INTERNATIONAL COMPUTER SCIENCE INSTITUTE

1947 Center St. • Suite 600 • Berkeley, California 94704-1198 • (510) 666-2900 • FAX (510) 666-2956

Embodied Construction Grammar in Simulation-Based Language Understanding*

Benjamin K. Bergen† **Nancy C. Chang**‡

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Abstract

We present Embodied Construction Grammar, a formalism for linguistic analysis designed specifically for integration into a simulation-based model of language understanding. As in other construction grammars, linguistic constructions serve to map between phonological forms and conceptual representations. In the model we describe, however, conceptual representations are also constrained to be grounded in the body's perceptual and motor systems, and more precisely to parameterize mental simulations using those systems. Understanding an utterance thus involves at least two distinct processes: *analysis* to determine which constructions the utterance instantiates, and *simulation* according to the parameters specified by those constructions. In this report, we outline a construction formalism that is both representationally adequate for these purposes and specified precisely enough for use in a computational architecture.

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†University of Hawaii at Manoa, Dept. of Linguistics, Moore 569, 1890 East-West Rd., Honolulu, HI 96822; bergen@hawaii.edu

‡University of California at Berkeley and International Computer Science Institute, 1947 Center Street, Suite 600, Berkeley, CA 94704; nchang@icsi.berkeley.edu

1 Overview

This document introduces a construction grammar formalism that is designed specifically for integration into an embodied model of language understanding. We take as starting point for Embodied Construction Grammar many of the insights of mainstream Construction Grammar (Goldberg 1995; Fillmore 1988; Kay and Fillmore 1999; Lakoff 1987) and Cognitive Grammar (Langacker 1991). Foremost among these is the observation that linguistic knowledge at all levels, from morphemes to multi-word idioms, can be characterized as *constructions*, or pairings of form and meaning. Along with other construction grammarians, we assume that language users exploit constructions at these various levels to discern from a particular utterance a corresponding collection of interrelated conceptual structures.

We diverge from other construction grammar research in our concern with precisely how constructional knowledge facilitates conceptually deep language understanding.[1] Understanding an utterance in this broader sense involves not only determining the speaker's intended meaning but also inferring enough information to react appropriately, whether with language (e.g., by answering a question) or some other kind of action (e.g., by complying with an order or request). These processes involve subtle interactions with variable general knowledge and the current situational and discourse context; static associations between phonological and conceptual knowledge will not suffice. Our model addresses the need for a dynamic inferential semantics by viewing the conceptual understanding of an utterance as the internal activation of *embodied schemas*, along with the mental *simulation* of these representations in context to produce a rich set of inferences.

An overview of the structures and processes in our model of language understanding is shown in Figure 1. Given an utterance in a particular communicative context, the first step toward understanding it is to hypothesize a set of constructions that may have given rise to the perceived speech string. This *analysis* process draws on a large repository of constructions that link phonological and conceptual schemas, as well as the current context, to produce a *semantic specification*, or *semspec*, that specifies which schemas are evoked by the constructions and how they are related in the utterance. The semspec serves as input to a process that actively simulates (or imagines) the specified events, actions, objects, relations, and states. The resulting inferences shape subsequent processing and provide the basis for the language user's response.

The embedding of construction grammar in a simulation-based language understanding framework has significant representational consequences. The key requirement is that constructions must have the flexibility to evoke and associate arbitrary elements of form and meaning, but they are allowed only restricted access to schemas and their *parameters* (or *roles*) (as described in more detail below). Thus, although the semantic schemas they evoke effectively tap into the whole of conceptual knowledge, constructions themselves remain a comparatively narrow interface. An adequate construction formalism must therefore provide coherent means of interacting with the representations used in the conceptual ontology and the context model, using notation defined precisely enough to support a computational implementation.

Perhaps the best way to introduce the ECG formalism is through an example analysis. Consider the phrase *out of France*, as in

(1) We flew out of France on Tuesday.

The remainder of this section provides an introductory tour of a possible analysis of this phrase, discussing first the schemas (Section 1.1) and then the constructions (Section 1.2) involved. We illustrate the formalism in greater detail with an extended analysis in Section 2, and address issues related to the overarching simulation-based framework in Section 3.

[1] Although we focus here on processes involved in language comprehension, we assume that many of the mechanisms we discuss will also be necessary for meaningful language production.

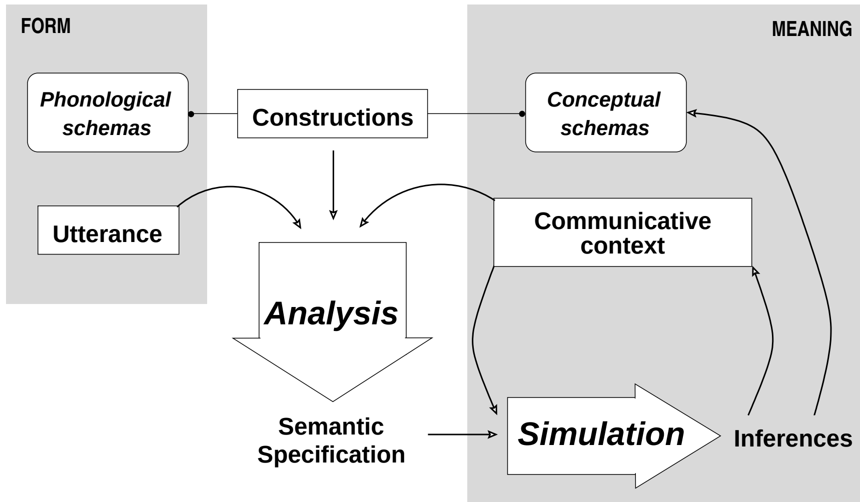

Figure 1: Overview of the simulation-based language understanding model, consisting of two primary processes: *analysis* and *simulation*. Constructions play a central role in this framework as the bridge between phonological and conceptual knowledge.

1.1 Embodied schemas

What is the embodied meaning of the expression *out of*? That is, what experience does it evoke in the hearer? Informally, we take the basic meaning of *out of* to be a complex spatial relation involving notions of containment and motion. Following the cognitive linguistic tradition (Johnson 1987; Lakoff and Johnson 1980), we model such embodied perceptual knowledge using a small set of grounded image schemas that capture recurrent sensorimotor patterns. We analyze our example as involving three of the image schemas that have been proposed in the literature, each of which specifies structured relationships among a set of *roles* that can take variable values (or *fillers*). The Container schema (Johnson 1987) structures our knowledge of enclosed (or partially enclosed) regions with roles including an interior and exterior separated by a boundary, and a portal through which entities may pass. The Trajector-Landmark schema (Langacker 1987) captures an asymmetric spatial relationship between a trajector, whose orientation, location, or motion is defined relative to a landmark. The Source-Path-Goal (or simply SPG) schema (Johnson 1987) structures our understanding of directed motion, in which a trajector moves (via some means) along a path from a source to a goal.

Previous work has addressed how image schemas can be grounded in perceptual representations (Regier 1996). We assume that the internal perceptual logic of image schemas, though crucial for simulation, need not be explicitly represented for the purpose of constructional analysis. That is, we can treat image schemas as being *parameterized* by their roles, such that a semspec listing only the schema name and the set of role fillers is sufficient for specifying a simulation. Our formalism thus represents image schemas as simply a set of role names (often with constraints), as shown in Figure 2 for the three image schemas needed for *out of*. Special keywords of the formal notation are shown in **bold**. The first line is a header that indicates that this is a **schema** definition and includes the name of the schema being defined. Next, after a line marked **roles**, is an indented block listing the schema roles. These roles provide the means by which other structures can set parameters for simulating the schema, as we will illustrate below.

Image schemas are only one of the rich knowledge structures needed for interpreting even the simplest utterances; others include Talmy's (1988) force-dynamic schemas (capturing interactions involving the application or exertion of force) and specific motor schemas used to perform actions. At the level of

```
schema Trajector-Landmark
  roles:
    trajector
    landmark
```

```
schema SPG
  roles:
    trajector
    source
    path
    goal
    means
```

```
schema Container
  roles:
    interior
    exterior
    portal
    boundary
```

Figure 2: Schemas needed to define the Out-Of schema.

simulation, these schemas must be defined in terms of sensorimotor representations that capture complex domain-specific interactions among multiple entities; Section 3.2 describes how parameterized representations called *executing schemas* (or *x-schemas*) (Bailey 1997; Narayanan 1997) can be used to simulate a wide variety of events and actions. But all of these schemas can, like image schemas, be described as a set of interdefined roles. They can thus be expressed within the same simple formalism used in Figure 2. At this higher level of granularity, our notion of embodied schema can be viewed as essentially equivalent to Fillmore's (1982) frames, which relate a culturally specific set of interdefined concepts (e.g., both *buy* and *sell* refer to a commercial event frame, and both *rob* and *steal* refer to a frame related to theft). Following Langacker (1987), we refer to all such structures, in which a set of interdefined concepts are structured configurationally, as *semantic schemas*, or *schemas* for short. (We sometimes use the term *frame* to refer to the formal notation for a schema and its parameters.)

