Towards a Theory of Anaphoric Binding in Event Semantics

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Abstract. Scope and (anaphoric) binding are tough problems for event semantics. Unlike the former, the latter has not even been attempted, it seems. The present paper makes an attempt and reports on the ongoing work, in the context of polynomial event semantics.
Polynomial event semantics is a variable-free dialect of Neo-Davidsonian event semantics originally developed as a new approach to (quantifier) scope. Extended to relative clauses, it had to face traces, which is a form of anaphora. The present paper extends the mechanism proposed for traces to (nominal) pronouns. The same mechanism happens to also apply to discourse referents. Anaphoric binding becomes oddly symmetric. Also comes to light is a close analogy of indefinites and unbound pronouns.

1 Introduction

Pronouns and in general anaphora is the elephant in the room of event semantics. From surveys such as [13] or comprehensive treatments [2], among others, one may get an impression that anaphora is subject *non grata*. At least [15] explicitly says that "pronouns are not our main focus here, so I will not pursue it further." A theory of meaning and entailment, however, rather sooner than later must confront pronouns – and, eventually, crossover, gaps, ellipsis, donkey anaphora, paycheck pronouns, etc.

In contrast, a closely related problem of scope and quantification is widely acknowledged in event semantics literature, as event quantification problem, and has received considerable attention: see [2] for survey. Dealing with quantification (and negation) in a non-traditional, variable-free way was the motivation for the polynomial event semantics [7, 8, 10] – a theory of meaning and entailment in a neo-Davidsonian tradition. It was later extended to relative clauses, including clauses with quantification and negation [9]. Giving denotations to traces, and paraphrasing relative clauses as independent matrix clauses linked via ‘pronouns’ came close to the treatment of anaphora. The present work elaborates that approach and applies to pronouns and discourse referents, including bound-variable anaphora.

As in the previous work, our goal is deciding entailments, with as few postulates as possible. As a whetstone we have been using the FraCaS textual inference problem set [3, 12] – which includes the dedicated section just for nominal anaphora, and another section for ellipsis, gapping and related phenomena. Anaphora also appears in ‘temporal reference’ and other sections. The hope is that the event semantics would deliver simple, postulate-free solutions to these and other entailment problems – especially in cases of VP modification (including temporal adverbials). Before we attempt that, however, we need to build the foundation for analyzing anaphora in event semantics, which has been entirely lacking. The present paper describes the current progress.

The paper hence focuses on developing the polynomial event semantics and reproducing standard analyses of (nominal, in this paper) anaphora, including bound-variable anaphora. Still, we already obtained interesting insights. Commonly, anaphoric binding is seen as asymmetric – which is particularly noticeable in dynamic semantics, which talks about “pushing discourse referents” and that a pronoun “pulls the value out of the context” [1]. On our account, however, we see a surprisingly symmetric picture of referents and pronouns. In particular, nominal pronouns, their antecedents as well as trace are all denoted by the identity relation – with different domains. We also see a close analogy of indefinites and unbound pronouns. Unlike many other analyses, sentences with unbound pronouns in our approach have a meaning, with a clear denotation.

After a brief reminder of the polynomial event semantics, §3 describes in detail so-called ‘relative denotations’, which first appeared in the compositional semantics of phrases with a trace. §4 applies them to nominal pronouns as well as their referents. In particular, §4.1 analyses several typical examples of bound-variable anaphora.

2 Polynomial Event Semantics: Brief Reminder

As a reminder of the polynomial event semantics, (1) shows the denotation of a simple sample sentence. The denotation is clearly built compositionally, matching the structure of the sentence:

(1) $$[\![\text{John traveled to Paris.}]\!] = (\mathsf{subj}'/\,\mathsf{john}) \;\cap\; \mathsf{Travel} \;\cap\; (\mathsf{toloc}'/\,\mathsf{paris})$$

Here john and paris are individuals (notated i) and Travel is a set of events (notated e), specifically, traveling events. Further, subj' is a relation between events and individuals, viz. 'agents'.[1] The *relational selection* (or, restriction) $\mathsf{subj}'/\,\mathsf{john}$ is then the set of events whose 'agent' is John:

$$\mathsf{subj}'/\,\mathsf{john} = \{e \mid (e, \mathsf{john}) \in \mathsf{subj}'\}$$

Likewise, $\mathsf{toloc}'/\,\mathsf{paris}$, to be abbreviated as TP, is the set of events involving Paris as the destination. The meaning of the whole sentence is the intersection of the meaning of its constituents: viz., the set of traveling events whose subject is John and destination is Paris. The denotation of a sentence is hence a set of events that witness it – or the formula like (1) that represents it, which may be regarded as a query of the record of world events. The sentence is true in that world if the result of the query is non-empty.[2]

Simple sets do not suffice, however, when it comes to (distributive) coordination such as:

(2) Bill and John traveled to Paris.

