An Improved Approach for Semantic Graph Composition
with CCG

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Abstract
This paper builds on previous work using Combinatory Categorial Grammar (CCG) to derive a transparent syntax-semantics interface for Abstract Meaning Representation (AMR) parsing. We define new semantics for the CCG combinators that is better suited to deriving AMR graphs. In particular, we define symmetric alternatives for the application and composition combinators: these require that the two constituents being combined overlap in one AMR relation. We also provide a new semantics for type raising, which is necessary for certain constructions. Using these mechanisms, we suggest an analysis of eventive nouns, which present a challenge for deriving AMR graphs. Our theoretical analysis will facilitate future work on robust and transparent AMR parsing using CCG.

1 Introduction
At the heart of semantic parsing are two goals: the disambiguation of linguistic forms that can have multiple meanings, and the normalization of morphological and syntactic variation. Among many techniques for semantic parsing, one profitable direction exploits computational linguistic grammar formalisms that make explicit the correspondence between the linguistic form of a sentence and the semantics (e.g., broad-coverage logical forms, or database queries in a domain-specific query language). In particular, English semantic parsers using Combinatory Categorial Grammar (CCG; Steedman, 2000) have been quite successful thanks to the CCGBank resource (Hockenmaier and Steedman, 2007; Honnibal et al., 2010) and the broad-coverage statistical parsing models trained on it (e.g., Clark and Curran, 2004; Lewis et al., 2016; Clark et al., 2018).

The CCG formalism assumes that all language-specific grammatical information is stored in a lexicon: each word in the lexicon is associated with a structured syntactic category and a semantic form, such that the compositional potentials of the category and the semantics are isomorphic. A small universal set of combinators are responsible for assembling constituents into a full syntactic derivation; each combinator operates on adjacent constituents with appropriate categories to produce a new constituent and its compositional semantics, subject to constraints. A full grammar thus allows well-formed sentences to be transduced into semantic structures. The categories and combinators cooperate to license productive syntactic constructions like control and wh-questions, requiring the correct word order and producing the correct semantic dependencies. For example, consider the sentence “Who did John seem to forget to invite to attend?”: the correct logical form—in propositional logic, something like \( \text{seem}(\text{forget}(\text{John}, \text{invite}(\text{John}, \text{who}, \text{attend}(\text{who})))) \)—is nontrivial, requiring a precise account of several constructions that conspire to produce long-range dependencies.

Whereas CCG traditionally uses some version of lambda calculus for its semantics, there has also been initial work using CCG to build parsers for Abstract Meaning Representation (AMR; Banerescu et al., 2013), a standard with which a large “sembank” of English sentences\(^1\) has been manually annotated.\(^2\)

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\(^1\)See [https://amr.isi.edu/download.html](https://amr.isi.edu/download.html)

\(^2\)As originally defined, AMR is English-specific. However, a companion annotation standard, corpus, and parsers exist for Chinese (Xue et al., 2014; Li et al., 2016; Wang et al., 2018), and initial investigations have been made toward adapting AMR to several other languages (Xue et al., 2014; Migueles-Abraira et al., 2018; Anchiêta and Pardo, 2018).
To date, dozens of publications have used the corpus to train and evaluate semantic parsers—most using graph-based or transition-based parsing methods (e.g., Flanigan et al., 2014; Wang et al., 2016; Lyu and Titov, 2018) to transform the sentence string or syntactic parse into a semantic graph via a learned statistical model, without any explicit characterization of the syntax-semantics interface. There is good reason to apply CCG to the AMR parsing task: apart from transparency of the syntax-semantics interface, state-of-the-art AMR parsers are known to be weak at reentrancy (e.g., Lyu and Titov, 2018), which presumably can be partially attributed to syntactic reentrancy in control constructions, for example. Prior work applying CCG to AMR parsing has begun to address this, but some of the important mechanisms that make CCG a linguistically powerful and robust theory have yet to be incorporated into these approaches.

