Does information *flow* in event structures?

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1. How do we want to represent temporal and spatial information given in natural language sentences? So, if someone utters:

(1) Bob has beaten Joe at 5.00 in the living room.

where would we store the information that what happened did happen at 5.00, and in the living room? The following view has been found useful: Temporal and spatial information is linked to the verb via an event argument which the verb takes in addition to the nominal arguments that are realized, obligatorily or facultatively, in the sentence. Thus we would represent, for example, the verb "beat" as a ternary relation between an agent, a patient, and an event:

(2) $BEAT(a, b, e)$

And now the information that some event in question happened "at 5 o'clock", this is the idea, this information will be predicated on the event argument. How exactly? It has been suggested that events themselves might be reconstructed as four-dimensional subsets of time and space. According to this view, an event of Bob beating Joe would be something like a little movie in time and space, and one would be able to read off from this very object the time and place where it took place. However, this notion of "event" can easily been shown to be too coarse grained in applications. I have argued elsewhere that events should be viewed as primitive objects that are not reconstructable out of other things. But on the other hand it is clear that events should be linked somehow to the time and space where they occur. Thus we assume that there is a function f_{man} which maps each event onto its spatio-temporal manifestation, that is, a subset of the four-dimensional space of times and spaces. So the above event e of Bob beating Joe, instead of being a little movie itself, will be mapped onto a little movie $f_{man}(e)$. By looking at this object, we will be able to decide whether its projection onto the time axis lies in an interval around 5 o'clock, and whether the place which it covers through time lies in the space called "the living room". As I will be mainly concerned with temporal information in the following, I want to make use of a second function f_{time} from the domain of events into the domain of sets of points of time. The function f_{time} can be defined as the composition of f_{man} and the projection function onto the time axis. So

(3) $f_{time}(e) = I$ iff e happens exactly during the time I.

Now temporal (and spatial) information about an event can ultimately be viewed as being computed in using these functions. For example, if we want to represent that the above event took place at 5 o'clock, we take

(4) $FIVE(e)$

as a shorthand for the more precise

(5) $t = f_{time}(e) \wedge t \subseteq [5 - \varepsilon, 5 + \varepsilon]$ for an appropriately small value ε.

Reasoning about events taking place in time thus has become calculating in the real numbers. In the same way – although more complicated, because places are not so "arithmetic" as times – reasoning about places is translated into reasoning in the three-dimensional euclidian space.

2. Cases where we want to make use of complex events.
Look at the following sentence:

(6) From 2.00 to 4.00, Jim watered the tulips and had a nap.

How do we represent this information? Evidently there are two events involved, e_1: Jim watering the tulips, and e_2: Jim having a nap. Will it be enough to say that (6) means:

(7) $\exists e_1 \exists e_2 (WATER(J, TULIPS, e_1) \wedge NAP(J, e_2) \wedge f_{time}(e_1) \subseteq [2.00; 4.00] \wedge f_{time}(e_2) \subseteq [2.00; 4.00])$

Formula (7) represents (6) along the following line: "The time between 2 and 4 o'clock is, so to speak, the temporal frame we are living in. Now we are told that *sometime* between 2 and 4, e_1 took place, and also *sometime* between 2 and 4, e_2 took place." I think this is what would be expressed by a sentence that explicitely makes use of the "between 2 and 4"-construction:

(8) (Sometime) Between 2.00 and 5.00, Jim watered the tulips.

The PP "from x to y" however is to be read in a more rigid way. It means that what is reported to have happened "from x to y" indeed covered the whole interval between x o'clock and y o'clock (within a reasonable standard of preciseness). Thus we would not want to find that the following sentences turned out to be logical consequences of (6):

(9) From 2.00 to 4.00, Jim had a nap.

(10) From 2.00 to 4.00, Jim watered the tulips.

However, this is what a representation like (7) will predict. So we will have to think about a more sophisticated way to represent (6). It seems that what is temporally located in the intervall [2.00;4.00] in sentence (6) should rather be some complex event built from e_1 and e_2 as parts: $e^* = e_1 \oplus e_2$. What (6) conveys now will not be the information that certain events happened *within* the time from 2.00 to 4.00, but that the time of the complex event was *exactly* the interval [2.00;4.00]:

(11) $\exists e_1 e_2 e^* (WATER(J, TULIPS, e_1) \wedge NAP(J, e_2) \wedge e^* = e_1 \oplus e_2 \wedge$
$f_{time}(e^*) = [2.00; 4.00])$

Intuitively we have some idea about what a "complex event" made up from two simpler events might look like. To make the above idea precise, however, it will be necessary to have a closer look at the event ontology and the operations that are defined there. This is what we will do in the sequel. Of course this is not the first time that the use of complex events was suggested. Also the connection between complex events and their spatio-temporal manifestations is rather wellunderstood. Not surprisingly, the idea is the following: If we have two events e_1 and e_2 and form their join $e^* = e_1 \oplus e_2$ the manifestation functions should be homomorphisms from $< D_E, \oplus >$ to $< A, \cup >$, where A is the power set of four dimensional spaces:

(12) $f_{man}(e_1 \oplus e_2) = f_{man}(e_1) \cup f_man(e_2)$ (= per definition)

(13) $f_{time}(e_1 \oplus e_2) = f_{time}(e_1) \cup f_{time}(e_2)$ (derived from (12))

Assuming this, we will be able to conclude in the above example that

(9') *Between* 2.00 and 4.00, Jim had a nap.

(10') *Between* 2.00 and 4.00, Jim watered the tulips.

because the temporal location of the complex event e^* will be the union of the times of e_1 and e_2, but hopefully we are saved from (3), (4). Are we? Well, this still depends on what is true for e^*. The general question we have to adress is the following:

(**) Assume P holds in e_1 and Q in e_2 – what do we know about $e_1 \oplus e_2$?

Not all options of how e^* should behave are undangerous for our case. In the next sections we will see some answers to (**) from the literature, and what their consequences with respect to the above example will be. We will see that not everything which sounds plausible is also of use when it comes to linguistic applications. This will lead to my own answer to (**).

