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4

Expanding the fragment: Syntactic categories and semantic types

4.1. Noun phrases

English has a variety of expressions like *the woman who is jogging down Blackstone Boulevard*, *the most disobedient puppy in Alexandra's puppy class*, *the house on the southeast of Chace Ave. and Hope St.*, etc. We will take it as given that these are all of the same grammatical category and will refer to them as NPs (see Chapter 1, n. 8). Let us assume that all expressions of the same syntactic category correspond to the same type (very broadly speaking) of semantic object. This assumption was already made for the case of S; we took each S to have a meaning of type <s,t>, i.e., a function from world–time pairs to truth values. Recall that our basic semantic toolbox so far consists of the set of truth values, worlds, and times. But none of these are obvious candidates for NP meanings. What, then, is the type of thing that NPs have as their semantic values?

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For the NPs illustrated above the answer seems simple: add to the toolbox a set of individuals, and assume that each NP picks out an individual. The notation e will denote the set of individuals; hence the value of an NP is some member of e. Of course, one immediately observes that this has a problem analogous to the problem of saying that the value of a sentence is a truth value. After all, the individual picked out by *the most disobedient puppy in Alexandra's puppy class* is entirely contingent on how the world happens to be: it could have been the puppy Mitka but it could instead have been the puppy Brunhilde. Besides, this can also depend on when this is uttered—the referent of the puppy-NP will change from year to year. Moreover, one can know the meaning of an NP without knowing who it picks out: I know what it means to say *the tallest man in the world on Jan. 1, 2011* but I have no idea who this is. So the solution is also analogous to the situation with sentences: the *intension* (the actual meaning) of an NP is a function from worlds and times to individuals—that is, some function in <s,e>. Note that this says that if one knows the meaning of an NP *and knows everything there is to know about the actual world and time*, one can indeed pick out the relevant individual. But we are not omniscient, so we know the meaning (the intension) without necessarily knowing the extension. Our toolbox for constructing meanings now consists of the set of worlds (w), the set of times (i) (we continue to use s for the set of world–time pairs), the set of truth values (t), and the set of individuals (e). Incidentally, one might wonder whether the individuals are separate from the worlds: does it make sense to talk about an individual independent of the world in which it is located? As for the case of times, we will here treat the set of individuals as separate from the set of worlds and the evidence for this is quite similar (we can march an individual from world to world using a counterfactual conditional). We return to this shortly.

The claim that NPs pick out (in any given world and time) an individual has some interesting consequences. First, this means we need to think of "individual" rather broadly; the domain of individuals needs to include quite abstract things like those things picked out by the NPs *the idea that the earth is flat*, *the desire to leave*, etc. Moreover, in addition to our normal individuals like you, me, and my dog we have plural individuals (*the dogs*). We will not deal with these here, save to say that they can be treated as a special kind of individual (Link 1983). Finally, there is a class of expressions traditionally called NPs which really do seem to resist being treated as individuals: these are "NPs" with quantificational determiners like *every*

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dog, *no dog*, *few dogs*, and so forth. These will simply be excluded from the fragment for now. They form the basis of some of the most interesting and rich work in semantics, and will be the subject of Chapter 10.

Consider now the case of names like *Mitka*, *Barack Obama*, etc. Traditional grammar tells us that these are "nouns" (they are considered "proper nouns" as opposed to "common nouns" like *dog*, *table*, *stream*, but both are called nouns). But in fact names (in English) have nothing in common syntactically, morphologically, or semantically with common nouns. Unlike ordinary common nouns, they do not take plural morphology. They do not occur with determiners like *the*.[1] And, as we will see below, while NPs denote individuals, common nouns surely do not (*the hungry dog* picks out an individual, but *dog* does not). On the other hand, names have exactly the same syntactic distribution as do ordinary NPs; the name *Mitka* can occur in all the same syntactic environments as an NP like *the disobedient husky*. Moreover, names and NPs are similar semantically: clearly a name picks out an individual, just like more a complex NP containing *the*. Given that names have the same syntactic distribution and the same semantic type as NPs in general, the conclusion is obvious: they are NPs. Our fragment will treat these as listed in the lexicon as NPs. Incidentally, we will also for now take complex NPs such as *the disobedient husky*, *the first man on the moon*, and so forth to just be listed in the fragment as single items; the internal structure of these is the subject of Chapter 8.

