The Bluffer's Guide To Computational Semantics

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FraCaS

A Framework for Computational Semantics

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Abstract

This is a glossary of concepts relevant for computational semantics. The choice of lemmata is based on the concepts mentioned in the Pitlochry document and on previous FraCaS discussions.

Motto

Invent a word if you like. It may be adopted. It may even become popular. But don't reckon on its retaining the sense you gave it and perhaps explained with great care. Don't recken on its being given a sense of the slightest utility. Smart little writers pick up words briskly; but only as a jackdaw picks up beads and glass.

C.S. Lewis, *Studies in Words*.

Glossary

abduction Form of synthetic inference, where a particular case is inferred from a rule and a result. The term was coined by C.S. Peirce who distinguished three forms of reasoning: deduction, induction and abduction. An example of abductive reasoning is to conclude on the basis of ψ, $\phi_1 \rightarrow \psi$ and $\phi_2 \rightarrow \psi$ that ϕ_1. This jump to the hypothesis ϕ_1 is not sound reasoning, of course, and Peirce was aware of this: 'It is however a weak kind of inference, because we cannot say that we believe in the truth of the explanation, but only that it may be true'. Abduction is often used in common sense reasoning, e.g., in diagnosis and other forms of reasoning from effect to cause. Plausible constraints for abductive reasoning are given in Cox and Pietrzykowski [22].

abstraction Antonym: application. In LAMBDA CALCULUS, abstraction is the process of replacing one or more occurrences of a constant in a term by a variable, and then binding that variable by means of a lambda operator. Taking an example from typed λ calculus (see TYPE), if $(a : \langle e, t \rangle, b : e)$ is a term, then $\lambda x : e.(a : \langle e, t \rangle, x : e)$ is the result of abstraction over $b : e$ in $(a : \langle e, t \rangle, b : e)$. Thus, abstraction takes place by replacing a term in an expression by a variable and looking at the result (the abstract) as a function. Alternatively but equivalently, one might look at an abstract as an expression which is partially specified and has one or more roles for objects to which it can get applied to become more fully specified.

Here is a natural language example. Abstracting from *John* in the expression *John loves Mary* gives *x loves Mary*, and considering this as a functional expression gives $\lambda x.x$ *loves Mary*, which denotes the characteristic function that gives true for all individuals that do love Mary.

adjective Word such as *red*, *tall*, etc., which can be used to modify a common noun (in ATTRIBUTIVE position) (*the red ball*) or in PREDICATIVE

position (*the ball is red*). In Montague's semantics adjectives are treated as PREDICATE MODIFIERS. Adjectives are to nouns what adverbs are to verbs. See also ADVERBIAL MODIFICATION.

adverbial modification Modification of a verb, e.g. from *jump* to *jump quickly*.

algorithm Effective procedure. If one accepts the Church/Turing thesis: any procedure that can be performed on a Turing machine.

ambiguity Comes in several flavours: lexical, structural, derivational. Typically disappears when additional lexical, structural or derivational information is given. This feature distinguishes ambiguity from VAGUENESS.

analytic An analytic sentence or analytic truth is a sentence which is true by virtue of its meaning alone. Antonym: SYNTHETIC. Given a natural language fragment and a set of MEANING POSTULATES for that fragment, a sentence of the fragment is *analytic* if it is true in any model satisfying all the meaning postulates. A sentence of the fragment is *synthetic* if it does have counterexamples among the models satisfying all the meaning postulates. Given that the meaning postulates constrain the meanings of the vocabulary in the right way, we may assume that the real world (or some suitable aspect of it) will make all the meaning postulates true, so the synthetic sentences are precisely those that the world could be in disagreement with. The logically valid sentences are those that are true in any model of the language, irrespective of any meaning postulates.

It should be noted that for Immanuel Kant, the distinction between analytic and synthetic judgements had to do with the kinds of justifications we have for those judgements. A judgement in Kant's sense is a statement together with a justification for it. Statements with justifications in terms of definitions of the terminology used he called analytic, all other statements synthetic. As the truth of mathematical statements is not only a matter of definition but also of proof, mathematical statements, except for the most trivial ones, were classified as synthetic. When in the subsequent development of the theory of knowledge justifications got divorced from statements, the analytic/synthetic distinction got confused with the distinction between *a priori* and *a posteriori* statements, with as one of the results that later philosophers found it hard to agree on the status of mathematical truths. Frege considered knowledge of the natural numbers as analytic. Beth tried to reanalyse the notion of analyticity. Quine distrusted the whole concept.

anaphor Singular of ANAPHORA, which is (originally) a plural noun. Typically, an anaphor is a pronoun or a definite description that picks up a reference to an ANTECEDENT. In computational linguistics, any kind of pronoun or definite description that picks up a reference from elsewhere in the context is usually called an anaphor, while in Chomsky-style linguistics, the term 'anaphor' is usually reserved for reflexive and reciprocal pronouns.

anaphora Anaphora is the phenomenon in natural languages whereby certain expressions depend for their intepretation on other expressions in the sentence or discourse. The most obvious kind of case is an example like *Our manager is away at the moment. He is attending a meeting at head office.* Here the reference of the pronoun *he* is determined by the reference of the noun-phrase *our manager* which is referred to as the antecedent of the pronoun. This is a case of discourse anaphora since the pronoun and its antecedent are in different sentences in the discourse. Other cases of anaphora involve binding rather than coreference. Thus in the sentence *None of the managers thinks that she has any right to a raise* the pronoun *she* is bound by its antecedent *none of the managers.* Cases of nominal anaphora are not limited to pronouns. Temporal anaphora is where a reference to a time point made by a tensed verb gets fixed by linking it to the temporal reference made by another tensed verb. In the following example, the temporal sequence of events is fixed by temporal anaphora: *I opened the door, I reached for the light switch, I touched something slimy, and I almost fainted from fright.* This can also involve binding.

More complex are cases involving *the other*, or role anaphora as in *the car . . . the engine.*

anaphora resolution Fixing the references of anaphora, taking the constraints and clues provided by the linguistic and non-linguistic context into account.

anchor (1) Connection between a referential expression, e.g., a pronoun, a demonstrative, a variable or a discourse referent, and an object in the world. (2) The object that an expression is anchored to.

The effect of an anchor for an expression is to import the object directly into the proposition expressed by the sentence in which it occurs: the sentence is interpreted as attributing a certain property to the object.

antecedent Preceding bit of information: (1) anaphoric antecedent (see ANAPHORA), (2) antecedent of a conditional (see COUNTERFACTUAL), (3) antecedent of ellipsis (see ELLIPSIS).

antonymy Meaning opposition. In the simplest cases, two concepts are antonyms if their extensions partition a certain domain of application. Example: *male* versus *female*. There are also less simple cases, clearly in the same family, but less easy to characterize semantically: *fall* versus *rise*, *come* versus *go*, *back* versus *forth*. One of the task of lexical semantics is to spell out the precise connections in each of these cases. See also MEANING RELATION.

application Antonym: abstraction. Application is the process of combining a functor with an argument.

artificial intelligence Systematic attempt at making machines think for themselves.

aspect In English: perfect and progressive.

Further reading: Verkuyl [68].

aspectual classification Classification of verbs which is intended to explain differences in aspectual behaviour. The most common classification goes back to Aristotle and distinguishes the following four classes: (i) states(*k*now, believe, love), (ii) activities (*walk, jump, swim*), (iii) accomplishments (*sing a song, build a house*), and (iv) achievements (*recognize, find, lose, die*).

assertion Antonym: PRESUPPOSITION. Declarative sentences can be used to make statements when uttered in suitable contexts. The assertion of the sentence when uttered in such a context is the information that the speaker commits himself to the truth of the statement. Thus, an assertion that ϕ can be viewed as a map from contexts where a speaker is not committed to ϕ to contexts where that speaker is committed to ϕ.

assignment Mapping of a set of variables to a set of values. This concept plays an essential role in the truth definition for first order logic.

assignment statement Basic command in imperative programming to load a new value into a register (i.e., a location in memory). If the register is named by variable v, then the command takes the form $v := t$, where t is an expression of the approprate type to fill the register. A special case is random assignment, which is the command to store any new value at the location. Notation: $v :=?$.

attitude See PROPOSITIONAL ATTITUDE.

attributive position See PREDICATIVE POSITION.

automata Computational machines. Four important machine classes are finite state machines, stack automata, linear bounded automata and Turing machines.

Further reading: [39].

baseline fragment Term used in the FraCaS project for the body of linguistic constructions with an uncontroversial, well understood semantics. As yet this is non-denoting term (see UNICORN for another example of this phenomenon).

belief revision When an attempt is made to update a database Δ with a statement ϕ that conflicts with it (in the sense that $\Delta \cup \{\phi\} \vdash \bot$), Δ will have to be revised before ϕ can be added to it. The general aim of the research area of belief revision is finding principled ways of minimizing the changes involved. Retracting information from a database is sometimes called *downdating*.

categorial grammar Phrase structure grammar of a sort in which categories (see CATEGORY) and rules for complex category formation play a key role.

category Generally the term *category* is used in many different contexts to refer to sets or classes of objects. In linguistics a category is usually a class of words or phrases that are syntactically related.

In Montague grammar, the start categories are N and S, for names and sentences respectively. Simple verb phrases are those parts of speech which can form a sentence by taking a name to the left, which gives them category (N\S). Quantified noun phrases take a verb phrase to their right to form a sentence, which gives them category (S/(N\S)), and so on.

category theory The mathematical theory of categories, where a category is a GRAPH (a set of nodes with arcs or arrows between a source node and a target node) with a rule for composing arrows head to tail to give another arrow, and for every node A a special arrow id_A, the identity arrow on A. Examples are the category **Set** (the nodes are sets, the arrows all the functions between sets), the category **Fin** (the nodes are finite sets, the arrows all the functions between finite sets), and the category **Sem** (the nodes are semigroups, the arrows all semigroup homomorphisms). Note that category theory has nothing to do with syntactic categories.

