

What is incremental interpretation?

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1.1 Incremental Understanding

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.

3.1 The input and knowledge level representations

The *Input Level of Representation (ILR)* is an incrementally constructed logical form which is non-propositional for most fragments. It is a standard lambda expression, as assumed in formal semantics (e.g. Dowty et al., 1981). We assume that it is constructed in a word-by-word manner, so that a logical form is associated with every sentence fragment that is encountered. To do this, we require an appropriate parsing algorithm given a particular grammar. One approach is due to Milward (1994, 1995), who provided word by word construction of lambda expressions for grammars like basic categorial grammar. Other fine-grained approaches to logical form construction include Ades and Steedman (1982), Barry and Pickering (1990), Henderson (1994), Pulman (1986), Stabler (1991, 1994) and Stevenson (1993). Details of grammar and parser are not relevant to this paper.

In this paper, we adopt a simple account of logical form in which the ILRs for *Mary gave John chocolates* are as follows:

| | |
|---------------------------|--|
| Mary | λPP_{mary} |
| Mary gave | $\lambda x \lambda y \text{gave}(\text{mary}, y, x)$ |
| Mary gave John | $\lambda y \text{gave}(\text{mary}, y, \text{john})$ |
| Mary gave John chocolates | $\text{gave}(\text{mary}, \text{chocolates}, \text{john})$ |

An account which produces these representations is certainly inadequate for many expressions involving quantifiers (e.g. Barwise & Cooper, 1981), but it is adequate for current purposes. A more sophisticated account is provided by Milward and Cooper (1994), who use underspecified representations to account for the incremental processing of sentences containing generalised quantifiers and scope ambiguities.

We explain the *Knowledge Level of Representation (KLR)* in two stages. First, it involves existential quantification over lambda-abstracted arguments. Notationally, λ is replaced with \exists . This produces the following representations for *Mary gave John chocolates*:

| | |
|---------------------------|--|
| Mary | $\exists PP_{\text{mary}}$ |
| Mary gave | $\exists x \exists y \text{gave}(\text{mary}, y, x)$ |
| Mary gave John | $\exists y \text{gave}(\text{mary}, y, \text{john})$ |
| Mary gave John chocolates | $\text{gave}(\text{mary}, \text{chocolates}, \text{john})$ |

These representations imply that processor assumes in turn that there exists an entity called Mary, that Mary gave some entity to some entity, that Mary gave some entity to John, and that Mary gave chocolates to John.

These propositions could be assessed with respect to general knowledge. The hearer could retain the information or reject it if it appeared to be impossible or implausible. But there would only be these two choices. In fact, a hearer may treat an utterance in many ways. For example, knowledge about the intentions of the speaker, an implausible content and a particular intonation might suggest that a sentence (or fragment) is ironic. Hence, the hearer may adopt the negation of what would otherwise be assumed. More generally, what a hearer concludes from an utterance is determined not just by the logical form of the utterance, but by the speech act that the hearer takes to have been performed, and other world knowledge (Searle, 1969). It is only if they believe they are listening to a reputable speaker talking sensibly and seriously that hearers will make the inference from the fact that a proposition was expressed to the proposition itself.

To allow for this, the propositions are nested within the two-place predicate *expresses*. The first argument is the speaker, the second the proposition. If Bill utters *Mary gave John chocolates*, the KLRs are:

| | |
|---------------------------|---|
| Mary | $\text{expresses}(\text{bill}, \exists P P \text{mary})$ |
| Mary gave | $\text{expresses}(\text{bill}, \exists x \exists y \text{gave}(\text{mary}, y, x))$ |
| Mary gave John | $\text{expresses}(\text{bill}, \exists y \text{gave}(\text{mary}, y, \text{john}))$ |
| Mary gave John chocolates | $\text{expresses}(\text{bill}, \text{gave}(\text{mary}, \text{chocolates}, \text{john}))$ |

The processor assumes, in turn, that Bill expresses that there exists an entity called Mary, that Bill expresses that Mary gave some entity to some entity, that Bill expresses that Mary gave some entity to John, and that Bill expresses that Mary gave chocolates to John. The listener can then decide whether to accept the propositions literally, or whether to draw any other conclusions.

At first sight, it might appear that the ILR could be embedded within the *expresses* predicate directly. If Bill utters *Mary gave*, the representation $\text{expresses}(\text{bill}, \lambda x \lambda y \text{gave}(\text{mary}, y, x))$ is propositional. However, a listener could not normally assess the plausibility of this fragment, because the plausibility of someone expressing something is likely to be dependent on the plausibility of what is expressed. We now get back to the original problem that the listener cannot determine the plausibility of $\lambda x \lambda y \text{gave}(\text{mary}, y, x)$, because it is not propositional and therefore cannot be compared with general knowledge.