Complex schemas like that needed for our example may involve instances of several schemas whose roles are aligned in a particular configuration. We will refer to such component schema instances as *constituents*, and associations between constituent roles as *bindings* (or *identifications*). The schema underlying *out of*, for example, has three constituents, corresponding to each of the three schemas defined in Figure 2. It also asserts a number of bindings: the source of the SPG schema is *bound* to (or *identified* with) the interior of the Container schema, and the goal of the SPG schema is bound to the exterior of the Container schema. (This distinguishes the meaning of *out of* in this context from that expressed by *into*, for example, which has the reverse set of associations.) Bindings allow constraints from the various schemas to interact. We define an Out-Of schema in Figure 3, accompanied by an (informal) iconic depiction of the overall meaning: a spatial relationship between a trajector and a container in which the trajector moves from the interior to the exterior of the container.

```
schema Out-Of
  constituents:
    tl instance of Trajector-Landmark
    cont instance of Container
    spg instance of SPG
  roles:
    source ⟷ spg.source ⟷ cont.interior
    goal ⟷ spg.goal ⟷ cont.exterior
    trajector ⟷ spg.trajector ⟷ tl.trajector
    landmark ⟷ tl.landmark ⟷ cont
  profiles tl, spg
```

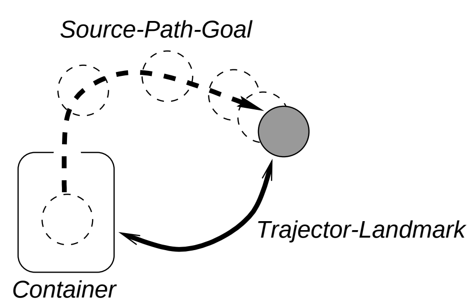

Figure 3: The Out-Of schema, along with an iconic representation.

Like the schemas we have seen so far, the Out-Of schema begins with an identifying header. This header is followed by two indented blocks, labeled **constituents** and **roles**. The first block lists the schema's constituents, where each constituent is given a local name, or *alias*, and is constrained to be an **instance of** the indicated schema. In the example, the tl constituent is constrained to be an instance of Trajector-Landmark. The next block lists the schema's roles and asserts bindings (indicated by a double-headed arrow $\longleftrightarrow$) between these roles (source, goal, trajector, and landmark) and those of its constituents. Like co-indexation in Head-Driven Phrase Structure Grammar (Pollard and Sag 1994) and other unification-based approaches to grammar (Shieber 1986), bindings cause type constraints and fillers to be shared between the bound roles. We use slot-chain notation standard in computational formalisms to refer to a role y of a structure x as x.y. Thus the first line in the block introduces a role source, which is identified with both the source role of the spg constituent and the interior role of the cont constituent. The last line of the schema indicates that one or more elements are *profiled*, or raised to prominence against the background of the entire schema (similar to the notion of profiling used by Langacker (1991)). As used here, it captures the intuition that the spatial relationship underlying the out-of schema can be viewed as an instance of either a Trajector-Landmark or an SPG schema — each defined relative to the other structures in the entire Out-Of schema — but not as itself an instance of a Container schema.

The formal notations we have introduced represent the main features of schemas that are relevant for analysis: schemas may be described in terms of roles and constituents; they may specify type constraints and bindings; and they may impose a particular profile. As we will see in the next section, many of the same representational mechanisms are used for describing constructions.

1.2 A first look at constructions

Our analysis of the phrase *out of France* involves three constructions: an OUT-OF construction that treats the phrase *out of* as a single unit conveying the spatial relation described above; a lexical FRANCE construction; and a SPATIAL-PREDICATION construction that licenses their combination. While *out of* may well lend itself to an analysis in terms of the individual semantic contributions of *out* and *of*, we assume for expository purposes that *out of* (like *into*) can also be analyzed as a single construction.

The OUT-OF construction, like all ECG constructions, associates elements of form and meaning, as well as constraints on those elements. As shown in Figure 4, these primary functions are captured by the main body of the construction, which consists of two indented blocks labeled **form** and **meaning**. Each block lists the form or meaning elements needed in the construction by their local aliases; like schema roles, these elements may be constrained to be instances of specific types. In the case of the OUT-OF construction, the form block specifies two elements with aliases o1 and o2 that are instances of particular phonological schemas (represented here as phonetic strings), while the meaning block specifies a single element with alias m that is an instance of the Out-Of schema. Form and meaning blocks may also express relational constraints on their elements. The only such constraint in the OUT-OF construction is the final line in the form block, which specifies a particular sequential ordering of the two form elements: o1 must directly precede o2. We notate this direct precedence relation with the (unidirectional) `meets` relation, one of the many possible binary relations between intervals set out in Allen's (1984) Interval Algebra.

In addition to its form and meaning blocks, the OUT-OF construction has a header line consisting of the keyword **construction** followed by the name of the construction (much like the schema formalism). The next line identifies the construction as a **subcase of** the SPATIAL-RELATION construction (not shown). This line introduces into the representation the notion of inheritance relations between constructions. Although the listed form and meaning constraints are specific to the OUT-OF construction, they have much in common with other such spatial relations; all of these pair a Trajector-Landmark schema (or, as in our example, a schema that profiles a Trajector-Landmark) with some phonological form, and they also interact with other

construction OUT-OF
subcase of SPATIAL-RELATION
form:
o1 **instance of** [aʷt]
o2 **instance of** [əv]
o1 `meets` o2
meaning:
m **instance of** Out-Of

construction FRANCE
subcase of REF-EXPR
form:
f **instance of** [fræns]
meaning:
r ⟷ France

Figure 4: The OUT-OF construction.

constructions in similar ways. The structure shared by these constructions is represented in a SPATIAL-RELATION construction and inherited by all spatial relations constructions. (Though not indicated explicitly in the examples shown so far, schemas also exhibit inheritance relations.)

Similarly, the FRANCE construction is marked as a subcase of the REF-EXPR (for referring expression) construction. Referring expressions and their associated Referent schema will be discussed in some detail in Section 2.1; for now it is sufficient to note that these constructions all associate some form with reference to a concrete or abstract entity, and that the FRANCE referrring expression inherits a meaning element r that is an instance of a Referent. Apart from this extra notation related to inheritance, the FRANCE construction is quite simple: it associates the appropriate form with a binding constraint between r and the schema France, which is a known entity in the understander's ontology. (Again, see Section 2.1 for more details.)

construction SPATIAL-PREDICATION
constituents:
rel **instance of** SPATIAL-RELATION
lm **instance of** REF-EXPR
form:
rel_f `before` lm_f
meaning:
rel_m.landmark ⟷ lm_m

Figure 5: The SPATIAL-PREDICATION construction.

The final construction used in our example phrase illustrates how constructions, like schemas, may exhibit constituent structure and thus capture more abstract patterns. The phrase *out of France* can be seen as instantiating a pattern in which a spatial relation with a particular landmark is associated with a particular word order. Despite the abstract nature of its associated elements, this pattern can still be expressed as linking form and meaning, using the same formal mechanisms as the simpler constructions. To express constituent structure, the SPATIAL-PREDICATION construction in Figure 5 also has a block labeled **constituents** that, like the form and meaning blocks, lists elements along with type constraints. These elements are themselves instances of constructions, also called *constructs*. That is, just as a schema's constituents are (instantiated) schemas, a construction's constituents are (instantiated) constructions.[2] The constituents in the example are given the aliases rel and lm, and restricted to instances of the SPATIAL-RELATION and REF-EXPR constructions, respectively. As in schema definitions, these aliases are for internal use within the construction and are chosen arbitrarily.

[2] Note that in both cases, the constituent substructures are instances of the same kind as their containing structures. This view of constituency thus extends the traditional, purely syntactic notion to include meaning.

The form and meaning blocks of the SPATIAL-PREDICATION construction impose various constraints on its constituents, or more specifically on their associated forms and meanings (or form and meaning *poles*). The form and meaning poles can be referred to separately with the relevant alias and a subscripted f (for form pole) or m (for meaning pole); note that the subscripts are typically redundant, since form constraints usually apply to elements of form, and meaning constraints usually apply to elements of meaning. A single form constraint on ordering (the interval relation before) indicates that rel_f must precede lm_f, though not necessarily immediately (since modifiers, for example, might intervene). The single semantic constraint serves to relate the meanings of its two constituents: since rel is an instance of SPATIAL-RELATION, rel_m is an instance of the Trajector-Landmark schema; the landmark role of this schema is identified with lm_m.

The product of analyzing these constructions as responsible for the phrase *out of France* is a set of interrelated semantic structures. During analysis (discussed further in Section 3.1), the OUT-OF and FRANCE constructions are triggered and their requirements satisfied, evoking the France schema and instances of the SPG, Trajctor-Landmark, and Container schemas, bound together as specified by the Out-Of schema. How, then, do we arrive at the configuration in which France is identified with both the Container schema and the landmark of the Trajector-Landmark schema?

The OUT-OF and FRANCE constructions trigger the SPATIAL-PREDICATION and instantiate its rel and lm constituents, respectively. The binding constraint of the SPATIAL-PREDICATION's meaning block then identifies the landmark of its rel_m (Out-Of) with lm_m (France). Recall that the Out-Of schema's landmark is subject to various other bindings; in particular, it is constrained to be an instance of a Container. Because bindings indicate identity and identity is transitive, France must also be an instance of a Container. Attempting to bind a semantic structure that is not an instance of a Container would fail due to the semantic mismatch. In this case, though we have not shown all the details of the analysis, France is acceptable as a Container since it is an instance of a Country; this schema is in turn a subcase of Geographical-Region and ultimately Container. The binding required for this construction thus succeeds.

Our brief introduction has highlighted the formal representations of both schemas (as parameterized descriptions that specify simulations) and constructions (as interface structures associating form and meaning elements). In the next section, we illustrate the interaction of these conceptual and linguistic representations in greater detail, deferring until the third section larger issues involved in the processes of constructional analysis and simulative inference.

2 A detailed analysis

This section shows our construction formalism at work in a more complex example. We present a collection of constructions that together license an analysis of the utterance in (2):

(2) Mary tossed me a drink.

Our analysis follows that of Goldberg (1995) in presuming that the ditransitive argument structure (more specifically, the active ditransitive argument structure) imposes an interpretation in which one entity takes some action that causes another entity to receive something. Thus, although the verb *toss* appears with a variety of argument structures, its appearance in the example sentence is allowed only if its meaning pole can be understood as contributing to such an event of transfer.