3. Generally, we know various sorts of positive answers to the question:

(**) Assume P holds in e_1 and Q in e_2 – what do we know about $e_1 \oplus e_2$?

The first sort of answer comes from aspectual theory and covers cases where P and Q are identical, and denote some process verbal predicate. In this case, the complex event will also be a P-event. So for example a running e_1 plus another running e_2 is again an event of running e^*. This observation about of process-events, in contrast to accomplishment-events, was indeed one of the reasons to think about the existence of complex events at all, because this construct made it possible to formulate this kind of generalization. I do not want to discuss aspectual questions in detail. But clearly the generalization found there will only answer few instances of question (**).

The second sort of answer is like a generalization of this case and was motivated by the study of plurality in natural language. There people make claimes about cases where $P = Q =$ some n-ary predicate that relates e_1 and e_2 with individuals $a_1 ... a_n$ and $b_1 ... b_n$ resp. With $a_i \oplus b_i$ being the plural join of the individuals in question, one assumes that

(14) If $P(a_1 ... a_n, e_1)$ and $P(b_1 ... b_n, e_2)$ then also $= P^*(a_1 \oplus b_1, ..., a_n \oplus b_n, e_1 \oplus e_2)$

(where P^* is the plural extension of the predicate P). To see an example: If Jim eats an apple a_1 in an event e_1, and Jim eats another apple a_2 in e_2, then the *EAT**-relation will hold between Jim (who is $J \oplus J$), the sum of apples $a_1 \oplus a_2$, and the sum of events $e_1 \oplus e_2$:

(15) $EAT(J, a_1, e_1) \wedge EAT(J, a_2, e_2) \rightarrow EAT(J, a_1 \oplus a_2, e_1 \oplus e_2)$

Again we find that this is not generally answering (**), but just in certain cases. No claim about joins of events is made which are not of the same shape; like: both being an eating, for instance. Both, theories about aspect, and theories about plural, rather make statements about the properties of certain predicates P rather than about joins of events. What we are in need of would be a general theory about event mereology.

4. A general answer

Let us come back to our initial example. We had two events, e_1 where Jim waters the tulips, and e_2 where Jim takes a nap. If we were asked about the nature of some complex event formed of these two, $e_1 \oplus e_2$, we would probably want to describe it as an event of *both* Jim watering the tulips and Jim having a nap:

(16) $WATER(J, T, e_1)$
$NAP(J, e_2)$
$WATER(J, T, e_1 \oplus e_2) \wedge NAP(J, e_1 \oplus e_2)$

Generalizing this idea, we can assume that complex events just collect all the information which is given about the simpler events below them. Such a principle is wellknown as "persistency principle":

(PP) If $P(e_1)$ and $Q(e_2)$ then
$P(e_1 \oplus e_2) \wedge Q(e_1 \oplus e_2)$

Note however that (PP) again is too general as is stands. It seems that not all objects of type $< E, t >$ (sets of events; I assume an extra type E for events, apart from e for individuals and t for truth values) can stand for P and Q. Look at the example again. Not only was e_1 an event of Jim watering the tulips and e_2 an event of Jim taking a nap, but probably also:

(17) $\neg \mathit{WATER}(J, T, e_2) \wedge \neg \mathit{NAP}(J, e_1)$

If both of these properties were to persist up to $e^* = e_1 \oplus e_2$, we would end with

(18) $\neg \mathit{WATER}(J, T, e^*) \wedge \mathit{WATER}(J, T, e^*)$
$\wedge \neg \mathit{NAP}(J, e^*) \wedge \mathit{NAP}(J, e^*)$

and in whatever sense this might be possible, it certainly won't be in first order logic.

To circumvent this sort of inconsistencies, we can in principle follow two strategies. One natural way out would be this: Well, we say, well, look at e_2. This was an event of Jim having a nap. This information is the relevant information about e_2. This is how we would refer to e_2, or describe it. Other formulae might be true of e_2 as well. It is not an event of Jim watering the tulips. It is not an event of raining in Ottawa. It is an event which has the property $\lambda e.e = e_2$. But all these are irrelevant properties of e_2. So let us hope that we can divide the properties of events into relevant properties and irrelevant properties. Assume that only for the relevant properties, principle (PP) holds. And hope, again, that this will circumvent formulae like (18) above.

The division of properties of events into "relevant" properties and "irrelevant" properties can be traced ever since people started using the term "event". The relevant properties also sometimes are called "event types", and often are given an extra status in the event ontology – for example, by representing them twice, once in the general domain $D_{<E,t>}$ and once again in a domain of event types (analogous considerations have been made for situations). But although we have no problems to accept, on intuitive grounds, that the description of e_2 as "Jim having a nap" is more relevant than a description like "not: Paul climbing the Nanga Parbat", it would be comforting to have a general criterion to separate "relevant" from "irrelevant" information. Moreover it is astonishing that no such asymmetry has ever been necessary for individuals. So we can keep in mind that (PP) plus the relevant/irrelevant-distinction could be a way to shape event mereologies, with still some points unsettled.

Another way to cope with the above inconsistencies would be, to decide that event mereologies have nothing to do with first order logic, at all. This line has been investigated most thoroughly by P.Lasersohn (Lasersohn(88), Lasersohn(92)). He develops model structures where an algebra of events and an algebra of propositions are linked by a support relation $\models$, and further axioms and assumptions restrict the shape of possible models. Thus he can even construct complex events from events where outright incompatible things happen, like John being hot and John being cold, or being wet and not wet.

This way to proceed comes along with a less-than-boolean logic on the propositions. Once an event structure is defined, we would have to re-study the simplest logical laws guiding our propositional algebra. It is thereby suggested that we really reason in a non-boolean way – either in general, or just when it comes to deal with events. Apart from being inconvenient in applications, this contradicts in a way the intentions of Davidson, who introduced the term "event" just to be able to *remain* within first order logic when it comes to the representation of temporal information, adverbial information, etc.

