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Steps toward Formalizing Context

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■ The importance of contextual reasoning is emphasized by various researchers in AI. (A partial list includes John McCarthy and his group, R. V. Guha, Yoav Shoham, Giuseppe Attardi and Maria Simi, and Fausto Giunchiglia and his group.) Here, we survey the problem of formalizing context and explore what is needed for an acceptable account of this abstract notion.

The issue of context arises in various areas of AI, including knowledge representation, natural language processing, and intelligent information retrieval. Although the word *context* is frequently used in descriptions, explanations, and analyses of computer programs in these areas, its meaning is frequently left to the reader's understanding; that is, it is used in an implicit and intuitive manner.[1]

An example of how contexts may help in AI is found in McCarthy's (constructive) criticism (McCarthy 1984) of MYCIN (Shortliffe 1976), a program for advising physicians on treating bacterial infections of the blood and meningitis. When MYCIN is told that the patient has *Chlorae Vibrio* in his intestines, it would immediately recommend two weeks of tetracycline treatment and nothing else. While this would indeed do away with the bacteria, the patient would perish long before that due to diarrhea. A "contextual" version of mycin should know about the context of a treatment and would realize that any prescription must be made in the light of the fact that there is alarming dehydration. Thus, in the contextual MYCIN, the circumstances surrounding a patient would have to be made explicit using a formal approach and would be used as such by the program.

The main motivation for studying formal contexts is to resolve the problem of generality in AI, as introduced by McCarthy (1987). McCarthy believes that AI programs suffer from a lack of generality. A seemingly minor addition (as in the MYCIN example) to the particular, predetermined possibilities that a program is required to handle often necessitates a partial redesign and rewrite of the program. Explicitly represented contexts would help because a program would then make its assertion about a certain context.

A more general objection to the implicit representation of context—unless the representation is part of a program that is not mission critical (in a broad sense of the term)—can be given as follows: Assume that we write longer (more involved in terms of complexity) or shorter (simpler in terms of complexity) axioms depending on which implicit context we are in. The problem is that long axioms are often longer than is convenient in daily situations. Thus, we find it handy to utter "this is clever," leaving any explanation about whether we are talking about a horse or a mathematical argument to the context of talk. However, shorter axioms might invite just the opposite of a principle of charity from an adversary. To quote McCarthy (1987, p. 1034):

> Consider axiomatizing on so as to draw appropriate consequences from the information expressed in the sentence, "The book is on the table." The [adversary] may propose to haggle about the precise meaning of on, inventing difficulties about what can be between

I wish honorable gentlemen would have the fairness to give the entire context of what I did say, and not pick out detached words (R. Cobden [1849], quoted in Oxford English Dictionary *[1978], p. 902).*

the book and the table, or about how much gravity there has to be in a spacecraft in order to use the word on and whether centrifugal force counts.

Although our aim in this article is to offer a review of recent formalizations of context—those that can be used for automated reasoning—we first identify the role of context in various fields of AI. We also consider some (logic-based) attempts toward formalizing context. The focus of this discussion is McCarthy's (1993) proposal that, in our view, is the groundwork for all other logicist formalizations.

The approach that we pursue in our own line of research is inspired by situation theory (cf. Barwise and Perry [1983] and especially Devlin [1991]) and is detailed in Barwise (1986). The essence of Barwise's proposal is reviewed, but objectivity and prudence dictate that we do not review our own work here. Therefore, we refer the interested reader to two recent papers that detail our standpoint (Akman and Surav 1995; Surav and Akman 1995).[2]

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Some Useful Definitions

According to the *Oxford English Dictionary,* the term *context* typically has two primary meanings:[3] (1) the words around a word, phrase, statement, and so on, often used to help explain (fix) the meaning and (2) the general conditions (circumstances) in which an event, action, and so on, takes place. Clearly, the first definition is closely related to linguistic meaning and linguists' use of the term, whereas the second—more general—definition is closer to a desirable account of context in AI.[4] In *The Dictionary of Philosophy* (Angeles 1981, p. 47), the same term is defined, better reflecting the second definition:

> **context** (L. contexere, "to weave together," from con, "with," and texere, "to weave": The sum total of meanings (associations, ideas, assumptions, preconceptions, etc.) that (a) are intimately related to a thing, (b) provide the origins for, and (c) influence our attitudes, perspectives, judgments, and knowledge of that thing.

Similarly, in *Collins Cobuild English Language Dictionary* (Collins 1987), the prevalent meanings of the term include the following: First, the context of something consists of the ideas, situations, events, or information that relate to it and make it possible to understand it fully. Second, if something is seen in context or if it is put into context, it is considered with all the factors that are related to it rather than considered on its own, so that it can properly be understood. Third, if a remark, statement, and so on, are taken or quoted out of context, it is only considered on its own, and the circumstances in which it was said are ignored. Therefore, it seems to mean something different from the intended meaning.

The Role of Context

In this section, we discuss context as it relates to natural language, categorization, intelligent information retrieval, and knowledge representation and reasoning.

Context in Natural Language

Context is a crucial factor in communication.[5] Ordinary observation proves its importance: Just consider the confusion that results from the lack of contextual information when, for example, you join a scheduled meeting half an hour late. Without the clues of the original context, you might find it hard to make sense of the ongoing discussion. In any case, participants would realize that they cannot assume a lot about your background knowledge and give you a quick rundown of the conversations so far. This is essentially the view of Clark and Carlson (1981), who regard context as information that is available to a person for interaction with a particular process on a given occasion. Their intrinsic context is an attempt to capture the information available to a process that is potentially necessary for its success. The intrinsic context for grasping what a speaker means on some occasion is the (limited) totality of the knowledge, beliefs, and suppositions that are shared by the speaker and the listener (that is, the common ground).

Leech (1981, p. 66) gives another particularly attractive quasidefinition, as follows:

> [W]e may say that the specification of context (whether linguistic or non-linguistic) has the effect of narrowing down the communicative possibilities of the message as it exists in abstraction from context.

Thus, context is seen as having a so-called disambiguating function (among others). To quote Leech (1981, p. 67) once again, "The effect of context is to attach a certain *probability* to each sense (the complete ruling-out of a sense being the limiting case of nil probability)." Consider the following simple (possibly trivial for human beings) segment of conversation (Barwise 1987a):

A (a woman, talking to B): I am a philosopher.

B (talking to C and referring to A): She is a philosopher.

C (talking to A): So, you are a philosopher.

Context eliminates certain ambiguities or multiple meanings in the message. In the previous segment, one of the first context-dependent words is *philosopher.* The meaning of this word is determined using the context of conversation. Although this segment is insufficient to carry the proper connotation of this word, our common understanding selects an appropriate meaning from a set of possible meanings.[6]

In the previous example, the indexicals (for example, I, you) can be bound to appropriate persons only with the help of context. For example, the sentences uttered by A and B have the same content, but we can only say this using some circumstantial information and conventions about the conversation. This circumstantial information might be formalized through context. To quote Recanati (1993, p. 235), "[T]he meaning of a word like 'I' is a function that takes us from a context of utterance to the semantic value of the word in that context, which semantic value (the reference of 'I') is what the word contributes to the proposition expressed by the utterance." This view was made popular by Kaplan's (1989) seminal work on the logic of demonstratives.

Another function of context arises when we deal with quantifiers in logic or natural language semantics. The range and interpretation of quantifiers depend on the context. For example, the quantifier *all* usually does not apply to all objects, only to those of a particular kind in a particular domain, determined by the contextual factors. Another example might be the interpretation of the meaning of *many.* In an automobile factory, 10 automobiles might not qualify as many, but if a person owns 10 automobiles, it counts as many. Clearly, even the last interpretation about a person with 10 automobiles is context dependent. One might propose that *many* can only be interpreted as a ratio, which, too, has a contextual dependency on the ratio. In a class of students, half the students cannot be considered as many, enough to cancel a midterm exam, but surely must be regarded as many in an influenza epidemic.

Context might be used to fill the missing parameters in natural language utterances. Consider an utterance of the sentence, "Carl Lewis is running." Here, the time and the place of the running action are determined by the context. For example, if we are watching a competing Lewis on television at the 1992 Barcelona Olympic Games, then the time and the place of the utterance are different from what we would get if we watch him practice from our window.

