Typed lambda calculi and possible worlds models

Chris Potts, Ling 236/Psych 236c: Representations of meaning, Spring 2013

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Course overview (current plan; adjustable)

i. Typed lambda calculi and possible worlds models
ii. Alternative approaches to meaning
iii. Grounded language understanding
iv. Question answering: Grounding in databases
v. Stochastic lambda calculus
vi. Distributional approaches to word meanings
vii. Composition in vector-space models 1: tensors
viii. Composition in vector-space models 2: recursive neural networks

Plan for today

1 Foundational issues and controversies

1.1 Natural language as logic

Montague (1970b:373):

> There is in my opinion no important theoretical difference between natural languages and the artificial languages of logicians; indeed, I consider it possible to comprehend the syntax and semantics of both kinds of languages within a single natural and mathematically precise theory. On this point I differ from a number of philosophers, but agree, I believe, with Chomsky and his associates.

Barwise & Cooper (1981:204):

> It is here that Montague made his biggest contribution. To most logicians (like the first author) trained in model-theoretic semantics, natural language was an anathema, impossibly vague and incoherent. To us, *the* revolutionary idea in Montague's PTQ paper (and earlier papers) is the claim that natural language is not impossibly incoherent, as his teacher Tarski had led us to believe, but that large portions of its semantics can be treated by combining known tools from logic, tools like functions of finite type, the λ-calculus, generalized quantifiers, tense and modal logic, and all the rest.

1.2 Truth, and more broadly, reference

Montague (1970b:373–374):

> The basic aim of semantics is to characterize the notions of a true sentence (under a given interpretation) and of entailment, while that of syntax is to characterize the various syntactical categories, especially the set of declarative sentences. It is to be expected, then, that the aim of syntax could be realized in many different ways, only some of which would provide a suitable basis for semantics. It appears to me that the syntactical analyses of particular fragmentary languages that have been suggested by transformational grammarians, even if successful in correctly characterizing the declarative sentences of those languages, will prove to lack semantic relevance; and I fail to see any great interest in syntax except as a preliminary to semantics.

Lewis (1970:18):

> My proposals regarding the nature of meanings will not conform to the expectations of those linguists who conceive of semantic interpretation as the assignment to sentences and their constituents of compounds of 'semantic markers' or the like. (Katz and Postal, 1964, for instance.) Semantic markers are *symbols*: items in the vocabulary of an artificial language we may call *Semantic Markerese*. Semantic interpretation by means of them amounts merely to a translation algorithm from the object language to the auxiliary language Markerese. But we can know the Markerese translation of an English sentence without knowing the first thing about the meaning of the English sentence: namely, the conditions under which it would be true. Semantics with no treatment of truth conditions is not semantics.

Partee (1997:9):

> I believe linguists did presuppose tacit competence in Markerese and moreover took it to represent a hypothesis about a universal and innate representation, what Jerry (J.A.) Fodor later dubbed the Language of Thought (e.g., Fodor (1975)), and therefore not in need of further interpretation (see Jackendoff 1996 for a contemporary defense of a similar view).

Lepore (1983:177–178): model-theoretic accounts also fail to adequately link language and the world:

> I will now argue that PTQ, like SS [representational theories like Katz'z —CP], does not provide enough to bridge the gap between utterance and assertion.
>
> Suppose that Frank utters the words "Barbara sekoilee," and all I know about Frank's language is that (E′) and (I′) hold:
>
> (E′) "Barbara sekoilee" is true in Finnish if and only if whatever "Barbara" picks out is one of the things "sekoilee" is true of.
>
> (I′) The meaning of "Barbara sekoilee" in Finnish is the proposition which results from taking the meaning of "Barbara" as argument of the meaning of "sekoilee."
>
> It would be quite remarkable if I were able to discern what Frank asserts when he utters "Barbara sekoilee," provided that (E′) and (I′) constituted the whole of my knowledge about Frank's language. Knowing that (E′) or that (I′), at best warrants my believing that Frank asserted that something named "Barbara" has the expression "sekoilee" true of it. It would remain a mystery to me which thing it is, and exactly what is true of it.

1.3 Entailment/inference

Moss (2009:84–85):

> One motivation for semantics found in textbooks is that it should be the study of *inference in language*: just as syntax has grammaticality judgments to account for, semantics has inference judgments. Now I happen to be mainly a logician, and this point resonates with me as a motivation for semantics. But the semantics literature, it almost never gives a full account of *any* inferences whatsoever. It is seriously concerned with truth conditions and figuring out how semantics should work in a general way. But it rarely goes back and figures out, for various fragments, what the overall *complete stock of inferences* should be.

I agree with Moss's general characterization, but with caveats. First, arguments about truth conditions *are* arguments about entailments (but, as Moss says, little attention is paid to the general nature of inference). Second, some authors in and around semantics have been concerned with entailment, including Hobbs et al. 1988; Hobbs 2004; Asher & Lascarides 2003; Fox & Lappin 2005. Third, entailment, in an extended pragmatic sense, is the focus of 'recognizing textual entailment' tasks in NLP; for relevant discussion, see Manning 2006; Zaenen et al. 2005; Crouch et al. 2006.

