In the beginning, IS-A was quite simple. Today, however, there are almost as many meanings for this inheritance link as there are knowledge-representation systems.

What IS-A Is and Isn't: An Analysis of Taxonomic Links in Semantic Networks

Ronald J. Brachman, Fairchild Laboratory for Artificial Intelligence Research

Many systems for representing knowledge can be considered semantic networks largely because they feature the notion of an explicit taxonomic hierarchy, a tree or lattice-like structure for categorizing classes of things in the world being represented. The backbone of the hierarchy is provided by some sort of "inheritance" link between the representational objects, known as "nodes" in some systems and as "frames" in others. This link, often called "IS-A" (also known as "IS," "SUPERC," "AKO," "SUBSET," etc.), has been perhaps the most stable element of semantic nets as they have evolved over the years.

Unfortunately, this stability may be illusory. There are almost as many meanings for the IS-A link as there are knowledge-representation systems. In this article* we catalog the more common interpretations of IS-A and point out some differences between systems that, on the surface, appear very similar.

Background. The idea of IS-A is quite simple. Early in the history of semantic nets, researchers observed that much representation of the world was concerned with the conceptual relations expressed in English sentences such as "John is a bachelor" and "A dog is a domesticated carnivorous mammal." That is, two predominant forms of statements handled by AI knowledge-representation systems were the *predication,* expressing that an individual (e.g., John) was of a certain type (e.g., bachelor), and the *universally quantified conditional,* expressing that one type (e.g., dog) was a subtype of another (e.g., mammal). The easiest way to get such statements into a semantic-net scheme was to have a link that directly represented the "is a" parts of such sentences. Thus, the IS-A link was born.

It was quickly noted that the IS-A connections formed a hierarchy (or, in some cases, a lattice) of the types being connected—that is, the IS-A relation is roughly a partial order. The hierarchical organization made it easy to distribute "properties" so that those being shared were stored in the hierarchy at the place covering the maximal subset of nodes sharing them. This organization made the semantic net an efficient storage scheme, since shared properties are not replicated every place they hold true. That they are "inherited" by all nodes below the ones where they are stored is the notion of *inheritance of properties,* virtually always mentioned in the same breath as the IS-A link.

In a graphical notation typical of those used for semantic networks, Figure 1 illustrates the distribution of properties in a simple hierarchy, where properties common to more than one concept appear at the most general level. These properties, usually expressed more formally than they are in this figure, are considered to be inherited by all nodes below the ones to which they are attached.

Once the pattern of a network of IS-A links with property inheritance was established, new schemes were developed to use the net for more elaborate kinds of statements, descriptions, etc.[1] A debate also arose: Was network structure just so much obfuscation of the simple predicative and conditional statements that the IS-A links represented? Semantic nets seemed only to provide an indexing facility for formulae, which could just as well (and perhaps better) be expressed in the language of first-

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order predicate logic.[2-4] The interesting thing about the debate was its "apples vs. oranges" flavor. Each time the logicians tried to pin down the intent of IS-A, the networkers would claim they were missing the point. The same seemed to be true of cross-net comparisons. One scheme was criticized for what the critic thought the IS-A connections should mean, while the author defended his scheme on the basis of what he thought he had meant. Furthermore, the meaning of the link was often relegated to "what the code does with it"—neither an appropriate notion of semantics nor a useful guide for figuring out what the link, in fact, means.

If nothing else, the various debates over semantic nets have strongly suggested that there is not just one IS-A link. We can make little progress until we at least understand what the link *could* mean. We cannot have a coherent debate on the merits of logic vs. semantic nets without making some firm logical claim about the import of IS-A. At the very least, it is difficult to imagine trying to justify the advantage of a semantic net over logic without formally characterizing its expressive power.