Some relations stated in natural language necessarily need a context for disambiguation. Consider an utterance of the sentence, "The engineering building is to the left of the library." In the context of the Bilkent campus (figure 1), if we are viewing the buildings from the publishing company, the utterance is true, but if we are in the tourism school, the utterance is false. More interestingly, if we are looking from the rector's residence, this utterance must be considered neither true nor false: The library is behind the engineering building. Thus, for natural languages, a fleshing-out strategy, that is, converting everything into decontextualized eternal sentences (Quine 1969), cannot be employed because we do not always have full and precise information about the relevant circumstances.

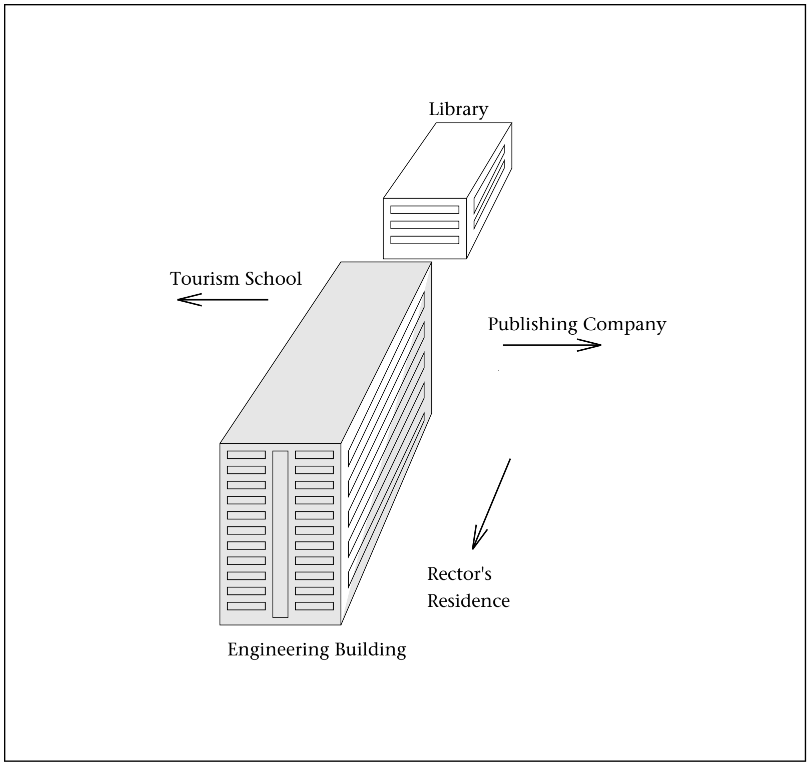

Figure 1. A Partial View of the Bilkent Campus.

Several studies in computational linguistics focused on the semantics of coherent multisentence discourse (or text).[7] The essential idea is that in discourse, each new sentence *s* should be interpreted in the context provided by the sentences preceding it. As a result of this interpretation, the context is enriched with the contribution made by *s*. (For example, an important aspect of this enrichment is that elements are introduced that can serve as antecedents to anaphoric expressions following *s*.) Emphasizing the representation and interpretation of discourse in context, discourse representation theory (van Eijck and Kamp 1996; Kamp and Reyle 1993) has influenced much subsequent work in computational linguistics.

To interpret extended discourse, some other researchers regard discourse as a hierarchically organized set of segments. The expectation is that each segment displays some sort of local coherence; that is, it can be viewed as stressing the same point or describing the same state of affairs. Grosz and Sidner (1986) outline a particularly illuminating model of this segmentation process, complete with an intentional constitution of discourse available in the segments.

Context eliminates certain ambiguities or multiple meanings in the message.

The use of general world knowledge (for example, knowledge about causality and everyday reasoning) is also fundamental for discerning much discourse. Early work by Schank and Rieger (1974) used such knowledge for computer understanding of natural language. More recent technical contributions by Charniak (1988) and Hobbs et al. (1993) can be seen as two formal attempts in this regard: (1) generate expectations that are matched into plausible interpretations of the discourse and (2) construct an (abduction-based) argument that explains why the current sentence is true.

Finally, it is worth noting that context has long been a key issue in social studies of language, that is, how human beings use language to build the social and cultural organizations that they inhabit. Lyons (1995, p. 292), thinking that this is natural, affirms that "in the construction of a satisfactory theory of context, the linguist's account of the interpretation of utterances must of necessity draw upon, and will in turn contribute to, the theories and findings of social sciences in general: notably of psychology, anthropology, and sociology." The reader is also referred to Goodwin and Duranti (1992) (and other articles in the same volume). They consider context a key concept in ethnographically oriented studies of language use and claim that this notion "stands at the cutting edge of much contemporary research into the relationship between language, culture, and social organization, as well as into the study of how language is structured in the way it is" (Goodwin and Duranti 1992, p. 32).

Context in Categorization

Categorization is one of the basic mental processes in cognition (Rosch 1978). We, as human beings, can categorize various types of objects, events, and states of affairs, and our categorizations depend on the circumstance and perspective. Consider the following scenario:

> In Springfield (the hometown of Bart Simpson), there are three barbers working for money and a man who does not work for money (because he has another job) but serves the community by shaving senior citizens on Sundays. If we look at the situation from a commonsense perspective, there are four barbers in town, but from, say, the mayor's point of view, there are only three (licensed, tax-paying, and so on) barbers.

Here, it is clear that context (or perspective) plays an important part in the correct classification.

Barwise and Seligman (1992) use natural regularities to study the role of context in categorization. An example regularity from Seligman (1993) is, "Swans are white." This is a typical natural regularity in the sense that it is both reliable and fallible. Natural regularities are reliable because they are needed to explain successful representation, knowledge, truth, and correct reference. They are fallible because they are needed to account for misinterpretation, error, false statements, and defeasible reference. Swans are, in general, white; thus, the regularity is reliable and explains a fact. There might be exceptions such as the Australian swans—they are usually black—but it does not mean that the regularity does not hold. Here, the fundamental problem with isolating the essential properties of a regularity is that any statement of them depends on some context of evaluation; that is, we should evaluate this regularity for, say, the European swans.

There is a correlation between nonmonotonic reasoning and the role of context-dependent factors in natural regularities. Although natural regularities are typically considered in philosophical discussions, they intuitively correspond to material implication in logic, and the effect of contextual factors is similar to the effect of nonmonotonicity. In logic, implication and nonmonotonicity are usually studied in a syntactic fashion, and the reasons behind the abnormalities are typically omitted from the discussion.

If we could completely describe all the contextual factors, then the problem would go away, and we would not require extra machinery. However, we must always include a *so forth* to cover the unexpected contextual factors; in many cases, it is simply impossible to state all the relevant ones (Tin and Akman 1992). Still, we must somehow be able to deal with them, which explains the introduction of the notion of context; using this notion in categorization should be useful.

Context in Intelligent Information Retrieval

A formal notion of context might be useful in information retrieval because it can increase the performance by providing a framework for well-defined queries and intelligent text matching. Given the explicit context, a query might be better described, and thus, the recall and precision might be enhanced. In this sense, we find the work of Hearst (1994) useful because she emphasizes the importance of context in full-text information access.

Traditional methods of information retrieval use statistical methods to find the similarities between the documents and the relevance of the documents to the query. In this respect, a formal context means that the query will be better described because it will contain more information than just a few keywords in the search. Inclusion of the context of the query also allows us to run more sophisticated methods to measure the relevance.

Various syntactic approaches can measure the relevance of a term to a document. Until recently, the only respectable methods were the statistical methods that are based on the frequency of occurrence. Lately, psychological, epistemic, and semantic considerations are beginning to flourish (Froehlich 1994). For example, Park (1994) studies the contributions of relevance to improving information retrieval in public libraries. According to her, the search criteria for any query should be set according to the users' criteria of relevance. Because different users exhibit different relevance criteria, the query formation is a dynamic task.