In this paper, we build on a core insight of previous work (e.g., Artzi et al., 2015; Beschke and Menzel, 2018) that AMR fragments can be directly represented as the semantics of CCG lexical entries. With appropriate definitions of the lexical items and combinatorial rules of CCG, the compositionality of CCG gives a derivation of a full AMR “for free”. In other words, AMR parsing can be reduced to CCG parsing (plus some additional semantic disambiguation and postprocessing). On a practical level, this should allow us to take advantage of existing CCG datasets and parsing methods for AMR parsing. In addition, explicitly storing AMR fragments in the CCG lexicon would provide a level of interpretability not seen in most statistical AMR parsers: the transparent syntax-semantics interface would decouple errors in the grammar from errors in the parsing model.

As a prerequisite for building a CCG-based AMR parser, or inducing a broad-coverage grammar (CCG lexicon) from data, we consider in this paper the formal mechanisms that would be necessary to derive AMRs with linguistic robustness. In particular, we address a variety of challenging syntactic phenomena with respect to AMR, showing the semantic fragments, associated syntactic categories, and combinators that will facilitate parsing of constructions including control, wh-questions, relative clauses, control, case marking, nonconstituent coordination, eventive nouns and light verbs. In so doing, we offer new semantics of combinators for semantic graphs beyond the proposals of previous work.

After an overview of related work (§2),3 we introduce our formalism for AMR graph semantics in CCG (§3). §4 gives example derivations for well-known linguistic phenomena including control, complex coordination, and eventive nouns. §5 discusses some implications of our approach.

2 Related Work

AMR formalizes sentence meaning via a graph structure. The AMR for an English sentence is a directed acyclic graph that abstracts away from morphological and syntactic details such as word order, voice, definiteness, and morphology, focusing instead on lexical semantic predicates, roles, and relations. Semantic predicate-argument structures are based on the PropBank frame lexicon (Kingsbury and Palmer, 2002) and its frame-specific core argument roles (named \textit{ARG0}, \textit{ARG1}, etc.). AMR supplements these with its own inventory of noncore relations like \texttt{:time} and \texttt{:purpose}, and some specialized frames for the semantics of comparison, for example. Named entities are typed and linked to Wikipedia pages; dates and other values are normalized. Edges in the graph correspond to roles/relations, and nodes to predicate or non-predicate “concepts”, which are lemmatized. Reentrancy is used for within-sentence coreference.

A limited amount of prior research has combined CCG and AMR. Artzi et al. (2015) and Misra and Artzi (2016) develop an AMR parser using CCG by reformulating AMR graphs as logical forms in lambda calculus. We opt here for an approach similar to that of Beschke and Menzel (2018), where AMR subgraphs with free variables are treated as the semantics in the CCG lexicon. This requires definitions of the combinators that operate directly on AMR subgraphs rather than lambda calculus expressions.

Beschke and Menzel (2018) situate their formalization within the literature on graph grammars. They formulate their approach in terms of the HR algebra (Courcelle and Engelfriet, 2012), which Koller (2015) had applied to AMR graphs (but not with CCG). In this formalism, graph fragments called s-graphs are assembled to derive full graphs. S-graphs are equivalent to the AMR subgraphs described in this paper.

3Due to space constraints, we assume the reader is familiar with the basics of both CCG and AMR.
In particular, Beschke and Menzel define the semantics of CCG combinators in terms of HR-algebraic operations on s-graphs. They discuss a small set of combinators from Lewis and Steedman (2014) that includes forward and backward application and forward, backward, crossed, and generalized variants of composition. We introduce equivalent semantics for application and composition (§3.2 and §3.3), avoiding the conceptually heavy notation and formalism from the HR algebra. They also specify Conjunction and Identity combinators, which we adapt slightly to suit our needs, and a Punctuation combinator. More significantly, they treat unary operators such as type raising to have no effect on the semantics, whereas we will take another route for type raising (§3.6), and will introduce new, symmetric versions of application and composition (§3.4 and §3.5). Finally, whereas Beschke and Menzel devote most of their paper to a lexicon induction algorithm and experiments, we focus on the linguistic motivation for our definition of the combinators, and leave the development of suitable lexicon induction techniques to future work.