My personal suspicion is that both approaches will turn out to be intertranslatable in the end. I have given a characterization result for Lasersohn-structures elsewhere, where it turns out that they are still reconstructable by using certain sets of events as representing propositions (– again not all, as was the case for event types). The discussion of these results would lead us too far astray here. We can keep in mind that there are alternative approaches to make (PP) work, which are more complicated than the one I sketched above, but which might turn out to be not so very different in the end.

Let us believe for the moment that (PP) is indeed what we want, and let us apply it to our example. How can we take profit from persistency when it comes to the representation of sentences of natural language? Look at sentence (6) again.

(6) From 2.00 to 4.00, Jim watered the tulips and had a nap.

Assuming (PP), we can represent it as

(19) $\exists e(\mathit{WATER}(J, T, e) \wedge \mathit{NAP}(J, e) \wedge [2.00; 4.00](e))$

because an event of the indicated kind will indeed exist in the model. But unfortunately the same event will also prove the truth of the following existential statements:

(20) $\exists e(\mathit{NAP}(J, e) \wedge [2.00; 4.00](e)) \wedge \exists e(\mathit{WATER}(J, T, e) \wedge [2.00; 4.00](e))$

which will in analogy to the first example be the representation of the sentences

(21) From 2.00 to 4.00, Jim had a nap.
From 2.00 to 4.00, Jim watered the tulips.

However we started from the observation that the latter two should not come out as logical consequences from sentence (6). Thus our tentative representation was too simple. Ok, you say, ok. Look at the complex event $e_1 \oplus e_2$. The description underlying the representation of sentence (6) fits $e_1 \oplus e_2$ well in that it seems to tell everything about $e_1 \oplus e_2$. The two latter sentences, although describing events among which $e_1 \oplus e_2$ can be found, would just by accident be true of $e_1 \oplus e_2$, so to speak. It is true that Jim has a nap in $e_1 \oplus e_2$. But only because there was some event e_2 below where Jim *really* takes a nap, and nothing else happens. In $e_1 \oplus e_2$ Jim has a nap, but more things are going on. $e_1 \oplus e_2$ is not the kind of event sentences refer to which tell us that "Jim has a nap" and nothing else. Thus we can claim that (6) should indeed be represented as:

(22) $\exists e(WATER(J,T,e) \wedge NAP(J,e) \wedge [2.00;4.00](e)$
$\wedge\ \forall \mathbf{Q}(\mathbf{Q}(\mathbf{e}) \rightarrow \forall \mathbf{e}'(\mathbf{WATER}(\mathbf{J},\mathbf{T},\mathbf{e}') \wedge \mathbf{NAP}(\mathbf{J},\mathbf{e}')$
$\wedge\ [\mathbf{2.00};\mathbf{4.00}](\mathbf{e}') \rightarrow \mathbf{Q}(\mathbf{e}')))$

The boldface part can be read as one possibility to spell out the idea that "nothing else happened" in the event in question. Do not pin me down on this. Recipies like that have been suggested by Lasersohn, but also by Kratzer in her situation models, where also persistency is one guideline for the flow of information and where also (not surprisingly?) the need arises to distinguish situations "relevantly" matching some description from situations "accidentially" matching some description [1]. To mention but one problem: the universal quantification $\forall Q$ will surely have to be restricted to less than the full set of sets of events, again.

If we trust in the idea however that we will find *some* way to formalize the "and nothing else happened"-part, we can again look at our examples and indeed: we do better. The crucial sentence

(10) From 2.00 to 4.00, Jim had a nap.

will now come out as:

(23) $\exists e(NAP(J,e) \wedge [2.00;4.00](e)$
$\wedge\ \forall \mathbf{Q}(\mathbf{Q}(\mathbf{e}) \rightarrow \forall \mathbf{e}'(\mathbf{NAP}(\mathbf{J},\mathbf{e}') \wedge [\mathbf{2.00};\mathbf{4.00}](\mathbf{e}') \rightarrow \mathbf{Q}(\mathbf{e}')))$

In the model structure underlying our considerations, no such event will exist. There will be an event which lasts from 2 o'clock to 4 o'clock and where Jim has a nap. But there other things are true (Jim watering the flowers, for instance), and thus the boldface part will be violated. The event where Jim has a nap and nothing else, in turn, will probably not have lasted from 2 to 4, because Jim still had had time to water the tulips. Thus the "nothing else happened"-strategy for representation of natural language sentences, together with (PP), seems to fit our sentences.

Does it? Let me turn to another case of unwanted indistinguishability. Assume that from 2 o'clock to 4 o'clock the following happened: Jim watered the tulips and *carefully* had an ice cream. Assume further that manner adverbs are also predicating over events (plus agents, maybe). So this is what will be true:

[1] Events and situations, at least under certain spellouts, have much in common – even that much that people have suggested to do with one term only. There are substantial differences however, both in the intuitions guiding the design of the formal spellout of the two notions, and in their applications.

(24) There are events e_1 and e_2 such that
$WATER(J, T, e_1)$
$\exists x(ICE\text{-}CREAM(x) \wedge EAT(J, x, e_2) \wedge CAREFUL(J, e_2))$

Due to persistency, all these informations will carry up to the complex event $e_1 \oplus e_2$. So we will have

(25) $WATER(J, T, e_1 \oplus e_2) \wedge \exists x(ICE\text{-}CREAM(x) \wedge EAT(J, x, e_1 \oplus e_2) \wedge CAREFUL(J, e_1 \oplus e_2))$

Refering to the complex event $e_1 \oplus e_2$, this will be the description that matches. But now look: the same situation (logically) arises in the following twin case:

(26) From 2.00 to 4.00, Jim carefully watered the tulips and had an ice cream.

