Deep Lexical Semantics

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Abstract. In the project we describe, we have taken a basic core of about 5000 synsets in WordNet that are the most frequently used, and we have categorized these into sixteen broad categories, including, for example, time, space, scalar notions, composite entities, and event structure. We have sketched out the structure of some of the underlying abstract core theories of commonsense knowledge, including those for the mentioned areas. These theories explicate the basic predicates in terms of which the most common word senses need to be defined or characterized. We are now encoding axioms that link the word senses to the core theories. This may be thought of as a kind of "advanced lexical decomposition", where the "primitives" into which words are "decomposed" are elements in coherently worked-out theories. In this paper we focus on our work on the 450 of these synsets that are concerned with events and their structure.

1 Introduction

Words describe the world, so if we are going to draw the appropriate inferences in understanding a text, we must have underlying theories of aspects of the world and we must have axioms that link these to words. This includes domain-dependent knowledge, of course, but 70-80% of the words in most texts, even technical texts, are words in ordinary English used with their ordinary meanings. For example, so far in this paragraph, only the words "theories" and "axioms" and possibly "domain-dependent" have been domain-dependent.

Domain-independent words have such wide utility because their basic meanings tend to be very abstract, and they acquire more specific meanings in combination with their context. Therefore, the underlying theories required for explicating the meanings of these words are going to be very abstract.

For example, a core theory of scales will provide axioms involving predicates such as *scale*, $<$, *subscale*, *top*, *bottom*, and *at*. These are abstract notions that apply to partial orderings as diverse as heights, money, and degrees of happiness. Then, at the "lexical periphery" we will be able to define the rather complex word "range" by the following axiom:

$$\begin{array}{l}(\forall\, x, y, z)range(x, y, z) \equiv \\ \quad (\exists\, s, s_1, u_1, u_2)scale(s) \wedge subscale(s_1, s) \wedge bottom(y, s_1) \\ \qquad \wedge\, top(z, s_1) \wedge u_1 \in x \wedge at(u_1, y) \wedge u_2 \in x \wedge at(u_2, z) \\ \qquad \wedge\, (\forall\, u \in x)(\exists\, v \in s_1)at(u, v)\end{array}$$

That is, x ranges from y to z if and only if there is a scale s with a subscale s_1 whose bottom is y and whose top is z, such that some member u_1 of x is at y, some member u_2 of x is at z, and every member u of x is at some point v in s_1. Many things can be conceptualized as scales, and when this is done, a large vocabulary, including the word "range", becomes available. For example, we can now use and interpret "range" in the sentences

The grades on the midterm ranged from 33 to 96.
The timber wolf ranges from New Mexico to Alberta.
Pat's behavior ranges from barely tolerable to deeply hostile.

by instantiating *scale* in different ways.

It would be good if we could learn relevant lexical and world knowledge automatically, and there has been some excellent work in this area (e.g., [8]). For example, we can automatically learn the correlation between "married" and "divorced", and maybe we can even learn automatically the corresponding predicate-argument structures and which way the implication goes and with what temporal constraints. But this is a very simple relation to axiomatize in comparison to the "range" axiom. The kinds of knowledge we need are in general much more complex than automatic methods can give us. Moreover, automatic methods do not always yield very reliable results. The word "married" is highly correlated with "divorced" but it is also highly correlated with "murdered".

If we construct the core theories and the linking axioms manually, we can achieve the desired complexity and reliability. It would not be feasible to axiomatize the meanings of 100,000 words manually. But it *is* feasible to axiomatize the meanings of several thousand words manually, and if the words are very common, this would result in a very valuable resource for natural language understanding.

This paper describes an effort in which a set of very common words somehow related to events and their structure are being linked with underlying core theories that have been developed. Section 3 describes previous work in identifying a "core WordNet" and subsequent efforts to examine and classify the words in various ways. This led to the identification of 446 words with senses that are primarily focused on events, viewed abstractly. In Section 3 we describe several of the core theories that are crucial in characterizing event words, including composite entities, scales, change, and causality. In Section 4 we illustrate the work being carried out now on linking WordNet and FrameNet word senses to each other and linking these to the core theories.