"Bill and John" are obviously not a single individual. Rather, they are a 'loose group', for the lack of a better word, indicating that they are both involved, but not necessarily together. We introduce the (associative and commutative) operator $\otimes$ to build such loose groups of individuals. The denotation of "Bill and John", therefore, is $\mathsf{john} \otimes$

[1] Since we take events in broad sense [13], including states, etc., 'agent' is to be understood as the event attribute roughly corresponding to the role played by the grammatical subject. Currently we take the events of, say, 'reading' and 'being read' as distinct, but relatable by semantic postulates.

[2] Negation requires elaboration: see [10, 9].

bill, to be called a poly-individual. Events in which Bill and John are subjects are then denoted by $\mathsf{subj}'/\ (\mathsf{john} \otimes \mathsf{bill})$, which is no longer a simple event set. We call it a polyconcept; a generalization of event sets (concepts). Event sets are regarded as (trivial) polyconcepts.

Set intersection extended to polyconcepts is written as $\sqcap$. That is, if two polyconcepts d_1 and d_2 happen to be ordinary sets, then $d_1 \sqcap d_2 = d_1 \cap d_2$. The operation $\sqcap$ also applies to individuals and poly-individuals; in particular,

$$i_1 \sqcap i_2 = \begin{cases} i_1 & \text{if i1 = i2} \\ \bot & \text{otherwise} \end{cases}$$

where $\bot$ is the empty poly-individual/polyconcept. It is the null of both $\sqcap$ and $\otimes$:

$$d \sqcap \bot = \bot \qquad d \otimes \bot = \bot$$

With thus introduced polyconcepts, the denotation of (2) can then be written as (3).

$$[\![\text{Bill and John traveled to Paris.}]\!]$$

(3) $$= \mathsf{subj}'/\ (\mathsf{john} \otimes \mathsf{bill}) \ \sqcap \ \mathsf{Travel} \ \sqcap \ \mathsf{TP}$$

(4) $$= (\mathsf{subj}'/\ \mathsf{john} \ \cap \ \mathsf{Travel} \ \cap \ \mathsf{TP}) \otimes (\mathsf{subj}'/\ \mathsf{bill} \ \cap \ \mathsf{Travel} \ \cap \ \mathsf{TP})$$

The meaning of the operator $\otimes$ is how it behaves, or distributes. In particular, the relational selection acts as homomorphism (or, 'commutes'):

$$\mathsf{subj}'/\ (\mathsf{john} \otimes \mathsf{bill}) = (\mathsf{subj}'/\ \mathsf{john}) \otimes (\mathsf{subj}'/\ \mathsf{bill})$$

What Bill and John act as a subject in is a loose group of two event sets: of Bill acting as a subject and of John. Intuitively, an event from both sets must have transpired. The operator $\sqcap$ distributes over $\otimes$ in case of simple concepts:

(5) $$(d_1 \otimes d_2) \sqcap j = (d_1 \sqcap j) \otimes (d_2 \sqcap j)$$

where j is an event set (not a group); d is an arbitrary polyconcept. See [10] for detail on equational laws, and [8] for a model.

The relational selection homomorphism and the above distributive laws give (4). The sentence (2) is hence justified by a pair of events, of John traveling to Paris, and of Bill.

For the choice "Either John or Bill" we introduce $\sqcup$ (when the choice is internal) or $\oplus$ (when external). Quantification is the generalization: "Everyone" is denoted by $\bigotimes_{i \in \mathsf{Person}} i$, to be abbreviated as $\mathcal{A}$ Person. A wide-scope existential and indefinite "a person" is $\bigoplus_{i \in \mathsf{Person}} i$ (abbreviated $\mathcal{I}$ Person) and the narrow-scope existential is $\bigsqcup_{i \in \mathsf{Person}} i$ (abbreviated $\mathcal{E}$ Person). Here Person is a set of individuals. For more detail (as well as negation, not used here), see [10, 9].