1.4 (Mental) representation

Lewis (1970:19):

> My proposals will also not conform to the expectations of those who, in analyzing meaning, turn immediately to the psychology and sociology of language users: to intentions, sense-experience, and mental ideas, or to social rules, conventions, and regularities. I distinguish two topics: first, the description of possible languages or grammars as abstract semantic systems whereby symbols are associated with aspects of the world; and second, the description of the psychological and sociological facts whereby a particular one of these abstract semantic systems is the one used by a person or population. Only confusion comes of mixing these two topics. This paper deals almost entirely with the first. (I discuss the second elsewhere: Lewis, 1968b and 1969, Chapter V.) [These works are cited here as Lewis 1969 and Lewis 1975 —CP.] (p. 19)

Partee (1997:18, fn. 11):

> When I once mentioned to Montague the linguist's preferred conception of universal grammar as the characterization of all and only the possible human languages, his reaction was to express surprise that linguists should wish to disqualify themselves on principle from being the relevant scientists to call on if some extraterrestrial beings turn out to have some kind of language.

Partee (1980):

> So I don't see how we can get a correct account of propositional attitudes without bringing psychology into the picture, but I also don't see how we can get along *with* it. The relevant psychological factors are ones which vary from speaker to speaker and moment to moment. No one can infallibly recognize logical equivalence, but there is no general way of determining who will recognize which equivalence when. The psychological correlates of word intensions are similarly variable across speakers and times. These were the very reasons why Frege suggested that if we want propositions to stand in a close relation both to language and to truth, we must not equate them with ideas.

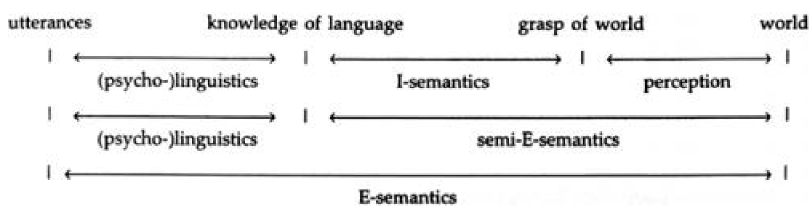
Katz (1972):

> "The arbitrariness of the distinction between form and matter reveals itself [. . .]"
>
> The question "What is meaning?" broken down:
>
> - What is synonymy?
> - What is antonymy?
> - What is superordination?
> - What is semantic ambiguity?
> - What is semantic truth (analyticity, metalinguistic truth, etc.)?
> - What is a possible answer to a question?
> - . . .

Jackendoff (1996:543):

> In order to treat semantics as an issue about the structure of the human organism, it is necessary to be careful about basic goals of the enterprise. In particular, the traditional preoccupation with explicating the notion of the truth or falsity of a sentence must be re-evaluated. For there is no longer a direct relation between an utterance and the world that renders the utterance true or false; there is instead the sequence of three relations diagrammed in the upper line of Figure 20.1.

Figure 20.1



A sample of Jackendoff's (1996:540–541) "basic questions for a theory of I-semantics":

i. What are the terms in which humans grasp the world? That is, what are the formal and substantive properties of human concepts / thoughts / ideas?

ii. How may these properties be formalized so as to develop a fully explicit and predictive theory?

iii. How are the terms in which humans grasp the world related systematically to linguistic expressions?

iv. In what respects, if any, are these terms not related systematically to linguistic expressions, being under the influence of nonlinguistic knowledge, context, etc.? Is there a natural division between linguistic and nonlinguistic factors?

v. How are the terms in which humans grasp the world related systematically to the world itself through the perceptual systems?

vi. In what respects, if any, are these terms not related systematically to the physical world? That is, to what extent are human concepts/thoughts/ideas abstract?

vii. How are the systems in (1)-(3) [his full listing—CP] wired in the brain, in terms of both broad localization and local neural connectivity?

See also Partee 1981; Katz 1996; Jackendoff 1992, 1997.

1.5 Compositionality

Definition 1 (Informal compositionality; Partee 1984:281)**.** The meaning of an expression is a function of the meanings of its parts and of the way they are syntactically combined.

For more formal definitions and discussion, see sec. 6.

2 Typed lambda calculi and their models

A brief and terse overview. For details, see Barendregt & Barendsen 1988; Barendregt 1992; Carpenter 1997; Gamut 1991; van Benthem 1991.

2.1 Types

Definition 2 (Semantic types)**.** Let B be a finite set of basic types. The set of semantic types is the smallest set *Types* such that

i. $B \subseteq \mathit{Types}$

ii. If $\sigma \in \mathit{Types}$ and $\tau \in \mathit{Types}$, then $\langle \sigma, \tau \rangle \in \mathit{Types}$

2.2 Expressions

Definition 3 (Well-formed expressions)**.** The smallest set *WFF* defined as follows (read '$\alpha : \sigma$' as '$\alpha \in \mathit{WFF}$ and α has type σ'):

i. For every type τ, we have a (possibly empty) set of constants $C_\tau \subseteq \mathit{WFF}$ of type τ.

ii. For every type τ, we have a countably infinite set of variables $V_\tau \subseteq \mathit{WFF}$ of type τ.

iii. If $\alpha : \langle \sigma, \tau \rangle$ and $\beta : \sigma$, then $(\alpha\ \beta) : \tau$.

iv. If $\alpha : \tau$ and χ is an variable of type σ, then $(\lambda \chi\ \alpha) : \langle \sigma, \tau \rangle$.