So the question we set off to investigate is, "Just what is it that IS-A links are intended to mean?" During this investigation we will find some interesting and perhaps surprising things, among them

- The more or less standard use of IS-A—as an indicator of default information— brings with it some potentially serious problems. One cannot use a network based on it to represent complex concepts, and the notion of cancellation that follows from it can wreak havoc with world knowledge.
- The tight association between inheritance and IS-A serves only to further confuse matters. Only by placing inheritance in perspective—it is an implementation issue, not an expressive power one—can we clarify what the claims about IS-A really are.

Along the way, we will develop a rational reconstruction of the IS-A relation, making some suggestions regarding how the next generation of knowledge-representation languages should be structured.

What IS-A is

This article will try to catalog the semantic relations that IS-A has been used to represent, although the catalog most likely will not be complete and may even be unfair to certain network designers. Perhaps because the topic has been such a murky area in the literature, this can be excused.

The IS-A intents. Before enumerating the IS-As, we must consider the kinds of things the link has been used to relate. Complicating matters is the fact that semantic net nodes have been thought to represent a variety of things—sets, concepts, kinds, predicates, propositions, prototypes, descriptions, depictions, general terms, individual terms, individuals, and probably other things as well. But understanding what is on either end of the link is also the key to understanding the import of the link.

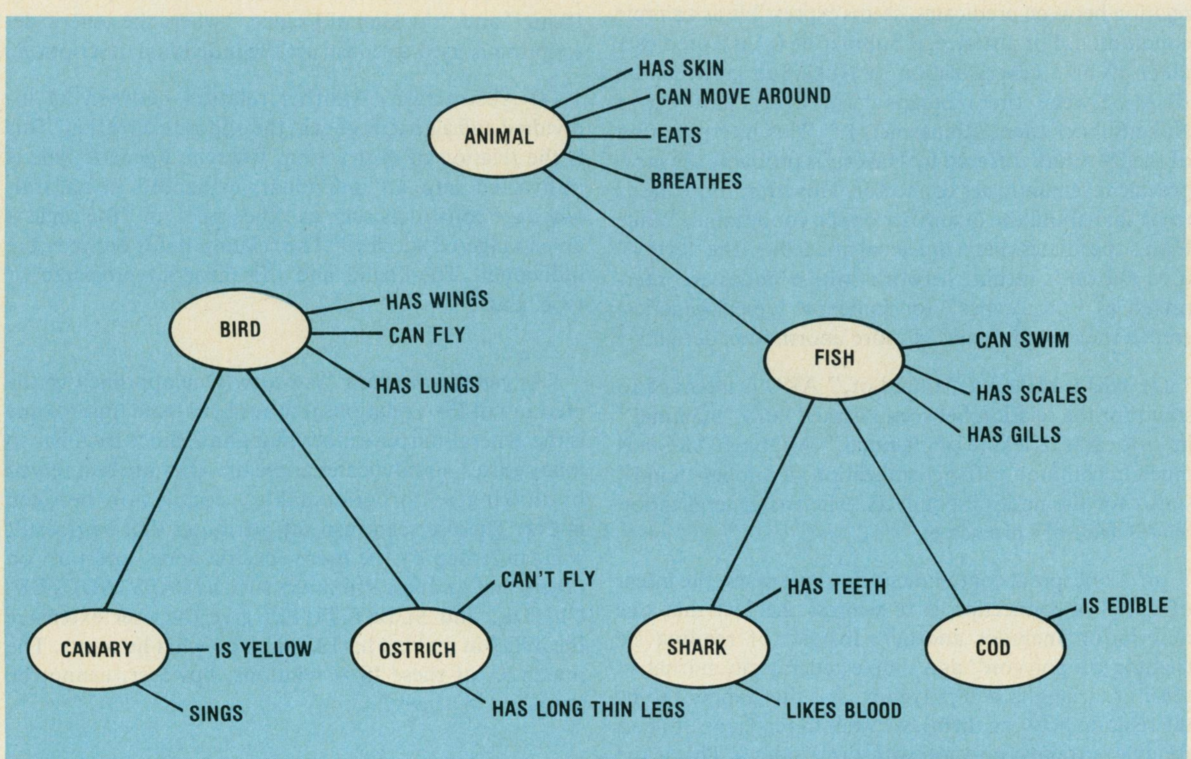

Figure 1. A semantic network.