3 Polyconcepts in Context: Relative Denotations

The paper [9] applied the polynomial event semantics to relative clauses. For example, for the following noun-modification phrase it *derived* the intuitive denotation:

(6)
$$\begin{aligned} &[\![\text{city John traveled to } \mathtt{T}]\!] \\ &\quad = \mathsf{City} \cap \{ i \mid [\![\text{John traveled to } i]\!] \neq \bot \} \end{aligned}$$

where $\mathtt{T}$ is trace. The paper [9] derived the denotation in two ways, one of which is compositional – which means giving denotation to the trace $\mathtt{T}$. We now elaborate this method and, in §4, apply to pronouns and their referents.

To handle trace, [9] had to generalize denotations from poly-individuals (and polyconcepts) d to relations between contexts and poly-individuals (resp. polyconcepts): in effect, set of pairs $\{(i, d) \mid i \in C\}$, for which we now adopt a more compact notation $d|i{:}C$. We call them relative denotations. The context C at present is a set of individuals (although it may be any other set). The denotation d in $d|i{:}C$ may itself be a relative denotation $d'|i'{:}C'$. We write such nested relative denotations as $d'|(i'{:}C' \times i{:}C)$, to be understood as

$$d'|(i'{:}C' \times i{:}C) \stackrel{\Delta}{=} d'|i'{:}C'|i{:}C = \{(i, (i', d')) \mid i' \in C', i \in C\}$$

Any denotation d can be converted – or embedded, relativized – to a relative denotation:

$$d \underset{\rho}{\overset{\iota}{\rightleftarrows}} d|i{:}C$$

where ι is inclusion (or, embedding) and ρ is retract (or, projection):

$$\begin{aligned} &\iota_C\ d = d|i{:}C \\ &\rho\ (d|i{:}C) = d \qquad \text{provided } d \text{ is independent of } i \end{aligned}$$

An alternative way to define the retract is to use the relational selection: after all, a relative denotation is a relation:

$$\rho_C\ r = d \qquad \text{where } r/C = \{d\}$$

Embeddings and projections are the inverses of each other; however, an embedding is not surjective and a projection is not total, in general. An important particular case (which we come across later) is C being a singleton. For the singleton context, the embedding is surjective and the projection is total: they form a bijection. In this case, the relative denotation is isomorphic to the non-relative one. (We shall use $\approx$ to explicate and emphasize an isomorphism.)

The relational selection $\mathsf{subj}'/\ \cdot$ is again homomorphism:

$$\mathsf{subj}'/\ (d|i{:}C) = (\mathsf{subj}'/\ d)|i{:}C$$

and hence commutes with ι and ρ:

$$\iota_C\ (\mathsf{subj}'/\ i) = \mathsf{subj}'/\ (\iota_C\ i) \qquad \rho\ (\mathsf{subj}'/\ i) = \mathsf{subj}'/\ (\rho\ i)$$

Polyconcept operations likewise commute:

$$(d_1|i{:}C) \circledast (d_2|i{:}C) = (d_1 \circledast d_2)|i{:}C \tag{7}$$

where $\circledast$ stands for $\sqcap$, $\otimes$, $\oplus$ or $\sqcup$. (7) does not apply to $(d_1|i_1{:}C_1) \sqcap (d_2|i_2{:}C_2)$ with $C_1 \neq C_2$, however. To bring them to the common ground, so to speak, we may embed the two relative polyconcepts in each other contexts. Recall, embedding applies to any poly-individual or polyconcept, including a relative polyconcept.

(8)
$$\begin{aligned}
&\iota_{C_2}(d_1|i_1{:}C_1) \;\circledast\; \iota_{C_1}(d_2|i_2{:}C_2)\\
&= (d_1|i_1{:}C_1)|i_2{:}C_2 \;\circledast\; (d_2|i_2{:}C_2)|i_1{:}C_1\\
&= (d_1|(i_1{:}C_1 \times i_2{:}C_2)) \circledast (d_2|(i_2{:}C_2 \times i_1{:}C_1))\\
&\approx (d_1|(i_1{:}C_1 \times i_2{:}C_2)) \circledast (d_2|(i_1{:}C_1 \times i_2{:}C_2))\\
&= (d_1 \circledast d_2)|(i_1{:}C_1 \times i_2{:}C_2)
\end{aligned}$$

where we have used the obvious relational isomorphisms.