2.3 Models and interpretation

Definition 4 (Denotation domains)**.** Each semantic type has a corresponding denotation domain:

i. The domain of type $\tau \in B$ is D_τ.

ii. The domain of a functional type $\langle \sigma, \tau \rangle$ is the set of all total functions from D_σ into D_τ.

The union of all the domains is $\mathbf{D}$.

Definition 5 (Models)**.** A model is a pair $\mathbf{M} = \langle \mathbf{D}, \|\cdot\|^{\mathbf{M}} \rangle$, where $\mathbf{D}$ is the infinite hierarchy of domains defined in def. 4, and $\|\cdot\|^{\mathbf{M}}$ is a valuation function interpreting the constants of the language, constrained so that $\|\alpha\|^{\mathbf{M}} \in D_\sigma$ iff α is of type σ.

Definition 6 (Assignment functions)**.** Given a model $\mathbf{M} = \langle \mathbf{D}, \|\cdot\|^{\mathbf{M}} \rangle$ and well-formed expressions *WFF*, a function g is an assignment function iff g is a total mapping from the set of variables in *WFF* into $\mathbf{D}$ where $g(\chi) \in D_\sigma$ iff χ is of type σ.

Definition 7 (Interpretation)**.** The interpretation function given model $\mathbf{M} = \langle \mathbf{D}, \|\cdot\|^{\mathbf{M}} \rangle$ and assignment function g is $[\![\cdot]\!]^{\mathbf{M},g} : \mathit{WFF} \mapsto \mathbf{D}$.

2.4 Axioms

The expression $\varphi[x \rhd a]$ says 'φ with all occurrences of x turned into a.' I assume that $\varphi[x \rhd a]$ has no effect if x is not a variable, and that $\varphi[x \rhd a]$ is permitted iff it does not result in accidental binding, that is, a term in which there is a λ that binds more variables than it did prior to substitution. For the full definition, see Carpenter 1997:44.

Definition 8 (α conversion)**.** $(\lambda x\ \varphi) \overset{\alpha}{\Longrightarrow} (\lambda y\ \varphi[x \rhd y])$ (permitted iff $\varphi[x \rhd y]$) is permitted)

Definition 9 (β conversion)**.** $((\lambda \chi\ \varphi)\ \psi) \overset{\beta}{\Longrightarrow} \varphi[\chi \rhd \psi]$ (permitted iff $\varphi[\chi \rhd \psi]$ is permitted)

Definition 10 (η conversion)**.** $(\lambda \chi\ (\varphi \chi)) \overset{\eta}{\Longrightarrow} \varphi$ (permitted iff χ is not free in φ)

The axioms all preserve meaning in the sense of the models described above. The special provisions are designed to ward off meaning changes. This correspondence is partly to blame for the limitations discussed in sec. 9.

(1) a. $\lambda x\ ((\mathbf{see}\ x)\ y) \overset{\alpha}{\Longrightarrow} \lambda z\ ((\mathbf{see}\ z)\ y)$

b. $\lambda x\ ((\mathbf{see}\ x)\ y) \overset{\alpha}{\not\Longrightarrow} \lambda y\ ((\mathbf{see}\ y)\ y)$

(2) a. $((\lambda x\ (\mathbf{happy}\ x))\ \mathbf{kim}) \overset{\beta}{\Longrightarrow} (\mathbf{happy\ kim})$

b. $((\lambda x\ (\lambda y\ ((\mathbf{see}\ x)\ y)))\ (\mathbf{friend\text{-}of}\ y)) \overset{\beta}{\not\Longrightarrow} (\lambda y\ ((\mathbf{see}\ (\mathbf{friend\text{-}of}\ y))\ y))$

(3) a. $(\lambda x\ (\mathbf{dog}\ x)) \overset{\eta}{\Longrightarrow} \mathbf{dog}$

b. $(\lambda x\ (\mathbf{see}\ x)\ x) \overset{\eta}{\not\Longrightarrow} (\mathbf{see}\ x)$

3 Intensional indices

- In intensional versions of the above, declarative sentences denote functions from intensional indices into truth values.
- To evaluate for truth, we need to do so at a particular index.
- If S is a declarative sentence, then asserting S might involve a pretense of $[\![S]\!](@)$, where @ denotes the actual world.
- (Not that you know which world you're in.)
- Information gain coresponds to eliminating worlds as contenders for the actual world.
- Montague's (1973) intensional indices are world–time pairs.
- Possible worlds are *complete* specifications of alternative realities.

Lewis (1970:24):

> Contingent sentences depend for their truth value on facts about the world, and so are true at some possible worlds and false at others. A possible world corresponds to a possible totality of facts, determinate in all respects.

4 Entailment and related Katzian notions/desiderata

Definition 11 (Generalized entailment for meanings)**.** For all domains $\mathbf{D}$ and meanings $a, b \in \mathbf{D}$:

i. If $a, b \in D_e$, then $a \sqsubseteq b$ iff $a = b$
ii. If $a, b \in D_s$, then $a \sqsubseteq b$ iff $a = b$
iii. If $a, b \in D_t$, then $a \sqsubseteq b$ iff $a = \mathtt{F}$ or $b = \mathtt{T}$
iv. If $a, b \in D_{\langle\sigma,\tau\rangle}$, $a \sqsubseteq b$ iff for all $d \in D_\sigma$, $a(d) \sqsubseteq b(d)$

Definition 12 (Generalized entailment for forms)**.** For all models $\mathbf{M}$, assignments g, and expressions α and β, $\alpha \Rightarrow \beta$ iff $[\![\alpha]\!]^{\mathbf{M},g} \sqsubseteq [\![\beta]\!]^{\mathbf{M},g}$.