Note that this departs from a traditional view that a category label like NP (noun *phrase*) is an appropriate label only for expressions containing more than one word. Along with this traditional view goes the idea that single words must have as their category one of what is traditionally called the "basic parts of speech"—noun, verb, adjective, preposition, determiner (or article), adverb, and perhaps a few others. (These are the "parts of

[1] There are examples where proper nouns occur with determiners, as in (i) and (ii):

(i) The Berrymans are coming over to dinner tonight.
(ii) Every Dmitri in the semantics class might be a bit annoyed at the use of the name *Mitka* in so many example sentences.

But we can analyze these as cases where a proper noun shifts its class and is used as an ordinary common noun. English is very free with shifting items from one category to another (along with a meaning change). It should, however, be noted that a number of semanticists have explored a different view of proper names according to which *Mitka* instead means something like "the one who is named Mitka."

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speech" that still form the subject of colorful posters decorating elementary school walls, along with such odd definitions as "a verb is an action word" and "an adjective describes a pronoun.") The traditional parts of speech are not entirely fiction—the notion that at least some of these categories are appropriate labels for a class of words is based on *morphological commonalities*. "Nouns," for example, can (generally) combine with the suffix /z/ to form plurals; "verbs" combine with (among others) the suffix *-ing*, "adjectives" can (generally) combine with *-er* to form comparatives, etc. Thus the grammar may well need access to the notion of a class of "nouns," "verbs," and "adjectives" for the purposes of the morphology. But even granted that, we have already seen that proper nouns do not show noun-like morphology. There is no reason then not to call them NPs. The category name is arbitrary; it could as well be 342, D, or Butternutsquash; a category is just the name for a group of expressions with the same syntactic distribution and semantic type. (Under the Categorial Grammar syntax developed in Chapter 6 it turns out that many category labels are not actually arbitrary since the names themselves encode distributional information. But there will be a set of basic category names, including NP, which remain arbitrary.) Incidentally, there are plurals (like *dogs*) and mass nouns (like *water*), which can function both as nouns (they can occur with the determiner *the* to give an NP) or as NPs as in *Dogs make good pets*, *Water is plentiful on this island*. When they are NPs they have some similarity to proper names: they name "kinds" of objects. (For much more detailed discussion, see Carlson 1980 among others.)

Still, there does seem to be one difference between a name such as *Barack Obama* and an NP like *the president of the US in 2011.* As discussed above, the referent of the latter depends on how the world happens to be. One can imagine worlds in which things had worked out differently and this NP picked out John McCain, or more distant worlds in which this picked out Dennis Kucinich. One can even imagine yet more distant worlds in which it picked out the lead dog of the winning Iditarod team (just imagine a massive change in the political system, a revision in the duties of the president, and a bit of dog worship). But the referent of a proper name like *Barack Obama* is stable; change the world all you want, let in a bit of dog worship and a massive change in the political system, and the referent of this NP remains the same. One can even change some rather fundamental properties—assume that Barack Obama not only is not president but happens to have

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been born in Kenya, moved to France, and became a master sommelier. The referent remains the same—just many things about him are changed.[2]

The account of this proposed by Kripke (1980) is to treat names as *rigid designators*. This simply means that a name does indeed denote a function from worlds to individuals, but the relevant function maps every world to the same individual. Any function which assigns the same value to everything in its domain is called a *constant function*. Note that this hinges on the assumption made earlier: that the domain of individuals is not world-dependent—the set of individuals is independent of the worlds.[3] Odd though this may seem at first glance, we can use the tool of counterfactual conditionals to give plausibility both to the claim that the same individual can march around from world to world, and for the claim that proper names are rigid designators. Consider the following sentences:

(1) If Barack Obama had been born in Kenya, he would not have been eligible to be president of the US.

(2) If Barack Obama had grown up in France, he would have become a master sommelier.