There is a yet another way to bring two relative concepts to the common ground (common context): narrowing. Unlike the previous approach, it does not preserve the denotation; rather, it makes it 'narrower'. First we introduce the narrowing operation

$$\Downarrow_{C_1} (d|i{:}C_2) \;\triangleq\; d|i{:}(C_1 \cap C_2)$$

Given two polyconcepts $d_1|i_1{:}C_1$ and $d_2|i_2{:}C_2$ we may try to combine them in one of the following ways:

(9)
$$d_1|i_1{:}C_1 \circledast \;\Downarrow_{C_1} (d_2|i_2{:}C_2)$$

(10)
$$\Downarrow_{C_2} (d_1|i_1{:}C_1) \;\circledast\; d_2|i_2{:}C_2$$

(11)
$$\Downarrow_{C_1 \cap C_2} (d_1|i_1{:}C_1) \circledast \;\Downarrow_{C_1 \cap C_2} (d_2|i_2{:}C_2)$$

One may think of (9) as interpreting the right concept in the context of the left. Likewise, (10) interprets the left polyconcept in the context of the right one; (11) is symmetric. We shall see in the next section the significance of these three different strategies for semantic analyses.

The strategies (9)-(11) may be written in an alternative form, by performing the construction (8) first, followed by the narrowing:

(12)
$$\begin{aligned}
&d_1|i_1{:}C_1 \circledast \;\Downarrow_{C_1} d_2|i_2{:}C_2\\
&= \;\Downarrow_{C_1} d_1|i_1{:}C_1 \circledast \;\Downarrow_{C_1} d_2|i_2{:}C_2\\
&= \;\Downarrow_{C_1 \times C_1} (d_1 \circledast d_2)|(i_1{:}C_1 \times i_2{:}C_2)
\end{aligned}$$

(13)
$$\begin{aligned}
&\Downarrow_{C_2} d_1|i_1{:}C_1 \;\circledast\; d_2|i_2{:}C_2\\
&= \;\Downarrow_{C_2 \times C_2} (d_1 \circledast d_2)|(i_1{:}C_1 \times i_2{:}C_2)
\end{aligned}$$

(14)
$$\begin{aligned}
&\Downarrow_{C_1 \cap C_2} (d_1|i_1{:}C_1) \circledast \;\Downarrow_{C_1 \cap C_2} (d_2|i_2{:}C_2)\\
&= \;\Downarrow_{(C_1 \cap C_2) \times (C_1 \cap C_2)} (d_1 \circledast d_2)|(i_1{:}C_1 \times i_2{:}C_2)
\end{aligned}$$

In an important case $C_1 \subset C_2$, the narrowing to the left

$$\begin{aligned} &\Downarrow_{C_2 \times C_2} (d_1 \circledast d_2)|(i_1{:}C_1 \times i_2{:}C_2) \\ = &\quad (d_1 \circledast d_2)|(i_1{:}C_1 \times i_2{:}C_2) \end{aligned}$$

is the identity. On the other hand, the narrowing to the right (which is the same as the symmetric narrowing in this case)

(15)
$$\begin{aligned} &\Downarrow_{C_1 \times C_1} (d_1 \circledast d_2)|(i_1{:}C_1 \times i_2{:}C_2) \\ \equiv &\quad \Downarrow_{C_1} d_1|i_1{:}C_1 \circledast \Downarrow_{C_1} d_2|i_2{:}C_2 \\ = &\quad d_1|i_1{:}C_1 \circledast d_2|i_2{:}C_1 \\ = &\quad (d_1 \circledast d_2[i_2{:=}i_1])|i_1{:}C_1 \end{aligned}$$

where $[i_2{:=}i_1]$ is a (meta)variable substitution. In other words, the narrowing behaves quite like binding – which is exactly how we will use it in linguistic analyses.