This work can be seen as an attempt at a kind of deep lexical semantics. Not only are the words "decomposed" into what were once called primitives, but also the primitives are explicated in axiomatic theories, enabling one to reason deeply about the concepts conveyed by the text.

2 Identifying the Core Event Words

WordNet ([6]) contains tens of thousands of synsets referring to highly specific animals, plants, chemical compounds, French mathematicians, and so on. Most of these are rarely relevant to any particular natural language understanding application. To focus on the more central words in English, the Princeton WordNet group has compiled a CoreWordNet, consisting of 4,979 synsets that express frequent and salient concepts. These were selected as follows: First, a list with the most frequent strings from the British National Corpus was automatically compiled and all WordNet synsets for these strings were pulled out. Second, two raters determined which of the senses of these strings expressed "salient" concepts ([3]). CoreWordNet is downloadable from

http://wordnet.cs.princeton.edu/downloads.html.

Only nouns, verbs and adjectives were identified in this effort, but subsequently 322 adverbs were added to the list.

We classified these word senses manually into sixteen broad categories, listed here with rough descriptions and lists of sample words in the categories. Word senses are not indicated but should be obvious from the category.

Composite Entities: the structure and function of things made of other things: perfect, empty, relative, secondary, similar, odd, ...

Scales: partial orderings and their fine-grained structure: step, degree, level, intensify, high, major, considerable, ...

Events: concepts involving change and causality: constraint, secure, generate, fix, power, development, ...

Space: spatial properties and relations: grade, inside, lot, top, list, direction, turn, enlarge, long, ...

Time: temporal properties and relations: year, day, summer, recent, old, early, present, then, often, ...

Cognition: concepts involving mental and emotional states: imagination, horror, rely, remind, matter, estimate, idea, ...

Communication: concepts involving people communicating with each other: journal, poetry, announcement, gesture, charter, ...

Persons: concepts involving persons and their relationships and activities: leisure, childhood, glance, cousin, jump, ...

Microsocial: social phenomena other than communication that would be present in any society regardless of their level of technology: virtue, separate, friendly, married, company, name, ...

Bio: living things other than humans: breed, oak, shell, lion, eagle, shark, snail, fur, flock, ...

Geo: geographical, geological and meteorological concepts: storm, moon, pole, world, peak, site, sea, island, ...

Material World: other aspects of the natural world: smoke, shell, stick, carbon, blue, burn, dry, tough, ...

Artifacts: physical objects built by humans to fulfill some function: bell, button, van, shelf, machine, film, floor, glass, chair, ...

Food: concepts involving things that are eaten or drunk: cheese, potato, milk, bread, cake, meat, beer, bake, spoil, ...

Macrosocial: concepts that depend on a large-scale technological society: architecture, airport, headquarters, prosecution, . . .
Economic: having to do with money and trade: import, money, policy, poverty, profit, venture, owe, . . .

These categories of course have fuzzy boundaries and overlaps, but their purpose is only for grouping together concepts that need to be axiomatized together for coherent theories.

Each of these categories was then given a finer-grained structure. The internal structure of the category of event words is given below, with descriptions and examples of each subcategory.

