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Language, Logic and Ontology – Uncovering the Structure of Commonsense Knowledge

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The purpose of this paper is twofold: (*i*) we argue that the structure of commonsense knowledge must be discovered, rather than invented; and (*ii*) we argue that natural language, which is the best known theory of our (shared) commonsense knowledge, should itself be used as a guide to discovering the structure of commonsense knowledge. In addition to suggesting a systematic method to the discovery of the structure of commonsense knowledge, the method we propose seems to also provide an explanation for a number of phenomena in natural language, such as metaphor, intensionality, and the semantics of nominal compounds. Admittedly, our ultimate goal is quite ambitious, and it is no less than the systematic 'discovery' of a well-typed ontology of commonsense knowledge, and the subsequent formulation of the long-awaited goal of a meaning algebra.

1. Language and Knowledge

Cognitive scientists have long recognized the intimate relationship between natural language understanding (NLU) and knowledge representation and reasoning (KR&R), or, in short, the intimate relationship between language and knowledge. In fact, research in natural language understanding (NLU) seems to have been slowly embracing what we like to call the 'understanding as reasoning' paradigm, as it has become quite clear by now that understanding natural language is, for the most part, a commonsense reasoning process at the pragmatic level. As an example illustrating this interplay between language understanding and commonsense reasoning, consider the following:

(1) *a) John advertised a house on every street*
b) John visited a house on every street

From the standpoint of commonsense, most readers would find no difficulty in a reading for (1*a*) that implies the advertising of the 'same' house on several streets. However, the same is not true in (1*b*), as one can hardly conceive of a single house physically existing on several streets. Thus, while a wide scope *a,* implying a single house is quite plausible in (1*a*), the more plausible reading in (1*b*) is the one implying several houses, making (1*b*) read something like '*on every street, John visited some house*'.

Lacking syntactic or semantic explanations, we argue that such inferences must be a function of our commonsense knowledge of how the ON relation between houses and streets is typically manifested in the real world (in the *possible world* we actually live in!). This process is even more complex due to the fact that different individuals may have different scope preferences in the same linguistic context, as the experiments of Kurtzman & MacDonald (1993) have suggested. Consistent with this 'understanding as reasoning' paradigm, an inferencing strategy that models individual preferences in the resolution of scope ambiguities at the pragmatic level has been suggested in (Saba & Corriveau, 1997; Saba & Corriveau, 2001). While (Saba & Corriveau, 2001) have showed that such problems do not always require the storage of and reasoning with vast amounts of background knowledge, other linguistic comprehension tasks clearly do. For instance, consider the resolution of 'He' in the following:

(2) *John shot a policeman. He immediately*
a) *fled away.*
b) *fell down.*

Clearly, such references must be resolved by recourse to commonsense knowledge – for example, that, typically, when $shot(x,y)$ holds between some x and some y, x is the more likely subject to flee (2*a*), and y is the more likely subject to fall down (2*b*). Note, however, that such inferences must always be considered defeasible, since quite often additional information might result in the retraction of previously made inferences. For example, (2*b*) might after all be describing a situation in which *John*, a 7-year old who was shooting a bazooka, fell down. Similarly, (2*a*) might actually be describing a situation in which the policeman, upon being slightly injured, tried to flee away, perhaps to escape further injuries!

Computationally, there are clearly a number of challenges in reasoning with uncommitted (or 'underspecified') logical forms, and this has indeed received considerable attention by a number of authors (e.g., see Kameyama, 1996, and the excellent collection of papers in van Deemter & Peters, 1996). However, the main challenge that such processes still face is the availability of this large body of commonsense knowledge along with a computationally effective reasoning engine.

While the monumental challenge of building such large commonsense knowledge bases was indeed faced head-on by a few authors (e.g., Lenat & Ghua, 1990), a number of other authors have since abandoned (and argued against) the 'knowledge intensive' paradigm in favor of more quantitative methods (e.g., Charniak, 1993). Within linguistics and formal semantics, little or no attention was paid to the issue of commonsense reasoning at the pragmatic level. Indeed, the prevailing wisdom was that a number of NLU tasks require the storage of and reasoning with a vast amount of background knowledge (van Deemter, 1996), and that has led some to conclude that these approaches were 'highly undecidable' (e.g., Reinhart, 1997).

In our view both trends were partly misguided. In particular, we hold the view that (*i*) language 'understanding' is for the most part a commonsense 'reasoning' process at the pragmatic level; and (*ii*) the 'understanding as reasoning' paradigm, and the underlying knowledge structures that it utilizes, must be formalized if we ever hope to build scalable systems (as John McCarthy likes to say, if we ever hope to build systems that we can actually understand!). In this light we believe the work on integrating logical and commonsense reasoning in language understanding (Allen, 1987; Pereira & Pollack, 1991; Zadrozny & Jensen, 1991; Hobbs, 1985; Hobbs *et al.*, 1993; and more recently Asher & Lascarides, 1998; and Saba & Corriveua, 1997) is of paramount importance[1].

Much of this work is directed towards formulating commonsense inferencing strategies to resolve a number of ambiguities at the pragmatic level. Although it has been shown (see e.g., Saba & Corriveau, 2001) that these inferences do not always require the storage of and reasoning with a vast amount of background knowledge, it is clear that a number of tasks do require such a knowledgebase. Indeed, substantial effort has been made towards building ontologies of commonsense knowledge (e.g., Lenat & Ghua, 1990; Mahesh & Nirenburg, 1995; Sowa, 1995), and a number of promising trends that advocate ontological design based on sound linguistic and logical foundations have started to emerge in recent years (e.g., Guarino & Welty, 2000; Pustejovsky, 2001). However, a systematic and objective approach to ontological design is still lacking. In particular, we believe that an ontology for commonsense knowledge must be *discovered* rather than *invented*, and thus it is not sufficient to establish some principles for ontological design, but that a strategy by which a commonsense ontology might be **systematically** and **objectively** designed must be developed. In this paper we propose such a strategy.

We should note here that while we do not claim we have achieved our ultimate goal, we believe that we are on the right path towards discovering (as opposed to inventing) 'the' structure of commonsense knowledge, and that such a systematic and strongly-typed structure will solve a number of problems that we have wrestled with for a number of years. We therefore believe that our work, while not final in many respects, is worthy of presenting to the NLP and AI research communities, hoping that others can pickup where we left off, by identifying errors, filling in some gaps, completing the picture along the way.