4 Nominal Pronouns and Referents

As the first example of pronouns, consider "It is famous.". In [9], the trace was given the denotation $i|i{:}\mathcal{I}$ where $\mathcal{I}$ is the set of all individuals. Since trace is anaphoric, it is tempting to likewise make $[\![\text{it}]\!] = i|i{:}\ \mathsf{Thing}$, relativized to the set of things (non-human individuals). Let's give in to the temptation. The whole sentence then receives the denotation:[3]

$$[\![\text{It is famous.}]\!]$$
$$= \mathsf{subj}'/\ (i|i{:}\ \mathsf{Thing})\ \sqcap\ \iota_{\mathsf{Thing}}\ \mathsf{Famous}$$

(16) $$= (\mathsf{subj}'/\ i\ \cap\ \mathsf{Famous})|i{:}\ \mathsf{Thing}$$

(17) $$= [\![i \text{ is famous.}]\!]|i{:}\ \mathsf{Thing}$$

Since "it" has a relative denotation, we need a relative denotation for $[\![\text{famous}]\!]$, obtainable by embedding. To lighten the notation, hereafter we shall apply embeddings silently as needed. One may have recognized the parenthesized expression in (16) as the denotation for "i is famous.".

[3] We are simplifying, but only slightly: see [10] for the treatment of copular clauses.

The sentence is grammatical and meaningful, even by itself: a listener is free to imagine a suitable referent for "it", not constrained by any prior discourse (which does not exist here). The denotation is inherently relative (ρ does not apply), which indicates it contains an unresolved anaphoric reference.

Next consider "John traveled to Paris$^{\triangleright}$." where Paris$^{\triangleright}$ is an NP creating a referent. We take its denotation to be the relativized paris:

(18) $[\![\text{Paris}^{\triangleright}]\!] = \iota_{\{\mathsf{paris}\}}\ \mathsf{paris} = \mathsf{paris}\ |i\colon \{\mathsf{paris}\} = i|i\colon \{\mathsf{paris}\}$

Oddly, $[\![\text{Paris}^{\triangleright}]\!]$ turns out almost the same as $[\![\text{it}]\!]$; only the former is relativized to the singleton $\{\mathsf{paris}\}$ and the latter to the set of all things. Therefore, the former can be projected to the non-relative denotation, but the latter cannot. For the whole sentence we obtain:

$$\begin{aligned}
&[\![\text{John traveled to Paris}^{\triangleright}.]\!]\\
&= \iota_{\mathsf{paris}}\, \mathsf{subj}'/\ \mathsf{john}\ \sqcap\ \iota_{\mathsf{paris}}\, \mathsf{Travel}\ \sqcap\ \mathsf{toloc}'/\ (i|i\colon \{\mathsf{paris}\})\\
&= (\mathsf{subj}'/\ \mathsf{john}\ \cap\ \mathsf{Travel}\ \cap\ \mathsf{toloc}'/\ i)|i\colon \{\mathsf{paris}\}\\
&= [\![\text{John traveled to } i]\!]|i\colon \{\mathsf{paris}\}\ .
\end{aligned}$$

Combining the two sentences and using (8) gives:

$$\begin{aligned}
&[\![\text{John traveled to Paris}^{\triangleright}\text{. It is famous.}]\!]\\
&= [\![\text{John traveled to Paris}^{\triangleright}.]\!] \otimes [\![\text{It is famous.}]\!]\\
&= ([\![\text{John traveled to } i_1]\!] \otimes [\![i_2 \text{ is famous}]\!])|\\
&\qquad (i_1\colon \{\mathsf{paris}\} \times i_2\colon \mathsf{Thing})
\end{aligned} \tag{19}$$

After all, "it" does not have to refer to Paris.

If, from pragmatic considerations, one decides that "it" resolves to "Paris", we can carry out this decision in our formalism, by applying the (right) narrowing $\Downarrow_{\{\mathsf{paris}\}\times\{\mathsf{paris}\}}$ obtaining (as in (15)):

$$([\![\text{John traveled to } i]\!] \otimes [\![i \text{ is famous}]\!])|i : \{\mathsf{paris}\}$$

The context becomes the singleton set. Recall, a polyconcept relative to a singleton context is isomorphic to the non-relative polyconcept. Therefore, the above denotation is equivalent to the pair $[\![\text{John traveled to Paris}]\!]$ and $[\![\text{Paris is famous}]\!]$. It is now "context-free": with no longer any unresolved dependencies, no appeal to listener's imagination.