The semantics in Chapter 2 for counterfactual conditionals leads to the conclusion that there is some individual—call that individual o—whose properties can vary from world to world but is nonetheless a single individual. Moreover, the name *Barack Obama* picks out o in our world, where he is President of the US in 2013 and was born in Hawaii, and continues to pick

[2] Notice that we can change large facts about a person—even their birthplace—as we move them from world to world while still considering them the same person. Lest one think that a person's birthplace is a necessary fact about them—rather than a contingent fact—consider the claims of the "Birthers." These are a group of people who have continually insisted that Barack Obama was actually born in Kenya (and hence ineligible to be president of the US). Notice that while this group insists on a world in which the Barack Obama individual was born somewhere else, they never once disputed that Barack Obama is Barack Obama. The dispute kept the individual constant, and simply centered on a world (not the actual one) in which that same individual had a different birthplace from his actual one (which is Hawaii).

[3] One might wonder how could this be, since it is a contingent fact as to who is born, and therefore who is "actual" in any given world. We can, however, assume that there is an equivocation here about the word "existence." Let us imagine some very abstract notion of "existence" which holds for all individuals who are present in any world. And of course one can also wonder about the proper account of fictional individuals like *Santa Claus*. These worries are all beyond the present scope.

out o in the world in (1) in which o was born in Kenya, and in the world in (2) in which o grew up in France.

While difficult, one can even change more basic facts about the individuals. My dog Mitka happens to be a Siberian husky, but I could meaningfully assert (3a) and even (3b):

(3) a. If Mitka had been a Labrador Retriever, I would have been able to let him off leash.
b. If Mitka had been a wolf, his fear of thunder would not have let him survive.

Again these sentences make sense if we can take the individual rigidly referred to by *Mitka*, locate him in a different world, and change his properties, while still tracking that it is the same individual. We will thus adopt Kripke's semantics for these. This allows us to account for the observations above, while keeping their semantic type the same as that of other NPs: functions of type <s,e>. They just happen to be constant functions.

***4.1.** The verb *think* takes as its object (or complement) a sentence as in *Chris thought that the earth was flat*. This verb is a good example of something which crucially combines with *intensions*. The object of Chris's thoughts is not just a truth value 1 or 0, but a set of worlds (all worlds compatible with what he believes). If one wishes to simplify, one can think of this as simply a single world—for the purposes of this question it makes no difference.

Notice that there is an interesting ambiguity in a sentence like the following:

(i) Bill thinks that the mayor of Providence will win the marinara sauce competition.

See if you can detect what the ambiguity is and describe—perfectly informally—how one might account for the ambiguity. (Do note that this exercise is *not* looking for a formal account, as the tools for that are developed only in Chapter 19. The hope is that the informal intuition might be accessible.) Keep in mind that phrases like *the mayor of Providence* are functions from worlds to individuals; this is crucial. Assume further that in putting the whole semantics together, some actual world is "plugged in" as the argument of the function so that this NP ends up denoting an individual, but the individual can vary from world to world. Incidentally, this phrase is also time-dependent (it actually denotes a

(*cont.*)

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function of type <s,e>) but this fact can and should be ignored here; keep the time constant.

Now notice that (ii) does not display the same type of ambiguity:

(ii) Bill thought that Buddy Cianci would win the marinara sauce competition.

Comment on why this is not surprising. (A historical note: Buddy Cianci is not the mayor of Providence at the time of writing this book. But he was, and indeed he did make award-winning marinara sauce.)

Before leaving this, we can also note that some NPs fail to refer to anyone in the actual world, giving rise to the classic notion of presupposition failure. The time-honored example (from Russell 1905) is *the (present) King of France*. As mentioned earlier, this book contains no in-depth discussion of presupposition, but we can note that one account is to treat the meaning of such NPs as partial functions from worlds to individuals, undefined for this world.

4.2. Intransitive verbs/verb phrases

The toolbox so far contains as basic building blocks a set of worlds, a set of times, a set of truth values, and a set of individuals. While there is controversy as to whether other primitives (e.g., events) are necessary, one can get surprisingly far using only these sets and constructing other semantic objects using sets and functions built out of these. As a first step, consider the case of sentences with intransitive verbs. First a small bit of housekeeping. Sentences with simple intransitive verbs in English can contain the verbs in the past tense, as in:

(4) The president coughed.

(5) Mitka howled.

But we are ignoring the semantics of the past tense (as we wish to ignore times), and so in using examples of this type it should be kept in mind that the semantics is incomplete. Note, incidentally, that we could not give a

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fuller account by recasting into the syntactic form which is called the *simple present*, as in (6) and (7), for the semantics of these is even more complex:

(6) The president coughs.

(7) Mitka howls.