Further reading: Bar and Wells [7].

character One of three aspects of meaning of expressions that are distinguished by Kaplan (the other two being EXTENSION and INTENSION). The character of an expression is a function from context to the intension for that expression in that context. INDEXICAL expressions such as *I*, *you*, have variable character. In Montague's Universal Grammar, the character of an expression is called its meaning.

classification Modelling domain-specific knowledge by means of a stratification of the domain of discourse in terms of classification features and distinctions such as *animate* versus inanimate. Special purpose classification languages such as KL-ONE have been developed for reasoning about classifications. Reasoning in KL-ONE is in fact a restricted form of first order reasoning. See also SORTAL RESTRICTION.

collective reading See PLURAL TERM.

common ground See COMMON KNOWLEDGE.

common knowledge Knowledge that is shared between two or more agents (normally taking part in a conversation) and known by those agents to be shared between them. See also SHARED BELIEF.

common sense Something every semanticist thinks (s)he has enough of.

common sense world See METAPHYSICS.

compositionality (principle of —) Principle according to which the meaning of a composite expression is a function of the meanings of its immediate constituents and the manner in which these constituents are put

together. It is commonly accepted now that in natural language semantics the principle advocates a methodology, rather than stating an empirical claim.

conversion Rewriting operation on expressions of Church's LAMBDA CALCULUS. There are three kinds of conversion in λ calculus: α conversion, β conversion and η conversion. α conversion is just shifting to an alphabetic variant. β conversion is an application of the equation $((\lambda x.M)N) = M[x := N]$, where M, N are λ terms and $M[x := N]$ denotes substitution of N for all free occurrences of x. η conversion is a special case of this where N is a variable x and where M does not have free occurrences of x, i.e., an application of the equation $((\lambda x.M)x) = M$.

concept (individual —) Function from contexts to entities. In Montague's PTQ [51], common noun denotations are properties of individual concepts. The reason for this treatment is the wish for a solution to semantic puzzles like: *The temperature is rising. The temperature is ninety*, from which it should not follow that *ninety is rising*. Montague's solution is to let *the temperature* denote an individual concept: a function from contexts (a world/time pairs) to temperature values which hold for those contexts.

concept analysis and formation The extent (or extension) of a concept is the set of things falling under it, its intent (not quite the same as intension) the set of attributes shared by all objects belonging to the concept. The extent of the concept *human* is the set of all human beings, while its intent is the set of all properties which all humans have (being mammal, being animal, being alive, and so on). Of course, in many cases one will need a particular context in order to be able to fix extension and intension of a concept. Formally, a context is a triple $\langle O, A, H \rangle$ where O is a set of objects, A a set of attributes, and $H \subseteq O \times A$ indicate which object has which attribute (oHa means: 'object o has attribute a'). For $P \subseteq O$ let P' be the set $\{a \in A \mid \forall o \in P : oHa\}$ and for $B \subseteq A$ let B' be the set $\{o \in O \mid \forall a \in B : oHa\}$. Thus, P' denotes the set of attributes shared by all objects in P, and B' denotes the set of objects having all attributes in B. A concept of context $\langle O, A, H \rangle$ is a pair $\langle P, B \rangle$ with $P \subseteq O$, $B \subseteq A$, $P' = B$ and $B' = P$. The extent of concept $\langle P, B \rangle$ is P, its intent is B. It is easy to see that for concepts $\langle P_1, B_1 \rangle$ and $\langle P_2, B_2 \rangle$, $P_1 \subseteq P_2$ iff $B_1 \supseteq B_2$. If $P_1 \subseteq P_2$ we say that $\langle P_1, B_1 \rangle$ is a subconcept of $\langle P_1, B_1 \rangle$. In formal concept analysis, a branch of applied lattice theory, these rudiments are worked out. It is to be expected that this by now a fairly well developed field will find application in natural language semantics.

Further reading: [23].

consequence (logical —) Statement which is true in any model of a given set of premisses Γ. The notation $\Gamma \models \phi$ is used for: ϕ is a logical consequence of Γ.

context (1) Source of values for indexical expressions in language. Words like *I, here, now* act as links to a context of utterance. Also, words like

current and *local*, as in *the current situation* or *the local police*, act as binders for linking nouns containing an implicit variable to a context. (2) In Montague grammar, a context of use is a formal specification of the pragmatic background information necessary to interpret the INDEXICAL EXPRESSIONs of the language fragment under consideration. A context for a language fragment containing the pronoun *I* has to include a specification of the speaker, and so on.

context dependency Property of natural language expressions that their meaning is determined or co-determined by context.

counterfactual Conditional expressing what would or might have happened had such and such been the case: *If John had bought that ticket, he would be rich now.* A well known semantic analysis of such constructions employs a similarity relation on POSSIBLE WORLDs, and evaluates the consequent of the conditional in those worlds in which the antecedent is true but that are otherwise similar to the actual world.

declarative See INDICATIVE.

de dicto/de re belief The sentence *John believes that the president of the USA is a criminal* can be used to report two different kinds of belief. If the reported belief is *de dicto* or 'about what is said', then John is reported to believe that whoever fits the description *president of the USA* has the stated property. If the belief is *de re* or 'about the thing', then John is reported to believe about the specific individual who fits the description that he has the stated property. In Montague grammar, the distinction between these two kinds of belief is drawn by either assuming that the description is generated *in situ* (this leads to the *de dicto* reading), or assuming that the sentence is the result of QUANTIFYING IN the description *the president of the USA* for *PRO* in the expression *John believes that PRO is a criminal* (this gives the *de re* reading).

default inference Inference based on the assumption that the explicitly given set of premisses Γ is tacitly extended with a set of premisses Δ to encode that we are in a 'standard' or 'default' situation. Γ has ϕ as a default consequence then means $\Gamma \cup \Delta \models \phi$. Extending Γ to Γ' may entail that the set of default assumptions Δ will have to be modified too. The result is that from Γ has ϕ as default consequence plus $\Gamma \subseteq \Gamma'$ it does not follow that Γ' has ϕ as a default consequence. Thus, default inference is a form of NON-MONOTONIC LOGIC.

definite Antonym: indefinite. Example: *the president of the USA*. A definite description is a description which, in the given context, can refer to one and only one object. The difference with a proper name is that the reference is fixed via a description of a property (such as *being president of the USA*).

deixis Pointing to the real world; an overly erudite synonym for indexicality (see INDEX).

demonstrative Word such as *that*, *this* which normally depends on some additional non-linguistic act of reference (e.g. pointing) to get its referent.

determiner Article. Syntactically, a determiner is an operator that combines with a common noun to form a noun phrase. Since noun phrases combine with verb phrases to form sentences, semantically a determiner can be viewed as a relation between common noun denotations and verb phrase denotations. In the simplest possible case, disregarding subtleties like the singular–plural distinction, determiners can be interpreted as relations between sets of individuals (noun denotations) and sets of individuals (verb phrase denotations). The determiner *some* is then interpreted as the relation of having a non-empty intersection, the determiner *every* as the relation of set-theoretic inclusion, and so on.

dialogue games Moves in a dialogue such as question, clarification, check which invoke a particular strategy to obtain information from one's interlocutor or confirm that the latest utterance has been understood.

discourse Minimal sense: anything that goes beyond a single sentence taken in isolation. Usual sense: a report of a linguistic communication with multiple participants.

discourse referent Thing we refer to in DISCOURSE when we don't know what we are talking about. The term was introduced by Karttunen.

discourse representation theory (1) Specific name for the theory of representing discourse in context proposed in Heim [38] and Kamp [40]. (2) Generic name for theories along the same lines.

discourse particle Particle like 'so', 'but', 'however', 'also'. Such particles steer the discourse, but the details of how they function are at present not well understood.

distributive reading See PLURAL TERM.

domain A class of terms containing its own continuous function space. Used to model the untyped lambda calculus. There are two functions which map between objects and the continuous functions they represent.

Further reading: Scott [61].

domain specificity (1) In the wrong place, a property to be avoided. Early computational language systems were often domain specific in that they relied on syntactic and semantic processing that was specially geared to a specific domain of application (e.g. weather reports). This allowed reasonable results to be obtained for that domain, but the whole system would have to be entirely rebuilt to be applied to a new domain. (2) In the right place, something entirely unavoidable. Language systems nowadays typically consist of a domain independent set of syntactic and semantic rules, plus additional domain specific information. This may

be statistical information about which syntactic constructions and word-senses are common or uncommon in the given domain, and/or it may be an explicit logical model of the domain used to support the kind of reasoning required by reference resolution and disambiguation. (3) *vs. task specificity.* In speech systems, 'task specific' is often used to mean the same as 'domain specific'. But it is often useful to distinguish between different tasks concerning the same domain.

donkey Animal turning up in Medieval example sentences to illustrate problems with the interpretation of pronouns. Donkeys were introduced into the modern semantic literature by Geach [35]. Also see UNICORN.

dynamic logic Logic with a semantics in terms of transitions from states to states. This kind of logic can be used to analyse imperative programming. For example, $y = 5 \rightarrow \langle x := y \rangle x = 5$ expresses that if $y = 5$ holds just before the assignment statement $x := y$ gets executed, then the assignment $x := y$ has as a result hat $x = 5$ holds afterwards. Dynamic logic is also useful for the analysis of change in natural language analysis, e.g., the change that comes about when a new referent gets introduced and becomes available for subsequent anaphora.

Further reading: Harel [37], Groenendijk and Stokhof [36].

dynamic semantics Semantics for natural language which focusses on the context change aspect of the meaning of natural language expressions, and employs some version of DYNAMIC LOGIC as logical representation language.

ellipsis The phenomenon where part of the syntax and/or semantics of a natural language sentence or text (the elliptic clause) has to be reconstructed on the basis of similarity with another part of the sentence or text (the antecedent). Here are some examples, with their linguistic labels. Gapping: *John went to Paris by car, and Bill by train*, comparative ellipsis: *John sent more letters to Mary than Bill to Sue*, verb-phrase ellipsis: *John wrote to Mary, and Bill did too*, 'one'-anaphora: *John owns a red BMW, and Bill owns a white one*, and sluicing: *Somebody left, but we don't know who*. It is unclear yet what the status of ellipsis phenomena with respect to the syntax-semantics distinction is. Some kinds of ellipsis (e.g. *gapping*) are close to syntax, other (e.g. *verb-phrase ellipsis*) behave much like ANAPHORA.

entailment Just another name for logical consequence.

epsilon operator Or: ϵ operator. Binds a variable x in a formula ϕ to form a term $\epsilon x.\phi$. In case there are objects satisfying ϕ, this term gets interpreted as an arbitrary object satisfying ϕ, otherwise the term gets mapped to a special object s to signify that there are no ϕ. Technically, this gets accomplished by a choice function Φ mapping every non-empty subset of a domain of discourse D to one of its elements, and mapping $\emptyset$ to the

special object s. Thus, epsilon terms provide witnessing terms for existential formulas. Hilbert introduced epsilon terms to analyse the Fregean quantifiers, but he used them only as a proof theoretic device.

event In the view of Reichenbach [59], an event is just a different way of looking at a fact. In the view of Davidson [24], events are objects referred to by sentences containing action verbs. The existence of negative facts (e.g. *John did not come*) but not of negative events would indicate some kind of distinction between facts and events. If there is a difference, there are clearly also very close connections: e.g. events are what make facts true (or false).

