

Elaborating a Knowledge Base for Deep Lexical Semantics

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Abstract

We describe the methodology for constructing axioms defining event-related words, anchored in core theories of change of state and causality. We first derive from WordNet senses a smaller set of abstract, general “supersenses”. We encode axioms for these, and we test them on textual entailment pairs. We look at two specific examples in detail to illustrate both the power of the method and the holes in the knowledge base that it exposes. Then we address the problem of holes more systematically, asking, for example, what kinds of “pairwise interactions” are possible for core theory predicates like *change* and *cause*.¹

1 Introduction

From the sentence

Russia is blocking oil from entering Ukraine.

we would like to be able to conclude

Oil can not be delivered to Ukraine.

But doing this requires fairly complex inference, because the words “block”, “enter”, “can”, “not” and “deliver” carve up the world in different ways. Our approach is to define words such as these by means of axioms that link with underlying core theories² explicating such very basic concepts as change of state and causality. Given the logical form of sentences like these two, we apply these axioms to express the meaning of the sentences in more fundamental predicates, and do a certain amount of defeasible reasoning in the core theories to determine that the second follows from the first.

More generally, we are engaged in an enterprise we call “deep lexical semantics” (Hobbs, 2008), in which we develop various core theories of fundamental commonsense phenomena and define English word senses by means of axioms using predicates explicated in these theories. Among the core theories are cognition, microsociology, and the structure of events. The last of these is the focus of this paper. We use textual entailment pairs like the above to test out subsets of related axioms. This process enforces a

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²<http://www.isi.edu/hobbs/csk.html>.

uniformity in the way axioms are constructed, and also exposes missing inferences in the core theories. The latter is a major issue in this paper.

In Section 2 we describe three aspects of the framework we are working in—the logical form we use, abductive interpretation and defeasibility, and the core theories of change of state and causality. In Section 3 we describe the methodology we use for constructing axioms, deriving from WordNet senses a smaller set of abstract, general “supersenses”, encoding axioms for these, and testing them on textual entailment pairs. In Section 4 we look at two specific examples to illustrate both the power of the method and the holes in the knowledge base that it exposes. In Section 5 we address the problem of holes more systematically, specifically asking, for example, what kinds of “pairwise interactions” are possible for core theory predicates like *change* and *cause*.

2 Framework

We use a logical notation in which states and events (eventualities) are reified. Specifically, if the expression $(p\ x)$ says that p is true of x , then $(p'\ e\ x)$ says that e is the eventuality of p being true of x . Eventuality e may exist in the real world (Rexist), in which case $(p\ x)$ holds, or it may only exist in some modal context, in which case that is expressed simply as another property of the possible individual e . (In this paper we use a subset of Common Logic³ for the syntax of our notation.)

The logical form of a sentence is a flat conjunction of existentially quantified positive literals, with about one literal per morpheme. (For example, logical words like “not” and “or” are treated as expressing predications about possible eventualities.) We have developed software⁴ to translate Penn TreeBank-style trees (as well as other syntactic formalisms) into this notation. The underlying core theories are expressed as axioms in this notation (Hobbs, 1985).

The interpretation of a text is taken to be the lowest-cost abductive proof of the logical form of the text, given the knowledge base. That is, to interpret a text we prove the logical form, allowing for assumptions at cost, and pick the lowest-cost proof. Factors involved in computing costs include, besides the number of assumptions, the salience of axioms, the plausibility of axioms expressing defeasible knowledge, and consilience or the degree to which the pervasive implicit redundancy of natural language texts is exploited. We have demonstrated that many interpretation problems are solved as a by-product of finding the lowest-cost proof. This method has been implemented in an abductive theorem-prover called Mini-Tacitus⁵ that has been used in a number of applications (Hobbs et al., 1993; Mulkar et al., 2007), and is used in the textual entailment problems described here. We are also working toward a probabilistic semantics for the cost of proofs (Blythe et al., 2011). Abductive interpretation accounts for script-like understanding of text—a script predicate provides the most economical interpretation (Hobbs et al., 1993)—but also enables interpretation of novel texts.