The essential work on relevance is owed to Sperber and Wilson (1986), who mainly consider the psychological relevance of a proposition to a context. Their assumption is that people have intuitions of relevance; that is, they can consistently distinguish relevant from irrelevant information. However, these intuitions are not easy to elicit or use as evidence because the ordinary language notion of relevance comes along with a fuzzy (variable) meaning. Moreover, intuitions of relevance are relative to contexts, and there is no way to control exactly which context someone will have in mind at a given moment. Despite these difficulties, Sperber and Wilson intend to invoke intuitions of relevance. According to them, a proposition is relevant to a context if it interacts in a certain way with the (context's) existing assumptions about the world, that is, if it has some contextual effects. These contextual effects include (1) *contextual implication,* a new assumption can be used together with the existing rules in the context to generate new assumptions; (2) *strengthening,* a new assumption can strengthen some of the existing assumptions; and (3) *contradiction* or *elimination*, a new assumption might change or eliminate some of the existing assumptions of the context.

Sperber and Wilson talk about degrees of relevance. Clearly, one piece of information might be more relevant to a particular context than another. To compare the relevance of pieces of information, they consider the *mental processing effort*, that is, the length of the chain of reasoning and the amount of encyclopedic information involved, and so on. Finally, they propose their celebrated *relevance maxim* (Sperber and Wilson 1986), which has two parts: (1) An assumption is relevant in a context to the extent that its contextual effects in this context are large. (2) An assumption is irrelevant in a context to the extent that the effort required to process it in this context is large.

Harter (1992) uses the theoretical framework of Sperber and Wilson to interpret psychological relevance in relation to information retrieval. According to him, reading a new bibliographic citation (the setting here is that of a user, accepting or rejecting a bibliographic document retrieved by a library information system) can cause a user to create a new context. A set of cognitive changes take place in that context; the citation and the context influence each other to give rise to new ideas. In other words, a retrieved citation (viewed as a psychological stimulus) is relevant to a user if it leads to cognitive changes in the user.

Using knowledge about data to integrate disparate sources can be considered a more sophisticated extension of information retrieval (Goh, Madnick, and Siegel 1995). Although networking technologies make phys-

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ical connectivity (and, hence, access to assorted data) feasible, much of these data are not perceived as meaningful because of the lack of information regarding the context of the data. This research aims at the development of a formal theory of context interchange (Reddy and Gupta 1995) using (1) context definitions (for example, defining the semantics, organization, and content of data) and (2) context characteristics (for example, data quality, security) and, thus, suggests a solution to the problem of semantic interoperation between (semantically) heterogeneous environments.

Context in Knowledge Representation and Reasoning

When we state something, we do so in a context. For example, 37 degrees centigrade is high in the context of a weather report but normal in the context of a medical diagnosis. In the context of Newtonian mechanics, time is ethereal, but in the context of general relativity, this is hardly the case. The examples can be continued. The main point is that if we are to reason in a commonsense way, we have to use certain contexts.

The importance of the notion of context has been realized by philosophers for centuries.[8] Early on, philosophers recognized that a causal connection between two events is only relative to a certain background and, thus, only in certain contexts. McCarthy (1987) was the first researcher to realize that the introduction of a formal notion of context is required for generality in AI.

According to McCarthy, there is simply no general context in which all the stated axioms always hold, and everything is meaningful. When one writes an axiom, it holds in a certain context, and one can always present another (more general) context in which the axiom fails. McCarthy formalizes relativized truth within a context using a special predicate holds(*p*,*c*), which states that proposition *p* holds in context *c*.[9]

If we compare the two approaches, namely, (1) using *holds* and (2) adding a context parameter to each function and predicate, we must prefer using *holds* because it allows us to use the notion of context uniformly as first-class citizens.[10] A problem with this approach (using *holds*) is that if we are to live in a first-order world (the world of first-order logic [FOL]), we have to reify *p* in holds(*p*,*c*). Alternative (modal) approaches to reifying assertions are investigated in Buvač, Buvač, and Mason (1995); Nayak (1994); and Shoham (1991).

Among the advantages gained as a result of the use of contexts are the following:[11]

Economy of representation: Different contexts can circumscribe (in a nontechnical sense) the parts of the knowledge base that are accessible in different ways, allowing the representation of many knowledge bases in a single structure.

Efficiency of reasoning: By factoring out a possibly large knowledge base, contexts might permit more competent reasoning about the real, intended scope.

Allowance for inconsistent knowledge bases: The knowledge base might be partitioned according to the context of its use. In this way, we can accommodate contradicting information in the same knowledge base as long as we treat such information carefully.

Resolving of lexical ambiguity: By using context, the task of choosing the correct interpretation of lexical ambiguity is made easier.[12] However, some argue that although a context formalism can represent lexical ambiguity, additional knowledge is needed to perform the resolution (Buvač 1996b).

Flexible entailment: Context might affect the entailment relation. For example, in a particular context, entailment might warrant a closed-world assumption, whereas in some other context, this assumption needs to be dropped (the classical case).

Being the largest commonsense knowledge-building attempt, CYC (Lenat 1995; Guha and Lenat 1990), has crucial pointers on reasoning with an explicit notion of context (Guha 1991). Some aspects of the representation of knowledge that are influenced by contextual factors include the following:

Language: The language (that is, the predicates, functions, and categories) used for representation should be appropriate for their intended domain. For example, MYCIN and ONCOCIN—two renowned medical diagnosis programs—overlap significantly in their domains; however, ONCOCIN has some concept of time, whereas MYCIN does not.

Granularity and accuracy: As with vocabulary, the application area, thus context, determines the granularity and accuracy of the theory.

Assumptions: The assumptions that a given task permits often lead to a simplification of the vocabulary. If we try to continue this simplification for large domains, at one point, the assumptions become unstable. Thus, either we should use a highly expressive vocabulary or distribute the assumptions to different tasks.

CYC researchers identify two approaches to building large commonsense knowledge bases and reasoning with them. First, the straightforward way that a knowledge base builder might choose is the introduction of an extremely expressive and powerful vocabulary. This approach increases the complexity of the problem because such a vocabulary causes difficulties in truth maintenance and produces large search spaces. The second way (Guha 1991) is to make the context dependence of a theory explicit. In this approach, assertions (axioms, statements) are not universally true; they are only true in a context. An assertion in one context might be available for use in a different context by performing a relative decontextualization. In CYC, the uses of context include the following:

A general theory of some topic: A theory of mechanics, a theory of weather in Alabama, a theory of what to look for when buying dresses, and so on: Such contexts are called *microtheories* (Guha 1991). Different microtheories make different assumptions and simplifications about the world. For any topic, there might be different microtheories of the topic, at varying levels of detail.

A basis for problem solving: For some difficult problems, we can form a particular context. We collect all related assumptions, rules, and so on, in that context (called the problem-solving context [PSC] in CYC [Guha and Lenat 1990]) and can process a group of related queries in a relatively small search space. Such contexts must be created dynamically and be disposed of afterward.

Context-dependent representation of utterances: Naturally, we can use anaphoric and indefinite statements without completely decontextualizing them. For example, the words *the person* might be used in a discourse without identifying him/her exactly.

Formalizations in Logic

The notion of context was first introduced to AI in a logicist framework by McCarthy in his 1986 Turing Award paper (McCarthy 1987).[13] McCarthy published his recent ideas on context in McCarthy (1995, 1994, 1993). Other notable works on formalizing context are S. Buvač et al. (Buvač, Buvač, and Mason 1995; Buvač and Mason 1993), Attardi and Simi (Attardi and Simi 1995, 1994), F. Giunchiglia et al. (Giunchiglia and Serafini 1994; Giunchiglia 1993), Guha (1991), and Shoham (1991). We reviewed McCarthy's (1987) early ideas in the previous section. In this section, we evaluate the other logicist formalizations, starting with McCarthy's more recent proposal.

McCarthy on Contexts

McCarthy (1993) states three reasons for introducing the formal notion of context.[14] First, the use of context allows simple axiomatizations. To explain, he states that axioms for static blocks world situations can be lifted to more general contexts—those in which the situation changes.[15] Second, contexts allow us to use a specific vocabulary of, and information about, a circumstance. An example might be the context of a (coded) conversation in which particular terms have particular meanings that they would not have in daily language in general.[16] Third, McCarthy proposed a mechanism by which we can build AI systems that are never permanently stuck with the concepts they use at a given time because they can always transcend the context they are in.

The third goal brings about two problems: First is when to transcend a context. Either the system must be smart enough to do so, or we must instruct it about when to transcend one or more levels up. Second is where to transcend. This problem can be clarified if we are prepared to accept that formulas are always considered to be asserted within a context.

The notion of context was first introduced to AI in a logicist framework by McCarthy in his 1986 Turing Award paper.