2. Language-Based Ontological Design

Our basic strategy for discovering the structure of commonsense knowledge is rooted in Frege's conception of Compositionality. According to Frege (see Dummett, 1981, pp. 4-7), the sense of any given sentence is derived from our previous knowledge of the senses of the words that compose it, together with our observation of the way in which they are combined in that sentence. The cornerstone of this paradigm, however, is an observation that has not been fully appreciated regarding the manner in which words are supposed to acquire a sense. In particular, the principle of Compositionality is rooted in the thesis that "our understanding of [those] words consists in our grasp of the way in which they may figure in sentences in general, and how, in general, they combine to determine the truth-conditions of those sentences." (Dummett, 1981, pp. 5). Thus, the meanings of words (i.e., the concepts), and the relationships between them, can be reverse-engineered, so to speak, by analyzing how these words are **used** in everyday language.

[1] Outside the domain of NLU, other pioneering work such as that of (McCarthy 1980), was also done in the same spirit, namely to integrate logical and commonsense reasoning.

This simple idea forms the basis of our strategy in discovering the structure of commonsense knowledge: what language allows one to say about a concept, tells us a lot about the concept under consideration. In other words, the nature of these concepts can be discovered from the manner in which they are **used** in everyday language. To illustrate this point further, consider the following examples, which (Montague, 1969) discussed in addressing a puzzle pointed out to him by Quine:

(3) $\|$ *John found a unicorn* $\| = (\exists x)\big(\textsc{unicorn}(x) \wedge \textsc{found}(j, x)\big)$

(4) $\|$ *John painted a unicorn* $\| = (\exists x)\big(\textsc{unicorn}(x) \wedge \textsc{painted}(j, x)\big)$

The puzzle Quine was referring to was the following: both translations admit the inference $(\exists x)(\textsc{unicorn}(x))$ – that is, both sentences imply the existence of a unicorn, although it is quite clear that such an inference should not be admitted in the case of (4). According to Montague, the obvious difference between (3) and (4) must be reflected in an ontological difference between *find* and *paint* in that the extensional type $(e \to (e \to t))$ both transitive verbs are typically assigned is too simplistic. Montague was implicitly suggesting that a much more sophisticated ontology (i.e., a more complex type system) is needed, one that would in fact yield different types for *find* and *paint*. One reasonable suggestion for the types of *find* and *paint*, for example, could be as follows:

(5) *find* **::** $(e_{\mathsf{Animal}} \to (e_{\mathsf{Thing}} \to t))$

(6) *paint* **::** $(e_{\mathsf{Human}} \to (e_{\mathsf{Representation}} \to t))$

Thus instead of the flat type structure implied by $(e \to (e \to t))$, the types of *find* and *paint* should reflect our commonsense belief that we can always speak of some Animal that found something (i.e., any Thing whatsoever), and of a Human that painted some illustration, or as we called it here a Representation. Before we proceed, however, we point out that throughout, we will use this Font for concept types in the ontology, and this FONT for predicate names. Thus, x:LivingThing means x is an object/entity of type LivingThing and $\textsc{apple}(x)$ means the predicate or property APPLE is true of x. Note, further, that in a flat-type system, the expression $(\exists x)\big(\textsc{unicorn}(x) \wedge \textsc{found}(j, x)\big)$ is equivalent to the typed expression $(\exists x : \mathsf{Entity})\big(\textsc{unicorn}(x) \wedge \textsc{found}(j : \mathsf{Entity}, x)\big)$ since there is one type of entity. With this background, the correct translations of (3) and (4) and the corresponding inferences can now be given as follows:

(7) $(\exists x{:}\mathsf{Thing})(\textsc{unicorn}(x) \wedge \textsc{found}(j{:}\mathsf{Rational}, x))$ (*John found a unicorn*)
$\Rightarrow (\exists x{:}\mathsf{Thing})(\textsc{unicorn}(x))$ (*there is a unicorn*)
$\Rightarrow (\exists x{:}\mathsf{Thing})(\textsc{found}(j{:}\mathsf{Rational}, x))$ (*John found something*)

(8) $(\exists x{:}\mathsf{Representation})(\textsc{unicorn}(x) \wedge \textsc{painted}(j{:}\mathsf{Rational}, x))$ (*John painted a unicorn*)
$\Rightarrow (\exists x{:}\mathsf{Representation})(\textsc{unicorn}(x))$ (*there is a unicorn representation*)
$\Rightarrow (\exists x{:}\mathsf{Representation})(\textsc{painted}(j{:}\mathsf{Rational}, x))$ (*John painted something*)

Eureka! Adding a rich type structure to the semantics seems to have solved Quine's puzzle, as the correct inferences can now be made: if John *found* a unicorn, then one can indeed infer that an actual unicorn exists[2]. However, the *painting* of a unicorn only implies the existence of a representation (an illustration) of something we call a unicorn! Stated yet in other words, (7) implies that a unicorn Thing exists, while (8) implies a unicorn Representation exists. There are two points that this discussion intends to emphasize: (*i*) is the need for a rich type structure to solve a number of problems in the semantics of natural language; and (*ii*) that this type structure is actually systematically discovered by an analysis of how ordinary language is used to talk about the world. This opinion will (hopefully) be further supported by our discussion of nominal compounds in the next section.

3. Nominal Compounds and Ontological Categories

The semantics of compound nominals have received considerable attention by a number of authors, most notably (Kamp & Partee, 1995; Fodor & Lepore, 1996; Pustejovsky, 2001), and to our knowledge, the question of what is an appropriate semantics for nominal compounds has not yet been settled. Recall that the simplest (extensional) semantic model for simple nominal constructions is that of conjunction (or intersection) of predicates (or sets). For example, assuming that $\text{RED}(x)$ and $\text{APPLE}(x)$ represent the meanings of *red* and *apple*, respectively, then the meaning of a nominal such as *red apple* is usually given as

(9) $\| \textit{red apple} \| = \{x \mid \text{RED}(x) \wedge \text{APPLE}(x)\}$

What (9) says is that something is a *red apple* if it is *red* and *apple*. This simplistic model, while seems adequate in this case (and indeed in many other instances of similar ontological nature), clearly fails in the following cases, all of which involve an adjective and a noun:

(10) *former senator*

(11) *fake gun*

(12) *alleged thief*

Clearly, the simple conjunctive model, while seems to be adequate for situations similar to those in (9), fails here, as it cannot be accepted that something is *former senator* if it is *former* and *senator*, and similarly for (11) and (12). Thus, while conjunction is one possible function that can be used to attain a compositional meaning, there are in general more complex functions that might be needed for other *types of ontological categories*. In particular, what we seem to have is something like the following:

[2] Of course, in such a type system we would have $\mathsf{Rational} \supset \mathsf{Animal}$ and therefore John, an entity of type $\mathsf{Rational}$, can be the subject of FOUND which expects an entity of type Animal.

$$
\begin{aligned}
(13)\quad & \|red\ apple\| &=& \ \{x|x \text{ is } \textsc{red} \text{ and } x \text{ is } \textsc{apple}\} \\
& \|former\ senator\| &=& \ \{x|x \text{ was but is not now a } \textsc{senator}\} \\
& \|fake\ gun\| &=& \ \{x|x \text{ looks like but is not actually a } \textsc{gun}\} \\
& \|alleged\ thief\| &=& \ \{x|x \text{ could possibly turn out to be a } \textsc{thief}\}
\end{aligned}
$$

It would seem, then, that different ontological categories require different semantic functions to compute the meaning of the whole from the meanings of the parts. In fact, the meaning of some compound might not be captured without resorting to temporal and/or modal operators. For example, we argue that the following are reasonable definitions for the concepts *fake*, *former* and *alleged*:

$$(14)\quad (\forall x : \mathsf{Physical})\Big(\textsc{fake}(x) \equiv_{df} \lambda P\Big[(\exists y : \mathsf{Physical})\big(\neg P(x) \wedge P(y) \wedge \textsc{looksLike}(x,y)\big)\Big]\Big)$$

$$(15)\quad (\forall x : \mathsf{Role})\Big(\textsc{former}(x) \equiv_{df} \lambda P\Big[(\exists t)\big((t < now) \wedge P(x,t) \wedge \neg P(x,now)\big)\Big]\Big)$$

$$(16)\quad (\forall x : \mathsf{Role})\Big(\textsc{alleged}(x) \equiv_{df} \lambda P\Big[(\exists t)\big((t > now) \wedge \neg P(x,now) \wedge \Diamond P(x,t)\big)\Big]\Big)$$

That is, 'fake' applies to some concept P as follows: a certain physical object x is a fake P *iff* it is not a P, but it actually looks like something else, say y, which is actually a P. On the other hand, what (15) says is the following: a certain x is a former P *iff* x was a P at some point in time in the past and is not now a P. Finally, what (16) says is that something is an 'alleged' P *iff* it is not now known to be a P, but could possibly turn out to be a P at some point in the future.

It is interesting to note here that the intension of *fake* and that of *former* and *alleged* was in one case represented by recourse to possible worlds semantics (the case of (15) and (16)), while in (14) the intension uses something like structural semantics, assuming that $\textsc{looksLike}(x,y)$ which is true of some x and some y if x and y share a number of important features is defined. What is interesting in this is that it suggests that possible-worlds semantics and structured semantics are not two distinct alternatives to representing intensionality, as has been suggested in the literature, but that in fact they should co-exist.

Additionally, several points should also be made here. First, the representation of the meaning of *fake* given in (14) suggests that *fake* expects a concept which is of type Physical Artifact, and thus something like *fake idea*, or *fake song*, for example, should sound meaningless, from the standpoint of commonsense[3]. Second, the representation of the meaning of *former* given in (15) suggests that *former* expects a concept which has a time dimension, i.e. is a temporal concept.

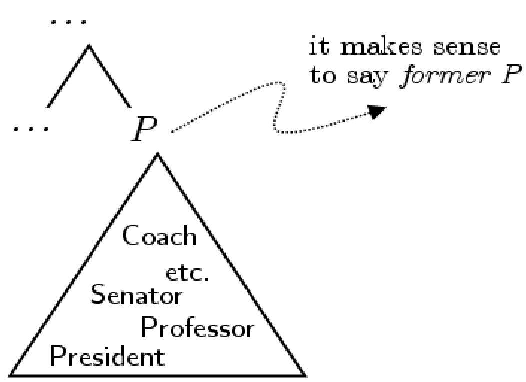
Finally, we should note here that our ultimate goal of this type of analysis is to discover the ontological categories that share the same behavior. For example, conjunction, which as discussed above is one possible function that can be used to attain a compositional meaning, seems to be adequate for all nominal constructions of

[3] One can of course say *fake smile*, but this is clearly another sense of *fake*. While *fake gun* refers to a gun (an Artifact) that is not real, *fake smile* refers to a dishonest *smile*, or a *smile* that is not genuine.

the form $[A\ \ N]$ where A is a physical property (such as *red*, *large*, *heavy*, etc.) and N is a physical object (such as *car*, *person*, *desk*, etc.), as expressed in (17)[4].

$$(17) \quad \|A\ \ N\| = \{x \mid A_{\mathsf{PhysicalProperty}}(x) \wedge N_{\mathsf{PhysicalThing}}(x)\}$$

Similarly, an analysis of the meaning of *former*, given in (15), suggests that there are a number of ontological categories that seem to have the same behavior, and could thus replace P in (15), as implied by the fragment hierarchy shown below.



A question that must be answered now is the following: assuming (15) is proper logical formulation of our commonsense understanding of what *former* means, then what is the logical counterpart of the fact that 'it does not make sense' to say *former father*? As we show in appendix A, the fact that 'it does not make sense to say *former father*' translates into logical contradiction. Finally, we should note that while the analysis we have been conducting in this section might shed some light on the difficult problem of nominal compounds, this is not the only linguistic tool that can help us discover the structure of commonsense knowledge. In fact, we can discover another piece of the puzzle by an analysis of adjectives and verbs that may or may not apply to nouns, which we discuss in the following section.

4. Type Inferences in Formal and Natural Languages

We first start this discussion by introducing a predicate $app(p,c)$ which is taken to be true of a property p and a concept c *iff* "it makes sense to speak of the property p of c". As an example, consider the following two sets of adjectives and nouns:

(18) $P = \{\text{LARGE}, \text{SMART}\}$

(19) $C = \{\mathsf{Table}, \mathsf{Elephant}\}$

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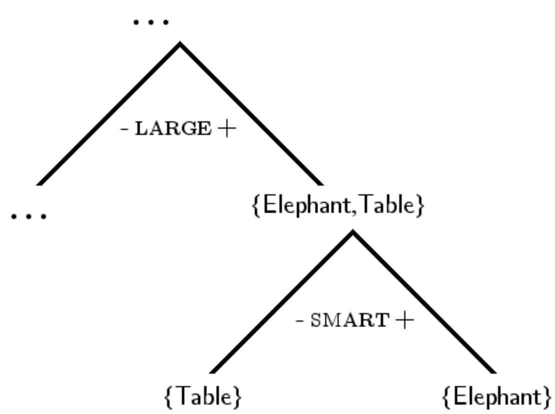
[4] While (17) states that some adjecgtives are intersective, (17) does not say anything about the meaning of such adjectives. See appendix B for such a discussion.