A related graph formalism called hyperedge replacement grammar is also used in the AMR parsing literature (Groschwitz et al., 2018; Björklund et al., 2016; Peng and Gildea, 2016; Peng et al., 2015; Chiang et al., 2013; Jones et al., 2012). Hyperedge replacement grammars (Rozenberg, 1997) are a formal way of combining subgraphs to derive a larger graph, based on an extension of Context Free Grammars to graphs instead of strings. Readers may assume that the graph formalism described in this paper is a simplified hyperedge replacement grammar which only allows hyperedges of rank 1.

3 Graph Semantics

AMR is designed to represent semantics at the sentence level. For CCG lexical entries and combinators to parse AMR semantics, this research needs to formalize how an AMR subgraph can be used as the semantic entry for a single word as well as how combinators are able to combine or modify AMR subgraphs.

This section will formalize AMR subgraph semantics and CCG combinators for function application, composition, and type raising. Additionally, this article proposes a new combinator symmetric application which is unique to graph semantics.

An AMR subgraph will be designed to include nodes and edges from the resulting AMR as well as some nodes which correspond to free variables. The basic shape of an AMR subgraph appears in figure 1.

Formally, an AMR subgraph is a tuple of:

1. $D$ - a connected, labelled, directed acyclic graph
2. $R$ - a root node
3. $FV$ - an ordered sublist of the nodes of $D$ (including the root) which are free and can be substituted during derivation

Though not shown in figure 1, the root of an AMR subgraph may be a free variable. Intuitively, a subgraph with at least one free variable corresponds to a function, and a subgraph with no free variables corresponds to a constant.

Textual notation. Taking inspiration from the PENMAN notation used for AMR, we use the notation $(a:{\text{rel1}} (b:{\text{rel2}} \ldots ))$ to denote an AMR subgraph rooted at a constant $a$, with a :rel1 edge to a free variable, $b$, which in turn has a child free variable, $c$.

Table 1 shows the formulation of graph semantics for all the combinators described below. The
| combinator                        | function (left/right) | argument (right/left) | result | FV ordering |
|----------------------------------|-----------------------|-----------------------|--------|-------------|
| Binary                           |                       |                       |        |             |
| Application                      | . . . 1 2            | a . . . 3            | . . . .| . . . .     |
| Composition (B)                 | . . . 1 2            | a . . . 3            | . . . .| . . . .     |
| Symmetric Application (SA)      | . . . 1 2            | a . rel . b . . . 3  | . . . .| . . . .     |
| Symmetric Composition (SB)      | . . . 1 2            | a . rel . b . . . 3  | . . . .| . . . .     |
| Type Raising (T)                | 1                     | 2                     | 1 . 2 .|             |
| N-ary (≤ 1 FV per operand)      | 1                     | 2                     | 1 . 2 .|             |
| Conjunction (k)                 | x                      | a . . . 1 2 . . . 3  | x : op1 a . . . 1 : op2 b . . . 3 |             |

Table 1: Formal semantic rules for AMR combinators. Boxed numbers stand for free variables (FVs) in the semantics of each of the constituents being combined: □ stands for the lowest indexed FV in the function (head) constituent, and □ for the lowest indexed FV in the argument constituent, if any. Ellipses . . . n denote optional dominating structure (if preceding) and optional dominated structure (if following). Any FVs in these optional structures are preserved in the result, in the order given in the last column. Crossing composition (B ×) and its symmetric equivalent behave semantically like their non-crossing counterparts. Not shown: exceptions to application and composition for the identity function (ID), discussed in §4.1. Other combinators (higher-order composition, substitution) are left to future work.

formulas are written in general form with attention paid to the resulting order of free variables, which distinguishes application from composition semantically. Another combinator in CCG, crossing composition, has the same semantics as regular composition. We leave the semantics of higher-order composition and substitution combinators to future work.