The basic relation relating contexts and propositions is ist(c, p). It asserts that proposition p is true in context c. Then, the main formulas are sentences of the form

c': ist(c, p) .

In other words, p is true in context c, which itself is asserted in an outer context c'.

To give an example of the use of ist,

c_0: ist(*context-of*("Sherlock Holmes stories"), "Holmes is a detective")

asserts that it is true in the context of Sherlock Holmes stories that Holmes is a detective. Here, c_0 is considered to be the *outer context*. However, in the context *context-of* ("Sherlock Holmes stories"), Holmes's mother's maiden name does not have a value.

Two key properties of context are as follows: First, contexts are abstract objects. Some contexts will be rich objects just like the situations in situation calculus.[17] Some contexts will not be as rich and might be fully described, for example, simple microtheories (Guha 1991). Second, contexts are first-class citizens: We can use contexts in our formulas in the same way we use other objects.

Relations and Functions Involving Contexts

There are some relations working between contexts. The most notable one is ≤, which defines a partial ordering over contexts. Between two contexts, we might consider a more general than relation ($c_1 \leq c_2$), meaning that the second context contains all the information of the first context and probably more. Using ≤, we can lift a fact from a context to one of its supercontexts using the following nonmonotonic rule:

$$\forall c_1 \forall c_2 \forall p (c_1 \leq c_2) \wedge \mathrm{ist}(c_1, p) \wedge \neg ab1(c_1, c_2, p) \rightarrow \mathrm{ist}(c_2, p) \ .$$

Here, c_2 is a supercontext of c_1, p is a proposition of c_1, $ab1$ is an abnormality predicate, and $\neg ab1(c_1, c_2, p)$ is used to support nonmonotonicity. Analogously, we can state a similar lifting rule between a context and one of its subcontexts:

$$\forall c_1 \ \forall c_2 \ \forall p (c_1 \leq c_2) \wedge \mathrm{ist}(c_2, p) \wedge \neg ab2(c_1, c_2, p) \rightarrow \mathrm{ist}(c_1, p) \ .$$

The difference between the abnormality relations is crucial: $ab1$ represents the abnormality in generalizing to a supercontext, whereas $ab2$ corresponds to the abnormality in specializing to a subcontext.

Guha … finds an essential use for formal contexts in implementing his so-called microtheories.

Here are some examples of functions on contexts that we might want to define:

value(c, t) is a function that returns the value of term t in context c:

value(*context-of*("Sherlock Holmes stories"), "number of wives of Holmes") = 0.

This example states that Holmes has no wife in the context of Sherlock Holmes stories.

specialize-time(t, c) is a context related to c in which the time is specialized to the value t:

c_0: ist(*specialize-time*(t, c), at(*JMC*, *Stanford*))

states that at time t in context c, JMC (John McCarthy) is at Stanford University. Instead of specializing on time, we can also specialize on location, speaker, situation, subject matter, and so on.

The formal theory of context can be used to model inference in the style of deduction. Thus, *assuming*(p, c) is another context like context c in which proposition p is assumed. Using this function, we might dynamically create a context containing the axioms we desire. The new context validates the following rules (McCarthy and Buvač 1994):

Importation: This is the rule $c : p \rightarrow q \vdash assuming(c, p) : q$.

Discharge: This is the rule $assuming(c, p) : q \vdash c : p \rightarrow q$.

When we take contexts in this natural deduction sense (as suggested in McCarthy [1987]), the operations of entering and leaving a context might be useful and shorten the proofs involving contexts. In this case, ist(c, p) will be analogous to $c \rightarrow p$, and the operation of entering c can be taken as *assuming*(p, c). Then, entering c and inferring p will be equivalent to ist(c, p) in the outer context.

Lifting Here are some of the things we can do with lifting. (By *lifting* a predicate from one context to another, we mean transferring the predicate to the other context with appropriate changes [when necessary].)

Transfer a formula verbatim: If two contexts are using the same terminology for a concept in an axiom, lifting is a natural choice. For example, the following lifting rule states that we can use the axioms related to the *on*(x, y) of *above-theory* context in *general-blocks-world* context without any change:

c_0: ∀ x ∀ y ist(*above-theory*, *on*(x, y)) → ist(*general-blocks-world*, *on* (x, y)) .

Change the arity of a predicate: In different contexts, the same predicate might take a different number of arguments. McCarthy's example for this is *on,* which takes two arguments in *above-theory* context and three arguments in a context c in which *on* has a third argument denoting the situation. The lifting rule is

c_0: ∀ x ∀ y ∀ s ist(*above-theory*, *on*(x, y)) → ist(*context-of*(s), *on*(x, y, s)) ,

where *context-of* is a function returning the context associated with the situation s in which the usual *above-theory* axioms hold.

Change the name of a predicate: Similar to the case with arities, we can change the name of a predicate by lifting rules. For example, we can translate *on* to *üzerinde* when we move from *above-theory* to *turkish-above-theory:*

c_0: ∀ x ∀ y ist(*above-theory*, *on*(x, y)) → ist(*turkish-above-theory*, *üzerinde*(x, y)) .

Other Issues McCarthy proposed relative decontextualization as a way to do the work of *eternal sentences*—the mythical class embracing those sentences that express the same proposition no matter what world the utterance takes place in (Quine 1969) (assuming that the world in question is linguistically similar to ours). McCarthy feels strongly that eternal sentences do not exist. His proposed mechanism depends on the premise that when several contexts occur in a discussion, there is a common context above all of them into which all terms and predicates can be lifted. (However, the outermost context does not exist.) Sentences in this context are relatively eternal. A similar idea is used in the PSCs of CYC.

Another place where context might be useful is the representation of mental states (McCarthy 1993). McCarthy proposes a scheme in which mental states can be thought of as outer sentences; for example,

believe(*Jon*, *publication*(*AAAI*)
= *AIMag*, *because* …) ,

where the ellipsis denotes the reasons for Jon's belief that *AI Magazine* is a publication of AAAI. The point of representing mental states with such sentences is that the grounds for having a belief can be included. The advantage gained by this is twofold: In a belief-revision system, when we are required to do belief revision, incorporating the reasons for having a belief simplifies our work. However, when we use beliefs as usual (that is, no belief revision is required), we simply enter the related context and assert them. For example, in an outer context, the sentence about *AI Magazin*e, with reasons, is asserted. In an inner context, the simpler sentence *publication*(*AAAI*) = *AIMag* would suffice because we have already committed ourselves to reasoning with this last proposition.

Guha on Contexts

Guha (1993, 1991) finds an essential use for formal contexts in implementing his so-called microtheories. *Microtheories* are theories of limited domains. Intuitively, microtheories are the context's way of seeing the world and are considered to have the following two basic properties: (1) a set of axioms is related to each microtheory and (2) a vocabulary tells us the syntax and semantics of each predicate and each function specific to the microtheory. Similar to McCarthy's conception, microtheories are interrelated through lifting rules stated in an outer context.

Guha suggests several ways of using contexts effectively in reasoning, including the following:

First, contexts might be useful in putting together a set of related axioms. In this way, contexts are used as a means for referring to a group of related assertions (closed under entailment) about which something can be said.

Second, contexts can be used as a mechanism for combining different theories. If the assertions in one context were not automatically available in other contexts, the system might as well be a set of disconnected knowledge bases. Therefore, by using lifting rules, different microtheories can be integrated.

Third, using contexts, we might have multiple models of a task. For example, for the task of finding out what to do in case of fire, we can offer different models for a workplace and for a house. In a workplace, the first thing to do might be to take away a file of documents, whereas in a house, children must be saved first.

Lifting rules might be used to transfer facts from one context (source) to another context (target). In the target context, the scope of quantifiers, the interpretation of objects, and even the vocabulary can change. Therefore, when we state a lifting rule, we must take all the possible outcomes into account. In the case of natural language, the problem becomes more complicated because indexicals and demonstratives come into play. Lifting rules should definitely be nonmonotonic. Guha uses default reasoning in the statement of lifting rules. His intuitions about the general lifting rules are as follows:

Default coreference: Although there are differences among contexts, it can be expected that there will be similarities and overlap. As a result, a significant number of terms in different contexts refer to (mean) the same thing. Such terms can be lifted from one context to another without any modification. Similarly, we can expect overlap in many formulas, which can be lifted from one context to another without any change. Therefore, it will be a great simplification if we assume that a lifting operation will not require any modification, unless it is explicitly stated that there should be a change.