Most commonsense knowledge is defeasible, i.e., it can be defeated. This is represented in our framework by having a unique “et cetera” proposition in the antecedent of Horn clauses that cannot be proved but can be assumed at a cost corresponding to the likelihood that the conclusion is true. For example, the axiom

```
(forall (x) (if (and (bird x)(etc-i x))(fly x)))
```

would say that if x is a bird and other unspecified conditions hold, $(etc-i)$, then x flies. No other axioms enable proving $(etc-i\ x)$, but it can be assumed, and hence participate in the lowest cost

³<http://common-logic.org/>.

⁴<http://www.rutumulkar.com/download/NL-Pipeline/NL-Pipeline.php>.

⁵<http://rutumulkar.com/download/TACITUS/tacitus.php>.

proof. The index i is unique to this axiom. In this paper rather than invent new indices for each axiom, we will use the abbreviation ($e \text{t} c$) to indicate the defeasibility of the rule. (This approach to defeasibility is similar to circumscription (McCarthy, 1980).)

We have articulated a number of core theories⁶. The two most relevant to this paper are the theory of change of state and the theory of causality. The predication ($\text{change}' e e1 e2$) says that e is a change of state whose initial state is $e1$ and whose final state is $e2$. The chief properties of change are that there is some entity whose state is undergoing change, that change is defeasibly transitive, that $e1$ and $e2$ cannot be the same unless there has been an intermediate state that is different, and that change is consistent with the before relation from our core theory of time. Since many lexical items focus only on the initial or the final state of a change, we introduce for convenience the predications ($\text{changeFrom}' e e1$) and ($\text{changeTo}' e e2$), defined in terms of change .

The chief distinction in our core theory of causality is between the notions of causalComplex and cause . A causal complex includes all the states and events that have to happen or hold in order for the effect to happen. A cause is that contextually relevant element of the causal complex that is somehow central to the effect, whether because it is an action the agent performs, because it is not normally true, or for some other reason. Most of our knowledge about causality is expressed in terms of the predicate cause , rather than in terms of causal complexes, because we rarely if ever know the complete causal complex. Typically planning, explanation, and the interpretation of texts (though not diagnosis) involves reasoning about cause . Among the principal properties of cause are that it is defeasibly transitive, that events defeasibly have causes, and that cause is consistent with before .

We also have a core theory of time, and the times of states and events can be represented as temporal properties of the reified eventualities. The theory of time has an essential function in axioms for words explicitly referencing time, such as “schedule” and “delay”. But for most of the words we are explicating in this effort, we base our approach to the dynamic aspects of the world on the cognitively more basic theory of change of state. For example, the word “enter” is axiomatized as a change of state from being outside to being inside, and the fact that being outside comes *before* being inside follows from the axiom relating the predicates change and before .

We find that reifying states and events as eventualities and treating them as first-class individuals is preferable to employing the event calculus (Gruninger and Menzel, 2010; Mueller, 2006) which makes a sharp distinction between the two, because language makes no distinction in where they can appear and we can give them a uniform treatment.

3 Methodology

Our methodology consists of three steps.

1. Analyzing the structure of a word’s WordNet senses.
2. Writing axioms for the most general senses
3. Testing the axioms on textual entailment pairs.

Our focus in this paper is on words involving the concepts of change of state and causality, or event words, such as “block”, “delay”, “deliver”, “destroy”, “enter”, “escape”, “give”, “hit”, “manage”, and “provide”. For each word, we analyze the structure of its WordNet senses. Typically, there will be pairs that differ only in, for example, constraints on their arguments or in that one is inchoative and the other

⁶<http://www.isi.edu/hobbs/csk.html>.

causative. This analysis generally leads to a radial structure indicating how one sense leads by increments, logically and perhaps chronologically, to another word sense (Lakoff, 1987). The analysis also leads us to posit “supersenses” that cover two or more WordNet senses. (Frequently, these supersenses correspond to senses in FrameNet (Baker et al., 2003) or VerbNet (Kipper et al., 2006), which tend to be coarser grained; sometimes the desired senses are in WordNet itself.)

For example, for the verb “enter”, three WordNet senses involve a change into a state:

- V2: become a participant
- V4: play a part in
- V9: set out on an enterprise

Call this supersense S1. Two other senses add a causal role to this:

- V5: make a record of
- V8: put or introduce into something

Two more senses specialize supersense S1 by restricting the target state to be in a physical location:

- V1: come or go into
- V6: come on stage

One other sense specializes S1 by restricting the target state to be membership in a group.

