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Computing the Temporal Structure of Events in Natural Language

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Abstract. A key step in Natural Language Processing is creating representations of sentences and discourses. Sentences describe states and events. Thus a crucial component of semantically interpreting them is determining the temporal structure of the events they describe. We present a general and declarative approach to doing so. This approach is based on an algebraic semantics of events and objects. Keywords: situation type, aspect, events.

1 Introduction

Recently, much work has been done on the temporal structure of events [1, 4, 6], a task crucial to constructing appropriate representations which, in turn, is a fundamental step in understanding and generating natural language. The structure of an event and its relationship to other events in a discourse depends on its *situation type* and *aspect* [1, 4]. For example, the sentences *Al walked in the park* and *Al found a ball*, which differ in situation type, result in different representations—the former introduces a temporally extended event into the discourse, the latter a point. If the order of the sentences is as above, the meaning is that Al found the ball *while* walking in the park, but if the order is the opposite, the meaning is that Al walked in the park *after* he found the ball.

We are developing a general approach to (a) computing the situation type of a sentence, (b) using it to determine the structure of the situation it describes, and (c) using that to determine the temporal structure of the given discourse, i.e., the relative temporal locations of the situations described in it. Here we report on components (a) and (b). Our approach applies uniformly to nominal expressions, locative and spatial adjuncts, and prepositional complements. It is significantly different from extant proposals which, while acknowledging the importance of situation type, suffer from some limitations [1, 4, 5]. They (a) assume that the situation type of the basic verbal predicate is available, i.e., they cannot compute it themselves, (b) are mostly procedural, and (c) do not always yield the right results.

Our approach is based on Krifka's algebraic semantics [2, 3]. In §2, we describe situation type, aspect, and the key algebraic concepts needed to formalize them. In §3, we show how to compositionally compute the situation type of a sentence. In §4, we motivate and present schemata for different situation types and apply this theory to temporal adverbials.

2 Primitives

2.1 Situation Types and Aspect

Each sentence describes a *situation*, i.e., a *state* or an *event* [11]. States, e.g., *be tall*, are homogeneous. Events may be *activities*, e.g., *walk in the park*, any part of which is also walking in the park, *achievements*, e.g., *win a race*, which is instantaneous, and results in a change of state, or *accomplishments*, e.g., *build a house*, which are characterized by a process and its culmination. (We do not consider *semelfactives* [9] for reasons of space.) Often, achievements and accomplishments, which have natural final endpoints, are called *telic* events and activities, which have arbitrary final endpoints only, *atelic* events.

Aspect is best defined as the viewpoint of a speaker towards a situation [9]. Two kinds of aspect are traditionally considered. The *perfective* describes a situation as a complete whole, e.g., *Al ate an apple*. The *imperfective* can be the *progressive* or the *habitual*; we consider only the former for reasons of space. A progressive sentence presents an event internally, e.g., *Al was eating an apple*. Another kind of aspect, the *neutral perfective*, has recently been defined [8]. It describes an event that has ended, but not necessarily at its natural endpoint e.g., *Al ate an apple (but not all of it)*. This aspect is essential in Japanese, Hindi,

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and Chinese, and is useful in giving the semantics of *for*-adverbials in English (see §4.3).

It is well-known in Linguistics that situation type and aspect are distinct concepts, the former referring to the intrinsic teleological structure of an event, the latter to a speaker's viewpoint of it. Situations are objective, but speakers choose an aspect according to what they wish to convey, and what their language allows. A particular situation may be viewed in a variety of ways depending on the aspect chosen. However, some recent analyses ignore this distinction, e.g., by identifying activities with the progressive, and accomplishments with the perfective [4, 1, 6]. This leads to unnatural analyses of terminated activities, e.g., *he walked in the park*, and ongoing accomplishments, e.g., *he was eating an apple*. This assumption also causes problems for temporal adverbials like *Al played the sonata for an hour*. A partial justification for assuming this correspondence might have been that the traditional aspects cannot account for all possible readings, but with the addition of the neutral perfective that is no longer the case. In our approach, temporal adverbials are taken to change the aspect, but not the situation type: this makes our analysis computationally perspicuous and yet, as we show, more accurate.