Compositional lifting: Between contexts, there might be differences in vocabularies both in the words used and in the intended denotations of these words. In this case, specifying lifting rules for individual predicates should be enough for the system to use these rules in the lifting of formulas involving the predicates.

Although Guha's proposal accommodates any level of nesting with context, in CYC, there are two levels: (1) microtheories and (2) the default outer level. The lifting rules and general facts are stated in the outer level, and a problem is solved by the construction of a PSC under this level, unless the problem is local to a microtheory.

S. Buvač et al. on Contexts

Buvač and Mason (1993) (and a more recent work, Buvač, Buvač, and Mason [1995]) approach context from a mathematical viewpoint. They investigate the logical properties of contexts. They use the modality ist(c, p) to denote context-dependent truth and extend the classical propositional logic to what they call the *propositional logic of context.* (The quantificational logic of context is treated in Buvač [1996a].) In their proposal, each con-

Buvač and Mason … approach context from a mathematical viewpoint.

text is considered to have its own vocabulary—a set of propositional atoms which are defined (or meaningful) in that context.

S. Buvač and Mason discuss the syntax and semantics of a general propositional language of context and give a Hilbert-style (Gallier 1987, p. 79) proof system for this language. The key contribution of their approach is providing a model theory for contexts. Two main results are the soundness and completeness proofs of this system. They also provide soundness and completeness results for various extensions of the general system and prove that their logic is decidable.

The formal system is defined by the axioms (PL, K, and Δ) and inference rules (MP, Enter, Exit) given below:

Giunchiglia … takes a context to be a theory of the world that encodes an agent's perspective of it and that is used during a given reasoning process.

(PL): $\vdash_c \phi$ (meaning: a formula ϕ is provable in context c [with a fixed vocabulary] provided ϕ is an instance of a tautology).

(K): $\vdash_c \text{ist}(c_1, \phi \rightarrow \varphi) \rightarrow (\text{ist}(c_1, \phi) \rightarrow \text{ist}(c_1, \varphi))$ (meaning: every context is closed with respect to logical consequence).

(Δ): $\vdash_c \text{ist}(c_1, \text{ist}(c_2, \phi) \vee \varphi) \rightarrow \text{ist}(c_1, \text{ist}(c_2, \phi)) \vee \text{ist}(c_1, \varphi)$ (meaning: every context is aware of what is true in every other context).

(MP): From $\vdash_c \phi$ and $\vdash_c \phi \rightarrow \varphi$,
infer $\vdash_c \varphi$.

(Enter): From $\vdash_{c'} \text{ist}(c, \phi)$, infer $\vdash_c \phi$;
(Exit): From $\vdash_c \phi$, infer $\vdash_{c'} \text{ist}(c, \phi)$.

This system has the following two features (Buvač and Mason 1993):

First, a context is modeled by a set of partial truth assignments that describe the possible states of affairs in the context. The ist modality is interpreted as validity: ist(c, p) is true if and only if the propositional atom p is true in all the truth assignments associated with context c.

Second, the nature of particular contexts is itself context dependent. S. Buvač and Mason's example is Tweety, which has different interpretations when it is considered in a nonmonotonic-reasoning– literature context and when it is considered in the context of Tweety and Sylvester. This observation leads us to consider a context as a sequence of individual contexts rather than a solitary context. In S. Buvač and Mason's terminology, such a property is known as *nonflatness* of the system. The acceptance of a sequence of contexts respects the intuition that what holds in a particular context can depend on how this context is reached.[18]

S. Buvač and Mason show that the acceptance of the outermost context simplifies the metamathematics of the contexts. They first assume that there is no outermost context and build a proof system on this assumption. Then, they show that introducing the outermost context only simplifies the way they are dealing with nonflatness.

F. Giunchiglia and Others on Contexts

Giunchiglia (1993) takes a context to be a theory of the world that encodes an agent's perspective of it and that is used during a given reasoning process. A context is necessarily partial and approximate. Contexts are not situations (of situation calculus) because a *situation* is the complete state of the world at a given instant.

In formalizing context, Giunchiglia's point of departure is partitioned databases (cf. Giunchiglia and Weyhrauch 1988) for origins of this work). Each partition, A_i, can have different vocabulary. For example, A_1 supports arithmetic operations, but A_2 might support logical operations. With this approach, the notion of well-formedness can be localized and can be distinct for each partition A_i. In formal terms, a context c_i is a triple $<L_i, A_i, \Delta_i>$, where L_i is the language of the context, A_i is the axioms of the context, and Δ_i is the inference mechanism of the context. Under this definition, linking (bridge) rules are of the form $<A_i, c_i> / <A_j, c_j>$, where A_i is a formula in c_i, and A_j is the newly derived formula in c_j (also called a *justified assumption*). Giunchiglia offers the following to show the use of bridge rules:

First, the usual modus ponens (MP) can be represented as $<A \rightarrow B, c_i> <A, c_i> / <B, c_i>$.

Second, a multicontextual version of MP is represented as $<A \rightarrow B, c_i> <A, c_j> / <B, c_k>$.

Third, McCarthy's ist formula (asserted in c') becomes $<A, c> / <\text{ist}(c, A), c'>$. (If we can prove A in context c, then we can prove in context c' that we can prove A in c.)

The first rule allows us to derive B inside a context just because we have derived $A \rightarrow B$ and A in the same context. Multicontextual MP allows us to derive B in context c_k just because we have $A \rightarrow B$ derived in context c_i and A derived in context c_j. If these three contexts are assumed to represent the beliefs of three agents, then it is seen that B is not asserted as a result of deduction in c_k but, rather, as a consequence of dissemination of results from c_i and c_j.

In a related work, Giunchiglia and Serafini (1994) formalize multilanguage systems of the sort described here and propose them as an alternative to modal logic. (Multilanguage systems allow a hierarchy of first-order languages, each language containing names for the language below.) They then offer technical, epistemological, and implementation motivations to justify their proposal. Two useful applications of multilanguage systems can be found in Giunchiglia, Traverso, and Giunchiglia (1992) and Giunchiglia and Serafini (1991).

Attardi and Simi on Contexts

Attardi and Simi (1995) offer a viewpoint representation that primarily depends on the view of context in a natural deduction sense. According to Attardi and Simi, contexts are sets of reified sentences of the FOL.

The main purpose of Attardi and Simi is to present a formalization of the notion of viewpoint as a construct meant for expressing varieties of relativized truth. The formalization is done in a logic that extends the FOL through an axiomatization of provability and with the proper reflection rules.[19]

The basic relation in the formalization is in(*'A'*, *vp*), where *A* is a sentence provable from viewpoint *vp* by means of natural deduction techniques. Viewpoints denote sets of sentences that represent the axioms of a theory. Viewpoints are defined as a set of reified metalevel sentences.

Because viewpoints are defined as sets of reified sentences, operations between viewpoints are carried out with metalevel rules, for example,

$$\frac{\mathrm{in}('B', vp \cup \{'A'\})}{\mathrm{in}('A \rightarrow B', vp)} \ .$$

This operation corresponds to the following in classical logic:

$$\frac{vp \cup \{A\} \vdash B}{vp \vdash A \rightarrow B} \ .$$

The effective use of viewpoints in doing useful proofs requires a connection between the metalevel and the object-level rules. The following rules make this connection:

$$vp_1 \vdash \mathrm{in}('A', vp_2) \,/\, vp_1 \cup vp_2 \vdash A \ .$$
(reflection)

$$vp \vdash_C A \,/ \vdash \mathrm{in}('A', vp) \ .$$
(reification)

The notation $\vdash_C$ stands for "classically derivable" or "derivable without using the reflection rules."

Attardi and Simi cite a wide range of examples using the viewpoints. For example, based on viewpoints, the notions of belief, knowledge, truth, and situation can be formalized as follows:

Belief: The belief of an agent *g* is captured by means of "in" sentences, using *vp*(*g*) as the viewpoint corresponding to the set of assumptions of the agent. Thus,

$$\mathrm{Bel}(g, A) = \mathrm{in}(A, vp(g)) \ ,$$

and by the reflection rule

$$\mathrm{in}(A, vp(g)) \rightarrow (vp(g) \rightarrow A) \ ,$$

we can use the beliefs of an agent.