Figure 6 is a simplified depiction of the analysis we develop in this section. The form and meaning domains linked by constructional knowledge are shown as gray rectangles on either side of the figure. Form elements — including phonological forms (shown as phonetic strings) and word order relations (shown as arrows on a schematic time line) — appear in the form domain. Meaning elements — including schemas (shown as rounded rectangles) and bindings among their roles (shown as double-headed arrows) — appear in the meaning domain. Between these domains lie six boxes, corresponding to the six constructs involved

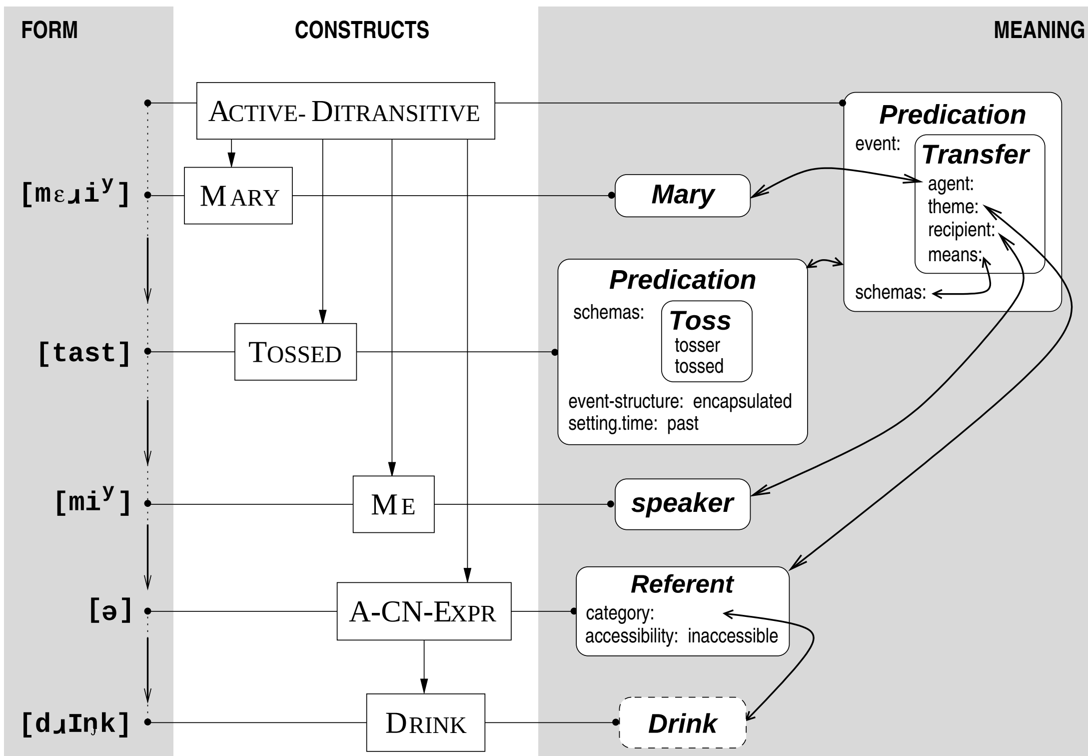

Figure 6: A depiction of a constructional analysis of *Mary tossed me a drink*. Constructs involved are shown in the center, linking elements and constraints in the domains of form and meaning. (Some details not shown.)

in the analysis. Each construct is labeled according to the construction it instantiates, is linked to other elements in the analysis in various ways. Horizontal lines with circular tips link each construct with its form and meaning elements, while vertical arrows between the boxes express constructional constituency. For example, the box for the MARY construct has a (form) link to the phonological form [mɛɹi^{y}] (residing in the form domain) and a (meaning) link to the concept Mary (residing in the meaning domain); in this analysis it is also a constructional constituent of the ACTIVE-DITRANSITIVE construct.

The constructions and schemas shown in the diagram (as well as several others not shown) are defined in this section using the ECG formalism. As will become clear, many of the details of the analysis — such as the specific constructions and schemas involved, as well as the implicit inheritance relations among them — are subject to considerable debate. Our current purpose, however, is not to offer the most general or elegant definition of any particular construction, but rather to demonstrate how the ECG formalism might be used to express the choices we have made. The analysis chosen here also highlights the interaction between lexical and clausal semantics, suppressing details of how the formalism could represent sub-lexical constructions and more significant interactions with the discourse context; alternative analyses are mentioned where relevant. (A more detailed and technical analysis using an earlier version of the formalism is available in Bergen, Chang, and Paskin (2000).)

We broadly divide the constructions to be defined into those that allow the speaker to *refer* and those that allow the speaker to *predicate*. This division reflects the differing communicative functions of reference (typically associated with entities) and predication (typically associated with events). Following Croft (1990, 1991, 2001), we take reference and predication to be primary propositional acts that motivate many traditional grammatical categories and relations; they also have natural interpretations in our framework as the main schemas structuring the simulation (Section 3.1). We organize our analysis accordingly: the referring expressions in our example — *Mary*, *me*, and *a drink* — are defined in Section 2.1, followed by expressions involved in prediction — both the main verb *tossed* and the ditransitive argument structure construction — in Section 2.2.

2.1 Referring expressions

The act of making *reference* (to some *referent* or set of referents) is a central function of linguistic communication. Speakers use language to evoke or direct attention to specific entities and events. A wide range of constructions is used for this function, including pronouns (*he*, *it*), proper names (*Harry*, *Paris*), and complex phrases with articles, modifiers, and complements (e.g., *a red ball*, *Harry's favorite picture of Paris*). But while the forms used in these constructions are highly variable, they all rely on the notion of reference as a core part of their meaning. We therefore define a relatively schematic REF-EXPR (referring expression) construction that has an underspecified form (notated as an instance of Schematic-Form) and an instance of a Referent schema as its meaning pole; both are shown in Figure 7.

schema Referent
  roles:
    category
    restrictions
    attributions
    accessibility
    resolved-ref

construction REF-EXPR
  form:
    f **instance of** Schematic-Form
  meaning:
    r **instance of** Referent

Figure 7: The Referent schema and REF-EXPR (referring expression) construction.

The roles of the Referent schema correspond to information that a referring expression may convey about a referent. In particular, specific subcases of the Ref-Expr construction may place constraints on the values of some subset of the referent's roles. These include its ontological category (e.g., human, ball, picture); restrictions and attributions that apply to various closed- and open-class featural characteristics of the referent (e.g., gender, number, color); and its default level of accessibility (Lambrecht 1994) in the current discourse context (active, accessible, inactive, unidentifiable, etc.).[3] All of these constraints are used in a separate reference resolution procedure that finds the most likely referent in context (for example, a particular known individual or event); this actual referent, when determined, is available through the resolved-ref role.

Our example includes three different referring expressions: *Mary*, *Me*, and *a drink*. We will analyze these as involving three constructions that are all subcases of the Ref-Expr construction — Mary, Me, and A-CN-Expr (*a* common noun expressions) — as well as the Drink construction (a subcase of Category-Label, not depicted). In fact, more general constructions corresponding to proper nouns, pronouns, and determined phrases could have been defined, and some constraints expressed by the constructions we show could have been inherited from these more general constructions instead of being explicitly expressed. To simplify the analysis, we have opted to define more specific constructions that make fewer commitments with respect to inheritance relations. Note, however, that the two approaches can be viewed as informationally equivalent with respect to the particular utterance under consideration.

We begin with the Mary and Me constructions (Figure 8), which are both similar to the France construction from Section 1. All of these constructions are specified as subcases of Ref-Expr; as a result, each has an inherited meaning element r that is an instance of the Referent schema. They differ only in the phonological string in their form poles and the specific constraints expressed in their meaning poles. The Mary construction identifies r with the Mary schema (though not shown, this schema constrains its instances to be individuals conventionally named "Mary"). The constraint that the referent is inactive should be interpreted as a minimum level of accessibility in the current context, reflecting the background salience of specific individuals as known ontological entities. Note that a single-headed arrow (⟵) is used here to indicate the binding of a specific value (inactive), rather than a variable role value, as the filler of the role.

The Me construction differs in several ways from the Mary construction. First, the referent is bound to the speaker role in the current context (notated here as current-space.speaker; see Section 4 for discussion of how this role relates to work in *mental spaces*). Second, pronouns like *me* have an active discourse status. Finally, the formal element's case role is assigned the value object, which distinguishes the Me construction from the constructions corresponding to *I* (subject case) and *my* (possessive case). (The case feature is discussed further in Section 2.2.2.)

construction Mary
  subcase of Ref-Expr
  form:
    f **instance of** [mɛɹi^y]
  meaning:
    r ⟷ Mary
    r.accessibility ⟵ inactive

construction Me
  subcase of Ref-Expr
  form:
    f **instance of** [mi^y]
    f.case ⟵ object
  meaning:
    r ⟷ current-space.speaker
    r.accessibility ⟵ active

Figure 8: The Mary and Me constructions.

[3]Though not explicitly shown here, the context model includes speaker and hearer roles as well as discourse context (referents and predications in previous utterances), situational context (entities and events present in the actual or simulated environment), and shared conceptual context (instances of schemas known to both speaker and hearer). For convenience we use a simplified version of Lambrecht's (1994) terminology for referential identifiablity and accessibility, though other discourse frameworks could be substituted.

construction A-CN-Expr
  subcase of Ref-Expr
  constituents:
    cat-label **instance of** Category-Label
  form:
    a-form **instance of** [ə]
    a-form `before` cat-label_f
  meaning:
    r.category ⟷ cat-label_m
    r.accessibility ⟵ unidentifiable

construction Drink
  subcase of Category-Label
  form:
    f **instance of** [dɹɪŋk]
  meaning:
    m ⟷ Drink

Figure 9: Constructions underlying *a drink*: A-CN-Expr and Drink constructions.

schema Bounded-Mass
  subcase of Bounded-Thing
  roles:
    boundary **instance of** Boundary
    mass **instance of** Substance

schema Drink
  profiles drink-entity **in** Drink-Action
  subcase of Bounded-Mass
  roles:
    boundary **instance of** Container
    mass **instance of** Liquid

Figure 10: The Bounded-Mass and Drink schemas.