We will thus find:

(27) There are events e_1 and e_2 such that
$WATER(J, T, e_1) \wedge CAREFUL(J, e_1) \wedge \exists x(ICE\text{-}CREAM(x) \wedge EAT(J, x, e_2))$ and thus
$WATER(J, T, e_1 \oplus e_2) \wedge \exists x(ICE\text{-}CREAM(x) \wedge EAT(J, x, e_1 \oplus e_2) \wedge CAREFUL(J, e_1 \oplus e_2))$

What we find here is that our representation of sentences like (26) and its twin above makes them *logically equivalent*. Both would be represented as asserting: There is an event, where Jim waters the tulips, where Jim eats an ice-cream, where Jim is careful and where nothing else happens. This is too sloppy, of course. We understand these sentences as *not* equivalent. Thus our representation again does not match the data.

We found the following up to now: When dealing with exact temporal information, we are in need of complex eventualities. To get control over the models including an event mereology, we asked question (**) about the properties of complex events. We found that the principle of persistency was an intuitively satisfying answer. We have seen that certain details are still unsettled, once we committ ourselves to (PP), but that persistency together with the recipy of "nothing else happens" as a silent additional ingredient of the way in which natural language sentences talk about events gave satisfying results. But then even this more elaborate strategy got stuck again. It is time for a radical change of perspective.

5. There was one tacit assumption we have kept through all the above considerations, and I want to suggest that this is the crucial point. When we were talking about some complex event where "Jim watered the tulips and had a nap", we never doubted that the word "and" in this sentence was standing for the boolean connective "$\wedge$ " (or one of its type shifted mates). It is wellknown however that other uses of the word "and" exist in natural language. Let me

give some examples: If we look at an ontology of individuals and their plural sums, as studied by Link, Loenning and others we know that we can refer to the plural object "Tom and Jerry". Given that T represents Tom, and J represents Jerry, "Tom and Jerry" will be refering to the plural sum of these:

(28) Tom and Jerry $\rightarrow T \oplus J$

The plural sum $T \oplus J$ will not be "Tom" now, although it is "Tom *and* Jerry". Tom is part of it, but is not identical to it. In the same way, $T \oplus J$ is not Jerry, although being "Tom and Jerry". Now, you might think that things are always different for proper names, but the same sort of example can be constructed using real predication. Assume that we have a plural object X consisting of a set x of men, and a set y of women:

(29) $X = x \oplus y$
$MEN(x) \wedge WOMEN(y)$

Thus X is a group of men and women. Nevertheless we would not claim that X is a group of women, although part of it is a group of women. Nor will we claim that X is a set of men (although some grammars work on that basis) – although X is a set of men *and* women. A final case is the wellknown example of the dog Fido. Fido is black and white [2]. Would we therefore claim that Fido is a black dog? No, we would not. *Parts* of Fido are black, where parts in some relevant sense are refered to, and also parts of Fido are white. But Fido himself is black and white in a sense different from being black and being white.

I want to suggest that also in the descriptions of complex events as "being an event of A and B ", the word "and" is used in this non-boolean sense. "A and B" will mean "being composed of an A-part and a B-part". Let me show how this idea can be formalized.

6. I want to introduce and study a new operation that will serve to represent the English word "and" and its counterparts in other languages. With this operation, an event ontology with joinable events will be constructable.

Assume that we live in a type theoretic language $\mathcal{L}$ over the three simple types e, E, and t. I take E to stand for the type "event", while e and t are individuals and truth values, as usual. Each model for $\mathcal{L}$ will then have a domain of events, D_E. On D_E a join operation $\oplus$ is to be defined, that is, $\oplus$ is a constant of type $< E, < E, E >>$. Corresponding to $\oplus$ we have a partial ordering $\leq$ on D_E such that for all e, e' in D_E: $e \leq e'$ iff $e \oplus e' = e'$. I want to assume for $\oplus$ and $\leq$ the sort of axioms that are also used to characterize a Link style plural ontology. Thus we might require that for all events e, $e \oplus e = e$ (idempotence of $\oplus$), that for all events $e \oplus e' = e' \oplus e$ (commutativity), that for all events $e \oplus (e' \oplus e'') = (e \oplus e') \oplus e''$ (associativity), that relative complements do exist, etc. Note that I do not assume any sort of relation between "propositions"

[2]Fido is *always* black and white. This is one of the analytic truths of life, just as Sally will always be crossing the channel.

and events. Many authors assume that some "holds-in"-relation $\models$ is available, and shape the event lattice in part by translating properties of the more or less boolean algebra of propositions into the event lattice. Nothing like this is to be the case here. Events are just like other individuals with a part-whole-relation. Predicates are to take them as arguments in the same way as they take individuals of type e. Link [1991] discusses axioms for a plural ontology on the domain of individuals. Our event domain $< D_E, \oplus, \leq >$ can be assumed to look much like these. I am aware that at least the assumption that the join of events is commutative has been attacked by various authors (N. Asher, for example, Asher[93]). I will come back to this issue below.

The new assumption we will make here is the following: We moreover have a constant $\oplus^*$ which operates on sets of events. Thus $\oplus^*$ is a constant of type $<< E, t >, << E, t >, < E, t >>>$. I will generally use e, e', e_i for events and R, S, Q for sets of events, and will thus omit omit the indices (*) on the operations. The operation $\oplus$ which operates on set of events (that is: $\oplus^*$) is to be defined in the following way:

(30) $\forall P \forall Q \forall e (P \oplus Q(e) \leftrightarrow \exists e_1 \exists e_2 (P(e_1) \wedge Q(e_2) \wedge e = e_1 \oplus e_2))$

The idea now is that this operation $\oplus$ is exactly the sort of "and" that we use when we want to say that in some event e, both P "and" Q happened. Let us look at an example. Let *DANCE* and *LAUGH* be constants in $\mathcal{L}$ of type $< e, < E, t >>$ and let J and L be individual constants. So $DANCE(J)$ and $LAUGH(L)$ are of type $< E, t >$, that is, denote sets of events. Assume that in some model for $\mathcal{L}$, there are events e^* and e in D_E such that

(31) $e^* \in DANCE(J)$ and $e \in LAUGH(L)$

Thus we will have that

(32) $(e^* \oplus e) \in (DANCE(J) \oplus LAUGH(L))$

Note that the models of $\mathcal{L}$ that will serve to represent sentences of English (for example) are meant so as to be *not* persistent in the sense used in Lasersohn: So $e^* \oplus e$ is not thought to be in $DANCE(J)$ and not in $LAUGH(L)$ either.