2.2 Algebraic Semantics

In algebraic semantics, *events* and *objects* are distinct sorts of entities, each structured as a join semi-lattice without a bottom element. $\sqcup$ is the operation of join, and $\sqsubseteq$ and $\sqsubset$ the corresponding relations of part and proper part, respectively. Thematic relations are defined as mappings of objects to events. The semantics of cumulative and quantized reference can be given in this framework. For example, both *beer* and *apples* are cumulative predicates, since beer combined with more beer is still beer and, adding more apples to apples yields apples. On the other hand, *a glass of beer* and *five apples* are quantized predicates. Suppose there are two distinct entities to which the predicate *a glass of beer* applies. This predicate then cannot apply to their join. No part of *five apples* is *five apples*. The definitions below are due to Krifka [2]. Note that $\mathsf{CUM}(P) \rightarrow \neg\mathsf{QUA}(P)$, if $|\text{domain}(P)| \geq 2$.

• **Cumulativity** is the property of atelic event predicates; i.e., CUM(*Al drank beer*).

$\forall P[\mathsf{CUM}(P) \leftrightarrow \forall x, y[P(x) \wedge P(y) \rightarrow P(x \sqcup y)]]$

• **Quantization** is the property of telic events; i.e., QUA(*Al ate an apple*).

$\forall P[\mathsf{QUA}(P) \leftrightarrow \forall x, y[P(x) \wedge P(y) \rightarrow y \not\sqsubset x]]$

An *event predicate*, i.e., a predicate computed from a clause that applies to events, is by default taken to apply to events in the perfective aspect. The progressive and neutral perfective aspects are defined as operators on event predicates. A given event predicate is transformed into another event predicate, such that the latter applies only to those events which correspond to the perfective events that the original predicate applies to, and which are, respectively, in the progressive or neutral perfective aspects. That is, if P applies to events in which Al (wholly) ate an apple, then $[\mathsf{PROG}(P)]$ applies to events that are subevents of his eating an apple and $[\mathsf{NEUT}(P)]$ applies to events that are subevents of his eating an apple, and at the end of which he was not eating an apple.

2.3 Properties of Thematic Relations

Thematic relations are homomorphisms from objects to events that preserve $\sqsubseteq$. Some properties, proposed by Krifka [3], are useful:

• **Uniqueness of objects**: R relates every event to a different object; e.g., the eating of an apple is related via the patient role to a specific apple. $\forall R[\mathsf{UNI\text{-}O}(R) \leftrightarrow \forall e, x, x'[R(e, x) \wedge R(e, x') \rightarrow x = x']]$

• **Mapping to objects**: R maps every subevent to a part of the object, e.g., every part of eating an apple involves eating a part of an apple. $\forall R[\mathsf{MAP\text{-}O}(R) \leftrightarrow \forall e, e', x[R(e, x) \wedge e' \sqsubseteq e \rightarrow \exists x'[x' \sqsubseteq x \wedge R(e', x')]]]$

• **Mapping to events**: R goes the other way; e.g., it maps every part of an apple to a part of the event of eating it. $\forall R[\mathsf{MAP\text{-}E}(R) \leftrightarrow \forall e, x, x'[R(e, x) \wedge x' \sqsubseteq x \rightarrow \exists e'[e' \sqsubseteq e \wedge R(e', x')]]]$

• **Graduality**: R is such that the object is subjected to the event gradually. For example, *writing a letter* or *eating an apple* affect their objects gradually, while *seeing a cat* or *finding a watch* do not. $\forall R[\mathsf{GRAD}(R) \leftrightarrow \mathsf{UNI\text{-}O}(R) \wedge \mathsf{MAP\text{-}O}(R) \wedge \mathsf{MAP\text{-}E}(R)]$

2.4 Lexical Entries

For each verb, we need its *argument structure*, which specifies its complements and adjuncts, and the properties that hold of its thematic relations. The relations GOAL, PATH, and PATIENT influence the situation type the most. We emphasize thematic relations, because previous approaches have not noted that complements and adjuncts behave differently. Consider the thematic relations of the verbs *walk* and *move*.

walk: ⟨AGENT, (GOAL)⟩ TEMP

move: ⟨AGENT, (PATIENT)⟩ GOAL TEMP

That is, *walk* requires an agent and can optionally have a goal complement and a temporal adjunct, while *move* requires an agent, but may have a complement patient, and goal and temporal adjuncts. We submit that complements affect the situation type of a clause, but adjuncts affect only its aspect; while *Al walked* is an activity, the complement GOAL *to his house* makes *Al walked to his house* an accomplishment. However, since *move* takes an adjunct GOAL, *Al moved hay to*

his barn is an activity—its situation type being determined by its patient *hay*, which is cumulative.

