-grained manner.

Good evidence comes from experiments that investigate the effects of plausibility during sentence processing. Traxler and Pickering (in press) monitored subjects' eye-movements whilst reading (1):

- (1) a. That's the pistol with which the man shot the gangster yesterday afternoon.

- b. That's the garage with which the man shot the gangster yesterday afternoon.
- c. That's the pistol in which the man shot the gangster yesterday afternoon.
- d. That's the garage in which the man shot the gangster yesterday afternoon.

Sentences (1a & d) are plausible, and (1b & c) are not. Subjects took longer to read *shot* in the implausible sentences than in the plausible sentences when they first encountered the word. Hence they regularly understood the fragment *that's ... shot* immediately. Note that the design rules out the possibility that the effect is due to any form of lexical relationship between *shot* and *pistol* or *garage*. The effect must be due to the plausibility of two of the fragments (considered as a whole) and the implausibility of the other two.

Marslen-Wilson, Tyler and Koster (1994) had subjects listen to passages like (2), as part of a larger experiment:

- (2) Mary lost hope of winning the race to the ocean when she heard Andrew's footsteps approaching her from behind. She was slowed down by the deep sand. She had trouble keeping her balance. Overtaking ...

Subjects named the word *her* faster than *him* when it was visually presented at the end of the passage. The fragment *overtaking her* is pragmatically sensible, but the fragment *overtaking him* is not. Hence subjects immediately understood the fragment *overtaking him/her* in relation to the discourse context and in terms of their general knowledge about races. In this condition, Mary is in discourse focus at the beginning of the target sentence, so an explanation in terms of focus would predict the opposite effect.

Garrod, Freudenthal and Boyle (1994) conducted a related study using eye-tracking. Two conditions had a pronoun refer to a focused antecedent:

- (3) Elizabeth was an inexperienced swimmer and wouldn't have gone if the male life-guard hadn't been standing by the pool. But as soon as she got out of her depth she started to panic and wave her hands about in a frenzy.
- a. Within seconds she sank into the pool.
 - b. Within seconds she jumped into the pool.

Garrod et al. detected a plausibility effect on the verb *sank/jumped* when it was first encountered. The processor must have immediately resolved the pronoun as referring to Elizabeth and assessed the plausibility of the pronoun-verb fragment. They did not find immediate plausibility effects when the pronoun referred to an unfocused entity. Notice that these results

cannot be explained in terms of lexical associations (for instance) since the subject of each verb is a pronoun.

Boland, Tanenhaus, Garnsey and Carlson (in press) found immediate effects of plausibility with some *wh*-questions using a version of self-paced reading in which subjects monitored the point at which the sentence stopped making sense, and Garnsey, Tanenhaus and Chapman (1989) showed similar effects using event-related brain potentials. Other studies showing rapid plausibility effects include Tyler and Marslen-Wilson (1977), Stowe (1989), Holmes, Stowe and Cupples (1989), Clifton (1993) and Trueswell, Tanenhaus and Garnsey (1994). In addition, Marslen-Wilson (1973, 1975) showed very rapid evidence for incremental understanding using a shadowing task. Finally, priming studies (e.g. Swinney, 1979) indicate that contextually inappropriate senses of words are rapidly discarded, even when the context is not a complete sentence.

These findings suggest that the processor performs fine-grained incremental understanding; there is a constant effort after meaning. However, some of these experiments show plausibility effects over fragments whose standardly assumed interpretation is non-propositional. This leads to a paradox, as we discuss below.

1.2 Formal Semantics of Sentence Fragments

In standard theories of semantics, propositions are the only entities that can be true or false, and can serve as the premises in inferences. General knowledge therefore consists of a data base of propositions. When a new fact (i.e. belief) is incorporated into general knowledge, it is also encoded as a proposition. Reasoning can employ propositions corresponding to what has just been processed together with propositions drawn from general knowledge. The conclusions take the form of a new proposition or propositions.

However, most sentence fragments do not have logical forms that correspond to propositions. It is therefore unclear how they can be integrated into general knowledge. In fact, the only strings that have propositional logical forms are main and embedded declarative sentences. Fragments such as NPs or sentences missing one or more NPs do not have propositional logical forms.

We illustrate this using first-order logic and the lambda calculus (Montague, 1974; see Dowty, Wall, & Peters, 1981). Readings of natural language expressions are represented as disambiguated logical forms. For instance, the proposition expressed by *John sees Mary* is represented as *sees(john,mary)*. The verb *sees* is interpreted as a predicate that takes two arguments, the first being the agent of the action, and the second being the patient. The proposition

represented by this logical form is true if and only if John and Mary stand in the relation of seeing, with John being the seer and Mary the seen. In contrast, the meaning of the verb phrase *sees Mary* is represented as $\lambda x \text{sees}(x, \text{mary})$. This does not represent a proposition, but rather a function that can be combined with the meaning of a subject NP to give a propositional logical form. Similarly, the meaning of *John sees* is represented as $\lambda x \text{loves}(\text{john}, x)$; this is a function that can be combined with the meaning of an object NP to give a propositional logical form. These representations $\lambda x \text{sees}(x, \text{mary})$ and $\lambda x \text{loves}(\text{john}, x)$ can be given model-theoretic interpretations, just as $\text{sees}(\text{john}, \text{mary})$ can. But their interpretations are non-propositional; they cannot be asserted to make a true or false claim about the world, and neither can they be used as premises in inference according to standard semantics.