(33) $e^* \oplus e \in \neg DANCE(J)$ and $e^* \oplus e \in \neg LAUGH(L)$

Only the "atomic" events at the bottom of the event ontology are "dancings", "laughings", "taking a bath", "drinking beer" etc. If an event splits up into subevents of the same kind, like for instance "taking a bath", then we will allow for subparts and superevents to all be in the extension of "taking a bath" of course, so no "atomicity" in the strict sense is required. But as soon as other events with other properties come in, the complex thing in general has neither of the simpler properties. Positive information is only available for simple events, generally. As for complex events, we only require that all of them have positive *complex* properties. This does not exclude, of course, that *contingently* they might also have simple properties, but this will then be world knowledge and not something required by the logical structure. So we may well have, for example, that an event e is the join of an event e_1 of Jim batting the fat, an event e_2 of Jim adding sugar to the fat, an event e_3 of Jim mixing sugar and fat, ...an event e_k of Jim taking the baked dough out of the oven. Now e has the complex property: $BAT(FAT, JIM) \oplus ADD(SUGAR, JIM) \oplus ... \oplus TAKE\text{-}OUT\text{-}OF\text{-}OVEN(DOUGH, JIM)$ but moreover e might have the simpler property $BAKE(CAKE, JIM)$. This simpler property is not identical to the complex one, of course. Although $BAKE(CAKE, JIM)$ is a subset of $BAT(FAT, JIM) \oplus ADD(SUGAR, JIM) \oplus ... \oplus TAKE\text{-}OUT\text{-}OF\text{-}OVEN(DOUGH, JIM)$, the converse is not true. As soon as there are two cakes baked by Jim, for example, we may join the components of the two bakings freely and will get another event of the complex form, which however is not a baking of a cake. – Let us come back to the initial example. Assume that e^* and e are events where only one of the two formulae in question are true, respectively, that is:

(34) $\neg LAUGH(L)(e^*)$ and $\neg DANCE(J)(e)$

What will follow from this? Remember that this was the point where only one of these two informations could persist, if not e was to be in P and also not in P, at the same time (assuming persistency). For us, the negated items will lead to:

(35) $e^* \oplus e \in (\neg DANCE(J) \oplus \neg LAUGH(L))$

This says that $e^* \oplus e$ consists of an event which is not in $DANCE(J)$ and an event which is not in $LAUGH(L)$, which is certainly true. Maybe one has the feeling that this is not how one would want to characterize $e^* \oplus e$. I would say that we probably never will refer to $e^* \oplus e$ with natural language by saying that it was a non-$DANCE(J)$ and a non-$LAUGH(L)$. But this is a linguistic fact, not one that has to do with the logics of events.

If we replace the constants J and L by a variable x of type e, the terms $DANCE(x)$ and $LAUGH(x)$ are again of type $< E, t >$. The expression

(36) $DANCE(x) \oplus LAUGH(x)$

will denote, in a model, relative to a variable assignment g, the set of events e such that there are subevents e', e'' of e such that e' is in $[[DANCE(x)]]^g$, e'' is in $[[LAUGH(x)]]^g$ and e is the join of these two. If $\mathcal{L}$ is to be a language with lambda abstraction, we can now go to the term

(37) $\lambda x(DANCE(x) \oplus LAUGH(x))$

and thus get an expression of type $< e, < E, t >>$. If we would like, we could thus generalize the join operation $\oplus$ on sets of events to all n-ary relations between individuals and an event. To keep matters simpler, I will refrain from this for the moment. Let me give some properties of the join operation which can easily be proved:

1. $\oplus$ on $D_{<E,t>}$ is commutative and associative:
Let R, Q, S be terms of type $< E, t >$ and $\mathcal{M}$ a model of $\mathcal{L}$. Now

   (a) $e \in R \oplus S$ iff
   there are e_1, e_2 such that $e = e_1 \oplus e_2$ and $e_1 \in R, e_2 \in S$ iff ($\oplus$ on events is commutative)
   there are e_1, e_2 such that $e = e_2 \oplus e_1$ and $e_1 \in R, e_2 \in S$ iff
   $e \in S \oplus R$

   (b) in the same way.

2. In general, $\oplus$ on $D_{<E,t>}$ is not idempotent. Let R be a constant of type $< E, t >$ and $\mathcal{M}$ a model of $\mathcal{L}$ where R is interpreted such, that there are events e, e' in $[[R]]$ but $e \oplus e'$ is not in $[[R]]$. This is an example where $R \oplus R \neq R$.

3. There are no terms Q of type $< E, t >$ such that for some event in some model, we would be able to derive that e is in Q and e is in $\neg Q$. (The definition of $\oplus$ is consistent.)

4. If in a model for some terms Q and S and event e we find that $Q(e) \wedge S(e)$ is true, then also $Q \oplus S(e)$ holds, but NOT vice versa!

5. How does the join interact with set union? If for some sets of events A, B we have that $A = A_1 \cup A_2$ and $B = B_1 \cup B_2$ then we have:

$$A \oplus B = A_1 \oplus B_1 \cup A_1 \oplus B_2 \cup A_2 \oplus B_1 \cup A_2 \oplus B_2$$

6. No de Morgan analogons will hold for $\oplus$. So we do *not* have that $A \oplus \neg A = D_{<E,t>}$: Let for example A be a constant of type $< E, t >$. Now we may have some events e where A is true: $A(e)$, and the others, e' will not be in A, such that $\neg A(e')$ is true. So we have as usual: $A \cup \neg A = D_{<E,t>}$. But $A \oplus \neg A$ will only be true for such events which are the sum of an A-event and a non-A-event – and these are not all, of course. Also we will not have anything like $\neg(A \oplus B) = (\neg A \oplus \neg B)$. $\neg(A \oplus B)$ is the complement of $(A \oplus B)$ on D_E as usual, but we have already seen examples of events which are both, $(A \oplus B)$ and $(\neg A \oplus \neg B)$.