In the view of Reichenbach, an event is just a different way of looking at a fact. In the view of Davidson, events are the denotations of action verbs. In Davidson's treatment of events, each action verb predicate is equipped with an extra argument place to hold a term referring to an event. Modifiers of the verb (e.g. temporal adverbs, manner adverbs and PPs) can then be treated as extra predications on the event conjoined to the main verbal predication. So *John saw Mary in London* can be analysed as $see(e, j, m) \land in(e, l)$. Adverb dropping inferences (from 'John saw Mary in London' infer 'John saw Mary') correspond to conjunct dropping. Davidson's treatment allows for modification of an n-ary predicate by m modifiers without having to construct a $n + m$-ary predicate. The neo-Davidsonian analysis pushes this even further, so that n-ary predications are treated as a conjunction of binary predications on the event, e.g. $see(e) \land agent(e, j) \land patient(e, m) \land in(e, l)$. Conjunct dropping can then be used to account for things like passivisation (*Mary was seen*).

An alternative treatment of adverbial modification can be framed in terms of PREDICATE MODIFIERs, giving exactly the same truth-conditions as an event-based treatment, and again without recourse to verbal predicates of variable arity. However, predicate modifier approaches make extensive use of MEANING POSTULATEs in order to validate adverb dropping inferences, whereas under Davidson's treatment the inferences follow as a matter of logical form alone.

Further reading: [24], [25], [4], [54], [41].

extension(al) Antonym: intension(al). A language E is extensional if the following holds for alle expressions E of the language. If e is a well-formed proper part of E, and if e is replaced in E by an expression having the same interpretation as e, then the interpretation of E does not change.

fact True atomic proposition. It depends on one's point of view whether there are also negative facts.

fancy Derogatory term used in this glossary for cases where changes of terminology are carried through for purposes other than furthering insight.

feature constraint Constraint on the applicability of a syntactic rewrite instruction stated in terms of features of the constituents. For example,

$$S ::= NP(\text{number=X}, \text{person} = Y)VP(\text{number=X}, \text{person} = Y)$$

states that a sentence may consist of an NP followed by a VP, provided that the two constituents agree in their number and person features.

feature logic Logic for FEATURE STRUCTURES.

Further reading: Keller [42].

feature structures Mathematical objects employed to represent linguistic objects, usually in the context of a UNIFICATION based formalism. An example is:

$$\left[\begin{array}{ll} \text{cat} & \text{NP} \\ \text{agr} & \left[\begin{array}{ll} \text{number} & \text{singular} \\ \text{person} & 3 \end{array} \right] \end{array} \right]$$

first order logic First order logic is the logic which allows quantification over *entities of the first order*, that is to say over *individual objects*. This logic was essentially invented by Gottlob Frege and later streamlined by Alfred Tarski. First order logic is very expressive. For natural language semantics one of its disadvantages is that its only building blocks are formulas and terms, while in natural language one needs semantic building blocks for many more categories of expressions. However, it is possible to enrich the language of terms so that it encompasses objects which can be put in correspondence with the natural language categories: see PROPERTY THEORY.

Further reading: Enderton [28].

focus (1) Ill-understood notion from the informal theory of information processing. Antonym: topic. The expression of new information in a sentence, brought into the foreground by an utterance of the senteice. In traditional truth conditional semantics this notion is difficult to capture. One might think of the focus as that which expresses the new information in an answer to a question. *Who spilt the milk on the pizza? Harry did/spilt the milk on the pizza.* There is normally a correpondence between this kind of focus and the intonation focus in a sentence. One way to think of this kind of focus is in terms of implicit questions that arise during the course of a discourse or dialogue. (2) Focus in context, for pronoun RESOLUTION. Local focus (Sidner): most salient noun phrase to serve as antecedent for a particular occurrence of a pronoun. Global focus (Grosz): the situation that you have to take into account in the task of resolving a particular occurrence a pronoun. (3) Focus in the sense of particle focus (*even, only*).

formal language theory Branch of mathematics which studies formal languages and their properties. There is a close connection with the theory of AUTOMATA.

Further reading: [39].

formal specification Set of techniques developed in computer science for the abstract specification of software. The idea, on at least some versions, is to first give a high level description of what a program is supposed to do and then to refine this in more and more detail until an actual program is obtained.

frame problem Problem which arrises in the context of modelling change. Effecting a change in the world will affect the value of several propositions that describe the situation. But how do we know which propositions are affected and which propositions are not? The problem has first been described by McCarthy [49] in terms of his so-called SITUATION CALCULUS. Shoham [62] gives a clear presentation of the problem in a more standard logical style.

Further reading: Brown [16].

Frege structure A weakly typed domain of terms with two classes of objects that represent true and false propositions respectively. All terms are taken to be individuals. The paradoxes are avoided as terms representing them do not fall into either class.

Further reading: Aczel [1].

generalized quantifier theory Generalized quantifier theory, first proposed by Mostowski [53], provides a relational perspective on quantifiers. In this perspective, a quantifier is viewed as a two-place relation on the power set of a domain of discourse E satisfying certain requirements. The power set of a set E, notation $\mathcal{P}(E)$, is the set of all subsets of E. A two-place relation on $\mathcal{P}(E)$ is a set of pairs of subsets of E. The relational perspective on quantification is implicit in Montague grammar. It covers non standard quantifiers (quantifiers which cannot be defined in first order logic, such as 'most'), it does not syntactically eliminate quantified noun phrases, and it can be used as one of the ingredients in a *non ad hoc* translation procedure from natural language to a language of logical representations.

Further reading: Barwise and Cooper [10], Van Benthem [13; 14], Van Eijck [27], and Westerståhl [69].

generation Producing natural language output on the basis of formal representations in some LOGICAL FORM language.

generic Antonym: specific. Generic statements such as *birds fly* are like universal statements, but are harder to refute, because of a certain DEFAULT element in their meaning, which allows certain counterexamples to be explained away as non-typical.

graded adjective Adjective which can apply to a noun to a certain degree, in the way 'beautiful' can to 'girl', but 'pregnant' cannot. Graded adjectives

allow formation of comparatives and superlatives, nongraded adjectives do not.

graph A collection of nodes together with a collection of directed links between those. The links are called arrows or arcs. For every arrow it is indicated what its source and target node are.

heuristic Fallible strategy for finding things.

higher order logic Logic in which quantification over objects of higher degree than the first (i.e., individual objects) is allowed. In second order logic, quantification over predicates is allowed, in typed logic, quantification over expressions of all types is allowed. Higher order logics have great expressive power but unpleasant meta-properties. In general, they do not admit of complete axiomatisations.

hyponymy The relation of hyponymy holds between two words if the extension of the first is a strictly smaller than the extension of the second. 'Bulldog' is a hyponym of 'dog', as the set of all bulldogs is a proper subset of the set of all dogs.

identity puzzles Puzzles related to the fact that the same object may appear to us under different guises, where the guises give rise to different names or descriptions for the object. Frege's morning star — evening star paradox is a prime example.

> She gave me some examples of the sort of thing philosophers got up to. Like, how can you tell that the 'Morning Star' and the 'Evening Star' are really the same thing? I bounced back by saying that surely they *weren't* the same thing: even if they shared a parent company they were still two separate titles and would therefore be considered quite distinct for budgeting and tax purposes and so on. Philosophy's a doddle, I thought, and I said, 'Okay. Do me another one.'
>
> Martin Amis, *Money: A Suicide Note*

iff if and only if.

illocutionary force A notion from SPEECH ACT theory, the basic force of an utterance (e.g. declarative, request, order) often indicated by the syntactic form of the sentence.

imperative Syntactic form used to request or order as in *Leave immediately. Please pass me the sugar*. Imperative mood is one of the three major moods of speech, the other two being INDICATIVE and INTERROGATIVE mood. Semantically, imperative mood conveys an intention of the speaker to make the addressee responsible for a certain action.

implicature A notion invented by the philosopher H.P. Grice. An implicature follows from a sentence but is not entailed by it. Conversational

implicatures arise through the interaction of the proposition expressed by a sentence with the context and general principles of cooperativeness. For example, if I ask *Is there a gas station near here?* and I answer *There's one round the corner on Union Street.* That implicates that I think it might be open and that it has petrol for sale. Conversational implicatures are cancellable, in that they can be explicitly negated. For example, I might continue my answer with *..but I think it might be closed now.* Conventional implicatures arise from the linguistic form of the sentence. For example, *He managed to get the car started* conventionally implicates that it was difficult for him to get the car started. These implicatures cannot be cancelled and they persist under negation (unlike ENTAILMENTS). Conventional implicatures have been considered as one kind of PRESUPPOSITION.

incremental procedure Procedure able to process input which is not yet complete, and able to later incorporate the rest of the input without having to do a complete recomputation. For instance, a parser might start to work before the whole input sentence has been spoken or typed. *Incremental interpretation* usually refers to the interleaving of syntactic, semantic and perhaps pragmatic processing, and can be used to prune away fragmentary syntactic analyses that are semantically or pragmatically anomalous. The term 'incremental' has been used to refer to a number of things, some of which are described below.

Fully incremental procedures are able to accept additions at any location in their input (not only at the end). A fully incremental procedure must be *confluent* (see NORMALIZATION), i.e. it should make no difference to the final result which bits of input are processed before which others. One way of guaranteeing confluence is to ensure that the processing operations are *monotonic*. Suppose that before processing any input, the range of possible results is R. Monotonicity means that as more input is processed, the range of possible results monotonically decreases: new input cannot reinstate a result that was previously discarded. (In practice, one is more likely to build up possible results rather than discard impossible ones, but the abstract characterisation of monotonicity still holds.)

Left-right incremental procedures process input in a strict left to right order, taking one 'chunk' at a time. Confluence/monotonicity is not required, and the order in which input is processed can potentially make a difference to the results.