Truth: Truth is captured as provability in a special theory, viz., the real world (RW). Ideally, everything that is true should be derivable in this theory, and truth can be defined as

$$\mathrm{True}(A) = \mathrm{in}(A, \mathrm{RW}) \ .$$

Knowledge: Attardi and Simi view knowledge as true belief:

$$\mathrm{K}(g, A) = \mathrm{Bel}(g, A) \wedge \mathrm{True}(A) \ .$$

Clearly, all the properties typically ascribed to knowledge can be derived, for example, $\mathrm{K}(g, A) \rightarrow A$.

Situations in the manner of Barwise and Perry: Attardi and Simi take situations as sets of basic facts (Barwise and Etchemendy 1987) and use an approach similar to that of belief. Thus, they define a basic relation

$$\mathrm{Holds}(A, s) = \mathrm{in}(A, vp(s)) \ ,$$

where *vp*(*s*) is the set of facts holding in a situation *s*. (See The Situation-Theoretic Approach.)

Shoham on Contexts

Shoham (1991) uses the alternative notation p^c to denote that assertion *p* holds in context *c*. According to him, every assertion is meaningful in every context, but the same assertion might have different truth values in different contexts.[20] Thus, his approach is different from the approaches of McCarthy, Guha, and S. Buvač et al.

Shoham describes a propositional language depending on his more general than relation ($\dot{\supset}$). The relation defines a weak partial ordering between contexts; not every pair of contexts is comparable under it. Is there a most general (or most specific) context? Mathematically, this question corresponds to, "Is there an upper (or lower) bound on $\dot{\supset}$?" In Shoham's proposal, the question is not answered, but when the system is analyzed, the existence of the most general and the most specific contexts is considered.[21]

The language Shoham describes is similar to FOL, but his relations $\dot{\supset}$, $\dot{\vee}$, $\dot{\wedge}$, and $\dot{\neg}$ work over contexts. Here, $x \,\dot{\wedge}\, y$ is defined as the greatest lower bound on *x* and *y* with respect to $\dot{\supset}$ (if it exists). Similarly, $x \,\dot{\vee}\, y$ is defined as a least upper bound of the contexts *x* and *y* (if it exists). When defined, $\dot{\neg} x$ is the context

Attardi and Simi … offer a viewpoint representation that primarily depends on the view of context in a natural deduction sense.

that is not comparable to x under $\dot{\supset}$.[22] A context set is *and-closed* if it is closed under conjunction, *or-closed* if it is closed under disjunction, *and-or-closed* if it is both, *not-closed* if it is closed under negation, and simply *closed* if it is all three. From these definitions, we see that if an or-closed context set contains both x and $\dot{\neg} x$ for some x, then the context set contains the most general context, that is, the *tautological context*. Similarly, under the same condition, an and-closed context set contains the most specific context, that is, the *contradictory context*.

What should be the logical status of p^c? Shoham takes it to be an assertion and introduces a simple language for discussing contexts and assertions about them. Basically, given a context set C with the partial order $\dot{\supset}$ and a propositional language $\mathcal{L}$, the set of well-formed formulas is the smallest set S such that the following is true:

First, if $c_1, c_2 \in C$, then $c_1 \dot{\supset} c_2 \in S$.
Second, if $p \in \mathcal{L}$, then $p \in S$.
Third, if $s \in S$ and $c \in C$, then $s^c \in S$.
Fourth, if $s_1, s_2 \in S$, then $s_1 \dot{\wedge} s_2 \in S$ and $\neg s_1 \in S$.

Abstract situations are the constructs that are more amenable to mathematical manipulation. An abstract situation *is defined as a … set of infons.*

Shoham's purpose is not really to offer the right semantics for p^c; he is more interested in identifying some options for achieving this ultimate goal and investigating the interaction between modal operators (for example, the knowledge operator K in the logic of knowledge and belief) and context. Some interesting proposals are given in this direction to investigate the notion of contextual knowledge, that is, the meaning of $K^c p$—his notation for "p is known in context c."

The Situation-Theoretic Approach

The standard reference on situation theory is Devlin (1991). The original work of Barwise and Perry (1983) is still worthy of study and remains an elegant philosophical argument for introducing situations. Unfortunately, the notation and (sometimes) the terminology of Barwise and Perry are rather outdated. Accordingly, we use Devlin's notation and terminology in the following discussion.

According to situation theory, *infons* are the basic informational units (discrete items of information). They are denoted as $\langle\langle P, a_1, \ldots, a_n, i\rangle\rangle$, where P is an n-place relation; $a_1, \ldots, a_n$ are objects appropriate for the respective argument places of P; and i is the polarity (1 or 0) indicating whether the relation does or does not hold.

Situations are first-class citizens of the theory and are defined intensionally. A *situation* is considered a structured part of the reality that an agent manages to pick out or individuate. Situations and infons are related by the supports relation:

s supports α (denoted $s \models \alpha$) means that α is an infon that is true of s.

For example, a situation s in which Bob hugs Carol would be described by $s \models \langle\langle hugs, Bob, Carol, l, t, 1\rangle\rangle$, where l and t together give the spatiotemporal coordinates of this hugging action.

Abstract situations are the constructs that are more amenable to mathematical manipulation. An *abstract situation* is defined as a (possibly not-well-founded [Barwise and Etchemendy 1987] set of infons. Given a real situation s, the set $\{\alpha \mid s \models \alpha\}$ is the corresponding abstract situation.

One of the important ideas behind situation theory is the *scheme of individuation,* a way of carving the world into uniformities. As constructs that link the scheme of individuation to the technical framework of the theory, types are important features of situation theory. Just as individuals, temporal locations, spatial locations, relations, and situations, types are also uniformities that are discriminated by agents. Relations can have their argument places filled either with individuals, situations, locations, and other relations or with types of individuals, situations, locations, and relations. Some basic types are *TIM* (the type of a temporal location), *LOC* (the type of a spatial location), *IND* (the type of an individual), and *SIT* (the type of a situation).

In situation theory, for each type T, an infinite collection of basic parameters $T_1, T_2, \ldots$ is introduced. For example IND_3 is an *IND* parameter. We use the notations $\dot{l}, \dot{t}, \dot{a}, \dot{s}$, and so on, to denote parameters of type *LOC*, *TIM*, *IND*, *SIT,* and so on, respectively. Sometimes, rather than parameters ranging over all individuals, we need parameters that range over a more restricted class, namely, restricted parameters, for example,

$$\dot{r}1 = \dot{a} \uparrow \langle\langle kicking, \dot{a}, \dot{b}, 1\rangle\rangle\ .$$
$$\dot{a} = IND3 \uparrow \langle\langle man, IND3, 1\rangle\rangle\ .$$
$$\dot{b} = IND2 \uparrow \langle\langle football, IND2, 1\rangle\rangle\ .$$

In this case, $\dot{r}1$ ranges over all men kicking footballs.

We use the term *parametric infon* to emphasize that in a particular infon, one or more parameters occurs free. Infons that have no free parameters are called *parameter free.* Related to parametric infons, an *anchor* is a construct by which we can assign values to parameters. Formally, an anchor for a set A of basic parameters is a function defined on A that assigns to each parameter T_i in A an object of type T. Therefore, if f is an anchor for A, and T_i is a parameter in A, then

$$\langle\langle \textit{of-type}, f(T_i), T, 1\rangle\rangle \ .$$

For example, if f anchors $\dot{a}$ to the type IND_3 individual Sullivan, we write

$$f(\dot{a}) = \text{Sullivan}$$

to denote this anchoring.