- V3: register formally as a participant or member

Knowing this radial structure of the senses helps enforce uniformity in the construction of the axioms. If the senses are close, their axioms should be almost the same.

We are currently only constructing axioms for the most general or abstract senses or supersenses. In this way, although we are missing some of the implications of the more specialized senses, we are capturing the most basic topological structure in the meanings of the words. Moreover, the specialized senses usually tap into some specialized domain that needs to be axiomatized before the axioms for these senses can be written.

In constructing the axioms in the event domain, we are very much informed by the long tradition of work on lexical decomposition in linguistics (e.g., Gruber, 1965; Jackendoff, 1972). Our work differs from this in that our decompositions are done as logical inferences and not as tree transformations as in the earliest linguistic work, they are not obligatory but only inferences that may or may not be part of the lowest-cost abductive proof, and the “primitives” into which we decompose the words are explicated in theories that enable reasoning about the concepts.

Figure 1 shows the radial structure of the senses for the word “enter”, together with the axioms that characterize each sense. A link between two word senses means an incremental change in the axiom for one gives the axiom for the other. For example, the axiom for `enter-S2` says that if x_1 enters x_2 in x_3 , then x_1 causes a change to the eventuality i_1 in which x_2 is in x_3 ; and the expanded axiom for `enter-S1.1` states that if x_1 enters x_2 , then there is a change to a state e_1 in which x_1 is in x_2 . So `enter-S2` and `enter-S1.1` are closely related and thus linked together.

Abstraction is a special incremental change where one sense `S1.1` specializes another sense `S1` either by adding more predicates to or specializing some of the predicates in `S1`'s axiom. We represent abstractions via arrows pointing from the subsenses to the supersenses. In Figure 1, `enter-S1.1` and `enter-S1.2` both specialize `enter-S1`. The predicate `enter-S1.1` adds an extra predicate describing e_1 as an in eventuality and `enter-S1.2` specializes e_1 to membership in x_2 , where x_2 is a group.

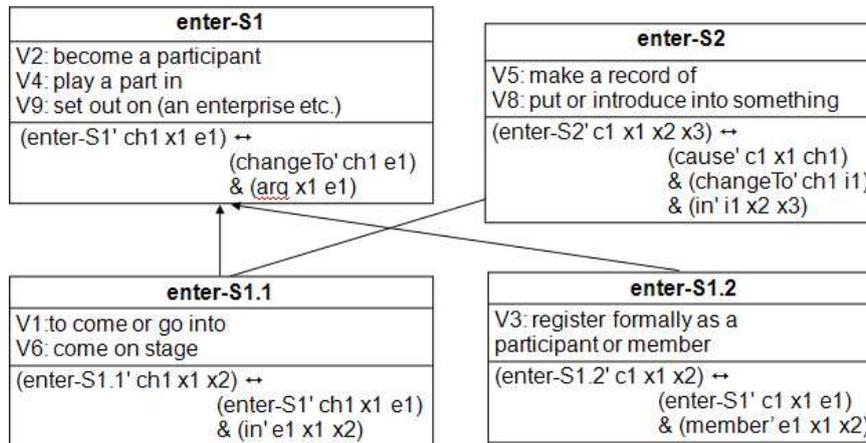


Figure 1: Senses of and axioms for the verb “enter”

The supersenses capture the basic topology of the senses they subsume. The extra information that the subsenses convey are typically the types and properties of the arguments, such as being a place or a process, or qualities of the causing event, such as being sudden or forceful.

For each set of inferentially related words we construct textual entailment pairs, where the hypothesis (H) intuitively follows from text (T), and use these for testing and evaluation. The person writing the axioms does not know what the pairs are, and the person constructing the pairs does not know what the axioms look like.

The ideal test then is whether given a knowledge base K consisting of all the axioms, H cannot be proven from K alone, but H can be proven from the union of K and the best interpretation of T. This is often too stringent a condition, since H may contain irrelevant material that doesn't follow from T, so an alternative is to determine whether the lowest cost abductive proof of H given K plus T is substantially lower than the lowest cost abductive proof of H given K alone, where “substantially lower” is defined by a threshold that can be trained (Ovchinnikova et al., 2011).