For predicates of interest to us, $\neg\mathsf{CUM}(P) \rightarrow \neg\mathsf{QUA}(P)$. Thus we can use just the feature $\pm$QUA. The entry for a verb also lists the features of the nominals it takes, and the properties of the resulting predicate. The entry also contains a lambda expression (see §3). The entry for a nominal specifies it as being + or −QUA. Depending on that, a bare nominal may or may not combine with determiners, numbers, and other quantifiers to give a noun phrase; e.g., *apple*, a quantized noun, can combine with a determiner, while *beer*, a cumulative noun cannot. Correspondingly, the entries for determiners, e.g., *an*, specify that they combine with a quantized noun to yield a quantized noun phrase. Rules of categorial grammar apply compositionally on the properties of different words to derive the properties of higher nodes.

3 Classifying Situation Types

Now we describe the procedure for determining the situation type of a sentence. As explained in §2.4, the reference type of a nominal can be determined from its head noun and determiners. We classify situation types and consider different kinds of verbs below. It is easy to see that accomplishments are gradual and quantized, activities are gradual and cumulative, and achievements are quantized and not gradual.

- **Activities:** [−QUA,+GRAD→ ACT]
- **Accomplishments:** [+QUA,+GRAD→ ACC]
- **Achievements:** [+QUA,−GRAD→ ACH]

Verbs such as *eat* and *drink* result in activities when combined with cumulative objects and in accomplishments when combined with quantized objects. When they have a direct object, their PATIENT relation is gradual; e.g., joining two events of *drinking beer* yields an event of *drinking beer*, i.e., the event predicate is cumulative. Also, the object is consumed gradually. The entry for *eat* is given below. The aspect of the resulting predicate is not specified in the citation form.

eat:(S[αQUA,+GRAD]/NP[AG])/NP[PAT,αQUA]

Verbs such as *walk* also yield activities with cumulative nouns and accomplishments with quantized nouns. However, these verbs can take a range of quantized nominals. In particular, they can take objects that have the thematic role of GOAL as in *Al walked to school* and result in accomplishments. This class of verbs can be specified as yielding an accomplishment with quantized patients and with thematic goals.

walk:(S[αQUA,+GRAD]/NP[AG])/NP[PAT,αQUA],
(S[+QUA,+GRAD]/NP[AG])/NP[GOAL]

Verbs such as *sleep* and *think* result in activities, irrespective of the reference type of their patient. Some verbs, e.g., *win*, always yield an achievement.

sleep: (S[−QUA,+GRAD]/NP[AG])/NP[TEMP]
win: (S[+QUA,−GRAD]/NP[AG])/NP[PAT]

Stativity is often indicated by the verb, which can be an existential verb, or a verb like *know* and *have*.

is: S[STATE]/NP[AG]
know: S[STATE]/NP[AG]/NP[PAT]

Computing the situation type is quite simple now. No special rules are needed; simple lambda conversion is sufficient. For details, see the diagram below.

ate; (S[αQUA,+GRAD,+PERF]/NP[AG])
/NP[PAT,αQUA];$\lambda e[eat(e)]$
an apple; NP[+QUA];
$\lambda P\lambda e\exists x[P(e) \wedge apple(x) \wedge PAT(e,x)]$
ate an apple; S[+QUA,+GRAD,+PERF]/NP[AG];
$\lambda e\exists x[eat(e) \wedge apple(x) \wedge PAT(e,x)]$
Al; NP[AG];
$\lambda P\lambda e\exists y[P(e) \wedge Al(y) \wedge AG(e,y) \wedge PAT(e,x)]$
Al ate an apple; S[+QUA,+GRAD,+PERF];
$\lambda e\exists x,y[eat(e) \wedge apple(x) \wedge Al(y) \wedge AG(e,y) \wedge PAT(e,x)]$

4 Temporal Structure of Events

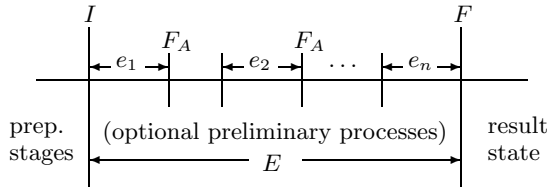
We now describe the temporal structure of events of different types. This structure is required for further processing, e.g., in inferring the relative temporal locations of events in a discourse. It is thus more fine-grained than the simple algebraic analysis that was needed up to now.