The final referring expression in our example is the phrase *a drink*. We analyze the main construction licensing this phrase as having more internal structure than the other two examples and thus allowing a more general pattern to be expressed. Like the Spatial-Predication construction from Section 1, the A-CN-Expr construction shown in Figure 9 has its own constructional constituent, cat-label, which is constrained to be an instance of a Category-Label construction. The Category-Label construction, though not shown here, is similar to the traditional notion of *common noun*. Its name in our formalism reflects its function of evoking an ontological category, which supplies the category of the overall referent. For example, the Drink construction needed for our analysis (also shown in Figure 9) is marked as a subcase of Category-Label, and links the appropriate phonological form with the category defined by the Drink schema shown in Figure 10, corresponding to a specific role of the action of drinking. That is, the schema needed here — one for a drinkable entity — is defined with respect to a Drink-Action schema. Although this action schema is not shown here, it has a drink-entity role that is profiled by the Drink schema, as indicated by the **profiles** tag in the definition. The Drink schema is also marked as a subcase of the Bounded-Mass schema, which relates a mass (constrained to be a Substance) to its enclosing boundary. (Other examples of expressions that denote a bounded mass include *a cup of a coffee*, *a whiskey*, and *a bucket of sand*.) Constraints on the mass and boundary roles are further constrained by the Drink schema to be a container and a liquid, respectively. Thus when the cat-label constituent of a A-CN-Expr construct is filled by a Drink construct, the category of the corresponding referent is constrained to be Drink.

The remaining new features of the A-CN-Expr are the form element [ə], which is constrained to appear somewhere `before` the cat-label constituent (or rather, before its form pole), and the constraint that the referent be contextually unidentifiable, which among other functions can introduce a new referent into the discourse context. These two constraints are not, of course, unrelated — in fact, they are precisely the form and meaning characteristics usually associated with indefinite determination. Unlike most traditional analyses, we have not defined a separate *a* determiner construction, electing instead to treat determination as being constructionally inseparable from reference. As usual, other alternatives are possible, but this analysis succinctly captures the constraints present in our example while demonstrating the flexibility of the ECG formalism as used for referring expressions.

2.2 Predicating expressions

The act of *predication* can be considered the relational counterpart to reference. Speakers make attributions and assert relations as holding of particular entities; and they locate, or ground, these relations (in time and space) with respect to the current speech context. Central cases of constructions used for predication include Goldberg's (1995) basic argument structure constructions and other clausal or multiclausal constructions. But many other kinds of construction — including the traditional notion of a *verb* as designating a relation between entities, as well as both morphological constructions and larger verb complexes that express tense, aspect, and modality — depend on the same background frame.

In Figure 11 we define a frame of predication that allows events to be specified and located with respect to the speech context; an instance of this Predication frame serves as the meaning pole of a schematic PRED-EXPR (predicating expression) construction (analogous to the REF-EXPR construction). The roles described here are not intended to be exhaustive, but they are sufficient for describing a wide range of predications, including the one in our example utterance.

```
schema Predication
  roles:
    event
    schemas
    event-structure
    setting
```

```
construction PRED-EXPR
  form:
    f instance of Schematic-Form
  meaning:
    p instance of Predication
```

Figure 11: The Predication schema and PRED-EXPR construction.

The first two roles of the Predication schema together specify the main conceptual content and participant structure being predicated, in terms of both the overall event and the particular set of schemas involved. The event role can be filled by a relatively limited set of schemas that describe basic patterns of interaction among a set of participants. These correspond roughly to what Goldberg (1995) refers to as "humanly relevant scenes", as well as to the basic scenes associated with children's cross-linguistically earliest grammatical markings (Slobin 1985); examples include Transitive (one participant manipulating or exerting force on another), Self-Motion (a self-propelled motion by a single participant), and Caused-Motion (one participant causing the motion of another). In general, event schemas do not specify the concrete actions they involve — whether, for example, the participant in an instance of Self-Motion sustains the motion by walking, hopping, or pushing through a crowd. These concrete schemas are instead usually provided by verbal constructions that constrain the schemas role. In general, clausal constructions affect the event role, while verbal constructions affect the schemas role; we will discuss the close relationship between these two roles below. The remaining roles supply additional information about how the event is to be understood. The event-structure role constrains the shape of the event asserted in the predication or the particular stage it profiles; cross-linguistic markers of linguistic aspect typically affect this role. The event may also be located in a particular setting in time or space; English tense markings, for example, generally affect a substructure time of the setting role.

The constructions underlying an utterance must together supply a compatible and sufficient set of constraints on the predicated event. Failure to fully meet this requirement can account for many phenomena related to the acceptability and grammaticality of particular combinations of verbal and clausal constructions. In the case of the example sentence, the two main constructions that interact to define the overall predication are the verbal TOSSED construction (Section 2.2.1) and the clausal ACTIVE-DITRANSITIVE construction (Section 2.2.2). These constructions exemplify the pattern mentioned above: the verbal construction is defined as binding a particular action schema (the Toss schema) to the schemas role, while the clausal construction binds a Transfer schema to the event role.[4] In the analysis we will develop, these separately contributed schemas are directly related in the final predication: the tossing action is understood as the *means* by which a transfer is effected.

Note that the precise relationship between the event and schemas roles varies; besides the means relationship, Goldberg (1995) mentions subtype, result, precondition, and manner as other possible relations. In general, these relations specify ways in which the underlying semantics associated with the two roles can be understood as part of one coherent event. The relevant relation depends in some cases on the analysis process, which is described in more detail in Section 3.1. For now we merely note that the separation of the event and schemas roles in the Predication frame provides some flexibility useful for handling this potential uncertainty: Individual constructions may specify as much or as little as needed about these roles and how they are related.

2.2.1 TOSSED as a VERB

The word *tossed* evokes a specific physical action, and it also carries tense and aspect information that applies to the larger event in which it is involved. In Figure 12, we define the VERB construction and its subcase TOSSED construction. Both constructions draw on the Predication frame defined above. Following Langacker (1991), we define a *verb* as a word whose meaning includes an instance of a (relational) predication, indicated in the figure as the pred element. This predication is further constrained to have its schemas role bound to some (unspecified) **filler**.

The TOSSED construction associates the phonological form [tast] with a number of meaning elements and constraints, all involving the pred element inherited from its base VERB construction. As required by the VERB construction, the TOSSED construction asserts a binding constraint on its schemas, whose filler in this case is specified as an instance of the Toss schema (defined below). (Note the new notation used to introduce the new meaning element t, constrain it to be an instance of Toss, and identify it with pred.schemas all in the same line.) The remaining constraints allow the TOSSED construction to bear both tense and aspect information. First, the relation's event-structure is set as encapsulated. As discussed further in Section 3.2.1, the English simple past tense can be modeled using executing schemas that suppress, or *encapsulate*, details of their internal structure during simulation. Second, the constraint on pred.setting.time as being past indicates that the time during which the relational predication holds, corresponding to Reichenbach's (1947) Event Time, must be prior to the (contextually specified) speech time.

Prototypically, the Toss schema represents knowledge about a low-energy hand action that causes an entity to move through the air. We defer until Section 3.2.1 a detailed representation of the corresponding active motor schema; for now we simply define it relative to a general Forced-Motion in which a forceful action causes an entity to move along some path. As shown in Figure 13, the constituents of the Forced-Motion schema instantiate three other schemas: a forceful interaction called Force-Dynamic-Transfer, SPG (defined in Section 1), and a Cause-Effect schema that captures the causal relationship between the other two. Though we will give these schemas only a cursory look for now (omitting some roles not relevant to the current discussion), they are all highly general schemas that recur across the definitions of more specific schemas. The Force-Dynamic-Transfer schema describes a force-dynamic interaction in which an energy-source

[4] Both constructions can in fact be viewed as combining two other constructions: TOSSED could be the result of a morphological construction combining the verbal stem *toss* with the appropriate *-ed* marker, resulting in a finite verb; and the information in the ACTIVE-DITRANSITIVE construction could be separately specified in a DITRANSITIVE argument structure construction and an ACTIVE clausal construction, which would also impose effects on the predication's information structure (not represented in the current analysis). These more compositional analyses are consistent with the overall analysis and can be expressed in our formalism.

construction VERB
  form:
    f **instance of** Schematic-Form
  meaning:
    pred **instance of** Predication
    pred.schemas ⟷ **filler**

construction TOSSED
  subcase of VERB
  form:
    f **instance of** [tast]
  meaning:
    pred.schemas ⟷ t **instance of** Toss
    pred.event-structure ⟵ encapsulated
    pred.setting.time ⟵ past

Figure 12: The VERB and TOSSED construction.

exerts a force on an energy-sink via some means, possibly through an instrument. Both the type and amount of force may also be specified. (This schema can be viewed as one of many force-dynamic interactions described by Talmy (1988).) Our simplified Cause-Effect schema lists only a cause and a resulting effect. The Forced-Motion schema binds these schemas such that the causer engages in some action that exerts force on the trajector, which as a result engages in a motion along a path. The schema is relatively abstract in that no particular forcing action or moving action is specified; many schemas and constructions may be defined using Forced-Motion as a background frame that gets specialized or profiled as appropriate.

schema Cause-Effect
  roles:
    cause
    effect

schema Force-Dynamic-Transfer
  roles:
    energy-source
    instrument
    energy-sink
    force-type
    force-amount
    means

schema Forced-Motion
  constituents:
    fdt **instance of** Force-Dynamic-Transfer
    spg **instance of** SPG
    c **instance of** Cause-Effect
  roles:
    causer ⟷ fdt.energy-source
    trajector ⟷ fdt.energy-sink ⟷ spg.trajector
    action ⟷ fdt ⟷ c.cause
    motion ⟷ spg ⟷ c.effect

Figure 13: The Cause-Effect, Force-Dynamic-Transfer, and Forced-Motion schemas.