### 3.1 Syntax-Semantics Isomorphism

A core property of CCG is that it provides transparency in the syntax-semantics interface: both syntactic categories and semantic forms are defined as functions permitting a compositional derivation of the sentence. The syntactic category determines which constituents may be constructed and in what word order. In the semantics, the word order (direction of the slashes) is irrelevant, but the functional structure—the arity and the order in which arguments are to be applied—must match in order for the semantics to remain well-formed as the sentence is derived based on the syntactic categories and combinatorial rules.

In other words, the functional structure of the category must be isomorphic to the functional structure of the semantics. For example, a hypothetical CCG category V \ W / X / (Y / Z) would naturally correspond to a ternary function whose first argument, Y / Z, is itself a unary function.

This brings us to the following principle:

**Principle of Functional Isomorphism.** The semantics of a word or constituent cannot have higher arity than the CCG category calls for. If the category has arity >1, the semantics may have lower arity thanks to currying. In practice, this is mainly useful for subjects—many CCG categories begin with S \ NP, and in the semantics, it often makes sense to defer the specification of the subject’s semantic role until the full S is built.

### 3.2 Function Application

In function application of AMR subgraphs, a free variable (blue) can be filled by the root of another AMR subgraph. The case of right function application is shown in figure 2a. Function application can only substitute the first free variable in FV corresponding to the rightmost syntactic argument.
3.3 Composition

Composition for AMR subgraphs is shown in figure 2b. While application and composition always differ syntactically, from a graph semantics point of view, this operation turns out to be the same as function application, where the root of one subgraph is substituted for a free variable in another subgraph.

The difference between application and composition is captured in the resulting order of free variables. In the case of composition, the argument’s free variables are placed first on the free variable stack followed by the function’s free variables. This allows free variables in the AMR subgraph to consistently match syntactic arguments in the CCG supertag. This is a difference between composition in this work and in Beschke and Menzel’s (2018) work where the semantics of application and composition is the same.

3.4 Symmetric Application

Symmetric application is a combinator unique to Graph Semantics. It is shown in figure 2d. Two subgraphs with free variables in the source and target of the same relation can merge to a single graph. In graph semantics, it is possible to do this type of operation where it is not clear which graph is a function of the other. Symmetric application has two major uses:

1. It is necessary to combine type-raised subgraphs.
2. It allows representing semantic information redundantly in more than one word.

The second use will be relied on in section 4.4. For a simple example consider nominative case in the English sentence “I ate”. Agentivity in AMR is represented with an edge :ARG0. In this sentence, agentivity is signalled both by nominative morphology of I and by its position relative to the verb—more specifically, its argument position (S\NP1). It might be a better analysis to say that agentivity is a part of the semantics of both I and ate. Using symmetric application, this relation :ARG0 can be a part of the semantics of each word, and then the relation can be merged during derivation.
3.5 Symmetric Composition

Symmetric application can easily be extended to allow symmetric composition, whose semantics is nearly the same. Just as composition can be used to adjust the order that constituents are normally combined and “save an argument for later”, symmetric composition can be used to change the order constituents combine in place of symmetric application. Examples of both symmetric and non-symmetric composition appear in figure 7.

Symmetric composition differs from symmetric application in the index of the argument’s free variable being unified and in the resulting order of free variables.

3.6 Type Raising

Type raising of an AMR subgraph is shown in figure 2c. Type raising must be specified by a relation rel which allows the resulting subgraph to accept an object which needs to fill that relation. The intuition behind type raising is that the resulting object should look for a function of the initial object and return that function’s output. A type-raised node is one that looks for a subgraph that needs to fill the target of a relation rel and the type-raised object inserts itself into this slot.