A quick analysis of the predicate $app(p,c)$ on the four adjective-noun combinations yields the following:

- $app(\text{LARGE},\mathsf{Table})$
- $app(\text{LARGE},\mathsf{Elephant})$
- $app(\text{SMART},\mathsf{Elephant})$
- $\neg app(\text{SMART},\mathsf{Table})$

That is, while it makes sense to say 'large table', 'large elephant', and 'smart elephant', it does not make sense to say 'smart table'. This kind of analysis yields the structure shown below.



First it must be pointed out that the above structure was *discovered* and not *invented*! Note also that a number of inferences can now be made, for example that whenever it makes sense to say 'smart' of some object c then it also makes sense to say 'large' of c. This kind of analysis is not much different from the type inferencing process that occurs in strongly-typed, polymorphic programming languages. For example, consider the linguistic patterns and the corresponding type inferences shown in table 1 below.

Pattern	**Type Inference**
$x + 3$	x is Number
`reverse`(x)	x is a Sequence
`insert`(x,y)	x is an `object`; y is Sequence of x `objects`
`head`(x)	x is a Sequence
`even`(x)	x is Number

Table 1. Linguistic patterns and their corresponding type inferences.

From $x + 3$, for example, one can infer that x is a `number` since numbers are the "kinds of things" that can be added to 3 (or, for the expression '$x + 3$' to make sense, x must be a number!) In general, the most generic type possible is inferred (i.e., these operations are assumed to be polymorphic). For example, all that can be inferred from `reverse`(x) is that x is the generic type `sequence`, which could be a `list`, a `string` (a sequence of `characters`), a `vector`, etc. Note also that in addition to actions (called functions or methods in programming lingo), properties (truth-valued functions) can also be used to infer the type of an object. For example, from `even`(x) one can infer that x is a `number`, since lists, sequences, etc. are not the kinds of objects which can be described by the predicate `even`. This process can be more formally described as follows:

1. we are given a set of concepts $C = \{c_1, \ldots, c_m\}$ and a set of actions (and properties) $P = \{p_1, \ldots, p_m\}$
2. a predicate $app(p,c)$, where $c \in C$ and $p \in P$ is defined such that the action (or property) p applies to (makes sense of) objects of type c.
3. for each property $p \in P$, a set $C_p = \{c \mid app(p,c)\}$, denoting all concepts c for which the property p is applicable, is generated.
4. a concept hierarchy is then systematically discovered by analyzing the subset relationship between the various sets generated.

To illustrate how this process (systematically) yields a type hierarchy, we consider a small set of concepts $C = \{\mathsf{List}, \mathsf{String}, \mathsf{Set}\}$ and a set of properties (or actions) $P = \{\text{EMPTY}, \text{MEMBEROF}, \text{SIZE}, \text{TAIL}, \text{HEAD}, \text{REVERSE}, \text{TOUPPERCASE}\}$ that may or may not be plausibly applied to a certain concept. Shown in figure 1 below is a number of sets that are generated by $app(p,c)$ (fig. 1a) and the concept hierarchy implied by the subset relationship among these sets (fig. 1b).

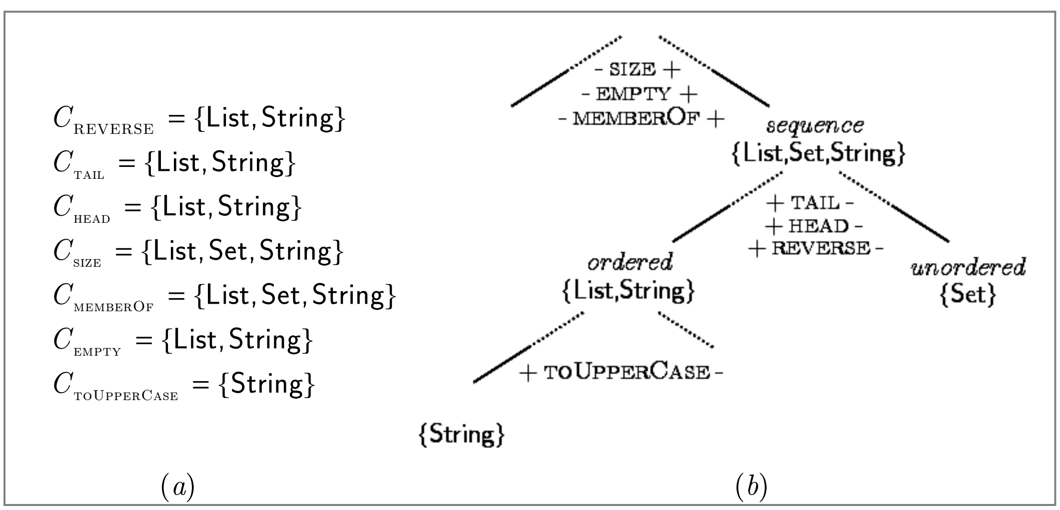


Figure 1. Sets generated by $app(p,c)$ (a) and the structure implied by these sets (b).

Note that each (unique) set corresponds to a concept in the hierarchy. Equal sets (e.g. C_{TAIL} and C_{HEAD}) correspond to the same concepts. The label of a given concept could be any meaningful label that intuitively represents all the sub-concepts in this class. For example, in figure 1*b* `sequence` was used to collectively refer to sets, strings and lists. Note that there are a number of rules that can be established from the concept hierarchy shown in figure 1*b*. For example, one can state the following:

(20) $(\forall c)(app(\text{REVERSE}, c) \supset app(\text{SIZE}, c))$

(21) $(\exists c)(app(\text{SIZE}, c) \wedge \neg app(\text{REVERSE}, c))$

(22) $(\forall c)(app(\text{TAIL}, c) \equiv app(\text{HEAD}, c))$

Here (20) states that whenever *it makes sense* to *reverse* an object *c*, then it also makes sense to ask for the *size* of *c*. This essentially means that an object to which the *size* operation can be applied is a parent of an object to which the *reverse* operation can be applied. (21), on the other hand, states that there are objects for which the *size* operation applies, but for which the *reverse* operation does not apply. Finally, (22) states that whenever it makes sense to ask for the *head* of an object then it also makes sense to ask for its *tail*, and vice versa.

Finally, it must be noted that in performing this analysis we have assumed that $app(p,c)$ is a Boolean-valued function, which has the consequence that the resulting type hierarchy is a strict binary tree. In fact, this is one of the main characteristics of our method, and has led to two important results: (*i*) multiple inheritance is completely avoided; and (*ii*) by not allowing any ambiguity in the interpretation of $app(p,c)$, lexical ambiguity, polysemy and metaphor are explicitly represented in the hierarchy. This is discussed below.