The narrowing we have just applied corresponds to the left-to-right interpretation (9); the opposite (10) does not affect the denotation and does not, hence, result in the pronoun resolution. On the other hand, for “John travel to it. Paris is famous.” the left-to-right interpretation (9) leaves the pronoun unresolved; we would have needed the right-to-left interpretation for the resolution. The theory therefore has the mechanisms for both interpretations. It is an empirical fact that in English left-to-right interpretation is commonly observed. Right-to-left is not unheard of: “John travel to it. I mean, travel to Paris.” Such right-to-left interpretation is common in scientific language: so-called ‘where’ clauses (or ‘here’ sentences). An example, claimed to require no explanation, is

$$f(b+2c)+f(2b-c) \quad \text{where } f(x)=x(x+a)$$

from [11, §2]. Here, ‘f’ in the main clause is resolved by the ‘f’ defined in the ‘where’ clause; a, b and c are free.[4]

The key idea hence is that discourse is a constraint on listeners’ imagination. The narrower is the context, the tighter is the constraint. In the limit, a proper noun is the anaphoric reference in the singleton context, which constrains it unambiguously. The close similarity of $[\![\text{Paris}^{\triangleright}]\!]$ and $[\![\text{it}]\!]$ should not be so surprising.

We must stress that the question of deciding which pronoun refers to which referent is in domain of pragmatics and outside the scope of our theory. What we propose is a semantic framework, in which to carry out analyses and obtain denotations *without* having committed to a particular referent resolution. Once we obtain denotations, we can can see the derived context, and then apply pragmatic and other referent resolution strategies.

In other words, whether to apply a narrowing and which narrowing to apply is the matter of *policy*, and is left to pragmatics. Narrowing by itself is the *mechanism* to carry out a particular decided policy within the formalism. Allowing for both left-to-right and right-to-left narrowing is a feature: unlike many other formalisms, we do not bake-in any preferred way of resolving pronouns, leaving it to policy.

[4] This sentence is itself an example of a ‘here’ sentence, giving the definitions for f, a, b, and c that appeared in an earlier formula.

4.1 Bound Variable Anaphora

Indefinites may also bind pronouns: “John traveled to $\mathrm{a}^{\triangleright}_{W}$ city. It is famous.” (assuming “it” refers to the above-mentioned city), where $\mathrm{a}^{\triangleright}_{W}$ is a referent-creating (wide-scope) indefinite (and therefore, it uses $\oplus$):

(20) $$[\![\mathrm{a}^{\triangleright}_{W}\ \text{city}]\!] = \bigoplus_{j \in \mathsf{City}} \iota_{\{\mathsf{j}\}} j = \bigoplus_{j \in \mathsf{City}} i | i\!:\ \{\mathsf{j}\}$$

Once again we see the identity relation $i|i{:}C$. The external choice $\oplus$ (of the city, in our case) distributes completely, giving

$$[\![\text{John traveled to } \mathrm{a}^{\triangleright}_{W} \text{ city. It is famous.}]\!]$$

(21) $$= (\bigoplus_{j \in \mathsf{City}} [\![\text{John traveled to } i_1]\!] | i_1\!:\ \{\mathsf{j}\}) \otimes ([\![i_2 \text{ is famous}]\!] | i_2\!:\ \mathsf{Thing})$$

(22) $$= \bigoplus_{j \in \mathsf{City}} ([\![\text{John traveled to } i_1.]\!] \otimes [\![i_2 \text{ is famous.}]\!]) | i_1\!:\ \{\mathsf{j}\} \times i_2\!:\ \mathsf{Thing}$$

$\{$Narrowing by $\Downarrow_{\{\mathsf{j}\} \times \{\mathsf{j}\}}\}$

$$\Rightarrow \bigoplus_{j \in \mathsf{City}} [\![\text{John traveled to } i.\ i \text{ is famous.}]\!] | i\!:\ \{\mathsf{j}\}$$

$\{$Bijection: context is singleton$\}$

$$\approx \bigoplus_{j \in \mathsf{City}} [\![\text{John traveled to } j.\ j \text{ is famous.}]\!]$$

where the use of narrowing reflects the assumption that “it” refers to a city. We must stress again that narrowing in general does not preserve denotations and is not free to use at will. Narrowing has to be justified by, and is the reflection of, a resolution decision made by pragmatics.

Incidentally, [9] related the result to the denotation of the sentence with the relative clause: “A city John traveled to is famous.”.