Deterministic procedures never have to do *any* recomputation to incorporate further input. Determinism can hold for both fully and left-right incremental procedures.

inconsistency Property that a set of sentences has if its deductive closure (under some logic under consideration) is the set of all sentences of the logical language. Inconsistent sets of sentences do not convey any information. This stern approach gets relaxed in logics which draw a distinction be-

tween explicit derivations of contradictions and contradictions that are left implicit (so-called para-consistent logics).

indefinite Example: *a man*. In classical logic, indefinites get treated as existential quantifiers. In Montague grammar, disregarding intensions, *a man* gets translated as $\lambda P \exists x (\text{man' } x \wedge Px)$. In dynamic semantics, indefinites get special treatment in that they are supposed to introduce new referents into the discourse.

index (1) In 'indexical expression': pointer to the real world. (2) In 'index of an expression': syntactic adornment for purposes of disambiguation. Example: *John$_i$ said that he$_i$ liked Sue*. The indices make clear that *he* anaphorically refers to *John*.

indexical expression Expression that has a link to the real world as part of its literal meaning. This link is sometimes called an ANCHOR in the RESOURCE SITUATION. Examples: in *I am here now*, 'I' is linked to the speaker in the situation of utterance, 'here' is linked to the location of utterance, and 'now' is linked to the speech time. All these expressions are indexical. The whole utterance is an example of a pragmatic ANALYTIC truth.

indicative One of the three major moods of speech, the other two being IMPERATIVE and INTERROGATIVE. Typically, an indicative sentence is used for making an ASSERTION, which is to say that indicative mood conveys an intention of the speaker to transmit information by means of a description of how things are. Example: *The cat is on the mat.*

indirect speech act A speech act whose communicative intention is distinct from the speech act directly indicated by the utterance. For example, *It's cold in here* is an assertion but may be used as a request to get somebody to close the window. The request is an indirect speech act in this case.

inference Process of drawing logical consequences.

infon Fancy way of referring to a LITERAL.

intension Antonym: extension. Pretheoretically, the distinction between extension and intension (or in Fregean terms: *Bedeutung* and *Sinn*, or *gerade Bedeutung* and *ungerade Bedeutung*) has to do with interpretation in a given context versus interpretation independent of context. Carnap [18], who coined the terminology, used *intension* for a function from models to extensions in that model. In POSSIBLE WORLD semantics, extensions are interpretations in a given world, while extensions are functions from worlds to extensions in that world. In Montague grammar, the intension of an expression is a function from pairs consisting of a world an a time point to the extensional interpretation for that expression for that world/time index. In the case of a sentential expression such as *It rains*,

the extension is the truth value of the expression in the model at the current world/time index, while its intension is a function from world/time indices to truth values.

intensional In its graded sense, as an attribute of theories, this is related to the strength of equality in that theory. The weaker (stronger resp.) the sense of equality, the more intensional (extensional resp.) the theory.

intensional isomorphism Proposal of Lewis [46], following Carnap [18], to explicate the notion of sameness of meaning. An intensional isomorphism maps INTENSIONS to intensions, intensions of syntactic constituents to intensions of constituents, and so on recursively.

intensional verb Example *John seeks a girlfriend* might mean that John is looking for Sue, who happens to be his girlfriend, but it might also mean that John is answering small ads in the lonely hearts column because he wants to create a situation in which he has a girlfriend. Under the second reading of this example, John is related, not to an individual, but to the set of possible contexts which contain a girlfriend for him. Such possible contexts are often called POSSIBLE WORLDS.

intention Relation between an agent and a possible action. Intentions are used in the semantics of (intentional) verbs like *want* and *desire*. Theories of intention analyse the semantics of such verbs in the context of notions of rational choice, planning and commitment.

Further reading: Cohen and Levesque [19].

interpretation Function in a model which assigns appropriate values to the term constants, function constants and predicate constants of that language.

interrogative mood One of the three major moods of speech, the other two being indicative and imperative mood. Semantically, interrogative mood conveys an intention of the speaker to sollicit information of the addressee. An interrogative is a request for information and normally takes the form of a question.

interrogatives (1) Questions. (2) Sometimes, e.g. in the tradition of *erotetic logic* (the logic of questions), one distinguishes the sentences (the interrogatives) from the corresponding speech acts (*the questions*). The reason for the distinction is that not all questions are expressed by interrogatives, and not all uses of interrogatives have the purpose of asking a question.

intersective adjective Adjective with the property that 'being an Adj N' is equivalent to being an N and being Adj'. Its translation typically takes a form like the following:

$$\lambda P \lambda x (Px \wedge Ax).$$

For example, *white* might be translated as:

$$\lambda P \lambda x (Px \wedge \textit{white' } x).$$

iota operator Or: ι operator. This operator maps singleton sets to their elements, everything else to some special *undefined* element. ι is sometimes used for the semantics of definite descriptions.

knowledge representation The field of ARTIFICIAL INTELLIGENCE devoted to the study of techniques for representing the kind of knowledge humans use in their everyday reasoning, as well as of the reasoning patterns themselves. This includes the study of commonsense reasoning, default and nonmonotonic reasoning, belief revision, and the study of the properties of various non-standard logics such as terminological logics.

One way of representing what an agent knows is by means of a set of axioms T in some logic. Assuming logical omniscience, the set of statements the agent knows to be true then is the set $\overline{T} = \{\phi \mid T \vdash \phi\}$, where $\vdash$ is the relation of logical deducibility for the logical language under consideration. Another way of representing this body of knowledge is as $\mathrm{Mod}(T) = \{M \mid \text{ for all } \phi \in T, M \models \phi\}$. One way to think of this is that, for all the agent knows, any member of the set of *possible worlds* $\mathrm{Mod}(T)$ might be the real world. For particular choices of representation language, the representation becomes more manageable. See PROLOG for an example.

lambda calculus Or: λ calculus. Abstract logical formalization of functions invented by Alonso Church. The syntax of λ calculus is given by $\Lambda ::= c \mid v \mid (\Lambda\Lambda) \mid (\lambda v.\Lambda)$, where c ranges over a set of constants and v over a set of variables. The only essential rule is the following equation: $((\lambda x.M)N) = M[x := N]$, where $M, N \in \Lambda$, and $M[x := N]$ denotes substitution of N for all free occurrences of x. An application of this equation to rewrite a term is called β conversion. The original λ calculus was untyped. Later, so called typed λ-calculi have appeared. See LAMBDA OPERATOR, TYPE.

Further reading: Barendregt [5], the classic textbook on the (untyped) lambda calculus.

lambda operator Or: λ operator. Binds a variable x in an expression E to form an expression $\lambda x.E$. In the typed λ calculus, if x is of type A and E is of type B then $\lambda x.E$ denotes the function of type $A \to B$ which maps (the interpretation of) a to (the interpretation of) $E[x := a]$.

lemma (1) In linguistics: same as lexical entry. (2) In mathematics: auxiliary theorem used in the proof of a more important theorem.

lexical entry The lexical entry of a word in a lexicon of a contemporary grammatical theory usually consists of the word (or its stem) and complex structures (typically FEATURE STRUCTURES) that represent the syntax, phonology and semantics of the word.

lexical semantics (also called *word semantics*) is concerned with: (i) the decomposition of word meanings into the meanings of smaller parts of language, including the decomposition of compound words and the decomposition of words into morphemes; (ii) the classification of words into

classes of semantically similar words; and (iii) MEANING RELATIONS between words. The main theoretical problem in lexical semantics is the difficulty of drawing a borderline between ANALYTIC and WORLD KNOWLEDGE. Another important problem is whether it is possible to derive a "proto" or LITERAL MEANING for each word, or whether a word with several different meanings must be given several LEXICAL ENTRIES. If one adopts the strategy of classifying multiple meanings into one literal and several derived meanings, the use of DEFAULTS is essential.

Further reading: A good overview of lexical semantics in Montague grammar is Dowty [25].

LF Meaning representation language that looks suspiciously like first order logic. In the Chomskyan tradition, this level is as close to semantics as you will ever get.

liar paradox The semantical paradox connected with the Liar sentence *This sentence is false*. Both the assumption that the Liar sentence is true and the assumption that it is false lead to a contradiction, which is the hallmark of a true paradox. As Gödel showed, a close relative of this paradox does affect first order logic: his famous incompleteness proof gives an explicit construction of a formalized version of a cousin of the Liar sentence in first order logic (his sentence is concerned with the concept of provability rather than truth, and it is a half-paradox rather than a full paradox). The Liar paradox does affect natural language semantics, for the Liar sentence is stated in natural language. A suitably dynamic perspective on the action of 'calling a sentence true' provides a way out. Such a revision theory of truth makes it possible to make semantic sense of the everyday usage of the truth and falsity predicates of natural language.

In axiomatic PROPERTY THEORY, the liar paradox cannot be shown to be a proposition, and hence its truth conditions cannot be considered.

literal In logic: atomic sentence or negated atomic sentence.

literal meaning The meaning of an expression "as is", in contrast to its meaning as a METAPHOR.

logical form See also LF. (1) A informal way of referring to the semantic structure of a sentence, usually as an expression in a logical formalism elucidating the truth-conditions of the sentence (e.g. an intensional higher-order logic). In this loose sense, there is no commitment to the logical formalism providing an ineliminable level of linguistic representation. (2) An (ineliminable) level of linguistic/semantic representation; see REPRESENTATIONALISM.

logical omniscience (problem of —) Difficulty that every attempt at representing knowledge by model-theoretic means, as the set of all possible worlds compatible with a body of knowledge, runs into, because this representation strategy implicitly assumes that the knowing agent has unlimited reasoning powers.

long-distance dependencies Where some kind of syntactic relation holds between two constituents, but the distance between the constituents is not restricted to some finite domain. Also known as *unbounded dependency* or *discontinuous constituency*. Relative clauses are one example: *The man who$_i$ John said that Fido bit []$_i$ is dead.* The relative pronoun *who$_i$* is related to the embedded clause *Fido bit []$_i$*. One could increase the distance between the related elements by further clausal embedding, e.g. *The man who John said that Mary thought Fido bit is dead.*

At a semantic level, long distance dependencies have been argued to result in a form of ABSTRACTION. The gap in the relative clause, []$_i$ acts as a kind of variable, which is bound by the relative pronoun *who$_i$* to form a property which is then applied to the noun phrase *the man*.

many-valued logic Logic based on a set of more than two truth-values. The initiator of this branch of non-classical logic is the Polish mathematician Jan Łukasziewicz. Many-valued logic can be seen as a generalization of PARTIAL LOGIC.