One fundamental split we can make, despite this variety, is between *generic* and *individual* interpretations of nodes. Roughly speaking, some semantic-net nodes are thought to be descriptions applicable to many individuals, while others are thought to represent either those individuals or descriptions applicable to a single individual.

That generic nodes can be more specific or less specific than other generic nodes gives semantic nets their network structure. Individual nodes tend to be at the same level of specificity. Thus, all internal nodes in the network are generic, while the leaves are individual. We can then immediately divide the IS-A relation into two major subtypes—one relating two generic nodes, and the other relating an individual and a generic. For example, if generic nodes are construed as sets and individual nodes as individuals, we would expect to find one IS-A for the subset relation and another for the membership relation.

Generic/generic relations. When two generics are related by an IS-A connection, the intent is usually that one is somehow related to, but less general than, the other. We have at least the following kinds of uses for generic/generic relations.

(1) Subset/superset. When nodes are taken to represent sets, the connection between two generic nodes represents the subset relation. For example, when Nuke.Subs and Submarines are construed to represent the sets of all nuclear-powered submarines and all submarines, respectively, "a Nuke.Sub is a Submarine" means "for every entity x if x is a member of Nuke.Subs, then x is a member of Submarines."

(2) Generalization/specialization. Generalization, a relation between predicates, seems expressible as a simple conditional. For instance, if Submarine (x) is a predicate taken to be a generalization of Nuke.Sub (x), then an IS-A between them means "for every entity x if Nuke.Sub(x) then Submarine(x)." This interpretation of the IS-A link, offered by Hayes,[3] is probably the most prevalent semantic net connector. However, more needs to be said about the quantifier on the conditional. While Hayes speculates that a universal quantifier (the "every" used above) is meant, networks whose nodes are interpreted as "prototypes" (or somehow typical generics) embed their conditionals in more unorthodox defaults.[5]

(3) AKO. Meaning "a kind of," AKO is intended to stand for the relation between "camel" and "mammal" in "the camel is a kind of mammal." Although AKO has much in common with generalization, it implies "kind" status for the nodes it connects, whereas generalization relates arbitrary predicates.

(4) Conceptual containment. In some cases, the intent of an IS-A connection is to express the fact that one description includes another. Instead of reading "a triangle is a polygon" as a simple generalization (that is, there are triangles and polygons, and this happens to be the relation between them), we want to read it as "to be a triangle is to be a polygon with three sides." This is the IS-A of lambda-abstraction, wherein one predicate is used in defining another.

(5) Role value restriction. Another relation between generics is the kind intended in "the trunk of an elephant is a cylinder 1.3 meters long," illustrating that some generic terms in representation languages are intended to refer to roles or "slots," not just to types.[6] The point here is that the filler of a given role (e.g., trunk) must itself be of a certain type. This version of IS-A does not contribute to the taxonomy, since it does not relate the main type discussed to a supertype or subtype.

(6) Set and its characteristic type. This relationship, also not taxonomic, is the one existing between the set of all elephants and the concept of an elephant. It associates the characteristic function of a set (e.g., a "prototype" in some systems) with that set.

Generic/individual relations. An IS-A connection between an individual and a generic generally means that an individual is describable by some general description. This relation is often called "instantiation."

(1) Set membership. If the generic is construed as a set, the relation is membership. "Clyde is a camel" means "Clyde is a member of (the set of) camels."

(2) Predication. This use of IS-A simply applies a predicate to an individual, usually involving a type predicate, such as Camel or Submarine. If the generic is Camel and the individual is Clyde, IS-A expresses the fact that Camel(Clyde).

(3) Conceptual containment. When the individual node is considered a structured description, conceptual containment could be the relation between it and a generic. For example, this is the relationship between "king" and "the king of France," where the generic description is used to construct the individual description.