4 Two Examples

Here we work through two examples to illustrate how textual entailment problems are handled in our framework. In these examples, given a text T and a hypothesis H, we ask if H can be proven from T, perhaps with a small number of low-cost assumptions.

Because the examples we deal with involve a great deal of embedding, we need to use the primed predicates, keeping the eventuality arguments explicit.

We also assume in these examples that lexical disambiguation has been done correctly. With more context, lexical disambiguation should fall out of the best interpretation, but it is unreasonable to expect that in these short examples. In practice we run the examples both with disambiguated and with nondisambiguated predicates.

In these examples we do not show the costs, although they are used by our system.

The first example is the pair

T: Russia is blocking oil from entering Ukraine.

H: Oil cannot be delivered to Ukraine.

The relevant part of the logical form of the text is

```
(and (block-V3' b1 x1 e1)(enter-S2' e1 o1 u1))
```

That is, there is a blocking event *b1* in which Russia *x1* blocks eventuality *e1* from occurring, and *e1* is the eventuality of oil *o1* entering Ukraine *u1*. The -V3 on *block* indicates that it is the third WordNet sense of the verb “block” and the -S2 suffix on *enter* indicates that it is the second supersense of “enter”.

The relevant part of the logical form of the hypothesis is

```
(and (not' n2 c2) (can-S1' c2 x2 d2) (deliver-S2' d2 x2 o2 u2))
```

That is, *n2* is the eventuality that *c2* is not the case, where *c2* is some *x2*'s being able to do *d2*, where *d2* is *x2*'s delivering oil *o2* to Ukraine *u2*. Note that we don't know yet that the oil and Ukraine in the two sentences are coreferential.

The axiom relating the third verb sense of “block” to the underlying core theories is

```
AX4: (forall (c1 x1 e1)
      (if (block-V3' c1 x1 e1)
          (exist (n1 p1)
                 (and (cause' c1 x1 n1)(not' n1 p1)(possible' p1 e1))))))
```

This rule says that for *x1* to block some eventuality *e1* is for *x1* to cause *e1* not to be possible. (In this example, for expositional simplicity, we have allowed the eventuality *c1* of blocking be the same as the eventuality of causing, where properly they should be closely related but not identical.)

The other axioms needed in this example are

```
AX1: (forall (c1 e1)
      (if (and (possible' c1 e1)(etc))
          (exist (x1)(can-S1' c1 x1 e1))))
```

```
AX2: (forall (d1 x1 c1 r1 x2 x3)
      (if (and (cause' d1 x1 c1)(changeTo' c1 r1)(rel' r1 x2 x3)
              (deliver-S2' d1 x1 x2 x3))))
```

```
AX3: (forall (c1 x1 x2)
      (if (enter-S2' c1 x1 x2)
          (exist (i1)(and changeTo' c1 i1)(in' i1 x1 x2))))
```

AX1 says that defeasibly, if an eventuality *e1* is possible, then someone can do it. AX2 says that if *x1* causes a change to a situation *r1* in which *x2* is in some relation to *x3*, then in a very general sense (S2), *x1* has delivered *x2* to *x3*. AX3 says that if *c1* is the eventuality of *x1* entering *x2*, then *c1* is the change into a state *i1* in which *x1* is in *x2*.

Starting with the logical form of H as the initial interpretation and applying axioms AX1 and AX2, we get interpretation H1:

```
H1: (and (not' n2 c2) (possible' c2 d2) (cause' d2 x2 c1)
        (changeTo' c1 r1)(rel' r1 o2 u2))
```

At this point we are stuck in our effort to back-chain to T. An axiom is missing, namely, one that says that “in” is a relation between two entities.

```
AX5: (forall (r x1 x2) (if (in' r1 x1 x2)(rel' r1 x1 x2)))
```

Using AX5, we can back-chain from H1 and derive interpretation H2:

```
H2: (and (not' n2 c2)(possible' c2 d2)(cause' d2 x2 c1)
        (changeTo' c1 r1)(in' r1 o2 u2))
```

We can then further back-chain with AX3 to interpretation H3:

H3: (and (not' n2 c2)(possible' c2 d2)(cause' d2 x2 c1)
(enter-S2' c1 o2 u2))

Again, we need a missing axiom, AX6, to get closer to the logical form of T:

AX6: (forall (p e1)
(if (and (possible' p,e1)(etc))
(exist (c x1) (and (possible' p c)(cause' c x1 e1))))))

That is, if something is possible, it is possible for something to cause it. Using this axiom, we can derive

H4: (and (not' n2 c2)(possible' c2 c1)(enter-S2' c1 o2 u2))

The final missing axiom, AX7, says that if x1 causes eventuality c2 not to occur, then c2 doesn't occur.