5. Language and Commonsense Knowledge

The work described here was motivated by the following two assumptions: (*i*) the process of language understanding is, for the most part, a commonsense reasoning process at the pragmatic level; and (*ii*) since children master spoken language at a very young age, children must be performing commonsense reasoning at the pragmatic level, and consequently, they must posses all the commonsense knowledge required to understand spoken language[5]. In other words, we are assuming that deciding on a particular $app(p,c)$ should not be controversial, and that children can easily answer questions such as those shown in table 2 below.

Note that in answering these questions it is clear that one has to be coconscious of metaphor. For example, while it is quite meaningful to say *strong table, strong man,* and *strong feeling*, it is clear that the senses of *strong* in these three cases are quite distinct. The issue of metaphors will be dealt with below. For now, all that matters, initially, is to consider posing queries such as $app(\text{SMART}, \mathsf{Elephant})$ – or equivalently, questions such as 'does it make sense to say *smart elephant*?', to a five-year old. In replying to such questions we claim that $app(v,c)$ is binary-valued –

[5] Thus it may very well be the case that *everything we need to know we learned in kindergarten*!

that is, while it could be a matter of degree as to how smart a **certain** elephant might be (which is a **quantitative** question), the **qualitative** question of whether or not it is meaningful to say ‘smart elephant’ is not a matter of degree[6].

Query	**Does it make sense to say…**
app(WALK,Elephant)	elephants walk?
app(TALK,Elephant)	elephants talk?
app(SMART,Elephant)	elephants are smart?
app(SMART,Mountain)	mountains are smart?
app(SCREAM,Book)	books scream?
app(HAPPY,Sugar)	happy sugar?

Table 2. Deciding on a particular $app(v,c)$ from the standpoint of commonsense.

With this background we now show that an analysis of how verbs and adjectives are used with nouns in everyday language can be used to *discover* the structure of commonsense knowledge:

- Select a set of adjectives and verbs, $V = \{v_1, \ldots, v_m\}$
- Select a set of nouns $C = \{c_1, \ldots, c_n\}$
- For every pair (v_i, c_j) where $v_i \in V$ and $c_j \in V$ generate a set of concepts $C_i = \{c \mid app(v_i, c)\},\ 1 \leq i \leq m$
- Build a hierarchical structure by analyzing the subset relationship between all sets $C_i \in \{C_1, \ldots, C_m\}$

As an initial example, consider the set of verbs V = {MOVE, WALK, RUN, TALK, REASON} and the set of nouns C = {Rational, Bird, Elephant, Shark, Animal, Ameba}. By repeatedly applying $app(v,c)$ the following sets can be generated:

[6] As Elkan (1993) has convincingly argued, to avoid certain contradictions logical reasoning must at some level collapse to a binary logic. While Elkan’s argument seemed to be susceptible to some criticism (e.g., Dubois *et al* (1994)), there are more convincing arguments supporting the same result. Consider the following:

(1) *John likes every famous actress*
(2) *Liz is a famous actress*
(3) *John likes Liz*

Clearly, (1) and (2) should entail (3), regardless of how famous Liz actually is. Using any quantitative model (such as fuzzy logic), this intuitive entailment cannot be produced (we leave the details of formulating this in fuzzy logic as an exercise!) The problem here is that at the qualitative level the truth-value of $famous(x)$ must collapse to either true or false, since at that level all that matters is whether or not Liz is famous, not how certain we are about her being famous.

$$
(23)\quad
\begin{aligned}
C_{\text{MOVE}} &= \{\mathsf{Rational}, \mathsf{Animal}, \mathsf{Bird}, \mathsf{Elephant}, \mathsf{Shark}, \mathsf{Ameba}\} \\
C_{\text{TALK}} &= \{\mathsf{Rational}\} \\
C_{\text{REASON}} &= \{\mathsf{Rational}\} \\
C_{\text{THINK}} &= \{\mathsf{Animal}\} \\
C_{\text{WALK}} &= \{\mathsf{Rational}, \mathsf{Bird}, \mathsf{Elephant}\} \\
C_{\text{RUN}} &= \{\mathsf{Rational}, \mathsf{Bird}, \mathsf{Elephant}\}
\end{aligned}
$$

First we note that while some decisions could 'technically' be questioned (say by a biologist) our strategy was to simply consider the question from the point of view of commonsense. In deciding on a particular $app(v,c)$ we considered poising to a five-year old queries such as *do elephants fly*, *do they run*, *do they talk*, etc. This initial process resulted in sets such as these:

$$
(24)\quad
\begin{aligned}
&+L_2- = \{\text{DEVELOP}, \text{FORM}\} \\
&+L_3- = \{\text{EVOLVE}\} \\
&+L_4- = \{\text{LIVE}, \text{DIE}, \text{BORN}, \text{GROW}\} \\
&+L_6- = \{\text{BRANCH}\} \\
&-R_6+ = \{\text{MOVE}, \text{TRAVEL}\} \\
&-R_7+ = \{\text{SLEEP}, \text{REST}, \text{EAT}, \text{DIGEST}, \text{BLEED}, \text{HURT}, \text{THINK}\} \\
&+L_8- = \{\text{SIT}, \text{JUMP}, \text{WALK}, \text{RUN}\} \\
&-R_9+ = \{\text{ROAR}, \text{SCREAM}, \text{CRY}, \text{YELL}\} \\
&+L_{10}- = \{\text{TALK}, \text{THINK}, \text{REASON}, \text{SUPPOSE}, \text{ASSUME}, \text{REFLECT}\} \\
&-R_{11}+ = \{\text{REASON}\}
\end{aligned}
$$

A subset analysis on these sets results in the hierarchy shown in figure 2 below. Note that some powerful inferential patterns that can be used in language understanding are implicit in the structure shown in figure 2. For example, what does not think does not hurt (L_7), what walks also runs (L_8), anything that lives evolves (L_3 and L_4), etc.

Note that according to our strategy every concept at the knowledge- (or commonsense) level must 'own' some unique property, and this must also be linguistically reflected by some verb or adjective. This might be similar to what Fodor (1998, p. 126) meant by "having a concept is being locked to a property". In fact, it seems that this one way to test the demarcation line between commonsense and domain-specific knowledge, as domain-specific concepts do not seem to be uniquely locked to any word in the language. Furthermore, the property a concept is locked to (e.g., the property THINK of Rational) is closely related to the notion of *immutability* of a feature discussed in (Sloman *et al*, 1998), where the immutable features of a concept are those features that collectively define the essential characteristics of a concept.