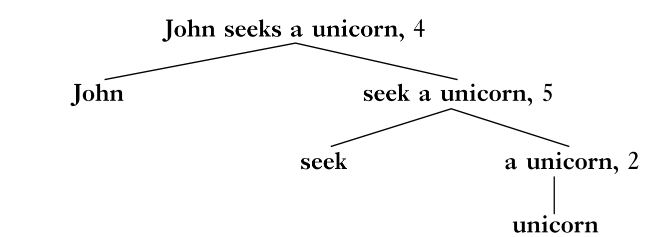
Definition 13 (Non-entailment, $\not\Rightarrow$)**.** If it's false that $\alpha \Rightarrow \beta$, then $\alpha \not\Rightarrow \beta$

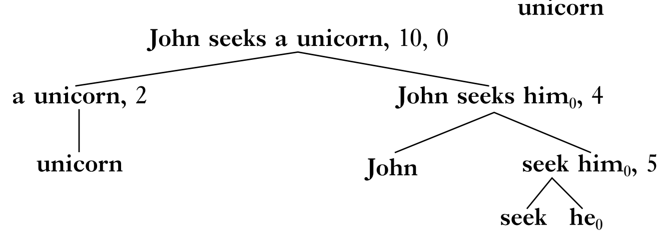
Definition 14 (Synonymy, $\equiv$)**.** If $\alpha \Rightarrow \beta$ and $\beta \Rightarrow \alpha$, then $\alpha \equiv \beta$.

Definition 15 (Antonymy)**.** [not sure . . . very tricky]

5 Syntax–semantics interface

Two semantically distinct Montagovian analysis trees, which are conceptually similar to logical forms.





In PTQ (Montague 1973), these are translated into an intensional logic, which is then interpreted. In UG (Montague 1970b), structures like this are interpreted directly. The current de facto standard in the field for the syntax–semantic interface is Heim & Kratzer 1998. For an extended modern treatment in the Montagovian mode, see Carpenter 1997.

6 Compositionality

Def. 1 states the compositionality principle informally. It is often attributed to Frege, but, as Janssen (1997:420) points out, Frege explicitly endorsed a 'principle of contextuality', which says "One should ask for the meaning of a word only in the context of a sentence, and not in isolation". This is more or less the contrary of compositionality. Janssen does concede that compositionality might be "in the spirit of his [Frege's —CP] later writings" (p. 421). See also Szabó 2012.

6.1 Definitions

Partee (1996:15–16) on 'unconstrained compositionality':

> Montague's paper 'Universal Grammar' [UG] [...] contains the most general statement of Montague's formal framework for the description of language. The central idea is that anything that should count as a grammar should be able to be cast in the following form: the syntax is an algebra, the semantics is an algebra, and there is a homomorphism mapping elements of the syntactic algebra onto elements of the semantic algebra. This very general definition leaves a great deal of freedom as to what sorts of things the elements and the operations of these algebras are.
>
> [...]
>
> It is the homomorphism requirement, which is in effect the compositionality requirement, that provides the most important constraint on UG in Montague's sense [...].

(4) Propositional logic interpretation as a homomorphism:

a. Syntax: $\langle P, \neg, \vee, \wedge \rangle$

b. Semantics: $\langle \{\emptyset, \{\emptyset\}\}, -, \cup, \cap \rangle$

c. The interpretation function $[\![\cdot]\!]$ is a homomorphism:

i. $[\![p]\!] \in \{\emptyset, \{\emptyset\}\}$ for all $p \in P$

ii. $[\![\neg\varphi]\!] = \{\emptyset, \{\emptyset\}\} - [\![\varphi]\!]$

iii. $[\![\varphi \vee \psi]\!] = [\![\varphi]\!] \cup [\![\psi]\!]$

iv. $[\![\varphi \wedge \psi]\!] = [\![\varphi]\!] \cap [\![\psi]\!]$

Dowty (2007) on 'rule-to-rule compositionality':

> For each syntactic rule the grammar specifies a unique corresponding semantic rule that applies to the meanings of the input expressions to yield a meaning for the newly formed expression. The nature of each compositional rule is not dependent on the form of the syntactic rule (though must observe type-theoretic well-formedness).

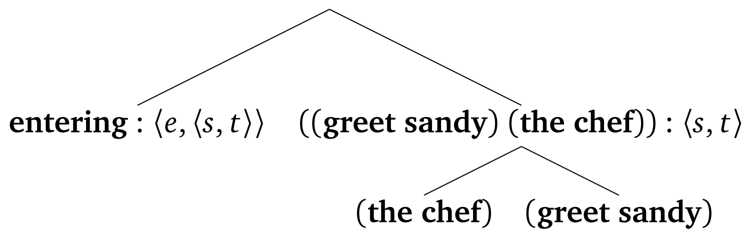
Dowty (2007) on 'context-free compositionality':

> When a rule f combines $\alpha, \beta(\ldots)$ to form γ, the corresponding semantic rule g that produces the meaning γ' of γ, from α' and β', may depend only on α' "as a whole", it may not depend on any meanings from which α' was formed compositionally by earlier derivational steps (similarly for β)."