AX7: (forall (n x1 n1 c2)
(if (and (cause' n x1 n1)(not' n1 c2))(not' n c2)))

Using this we derive interpretation H5.

H5: (and (cause' n2 x3 n)(not' n c2)(possible' c2 c1)(enter-S2' c1 o2 u2))

We can now apply the rule for "block", identifying b1 and n2, x1 and x3, e1 and c1, o1 and o2, and u1 and u2, yielding H6 and establishing the entailment relation between H and T.

H6: (and (block-V3' n2 x3 c1)(enter-S2' c1 o2 u2))

Our second example is the text-hypothesis pair

T: The plane managed to escape the attack.

H: The plane was not captured.

The relevant parts of the logical forms of T and H are as follows:

T: (and (manage-V1' m1 p1 e1)(escape-S1' e1 p1 a1))

H: (and (not' n2 c2)(capture-S1' c2 x2 p2))

The axioms relating these words to the core theories are as follows:

AX1: (forall (cp c x2 n chf a y1 x3 y0 x2)
(if (and (changeTo' cp c)(cause' c x2 n)(not' n chf)
(changeFrom' chf a)(at' a y1 x3)(arg' y0 x2))
(capture' cp y0 y1)))

AX2: (forall (es x0 x1)
(if (escape' es x0 x1)
(exist (ch a)
(and (cause' es x0 ch)(changeFrom' ch a)(at' a x0 x1))))))

AX3: (forall (m y0 e1)
(if (manage' m y0 e1) (Rexist (m e1))))

The first says that a change to a situation in which x_2 is causing y_1 not to change location is a capturing by some y_0 of y_1 . The second says that escaping implies causing a change from being at a location. The third says that if you manage to do e_1 , then e_1 occurs.

Using these axioms, we would like to establish the entailment relation from T to H. However, in order for this reasoning to go through, we need several more axioms—saying that if an eventuality does not hold, there has been no change to that eventuality, and nothing has caused it to occur; that double negation cancels out; and that if something is caused, it occurs.

It may seem at first blush that any new text-hypothesis pair will reveal new axioms that must be encoded, and that therefore it is hopeless ever to achieve completeness in the theories. But a closer examination reveals that the missing axioms all involve relations among the most fundamental predicates, like *cause*, *change*, *not*, and *possible*. These are axioms that should be a part of the core theories of change and causality. They are not a random collection of facts, any one of which may turn out to be necessary for any given example. Rather we can investigate the possibilities systematically. That investigation is what we describe in the following section.

5 Relations among Fundamental Predicates

For completeness in the core theories, we need to look at pairs of fundamental predicates and ask what relations hold between them, what their composition yields, and for each such axiom whether it is defeasible or indefeasible. The predicates we consider are *possible*, *Rexist*, *not*, *cause*, *changeFrom*, and *changeTo*.

The first type of axiom formulates the relationship between two predicates. For example, the rule relating *cause* and *Rexist* is

```
(forall (x e) (if (cause x e)(Rexist e)))
```

That is, if something is caused, then it actually occurs. Other rules of this type are as follows:

```
(forall (x e) (if (Rexist e)(possible e)))
```

```
(forall (e) (if (and (Rexist e)(etc))(exist (x)(cause x e))))
```

```
(forall (e2)
  (if (changeTo e2)
    (exist (e1)(and (changeFrom e1)(not' e1 e2)))))
```

```
(forall (e1)
  (if (changeFrom e1)
    (exist (e2)(and (changeTo e2)(not' e2 e1)))))
```

```
(forall (e) (if (changeTo e)(Rexist e)))
```

```
(forall (e) (if (changeFrom e)(not e)))
```

```
(forall (e) (if (and (Rexist e)(etc))(changeTo e)))
```

That is, if something occurs, it is possible and, defeasibly, something causes it. If there is a change to some state obtaining, then there is a change from its not obtaining, and vice versa. If there is a change to something, then it obtains, and if there is a change from something, then it no longer obtains. If some state obtains, then defeasibly there was a change from something else to that state obtaining.