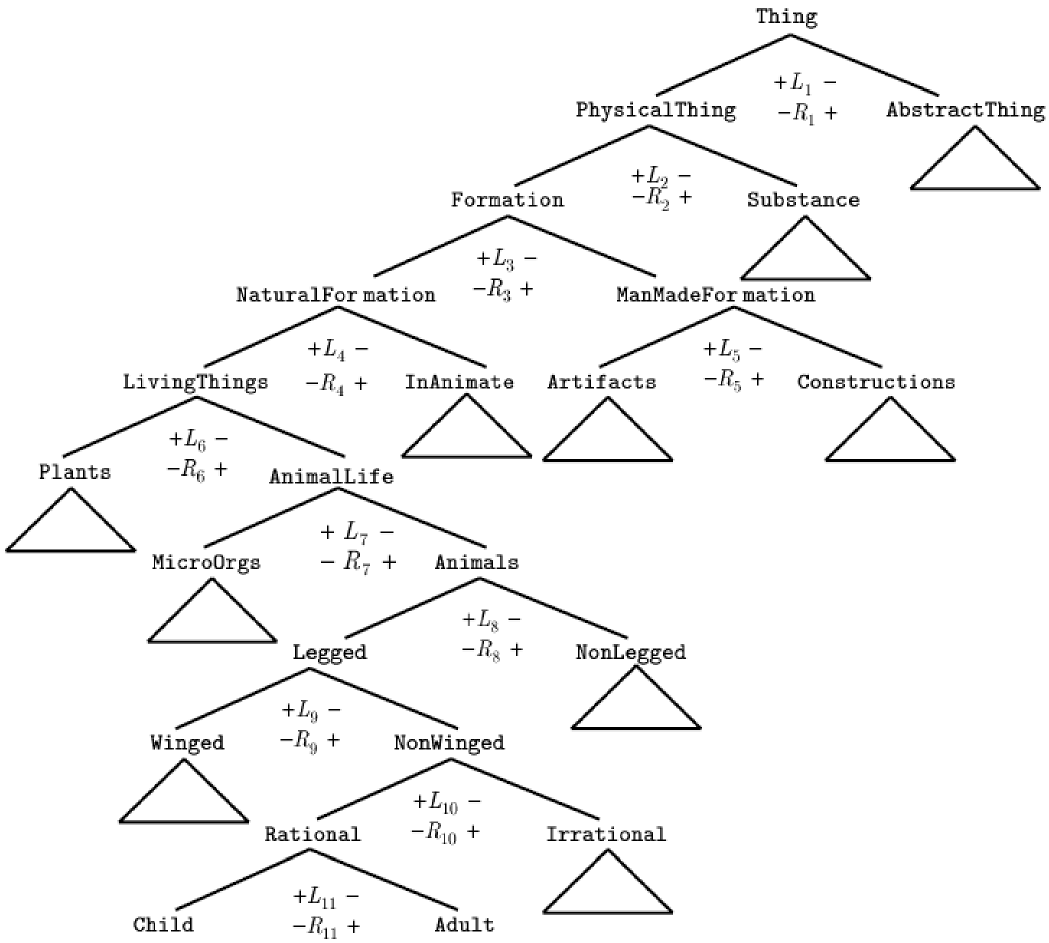


Figure 2. An Adult is a Physical, Living Thing that is FORMED, it GROWS, it DEVELOPS, it MOVES, it can WALK, RUN, HEAR, SEE, TALK, THINK, REASON, etc.

6. Polysemy and Metaphor

In our approach the occurrence of a verb or an adjective in the hierarchy always refers to a *unique sense* of that verb or adjective. This has meant that a highly ambiguous verb tends to apply to concepts higher-up in the hierarchy. Moreover, various senses (shades of a meaning) of a verb v end-up applying at various levels below v. For example, in the small fragment hierarchy shown in figure 3 where we have assumed that we MAKE, FORM, and DEVELOP both Ideas and Feelings, although Ideas are FORMULATED while Feelings are FOSTERED. Thus DEVELOPING, FORMULATING, and FORMING are considered specific ways of MAKING (that is one sense of MAKE is DEVELOP, or one way of MAKING is DEVELOPING).

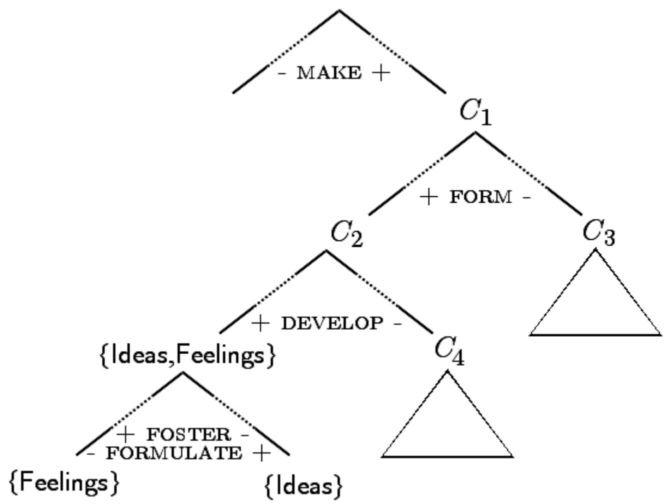


Figure 3. An explanation of polysemy.

While the occurrence of similar senses of verbs at various levels in the hierarchy represents polysemy, the occurrence of the same verb (the same lexeme) at structurally isomorphic places in the hierarchy indicates metaphorical derivations of the same verb. For example, consider the following:

(25) *app*(RUN, LeggedThing)

(26) *app*(RUN, Machine)

(27) *app*(RUN, Show)

(25) through (27) state that we can speak of a legged thing, a machine, and a show *running*. Clearly, however, these examples involve three different senses of the verb *run*. It could be argued that the senses of *run* that are implied by (26) and (27) correspond to a metaphorical derivation of the actual running of natural kinds, the sense implied by (25). It is also interesting to note that these metaphorical derivations occur at various levels: first from natural kinds to artifacts; and then from physical to abstract. This is not inconsistent with research on metaphor, such as Lakoff's (1987) thesis that most of linguistic derivations are metaphorical in nature, and that these metaphors are derived from physical concepts (that can all be reduced to a handful of experiential cognitive schemas!) Note also that the mass/count distinction on the physical side seems to have a mirror image of a mass/count on the abstract side. For example, note the following similarity between `water` (physical substance) and `information` (abstract substance, so to speak):

- `water/information` flows
- `water/information` can be diverted, filtered, processed, etc.
- we can be flooded by `water/information`
- we can drown in `water/information`
- a little bit of `water/information` is (still) `water/information`

One interesting aspect of these findings is to further investigate the exact nature of this metaphorical mapping and whether the map is consistent throughout; that is, whether same-level hierarchies are structurally isomorphic, as the case appears to be so far (see figure 4)[7].