- **State:** Having to do with an entity being in some state or not: have, remain, lack, still, . . .
- **Change**: involving a change of state:
  - Abstractly: incident, happen
  - A change of real or metaphorical position: return, take, leave, rise, . . .
  - A change in real or metaphorical size or quantity: increase, fall, . . .
  - A change in property: change, become, transition, . . .
  - A change in existence: develop, revival, decay, break, . . .
  - A change in real or metaphorical possession: accumulation, fill, recovery, loss, give, . . .
  - The beginning of a change: source, start, origin, . . .
  - The end of a change: end, target, conclusion, stop, . . .
  - Things happening in the middle of a change: path, variation, repetition, [take a] break, . . .
  - Participant in a change: participant, player, . . .
- **Cause:** having to do with something causing or not causing a change of state:
  - In general: effect, result, make, prevent, so, thereby, . . .
  - Causes acting as a barrier: restriction, limit, restraint, . . .
  - An absence of causes or barriers: chance, accident, freely, . . .
  - Causing a change in position: put, pull, deliver, load, . . .
  - Causing a change in existence: develop, create, establish, . . .
  - Causing a change in real or metaphorical possession: obtain, deprive.
- **Instrumentality:** involving causal factors intermediate between the primary cause and the primary effect: way, method, ability, influence, preparation, help, somehow, . . .
- **Process:** A complex of causally related changes of state:
  - The process as a whole: process, routine, work, operational, . . .
  - The beginning of the process: undertake, activate, ready, . . .
  - The end of the process: settlement, close, finish, . . .
  - Things that happen in the middle of a process: trend, continuation, steady, postpone, drift, . . .
- **Opposition:**

    - Involving factors acting against some causal flow: opposition, conflict, delay, block, bar, . . .
    - Involving resistance to opposition: resist, endure, . . .
- **Force:** Involving forces acting causally with greater or lesser intensity: power, strong, difficulty, throw, press, . . .
- **Functionality:** A notion of functionality with respect to some human agent's goals is superimposed on the causal structure; some outcomes are good and some are bad:
    - Relative to achieving a goal: use, success, improve, safe, . . .
    - Relative to failing to achieve a goal: failure, blow, disaster, critical, . . .
    - Relative to countering the failure to achieve a goal: survivor, escape, fix, reform, . . .

As with the broad categories, these subcategories are intended to group together words that need to be defined or characterized together if a coherent theory is to result.

3 Some Core Theories

The enterprise is to link words with core theories. The last section gave an indication of the words involved in the effort, and a high-level analysis of the concepts needed for defining or characterizing them formally. This section sketches some of the principal core theories, including concepts used in Section 4. Descriptions of all the core theories, with axioms, can be found at

http://www.isi.edu/∼hobbs/csk.html

Currently, there are sixteen theories defining or characterizing 230 predicates with 380 axioms. The theories differ from other commonsense knowledge bases, such as Cyc [4] or SUMO [7], primarily in the abstract character and linguistic motivation of the knowledge.

Eventualities and their Structure: Eventualities are possible or actual states or events. As axiomatized, they are isomorphic to predications, and just as predications have arguments, eventualities have participants. We can define a predicate $relatedTo$ that holds between two entities x and y when they are participants in the same eventuality, or equivalently, when they are arguments of the same predication.

Set Theory: This is axiomatized in a standard fashion, and provides predicates like *setdiff* and *deleteElt*, the latter expressing a relation between a set and the set resulting from deleting an element from it.

Composite Entities: This is a very general theory of things made of other things, one of the most basic notions one can imagine. A composite entity is characterized by a set of components, a set of properties of these components, and a set of relations among the components and between the components and the whole. With this theory we can talk about the structure of an entity by explicating its components and their relations, and we can talk about the environment of an entity by viewing the environment as composite and having the entity among its components. The predicate *partOf* is a very broad notion covering among other relations the *componentOf* relation. We also introduce in this theory the figure-ground relation *at* which places an external entity "at" some component in a composite entity.

Scales: This theory was mentioned in the introduction. In addition to defining the basic vocabulary for talking about partial orderings, we also explicate monotone-increasing scale-to-scale functions ("the more ... the more ..."), the construction of composite scales, the characterization of qualitatively high and low regions of a scale (related to distributions and functionality), and constraints on vague scales based on associated subsets (e.g., if Pat has all the skills Chris has and then some, Pat is more skilled than Chris, even though such judgments in general are often indeterminate).