Let s be a given situation. If $\dot{x}$ is a parameter, and I is a set of infons (involving $\dot{x}$), then there is a type

$$[\dot{x} \mid s \models I] \ .$$

This is the type of all those objects to which $\dot{x}$ can be anchored in s, such that the conditions imposed by I obtain. We refer to this process of obtaining a type from a parameter $\dot{x}$, a situation s, and a set I of infons as *type abstraction.* $\dot{x}$ is known as the *abstraction parameter,* and s is known as the *grounding situation.*

In situation theory, the flow of information is realized through constraints, represented as

$$S_0 \Rightarrow S_1 \ .$$

Here, S_0 and S_1 are situation types. Cognitively, if this relation holds, then it is a fact that if S_0 is realized (that is, there is a real situation $s_0 : S_0$), then so is S_1 (that is, there is a real situation $s_1 : S_1$). For example, with the constraint $S_s \Rightarrow S_f$, we might represent the regularity "smoke means fire," provided that we have

$$S_s = [\dot{s} \mid \dot{s} \models \langle\langle \textit{smoke-present}, \dot{l}, \dot{t}, 1\rangle\rangle] \ .$$

$$S_f = [\dot{s} \mid \dot{s} \models \langle\langle \textit{fire-present}, \dot{l}, \dot{t}, 1\rangle\rangle] \ .$$

This constraint is read as "S_S involves S_f" and represents a fact (that is, a factual, parameter-free infon):

$$\langle\langle \text{involves}, S_s, S_f, 1\rangle\rangle \ .$$

Attunement to this constraint is what enables an intelligent agent that sees smoke in a situation to realize that there is a fire.

Barwise on Contexts

Barwise's ideas on circumstance, thus on context, are best articulated in his work on conditionals and circumstantial information (Barwise 1986). Situations represent a way of modeling contexts. In fact, in Barwise (1987b), the author expounds why a context is a situation. Briefly, he proposes that a definite relationship exists between situations and what are known as *context sequences* in possible world semantics (Akman and Tin 1990). In possible world semantics, given a sentence s, the person p who uttered the sentence, the spatiotemporal location of the utterance l, and t, the object o *that* p is referring to, and so on, are all lumped together into a sequence $c = \langle p, l, t, o, \ldots\rangle$. Basically, c represents various contextual elements that play a role in obtaining the propositional content of any particular use of s. Barwise claims that c is nothing more than a representation of a situation, the portion of the world that is essentially needed (relevant) to determine the content of the utterance of s. Thus, he claims that by admitting situations, one no longer needs ad hoc devices such as c.

The Missing Pollen Let us consider Claire (Barwise's then nine-month-old daughter). Barwise knows that if Claire rubs her eyes, then she is sleepy, expressed by the conditional statement, "If Claire rubs her eyes, then she is sleepy."

For months, this was a sound piece of (conditional) knowledge that Barwise and his wife used to understand Claire and learn when they should put her to bed. However, in early summer, this knowledge began to fail them. Combined with other symptoms, Barwise and his wife eventually figured out that Claire was allergic to something. They called it pollen X because they did not know its precise identity; so, pollen X could also cause Claire to rub her eyes.

Barwise formalizes the problem stated in this example as follows: Briefly, with constraint $C = [S \Rightarrow S']$, a real situation s contains information relative to such an actual constraint C if $s : S$. Clearly, s can contain various pieces of information relative to C, but the most general proposition that s contains, relative to C, is that s' is realized, where $s' : S'$.

Thus, we can represent this conditional information with the following parametric constraint C:

$$S = [\dot{s} \mid \dot{s} \models \langle\langle \textit{rubs, Claire, eyes}, \dot{l}, \dot{t}, 1\rangle\rangle].$$

$$S' = [\dot{s} \mid \dot{s} \models \langle\langle \textit{sleepy, Claire}, \dot{l}, \dot{t}, 1\rangle\rangle] \ .$$

$$C = [S \Rightarrow S'] \ .$$

Before pollen X was present, this constraint represented a reasonable account. However, when pollen X arrived, the constraint became inadequate and required revision. Barwise points out two alternatives to deal with the problem:

First, from [if ϕ, then φ], infer [if ϕ and β, then φ].

Second, from [if ϕ, then φ], infer [if β, then if ϕ, then φ].

Here, β corresponds to the additional background conditions.

Barwise chooses the second way, modifies *involves,* and makes the background assump-

In situation theory, we represent implications with constraints.

	Mc93[1]	**Gu91**[2]	**Sh91**[3]	**Gi93**[4]	**BM93**[5]	**AS95**[6]	**Ba86**[7]
Logic vs. Situation Theory (S.T.)	Logic	Logic	Logic	Logic	Logic	Logic	S.T.
Modal Treatment	No	No	Yes	No	Yes	No	No
Natural Deduction	Yes	Yes	No	Yes	Yes	Yes	No
Paradox Free	No	No	Yes	Yes	Yes	Yes	?
Circularity	No	No	No	No	No	Yes	Yes

Table 1. Comparison of Approaches toward Formalizing Context.

Notes

1. Mc93 = Notes on formalizing context (McCarthy 1993).
2. Gu91 = Contexts: A formalization and some applications (Guha 1991).
3. Sh91 = Varieties of context (Shoham 1991).
4. Gi93 = Contextual reasoning (Giunchiglia 1993).
5. BM93 = Propositional logic of context (Buvač and Mason 1993).
6. AS95 = A formalization of viewpoints (Attardi and Simi 1993).
7. Ba86 = Conditionals and conditional information (Barwise 1986).

tions explicit by introducing a third parameter B:[23]

$$S_0 \Rightarrow S_1 \mid B \ .$$

With the new *involves,* the missing pollen example can be solved with the introduction of a B, which supports the following:

$$\langle\langle \mathit{exists, pollen\ X}, \dot{l}, \dot{t}, 0\rangle\rangle \ .$$

$$S = [\dot{s} \mid \dot{s} \models \langle\langle \mathit{rubs, Claire, eyes}, \dot{l}, \dot{t}, 1\rangle\rangle] \ .$$
$$S' = [\dot{s} \mid \dot{s} \models \langle\langle \mathit{sleepy, Claire}, \dot{l}, \dot{t}, 1\rangle\rangle] \ .$$
$$B = [\dot{s} \mid \dot{s} \models \langle\langle \mathit{exists, pollen\ X}, \dot{l}, \dot{t}, 0\rangle\rangle] \ .$$

$$C = [S \Rightarrow S' \mid B] \ .$$

In the beginning, it was winter, and there was no pollen. The context, call it c_1, must be a situation type that supports

$$c_1 \models \langle\langle \mathit{exists, pollen\ X}, \dot{l}, \dot{t}, 0\rangle\rangle$$

(and possibly other things related to Claire, rubbing one's eyes, and so on). Using context c_1 as the grounding situation, we do not violate the background condition B of constraint C and, thus, can conclude that "Claire is sleepy."

Later, in summer, the new context, c_2, supports the infon

$$c_2 \models \langle\langle \mathit{exists, pollen\ X}, \dot{l}, \dot{t}, 1\rangle\rangle \ ,$$

and when we use c_2 as the grounding situation, we are faced with an inconsistency between B and c_2. Therefore, C becomes void in the new context of the talk, and the conclusion "Claire is sleepy" cannot be reached.

I Am a Philosopher We will prove that the content of all three sentences (given earlier) is the same; that is, A is a philosopher.

We have three contexts associated with each individual in the conversation: c_A, c_B, and c_C, respectively. We represent the indexicals with special parameters $\dot{I}$, $\dot{\mathit{You}}$, and $\dot{\mathit{She}}$.

In c_A, we have the following infons supported:

$$\langle\langle \mathit{corresponds}, \dot{I}, A, 1\rangle\rangle$$

$$\langle\langle \mathit{philosopher}, \dot{I}, 1\rangle\rangle \ ,$$

where *corresponds* is a function that associates an indexical to a person, and utterances about being a philosopher are represented with infons of type $\langle\langle \mathit{philosopher}, \dot{x}, 1\rangle\rangle$.

c_B supports

$$\langle\langle \mathit{corresponds}, \dot{\mathit{She}}, A, 1\rangle\rangle$$

$$\langle\langle \mathit{philosopher}, \dot{\mathit{She}}, 1\rangle\rangle \ .$$

c_C supports

$$\langle\langle \mathit{corresponds}, \dot{\mathit{You}}, A, 1\rangle\rangle$$

$$\langle\langle \mathit{philosopher}, \dot{\mathit{You}}, 1\rangle\rangle \ .$$

Now, it is a trivial matter to observe that $\dot{I}$, $\dot{\mathit{You}}$, and $\dot{\mathit{She}}$ all collapse to A because the anchoring

$$f(\dot{I}) = A$$

$$f(\dot{\mathit{You}}) = A$$

$$f(\dot{\mathit{She}}) = A$$

does the job. Consequently, the utterance of A might be decontextualized as $\langle\langle \mathit{philosopher}, A, 1\rangle\rangle$.