Sentences with "eventive" verbs (*coughs*, *runs*, *howls*) in the tense which is called simple present in English actually do not make a statement about an event holding true at the moment of utterance. For example, (6) does not entail that the president is coughing at this moment, but that this happens from time to time with some regularity. These are called *habitual* statements. So we will refrain from using these sentences, and stick to past-tense cases.

We begin with the syntax. We will refer to the category of intransitive verbs as V_I, and will at this point assume that English contains the two phrase structure rules in (8):

(8) a. S → NP VP b. VP → V_I

Of course, a different possibility would be to adopt only the rule in (8a) and simply think of *cough*, *howl*, and so forth as lexical VPs. After all, it was shown above that single words could be lexical NPs, and it would make sense to take the same solution here. But in the present case the situation is more complex, for here transitive verbs (*like*, *kill*, etc.), ditransitive verbs (*give*, *put*, etc.), and intransitive verbs (and many other things that are traditionally call ed "verbs") *do* have common properties. They are the class that takes past-tense morphology, the -*ing* suffix, etc. In other words, the morphology treats them as a single class, giving some basis for the traditional notion that these form a single "part of speech." For now, then, let us stick with tradition and call these all verbs (using a subscript feature as above in order to distinguish their syntactic distribution—and, shortly, their semantic type) which leads us to adopt the two rules in (8). All of this will be modified in Chapter 6 when we turn to Categorial Grammar.

The simplest semantics to associate with the rule (8b) is one which says that meaning of the VP is the same as the meaning of the V_1. Put in the official notation then, (8b) can be recast as follows:

TR-4. If α is an expression of the form <[α], V_I, [[α]]>, then there is an expression β of the form <[α], VP, [[α]]>.

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The remaining challenge is to determine the type of meaning for the intransitive verb (and hence the VP) itself. This can easily be done without introducing any new primitives into the basic set: let these pick out (in a world and at a time) a *set* of individuals.

At first, this seems odd. But first, note that—as with NPs and Ss—there is a distinction between the *intension* of an intransitive verb and its *extension*. The intension is a function from worlds (and times) to sets; it is only the extension that is a set. Indeed, if you knew everything about the world (and time) that you were living in, and you knew the meaning of the word *cough*, you could determine the set of coughers. So intransitive verbs have meanings of type <s,<e,t>>. To make this a bit more intuitive, we digress briefly to talk about word meaning. Modeling the meaning of intransitive verbs as functions into sets of individuals gives some nice tools for talking about the relationship between the meanings of different words that clearly have certain semantic properties in common.

4.3. A brief look at lexical semantics

Thus while this book is primarily about compositional semantics—how the meanings of smaller expressions (including individual words) combine to give the meanings of larger expressions—that project itself is obviously intimately tied up with *lexical semantics*, i.e., the project of determining the meanings of the basic units (the words). And the tools developed so far are quite useful for lexical semantics as well as compositional semantics. Consider, for example, the fact that (9) entails (10) and that this is clearly a fact about the meanings of *dance* and *move*:

(9) Sabrina danced.

(10) Sabrina moved.

If we stick to the idea that the extension of any intransitive verb is a set of individuals, there is a simple way to express the relation between these two verbs. One part of the meaning of [[dance]] is that for every individual in the set it picks out, that individual is also in the [[move]] set. Put differently, the extension of [[dance]] at any world is a subset of [[move]] (in that world). (Of course [[dance]] is richer than just this, so the full lexical entry will say more.)

This also provides tools for the meanings of certain words which are often thought of as being decomposable into other bits of meanings. To illustrate, we turn from intransitive verbs to nouns. As will be discussed more fully in Chapter 8, nouns also plausibly have as their meanings world- and time-dependent sets of individuals. Some noun meanings lend themselves to a combination of other concepts. A famous example (see, e.g., Katz and Fodor 1963) is *bachelor*, which in early work on lexical semantics within generative grammar was treated as being composed of a few primitive concepts. Oversimplifying somewhat, we can reconstruct this idea by saying that [[bachelor]] is a function from worlds and times to sets of individuals such that for any world w and time i [[bachelor]] at w and i is the set: $\{x|x \in$ [[male]] (at i and in w) and $x \in$ [[adult]] (at i and w) and $x \notin$ [[married]] (at i and w)$\}$. This recapitulates—in model-theoretic terms—the early "lexical decomposition" analysis of this in terms of primitive concepts. Of course the above needs refining, but we have the tools to make the necessary refinements. For a bachelor is not any unmarried male adult, but one who has never been married. Thus we can revise the above by requiring that for each x in the [[bachelor]] set at world w and time i, there is no time i' prior to and including i at which $x \in$ [[married]].