(4) Abstraction. Another relation between an individual and a generic goes in the opposite direction. This is the relation of abstraction, wherein a generic type is abstracted into an individual, evidenced in natural-language constructs such as "the eagle" in "the eagle is an endangered species." The relation holds between the individual, The-Eagle, and the (generic) predicate or type, Eagle.

The general-purpose IS-A link. One approach to the plethora of IS-A relations that surfaces from time to time is the general-purpose inheritance link. Since IS-A has so many guises, its advocates argue that they are best served by making a "programmable" connection between nodes. The user can turn off attributes that he doesn't want inherited by the more specific node, and turn on others that he does. Primitives such as PASS, ADD, EXCLUDE, and SUBSTITUTE[7] give the user extensive flexibility in making his IS-A link do what he wants. The semantics of these IS-A relations, however, cannot be predicted in general.

Analysis of IS-A intents. Given the representative uses of IS-A discussed earlier, we can observe several different dimensions along which IS-A links can vary. First is the type of conceptual entity that a node can represent (description, set, predicate), which has a direct effect on the import of the IS-A link. Second is the basic syntactic function of the link. In particular, we contrast a sentence-forming intent with a description-forming one. Third, for sentence-forming IS-As, we have a notion of the "quantifier" of the statement (e.g., universal vs. default). For these types of relations, we also need to consider modality (necessity vs. contingency). Finally, we must consider whether the link, by its presence in a network, makes an assertion.

Effects of node-meaning. The first major influence on the meaning of the IS-A relation comes from the types of the related items. For example, if IS-A is a relation between two sets, it usually concerns their membership, which is typically subset. The generic/individual version is usually the set membership relation, although there are variations.[8]

In contrast, when the items to be related are predicates, IS-A typically has something to say about predications that follow from other predications, using the material conditional logical operator, $\supset$. For example, "a whale is a mammal" corresponds to the universally quantified sentence, Whale(x) $\supset$ Mammal(x). The hierarchy derived from this style of IS-A has an "if . . .then . . ." flavor—for example, *if* something is a whale, *then* it is a mammal. (Notice, however, that this fails to say what it is that makes something a whale in the first place.)

When the objects related by IS-A are intended to be descriptions or concepts, the relation between them is either about the structure of the descriptions or about the classes of objects satisfying the descriptions. As an example of the first case, an IS-A such as "a triangle is a polygon" says that part of the description of any triangle is that it is a polygon. The same definition-inclusion relation holds if one of the descriptions is an individual description.

This type of IS-A relation that carries structure between structured descriptions is one of the most radical departures from representation schemes based on standard predicate logic. Almost all of the other IS-A relations are easily expressed in standard quantificational languages.

Sentence-forming vs. concept-forming. In most semantic nets, IS-A links are used to make statements about the world. For example, imagine we have a node that we want to stand for the class of Indian elephants, and we call it Indian-Elephant. If we want to state that these elephants are typically brown, we would simply assert "Indian-Elephant IS-A Brown-Thing."

This kind of statement-making about independently motivated classes is standard fare for semantic nets. However, cleverly named nodes make it easy to gloss over something we cannot do with the above kind of IS-A—namely, make Indian-Elephant have India and Elephant as parts of its meaning. There must be another kind of IS-A to express this kind of relation, for merely having the right lexical sequences as parts of a long, hyphenated name buys us nothing. Indian-Elephant could just as well have been called G0047. Thus, a basic split between statement-forming and concept-forming IS-As should be made. (Earlier in this discussion, we talked about the concept-forming IS-A relation as "conceptual containment." The dichotomy of these two kinds of IS-A is discussed at length elsewhere.[4])

A weak sense of "every." Just about everyone uses the IS-A relation to make a statement about a pair of classes or about a class and an individual. The universal quantifier is the obvious one to assume for such statements,[3] although this does not appear to be the assumption of every semantic net designer. In particular, many IS-As are thought to be "cancellable." For example, "Bird IS-A Flying-Thing" is taken to apply for any bird, as long as it is not explicitly known that this bird cannot fly—that is, "flying" is a default property for birds.[5] Sometimes we want to make this kind of statement, which can have exceptions and sometimes we do not (e.g., "Person IS-A Mammal"). So, for any sentence-forming IS-A link, we need to know if it is a true universal or merely a default.