The Obligatory Tweety Example As we stated before, in situation theory, we represent implications with constraints. While stating the constraints, we can use background conditions to add nonmonotonicity:

$$S_0 = [\dot{s} \mid \dot{s} \models \langle\langle \mathit{bird}, \dot{x}, 1\rangle\rangle] \ .$$

$$S_1 = [\dot{s} \mid \dot{s} \models \langle\langle \mathit{flies}, \dot{x}, 1\rangle\rangle] \ .$$

$$B = [\dot{s} \mid \dot{s} \models \langle\langle \mathit{penguin}, \dot{x}, 0\rangle\rangle \wedge \dot{s} \models \langle\langle \mathit{present, Air}, 1\rangle\rangle] \ .$$

$$C = [S_0 \Rightarrow S_1 \mid B] \ .$$

The constraint C states that every bird flies unless it is a penguin, or there is no air. Here, the important contribution of the situation-theoretic account is that the environmental factors can easily be included in the reasoning phase by suitably varying *B*.

Conclusion

The comparison of the previous approaches is summarized in table 1, where the first row marks the language of formalization. Not all the pertinent works (by an author or a group of authors) are listed; instead, an exemplary publication was selected as a starting point. Except for Barwise, all the previous approaches are stated in a more or less logicist framework. Among these, Shoham, and S. Buvač and Mason propose context as a modal operator; S. Buvač and Mason further consider contextual reasoning in a natural deduction sense and allow operations of entering and exiting contexts. F. Giunchiglia and coworkers propose their multilanguage systems as a true alternative to modal logic.

Among the previous approaches, McCarthy's and Guha's are not paradox free, whereas S. Buvač and Mason's and Attardi and Simi's approaches are paradox free. Shoham's approach must be paradox free: It is basically propositional modal logic. We do not know whether Barwise's (hence our) approach is paradox free or not. However, in a thought-provoking work (Barwise and Etchemendy 1987), situation theory is shown to be powerful enough to deal with circularity. The last row of the table reflects this power. (It must be noted that an important portion of Attardi and Simi's work also focuses on evading paradoxes.)

Clearly, other tables can be made to highlight the motivations, expressiveness, and complexity of particular approaches.[24] However, in the end, applicability is the sole basis of ratification for any approach. Although the idea of formalizing context seems to have caught on and produced good theoretical outcomes, the area of innovative applications remains relatively unexplored—evidently where further research on context should converge.

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Notes

1. In an early influential paper, Clark and Carlson (1981) state that *context* has become a favorite word in the vocabulary of cognitive psychologists and that it has appeared in the titles of a vast number of articles. They then complain that the denotation of the word has become murkier as its uses have been extended in many directions and deliver the now-widespread opinion that context has become some sort of a "conceptual garbage can."

2. The two workshop proceedings in which our papers appear can also be an excellent starting point to get a taste of current research in contextual reasoning.

3. The *Oxford English Dictionary* also gives several other meanings, most of which are not currently used.

4. This quest for a more general meaning is in the spirit of the following observation of McCarthy (1989, p. 180): "Almost all previous discussion of context has been in connection with natural language, and the present paper relies heavily on examples from natural language. However, I believe the main AI uses of formalized context will not be in connection with communication but in connection with reasoning about the effects of actions directed to achieving goals. It's just that natural language examples come to mind more readily."

5. Linguists have talked about context for over a century and have many interesting results. Much, much more would need to be said about context in linguistics but because we cannot hope to do justice to such a great body of work in this review, we are content with a brief, superficial appraisal.

6. According to the *Merriam-Webster Dictionary* (Merriam-Webster 1974), the word *philosopher* can stand for any of the following: a reflective thinker (scholar); a student of, or specialist in, philosophy; one whose philosophical perspective enables him/her to meet trouble calmly. Most probably, it is the second meaning the reader typically thinks of.

7. Establishing coherence is an integral part of the interpretation task. Allen (1995, p. 465) explains it nicely: "A discourse is coherent if you can easily determine how the sentences in the discourse are related to each other. A discourse consisting of unrelated sentences would be very unnatural. To understand a discourse, you must identify how each sentence relates to the others and to the discourse as a whole. It is this assumption of coherence that drives the interpretation process."

8. Cf. Wittgenstein (1984, p. 166): "'He measured him with a hostile glance and said …'. The reader of the narrative understands this; he has no doubt in his mind. Now you say: 'Very well, he supplies the meaning, he guesses it.'—Generally speaking: no. Generally speaking he supplies nothing, guesses nothing.—But it is also possible that the hostile glance and the words later prove to have been pre-

tense, or that the reader is kept in doubt whether they are so or not, and so that he really does guess at a possible interpretation.—But then the main thing he guesses at is a context. He says to himself for example: The two men who are here so hostile to one another are in reality friends, etc. etc."

9. In McCarthy's newer work (1993), *holds*(*p,c*) is renamed ist(*c, p*).

10. This preference for *holds* is understandable because "[f]ormalizing commonsense reasoning needs contexts as objects, in order to match human ability to consider context explicitly" (McCarthy 1989, p. 180). Furthermore, adding a context parameter to, say, each predicate would be unnatural. Consider the following example about the predicate *at,* adapted from McCarthy and Buvač (1994). In one context, *at* can be taken in the sense of being regularly at a place; in another, it can mean physical presence at a certain instant. Programs based on formalized contexts would extract the appropriate meaning automatically. Otherwise, a need arises to use two different predicates, for example, at_1 and at_2.

11. In identifying the given computational advantages of the notion, we heavily depended on Shoham (1991, pp. 395–396).

12. A good example (Shoham 1991) is the use of the word *glasses*: The appropriate meaning would be different in the context of a wine-and-cheese party and in the context of a visit to an ophthalmologist.

13. Contexts were not mentioned in McCarthy's Turing award talk in 1971.

14. A newer and expanded treatment is available in McCarthy and Buvač (1994). The most recent reference is McCarthy (1995), although this report presents only a brief introduction.

15. The word *lifting,* used frequently in this article, is discussed later.

16. A more concrete use (from computer science) can be identified if we form an analogy with programming language and database concepts. McCarthy's approach corresponds to the use of local variables and local functions in programming languages and views in database systems. In each case, the meaning of a term depends on the context in which it is used.

17. A rich object cannot be defined or completely described. A system can be given facts about a rich object but never the complete description.

18. The formal system presented earlier implicitly assumes flatness (every context looks the same regardless of which context it is being studied from) and would have to be modified to deal with nonflatness, which is done by replacing the rules Enter and Exit with a single rule *C* (Buvač, Buvač, and Mason 1995).

19. The reader is referred to Attardi and Simi (1991) for an early sketch of the theory of viewpoints. This theory is basically an extension of first-order logic (FOL), adjoined by a carefully formulated reflective theory where mixed object-level and meta-level statements are allowed.

20. Shoham (1991) notes that "a general treatment of contexts may indeed wish to exempt contexts from the obligation to interpret every assertion" (p. 400).

21. Shoham gives a particularly nice account of the phrase *more general than* (Shoham 1991, p. 398): "[W]hether one of the two contexts *human beings in general* and *human beings in conditions where influenza viruses are present* is more general than the other depends on what we mean by each one. If the first context includes some information about people and the second context includes that information plus further information about viruses, then the former is more general. If the first includes all information about people and the second some subset of it that has to do with viruses, then the latter is more general. Otherwise, the two are noncomparable."

22. The phrase *not comparable* means that each context contains some axioms that are not contained in the other context; cf. the preceding note.

23. Although these alternatives are equivalent from a logical point of view, the second is more appropriate to reflect the intuitions behind the background conditions. In the first case, the rule "if ϕ, then φ" is directly modified to use background conditions, whereas in the second case, it is not touched but is evaluated only when the background conditions hold. The introduction of background conditions for rules corresponds to a nonmonotonic reasoning mechanism.

24. We refer the reader to Massacci (1996) for some complexity results regarding contextual reasoning.

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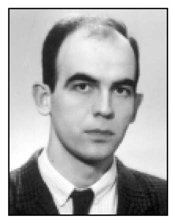

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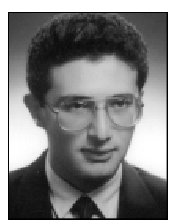

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