The use of KLR representations with existentially quantified contents accounts for the experimental evidence for incremental understanding. The KLR representations are of course quite weak, but weaker propositions still (e.g. that Bill expresses that Mary gave either something or nothing to John) would obviously be too weak to account for the findings. However, the

hearer might assume stronger propositions. The KLR for *John killed* is $\text{expresses}(\text{speaker}, \exists x \text{killed}(\text{killed}, x))$, i.e., that the speaker is expressing that there is some entity that John killed. But the listener might assume the stronger proposition that this entity is a living thing. The KLR would be $\text{expresses}(\text{speaker}, \exists x \text{living-thing}(x) \ \& \ \text{killed}(\text{john}, x))$. On this account, the sentence *John killed time* would precipitate revision at the KLR. Such stronger propositions would be most likely when the verb imposes strong constraints (e.g. selection restrictions) on possible arguments.

An interesting further possibility is for the construction of ILRs to be fine-grained, but for the construction of KLRs to be rather more coarse-grained. The processor might, for instance, only existentially quantify over lambda-expressions that serve as an argument in the ILR (cf. Barry & Pickering, 1990). For this paper, we ignore these refinements, and assume that both ILRs and KLRs are constructed word-by-word, with the KLR employing simple existential quantification.

3.2 Retraction and Reasoning

Garden paths as input level misanalysis. The ILR is constructed monotonically unless the parser realises it has chosen the wrong syntactic analysis. Hence, misanalysis at the input level corresponds to "garden-path" phenomena (Bever 1970; Frazier, 1979; Frazier and Rayner 1982). Garden-paths are standardly characterised in syntactic terms, but can also be characterised in terms of the ILR. For example, at least some reduced complement sentences like *John heard Fred left* cause subjects to garden path (e.g. Ferreira & Henderson, 1990; Frazier & Rayner, 1982; Rayner & Frazier, 1987; Pickering & Traxler, 1995b; Trueswell, Tanenhaus, & Kello, 1993). At least if *heard* preferentially takes an NP-object, most accounts assume that the processor initially attaches *Fred* as its object. But when it encounters *left*, it realises that *Fred* is the subject of *left*, and that *Fred left* is the (reduced) complement of *heard*. This reanalysis causes a garden path effect. But in terms of the logical form, the processor initially analyses *John heard Fred* as $\text{heard}(\text{john}, \text{fred})$. This cannot be combined with the logical form of *left*, so the processor adopts the alternative logical form, under which the second argument of *heard* has sentential meaning rather than noun phrase meaning. It then constructs the correct logical form $\text{heard}(\text{john}, \text{left}(\text{fred}))$. Similar accounts explain the misanalysis of other sentences like *The horse raced past the barn fell* and *When Mary was eating the pudding became cold*.

A revision to the ILR will normally cause the KLR to undergo revision as well. Hence garden paths involve misunderstanding as well as syntactic and logical form misanalysis. If the KLR has been used as a premise in inferencing, then the conclusions will normally have to be

abandoned as well. This explains the finding that the processor finds it harder to recover from plausible than implausible misanalyses (Pickering & Traxler, 1995a, 1995b). If the KLR contains a plausible proposition, the reader becomes more committed to the analysis than if the KLR is implausible. A plausible KLR is more likely to precipitate inferences that will subsequently have to be abandoned than an implausible KLR. Alternatively, an implausible KLR may cause the reader to seek another syntactic analysis immediately.

“Pure” Retraction of the KLR. In contrast, KLR retraction regularly occurs without corresponding ILR retraction. For example, in *John loves nothing*, the ILR for *John loves* is $\lambda x \text{ loves}(\text{john}, x)$. This is refined to give the ILR $\neg \lambda x \text{ loves}(\text{john}, x)$ for *John loves nothing*, without retraction. But the KLR for *John loves* states that the speaker is expressing that there is some entity that John loves. This is incompatible with the KLR for *John loves nothing*, which states that the speaker is expressing that there is no entity that John loves. Hence the KLR for *John loves* is abandoned.

This model predicts that pure retraction of the KLR will cause disruption. Thus, *John loves nothing* should cause some disruption not found in, say, *John hates everything*. Recovery from syntactic (and, in our terms, ILR) misanalysis is hard if the misanalysis is long-lived (Ferreira & Henderson, 1991; Warner & Glass, 1987). Similarly, we predict that recovery from pure KLR misanalysis will be hard if it is long-lived, so that *Mary gave her new and extremely clever friend nothing* should be disruptive.