(5) Consider the prescriptive rule saying that the implicit argument of fronted participial construction must be the subject of the matrix clause. This rule is not context-free compositional:

a. Entering the restaurant, the chef greeted Sandy.

b.



c. Assuming context-free compositionality, the rule cannot be right.

d. What's more, essentially no speakers maintain the rule, even those who advocate it: `http://arnoldzwicky.wordpress.com/category/danglers/`

6.2 Direct and indirect interpretation

Definition 16 (Indirect interpretation)**.**

$$\text{natural language} \leadsto \text{logic} \overset{[\![\cdot]\!]}{\Longrightarrow} \text{model}$$

Definition 17 (Direct interpretation)**.**

$$\text{natural language} \overset{[\![\cdot]\!]}{\Longrightarrow} \text{model}$$

Montague (1970b) is a direct interpretation system. Montague (1973) is an indirect translation system. Assuming both steps in the indirect mode are homomorphisms, the middle step can be eliminated by function composition. For a (rare!) indirect translation system where the intermediate step cannot be eliminated, see Potts 2005!

6.3 Other perspectives

- Overviews: Partee et al. 1993:§13.1; Szabó 2012; Pagin & Westerståhl 2010
- Partee (1984) discusses the nature of the compositionality principle in semantics and looks at a number of potential challenges and counterexamples, most stemming from context-dependence.
- The 'direct compositionality' of Jacobson (1999, 2000), Barker (2002, 2005), and Shan (2001) demands a particularly austere syntax and tight syntax–semantics connection. See also the essays in Barker & Jacobson 2007.
- Zadrozny (1992) and Horwich (1997) argue that compositionality has no empirical bite, because any analysis can be cast in compositional terms.

7 Famous examples

7.1 PTQ

Definition 18 (Montagovian types; Montague 1973)**.** The set of Montagovian semantic types is the smallest set $\mathit{Types}_{\mathbf{M}}$ such that

i. $e, t \in \mathit{Types}_{\mathbf{M}}$

ii. If $\sigma, \tau \in \mathit{Types}_{\mathbf{M}}$, then $\langle \sigma, \tau \rangle \in \mathit{Types}_{\mathbf{M}}$

iii. If $\sigma \in \mathit{Types}_{\mathbf{M}}$, then $\langle s, \sigma \rangle \in \mathit{Types}_{\mathbf{M}}$

Correspondingly, Montague (1973) has no variables over possible worlds, nor do any constants denote possible worlds. The intensionality of the system is entirely hidden away in the interpretation function and two operators: $({}^{\wedge}\alpha)$ intensionalizes α and $({}^{\vee}\alpha)$ extensionalizes it at the current index of interpretation. This seems to have been driven by Montague's view of the linguistic reality of possible worlds. It's puzzling that he would care to have his type-system reflect this, since it contains a vast number of linguistically implausible types. This classic textbook treatment of Montague's position is Dowty et al. 1980, which even appears in Wallace 1996. See also Campbell 2009.

7.2 Gallin

Definition 19 (Gallinian types; Gallin 1975)**.** The set of Gallinian semantic types is the smallest set $\mathit{Types}_{\mathbf{G}}$ such that

i. $e, t, s \in \mathit{Types}_{\mathbf{G}}$

ii. If $\sigma, \tau \in \mathit{Types}_{\mathbf{G}}$, then $\langle \sigma, \tau \rangle \in \mathit{Types}_{\mathbf{G}}$

Correspondingly, Gallin (1975) has variables over possible worlds and could have constants referring to possible worlds. The intensionality of the system is right there in the open. A constrained version of Montague's $({}^{\wedge}\alpha)$ can be defined as $(\lambda w\ (\alpha\ w))$, and $({}^{\vee}\alpha)$ can be defined as $(\alpha\ w)$ where w is the current index of interpretation. Gallin's version is the standard. See Gamut 1991 for an extended textbook presentation.

7.3 Language in Action

Definition 20 (Benthemian types; van Benthem 1991)**.** The set of Benthemian semantic types is the smallest set $\mathit{Types}_{\mathbf{JFAKvB}}$ such that

i. $e, t \in \mathit{Types}_{\mathbf{JFAKvB}}$

ii. If $\sigma, \tau \in \mathit{Types}_{\mathbf{JFAKvB}}$, then $\langle \sigma, \tau \rangle \in \mathit{Types}_{\mathbf{JFAKvB}}$

The twist is that t indexes the set of propositions (the powerset of the set of worlds). The system thus has an extensional feel to it but has some of the expressive power of Gallin's or Montague's.

8 Reference, sense, and beyond

Frege (1892/1980:57):

> It is natural, now, to think of there being connected with a sign (name, combination of words, letter), besides that to which the sign refers, which may be called the reference of the sign, also what I should like to call the *sense* of the sign, wherein the mode of presentation is contained.