7. Let us now come back to our initial examples. I will give the representations of the respective sentences, and we will see that these representations will allow us to refer to the complex events in question but still give a fine-grained description of them so as to keep non-equivalent sentences non-equivalent. In the sample treatments I will take the liberty to assume that the order of semantic combination proceeds as conveniently as possible. Especially I will only make use of the join $\oplus^*$ on $D_{<E,t>}$, not of its type shifted analogons on $D_{<e^n,<E,t>>}$. Remember our first example:

(6) From 2.00 to 4.00, Jim watered the tulips and had a nap.

First we compute the two meanings

(i.) Jim watered the tulips $\longrightarrow \lambda e.WATER(J, T, e)$

(ii.) Jim had a nap $\longrightarrow \lambda e.NAP(J, e)$

These are then conjoined:

(iii.) (i.) and (ii.) $\longrightarrow [\lambda e.WATER(J, T, e)] \oplus [\lambda e.NAP(J, e)]$

The next step is, to add the temporal information, this time using boolean conjunction:

(iv.) "from 2.00 to 4.00" and (iii.)
$\longrightarrow \lambda e[2.00; 4.00](e) \cap [\lambda e.WATER(J, T, e)] \oplus [\lambda e.NAP(J, e)]$
$\Longleftrightarrow \lambda e'.[2.00; 4.00](e') \wedge [\lambda e.WATER(J, T, e)] \oplus [\lambda e.NAP(J, e)](e')$

Now we can existentially bind the event parameter to get the overall sentence meaning. Thus we will end with:

(v.) $\exists e'[2.00; 4.00](e') \wedge [\lambda e.WATER(J, T, e)] \oplus [\lambda e.NAP(J, e)](e'))$
$\Longleftrightarrow \exists e[[2.00; 4.00](e) \wedge \exists e_1(WATER(J, T, e_1) \wedge \exists e_2(NAP(J, e_2)$
$\wedge\, e = e_1 \oplus e_2))]$ by definition of $\oplus$.

The final formula is exactly what (6) should mean. What will happen in the adverbial example? Let me demonstrate the outcome of the twin pair of sentences we saw in section 5. and check that the non-equivalence is accounted for:

(26) Jim carefully watered the tulips and ate an ice cream.

(38) Jim watered the tulips and carefully ate an ice cream.

The first sentence will be computed as follows:

(i.) Jim carefully watered the tulips $\longrightarrow \lambda e(WATER(J, T, e) \wedge CAREFUL(J, e))$

(ii.) Jim ate an ice cream $\longrightarrow \lambda e.\exists x(ICE\text{-}CREAM(x) \wedge EAT(J, x, e))$

(iii.) i. and ii. $\longrightarrow \lambda e(WATER(J, T, e) \wedge CAREFUL(J, e)) \oplus \lambda e.\exists x(ICE\text{-}CREAM(x) \wedge EAT(J, x, e))$

(iv.) exist. clos. $\longrightarrow \exists e^* \lambda e(WATER(J, T, e) \wedge CAREFUL(J, e)) \oplus \lambda e.\exists x(ICE\text{-}CREAM(x) \wedge EAT(J, x, e))(e^*)$
$\Longleftrightarrow \exists e(\exists e_1(WATER(J, T, e_1) \wedge CAREFUL(J, e_1) \wedge$
$\exists e_2 \exists x(ICE\text{-}CREAM(x) \wedge EAT(J, x, e_2) \wedge e = e_1 \oplus e_2)))$

The second sentence on the contrary will end as:

(i.) Jim watered the tulips
$\longrightarrow \lambda e(WATER(J, T, e))$

(ii.) Jim carefully ate an ice cream
$\longrightarrow \lambda e.\exists x(\mathit{ICE\text{-}CREAM}(x) \wedge \mathit{EAT}(J, x, e) \wedge \mathit{CAREFUL}(J, e))$

(iii.) i. and ii. $\longrightarrow \lambda e(\mathit{WATER}(J, T, e)) \oplus \lambda e.\exists x(\mathit{ICE\text{-}CREAM}(x)$
$\wedge\, \mathit{EAT}(J, x, e) \wedge \mathit{CAREFUL}(J, e))$

(iv.) exist. clos. $\longrightarrow \exists e^* \lambda e(\mathit{WATER}(J, T, e)) \oplus \lambda e.\exists x(\mathit{ICE\text{-}CREAM}(x)$
$\wedge\, \mathit{EAT}(J, x, e) \wedge \mathit{CAREFUL}(J, e))(e^*)$
$\Longleftrightarrow \exists e(\exists e_1(\mathit{WATER}(J, T, e_1) \wedge \exists e_2 \exists x(\mathit{ICE\text{-}CREAM}(x) \wedge \mathit{EAT}(J, x, e_2) \wedge$
$\mathit{CAREFUL}(J, e_2) \wedge e = e_1 \oplus e_2)))$

Thus it is ensured that the manner adverb "carefully" stays with its proper event throughout the entire calculation.

8. Boolean contra non-boolean conjunction

One of the main consequences of the introduction of the summation operation $\oplus$ is, that the word "and" comes out as ambiguous. Of course this is not too pleasant a claim to make. After all, the boolean connective "and" is one of the very few words in natural language where the lexical semantic is settled at all. However, the new operation $\oplus$ is weaker than the boolean "$\wedge$ ", and thus we might have the idea that instead of always using the latter, we should always use the former. Can we hope to find that $\oplus$ is indeed always the correct representation for "and" on sets of events? Or else: how does canonical boolean "and" relate to $\oplus$? The canonical alternative "and" on sets of events (sets generally) will be the type lifted version of the boolean "and", namely set intersection:

(39) $[[A \text{ and } B]] = [[A]] \cap [[B]]$

where A, B are translated into terms of type $< E, t >$, let it be α and β. But in all models where $\oplus$ is defined on sets of events in addition to set intersection, we have the following:

(40) $\alpha \cap \beta$ is a subset of $\alpha \oplus \beta$.