1.3 The Paradox of Incremental Interpretation

The experimental evidence discussed above demonstrates fine-grained incremental understanding. It appears to show that the processor understands fragments whose logical forms, according to standard formal semantics, are not propositional. This should not be possible.

For example, Marslen-Wilson et al. (1994) showed that the fragment *overtaking him* was implausible in their contexts. This fragment is standardly assigned a non-propositional logical form, essentially because *overtaking* is not a tensed verb. Traxler and Pickering (in press) and Garrod et al. (1994) found plausibility effects for fragments consisting of a sentence missing at least one NP (in technical terms, containing a verb whose argument frame was unsaturated).

In some experiments, some of the critical fragments might have formed acceptable sentences. If so, they could have been assigned propositional logical forms during incremental processing. But this cannot serve as a resolution of the paradox. In some experiments (e.g. Marslen-Wilson et al., 1994), the fragments (e.g. *overtaking him*) could not be complete sentences. In others (e.g. Traxler & Pickering, in press), the sentences would have been highly elliptical at best (e.g. *That's the garage in which the man shot.*). In these cases, the elliptical argument (e.g. the thing shot) would have to be supplied semantically for plausibility effects to occur. Finally, note that such an account leads to the unlikely conclusion that any sentence containing a transitive verb used non-elliptically would produce a garden path. Hence, we can conclude that the processor regularly treats sentence fragments as incomplete, but at the same time allows their interpretations to be used in understanding.

Experimental evidence therefore suggests that the meanings of many sentence fragments with non-propositional semantic representations are integrated with general knowledge during sentence comprehension. We call this *The Paradox of Incremental Interpretation*. We now

consider possible ways to resolve this paradox. We first discuss and reject two “one-level” accounts of incremental interpretation, in which the logical form is directly employed in understanding. Instead, we propose a “two-level” account, which separates the construction of the logical form from understanding.

2 One-Level Solutions

2.1 Reasoning with Non-Propositions

We have assumed that reasoning (i.e. inference) is generally taken to be the process of deriving conclusions from sets of premises. Both premises and conclusions must be propositional. These assumptions are central to standard semantics. For instance, the standard definition of logically valid inference involves propositions: an inference is logically valid iff the truth of the premises guarantees the truth of the conclusions. Non-logical forms of reasoning, such as induction, abduction, case-based reasoning and analogical reasoning are also defined over propositions.

However, we could try to circumvent the paradox of incremental interpretation by allowing reasoning with non-propositions. Reasoning over non-propositions can be defined in terms of an “informativeness relation” (Keenan & Faltz 1985). For example, *sings loudly* is taken to be more informative than *sings*, and *John loves* as more informative than *John likes*. Thus, from the interpretation of *sings loudly*, the interpretation of *sings* can be inferred, and from the interpretation of *John loves*, the interpretation of *John likes* can be inferred. For properties such as *is an animal*, the notion of inference obtained closely corresponds to the relations used in many semantic networks, in which properties are arranged in hierarchies, from specific to general (e.g. Collins & Quillian 1969).

This account allows inferences between non-propositions and other non-propositions. However, it does not license inference from non-propositions to propositions, or from a non-proposition and a proposition to a proposition. This is because non-propositions make no claim about the world; and hence no proposition, which does make a claim about the world, can follow from a non-proposition. Hence, if fragments are interpreted as non-propositions, it is possible to derive other non-propositions in inference, but not to derive propositions. We would then require a non-propositional theory of knowledge representation as a whole. If this is coherent at all, it would require a drastic change in our basic assumptions about the nature of belief. It would therefore only be worth considering as a last resort.

2.2 Interpreting Sentence Fragments as Propositions

An alternative solution is to abandon standard formal semantics and to assign propositional interpretations to fragments such as *that's the garage with which the man shot, overtaking her* and *within seconds she jumped*. We can associate propositional “constraints” with sentence fragments (Haddock, 1987, 1989; Mellish, 1985). As more of the sentence is encountered, more constraints are added. The proposition expressed by the complete sentence is simply the conjunction of all the constraints. For example, in *John loves Mary*, the processor first encounters *John* and imposes the constraint that there exists someone called John. It then encounters *loves*, and adds the constraint that there exists some entity that John loves. On encountering *Mary*, it adds the further constraint that there exists a person called Mary that John loves. These constraints incrementally narrow down the meaning of the sentence. Since fragments are assigned propositional interpretations, their meanings can be integrated with general knowledge and can serve as premises in reasoning. Thus we can explain why some fragments appear plausible and some implausible.