Change of State: The basic predicate for change of state is *change*. The expression $change(e_1, e_2)$ means that state e_1 changes into state e_2. The states must share a participant, and a state cannot change into the same state without going through an intermediate different state. The concept of *change* is linked with the theory of time in the obvious ways. We also define one-argument predicates $changeFrom$ and $changeTo$, suppressing one or the other argument of *change*. We define events as eventualities that involve a change of state and states (the predicate *state* used below) as eventualities that don't. The concept *remove* referred to in Section 4 can be defined in terms of *change* and *deleteElt* as a change of state from a dynamic set having one set of elements to its having a subset of those elements.

Cause: We characterize a causal complex for an effect by two strict properties: If every eventuality in a causal complex happens, the effect happens, and everything in the causal complex is relevent to the effect in a way that can be made precise. The predicate *cause* then captures a defeasible notion that isolates the most significant element in a causal complex, often the element that does not normally hold. Most of our causal knowledge and causal reasoning is in terms of *cause* rather then the idealized notion of causal complex. The concept *cause* has the expected properties, such as defeasible transitivity. In addition, in this theory we define such concepts as *enable*, *prevent*, *help*, and *obstruct*. There are also treatments of attempts, success, failure, ability, and difficulty.

Events: This theory is about how changes of state and causality compose into more complex events, processes and scenarios. It includes definitions of conditional, iterative, cyclic, and periodic events, and is linked with several well-developed ontologies for event structure, e.g., PSL ([2]).

The other core theories that have been constructed include a well-developed theory of time, a rather sparse theory of space, and a large number of theories explicating a commonsense theory of cognition.

4 Some Word Senses Linked to Core Theories

This section provides two examples of very basic words and how their various word senses in WordNet and in FrameNet ([1]) can be linked axiomatically to each other and to the core theories.

"Have": In WordNet the verb "have" has 19 senses. But they can be grouped into three broad "supersenses". In its first supersense, X has Y means that X is in some relation to Y. The WordNet senses this covers are as follows:

1. a broad sense, including have a son, having a condition hold and having a college degree
2. having a feature or property, i.e., the property holding of the entity
3. a sentient being having a feeling or internal property
4. a person owning a possession
7. have a person related in some way: have an assistant
9. have left: have three more chapters to write
12. have a disease: have influenza
17. have a score in a game: have three touchdowns

The supersense can be characterized by the axiom

$$have\text{-}s1(x, y) \supset relatedTo(x, y)$$

In these axioms, supersenses are indexed with s, WordNet senses with w, and FrameNet senses with f. Unindexed predicates are from core theories.

The individual senses are then specializations of the supersense where more domain-specific predicates are explicated in more specialized domains. For example, sense 4 relates to the supersense as follows:

$$have\text{-}w4(x, y) \equiv possess(x, y)$$
$$have\text{-}w4(x, y) \supset have\text{-}s1(x, y)$$

where the predicate *possess* would be explicated in a commonsense theory of economics, relating it to the priveleged use of the object. Similarly, $have\text{-}w3(x, y)$ links with the supersense but has the restrictions that x is sentent and that the "relatedTo" property is the predicate-argument relation between the feeling and its subject.

The second supersense of "have" is "come to be in a relation to". This is our *changeTo* predicate. Thus, the definition of this supersense is

$$have\text{-}s2(x, y) \equiv changeTo(e) \wedge have\text{-}s1'(e, x, y)$$

The WordNet senses this covers are as follows:

10. be confronted with: we have a fine mess
11. experience: the stocks had a fast run-up
14. receive something offered: have this present
15. come into possession of: he had a gift from her
16. undergo, e.g., an injury: he had his arm broken in the fight
18. have a baby

In these senses the new relation is initiated but the subject does not necessarily play a causal or agentive role. The particular change involved is specialized in the WordNet senses to a confronting, a receiving, a giving birth, and so on.

The third supersense of "have" is "cause to come to be in a relation to". The axiom defining this is

$$have\text{-}s2(x, y) \equiv cause(x, e) \wedge have\text{-}s2'(e, x, y)$$

The WordNet senses this covers are

5. cause to move or be in a certain position or condition: have your car ready
6. consume: have a cup of coffee
8. organize: have a party
13. cause to do: she had him see a doctor
19. have sex with

In all these cases the subject initiates the change of state that occurs.