This is so because if e is in α and also in β then e not only in $\alpha \cap \beta$ but also as $e \oplus e = e$ in $\alpha \cap \beta$. So whenever an event e is in $\alpha \cap \beta$, the predicate $\alpha \oplus \beta$ will automatically also be true of e. Can we uniformly replace set intersection by $\oplus$ then?

Probably not. Let me first look at examples from the realm of individuals. Without going into the details, it is clear that an analogous summation operation can be defined on the domain of sets of individuals $D_{<E,t>}$ to handle, for instance, the Fido-type examples. But now we find that there are sentences which suggest that replacing boolean conjunction by the summation operation will be too weak:

(41) The toy car was red and made from wood.

(42) Fido is fluffy and white.

I guess that the first sentence will be felt to be at least inappropriate, if not downright false if the toy car in question was indeed made from wooden parts which were green, and iron parts which were red, for example. For such an object T the formula

(43) $RED \oplus WOOD(T)$

however is true. This shows that in any case we will not want to replace boolean "and" by summative "and" throughout language. (This would be surprising anyway, given that we lived on boolean conjunction quite comfortably for over 100 years now.)

Let us now proceed to the event examples. Here matters become somewhat more intricate, because it turns out that (at least starting from the set of examples I have happened to come across – other people coming from a different angle might end with clearer ideas) – that the distinction of boolean versus summative conjunction interacts with general principles of temporal localization for events in discourse. How this? Look at the following two examples:

(A) From 9.00 to 12.00, Jim had a nap and repaired Emma.

(B) From 9.00 to 12.00, Jim had a nap and Lukas repaired Emma.

What do these sentences mean? (A) is of the same type as all our above examples, starting from (6). There are two events involved, e_1 and e_2, we form their sum and claim that the complex event lasted from 9.00 to 12.00. This is not the case for the simple events themselves. Moreover we might note that we understand e_1 to precede e_2 in time: the repair seems to start, roughly, where the nap ends. Let me abbreviate this as $e_1 \ll e_2$. (B) on the other hand suggests that the two events, f_1 and f_2, which we are talking about happened at the same time, namely from 9.00 to 12.00. In other words: the temporal predicate distributes down on the simple events. f_1 and f_2 co-occur [3]: $f_1 \circ f_2$. These are the empirical observations to be made about (A) and (B). How can we lay this down in terms of our theory, as it stands up to now? For (A) again things are rather clear. Where we would like to end is with a formula like

(44) $\exists e \exists e_1 \exists e_2 (NAP(J, e_1) \wedge REPAIR(J, E, e_2) \wedge e = e_1 \oplus e_2$
$\wedge [9.00; 12.00](e) \wedge e_1 \ll e_2)$

I will discuss in a moment where the clause about the two simple events following one another comes from. For example (B) however we have basically two options to get what it says:

(B1): We have two simple events which overlap in time. We form their sum. The sum lasts from 9.00 to 12.00. As it is formed from overlapping parts, these also last from 9.00 to 12.00 *as a logical consequence*.

[3] I borrow the "overlap"-symbol here, but use it in the narrower sense of temporal co-occurrence.

(45) $\exists e \exists e_1 \exists e_2 (NAP(J, e_1) \wedge REPAIR(L, E, e_2) \wedge e = e_1 \oplus e_2 \wedge [9.00; 12.00](e) \wedge e_1 \circ e_2)$

(B2): The sentence, just as the toy car example, is indeed making use of boolean conjunction: It is the boolean conjunction of the sentences "from 9.00 to 12.00, Jim had a nap" and "from 9.00 to 12.00, Lukas repaired Emma". Thus the fact that there are two events which overlap in time comes out as a logical consequence.

(46) $\exists e_1 (NAP(J, e_1) \wedge [9.00; 12.00](e_1)) \wedge \exists e_2 (REPAIR(L, E, e_2) \wedge [9.00; 12.00](e_2))$

In this representation no complex events are mentioned at all.

Which combination will yield the more coherent overall picture? Should we assume (A) and (B1), or (A) and (B2)? And where does the temporal information come from at all? Let me first look at the combination "(A) and (B2)": It suggests that we have to make the major decision when we translate the word "and", in computing sentences like (A) and (B). Summative "and" goes along with temporal sequence of events. Boolean "and" means nothing specific – in our case, further factors lead to co-occurrent events. This way to proceed opens the scene for one fashionable assumption about joins of events (and summation of sets of events, as a consequence) which I left unmentioned up to now. It was often suggested that the join of events should match the idea of "glueing together little movies" in that it is non-commutative. Thus if we refer to a complex event $e_1 \oplus e_2$ we will know that e_1 precedes e_2. In other words: the join operation is only defined for e_1 and e_2 if e_1 precedes e_2. Thus

(47) Jim had a nap and repaired Emma

will only refer to complex events of Jim *first* having a nap and *afterwards* repairing Emma, while for

(48) Jim repaired Emma and had a nap

things are the other way round. One level higher up, this perspective will lead to the observation that for two sets of events P and Q, the sum $P \oplus Q$ is no longer the same as $Q \oplus P$. $P \oplus Q$ will only contain the complex events $e_1 \oplus e_2$ where e_1 in P precedes e_2 in Q. For $Q \oplus P$, the other way round again. This way to proceed would be in the spirit of N.Asher (1993), but was also suggested by F.Veltman (p.c.). It would reveal the mystery where the temporal part comes from in the formula (44). It is just built in the join operations. So we only will have to "guess" once during the computation of (A) and (B) – namely where we decide which sort of "and" is in play. The other combination (A) and (B1) takes a different perspective. We claim that both examples use non-boolean "and" and would have to rely to independent principles of temporal reasoning to locate the events in question appropriately. This looks mysterious at first sight. Never let too much pragmatic and world knowledge reasoning enter your theory! But on the other hand it is well known that there *are* principles guiding the sequence of events in narrative discourse. Hinrichs (Hinrichs[1986]) among others has investigated how aspectual properties of the verbs determine how we understand two event(ualitie)s to be located relative to another. Note that the same constellations as in (A) and (B) can be found in two-sentence discourses where no joins are made at all – that is, where we have to rely on discourse relational reasoning anyway to fix things in the right order:

(49) Jim had a nap. (Then) He repaired Emma.