Given the constraints just specified, the Toss schema (Figure 14) has a relatively straightforward description as profiling the action role of the Forced-Motion schema. That is, the action of tossing profiles a (somewhat) forceful action on an entity that causes its resulting motion. The Toss schema names two roles — a tosser and a tossed object — that are identified with roles in the base Forced-Motion schema, where the tossed role is additionally constrained to be a Bounded-Thing. (Note that the formalism allows both a role identification constraint and a type constraint to be expressed simultaneously.) Besides these direct role bindings, an additional block labeled **constraints** restricts the degree of force used in the causal action to be low and the manner of motion undergone by the trajector to be a Fly action.

```
schema Toss
  profiles action in Forced-Motion
   roles:
     tosser ⟷ causer
     tossed ⟷ trajector instance of Bounded-Thing
   constraints:
     action.force-amount ⟵ low
     motion.means instance of Fly
```

Figure 14: The Toss schema.

2.2.2 The Active-Ditransitive construction

The only remaining construction to define is the argument structure construction spanning the entire utterance. Following Goldberg (1995), we analyze the Active-Ditransitive construction as specifying the predicated event as one of Transfer, in which an agent acts by some (forceful) means to cause a recipient to receive the theme entity. Like the Forced-Motion schema previously defined, this schema has causal structure, and it involves a forceful action on the part of an agent. We need only introduce a simplified Receive schema for the action of the recipient; both schemas are shown in Figure 15.[5] The asserted role identifications align the various constituent schemas appropriately. Like the Forced-Motion schema, the Transfer schema does not specify the particular action taken to effect the transfer; specific verbs — such as *toss* in our example — are associated with meanings that interact with this schema to produce a complete predication.

```
schema Receive
  roles:
    receiver
    received
```

```
schema Transfer
  constituents:
    fdt instance of Force-Dynamic-Transfer
    rec instance of Receive
    c instance of Cause-Effect
  roles:
    agent ⟷ fdt.energy-source
    theme ⟷ rec.received
    recipient ⟷ rec.receiver
    means ⟷ fdt
  constraints:
    c.cause ⟷ fdt
    c.effect ⟷ rec
```

Figure 15: The Receive and Transfer schemas.

The Active-Ditransitive construction using this Transfer schema is shown in Figure 16. Since this construction is defined as a subcase of the Pred-Expr, it has an inherited instance of the Predication frame in its meaning pole. It also has four constituents, deliberately given aliases parallel to those in the closely related Transfer frame.

[5] See Goldberg (1995) for motivation of details of the analysis, such as the choice of the action of receiving rather than a state of possession as the result of the transfer action. Also note that we have defined the Receive schema as simply as possible; a fuller description would show how force dynamics and motion might be involved, as discussed below.

construction ACTIVE-DITRANSITIVE
subcase of PRED-EXPR
constituents:
agent **instance of** REF-EXPR
action **instance of** VERB
recipient **instance of** REF-EXPR
theme **instance of** REF-EXPR
form:
agent_f `before` action_f
action_f `meets` recipient_f
recipient_f `meets` theme_f
recipient_f.case $\longleftarrow$ object
agent_f.case $\longleftarrow$ subject
theme_f.case $\longleftarrow$ object
meaning:
p $\longleftrightarrow$ action_m.pred
p.event $\longleftrightarrow$ tr **instance of** Transfer
tr.agent $\longleftrightarrow$ agent_m
tr.theme $\longleftrightarrow$ theme_m
tr.recipient $\longleftrightarrow$ recipient_m
tr.means $\longleftrightarrow$ p.schemas

Figure 16: The ACTIVE-DITRANSITIVE construction.

We first discuss the form constraints asserted by the construction. The three constraints on the order of the construction's constituents reflect intuitions suggested by the examples in (3):

(3) a. Mary tossed me a drink.
b. Mary happily tossed me a drink.
c. * Mary tossed happily me a drink.
d. * Mary tossed me happily a drink.
e. Mary tossed me a drink happily.

That is, the agent must precede the action (though not necessarily immediately), and no intervening material is allowed between the action and recipient constituents, nor between the recipient and theme constituents. To enforce case restrictions on pronouns filling the constituents of the ACTIVE-DITRANSITIVE construction, the agent, theme, and recipient constituents are constrained to have the appropriate case values, accounting for the judgments in (4):[6]

(4) a. * Mary tossed I/my a drink.
b. * Me/my tossed Mary a drink.

The meaning constraints are slightly more complicated. The inherited Predication p is identified with the pred element of the ACTIVE-DITRANSITIVE's action_m constituent. (Recall that all instances of VERB inherit the pred instance of Predication.) This binding — shown in Figure 6 as the double-headed arrow linking the two Predication schemas — incorporates any relevant predication constraints expressed by the

[6] Our use of a formal case attribute does not preclude the possibility that case patterns may be motivated by semantic regularities (Janda 1991). The current analysis is intended to demonstrate how constraints on such a form attribute could be imposed; a more detailed analysis would involve defining constructions that capture the form and meaning regularities related to case marking.

action constituent. When the action constituent is instantiated by TOSSED, for example, this identification constraint sets the features related to tense and aspect (past, encapsulated), and the schemas role is specified as an instance of Toss. The ACTIVE-DITRANSITIVE also evokes an instance of the Transfer schema, which is directly bound to the predication's event role. The agent, theme, and recipient roles of this schema are bound straightforwardly to the appropriate constituent meaning poles. The means role is, somewhat less intuitively, identified with p.schemas; since the predications of the ACTIVE-DITRANSITIVE construction itself and its action constituent are also bound, both p.schemas and tr.means are therefore equivalent to action_f.pred.schemas (i.e., the schemas specified by the action constituent).

The overall effect in the example — when the action role is filled by the verb TOSSED — is that an instance of the Transfer schema (contributed by the argument structure construction) has its means role bound to an instance of the Toss schema (contributed by the verbal construction); analysis is successful only when these meanings are compatible. Compatibility depends on several factors, but the most relevant one here is whether all the type constraints specified by the various constructions and schemas are satisfied. From Figure 15, the means role of the Transfer schema is constrained to be an instance of Force-Dynamic-Transfer. Fortunately, this constraint is satisfied by the Toss schema, which profiles the action role of its base Forced-Motion schema; this action role is defined as an instance of Force-Dynamic-Transfer. These bindings thus succeed, with the net result that the forceful action involved in the transfer event is identified with the forceful action involved in a tossing action, and the agent of transfer is identified with the tosser. Similar propagation of binding constraints also leads the tossed object to be identified with the theme of the transfer event, although in this case we have not shown the relevant internal structure of the Receive schema.[7]

As just shown, the formalism permits the expression (and enforcement) of bidirectional constraints between verbal and clausal semantics — in this case, for example, a restriction on ditransitive construction to verbs that entail some force-dynamic transfer (Langacker 1991):

(5) * She slept the baby-sitter a break. *(Her sleeping gave the baby-sitter a break.)*

In an attempted analysis of the sentence in (5) as an instance of the ACTIVE-DITRANSITIVE construction, the construction filling the action constituent would be that corresponding to *slept*. The lack of the requisite force-dynamic semantics in the schema associated with sleeping accounts for the sentence's questionable acceptability; Section 3.3.1 discusses related phenomena arising during analysis that likewise depend on semantic compatibility.

We have now completed our extended tour through the constructions licensing one analysis of *Mary tossed me a drink.* As should be clear from the disclaimers along the way, some details have been simplified and complications avoided for ease of exposition. But while the resulting analysis may not capture all the linguistic insights we would like, we believe that issues related to the content of the construction are separable from our primary goal of demonstrating how a broad variety of constructional facts can be expressed in the Embodied Construction Grammar formalism. The next section situates the formalism in the broader context of language understanding, using the constructions and schemas we have defined to illustrate the analysis and simulation processes.

3 ECG in language understanding

Now that we have shown how constructions and semantic schemas can be defined in the ECG formalism, we shift our attention to the dynamic processes that use the formalism for language understanding. Section 3.1

[7] A fuller definition of the Receive schema would show constituent structure including an SPG; this SPG instance would thus be (part of) the effect of the instance of Force-Dynamic-Transfer in the Transfer schema. Since the forceful actions of the Toss and Transfer schemas are identified, their respective effects are as well, resulting in a binding between their tossed and theme roles.

shows how the analysis process finds relevant constructions and produces a semantic specification, and Section 3.2 then shows how the simulation can use such a semspec, along with its associated embodied structures, to draw inferences that constitute part of the understanding of the utterance. In Section 3.3, we consider issues that arise in attempting to account for wider linguistic generalizations and sketch how they might be handled in our framework.

3.1 Constructional analysis

Constructional analysis is a complex undertaking that draws on diverse kinds of information to produce a semantic specification. In particular, since constructions carry both phonological and conceptual content, a construction *analyzer* — essentially, a parser for form-meaning constructions — must respect both kinds of constraint. Analysis consists of two interleaved procedures: the search for candidate constructions that may account for an utterance in context; and the unification of the structures evoked by those constructions in a coherent semspec. We illustrate both procedures in the vastly simplified situation in which the known constructions consist *only* of the constructions defined in Section 2. The search space is thus extremely limited, and the unification constraints in the example are relatively straightforward.