A similar derivation does not work for (23):

(23) $$[\![\text{John traveled to every city. It is famous.}]\!]$$

(24) $$= (\bigotimes_{j \in \mathsf{City}} [\![\text{John traveled to } i_1]\!] | i_1\!:\ \{\mathsf{j}\}) \otimes ([\![i_2 \text{ is famous}]\!] | i_2\!:\ \mathsf{Thing})$$

The key transition from (21) to (22) is the distribution of $\otimes$ into $\oplus$, followed by the application of (8). The similar transition does not apply to (24) because $\otimes$ does not distribute in each other. We could have applied (8) to "John traveled to every city", obtaining

$$\begin{aligned}&[\![\text{John traveled to every city}]\!]\\ &= (\bigotimes_{j \in \mathsf{City}} [\![\text{John traveled to } i_j]\!])|\prod_{j \in \mathsf{City}} i_j \colon \{\mathsf{j}\}\end{aligned}$$

It does not help, however, in binding "it" because the simple context i: Thing cannot be meaningfully intersected with the tuple $\prod_{j \in \mathsf{City}} i_j \colon \{\mathsf{j}\}$. Therefore, the narrowing cannot be applied. On the other hand, if the pronoun were "they", the binding would have worked.

The same argument shows why there is anaphoric binding of "it" in (25) but not in (26).[5]

(25) A donkey enters. It brays.

(26) Every donkey enters. It brays.

More interesting cases of bound variable anaphora are found in (27) and (28). (The latter is [1, (113)]).

(27) Every boy loves his father.

(28) A referee rejected every paper she reviewed.

For (27), we obtain

$$\begin{aligned}&[\![\text{Every boy loves his father.}]\!]\\ &= \mathsf{subj}'/\ [\![\text{Every boy}]\!]\ \sqcap\ \mathsf{Love}\ \sqcap\ \mathsf{ob1}'/\ [\![\text{his father.}]\!]\end{aligned}$$

where (using the embedding, eventually)

$$[\![\text{Every boy}]\!] = \bigotimes_{j \in \mathsf{Boy}} j = \bigotimes_{j \in \mathsf{Boy}} (k|k \colon \{\mathsf{j}\})$$

"Father" is denoted by a set of individuals Father, which is then restricted by "his". The operator $\mathcal{E}$ denotes a choice of an individual from the resulting set:[6]

$$[\![\text{his father}]\!] = \mathcal{E}(\mathsf{Father} \cap \mathsf{of}'/\ i)|i \colon \mathsf{Male}$$

[5] The example is due to Carl Pollard.

[6] The set of "father of i" is not necessarily singleton, if we take "father" in a broad sense, including stepfather, godfather, etc.

Overall, we obtain:

$$\begin{aligned}
&[\![\text{Every boy loves his father.}]\!]\\
&= \bigotimes\nolimits_{j\in\mathsf{Boy}}(\mathsf{subj}'/\ k \ \sqcap\ \mathsf{Love}\ \sqcap\ \mathcal{E}\ \mathsf{ob1}'/\ (\mathsf{Father}\cap\mathsf{of}'/\ i))|\\
&\qquad\qquad\qquad\qquad\qquad\qquad k\text{: }\{\mathsf{j}\}\times i\text{: }\mathsf{Male}\\
&\{\text{Narrowing }\Downarrow_{\{\mathsf{j}\}\times\{\mathsf{j}\}}\text{, assuming “his” refers to the boy}\}\\
&\Rightarrow \bigotimes\nolimits_{j\in\mathsf{Boy}}(\mathsf{subj}'/\ k \ \sqcap\ \mathsf{Love}\ \sqcap\ \mathcal{E}\ \mathsf{ob1}'/\ (\mathsf{Father}\cap\mathsf{of}'/\ i))|\\
&\qquad\qquad\qquad\qquad\qquad\qquad k\text{: }\{\mathsf{j}\}\times i\text{: }\{\mathsf{j}\}\\
&\approx \bigotimes\nolimits_{j\in\mathsf{Boy}}(\mathsf{subj}'/\ j \ \sqcap\ \mathsf{Love}\ \sqcap\ \mathcal{E}\ \mathsf{ob1}'/\ (\mathsf{Father}\cap\mathsf{of}'/\ j))\\
&= \bigotimes\nolimits_{j\in\mathsf{Boy}}[\![j\text{ loves a father of }j]\!]
\end{aligned}$$