(50) Jim had a nap. Lukas repaired Emma.

(I am aware that especially the first two sentence are almost incoherent without an intermediate "then". Things become better if we take longer lists of activities of Jim.) Sequence (49) will be naturally understood as talking about two subsequent events (this is in accordance with the theory in Hinrichs(86)). Somehow this will have to be concluded from what we know about taking naps and repairing locomotives. However I feel that I can understand (50) as describing some overall scene, or state of the world, in any case as two *co-occurrent* events to happen (this is not so much in accordance with Hinrichs (86)). The important thing to observe now is that *subsentential* conjunction seems to exhibit the same patterns as sentence sequencing *in discourse*. This observation has often been made before. But now: If we have to reason about relative temporal location of events in discourse anyway (call this TR in the following), we might also apply this to subsentencial constellations! Thus we would want to treat all instances of "and" as summation and get the boolean flavour in (B) due to the fact that the two lower events are found to co-occur.

Things look as if both perspectives had their pros and cons. The points of uncertainty lie at different places (boolean-nonboolean versus TR). (A) and (B2), the boolean/nonboolean distinction, goes well with the above Fido-examples. (A) and (B1), the uniform-summation-treatment, fits better with general discourse principles. What are we to do? There is one basic difference between the two approaches however: In the boolean-nonboolean distinction mainly two temporal relations are accomodated, sequence or co-occurrence. The uniform-summation- treatment together with TR allows in principle for arbitrary relative localizations of the events in question. Can we find examples which exploit this possibility? I think there are at least examples where complex events can show more than the simple "one-after-the-other" pattern.

(51) Bob pulled and carried his goat from Davos up to the Weisshorn.

There is a complex event consisting of Bob pulling his goat, and Bob carrying his goat. Clearly the spatial information "all the way from Davos to the Weisshorn" does not distribute down to the simpler events. We would not like to infer that

(52) Bob pulled his goat from Davos up to the Weisshorn.
Bob carried his goat from Davos up to the Weisshorn.

On the other hand, it is clear that (51) need not mean that *first* Bob pulled the goat and *then* he carried her for the rest of the way. We will rather imagine that the two ways to get the animal further on her way up to the Weisshorn followed each other in alternation [4]. The complex event looks like this, so to speak:

...........————..................—————..............———-
pull carry pull carry pull ...

This example suggests that we can think of more complex ways how two events are related in time than just co-occurrence or sequence. Further study will be necessary to exhibit all patterns and the regularities guiding our choices which one to understand. But if (51) is to be taken serious, it favours the more flexible "(A) and (B1)" perspective.

9. A dynamic coda

The previous section has been talking a lot about temporal relations between events. I have refrained from giving a precise algorithm to do the TR however, and have especially not indicated how the treatment in section 7. could be extended to incorporate the temporal localizations. This was not without reason. The summation operation $\oplus$ defined on sets of events $D_{<E,t>}$ inherently belongs to the sort of semantics that has been called "static" since 1982, when H.Kamp and I.Heim came up with the first versions of discourse semantics. Now what sort of semantics would it be, to relate events in time, one to another? I think that representing sequences of the kind

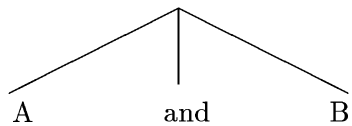
A happened. And then B happened.
A happened. And meanwhile B happened.

are basically of an anaphoric character. The second sentence refers back to the time when the first event had occured, and relates the second event to this first point or interval of time. It is possible however to simulate these mechanisms in a static framework; for example by making use of infinitely many time constants which are ordered in a row in proceeding with the computation of the discourse. Still, I feel that it is too much a simulation of the dynamic treatment to be of primary interest at this place. Let me instead sketch shortly what a dynamic treatment of sentences involving complex events may look like. I will however only give a scheme where the reader can fill in and test her favourite examples by herself.

I will use the incremential view presented in the Kamp/Reyle book on DRT (Kamp/Reyle(1994)) which is best fit for informal reasoning. Standard ways to translate this into file change semantics, DMG, and other dynamic compositional frameworks are known. The idea in DRT is that we get an "LF"-tree and we eat up all the leaves in building the corrseponding DRS, step by step. The

[4]which brings us back to the alternatingly- examples of P.Lasersohn! But whereas the bare "alternatingly"-construction still has that explicit word in them which could be used as a binary operator in a treatment without complex events, such a solution is absolutely out in our examples.

new assumption is the following: Non-boolean "and" is translated as a ternary relation between events: $e_k = e_i \oplus e_j$ where the word "and" knows the correct two argument indices i and j, and introduces e_k as its own new referential argument. (Note that "and" has ended as the lower-type event join, instead of the higher-type operation on sets of events. The non-quantificational character of indefinites in dynamic semantics is borne out again.) Assume we start with a ternary tree



where A and B describe two events; indeed they work like event indefinites. The computation on A will give the preliminary DRS

e_i
$A(e_i)$

Next we will work on B which introduces e_j, and as the previous event e_i is already known now, we can use both the information A about e_i and B about e_j to make a guess on how they should relate in time. I will note this as $f(e_i, e_j)$. So this is where TR takes place.

e_i, e_j
$A(e_i), B(e_j)$ $f(e_i, e_j)$

Now the "and" is worked on. "and" must carry the two argument indices i and j, and will introduce e_k where k is a new index. It will say that there is an event e_k which is the sum of e_i and e_j.

e_i, e_j, e_k
$A(e_i), B(e_j)$ $f(e_i, e_j)$ $e_k = e_i \oplus e_j$

The major part – the spellout of "TR" – is left out here. However two things can be found again which are in the spirit of the overall paper, and which I wanted to show: We have to have a treatment for the "other", nonboolean "and". And: Again, persistency on the event lattice will buy us nothing.

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