One of the central claims of Montague's work is that Fregean senses are just more abstract and general referents:

(6) **the president of the U.S.** : $\langle s, e\rangle$ (Montagovian sense)

$$\begin{bmatrix} \langle @, 1984\rangle & \mapsto & [\![\textbf{Ronald Reagan}]\!] \\ \langle @, 1992\rangle & \mapsto & [\![\textbf{George H.W. Bush}]\!] \\ \langle @, 1996\rangle & \mapsto & [\![\textbf{Bill Clinton}]\!] \\ \langle @, 2002\rangle & \mapsto & [\![\textbf{George W. Bush}]\!] \\ \langle @, 2009\rangle & \mapsto & [\![\textbf{Barack Obama}]\!] \end{bmatrix}$$

a. $[\![\textbf{the president of the U.S.}]\!](\langle @, 1984\rangle) = [\![\textbf{Ronald Reagan}]\!]$ (referent)

b. $[\![\textbf{the president of the U.S.}]\!](\langle @, 1996\rangle) = [\![\textbf{Bill Clinton}]\!]$ (referent)

Katz & Katz (1977:81–82):

> The "denotations" of this paper [Montague 1970a—CP] are what Montague later came to call "senses" and to what we are granting the name "intensions," that is, functions from possible worlds to extensions. Hintikka is even more explicit. In "Semantics for Propositional Attitudes" he argues for a semantic theory drawing only on the notions available in modal logic: "the only entities needed in the so-called theory of meaning are, in many interesting cases, and perhaps even in all cases, merely what is required in order for expressions of our language to be able to refer." D. Lewis argue that interpretations of sentences should be "an assignment of extension in every possible world." [footnote: Lewis 1969:171]

Frege's (1892/1980:73) proto-conventional implicatures:

> Subsidiary clauses beginning with 'although' also express complete thoughts. This conjunction [. . .] actually has no sense and does not change the sense of the clause but only illuminates it in a peculiar fashion [footnote: Similarly in the case of 'but and 'yet'.] We could indeed replace the concessive clause without harm to the truth of the whole by another of the same truth value; but the light in which the clause is placed by the conjunction might then easily appear unsuitable, as if a song with a sad subject were to be sung in a lively fashion.

See also Frege 1918/1994; Horn 2007; Zalta 2013.

9 Intensions and hyper-intensions

In the above setting, if two expressions have the same extension in all possible worlds, then they are synonymous. As a result, all tautologies are synonymous with each other, as are all contradictions.

(7) a. John believes that the Morning Star is the Morning Star.
b. John believes that the Morning Star is the Evening Star.

(8) Adapted from Katz & Katz 1977:84:

a. John believes that Robert has two wives.
b. John believes that the number of Robert's wives is equal to the even prime.

(9) Katz & Katz (1977:88):

a. a square circle
b. a consistent division of a number by zero
c. a cube with a hundred edges
d. the largest natural number
e. something that does not exist in any possible world

f. the even prime/the number two
g. a triangle/a trilateral
h. a table which is not furniture/an elephant that is not an animal
i. 2+2=4/a consistent first order formalization of arithmetic is incomplete
j. one/the number which results when seven is subtracted from eight and zero is added one million times

Frege (1892/1980:58) seems to say that senses are richer:

> The expression 'the least rapidly convergent series' has a sense but demonstrably has no reference, since for every given convergent series, another convergent, but less rapidly convergent, series can be found. In grasping a sense, one is certainly not assured of a reference.

Lewis (1970:25) on meaning beyond intension:

> Intensions, our functions from indices to extensions, are designed to do part of what meanings do. Yet they are not meanings; for there are differences in meaning unaccompanied by differences in intension. It would be absurd to say that all tautologies have the same meaning, but they have the same intension; the constant function having at every index the value truth. Intensions are part of the way to meanings, however, and they are of interest in their own right.

Partee (1980):

> If P and Q are logically equivalent, we cannot validly make an inference from (1) to (2).
>
> (1) Irene believes that P.
>
> (2) Irene believes that Q.
>
> This problem is widely admitted, but seldom confronted within Montague semantics, since it results directly from the assumption that propositions are the intensions of sentences and are functions from possible worlds to truth values. Montague's semantics requires that logical equivalents be intersubstitutable everywhere, and it will take major modification to remove that requirement. [. . .]
>
> Suppose we view Montague's semantics as a super-competence model: a semantics for English as spoken by God. Then the semantics works perfectly well for the level 0 parts of the language, but it still fails for the propositional attitudes, since God would *not* make the inference from (1) to (2).

Lewis (1970:31) on meaning beyond intension:

> We have already observed that intensions for sentences cannot be identified with meanings since differences in meaning — for instance, between tautologies — may not carry with them any difference in intension. The same goes for other categories, basic or derived. Differences in intension, we may say, give us *coarse* differences in meaning. For *fine* differences in meaning we must look to the analysis of a compound into constituents and to the intensions of the several constituents.

Katz (1996:612) says Lewis's response is insufficient:

> If referential semanticists follow Lewis and take sameness and difference of the Carnapian intensions assigned to the constituents of expressions as sufficient for the expressions to be synonymous or nonsynonymous, they will wrongly mark synonymous expressions like "square" and "a parallelogram having four equal sides and four right angles" as nonsynonymous. If they do not follow Lewis and count only sameness and difference of the Carnapian intensions assigned to the expressions as a whole as sufficient for them to be synonymous or nonsynonymous, they will wrongly mark nonsynonymous but necessarily co-referential expressions like "two" and "the even prime" as synonymous.