4.1 Accomplishments and Activities

Accomplishments and activities share the property of graduality. Both are comprised of subevents. Consider the accomplishment, *build the 39th street bridge*. Conceptually, the building of a bridge involves various subevents, e.g., laying the foundation, installing pillars, etc. Accomplishments can be described as a sum of their subevents (since the property MAP-E holds of them). Often there are preparatory stages associated with an accomplishment. For example, the preparatory stage of writing a paper may include having an idea and learning to use an editor. However, the event of learning to use an editor does not have the property MAP-O, with respect to the paper, since parts of it cannot be mapped on to parts of the paper. Thus it is not a proper part of the accomplishment, merely a preparatory stage for it. A resultant state may also be associated with accomplishments, here, the state of having written a paper.

The figure below describes an event. I is its initial endpoint and F its final endpoint. Telic events end naturally at F; i.e., for them $F = F_N$. Atelic events end only arbitrarily; i.e., for them $F = F_A$.

The e_i are the *subevents* of E. For achievements, the proper initial endpoint, $I_P = F_N$. However, as described in §4.2, they may optionally involve preliminary processes from I to F_N.



The aspect of a clause determines the temporal schema to be introduced into the temporal representation for the current discourse. The perfective, which is the default aspect (§3), causes the entire schema to be introduced. The progressive and the neutral perfective introduce only some subevents of the schema. The progressive does not imply that the event ended and presents it internally. Consider the sentence, *Al was eating an apple*. This sentence is true of all the eating subevents; i.e., the perfective implies the progressive before F. However, the progressive does not imply the perfective. We cannot conclude *Al ate an apple* from *Al was eating an apple*. The neutral perfective includes the join of subevents till the arbitrary final endpoint and implies that the event did not continue to be completed. For example, *Al ate an apple for ten minutes* is in the neutral perfective. Its temporal schema includes the join of the subevents such that their duration adds up to ten minutes. A crucial distinction between the neutral perfective and the progressive is that the progressive can be used for any part of the event, but the neutral perfective applies only to those parts that have an associated F_A.

Using the rules of §3, the *when*-clause in discourse 1 is assigned the situation type of accomplishment and the perfective aspect. Therefore, its entire schema is introduced into the temporal representation for the discourse. The succeeding sentences are then mapped on to the available subevents in the schema.

1. When they built the 39th street bridge, ...
   (a) A local architect drew up the plans.
   (b) They used the best materials.
   (c) They solved most of the traffic problems.

However, if the *when*-clause is in the progressive, as in 2, then only the subschema that lies between the initial endpoint and the final endpoint is included. As a result, subsequent clauses such as 1(a)–(c) must be located within that interval.

2. When they were building the 39th street bridge

From discourse 1, we can conclude (using rules proposed by Dowty and adapted by [10]) that the drawing up of the plans occurred before the building, and the solving of the problems after. But if the discourse begins with 2, the drawing up of the plans and the solving of the traffic problems overlap with the building of the bridge; they cannot precede or follow it.

4.2 Achievements

Achievements are instantaneous; i.e., their thematic relations are −GRAD. Though all achievements do not require a preparatory stage, some achievements do require that some activity take place before the actual event (i.e., before F_N). For example, *Al won a race* requires that the participant do some running before he can win the race. However, a proper subevent of winning the race cannot be called *winning the race* (it could only be referred to as *running in the race*).

Here, the only final endpoint possible is the natural final enpoint, F_N. The subevents that precede F_N are called preliminary processes. The subevents preceding F_N are not associated with arbitrary endpoints, because achievements are −GRAD. Consequently, the neutral perfective does not apply to achievements, since it can only focus on an F_A. The progressive includes only the preliminary processes of the event.

Note that we distinguish between preparatory stages and preliminary processes. Interestingly, this distinction is not only crucial from the temporal standpoint, but also principled from the linguistic standpoint. In 3 below, the initial clause is in the perfective; in 4, it is in the progressive.