Each KLR may be automatically superseded by the next KLR when it is constructed. Problems would only arise if inferences drawn from an earlier KLR were incompatible with the new KLR. For instance, the KLR for *John loves no woman* is not incompatible with the KLR for *John loves*. If the previous KLR were not abandoned, then the hearer would conclude (at the end of the sentence) that the speaker is expressing the claim that John loves something that is not a woman. There is no intuitive evidence for this, so we suspect that the earlier KLR is automatically abandoned. We therefore suggest that only one KLR is ever entertained. However, the implications of earlier KLRs will be felt if they have been employed in much knowledge-level processing. This suggests a difference between KLR construction and general processes of belief revision, where all propositions may be retained unless rendered implausible by new evidence.

Inferences based on the KLR: reasoning and retraction. We assume that the KLR can be rapidly employed in reasoning in combination with relevant aspects of general knowledge. Pure KLR retraction (like mixed ILR/KLR retraction) should be particularly disruptive if the KLR has been extensively integrated with general knowledge, and if a lot of reasoning has occurred. We consider “bridging” inferences and elaborative inferences in turn.

"Bridging" inferences link successive parts of a discourse, in order to make it coherent (Haviland & Clark, 1974). In understanding the connection between the successive clauses in *John went to the fridge, got the milk and drank some*, the hearer must infer that there was milk in the fridge. This can only be derived if the KLR is integrated with general knowledge. In this example, the bridging inference may be made during the sentence, rather than at its end, with the hearer assuming that the milk is in the fridge immediately *milk* is reached. If so, knowledge-level processing occurs whilst the sentence is encountered. If the sentence turned out to be *John opened the fridge, got the milk, and put it in*, the bridging inference would be withdrawn, and we would predict some disruption.

"Elaborative" inferencing occurs in deeper processes of discourse comprehension. Understanding the ramifications of a very simple story involves making a large number of inferences (e.g. Minsky, 1975). In processing *It was Martha's birthday. John thought he would buy a balloon* we can make numerous inferences quickly and effortlessly — that John and Martha are young children, that John knows that it is Martha's birthday, that John is a friend of Martha, that John bought the balloon to give to Martha, and so on. It may be necessary to retract any or all of these inferences in the light of subsequent information. For example, the story could continue *Martha would be retiring ...* or *Martha thought it was for her but ...*

Hearers use knowledge level reasoning to make sense of what they have heard and to integrate its meaning with current context. Much of this reasoning appears to be very fast — fast enough to be computed incrementally as a sentence is encountered — and to be subject to equally rapid retraction. In this regard, reasoning about language is no different from reasoning in any other domain. Almost all common-sense, everyday inferences are plausible, defeasible, non-monotonic inferences rather than deductive inferences, and are invariably subject to retraction, if new information is added (Oaksford & Chater, 1991).

Not all knowledge level retraction is straightforward. For example, elaborative inferencing can go far astray if a reader misinterprets a story. The above story could continue for some time before it became clear that Martha was not a child, and that John was a very rich adult who was buying her a hot-air balloon. In this case, the reader could be seriously misled. Similarly, not all input level retraction is hard. Locally ambiguous reduced relatives like *The horse raced past the barn fell* often cause intuitively strong garden path effect, but reduced complements like *John heard Fred left* often do not (e.g. Pritchett, 1992).

Is the ILR used in reasoning? We suggest that the ILR is not used in reasoning. Its role is as an intermediate representation between form and understanding, similar, in this respect, to a syntactic representation like a phrase-structure tree. The KLR is used in understanding, so there is no need to employ the ILR as well.

We assume that general knowledge is unavailable in the input level, so the only possible form of inference at this level would be logical inference. It could not be very successful, because there is strong evidence that people are extremely poor at even very simple logical inference, and find logically complex natural language expressions more or less uninterpretable (Evans, 1989; Johnson-Laird, 1983). In addition, it could only be used to derive new propositions on the rare occasions when the ILR is propositional, as discussed above. On those occasions, it would be possible to perform a very few operations like stripping away double negations. It might also be possible to perform reasoning with multiple propositions (e.g. syllogisms), but only if the processor remembered ILRs for earlier fragments. This would be very strange, because earlier ILRs could otherwise be forgotten.