Katz & Katz (1977:93) say Montague secretly has a full sense theory:

> However, Montague *does* use an intermediate system of representations in order to formulate his theory of reference and it is natural to interpret them as representations of senses. Montague associates with each English expression a number of *analysis trees*. [. . .] Analysis trees, unlike expressions, have unambiguous syntactic structures and it is analysis tees that are assigned both intensions and extensions (or "denotations" as Montague calls them) relative to interpretations (or "models").

Seems like this won't help with *square* and *parallelogram having four equal sides and four right angles*.

10 Meaning postulates and open-class lexical items

Carlson (1977):

Foreword

In the spring of 1976, Terry Parsons and Barbara Partee taught a course on Montague grammar, which I attended. On the second to the final day of class, Terry went around the room asking the students if there were any questions at all that remained unanswered, and promised to answer them on the last day of class. I asked if he really meant ANY question at all, which he emphatically said that he meant. As I had encountered a few questions in my lifetime that remained at least partially unresolved, I decided to ask one of them. What is life? What is the meaning of life? After all, Barbara and Terry had promised to provide answers to any question at all.

On the final day of class Barbara wore her Montague grammar T-shirt, and she and Terry busied themselves answering our questions. At long last, they came to my question. I anticipated a protracted and involved answer, but their reply was crisp and succinct. First Barbara, chalk in hand, showed me the meaning of life.

$$^{\wedge}\underline{\text{life}}'$$

Terry then stepped up and showed me what life really is.

$$^{\vee\wedge}\underline{\text{life}}'$$

As we were asked to show on a homework assignment earlier in the year, this is equivalent to: $\underline{\text{life}}'$.

Leaving me astounded that I had been living in such darkness for all these years, the class then turned to the much stickier problem of pronouns.

Thomason (1974:48-49), cited by Lepore (1983:180):

> The problems of a semantic theory should be distinguished from those of lexicography [...] A central goal of (semantics) is to explain how different kinds of meanings attach to different syntactic categories; another is to explain how the meanings of phrases depend on those of their components. [...] But we should not expect a semantic theory to furnish an account of how any two expressions belonging to the same syntactic category differ in meaning. "Walk" and "run," for instance, and "unicorn" and "zebra" certainly do differ in meaning, and we require a dictionary of English to tell us how. But the making of a dictionary demands considerable knowledge of the word.

In theories of the sort described here, lexical semantics is done via meaning postulates, which seek to ensure the needed entailments of lexical items and capture relationships between them:

(10) For all models $\mathbf{M} = \langle \mathbf{D}, ||\cdot||^{\mathbf{M}} \rangle$ appropriate for English:

a. $||\textbf{dog}||^{\mathbf{M}} \sqsubseteq ||\textbf{mammal}||^{\mathbf{M}}$

b. $||\textbf{dog}||^{\mathbf{M}} \sqsubseteq ||\neg\textbf{cat}||^{\mathbf{M}}$

c. $||\textbf{couch}||^{\mathbf{M}} = ||\textbf{sofa}||^{\mathbf{M}}$

d. For all $P \in D_{\langle e,\langle s,t\rangle\rangle}$ and $a \in D_e$, $||\textbf{find}||^{\mathbf{M}}(P)(a) \sqsubseteq ||\textbf{exist}||^{\mathbf{M}}(P)$ (cf. **seek**)

For discussion, Zimmermann 1999; Lepore 1983. For serious lexical semantics, see Levin & Rappaport Hovav 1995; Levin 1993; Levin & Rappaport Hovav 2005.

11 Meanings as partial functions

Arguably the dominant semantic account of presuppositions analyzes them using partial functions. For example, assume that *both*, as in *both linguists*, presupposes that exactly two salient objects have the property named by its first argument. On a partial-function analysis of this presupposition, we say that *both* denotes a function with only two-membered properties in its domain. Attempting to apply such a function to a property with one or three members results in *undefinedness*.

In defining the models above, I assumed that all functions were total. Some challenges arise when partiality is allowed:

- Partiality introduces a discrepancy between the expressions of the logic and the denotations they pick out: some expressions lack denotations entirely even though they are well-formed. For instance, if $\beta : \sigma$ and $\alpha : \langle\sigma, \tau\rangle$, then $(\alpha\ \beta)$ is well-formed. But if $[\![\beta]\!]$ is not in the domain of $[\![\alpha]\!]$, then $[\![(\alpha\ \beta)]\!]$ is undefined.

- It seems a mistake to make well-formedness of expression dependent on the models.

- Relational interpretations avoid the issue. Farmer (1990:1272): "neither natural nor efficient". Muskens (1989, 1995): the height of naturalness and efficiency.

- Schönfinkel (Currying) identifies an isomorphism between $D_{\langle\sigma\times\rho,\tau\rangle}$ and $D_{\langle\sigma,\langle\rho,\tau\rangle\rangle}$. This isomorphism disappears if we allow partial functions (Tichý 1982; Muskens 1989, 1995).

- Muskens (1989:330): "If, for example, D is some domain then the partial functions from $D \times D$ into D cannot in general be isomorphic to the partial functions from D into the partial functions from D into D. If D has two elements then the first of these sets has $3^{2\times 2} = 81$ elements, while the cardinality of the second one is $(3^2 + 1)^2 = 100$. So the Schönfinkel identification is no longer possible."

- This shows that there is perhaps an over-abundance of unary functions. But only a *shortage* would worry me. Is the mapping from unary functions to multi-argument functions total? If so, then it seems we can still view things in either way.