3. When Al won the race, he took steroids.

4. When Al was winning the race, he took steroids.

The interpretation of 3 is that Al took the steroids before the actual running commenced, i.e., during its preparatory stages. In 4, however, the taking of the steroids is forced to have taken place during the running because the preparatory stages are not introduced into the discourse by the progressive. The pragmatic rule of *enablement* cannot push the taking of the steroid before the running because of restrictions imposed by the progressive. This is important because the notions of preparatory stages and preliminary processes have been used almost synonymously in the literature [4]. No semantic or pragmatic justification for these definitions has been available.

4.3 Temporal Adverbials

It is often claimed that *in*-adverbials change the situation type of an achievement to an accomplishment; e.g., that in 5, the *in*-adverbial adds preparatory stages to the event of reaching the top and thereby converts an achievement into an accomplishment [4]. Therefore, sentence 5 must have the property +GRAD. which includes the properties of mapping events to objects or vice versa (see 2.3). Parts of reaching the

top in two days are not the reaching in two days of "parts of the top." Thus, accomplishments and *in*-adverbialized achievements are semantically distinct.

5. Laura reached the top in two days

In-adverbials add duration to an event. In the case of achievements, they add duration to its preliminary processes, and force it to be non-empty. For this reason, they are not felicitous with "unexpected" achievements like *find a dollar*, which do not include preliminary processes (*Al was finding a dollar).

Achievements in the progressive have to be interpreted as loaded, or after the fact, descriptions. For example, sentence 6 represents the speaker's subjective viewpoint that the event of Mary's reaching the top took place; it then allows reference to its preparatory stages.

6. When Mary was reaching the top, she stumbled

Formally, an *in*-adverbial converts a telic sentential predicate into a durative (and telic) one. Since accomplishments are durative, they are unchanged; however, achievements become +DUR. In each case, the length of the duration is fixed by the adverbial.

$(\mathrm{S}[+\mathrm{QUA},\alpha\mathrm{GRAD},+\mathrm{DUR}]/\mathrm{S}[+\mathrm{QUA},\alpha\mathrm{GRAD}])/\mathrm{NP}[+\mathrm{TEMP}]$
$\lambda Q\lambda P\lambda e\exists t[P(e) \wedge \mathsf{DURATION}(e,t) \wedge Q(t)]$

Traditionally, *for*-adverbials are said to convert activities into accomplishments and accomplishments into activities; e.g., sentence 7 is seen as an accomplishment [9], which implies that it must have a natural endpoint. However, the endpoint in 7 is not natural—it could easily have been *half an hour* or *two hours*. Therefore, characterizing sentence 7 as an accomplishment is not quite correct.

7. Al walked in the park for an hour

The claim that *for*-adverbials change an accomplishment into an activity implies that, while 8 is an accomplishment, 9 is an activity. Sentence 8 means that Sue played the sonata till its (natural) end; however, sentence 9 suggests that she stopped at an arbitrary point. If sentence 9 really was an activity, then it would also imply that the event did not continue. However, you can easily override this implicature by adding: "and then she played it some more."

8. Sue played the sonata

9. Sue played the sonata for a few minutes

In our approach *for*-adverbials change the aspect of both activities and accomplishments to the *neutral perfective*, which was motivated in §2.1. This uniformly explains the adjunction of a *for*-adverbial to both activities and accomplishments: the former are assigned an arbitrary endpoint at a specific duration; the latter are assigned an arbitrary endpoint at a specific duration that *replaces* their natural endpoint.

$(\mathrm{S}[\alpha\mathrm{QUA},+\mathrm{GRAD},+\mathrm{NEUT}]/\mathrm{S}[\alpha\mathrm{QUA},+\mathrm{GRAD}])$
$/\mathrm{NP}[+\mathrm{TEMP}]$
$\lambda Q\lambda P\lambda e\exists t[[\mathsf{NEUT}(P)](e) \wedge \mathsf{DURATION}(e,t) \wedge Q(t)]$

5 Conclusions

We presented a general approach to giving the temporal semantics of sentences that takes care of both their situation type and aspect. This approach presents systematic rules, along with lexical entries, that may be used to compute the temporal structure of complex sentences. We have tried to preserve linguistically important distinctions in our analysis to make it apply to a number of phenomena concerning events. We proposed a general schema representation for events, each of whose components is intuitively motivated and plays some role in the semantics of different sentences. Thus our approach has the advantages of being theoretically well-founded, declarative, and of wide applicability to a number of natural languages.

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