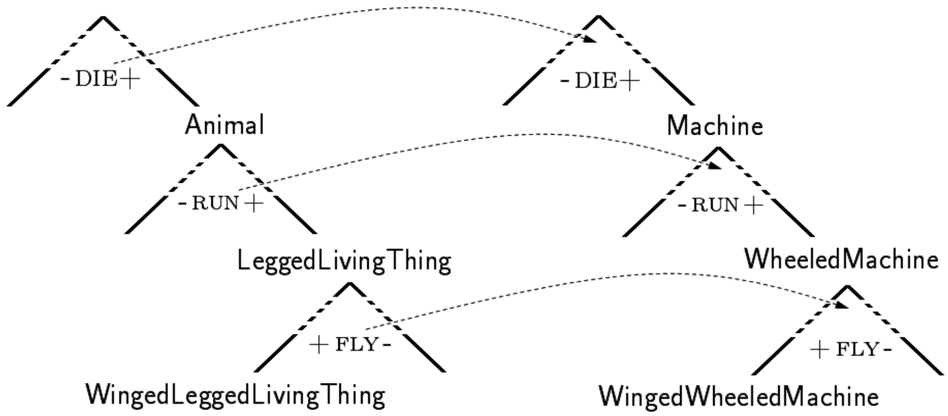


Figure 4. Isomorphic structures explaining metaphors.

7. Towards a Meaning Algebra

If Galileo was correct and *mathematics is the language of nature*, then Richard Montague (see the paper on ELF in (Thomasson, 1974)), is trivially right in his proclamation that *there is no theoretical difference between formal and natural languages*. Moreover, if Montague is correct, then there should exist a formal system, much like arithmetic, or any other algebra, for concepts, as advocated by a number of authors, such as Cresswell (1973) and Barwise (1989), among others. What we have in mind is a formal system that explains how concepts of various types combine forming more complex concepts. To illustrate, consider the following:

(28) *artificial* :: NaturalKind → Artifact

(29) *flower* :: Plant

(30) *flower* :: Plant ⊃ LivingThing

(31) *flower* :: Plant ⊃ LivingThing ⊃ NaturalKind

(32) *artificial flower* :: Artifact

What the above says is the following: *artificial* is a function that takes a NaturalKind and returns an Artifact (28); a *flower* is a Plant (29); a *flower* is a Plant which is a

[7] Conservatively, the mapping might turn out to be homomorphism and not an isomorphism: some abstract concepts might not be derived metaphorically.

LivingThing (30); a *flower* is a Plant, which is a LivingThing, which in turn is a NaturalKind (31); and, finally, an *artificial flower* is an Artifact (32). Therefore, '*artificial c*', for some NaturalKind *c*, should in the final analysis have the same properties that any other Artifact has. Thus, while a *flower*, which is of type Plant, and is therefore a LivingThing, grows, lives and dies like any other LivingThing, an *artificial flower*, and like any other Artifact, is something that is manufactured, does not grow, does not die, but can be assembled, destroyed, etc.

The concept algebra we have in mind should also systematically explain the interplay between what is considered commonsense at the linguistic level, type checking at the ontological level, and deduction at the logical level. For example, the concept *artificial car*, which is a meaningless concept from the standpoint of commonsense, is ill-typed since Car is an Artifact, and Artifact does not unify with NaturalKind – neither type is a sub-type of the other. The concept *former father*, on the other hand, which is also a meaningless concept from the standpoint of commonsense, escapes type-checking since *father,* which is a Role, is a type that *former* expects as shown in (29) below.

(29) *former* :: Role → Role

However, as we show in appendix A, the fact that the concept *former father* is meaningless, while it escapes type-checking, is eventually caught at the logical level by resulting in a contradiction. Thus what is meaningless at the linguistic level should be flagged at the type-checking level, or, if happens to escapes type-checking, such as *former father,* it should eventually result in a logical contradiction at the logical level (see appendix A concerning *former father*). The picture we have in mind therefore can be summarized as shown in figure 5 below.

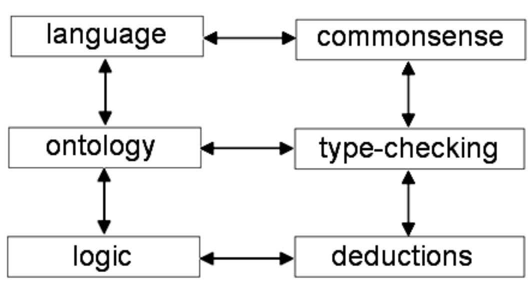


Figure 5. The interplay between language, ontology and logic.

The strongly-typed concept algebra that we envision is one that would also explain why removing the middle noun form (33), for example, changes the subject considerably while the same is not true in (34):

(33) *computer book sale*

(34) *information management system*

That is, what is the nature of the ontological categories that behave similar to *book* and what are those that are similar to *management*? This specific problem is crucial for such tasks as subject-based information retrieval.

Finally, a remark must be made about the distinction between analytic and synthetic knowledge. What we have been suggesting in this paper is a process that would hopefully lead to the *discovery* of a strongly-typed ontology of commonsense knowledge, along with a strongly-typed concept algebra. While this is a challenging Endeavour in its own right, alone this will do little to the construction of natural language understanding systems, unless an inferencing strategy that utilizes this ontology is properly formulated. While the ontology provides the synthetic knowledge that an NLU system might need, an NLU system must clearly use quite a bit of analytic knowledge. A typical example would be the following:

(36) $(\forall \textsc{p})((\exists \mathsf{C}_1)(app(\textsc{p},\mathsf{C}_1)) \supset (\forall \mathsf{C}_2)((\textsc{isa}(\mathsf{C}_2,\mathsf{C}_1)) \supset app(\textsc{p},\mathsf{C}_2)))$

That is, any property $\textsc{p}$ that applies to (or makes sense of) some concept C_1, also applies to (or makes sense of) any other concept C_2 of its subtypes. Clearly there are numerous other such rules that should ultimately be added.