Is this necessary? There is another dimension along which IS-As can vary, although it is rarely used in semantic net systems. Some truths could have been otherwise. For example, a particular circle could have had a radius other than the one that it has. However, the fact that its circumference is $2\pi r$ (no matter what that radius is) could not be otherwise. The second is a necessary truth, while the first is a contingent truth. Some IS-As are not only exceptionless, but they can also never be false.

To assert or not to assert. In many systems, the IS-A link asserts a truth by its mere presence. Having the statement "Clyde IS-A Camel" in your semantic net means your system "believes" that fact about Clyde. If this is the only form of IS-A relation, we are not free to contemplate a proposition without asserting it. Thus, the distinction between asserted IS-As and IS-As that are only structural adds another dimension to the IS-A connection.

Summary. We might summarize the meanings of the IS-A link in a matrix such as the one in Table 1. Each row in the table, labeled with the kinds of generics and individuals related by IS-A, shows the corresponding meaning of IS-A between (1) two generics and (2) a generic and an individual. For example, the second row indicates that when generics are construed as predicates and individuals as constants, "<generic> IS-A <generic>" is a universally quantified material conditional statement and "<individual> IS-A <generic>" is a predication. The third-to-last row is the only exception since the abstraction IS-A goes from a generic to an individual. The last two rows illustrate the IS-As between generics of different types, $g1$ being the subordinate node and $g2$ the superordinate.

A logical question. Our analysis has left us with this picture: The kinds of things to say with IS-A split fundamentally into those that take one concept and form another out of it, and those that make some sort of statement about the relation between two sets or the arguments to two predicates. The ones that make statements have four subcomponents:

- the *assertional force* of the statement—whether the statement represented by the IS-A is taken as a statement of fact;
- the *modality* of the statement—whether the truth represented by IS-A is necessary or merely contingent (and thus could be contemplated to be otherwise);
- the *quantifier* of the statement—whether its content is to be considered universally true or just "true unless explicitly cancelled"; and
- the *matrix*, or content, of the statement—generally structured as a set inclusion (or membership, for a generic/individual IS-A) or a material conditional (or predication, for a generic/individual IS-A) statement.

These four subcomponents look suspiciously like the pieces that make up special cases of standard logical statements in, let us say, prenex normal form. Is the IS-A link, then, accounted for completely by standard, off-the-shelf logical machinery?

Much of it can be. However, the factors combined force us out of the realm of the standard, well-understood forms of logic. We won't belabor the point, since it is treated in depth elsewhere,[4] but the modalities and defaults are enough to put us on tricky logical ground. When lambda abstraction (or the concept-forming kind of IS-A) is added, a semantically well-specified semantic-net account might be as reasonable a logic as any other. In addition, other factors make the concept-forming style of IS-A and the resultant network-style languages look like real alternatives to standard predicate logic accounts. For example, having structured terms that are interrelated provides a basis for a formal account of the terminology used to describe a domain, whereas the standard forms of logic do not support defined, non-atomic predicates.

Perhaps most important is that semantic-net-style representation emphasizes certain compelling patterns in knowledge representation that do not emerge from predicate-logic-based ones. For example, at least one interpretation of the concept/role paradigm can be expressed easily in a standard logical language,[3] but that pattern is just one among infinitely many. Network schemes have elevated the pattern to the level of a built-in form because of its widespread utility in representing knowledge. Another compelling pattern is the distinction of IS-A from "is." Semantic nets, reflecting the prevalence of reasoning based on types, have made a prominent distinction between the sense of "is" in "John is a man" and all other senses of "is," such as in "John is running scared" and "John is extremely tall."