For (28), we first compute the denotation of the relative clause clause along the lines of (6):

$$\begin{aligned}
&[\![\text{paper she reviewed }\mathtt{T}]\!]\\
&= (\mathsf{Paper}\cap\{k\mid[\![i\text{ reviewed }k]\!]\neq\bot\})|i\text{: }\mathsf{Female}\\
&\triangleq P_i|i\text{: }\mathsf{Female}
\end{aligned}$$

For conciseness, we write P_i for the parenthesized denotation. Then

$$[\![\text{every paper she reviewed }\mathtt{T}]\!] = \mathcal{A}(P_i|i\text{: }\mathsf{Female}) = (\mathcal{A}P_i)|i\text{: }\mathsf{Female}$$

If we take

$$[\![\text{A referee}]\!] = \bigoplus\nolimits_{j\in\mathsf{Referee}} k|k\text{: }\{\mathsf{j}\}$$

as in (20), we obtain for the whole sentence the denotation that can be narrowed to $\bigoplus_{j\in\mathsf{Referee}}[\![j\text{ rejected }\mathcal{A}P_j]\!]$. On the other hand, had we chosen $[\![\text{A referee}]\!]$ to be $\mathcal{E}$ $\mathsf{Referee}$ and distribute it inside $\mathcal{A}P_i$:

$$\left(\bigotimes\nolimits_{k\in P_i}\mathcal{E}\ \mathsf{subj}'/\ \mathsf{Referee}\sqcap\mathsf{Rejected}\sqcap\mathsf{ob1}'/\ k\right)|i\text{: }\mathsf{Female}$$

the narrowing cannot be applied, and “she” remains unbound. The binding of “she” to a referee hence works out only on the surface reading – the harsh referee does not vary with papers, – as was pointed in [1].

5 Related Work

Anaphora in general, and its particular approach: dynamic semantics, is an active area with enormous literature (not as far as event semantics, however). A concise overview is given in [1]. Although [1] pursues a rather different from us approach – dynamic semantics for anaphora and continuation semantics for the theory of scope – it is surprisingly related: It also represents the context as a (nested) tuple. The paper [1] is quite more precise and rigorous in its treatment of context, which we aspire to.

One contentious point in the theories of bound-variable anaphora is treating a pronoun as a bound variable. A strong argument against is given in Dekker's PLA [4]. Like [1], we side-step this argument: after all, there are no bound variables in our semantics (at least, not as conventionally understood). PLA [4], among many others, consider an unresolved pronoun as a failure to give a denotation. In contrast, we (again, as [1]) take sentences with unresolved pronouns to be meaningful, with well-defined denotations.

Since the pioneering work of Heim [6], the dynamic semantics tradition takes an individual sentence to mean its "context change potential": if discourse is a file of cards, an individual sentence is adding or modifying a card. It is the entire file rather than a sentence that has truth conditions. This seems to be too narrow a view of 'truth conditions'. In our approach, a sentence denotation is generally a relation, between context and events witnessing the truth of the sentence. A relation between context and truth conditions may still be called truth conditions.

Our denotation (17) for "It is famous" – the relation, or a set of pairs of a thing and a witness of its being famous – closely relates to the meaning of the question "What is famous?" in Hamblin theory of interrogatives [5], and to the alternative semantics [14].

6 Conclusions and Future Work

We have thus seen that anaphoric dependencies can, after all, be expressed in a variable-free event semantics, and in a surprisingly symmetric way. Both the referent and the reference have the meaning of a polyconcept relative to a context. Traces and indefinites also have the same meaning. The analogy of indefinites with unbound pronouns seems worth looking into further.

We have limited ourselves to nominal anaphora in this paper. Pronouns may also refer to events – which was one of the motivations for the (Neo-)Davidsonian semantics. The extension to event anaphora is forthcoming. Although we have not discussed FraCaS problems, many are already solvable in the approach presented here. We show details in the upcoming work.

The development of the theory of anaphoric binding in event semantics has just began. Dynamic semantics literature (including [1]) has the wealth of interesting examples of anaphora to investigate, from crossover to donkey anaphora to gaping and ellipsis – and also anaphoric references to times, worlds, degrees, events. The eventual goal is to apply our analyses to entailments.

On the implementation front, it is interesting to integrate our approach with the existing libraries for anaphora resolution.

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