The second type of axiom involves the composition of predicates, and gives us rules of the form

(forall (e1 e2 x) (if (and (p' e1 e2)(q' e2 x)) (r' e1 x)))

That is, when p is applied to q , what relation r do we get?

Figure 2 shows the axioms encoding these compositions. The rows correspond to the $(p' e1 e2)$'s and the columns correspond to the $(q' e2 x)$'s, and the cell contains the consequents $(r' e1 x)$. If the rule is defeasible, the cell indicates that by adding (etc) to the antecedent. The consequents in italics are derivable from other rules.

	(possible' e2 e3)	(Rexist' e2 e3)	(not' e2 e3)	(cause' e2 x2 e3)	(changeFrom' e2 e3)	(changeTo' e2 e3)
(possible' e1 e2)	(possible' e1 e3)	(possible' e1 e3)		<i>(possible' e1 e3)</i>		<i>(possible' e1 e3)</i>
(Rexist' e1 e2)	(possible' e1 e3)	(Rexist' e1 e3)	(not' e1 e3)	<i>(Rexist' e1 e3)</i>	<i>(not' e1 e3)</i>	<i>(Rexist' e1 e3)</i>
(not' e1 e2)	(not' e1 e3)	(not' e1 e3)	(Rexist' e1 e3)	(etc) -> (not' e1 e3)	(Rexist' e1 e3)	(etc) -> (not' e1 e3)
(cause' e1 x1 e2)	<i>(possible' e1 e3)</i>	(cause' e1 x1 e3) <i>(Rexist' e1 e3)</i>	<i>(not' e1 e3)</i>	(cause' e1 x1 e3) <i>(Rexist' e1 e3)</i>	<i>(not' e1 e3)</i> <i>(changeFrom' e1 e3)</i>	<i>(cause' e1 x1 e3)</i> <i>(changeTo' e1 e3)</i>
(changeFrom' e1 e2)		(changeFrom' e1 e3)	(changeTo' e1 e3) <i>(Rexist' e1 e3)</i>	(etc) -> (changeFrom' e1 e3) (etc) -> (not' e1 e3)	<i>(Rexist' e1 e3)</i>	(etc) -> (not' e1 e3)
(changeTo' e1 e2)	<i>(possible' e1 e3)</i>	(changeTo' e1 e3) <i>(Rexist' e1 e3)</i>	(changeFrom' e1 e3) <i>(not' e1 e3)</i>	(etc) -> (changeTo' e1 e3) <i>(Rexist' e1 e3)</i> <i>(cause' e1 x1 e3)</i>	<i>(not' e1 e3)</i> <i>(changeFrom' e1 e3)</i>	<i>(Rexist' e1 e3)</i> <i>(changeTo' e1 e3)</i>

Figure 2: Axioms expressing compositions of fundamental predicates

For example, in the possible-possible cell, the rule says that if it is possible that something is possible, then it is possible. To take a more complex example, the changeFrom-cause cell says that if there is a change from some entity causing (or maintaining) a state, then defeasibly there will be a change from that state. So if a glass is released, it will fall.

We have also looked at axioms whose pattern is the converse of those in Figure 2. For example, if something does not hold, then it was not caused. Many of the axioms used in the examples are of this sort.

6 Conclusion

If we are ever to have sophisticated natural language understanding, our systems will have to be able to draw inferences like the ones illustrated here, and therefore they will need axioms of this complexity or something equivalent. Because of their complexity, we cannot expect to be able to acquire the axioms automatically by statistical methods. But that does not mean the situation is bleak. We have shown in this paper that there is a systematic methodology for developing axioms characterizing the meanings of words in a way that enforces uniformity and for elaborating the core theories these axioms are anchored in. Doing this for several thousand of the most common words in English would produce a huge gain in the inferential power of our systems, as illustrated by the textual entailment examples in this paper, and would be an enterprise no greater in scope than the manual construction of other widely used resources such as WordNet and FrameNet.

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