All in all, one can say confidently that network schemes with their IS-A links *do* contribute to the world of representation. Unfortunately, the nature of that contribution is not always clear, and expressive power is not always the real issue.

Composites and cancellation

The default interpretation of IS-A. Although Hayes[3] has suggested that the material conditional (if. . . then. . .) is the connective represented by IS-A, the most prevalent use of IS-A seems to be as a default. "Bird IS-A Flying-Thing" is usually taken to be a truth about birds until it is explicitly retracted, or "cancelled."

This approach has a simple motivation. Without the ability to cancel properties in general, a semantic net cannot represent exceptions, and the world is such that exceptions are an important aspect of knowledge representation. Unfortunately, while the default view of IS-A allows a semantic net to deal with an exception-full world, it keeps us from being able to express some important things.

One particular consequence of the default view is that the nodes—intuitive hyphenated names notwithstand-

Table 1.
Summary of the IS-A link.

GENERIC NODES	INDIVIDUAL NODES	GENERIC/GENERIC LINK	GENERIC/INDIVIDUAL LINK
Set	Individual	Subset	Member
Predicate	Constant	Univ. material conditional	Predication
Kind	Individual	AKO (subkind)	Membership in kind
Structured description	Individual concept	Conceptual containment	Conceptual containment
Structured description	Individual	----	Description (falling under)
Prototype	Individual	Sharing of typical properties	Similarity to prototype
Role	Individual	----	Specification of role filler
Predicate or structured description	Kind	----	Abstraction
g1/g2: Role/ Structured description or predicate or prototype	----	Constraint on role filler value restriction	----
g1/g2: Set/ Prototype or predicate or structured description	----	Characteristic function of set	----

ing—cannot be thought to represent the concepts that their names suggest. Instead, they must be considered simply as holding points for bundles of default properties, because of the strictly one-way nature and cancellability of the properties expressed by the default IS-As. That is, *if* Clyde is an elephant, *then* he has the properties typical of elephants.

This rule does not work the other way around. If Clyde has typical elephant properties, we cannot conclude that he is an elephant, since he could be just about anything. For example, he could be a giraffe, with none of the typical giraffe properties (all cancelled) and with exactly those properties typical of elephants. Thus, a node such as Elephant doesn't really stand for the concept of an elephant, for none of its properties embody the definition of an elephant. Instead, the Elephant node is a strange thing—a collection of typical elephant properties.

Perhaps good intentions have led to the almost universal adoption of defaults rather than definitional connections. Arguably, there are no defining properties for elephanthood. The elephant is a "natural kind," as are most, if not all, of the concepts an AI system will have to deal with (leave abstract and defined concepts such as "rhombus" to the mathematicians, and leave the philosophers to argue about whether "bachelor" can be defined).

We cannot, however, represent even the simplest of conceptual composites with only defaults. For example, the best we could do with "elephant with blue eyes" would be to assert that an Elephant-With-Blue-Eyes *typically* has blue eyes. An AI system can use a strictly default-based network as a database repository for such classificatory facts as the user sees fit to tell it (e.g., Clyde IS-A Elephant), but it cannot draw any such conclusions itself. Without being *explicitly* told, the system would not know for sure that an elephant with blue eyes *was* an elephant.

The myth of cancellation. The preponderance of default-style nodes in semantic nets has admitted cancellation of properties into the realm of representation. With it has unfortunately come a raft of technical problems.[9] Even worse, the semantic consequences of cancellation have hardly begun to be thought through. The intuitive feeling is that cancellation can be constrained to handle just the meaningful cases of exceptions; the truth is that cancellation admits bizarre, unintuitive structures quite easily.