8. Concluding Remarks

In this paper we argued for and presented a new approach to the systematic design of ontologies of commonsense knowledge. The method is based on the basic assumption that "language use" can guide the classification process. This idea is in turn rooted in Frege's principle of Compositionality and is similar to the idea of type inference in strongly-typed, polymorphic programming languages. The experiment we conducted shows this approach to be quite promising as it seems to have answered a number of questions simultaneously. In particular, the approach seems to (*i*) completely remove the need for multiple inheritance; (*ii*) provide a good explanation for polysemy and metaphor; and (*iii*) suggest a good model for the semantics of compound nomianls.

Much of what we presented here is work in progress, more so than a final result. Therefore, we are well aware that it might be quite ambitious to expect this process to yield a complete classification in a strict binary tree (no multiple inheritance). Although we could not discuss such details for lack of space, we believe that it is worth pursuing this strategy as it appears to shed some light on a number of phenomena such as the semantics of compound nominals, polysemy and metaphor. Finally, we must note that another interesting aspect that could not be discussed here is the part-whole relationship. In particular, it seems that some (but not all) verbs that apply to a concept apply to their parts. For example, GROW in *app*(GROW,Arm) and *app*(GROW,Leg) is very much related to *grow* in *app*(GROW,Person). That is, when we refer to a person growing, aging, etc. we are indirectly referring to the growing or aging of the parts. A great deal of work is still needed to formalize the entire approach as well as work out the various inference rules that will eventually be needed in a natural language understanding system.

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Appendix A

Using the logical formulation of the meaning of *former* given above, we show here how the concept '*former father*' translates into a logical contradiction.

First, we reiterate the meaning of 'former' in (1). In (2) we state the fact that the role type Father has an essential temporal property, namely that once someone is a father they are always a father. The deductions that follow should be obvious.

1. $(\forall x : \mathsf{Role})\big(\textsc{former}(x) \equiv_{df} \lambda P\big[(\exists t)\big((t < now) \wedge P(x,t) \wedge \neg P(x,now)\big)\big]\big)$
2. $(\forall x)\big((\exists t_1)\big(\textsc{father}(x,t_1) \supset (\forall t_2)\big((t_2 > t_1) \supset \textsc{father}(x,t_2)\big)\big)\big)$
3. $(\exists t)\big((t < now) \wedge \textsc{father}(x,t) \wedge \neg\textsc{father}(x,now)\big)$ (1) applied on $\textsc{father}$
4. $(t < now) \wedge \textsc{father}(x,t) \wedge \neg\textsc{father}(x,now)$ EI of (3)
5. $\textsc{father}(x,t)$ $\wedge$ – elimination of (4)
6. $(\exists t_1)\big(\textsc{father}(x,t_1) \supset (\forall t_2)\big((t_2 > t_1) \supset \textsc{father}(x,t_2)\big)\big)$ UG of (2)
7. $\textsc{father}(x,\mathsf{u}) \supset (\forall t_2)\big((t_2 \geq \mathsf{u}) \supset \textsc{father}(x,t_2)\big)$ EI of (6)

8. $(\forall t_2)((t_2 > t) \supset \textsc{father}(x, t_2))$ (5), (7) and MP
9. $(t_2 > t) \supset \textsc{father}(x, t_2)$ UG of (8)
10. $(t < now)$ $\wedge$ – elimination of (4)
11. $\textsc{father}(x, now)$ (9), (10) and MP
12. $\neg\textsc{father}(x, now)$ $\wedge$ – elimination of (4)
13. $\perp$ (11) and (12)

Appendix B

In (17) we stated that the meaning of some adjectives, namely those expressing a physical property of a PhysicalThing are intersective. Specifically, we argued that for constructions of the form [*A N*] where *A* is a physical property (such as *red*, *large*, *heavy*, etc.) and *N* is a object of type PhysicalThing (such as *car*, *person*, *desk*, etc.), the meaning of [*A N*] can be obtained as follows:

$$\|A\ \ N\| = \{x \mid A_{\mathsf{PhysicalProperty}}(x) \wedge N_{\mathsf{PhysicalThing}}(x)\}$$

Note here that the above expression is not a statement about the meaning of any particular adjective. Instead, (17) simply states is that some adjectives, such as *large*, *heavy*, etc. are intersective. Therefore, in $\|\ large\ table\ \| = \{x \mid \textsc{large}(x) \wedge \textsc{table}(x)\}$, for example, it is assumed that the meaning of *large*, namely the predicate $\textsc{large}(x)$ has been defined.

Although the semantics of such adjectives is not our immediate concern here, it must be pointed out that semantics of such (intersective) adjectives, which are presumably the simplest, can be quite involved, as these adjectives are very context-sensitive – clearly the sense of '*large*' in '*large elephant*' is quite different from the sense of '*large*' in '*large bird*'.

Assuming the existence of a predicate, $\textsc{typical}_{\textsc{a}}(x)$, which is true of some object x and one of its attributes $\textsc{a}$, if x is a typical object with respect to $\textsc{a}$, then the meanings of such adjectives as *large* and *heavy*, for example, could be defined as follows:

$$\begin{aligned}(1)\quad & large \Rightarrow (\forall x : \mathsf{PhysicalThing})(\textsc{large}(x) \equiv_{df} \\ & \lambda P[P(x) \wedge (\exists y : \mathsf{PhysicalThing})(P(y) \wedge \textsc{typical}_{\textsc{size}}(y) \\ & \wedge \textsc{size}(x, s_1) \wedge \textsc{size}(y, s_2) \wedge (s_1 >> s_2))])\end{aligned}$$

$$\begin{aligned}(2)\quad & heavy \Rightarrow (\forall x : \mathsf{PhysicalThing})(\textsc{heavy}(x) \equiv_{df} \\ & \lambda P[P(x) \wedge (\exists y : \mathsf{PhysicalThing})(P(y) \wedge \textsc{typical}_{\textsc{weight}}(y) \\ & \wedge \textsc{weight}(x, w_1) \wedge \textsc{weight}(y, w_2) \wedge (w_1 >> w_2))])\end{aligned}$$

What (1) and (2) say is the following: that some object x, which is a P, is *large* (*heavy*) P, *iff* it has a SIZE (WEIGHT) which is larger than the SIZE (WEIGHT) of another P object, y, which has a typical SIZE (WEIGHT) as far P objects go.

It would seem, then, that the meaning of such adjectives is tightly related to some attribute (large/size, heavy/weight, etc.) Of course, the semantics of other intersective adjectives can be more complex (consider: *famous*, *important*, *obvious*, etc.), although this is beyond the scope of this paper. What we simply wanted to highlight in this discussion is the importance of this kind of linguistic analysis in discovering the nature of various ontological categories, which is the underlying strategy in our approach to the discovery of the structure of commonsense knowledge.