A typical analysis begins with the phonological forms in an utterance evoking one or more constructions in which they are used. Given our reduced search space, this happens unambiguously in our example: the lexical constructions underlying the words *Mary*, *tossed*, *me*, and *drink* (ignoring the possible verb stem construction with the same form) each trigger exactly one construction; since no additional form constraints remain to be satisfied, the various schemas evoked by the constructions are added to the semspec. The word *a* similarly cues the A-CN-EXPR construction (since the phonological form corresponding to *a* is part of its form pole). The cued construction has an additional cat-label constituent to fill; fortunately, the relevant form and meaning constraints are easily satisfied by the previously cued DRINK construct. The ACTIVE-DITRANSITIVE is triggered by the presence of the other analyzed constructs in the observed order; its constraints are then checked in context. As mentioned in Section 2.2.2, it is this step — in particular, ensuring that the construction's semantic requirements are compatible with those of its verbal constituent — that poses the main potential complication. In our example, however, the schemas as defined are enough to license the bindings in question, and the utterance is successfully analyzed.

We mention in passing some issues that arise when constructional analysis is not restricted to our carefully orchestrated example sentence. The search for candidate constructions, for example, grows much harder with larger sets of constructions and their attendant potential ambiguities. The number of constraints to be satisfied — and ways in which to satisfy them — may also make it difficult to choose among competing analyses. Approaches to these essentially computational problems vary in cognitive plausibility, but a few properties are worth noting as both cognitively and computationally attractive. As in our toy example, analysis should proceed in both bottom-up and top-down fashion, with surface features of the utterance providing bottom-up cues to the constructions involved, and cued constructions potentially supplying top-down constraints on their constituents. An equally important principle (not yet explicit in our example constructions) is that processing should reflect the graded nature of human categorization and language processing. That is, constructions and their constraints should be regarded not as deterministic, but as fitting a given utterance and context to some quantifiable degree; whether several competing analyses fit the utterance equally well, or whether no analysis fits an utterance particularly well, the result of processing is the *best-fitting* set of constructions.[8]

[8]Both probabilistic and connectionist models have some of the desired properties; either approach is theoretically compatible with the ECG formalism, where constructions and their constraints could be associated with probabilities or connection weights. See Narayanan and Jurafsky (1998) for a probabilistic model of human sentence processing that combines psycholinguistic data involving the frequencies of various kinds of lexical, syntactic and semantic information. The resulting model matches human data in the processing of garden path sentences and other locally ambiguous constructions.

The semantic specification resulting from the unification process described above is shown in Figure 17. Predications and referents are shown in separate sections; in a coherent semspec, all schemas are eventually bound to some predication or referent structure. The depicted schemas and bindings illustrate the main ways in which the constructions instantiated in a successful analysis contribute to the semspec:

- Constructions may directly evoke schemas (and the bindings they specify) in their meaning poles. The three referents and single predication shown can each be traced to one or more constructions, and each schema effects various bindings and type constraints on its subparts and roles.
- Constructions may effect bindings on the roles of their schemas and constituents. Most of the bindings shown in the figure come from the ACTIVE-DITRANSITIVE construction and its interaction with its constituents. Note also that the figure shows a single predication, the result of unifying the predications in the TOSSED and the ACTIVE-DITRANSITIVE constructions; the Drink category has likewise been unified into the appropriate referent frame.
- Constructions may set parameters of their schemas to specific values; these values have fixed interpretations with respect to the simulation. The TOSSED construction, for example, sets its associated predication's setting.time to be past (shorthand for locating the entire event previous to speech time) and its event-structure to be encapsulated (shorthand for running the simulation with most details suppressed, to be discussed in the next section).

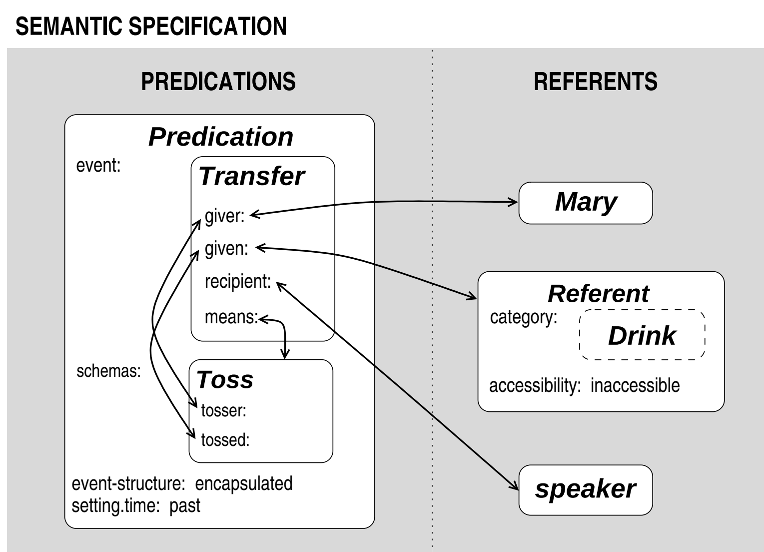

Figure 17: Semantic specification showing predications and referents produced by the analysis of *Mary tossed me a drink.*

The figure does not show the constituent schemas evoked by several of the schemas, including the instances of Force-Dynamic-Transfer in both the Transfer and Toss actions that are unified as a result of analysis. It also does not show how the semspec interacts with context and reference resolution procedures. Nevertheless, the semspec contains enough information for an appropriate simulation to be executed, based primarily on the Toss schema and the embodied motor schema it parameterizes. In Section 3.2 we describe how such dynamic knowledge is represented and simulated to produce the inferences that result from our example sentence.

3.2 Simulative inference

We have claimed that constructional analysis is merely a crucial first step toward determining the meaning of an utterance, and that deeper understanding results from the simulation of grounded sensorimotor structures parameterized by the semspec. This section first describes active representations needed to describe, for example, the tossing action (Section 3.2.1), and then discusses how these representations are simulated to produce fine-grained inferences (Section 3.2.2).

3.2.1 An execution schema for tossing

Executing schemas, or *x-schemas*, are dynamic representations motivated in part by motor and perceptual systems (Bailey 1997; Narayanan 1997), on the assumption that the same underlying representations used for executing and perceiving an action are brought to bear in understanding language about that action. The x-schema formalism is an extension of Petri nets (Murata 1989) that can model sequential, concurrent, and asynchronous events; it also has natural ways of capturing features useful for describing actions, including parameterization, hierarchical control, and the consumption and production of resources. Its representation also reflects a basic division into primitives that correspond roughly to stative situations and dynamic actions.

We use tossing, the central action described by our example utterance, to illustrate the x-schema computational formalism. The Toss schema evoked by the TOSSED construction parameterizes the Tossing-Execution schema, which is the explicit, grounded representation of the sensorimotor pattern used (by an implicit tosser) to perform a tossing action, shown in Figure 18. Informally, the figure captures a sequence of actions that may be performed in tossing an object (the tossed parameter), including possible preparatory actions (grasping the object and moving it into a suitable starting position) and the main tossing action of launching the object (shown in the hexagon labeled nucleus). This main event may include subsidiary actions that move the object along a suitable path before releasing the object, all with low force. A number of perceptual conditions (shown in the area labeled *percept vector*) must also hold at specific stages of the event: the tossed object must be in the hand (of the tosser) before the action takes place, and afterward it will be flying toward some target. (The target role was not shown in the Toss schema definition from Figure 14, but would be bound to its spg.goal.)

The x-schema formalism provides a graphical means of representing the actions and conditions of the dynamic event described. An x-schema consists of a set of *places* (drawn as circles) and *transitions* (drawn as hexagons) connected by *arcs* (drawn as arrows). Places typically represent perceptual conditions or resources; they may be *marked* as containing one or more *tokens* (shown as black dots), which indicate that the condition is currently fulfilled or that the resource is available. In the stage depicted in the figure, for example, two places in the percept vector are marked, indicating that the object to be tossed is currently in the tosser's hand, and that the tosser currently has some energy. (The figure does not show incoming arcs from separate perceptual input mechanisms that detect whether the appropriate conditions hold.) The other places in the figure are control states for the action (e.g., enabled, ready, ongoing, done, which we discuss in Section 3.2.2). The overall state of the x-schema is defined as the distribution of tokens to places over the network; this assignment is also called a *marking* of the x-schema.

Transitions typically represent an action or some other change in conditions or resources; the ones shown each correspond to a complex action sequence with subordinate x-schemas whose details are suppressed, or *encapsulated*, at this level of granularity. The figure shows how the tossing x-schema's main launching action could be expanded at a lower level of granularity; the subordinate schemas are drawn with dotted lines to indicate that they are encapsulated. Note that these transitions also have labels relevant to the overall control of the action (prepare, start, finish, iterate, nucleus); again, these will be discussed in Section 3.2.2. Directed arcs (depicted in the figure as arrows) connect transitions to either *input places* (i.e., places from which it has an incoming arc) or *output* places (i.e., places to which it has an outgoing arc).

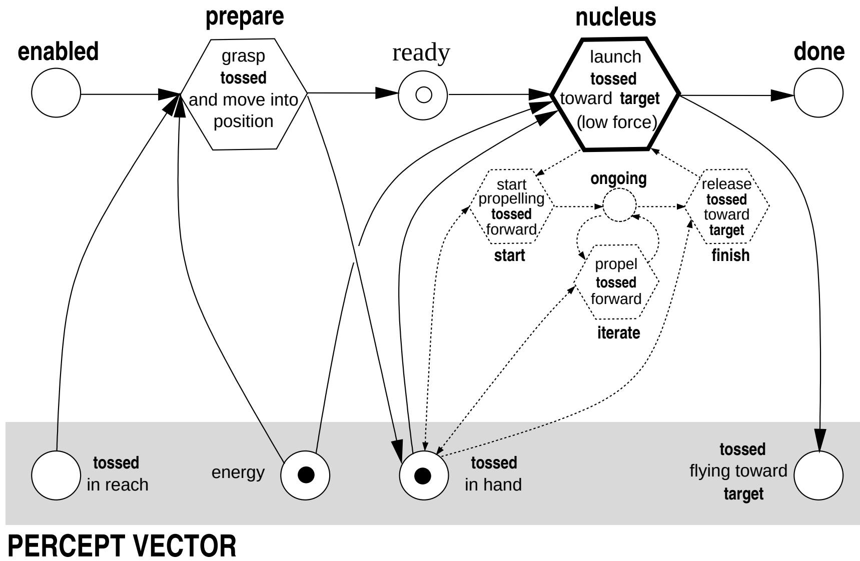

Figure 18: A simplified x-schema representing motor and perceptual knowledge of the tossing action, defined relative to the tosser. (Not all arcs are shown.)