For example, we could easily imagine the node 3-Legged-Elephant appearing below Elephant with the cardinality of the leg-set changed, assuming that elephants typically have four legs. But we could later decide to cancel that property, having 4-Legged-Elephant below 3-Legged-Elephant. Since the names are so suggestive, this would look reasonable. However, 4-Legged-Elephant is really just a set of properties, not the concept of a four-legged elephant. In fact, it is the same set as that represented by Elephant. We could go on cancelling ad infinitum. Or we could easily form structures that say that (1) "an Indian-elephant is an elephant," (2) "Clyde is an Indian-elephant," and (3) "Clyde is not an elephant." Arbitrary cancellation is not very constructive.

What IS-A isn't

One important observation to be made about our analysis of the semantics of the IS-A link is that inheritance of properties has played no part in our understanding. This is not without good reason. Even though much has been made in the past of the significance of inheritance in semantic nets, no one has been able to show that it makes any difference in the expressive power of the system that advertises it. At best, any argument that inheritance was useful was made on pragmatic grounds: it saves storage space in an implementation or "localizes" information to be changed.

Without denying the importance of implementation concerns, we submit that to the extent inheritance is a useful property, it is strictly implementational and bears no weight in any discussion of the expressive or communicative superiority of semantic nets. For one thing, any expression of properties at "the most general place" in a network-style system can be duplicated easily in a logical system. We simply associate the property axioms with the most general predicate, and the standard conditionals do the rest. Furthermore, inheritance is only one cut at the time/space tradeoff for storing properties in a semantic net. It may be tremendously easier in some cases to store all properties explicitly where they apply to cut down search time.

Thus, although the IS-A relation can be factored into subcomponents, the useful ones for semantic purposes are those discussed earlier (assertional force, modality, etc.)—not "pass this property" and "block this one." While "pass this property" and "block this one" may be very useful for implementing a particular IS-A methodology, they should not encroach on discussions of the adequency of semantic net schemes for representing knowledge.

What IS-A ought to be

What might be a viable prescription for future IS-A schemes? First, we should carefully distinguish between description- or term-forming operators and sentence-forming ones. Because structured predicates, or concepts, are important in expressing knowledge, technical vocabulary should be preserved in a representation, such as a network-style representation scheme where the principal relation is the IS-A of conceptual containment distinct from a network (or set of axioms) expressing the facts of the world. Since this assertional network is where statements about the world are made, it needs the expressive and inferential power of standard predicate logic, perhaps provided by a standard quantificational or a more network-like language using the sentence-forming style of IS-A. The three-part "prefix" of this IS-A would include the statement's assertional force, its modality, and its quantifier. This strategy for designing representation systems is explored in depth in the article in this issue by Brachman, Fikes, and Levesque.

While semantic nets have prospered as a framework for knowledge representation, their keystone construct —the IS-A link—has wavered considerably in its interpretation. IS-A has been used principally to form sentences that could be asserted, particularly sentences with a default import. However, IS-A has been used to mean many other things, making comparisons between networks and logic all but impossible. The analysis presented in this article indicates that things might be a lot clearer if IS-A were broken down into its semantic subcomponents and those subcomponents then used as the primitives of a representation system. ■

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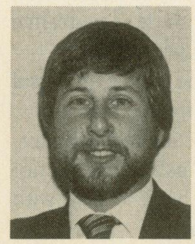

Ronald J. Brachman is a senior computer scientist and manager of the Knowledge Representation and Reasoning Group at the Fairchild Laboratory for Artificial Intelligence Research. Earlier, at Bolt Beranek and Newman Inc., he was instrumental in the development of the KL-One representation system.

Brachman was coeditor of the *Sigart Newsletter's* special issue on knowledge representation and has given numerous lectures on the subject, including the invited lecture "Recent Advances in Representational Formalisms" at the 1980 Conference of the American Association for Artificial Intelligence. He is currently the vice chairman of ACM's Sigart.

He received the PhD from Harvard University in 1977.

Brachman's address is Fairchild Laboratory for Artificial Intelligence Research, 4001 Miranda Ave., Palo Alto, CA 94304.