Further reading: Urquhart [67] gives an instructive survey of this field.

mass noun Antonym: count noun. Mass nouns are syntactically singular (*water/*waters was/*were everywhere*) but do not co-occur with singular indefinite determiners like *a*. However, mass nouns can occur in the plural either to indicate different types of a substance (*John tasted several whiskies*) or a number of conventionalised measures of the substance (*John dranks several whiskies and then fell down*). Count nouns can also take on a mass sense via a 'universal grinder' (*When the truck had gone, there was dog all over the road*).

mass term Antonym: count term. (1) Semantically, a mass term is one that refers to objects with divisive and cumulative reference. For example, the noun phrase *some whisky* refers to an object that is divisible (if you take a portion of the whisky you still have some whisky) and cumulative (if you add some more whisky, you still have some whisky). Singular count terms, e.g. *a chair* are neither divisible nor cumulative. PLURAL count terms are cumulative (if you have some chairs and add some more, you still have some chairs) but not straightforwardly divisible, since at some point plural terms will get divided down into non-divisible singular terms. (2) Syntactically there is a distinction between mass and count nouns (see MASS NOUN) that often — but not always — runs parallel to that between mass and count terms.

meaning (1) What language is about. (2) In Montague grammar, *meaning* is used as a technical term for a function from CONTEXTs to EXTENSIONs.

meaning postulate Formula intented to constrain the class of possible models of a language with the purpose of enforcing certain relations between elements in the vocabulary of the language.

To impose restrictions on the possible interpretations of the basic vocabulary of a formal language, one can stipulate that certain concepts should involve others. For instance, one may want to ensure that the concept of walking involves the concept of moving relative to something. Assuming that we have expressions $\lambda x.W(x)$ for walking and $\lambda y \lambda x.M(x,y)$ for moving with respect to, we can express the requirement as: $\lambda x.W(x)$ should involve $\lambda x.\exists y.(object(y) \wedge M(x,y))$. The semantic requirement is then imposed by restricting attention to models in which the first concept does indeed involve the second one, i.e., to models satisfying the relevant meaning postulate.

meaning relation In general any relation between the meanings of language units. Some well-known examples are ANTONYMY, ENTAILMENT, HYPONYMY, PARAPHRASE and SYNONYMY.

measure expression An expression like *two litres of*, *three kilos of* or the numeral *four*. Measure expressions describe the quantity or number of some object(s). Measure expressions have the effect of prohibiting cumulative and divisive reference (see MASS TERM); adding or removing anything from *two litres of whisky* or *four chairs* will not leave you with something that is still two litres of whisky or four chairs.

metaphor Expression whose intended meaning is different from the LITERAL MEANING, and must be derived through a comparison with a similar object or situation. Example: *The computer program crashed.* Many expressions originally introduced as metaphors are now so commonly used that they are not recognized as such anymore.

metaphysics (natural language —) Body of assumptions about the structure of the universe (the common sense world) implicit in our use of natural language, and often very difficult to make explicit.

metonymy Use of an attribute or adjunct of an object to refer to the object, e.g. *the White House* for the presidency of the United States. It is a phenomenon that is rife in everyday conversation, but has not been subject to much investigation in formal or computational semantics.

modality Non-truth functional functor forming sentences out of sentences. Modalities depend on the informational content of contexts, situations or worlds, which generally goes beyond the valuation at the current context. The archetypical modalities are *necessity* and *possibility*. If these are interpreted as describing properties of the world, then they are called *alethic modalities*, if they are interpreted as a reflection of an agent's knowledge of the world, they are called *epistemic modalities*. *It is possible that it rains* usually expresses epistemic modality, while *It is impossible that it rains on Mars* presumably expresses alethic modality. Other examples of modalities are the temporal modalities *at some time in the future*, *always in the future*, *at some time in the past* and *always in the past*.

modal logic Originally, the logic of *necessity* and *possibility*. The explication of the meaning of these concepts in terms of possible worlds, due to Carnap, Kanger and especially Kripke, has brought a wide range of applications. Possible world semantics plays a role in epistemology (Hintikka), in linguistics (Montague), in computer science (Pratt) and in artificial intelligence (Moore). Modal logic is often used as a general term to cover all kinds of logics with a possible worlds semantics.

modal operator Sentential logical operator which represents a modality. Prime examples are $\Box$ and $\Diamond$ for necessity and possibility, respectively, and the operators K and B in Hintikka's epistemic logic, for knowledge and belief of a rational agent.

model A model for a formal language is a domain of discourse D together with a set of instructions I for interpreting the non-logical vocabulary of the language. In the simplest case, D is a set of individuals, and I gives information about which individual is named by which name in the language, which set of individuals is denoted by which one place predicate symbol of the language, and so on.

monotonic semantics A (possibly FANCY) approach to semantic interpretation that focuses on the incremental resolution of UNDERSPECIFICATION and on the REVERSIBILITY of this process. QUASI LOGICAL FORM has been used as meaning representation language to support monotonic semantic interpretation, but does not necessarily constitute the only formalism suitable for this task.

Montague grammar A reasonably happy marriage between categorial grammar and intensional type theory, albeit with some sado-masochistic streaks. A classic version of the approach is given in [51].

Further reading: Dowty, Wall and Peters [26] give a textbook treatment of standard Montague grammar. A more recent textbook which also gives a discussion of later developments, is Gamut [33].

natural logic Logic for natural language expressed in natural language, more or less in the tradition of Aristotelian syllogistics.

Further reading: Sommers [63].

negation Semantically, (classical) negation is the function of type $\{0,1\} \rightarrow \{0,1\}$ which maps truth to falsity and falsity to truth.

In partial logic, negation is a function of type $\{0,1,*\} \rightarrow \{0,1,*\}$, and one has to distinguish between weak and strong negation. Weak negation acts like classical negation on the values truth and falsity, but maps the value undetermined to itself. Strong negation acts like classical negation on truth and falsity, but maps undetermined to false. Strong negation is also called exclusive or external negation.

In intuitionistic logic, negation is an intensional concept. Intuitionistically, negating a proposition means asserting the existence of a method

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to transform any hypothetical proof of the proposition into a contradiction.

non-monotonic logic Logic with the property that the validity of an argument from a set of premisses Γ to a conclusion C may get lost if the set Γ is extended.

Non-monotonic logics have been used to analyse common sense reasoning. Examples are Reiter's default logic [60], McCarthy's circumscription [48] and Moore's autoepistemic logic [52]. The use of non-monotonic logics for the analysis of common sense reasoning was first advocated by McDermott and Doyle [50].

normalisation Bringing an expression into normal form by a sequence of rewriting steps. An expression a is in normal form is there is no expression b with $a \to b$ (expression a rewrites to expression b). Normalisation only works in rewrite systems which have the property of *confluence* (also called the *Church–Rosser* property). A rewrite system is confluent if $a{\twoheadrightarrow}b$ and $a{\twoheadrightarrow}c$ (where $\twoheadrightarrow$ stands for the reflexive transitive closure of the rewrite relation) implies there is an expression d with $b{\twoheadrightarrow}d$ and $c{\twoheadrightarrow}d$.

notation Not to be confused with *theory* in semantics. Representations that are in one-to-one correspondence to other representations via a translation function are notational variants of each other. Polish notation and infix notation for propositional logic, e.g., are just notational variants: both $CCCpqpp$ and $(((p \to q) \to p) \to p)$ express Peirce's law. The translation function from Polish to infix is given by: $p^\bullet = p$, $(N\phi)^\bullet = \neg\phi^\bullet$, $(C\phi\psi)^\bullet = (\phi^\bullet \to \psi^\bullet)$. Another example is matrix notation versus modal logic notation for expressing FEATURE CONSTRAINTS.

operator (1) function expression denoting an operation on some domain A, i.e., a function in $A^n \to A$ (such an operation is called n-ary). Examples are the negation operator $\neg$, which denotes the function $\lambda x.|x - 1|$ in $\{0,1\} \to \{0,1\}$, and the disjunction operator $\vee$, which denotes the function $\lambda xy.\max(x,y)$ in $\{0,1\}^2 \to \{0,1\}$. (2) An expression that alters the context of evaluation of any expression within its SCOPE, e.g. by assigning a value to a variable or changing the possible world used as an index of evaluation. Examples of operators are the λ-operator, the quantifiers of first-order logic, the ι-operator, the Montagovian intension operator ˆ and the modal operators $\Box$ and $\Diamond$.

paradox Statement with the property that both the assumption that it is true and the assumption that it is false leads to a contradiction (in some logic). A prime example is the Russell paradox, which results from considering (in naive set theory) the set $R = \{x \mid x \notin x\}$ (the set of all sets which are not members of themselves). Both the assumption that $R \in R$ and the assumption that $R \notin R$ lead to a contradiction. The solution in this case was to modify and refine the reasoning system of naive set theory. An example of a paradox with relevance for natural language semantics is the LIAR PARADOX.

paraphrase Relation which holds between a word and a multiple description with the same meaning.

parsing Determining the syntactic structure of a natural language expression.

partial logic Logic based on partial model-theoretic parameters, such as partial interpretations and partial truth-assignments. One of the pioneers in this field is Luckasziewicz.

partial model Model which does not assign definite truth values to all atomic sentences of some language. In the case of predicate logic, a model M has a partial interpretation of some one-place predicate P if is at least one objects a in the domain of M with the property that P is neither true nor false of a. If it occurs in the language, the truth predicate is a prime candidate for a partial interpretation, in order to avoid the LIAR PARADOX.

partiality General name for incomplete specification. In a functional view on the mathematical universe, partiality is embodied in partiality of functions. A partial function is a relation f between a domain D and a range R such that every element of D is related to *at most* one element of R.

perception verb Verb expressing a relation between a subject and a perceived object (or sometimes a perceived situation or SCENE). Examples in: 'To *see*, to *hear*, to *touch*, to kiss, to die, in sweetest pain . . . (Dowland).'

planning The subfield of ARTIFICIAL INTELLIGENCE concerned with giving robots the ability to develop plans to achieve their goals in novel situations.

plural term Expression that denotes a group of individuals, for instance *two men, Jan and Robin, the researchers*. A possible type logical translation of *two men* is the following:

$$\lambda P \exists xy (x \neq y \wedge man' \, x \wedge man' \, y \wedge Px \wedge Py).$$