However, the meaning of the complete sentence may not be compatible with the meaning assigned to particular fragments. After *John loves*, the processor assumes that there exists someone called John and there exists some entity that John loves. But none of the following is compatible with that assumption:

- (4)
- a. John loves nothing.
 - b. John loves Mary if he loves anybody at all.
 - c. John loves Mary as far as I know.
 - d. John loves Mary or hates her.

Within this approach, we have two choices. We can assume some weaker constraint for a sentence fragment like *John loves* that will be compatible with any potential continuation. Alternatively, we can allow constraints to be retracted.

The first solution fails because there is no constraint strong enough to account for incremental understanding which is also compatible with any continuation. Examples (4) suggest that *John loves* does not place restrictions on the state of the world. More precisely, notice that *John loves something* and *John loves nothing* are possible sentences beginning with *John loves*. Assuming that the semantics of *John loves nothing* is the negation of the semantics of *John loves something*, every possible state of the world is consistent with one of these continuations. Hence nothing can be excluded for certain at *John loves*.

Formally, any constraints made after *John loves* must be compatible with both the proposition p , that John loves something and its negation, $\neg p$. In classical logic, the only thing compatible with both p and $\neg p$ is the proposition T , which provides no constraint. Proof: if proposition p implies constraint i and the negation of the proposition, $\neg p$, also implies i , then p or $\neg p$ implies i . In classical logic, p or $\neg p$ is always true, so the only things that it implies are also true. But if i is always true, it provides no constraint upon how the world is. Therefore, assuming classical logic, no certain yet contentful constraints can be made after processing *John loves*.

The processor might perhaps store more than one set of constraints in parallel. For example, the fragment *John loves* might generate the constraint that there exists some entity that John loves on one analysis, and the constraint that there exists no entity that John loves on the other analysis. The first analysis might be preferred, hence leading to the psycholinguistic manifestations of incremental understanding. This account is similar to ranked parallel accounts of parsing (e.g. Gorrell, 1989), and clearly requires a considerable amount of information to be stored. However, there is a more serious problem. Storing both analyses accounts for the sentences *John loves something*, *John loves Mary* and *John loves nothing*. But it cannot account for *John loves no woman*. This sentence is compatible either with John loving something other than a woman, or with John loving nothing at all. In fact, the processor cannot consider a finite set of possible sets of constraints compatible with *John loves* that will be compatible with all possible continuations. Hence a parallel constraint-based account of incremental interpretation that avoids the need for retraction is impossible.

These arguments only apply to the propositional content of a sentence or fragment. Some other information may not be subject to retraction. For instance, it may be that the fragment *John loves* presupposes that John exists. This remains true whether the sentence ends with *something* or *nothing*. However, some presuppositions are subject to retraction. The fragment *A unicorn is coming* presupposes that a unicorn exists, but the complete sentence could be *A unicorn is coming, my father said*, from which it does not follow that a unicorn exists. More importantly, the information that can be gained from computing presuppositions incrementally cannot explain the plausibility effects discussed above.

Information *about* what has been heard may not be subject to retraction. For instance, the fragment *John loves* is about John and about an act of loving (which may or may not actually occur). This will remain the case however the sentence concludes. But these facts do not imply that there exists some entity that John loves. Hence we cannot explain the experimental findings in this way. We can now conclude that any propositional interpretations for fragments sufficient to explain incremental understanding may have to be retracted. Incremental understanding necessitates that the processor jumps to uncertain conclusions whilst

processing a sentence. More specifically, any one-level account of incremental interpretation must have mechanisms for retracting constraints, even in cases where there is no syntactic ambiguity.

If the processor retracts by simply backtracking, it encounters the same problems faced by the parallelism account discussed above. If it assumes after *John loves* that there exists an entity that John loves, it must backtrack on encountering *John loves nothing*. But how would it know how to interpret *John loves* this time? If the sentence continued *John loves no woman*, then this reanalysis would have been inappropriate. It is clear that the processor could only decide what constraints to apply to *John loves* after having provided an interpretation for the whole sentence. It would then have to use this to determine the interpretation of a fragment, which is clearly the wrong way round.

Alternatively, the processor could seek to modify the interpretation assigned to a fragment. A major problem would be knowing which part of the interpretation to retract. In the sentence *John arrived with nothing*, the processor would wish to retract the assumption that John arrived with something. It would not wish to retract the assumption that John arrived (somewhere). The processor would have to label the constraints that it had applied with respect to their position within the original syntax. It would therefore have to store a large amount of syntactic information. This is incompatible with standard constraint-based approaches (Haddock, 1987, 1989; Mellish, 1985), in which the only information retained at each stage is the semantic information associated with the constraints (a set of possible worlds and possible referents).

We conclude that no one-level account of incremental interpretation that incorporates the information necessary for incremental understanding into the incremental construction of logical form is appropriate. Instead, these components of incremental interpretation should be separated.

3 Two Level Incremental Interpretation

We now propose that incremental interpretation involves two levels of representation: an input level, which serves as the vehicle for compositional semantics, and a knowledge level, which forms the basis for understanding. We define these two levels of representation, and show how they are related. We show how they can account for language comprehension, and discuss reasoning, recovery from misanalysis and modularity in terms of this account.