4.2. The situation is even more interesting: possible worlds also appear to be necessary to give a full treatment of even a simple word like *bachelor* which is often trotted out in lexical semantics courses to illustrate how words decompose into other concepts. Thus most speakers have the intuition that a Catholic priest is not felicitously referred to as a *bachelor*, nor is a gay man in a state which does not recognize same-sex marriage.

(i) How can the use of possible worlds provide a way to capture these intuitions?
(ii) Having done (i), does this also us to eliminate any other part of the above definition? Note too that we did not put [[human]] in the definition above although this might have struck the reader as a missing ingredient. But given (i), do we need it?

Moral: A speaker's ability to use perfectly ordinary words like *bachelor* involves counterfactual reasoning.

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4.4. Back to the compositional semantics

With this much, we can now formulate the semantics for the rule in (8a). Recasting into the official notation yields TR-5 (given extensionally):

TR-5. If α is an expression of the form <[α], NP, [[α]]> and β is an expression of the form <[β], VP, [[β]]>, then there is an expression γ of the form <[α-β], S, 1 if [[α]] $\in$ [[β]], and 0 otherwise>.

Notice that TR-5 as formulated above leaves no room for treating certain kinds of presupposition failure as a case of a sentence being neither true nor false. In other words, for the sake of discussion take *stop-smoking* as a single intransitive verb. It is sometimes assumed that when predicated of someone who never smoked the result is neither 1 nor 0 but is simply undefined. The semantics above provides no way to accommodate for this view; every sentence of the form *NP stopped smoking* will be either true or false. We remedy this directly below.

4.3. Give the intensional version of TR-5.

TR-5 is based on treating the meaning of an intransitive verb as (relative to a world and time) a set of individuals. But as shown in Chapter 2, any set can be recast as the characteristic function of that set. Thus an intransitive verb like *cough* or *howl* can instead be taken as picking out (in any world and time) a function from individuals to truth values. Using e to mean the set of all individuals, this then picks out a function of type <e,t> (so its full meaning is a function of type <s,<e,t>>). Using functions rather than sets has two potential advantages. First, it provides a more general tool for modeling meanings, as will be clear later. Second, it is a richer notion than the set version because potentially there could be *partial functions* (in this case, a function defined only for a subset of the domain of individuals). If these do exist, one can always recover a set of individuals from a (possibly partial) function of type <e,t>: the relevant set is the set mapped to true by the function. But one cannot recover the function from the set (if something is not in the set, it could be that it is assigned 0 by the function, or it could be that it is simply not in the domain of the function). For the most part this book will make little use of partial functions, but will leave open the possibility of using it for presupposition failure. Under this technique [[stop-smoking]] maps an individual to true (at a time i) if that individual smoked at a time earlier than i and does not smoke at i; false (at time i) if that individual smoked at a time earlier than i and also smokes at i, and undefined otherwise.

Having made this revision on the semantic types, we revise TR-5 as follows (given extensionally here):

TR-5′. If there is an expression α of the form <[α], NP, [[α]]> and an expression β of the form <[β], VP, [[β]]>, then there is an expression of the form <[α-β], S, [[β]]([[α]])>.

If there are partial functions and if [[α]] is not in the domain of [[β]] then we have undefinedness (and hence the result is undefined at the world and time in question); otherwise the VP-function applies to the individual in question and yields either 1 or 0.

4.4. Give TR-5′ in its intensional form.

4.5. Illustrating the syntactic/semantic composition

Let us illustrate the workings of the fragment that has been developed so far (along with a suitable lexicon). Consider (11).

(11) The disobedient husky escaped and the obedient husky slept.