However, this translation covers only part of the meaning of the plural term. It only takes care of DISTRIBUTIVE READINGS. *Two men arrived* would get translated (disregarding tense) as:

$$\exists xy (x \neq y \wedge man' \, x \wedge man' \, y \wedge arrive' \, x \wedge arrive' \, y).$$

This translation procedure breaks down for examples like *Two men gathered*. The trouble is that the verb here forces a COLLECTIVE READING of the plural term. Another example is *Jan and Robin wrote a deliverable*, which may mean that the two researchers wrote a deliverable together.

polarity Negative polarity items are natural language expressions that are licenced by negative contexts, or more precisely by monotone decreasing contexts (contexts where replacing a set denoting expression by a set

denoting expression with a smaller extension yields a valid argument. Example: from *No man spoke* it follows that *No man spoke harshly.* Because the context *No man* — is monotone decreasing, the polarity item *lifted a finger* is licensed in *No man lifted a finger to help.* Compare this with *?Everyone lifted a finger to help.*

polymorphism Type-theoretical notion referring to multiple typing of a single object or term. Polymorphy is the result of allowing type variables in typed λ-calculi. An example of a function with multiple types is $\lambda x.x : A \rightarrow A$ (this is the identity function, which has all types $A \rightarrow A$, for A an arbitrary type). In natural language semantics, polymorphism is useful for a uniform semantic treatment of operators which can occur at different category levels, e.g., to express what sentential conjunction (*'It rained and it was cold'*), noun phrase conjunction (*'women and children'*), and verb phrase conjunction (*'walked and talked'*) have in common. See also TYPE SHIFTING.

possible world Complete specification of what (some relevant aspect of) the world could be like, for all we know. The concept first appeared in the work of Leibniz (and was ridiculed by Voltaire). It was given a technical sense by Carnap, Kripke, Lewis, and Hintikka in the semantics of possible worlds. Agent A's knowledge of ϕ is explained in terms of A's relation to a set of possible worlds, in each of which ϕ is true.

pragmatics Discipline which studies the use of language, as opposed to its structure (which constitutes the field of syntax), and its meaning (which is the domain of semantics).

Further reading: Levinson [45].

predicate The extension of a PROPERTY. Classically, a predicate characterises a set; a first order predicate is the denotation of an open formula $\phi(\overline{x})$ of first order logic, that is, the set of all tuples satisfying ϕ in some model for the language under consideration. A higher order predicate is the denotation of an open formula ϕ in a higher order language, where ϕ also contains variables for objects of higher types.

predicative position Position after a copula. Antonym: attributive position. In *John is angry,* 'angry' is in predicative position, in *An angry man shouted at me,* 'angry' is in attributive position.

presupposition Condition which has to be fulfilled in order that an utterance of a natural language sentence can be used to make a statement. *John's wife beats John* presupposes that John is married.

Prolog Prolog is a declarative programming language where knowledge gets represented as a finite set of Horn program clauses, i.e., first order sentences of the form $\forall x_1 \cdots x_m((A_1 \wedge \cdots \wedge A_n) \rightarrow A)$. It follows immediately from the format that any Prolog program P is consistent. Also, we have,

again by virtue of the format, that for any Prolog program P and existential conjunction $\phi = \exists x_1 \cdots x_m (A_1 \wedge \cdots \wedge A_n)$ (these are the negations of the Prolog goal clauses) that $P \models \phi$ iff the least Herbrand model for P (the model based on the set of closed terms of P, with the smallest interpretation of the predicates that make all program clauses true) makes ϕ true. So there is no need to look at the set of all models of P, but this is due to the special forms of the body of knowledge and of the conclusions we wish to draw from it.

pronoun Pronouns are expressions like *I, she, him.* The occurrence of *he* in *Every boy promised that he would come*, in the reading where the boys promise to come can be analysed as a variable bound by a quantifier, as in first order logic. The first person singular personal pronoun can be said to be a variable bound to the speaker in the given context, and similarly for the other personal and deictic pronouns. In DYNAMIC SEMANTICS it is claimed that the semantic behaviour of pronouns is better captured by comparing them to the variables in imperative programming languages.

proof theory Study of rule systems for calculating logical consequence. See also THEOREM PROVING.

Further reading: Prawitz [55].

proper name Canonical means of referring to individuals irrespective of context. In Montague grammar, proper names are treated as properties of properties, to lift them to the same logical type as quantified noun phrases. For instance (disregarding intensions), *John* is translated into $\lambda P P(john')$.

property A first order property is the denotation of an open formula $\phi(\bar{x})$ of first order logic, i.e., the set of all tuples satisfying ϕ in some model for the language under consideration. A higher order property is the denotation of an open formula ϕ in a higher order language, where ϕ also contains variables for object of higher types. For instance, $X(j)$ denotes the property of being a first order property of j.

In PROPERTY THEORY, a property is an object which forms a proposition when applied to a term. The extension of a property is the set of terms with which it forms a true proposition.

property theory A generic term that refers to all theories in which propositions and properties are taken to be primitive notions. They should perhaps more correctly be referred to as Theories of Propositions, Properties and Truth. Rather than taking propositions to denote truth-values (or sets of possible worlds), and properties to denote sets of individuals (or functions from worlds to sets of individuals), both are taken to be represented by syntactic objects. At its weakest, the notion of equality is that of syntactic identity in the representation. This results in a highly intensional theory: propositions need not be equated if they are always true together, and properties can be distinguished even if they (necessarily) hold of the same individuals. Typically, the truth conditions of

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a proposition are found by applying a truth operator. Such operators are potentially problematic in that they can lead to paradoxes. Higher-order logics (such as Montague's Intensional Logic) avoid the paradoxes by banning self-predication through strong typing. In Property Theory, the paradoxes can be avoided by adopting a weak representationalist view, where not all syntactic objects of the appropriate form can be taken to be propositions, and so they cannot meaningfully have the truth operator applied to them. This allows such theories to be weakly typed, and thus permit unproblematic instances of self-predication.

Theories of Propositions, Properties and Truth can be construed as partial reconstructions of Frege's programme (in "Sense and Reference"), without its paradoxes, and where there are more than two propositions. The premise that properties should be taken to be basic terms can be traced back to Aristotelean thought. A weak Property Theory is characterised by Aczel's Frege Structures [1]. Turner has provided a first-order axiomatisation of Frege Structures, and has shown how it can be used in a PTQ fragment of natural language semantics [66]. Such a theory of properties allows the definition of dependent types in constuctive mathematics, whilst maintaining a classical interpretation of the notion of proposition.

proposition Content of a declarative sentence. In Montague grammar: expression with a truth value as extension, and a set of possible worlds as intension.

propositional attitude Relation between a subject and a PROPOSITION, such as *knowing, believing* or *saying.*

In Montague Grammar, propositional attitudes are treated as relations between individuals and sets of possible worlds. This treatment immediately leads to the problem of LOGICAL OMNISCIENCE.

In more fine-grained theories of propositions, such as PROPERTY THEORY, propositional attitudes are essentially treated as relations between individuals and syntactic objects. This leads to the problem of 'logical ignorance': from the fact that A believes that $p \wedge q$ it does not even follow that A believes that $q \wedge p$.

PTQ Fragment of English described in Montague [51]. See also MONTAGUE GRAMMAR.

quantifier Expression like 'for all' (or $\forall$) and 'there exists' (or $\exists$). These are the standard or first order quantifiers. GENERALIZED QUANTIFIER THEORY also covers the so-called non-standard quantifiers, i.e., the quantifiers which cannot be defined in terms of $\forall$ and $\exists$, such as 'most'.

quantifying in Substituting a quantified phrase for an NP place holder (such as an indexed pronoun) in a syntactic expression E, with the semantic effect that the quantified phrase gets scope over every operator in E. According to Montague, this is the 'proper treatment of quantification in ordinary English'.

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quasi logical form Meaning representation language allowing underspecification: quantified expressions and operators with undetermined scopes, relations which are not yet determined, anaphors without a fixed antecedent.

questions See INTERROGATIVES.

query (database —) Question posed to a database in an appropriate query language. E.g., if the database is in Prolog then the query has to be in Horn clause format.

reference See SENSE.

referent Object denoted by a REFERENTIAL TERM.

referential term A noun phrase that *refers to* or *denotes* a particular object. Typical examples of referential terms are proper names of real things, such as persons, places, dates. Other DEFINITE noun phrases, such as pronouns, demonstratives and definite descriptions, also often function as referential terms, though not invariably.

relative clause Noun phrase modifier derived from a sentence. *Restrictive* relative clauses are those which restrict the possible referents of the noun phrase, whereas *non-restrictive* ones, which also are quite common, only add additional information.

representationalism (1) The thesis that beliefs and other propositional attitudes involve the presence, in the believer's mind, of a structure with syntactic articulation that among other things identifies the content of the PROPOSITIONAL ATTITUDES. A well-known expression of this view is found in Fodor [31]. (2) The thesis that the central relationship to be explicated by semantics is that between language and thought — how is a sentence or text related to the thought or thoughts which the speaker means to express by it — rather than the relation between language and the world. (3) The thesis that the relationship between a language and the world cannot be adequately described by classical model-theoretic methods, which define the truth conditions of sentences directly from their syntactic structure, but that this requires one or more levels of representation which make semantic as well as syntactic information explicit.

resolution (1) Strategy in proof theory, proposed by Robinson. (2) Pronoun resolution: Process of finding a suitable antecedent for an occurrence of a pronoun.

resource situation The domain of quantification of quantifiers in natural language sentences is contextually restricted. For a sentence such as *Everybody is asleep* to be judged true in a situation it is not necessary that all individuals in the universe of discourse are asleep; it is sufficient that all the elements of a contextually determined set of individuals are. In SITUATION THEORY, it is claimed that this set is determined by identifying a situation and using the constituents of that situation as the universe

of discourse. Barwise and Perry [12] called this situation the 'resource situation'.

reversibility Property of some natural language processing systems that can be 'put in reverse gear' to produce natural language output for suitable LOGICAL FORM input.

role relation See THEMATIC ROLE.

scene Perceived situation.