The non-propositional reasoning based on lexical entailments employed by Keenan and Faltz (1985) could take place within the ILR, but it would commonly produce the wrong results. If the processor inferred $\lambda x \text{likes}(\text{john}, x)$ from $\lambda x \text{loves}(\text{john}, x)$, it would then incorrectly assume that John likes nothing when it encountered *John loves nothing*. Even if this only occurred with propositional fragments alone, the wrong results would occur if the language permitted the fragment to be subsequently negated. Pure decomposition (e.g. replacing the meaning of *bachelor* with its definition as an unmarried man) does not suffer these problems, but its value would be very limited if it could not be employed in reasoning. In addition, some off-line evidence suggests that lexical decomposition does not occur (Fodor, Garrett, Walker, & Parkes, 1980). Note that the experimental evidence for incremental understanding shows rapid effects of lexical content in parsing, but this can be explained purely in terms of KLR processing. We conclude that the ILR is inferentially inert, in that it plays no role in reasoning.

4 Conclusions

This dichotomy between the ILR and the KLR is compatible with Fodor's (1983) distinction between *modular* and *central* processes. Modular processes are *informationally encapsulated*: they use only perceptual input and information from within the module, and do not have access to general world knowledge (or, for that matter, to information internal to other modules). With respect to language, Fodor notes that:

... there is a wide choice of properties of utterances that *could* be computed by computational systems whose access to background information is, in one way or another, interestingly constrained ... there is, in the case of language, a glaringly obvious galaxy of candidates for modular treatment — viz., those properties that

utterances have in virtue of some or other aspects of their linguistic structure (where this means, mostly, grammatical and/or logical form). [1983, p.88; Fodor's italics].

The construction of the ILR is a modular process, but the use of the KLR in reasoning is part of central processes.

This quotation raises the question of precisely which aspects of meaning are encoded in the ILR. Some intuitions are clear: function-argument structure, for example, must surely be represented, and rhetorical force cannot be. A fully developed formal semantics could specify what could be extracted purely from the form of a sentence with any recourse to general knowledge. This would provide an upper bound on the ILR. This might include rather more than what is standardly considered by formal semantics. For example, it may be possible to include information derived from intonational structure (cf. Steedman, 1991). However, the ILR might not make use of all the information that a formal semantics could specify. For instance, it might not normally compute a fully disambiguated representation in sentences involving multiple quantifiers, but might instead represent underspecified structures that are compatible with different readings. This paper has not attempted to determine the precise nature of the ILR.

We have outlined a two-level account of language comprehension, but the discussion of modularity makes it apparent that similar distinctions may apply in perceptual processing. Quite generally, an input/knowledge level distinction appears to be crucial in keeping separate what is perceived from what is inferred (cf. Fodor, 1989). One level of representation records the perceptual input; a second level of representation extends beyond what has actually been perceived, and can act as a basis for further inference. So, in the perception of partly occluded stimuli, a representation analogous to our ILR records what has been perceived. A representation analogous to our KLR makes suggestions about the nature of the whole stimulus, thus allowing inferences about this putative stimulus to be made. These inferences may have to be withdrawn if the stimulus is not as expected, but will often turn out to be correct, and hence will facilitate efficient processing. Note that our ILR is already quite a "deep" level of processing, in the sense that it is a considerable abstraction from the original form of the stimulus, though it is "shallow" in that it is isolated from general knowledge.

Incremental interpretation refers to two very different processes, the incremental construction of logical form and incremental understanding. We have argued that these processes use two different representations, the ILR and the KLR. The ILR is a standard formal semantic representation, and is non-propositional for most fragments. It is constructed monotonically except in the case of syntactic misanalysis. It is an inferentially inert and short-lived inter-

mediary representation which serves to facilitate the construction of the KLR. The KLR is propositional, and forms the basis of the understanding of a sentence or sentence fragment. It will quite often have to be retracted, along with any inferences derived from it, when the ILR remains unaltered.

According to this account, the language processor is constantly trying to interpret what it has encountered to as deep a level as possible, as quickly as possible. It does this by assigning propositional interpretations to fragments that do not standardly receive such interpretations, so that it can interpret the fragments in relation to general knowledge and can draw important inferences. However, we showed that any useful propositional interpretation of a fragment will be wrong on occasion. If the interpretation does turn out to be wrong, the processor retracts it. But it retains the non-propositional logical form assigned to the fragment, so reanalysis is facilitated. In other words, when the KLR goes wrong, the processor has the ILR to fall back on. The processor has the best of both worlds: rapid incremental understanding, but minimal problems from over-hasty analysis.

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