FrameNet has five simple transitive senses for "have". Their associated frames are

1. Have associated
2. Possession
3. Ingestion
4. Inclusion
5. Birth

The first sense corresponds to the first WordNet supersense:

$$have\text{-}f1(x, y) \equiv have\text{-}s1(x, y)$$

The second sense is WordNet sense 4.

$$have\text{-}f2(x, y) \equiv have\text{-}w4(x, y)$$

The third sense is WordNet sense 6. The fourth sense is the *partOf* relation introduced in Section 3. It is a specialization of WordNet sense 2.

$$have\text{-}f4(x, y) \equiv partOf(x, y)$$
$$have\text{-}f4(x, y) \supset have\text{-}w2(x, y)$$

The fifth sense is WordNet sense 18.

By relating the senses in this way, an NLP system capable of inference can tap into both resources, for example, by accessing the WordNet hierarchy or the WordNet glosses expressed as logical axioms ([5]), and by accessing the FrameNet frames, which are very close to axiomatic characterizations of abstract situations. In addition, it allows us to access the core theories explicating predicates like $relatedTo$ and *partOf*.

"Remain:" There are four WordNet senses of the verb "remain":

1. Not change out of a state: He remained calm.
2. Not change out of being at a location: He remained at his post.
3. Entities in a set remaining after others are removed: Three problems remain.
4. A condition remains in a location: Some smoke remained after the fire was put out.

The first sense is the most general and subsumes the other three. We can characterize it by the axiom

$$remain\text{-}w1(x,e) \supset arg(x,e) \wedge \neg changeFrom(e)$$

By the properties of $changeFrom$ it follows that x is in state e. In the second sense, the property e of x is being in a location.

$$remain\text{-}w2(x,e) \equiv remain\text{-}w1(x,e) \wedge at'(e,x,y)$$

The fourth sense is a specialization of the second sense in which the entity x that remains is a state or condition.

$$remain\text{-}w4(x,e) \equiv remain\text{-}w2(x,e) \wedge state(x)$$

The third sense is the most interesting to characterize. There is a process that removes elements from a set, and what remains is the set difference between the original and the set of elements that are removed. In this axiom x remains after process e.

$$remain\text{-}w3(x,e) \equiv remove'(e,y,s_2,s_1) \wedge setdiff(s_3,s_1,s_2) \wedge member(x,s_3)$$

That is, x remains after e if and only if e is a removal event by some agent y of a subset s_2 from s_1, s_3 is the set difference between s_1 and s_2, and x is a member of s_3.

There are four FrameNet senses of "remain". The first is the same as WordNet sense 1. The second is the same as WordNet sense 3. The third and fourth are two specializations of WordNet sense 3, one in which the removal process is destructive and one in which it is not.

There are two nominalizations of the verb "remain"—"remainder" and "remains". All of their senses are related to WordNet sense 3. The first WordNet noun sense is the most general.

$$remainder\text{-}w1(x,e) \equiv remain\text{-}w3(x,e)$$

That is, x is the remaineder after process e if and only if x remains after e. The other three senses result from specialization of the removal process to arithmetic division, arithmetic subtraction, and the purposeful cutting of a piece of cloth.

5 Summary

We understand language so well because we know so much, and our computer programs will only approach what we might call "understanding" when they have access to very large knowledge bases. Much of this knowledge will be of a technical nature and can perhaps be acquired automatically by statistical methods or from learning by reading. But the bulk of the inferences required for understanding natural language discourse involve very basic abstract categories. In the work described here, we have identified the words which because of their frequency are most demanding of explication in terms of the inferences they trigger. We have constructed abstract core theories of the principal domains that need to be elaborated in order to express these inferences in a coherent fashion. We are in the process of defining or characterizing the meanings of a moderately large set of words related to the structure of events in terms of the core theories. In combination with other knowledge resources, this work should take us a step closer to sophisticated, inference-based natural language processing.

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