scope (1) See OPERATOR (sense 2). The scope of an operator (e.g. quantifier, modal operator, tense operator) is the expression whose interpretation is affected by the changes the operator makes to the context of evaluation. (2) In computer programming languages a distinction is drawn between *scope* and *extent*. Scope refers to a body of code whose interpretation is affected by the changes to the evaluation context brought about by the operation (typically the assignment of some value to some register/variable). Extent refers to the temporal duration of the change to the evaluation context. The change to context may still be in effect even after the evaluation of the code within the operator's scope; for example, an assignment to a register is usually left intact beyond the scope of the assignment and is only undone when the register needs to be reassigned. Dynamic binding in programming languages exploits the fact that the extent of an assignment can go beyond its scope. Dynamic binding is bad programming practice since the extent of an assignment can depend on details of the language implementation that are not reflected in its denotational semantics. But if the intended evaluation scheme is fixed in advance, dynamic binding can be used to great effect. It is arguable that the difference between the syntactic and dynamic scopes of quantifiers in Dynamic Predicate Logic bears some relation to the difference between scope and extent.

scoping algorithm The scope of quantifiers in (English) sentences is not completely fixed by the syntactic structure of the sentence, so that *every man got on a bus* has two readings depending on whether the men all got onto the same bus or onto different buses. A scoping algorithm determines the possible relative scopes of quantifiers consistent with the syntactic structure of a sentence, and perhaps additionally other pragmatic constraints on plausible scopings. Cooper storage [21] is a particularly well-known abstract specification of what can be seen as a scoping algorithm. For some reason, nearly all scoping algorithms assume that it is only the scope of quantifiers that is left underspecified by syntax, and that the scope of other operators is fixed.

self reference In natural language: Using language to talk about language, as in *This sentence is true*, where a sentence is used to talk about itself. Some theorists (e.g., Tarski) took the position that all self reference is vicious, but this position carries a condemnation of natural language semantics

in its wake. The current viewpoint is that self reference is only vicious when it leads to a version of the LIAR PARADOX, and that the sting of self reference can be removed by means of a partial evaluation of the truth predicate that avoids this paradox.

semantic network GRAPH used for encoding semantic information, e.g., a data structure network, a KL-ONE structure, or some other kind of conceptual structure with nodes and arcs.

semantic paradoxes PARADOXes such as the Russell paradox and the LIAR PARADOX.

semantics of programming The semantics of imperative programs can be given in terms of a logical specification of input–output behaviour. The meaning of an imperative program is fully specified by a description of how the programs acts on any given input. For example, the meaning of the ASSIGNMENT STATEMENT $x := y$ is given by the relation between memory states $\{\langle s, s' \rangle \mid s' = s(x|s(y))\}$, where $s(x|s(y))$ denotes the result of changing the value of x in s in the specified manner and leaving every other memory location unchanged. There is a rather close connection between semantics of imperative programming and DYNAMIC SEMANTICS for natural language.

The semantics of functional programs is usually given in terms of DO-MAINs, for a functional program f can act as program (function) and data (object), so it can in some sense be applied to itself. Domain theory makes it possible to switch back and forth between the program and the data guise of f. There is a rather close connection between the semantics of functional programming and PROPERTY THEORY.

sense Has *reference* as a twin. The pair *sense—reference* is the standard English translation of the distinction Frege made between *Sinn* and *Bedeutung*. According to Frege [32], the sense of an expression is somehow more involved than its reference. The reference of a sentence, for example, is just its truth value, but, as Frege observed, if someone has a relation to a proposition (i.e., to what is expressed by a sentence), then whatever this is, it is not a relation to a truth value alone.

In Montague grammar, the sense—reference distinction takes the guise of the distinction between INTENSION and EXTENSION, but it should be noted that while this is an explication that makes the distinction precise, it does certainly not solve all the problems that Frege raised.

In PROPERTY THEORY, Frege's distinction is reanalyzed by taking a 'representationalist' view of propositions, where two propositions are intensionally equal iff they are syntactically the same. This solution seems to err in the other direction.

sentence In logic: same as closed formula.

shared belief A belief of a group of agents, of whom all the members also believe that this belief is indeed held by everone else. Shared belief describes the optimal belief of such a group. Shared beliefs are of crucial importance to comprehend rational cooperative and conventional behavior of groups of agents (Lewis).

singular term Term denoting an individual entity. Antonym: PLURAL TERM.

situation (1) As a technical term used in SITUATION THEORY it means a part of the world characterized by a set of INFONS. (2) The term is used in Kratzer's situation semantics to mean a part of a possible world.

situation calculus Knowledge representation medium for ARTIFICIAL INTELLIGENCE.

situation semantics Situation semantics is one example of application of SITUATION THEORY to natural language semantics. It is based on the idea that the MEANING of a sentence is a relation between situations, called 'described situation', RESOURCE SITUATION, and 'discourse situation'. One of the basic ideas is that the described situation of a natural language utterance is specified, among other things, in terms of resource situations and a discourse situation. For instance, the personal pronoun I is always interpreted as the (unique) speaker in the discourse situation.

Further reading: The basic ideas of situation theory were introduced in Barwise and Perry [12]. Gawron and Peters proposed a grammar based on situation theory in [34].

situation theory Situation theory is the theory of the role of SITUATIONS and PARTIALITY in logic and semantics. Early work on situation theory by Barwise [8] was motivated by the observation that certain classes of statements (e.g., those containing PERCEPTION VERBS) can only be interpreted as statements about parts of the world, or situations.

Further reading: Situation theory and situation semantics were first extensively discussed in Barwise and Perry [12]. Later work by Barwise is contained in [9]. The most recent formulation of the version of situation theory due to Barwise and associates can be found in [11]. Alternative versions of situation theory have been proposed by Landman [44] and by Fenstad *et al.*, among others. Yet another reconstruction is given in Escriba [29]. A form of situation theory closer to traditional possible worlds semantics has been proposed by Kratzer [43].

skolemisation A method of translating a first order formula into an equivalent quantifier free formula, possibly containing additional function symbols. An important component of reducing formulas to clausal form, as required in most first-order THEOREM PROVING.

sort A sort system divides a domain of objects into a number of sets, each being a sort. Normally, the sort system also comes equipped with a subsort ordering over the sorts (corresponding to the subset relation). For example,

the domain of animals might get sorted into sets of mammals, reptiles, insects, cats, dogs, lizards, bees, wasps, males, females, hermaphrodites etc etc. Here, 'cat' and 'dog' are both subsorts of 'mammal'. Sorts do not always form a hierarchy, but often a sort system is composed of a number of overlapping sub-hierarchies (e.g. male/female; mammal/reptile/insect).

In a typed system, sorts of expressions of higher types can be derived from the sorts of expressions of basic types. For example a transitive verb like *read* can be taken to have the type $e \rightarrow e \rightarrow t$, where the first argument of type entity must be of sort 'human' (h) and the second of sort 'written material' (w), giving a sorted type $e_h \rightarrow e_w \rightarrow t$. This imposes SORTAL RESTRICTIONs on the arguments to the verb.

In THEOREM PROVING, a sort system can be used to improve efficiency by reducing the search space. If it is known that an unresolved/variable argument of a predicate must be of type s, then one need only consider resolvents falling within the subset s of objects, and not the entire domain.

sortal restriction See SORT. Sortal restrictions can be used as a way of filtering out certain kinds of semantically anomalous sentence, e.g. *Colourless green ideas sleep furiously.* However, the prevalence of METONYMY means that coherent sentences violating sortal restrictions are not uncommon, e.g. *Downing Street informed the White House of developments.* Negation and modals can also override sortal violations, e.g. *Ideas cannot sleep.* Sortal restrictions are nowadays seen as soft constraints on semantic interpretability, rather than inviolable ones.

speech act An act achieved by making a linguistic utterance, normally conceived as the utterance of a sentence by a single speaker.

statement Piece of information conveyed by an INDICATIVE sentence when used in a context where its PRESUPPOSITION is fulfilled.

sugar (syntactic —) See NOTATION. Syntactic sugar is the provision of a more readable, less cluttered notation. For example, syntactic sugaring of formulas involving generalized quantifiers might allow one to re-express $Most(\lambda y. P(y))(\lambda z.Q(z))$ as $Most\, x. P(x) : Q(x)$. Syntactic sugar can sometimes be misleading. The sugared version here makes it look as though $Most$ is a variable binding operator, whereas in fact it just expresses a relation between sets/properties.

synonymy Sameness of meaning. See MEANING RELATION and INTENSIONAL ISOMORPHISM.

synthetic See ANALYTIC.

temporal logic General name for logics with temporal operators such as *at some time in the future* or *always in the past.* Temporal logic is most often presented as a branch of modal logic, with time-points or time-intervals as indices or possible worlds.

The simplest temporal logic is the point-based logic with future operators F (at least once in the future) and G (always in the future), and past operators P (at least once in the past) and H (always in the past) due to Prior [56]. The two modal schemata $H\phi \leftrightarrow \neg P\neg\phi$ and $G\phi \leftrightarrow \neg F\neg\phi$ enforce that P, H and F, G are Interpreted as pairs of dual operators, while the schemata $\phi \rightarrow HF\phi$ and $\phi \rightarrow GP\phi$ together enforce that the 'later than' accessibility relation used for interpreting P and H is the converse of the 'earlier than' accessibility relation used for interpreting F and G. Other reasonable requirements on 'later than' are transitivity, absence of past or future endpoints and linearity. The latter constraint is not beyond dispute, witness the existence of branching time temporal logics. Montague semantics uses a point-based temporal logic with operators F, G, P, H, combined with an alethic modal logic with operators $\Diamond, \Box$. His indices are pairs $\langle t, w \rangle$ consisting of a time-point t and a possible world w at that time-point. When the world parameter is kept fixed, the temporal accessibility relation is linear, while keeping the time parameter fixed while moving to a different world gives a range of different future possibilities, from the vantage point of some time in the past. This set-up gives a possibility, in principle at least, to treat counterfactual conditionals, as in *It didn't rain, but it might have rained*. Enrichments are addition of a 'now' operator N, and of binary operators S and U for 'since' and 'until' (two extensions studied by Kamp). An interval-based temporal logic was developed by Allen [3]. An excellent overview of temporal logic is given in Van Benthem [15].

tense In English: present, past, pluperfect, future. For a classical logical analysis, see Reichenbach [59].

thematic role In a simple event-describing sentence like *Mickey kicked Pluto* the participating individuals play different roles. For instance, Mickey is often said to be the *agent* of the above sentence (event), whereas Pluto is said to be the *patient*. A theory of thematic roles is potentially interesting if it is possible to make any non-trivial inferences from the fact that a certain individual fills a certain role. Of course, this is indeed possible if thematic roles are defined individually, with a distinct set of roles for each verb. A fancy way to represent the content of the above sentence is then e.g. as $kick(e) \land kicker(e, Mickey) \land kickee(e, Pluto)$. But theories of thematic roles aim at finding general roles, which fit several verbs. The problem is that perhaps with the exception of *agent*, there is not much agreement on the role types that are necessary, and on how to assign them to each verb.

theorem proving (Automatically) finding whether some theorem follows from a logical theory (see Ramsay [57] for a useful overview, and Fitting [30] for an excellent textbook).