We assume the lexical items *escaped*, *slept*, etc. of category V_1 with meanings of type <s,<e,t>>; and *the-disobedient-husky* and *the-obedient-husky* of category NP with meanings of type <s,e>. Extensionally, a V_1 denotes a function in <e,t> and an NP denotes some member of e. If we actually knew all the facts about the world in question, we could show out the actual extensions of each of these at that world. By way of illustration, imagine a "universe" with four individuals {a,b,c,d}. Further, imagine a world w_1, whereby [[the-disobedient-husky]](w_1) = a and [[the-obedient-husky]](w_1) = c. Assume further that [[escaped]](w_1) is the function mapping a and c to 1 and b and d to 0 (thus it characterizes the set {a,c}, while [[slept]](w_1) maps b to 1 and a, c, and d to 0 (thus it characterizes the set {b}). We can now use the notation in (12) as one way to illustrate how it is that the grammar proves (11) as well-formed and puts together its meaning.

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In the semantic part, we are showing *only* the extension of each expression at w_1. We give each expression as a triple of phonology, category, meaning (actually, extension). For visual ease we will omit the brackets <...> around each triple, and we will omit the brackets [...] and [[...]] around the sound and meaning parts respectively.

(12) the-disobedient-husky; NP; a
escaped; V_I; a → 1, b → 0, c → 1, d → 0
these two lines just show the information that is in the lexicon
escaped; VP; a → 1, b → 0, c → 1, d → 0 (by TR-4)
the-disobedient-husky escaped; S; 1 (by TR-5′)
the-obedient-husky; NP; c
slept; V_I; a → 0, b → 1, c → 0, d → 0 (these two lines again given by the lexicon)
slept; VP; a → 0, b → 1, c → 0, d → 0 (by TR-4)
the-obedient-husky slept; S; 0 (by TR-5′)
the-disobedient-husky escaped and the-obedient-husky slept; S; 0 (by TR-1)

There are many other ways one could illustrate this. Since we generally do not have all the facts of some actual world at our disposal, we could write the semantic composition more generally. For example, the semantic part of the fourth line can be rewritten as follows: $[[\text{escape}]]^w([[\text{the-disobedient-husky}]]^w)$. Remember that formulas like this contain a hidden clause at the beginning: so this says that for all worlds w, the value of this expression is the value [[escaped]] at w applied to the value of [[the-disobedient-husky]] at w. Thus one can show part of the composition as in (13):

(13) the-disobedient-husky; NP; [[the-disobedient-husky]] w
escaped; V_I; $[[\text{escaped}]]^w$
escaped; VP; $[[\text{escaped}]]^w$ (by TR-4)
the-disobedient-husky escaped; S; $[[\text{escaped}]]^w$ $([[\text{the-disobedient-husky}]]^w$ (by INT-TR-5′)

In fact, in general we will illustrate the semantics this way (since we could not list the actual function which corresponds to, e.g. [[escaped]]). Among other difficulties in doing that, we would have to list this out for every possible world. But it is sometimes useful to pick a world and demonstrate the composition extensionally as in (12) as a reminder that the semantics is not computing formulas, but actual model-theoretic objects. Formulas—as in (13)—are just what we humans need in order to write out those objects. It is also generally not necessary to put in each rule that licenses the next line;

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this is useful only when it serves some clarificational purpose. The literature contains other methods for visually displaying the syntax and semantics at work. Often this is shown as an annotated tree. A traditional tree shows just the phonological part—what precedes what—and the categories of each expression, but not the meanings). One could then "decorate" each node label with the semantics.

4.5. Consider the following model of a tiny universe. We will be concerned with just one world and one time, so we can consider everything extensionally. Our universe has four individuals {a,b,c,d}. At the world in question, [[howl]] maps a and c to 1, b and d to 0. [[cough]] maps b to 1 and all other individuals to 0. [[Balto]] picks out a; [[the hungry dog]] picks out d. Show the full syntactic and semantic composition for

(i) Balto howled and the hungry dog coughed.

In this case, the task is to show the actual extension of each expression at the world in question; thus use (12) as the model for showing this.

4.6. To make things interesting, and to give a flavor for intensionality, let us add in another world. World 1 (which we will label as w_l) will be exactly the world set up in Exercise 4.5. World 2 (labeled w_2) is as follows: [[Balto]] still picks out a (of course, since it is a rigid designator); [[the hungry dog]] picks out c; [[is-howling]] maps all four individuals to 0; and [[is-coughing]] maps a, c, and d to 1 and b to 0. Now show the syntactic and semantic composition where at each step you should show the full function from each of the two worlds to its value, and show how this is computed step by step.