(11) Example from (Muskens 1995:12): Assume $D_e = \{a, b\}$. Let $x \mapsto \#$ indicate that x is not in the domain of the function in question.

$$F_1 \in D_{\langle e,\langle e,e\rangle\rangle} = \begin{bmatrix} a & \mapsto & \# \\ b & \mapsto & \begin{bmatrix} a & \mapsto & a \\ b & \mapsto & b \end{bmatrix} \end{bmatrix} \qquad F_2 \in D_{\langle e,\langle e,e\rangle\rangle} = \begin{bmatrix} a & \mapsto & \begin{bmatrix} a & \mapsto & \# \\ b & \mapsto & \# \end{bmatrix} \\ b & \mapsto & \begin{bmatrix} a & \mapsto & a \\ b & \mapsto & b \end{bmatrix} \end{bmatrix}$$

$$\searrow \qquad \swarrow$$

$$F \in D_{\langle e\times e,e\rangle} = \begin{bmatrix} (a,a) & \mapsto & \# \\ (a,b) & \mapsto & \# \\ (b,a) & \mapsto & a \\ (b,b) & \mapsto & b \end{bmatrix}$$

The value $F_2(a)$ has no elements in its domain! Can't we just identify this function with the undefined value? If we can, then $F_1 = F_2$. Perhaps this is a quirk of this example.

12 Type-shifting

The type-shifting framework of Partee (1987):

Definition 21 (ident). $\lambda x\ \lambda y\ (x = y)$ e to $\langle e, t\rangle$

Definition 22 (lift). $\lambda x\ \lambda f\ (f\ x)$ e to $\langle\langle e, t\rangle, t\rangle$

Definition 23 (THE). $\lambda f\ \lambda g\ \exists x\ \big(\forall y\ ((f\ y) \leftrightarrow (x = y)) \land (g\ x)\big)$ $\langle e, t\rangle$ to $\langle\langle e, t\rangle, t\rangle$

Definition 24 (a). $\lambda f\ \lambda g\ \exists x\ ((f\ x) \land (g\ x))$ $\langle e, t\rangle$ to $\langle\langle e, t\rangle, t\rangle$

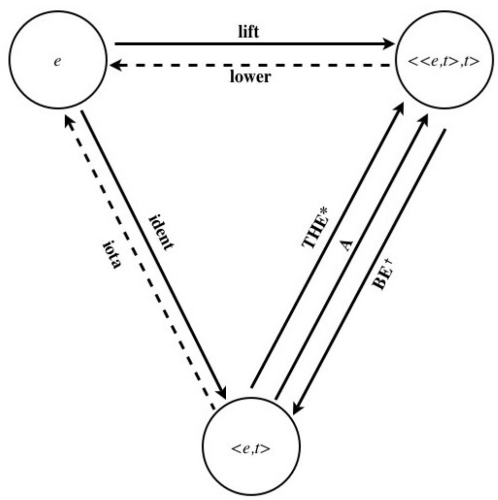
Definition 25 (BE). $\lambda P\ \lambda x\ \big(P\ (\lambda y\ (y = x))\big)$ $\langle\langle e, t\rangle, t\rangle$ to $\langle e, t\rangle$

Definition 26 ($\|$iota$\|^{\mathbf{M}}$). The function $F \in D_{\langle\langle e,t\rangle,e\rangle}$ such that for all $f \in D_{\langle e,t\rangle}$ $\langle e, t\rangle$ to e

- $F(f)$ is defined iff there is exactly one $d \in D_e$ such that $f(d) = \mathtt{T}$
- where defined $F(f)$ is the unique $d \in D_e$ such that $f(d) = \mathtt{T}$

Definition 27 ($\|$lower$\|^{\mathbf{M}}$). The function L such that for all $P \in D_{\langle\langle e,t\rangle,t\rangle}$, $\langle\langle e, t\rangle, t\rangle$ to e

- $L(P)$ is defined iff there is exactly one $d \in D_e$ such that for all $f \in D_{\langle e,t\rangle}$, $P(f)$ iff $f(d)$
- where defined, $L(P)$ is the unique $d \in D_e$ such that $P(f)$ iff $f(d)$



*outputs the empty set of sets if the input is not a singleton

†outputs the empty set if the input has no singletons in its domain

(12) a. Kim should see a doctor
b. Kim is a doctor.
c. A doctor entered. He looked cheerful.

(13) a. Kim met with the winner.
b. Kim is the winner.
c. The winner is Kim.

See also van Benthem 1991; Winter 2002; Asudeh 2004; Partee & Rooth 1983; Groenendijk & Stokhof 1989; Chierchia 1982, 1998; Jacobson 1992; McNally 1998; Bittner 1999; Jacobson 1999, 2000; Beck & Rullmann 1999; Barker 2005; Shan & Barker 2003; Mikkelsen 2004; Shan & Barker 2006; Barker & Shan 2008.

13 Looking ahead

i. Which aspects of these formal theories should be retained?

ii. What aspects of these formal theories should be discarded?

iii. What is our response to so-called hyperintensionality?

iv. Whither Fregean senses?

v. Can/Should the Montagovian program be pursued in a setting in which the denotations are mental representations?

vi. Is compositionality the aid to learning and expression that its proponents assume it to be?

vii. Are meaning postulates a sustainable vehicle for lexical semantics?

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