Resolution theorem proving involves first reducing the theory and the negation of the putative theorem to quantifier free conjunctive normal form (a set of skolemised disjunctions, or *clauses*), and then repeatedly

applying a resolution rule (based on *cut* from the Gentzen sequent calculus) in an attempt to derive an empty, i.e. contradictory, resolvent. The resolution rule takes two clauses, $\neg P_1^1 \vee \ldots \vee \neg P_m^1 \vee Q_1^1 \vee \ldots \vee Q_n^1 \vee R^1$ and $\neg R^2 \vee \neg P_1^2 \vee \ldots \vee \neg P_i^2 \vee Q_1^2 \vee \ldots \vee Q_j^2$, and by unifying R^1 and R^2 and applying the variable substitutions produces a resolvent $\neg P_1^{1'} \vee \ldots \vee \neg P_m^{1'} \vee \neg P_1^{2'} \vee \ldots \vee \neg P_i^{2'} \vee Q_1^{1'} \vee \ldots \vee Q_n^{1'} \vee Q_1^{2'} \vee \ldots \vee Q_j^{2'}$. Empty resolvents can only be obtained by resolving P with $\neg P$. Resolution is a sound and complete inference rule for the first-order predicate calculus, but resolution provers cannot be guaranteed to terminate. Various search strategies have been proposed to control the choice of clauses to resolve, not all of which preserve completeness.

Backwards chaining is an inference rule that is only complete for the Horn clause subset of first-order logic (i.e. clauses must contain at most one unnegated literal). The backwards chaining rule takes a set of goals $\{G_1, \ldots, G_i, \ldots, G_n\}$ derived from the theorem to be proved, and a clause $Q_1 \wedge \ldots \wedge Q_m \rightarrow P$ from the theory, unifies P with one of the goals G_i, and replaces G_i in the set of goals by the clause body $Q_1, \ldots, Q_m$. The original goal is proved when one backward chains to an empty set of goals. Backwards chaining is a special instance of resolution—linear input resolution. This can be seen if the goals are negated, $\neg G_1 \vee \ldots \vee \neg G_i \vee \ldots \vee \neg G_n$ and the clause put into disjunctive form, $\neg Q_1 \vee \ldots \neg Q_m \vee P$ and where the resolution is made by unifying G_i and P. For any resolution, at least one clause must come from the original problem statement.

Pure PROLOG is a backwards chaining theorem prover, but due to its depth-first rather than breadth-first search strategy, it is not even complete for Horn clauses. Prolog extends pure prolog with the addition of a *negation as failure* rule—\+P is true/provable iff P is not provable—where negated literals can occur in the bodies of Horn clauses. Negation by failure is at best an approximation to classical negation. There are backwards chaining theorem provers exploiting an additional *model elimination* rule that are complete for first order logic, e.g. Stickel [64].

truth One of the things Pilate didn't care about.

truth conditions The conditions under which a sentence ϕ holds in a model M, or a situation, or for that matter, the world. Often expressed as $M \models \phi$ iff ... [followed by a specification of what has to hold for the components of ϕ].

truth definition vs truth criteria A truth definition for a particular language specifies what it means for a sentence of that language to be true in a given situation. Truth criteria for a particular sentence specify what finding out whether that sentence is true would involve. Of course, it is possible to know what a sentence means without knowing whether the sentence is true. In such a case we can apply the truth definition without knowing how to apply the truth criteria. Natural language semantics

provides truth definitions, not truth criteria, and the two should not be confused.

truth function Function of type $\{0,1\}^n \to \{0,1\}$, where n is the number of arguments of the function.

truth functional Property of an operator of being interpreted as a truth function. The Boolean connectives 'and', 'or' and 'not', as used in propositional logic, are truth functional.

truth value Member of the set $\{0,1\}$, where 0 stands for false and 1 for true.

type Means of classifying mathematical objects such as computer programs. Types are usually syntactic expressions. The use of typing was first proposed by Bertrand Russell as a means to avoid the paradoxes of naive set-theory, but it has been superseded there by an axiomatic approach and a distinction between sets and classes. Logical theories of types have been developed in the context of constructive mathematics and the foundations of functional programming; they take the shape of *typed* λ-calculi. The type information on an object o can be used as a partial specification of what o is like. In programming theory, this is used for partial correctness proofs and as a step towards efficient implementations. In the semantics of Montague grammar, logical types are counterparts of linguistic categories. The idea is that a category such as Common Noun corresponds to a class of functions from possible worlds to sets of entities, and so on.

type shifting Assigning a meaning to an expression with a different type from the one it usually has (its basic type). For instance, *and* has basic type $\langle(t,t),t\rangle$, i.e., it takes two expressions with type t (truth value) and yields a new expression of type t. But natural language also has verb phrase conjunction: *Johnny kicked and screamed*, and here we need a shift to type $\langle(\langle e,t\rangle, \langle e,t\rangle), \langle e,t\rangle\rangle$, i.e., from pairs of sets of things to sets of things.

type theory The (meta-) mathematics of types. The simple (non-constructive) theory of types is a favorite medium of meaning representation for Montague grammarians.

In the last twenty-five years type theory has been a main focus of development in meta-mathematics and theoretical and applied computer science. Type theory got married to proof theory by means of the so-called Curry-Howard isomorphism, which considers propositions as types and proofs of those propositions as terms, i.e., as 'inhabitants' of those types. This mapping made type theory a medium for representing mathematical reasoning and led to the development of automated proof-checkers, e.g. in De Bruyns *Automath* project [17]. Martin-Löf's intuitionistic type theory [47] presents a rich typed λ-calculus as a foundation of constructive mathematics. Nowadays, many other type theories are being investigated. Well-known type-theoretical formalisms are Girard's system **F**, Reynold's

second-order λ-calculus, and Coquand and Huet's calculus of constructions. A systematization of the interrelations between these different type theories is given by the so-called λ-cube of Barendregt [6].

Applications of the above-mentioned developments in type theory in computer science include theorem-proving (e.g. Edinburgh LCF) and functional programming (e.g. Milner's ML). Proposals to model the constructive aspect of discourse processing in natural language using type construction can be found in Ahn and Kolb [2] and Ranta [58].

Further reading: A good introduction to type theory and functional programming is Thompson [65].

underspecification A representation is underspecified if it subsumes (i.e., provides less specific information than) a number of distinct further specifications of it. Underspecified representations are valuable in representing AMBIGUITY and certain kinds of PARTIALITY and VAGUENESS.

A simple example of underspecification is a FEATURE STRUCTURE like

$$[num = X]$$

which subsumes the two distinct structures

$$[num = plur]$$
$$[num = sing]$$

UNIFICATION can be used as a way of combining two underspecified feature structures to produce a more specified structure. While unification-based representations are well entrenched as a means of representing syntactic underspecification, there is no wide consensus on how to represent semantic underspecification (though using QUASI LOGICAL FORMs is one proposal).

unicorn Shy animal inhabiting the possible worlds of Montague semantics which only shows up to illustrate puzzles of intensionality. Also see DONKEY.

unification Unification is an operation on a domain of objects for which a certain kind of specificity ordering, $\subseteq$, is defined. Taking SORTs as an example of such a domain, we can write $dog \subseteq mammal$ to say that the sort dog is more specific than the sort $mammal$. The unification of two objects, $x \cap y$, is the least specific object z that is as specific or more specific than both x and y. For example, $dog \cap female = bitch$. Unification can often be seen as an operation for combining bits of partial information to produce less partial information.

In many applications, 'more specific than' can be read as 'more instantiated than'. The unification of two terms built up from function symbols, variables and constants — $f(a, X)$ and $f(Y, b)$ — is $f(a, b)$ and instantiates the variables X and Y to the constants b and a. This form of unification

is particularly important in THEOREM PROVING. Efficient unification algorithms exist for unifying first-order terms (i.e. where variables cannot range over function symbols), returning substitutions for variables that give rise to the (unique) unifier.

Higher order unification allows variables to range over function and predicate symbols as well, and returns lambda terms as substitutions for them. As well as being undecidable, higher order unification does not always produce a unique unifier. For example, unifying $F(X, b)$ and $g(Y)$ can give rise to the following distinct solutions:

$$F \leftarrow \lambda U, V.\, U \qquad F \leftarrow \lambda U, V.\, g(h(U, V))$$
$$X \leftarrow g(Y) \qquad\qquad X \leftarrow X$$
$$Y \leftarrow Y \qquad\qquad\quad Y \leftarrow h(X, b)$$

For the operation of unification to yield a unique result, the specificity ordering must satisfy the following property: for any two objects x and y having some object z_1 that is more specific than both, there must be a unique least specific object, z, that is more specific than x and y. Unification also has an inverse operation of *generalization*, which takes the most specific object less specific than the two objects generalized.

universal algebra Mathematical theory about classes of algebras, where an algebra is a carrier set with a number of operations defined on it. One of the fundamental results of universal algebra is the theorem due to Birkhoff that a class of algebras is equationally definable iff it is closed under taking subalgebras, homomorphic images and products.

Further reading: Cohn [20].

update New piece of information to be added to a database or knowledge base. If the update is inconsistent with the database, the updating process will have to involve data or concept revision (see BELIEF REVISION).

vagueness Property of expressions for which the boundaries of the class of situations where they apply is not clear-cut.

variable Syntactic expression serving as a place holder for another expression of the same type. Individual variables serve as place holders for proper names. Predicate variables serve as place holders for properties. One might think of *John likes Mary* as the result of combining the filler expression *John* with the gapped expression — *likes Mary*, which in turn is the result of combining the filler expression *Mary* with the gapped expression — *likes* ⋯ by filling the second gap. Instead of marking the open slots typographically or referring to them by number, it is more convenient to keep the gaps open by means of variable names: *John likes Mary* is the result of substituting *John* for x in *x likes Mary*. *John likes himself* is the result of substituting *John* for x in *x likes x*.

word semantics See LEXICAL SEMANTICS.

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