X-schemas model dynamic semantics by the flow of tokens. Tokens flow through the network along *excitatory* arcs (single-headed arrows), according to the following rules: When each of a transition's (excitatory) input places has a token, the transition is *enabled* and can *fire*, consuming one token from each input place and producing one token in each output place. An x-schema *execution* corresponds to the sequence of markings that evolve as tokens flow through the net, starting from an initial marking. Given the initial marking shown in the figure, the transition labeled nucleus can fire, consuming tokens from each input place. The firing of this transition causes the execution of the subordinate sequence of actions; once these have completed, the transition's firing is complete and tokens are placed in its output places, asserting that the tossed object is now on its trajectory. The overall token movement can be interpreted as the expenditure of energy in a movement that results in the tossed object leaving the tosser's hand and flying through the air.

Most of the arcs shown in the Toss-Execution schema are excitatory; places and transitions may also be connected by *inhibitory* and *enabling* arcs. Inhibitory arcs (not shown in the figure), when marked, prevent the firing of the transitions to which they have an outgoing connection. Enabling arcs (shown as double-headed arrows) indicate a static relationship in which a transition requires but does not consume tokens in enabling places. The figure shows two of the subschemas encapsulated within the nucleus transition as having enabling links from the place indicating that the object is in the tosser's hand; this makes sense since contact with the object is maintained throughout the action of propelling the tossed object. (Again, the arcs are drawn using dotted lines to indicate their encapsulated status.)

The x-schema formalism has just the properties needed to drive simulation in our framework. X-schemas can capture fine-grained features of complex events in dynamic environments, and they can be parameterized according to different event participants. Constructions can thus access the detailed dynamic knowledge that characterizes rich embodied structures merely by specifying a limited set of parameters. Moreover, the tight coupling between action and perception allows highly context-sensitive interactions, with the same x-schema producing strikingly different executions based on only slight changes in the percept vector or in the specified parameters. In the next section we show how x-schemas can be used for fine-grained inference on the basis of an analyzed utterance.

3.2.2 Simulation-based inferences

We complete the discussion of our example sentence by summarizing how the active representations just described are invoked during simulation. The semspec in Figure 17 contains all of the parameters necessary to run the simulation, calling the Toss-Execution schema described in the last section, a Transfer schema for the overall event, and the relevant referents. We assume that the semspec referents are resolved by separate processes not described here; we simply use the terms MARY, SPEAKER, and DRINK to refer to these resolved referents. Our example semspec asserts that the specified tossing execution takes place (in its entirety) before speech time. In other words, the marking state is asserted to have evolved such that the nucleus transition has fired and resulted in the marking of the done place.

The dynamic semantics described in the last section give x-schemas significant inferential power. The parameterization and marking state asserted by the semspec can be projected or regressed to determine subsequent or preceding markings. The asserted marking thus implies, for instance, that the object in hand place was marked at an earlier stage of execution (shown in the figure as part of Toss.ready), and that the energy place has fewer tokens after execution than it did before (not shown in the figure). Part of the inferred trace of evolving markings is shown in Figure 19, organized roughly chronologically and grouped by the different stages associated with the event-level transfer schema and the action-level tossing schema. We use the labels TRANS and TOSS to refer to the particular schema invocations associated with this semspec.

TRANS.ready		SPEAKER does not have DRINK
TRANS.nucleus		MARY exerts force via TOSS
	TOSS.enabled	DRINK in reach of MARY
	TOSS.ready	DRINK in hand of MARY
	TOSS.nucleus	MARY launches DRINK toward SPEAKER
		MARY expends energy (force-amount = low)
	TOSS.done	DRINK flying toward SPEAKER
		DRINK not in hand of MARY
TRANS.nucleus		MARY causes SPEAKER to receive DRINK
TRANS.done		SPEAKER has received DRINK

Figure 19: Some inferences resulting from simulating *Mary tossed me a drink*.

The stages singled out in the table are, not coincidentally, the same as in the bold labels in Figure 18. These labels play an important structuring role in the event: many actions can be viewed as having an underlying process semantics characterized by the identified stages. The common structure can be viewed as a generalized action controller that, for a particular action, is bound to specific percepts and (subordinate) x-schemas. This generalized action controller captures the semantics of event structure and thus provides a convenient locus for constructions to assert particular markings affecting the utterance's aspectual interpretation. The resulting inferences have been used to model a wide range of aspectual phenomena, including the interaction of inherent aspect with tense, temporal adverbials and nominal constructions (Narayanan 1997; Chang, Gildea, and Narayanan 1998). For current purposes, it is sufficient to note that certain constructions can effect specific markings of the tossing x-schema:

(6) a. Mary is about to toss me a drink. *(ready place marked)*

b. Mary is in the middle of tossing me a drink. *(ongoing place marked)*

c. Mary has tossed me a drink. *(done place marked)*

As previously mentioned, tense and aspect markers can also force an entire x-schema to be viewed as encapsulated within a single transition, much like the subordinate x-schemas shown in Figure 18. Such an operation has the effect of suppressing the details of execution as irrelevant for a particular level of simulation. In the example sentence we have been considering, this encapsulated aspect is imposed by the TOSSED construction described in Section 2. As a result, while the full range of x-schematic inferences are available at appropriate levels of simulation, the default simulation evoked by our example may eschew such complex details such as how far the tosser's arm has to be cocked and at what speed a particular object flies.

3.3 Scaling up

In this section we venture outside the safe haven of our example and show how the semantic expressiveness of the ECG formalism can be exploited to model some of the remarkable flexibility demonstrated by human language understanders. The key observation is that the inclusion of detailed semantic information adds considerable representational power, reducing ambiguities and allowing simple accounts for usage patterns that are problematic in syntactically oriented theories. Section 3.3.1 explores the use of semantic constraints from multiple constructions to cope with ambiguous word senses, while Section 3.3.2 attacks the problem of creative language use by extending the formalism to handle metaphorical versions of the constructions we have defined.

3.3.1 Sense disambiguation

Section 2 showed how verbal and clausal constructions interact to determine the overall interpretation of an event, as well as to license (or rule out) particular semantic combinations. This account provides a straightforward explanation for the differing behavior of *tossed* and *slept* with respect to the ditransitive construction:

(7) a. Mary tossed/*slept me a drink. *(transfer)*

b. Mary tossed/*slept the drink into the garbage. *(forced motion)*

A similar pattern and account could be given for (7b). (Though not shown, it is the equivalent of Goldberg's (1995) CAUSED-MOTION construction.) In both examples, the acceptability of the verb *toss* hinges directly on the fact that its associated semantic schema for tossing — unlike that for sleeping — explicitly encodes an appropriate force-dynamic interaction. The examples in (7) involving *tossed* also illustrate how the same underyling verb semantics can be bound into different argument structures. Thus, in (7a) the tossing action is the means by which a transfer of the drink is effected; in (7b) the tossing action is used as part of an event of forced motion.

The same mechanisms can also help select among verb senses that explicitly profile different parts of an event:

(8) a. Mary rolled me the ball. *(forced motion)*

b. The ball rolled down the hill. *(directed motion)*

The verb *rolled* as used in (8a) is quite similar to the use of *tossed* in our example sentence, referring to the causal, force-dynamic action taken by Mary to cause the speaker to receive an object. But the sentence (8b) draws on a distinct but intimately related sense of the verb, one that refers to the resulting revolving motion itself.

A simple means of selecting the appropriate sense within the ECG framework is to cast the schema associated with rolling in terms of the Forced-Motion schema shown in Figure 13; the two senses of the verb *rolled* could profile the action and motion roles, respectively, of the Forced-Motion schema. The verbal construction may remain noncommittal with respect to the particular sense it contributes. The requisite sense disambiguation will depend instead on the semantic requirements of the particular argument structure construction involved. Thus, the ACTIVE-DITRANSITIVE construction's need for a sense involving force-dynamic interaction will select for the sense profiling action. Although we have not shown the DIRECTED-MOTION construction that accounts for the use in (8b), it could be defined as requiring a verbal argument that profiles its motion role (an instance of SPG). Note that the senses contributed by the verb are purely semantic, avoiding the need to specify the particular syntactic alternations they each afford.

We have focused so far on the interactions between verbal and clausal requirements, but in fact, semantic constraints imposed by features of entities also play a decisive role in sense disambiguation:

(9) Mary poured me a drink. *(creation with intent to transfer)*

The sentence in (9) cannot be analyzed in the same way as our example from Section 2: pouring cannot be the direct means of a (successful) transfer, since no drink exists until the pouring action has happened. Rather, *pour* is used as a verb of creation, and the result of pouring is a newly created drink; this drink — and not its contents — is the actual theme entity that is received in the Transfer schema. This sentence draws on a variant of the ditransitive construction requiring only that the agent creates an entity with the *intent* that the recipient will receive it.

In this case, the verbal and clausal constructions alone do not suffice to disambiguate the intended sense of *pour* and variant of ACTIVE-DITRANSITIVE. Clearly, the explanation lies in the interaction among the ditransitive construction, the Pour schema, and the Drink schema. In particular, we assume that a pouring action can potentially produce a Bounded-Mass, which is compatible with the definition of Drink. (For example, the pouring schema definition could include a creation schema relating the pouring action to its resulting bounded mass.) Although this situation is more complex than the other sense disambiguation cases, it is possible to devise a solution based on the same principles of profiling and bindings. The result is that although the verb *pour* is inherently ambiguous when used in ditransitive expressions, its meaning pole is elaborated enough that features of potential nominal fillers can be used to select the correct sense.[9]

3.3.2 Metaphor: a case study in construal

The examples discussed in the last section demonstrate some relatively limited means of applying semantic constraints to problems that resist purely syntactic solutions. These mechanisms exploit static properties of the schema formalism, such as inheritance relations, constituency, type constraints, and profile relations. By themselves, however, such static properties can encode only conventionalized patterns of meaning. They cannot capture unexpected or unusual patterns of usage; they cannot account for the ubiquity of creative language use, nor for the relative ease with which humans understand such usages. Lexical and phrasal constructions can occur in novel configurations that are nevertheless both meaningful and constrained. Ultimately, in a full-scale language understanding system intended to be robust to varying speakers and contexts, it would be neither possible nor desirable to pre-specify all potential uses of a semantic schema: under the right circumstances, constructs that do not explicitly satisfy a given semantic requirement may still be treated as if they do. Rather, creative linguistic production must be mirrored by creative linguistic understanding. We use the general term *construal* to refer to a widespread set of flexible processing operations that license creative language use, including novel metaphorical and metonymic expressions (Lakoff and Johnson 1980), as well as implicit type-shifting processes that have been termed *coercion* (Michaelis, this volume). In this section we highlight metaphorical construal as a case study of how construal might be treated by a simple

[9]A related effect is illustrated by the effect of *boulder* in the sentence *?Mary tossed me a boulder.* Given the minimal effort associated with tossing, and the heftiness associated with boulders, the sentence could take on dubious pragmatic status. But this reading depends on prior knowledge about the individuals involved; in a context in which both Mary and the speaker are known to have superhuman strength, the sentence may seem perfectly acceptable.

extension to the ECG formalism.

Metaphors are a pervasive source of creative language use, allowing speakers to structure a more abstract *target domain* in terms of a more concrete *source domain* (Lakoff and Johnson 1980). Metaphors can be characterized as conventionalized mappings spanning domains of knowledge, typically linking a perceptually and motorically embodied source domain (such as object manipulation, physical proximity, or physical force) onto a relatively more abstract target domain (such as reason, emotional connection, or social action). Some metaphorical uses might be treated simply as conventionalized linguistic units; the use of *delivered* in (10a) below exemplifies a conventionalized use of a metaphor in which the verbal communication of ideas is interpreted as the physical transfer of objects. But metaphors can also structure novel uses of constructions, as shown by the use of *tossed* in (10b). It is this second, creative use of metaphor that we consider an instance of construal and attempt to address in this section.

(10) a. Our president has just delivered the most important speech of his short career.

b. Mary tossed *The Enquirer* a juicy tidbit.

Sentence (10b) employs nearly the same constructions as our extended example, including the Mary, Tossed, A-CN-Expr, and Active-Ditransitive constructions. The remaining constructions needed require a few modifications to those previously defined. We ignore the internal structure of *The Enquirer* for current purposes and treat it as a referring expression whose meaning is a specific news agency. The word *tidbit* is somewhat more interesting, since it may be considered to have two conventionalized senses that are related but distinct. Both senses refer to a high-quality but small unit, differing only in whether they refer to food or to information. Similarly, *juicy* can characterize the consistency of a morsel of information or of sustenance.

In determining whether sentence (10b) could be produced by the Active-Ditransitive construction, the analyzer must find four constructs to fill its constituent roles and thereby instantiate the Transfer schema. This process yields an apparent type mismatch: the news institution *The Enquirer* cannot be a literal recipient (though not shown earlier, the Receive schema requires an active Receiver). The analyzer must also choose between the two possible senses of *tidbit* and *juicy*; although the food senses of these words fit the requirements of the Transfer schema, the overall analysis seems unable to satisfies all relevant constraints at once.

A potential solution to the analyzer's problems is the introduction of a metaphorical map that captures the intuitions described above. Figure 20 defines a Conduit metaphor that allows a target domain involving Communication to be structured in terms of a corresponding source domain of Object-Transfer; the schemas are not defined here, but the relevant roles for each are shown in the figure. (The notation is similar to that used in the schema and construction formalisms.) The mappings listed in the **maps** block assert that a speaker communicating some information to a hearer can be construed as physical agent sending a physical recipient some object.

We assume the analyzer has access to ontological information categorizing *The Enquirer* as an institution that can collect verbal information, making it a suitable hearer in the Communication schema. (We ignore for now the additional metonymy that could link *The Enquirer* to an associated reporter.) Access to the Conduit metaphor could help the analyzer deal with the sentence in (10b) by allowing *The Enquirer* to be construed as a suitable recipient in an Object-Transfer schema. Further analysis is affected by this mapping: If the recipient is metaphorical, then in the most likely analysis the object is metaphorical as well, leading to the selection of the information-related senses of *juicy* and *morsel*. Similarly, both the overall event and the means by which it was asserted to have taken place must be interpreted as a verbal, rather than physical, acts of transfer.

A hallmark of metaphorical usage is that the mapping of inferences from source to target domain can involve relatively subtle simulative detail. For example, we know from Section 3.2 that *toss*, when used in a ditransitive context, implies that the launching action involves low force. Mapped to the target domain

```
metaphor Conduit
  source: Object-Transfer
  target: Communication
  maps:
    sender ↦ speaker
    recipient ↦ hearer
    object ↦ information
```

Figure 20: The Conduit metaphor.

of communication, this inference becomes one of casualness on the part of the speaker. (For a technical description of how metaphorical inference can be performed and propagated to a target domain, the reader is directed to Narayanan (1997).) The inclusion of metaphor maps in the formalism, along with appropriate interfaces to the active simulation, opens the door to creative metaphorical inferences of this kind.

4 Concluding remarks

In this report, we have formalized and extended ideas from the construction grammar literature to accommodate the requirements of a larger simulation-based model of language understanding. Constructions in this model serve to evoke and bind embodied semantic structures, allowing language understanding to depend on both specifically linguistic knowledge and general conceptual structures. We have attempted to illustrate the representational properties of our formalism for a variety of linguistic phenomena, including straightforward issues that arise in our example analysis, as well as more complex issues surrounding sense disambiguation and metaphorical inference.

The ECG formalism diverges in several respects from other construction grammars in the literature, in large part due to its non-trivial interactions with both the analysis and simulation processes. It is also motivated and constrained by the need to develop a computational implementation of the overall model, which explains similarities it bears to object-oriented programming languages, as well as to some implementation-oriented versions of HPSG (Pollard and Sag 1994). As we have noted, the presentation in the current work has focused on the formalism itself, simplifying many details to highlight how particular analyses can be expressed within the overall framework. We thus conclude by briefly expanding on some of the issues that motivate ongoing and future research.

Our example constructions use a somewhat restricted set of formal elements. But constructions can have formal realizations that span levels of description, including syntactic, lexical, morphological, phonological, and prosodic cues (for examples, see the discussion of *there*-constructions in Lakoff (1987)). In other work (Bergen, Chang, and Paskin 2000), we have shown how minor extensions allow the formalism to cover a broader range of phenomena in a common notation. For example, the same set of interval relations we use to express syntactic order can be applied to enforce word-internal order of morphemes and to align prosodic contours with lexical hosts.

Our discussion has also deliberately sidestepped complications related to situational and discourse context, but work in progress is exploring how the mechanisms we have introduced can be extended to address discourse-level phenomena in general and mental spaces phenomena (Fauconnier 1985) in particular. The notion of a *space* as a domain of reference and predication fits in especially well with semantic specifications, which are described here as likewise containing referents and predications. We can thus view semspecs as being situated in some space, and these spaces can be evoked, introduced, and constrained by constructions called *space builders*. Other constructions — and their corresponding semspecs — can then be defined relative to the currently active space. For example, a space-building construction X-SAID-Y might be defined to handle reported speech:

(11) Frank said, "Mary tossed me a drink."

Such a construction would presumably introduce an embedded space for the reported speech and require the corresponding constituent to associate its semspec with that embedded space. Given such a constraint, the ME construction — defined in Section 2.1 as identifying its referent with the speaker in the *current* space — would correctly designate the speaker in the embedded space (Frank), and not the global speaker. A more general treatment of mental spaces phenomena awaits further research, but the potential for applying the formal tools of ECG to capture interactions between constructions and multiple spaces appears promising.

Another dimension of ongoing research focuses on neural (or connectionist) modeling of our computational architectures. Previous models have explicitly related the conceptual structures and mechanisms mentioned here — including image schemas (Regier 1996), x-schemas (Bailey 1997), and metaphor maps (Narayanan 1997) — to neural structures. X-schemas, for example, are defined at the computational level as representing abstractions over neural motor control and perceptual systems (Bailey 1997). At a more detailed connectionist level of representation, Shastri, Grannes, Narayanan, and Feldman (1999) implement x-schemas as interconnected clusters of nodes. The binding of roles to other roles and to fillers has also been subject to extensive connectionist modeling, in particular as part of the SHRUTI model (Shastri and Ajjanagadde 1993). Although we have not emphasized this point here, the representational and inferential mechanisms used in the ECG formalism have been restricted to those that can be realized in a connectionist architecture.

As the strands of research mentioned here might suggest, the goals and methods driving both the formalism we have introduced and our broader approach to language understanding are inherently interdisciplinary. Our main goal has been to show how an embodied construction grammar formalism permits fine-grained interactions between linguistic knowledge and detailed world knowledge. The work presented here also, however, exemplifies the methodology of applying converging computational, cognitive and biological constraints to flesh out in formal detail insights from theoretical linguistics. Although many challenges remain, we are hopeful that the ideas we have explored will help to stimulate the continued integration of diverse perspectives on language understanding.

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