In graph semantics, to make a non-function into a function, at least one free variable and relation must be added. The type-raised graph thus has a free-variable root, a relation rel, and its original node as a target of rel. A simple example is a type-raised subject (i/i) which raises its type to be (□:ARG0 i/i) to place itself in the agent role of its predicate.

Note that after type raising, the relation rel will be an edge in both the type-raised object and the function that it accepts. Function application cannot be used to merge this relation. Type raising of graphs creates a need for a new combinator, unique to operations in graph semantics, which can merge graphs with respect to a relation they have in common. An example of type raising for deriving complex coordination is shown in figure 5.

Note that in this strategy of representing type raising, the isomorphism between functions in semantics and syntactic category is maintained. This fits with CCG’s philosophy of a transparent syntax-semantics interface (§3.1). Whereas in Beschke and Menzel’s (2018) strategy where type raising does not affect semantics, there is a mismatch between semantics and syntactic category.

4 Linguistic Examples

This section explains the use of the combinators discussed in §3 by example. Figure 4 shows the use of application (and identity application) combinators to derive a simple sentence. Figure 5 demonstrates type raising, symmetric composition, and conjunction as tools to derive a sentence with complex coordination.

4.1 Fundamentals

This section discusses basic semantic types necessary for a full CCG derivation.

Transitive and Intransitive Verbs. Figure 3a shows the semantics for a transitive verb. Since “read” has more than one semantic argument, the order of free variables matters: 1, the first free variable, must correspond to NP1, the rightmost syntactic argument.

Adjectives. Figure 3b shows the semantics for an adjective. Note that, unlike in the examples above, the root of this subgraph is a free variable, since the root of this subgraph is what will be filled in. Ordinary adverbs have similar semantics.

Prepositional Phrases (Adjunct). Figure 3c shows semantics for the locative preposition “at”. To derive a prepositional phrase, assume available constituents “at”: □:location □ and “the library”: (l/library), which may be combined by application.

An alternative syntactic treatment would be to use the particle adjunct category: S/fs NP,S. suggests treating English prepositions as particles because they permit stranding, e.g., the library that I work at.
Figure 3: Linguistic examples as AMR subgraphs: (a) transitive verb, (b) adjective, (c) preposition (verb adjunct), (d) determiner (identity semantics).

Figure 4: application and identity: “John likes the cat”

Null Semantics: Articles, etc. Some linguistic features are not represented in AMR. These include tense and definite/indefinite articles. For CCG derivations to deal with these elements, there will need to be a semantic representation which allows them to be “syntactic sugar”, affecting the syntactic category but adding nothing to the semantics in the derivation. We call this the identity function, following Beschke and Menzel (2018), and notate it as $\text{ID}$. More precisely, if a constituent $a$ has $\text{ID}$ as its semantics, then $a$, when combined with another constituent $b$ via application or composition (either as the function or as the argument), will produce $b$’s semantics for the resulting constituent. The special notation $\text{ID}$ is used to represent the identity function. An example of a word with identity semantics is “the” (figure 3d and figure 4), and further examples appear in derivations below.
John likes and Mary hates cats.

Figure 5: complex coordination and type raising: “John likes and Mary hates cats.”

John was eaten by bears.

Figure 6: passive: “John was eaten by bears.”

4.2 Passives, Control, and Wh-questions

Figures 6 and 7 show CCG derivations with AMR semantics for three well-known linguistic phenomena in English: passives, control, and wh-questions. In a passive construction, a core argument may be added by a syntactically optional adjunct phrase as in figure 6. Note that in this semantic representation, only syntactically required arguments are represented in a word’s semantics, and so the passive verb eaten does not include an :ARG0 edge.

Figure 7 shows both control and wh-question formation. Control is an important problem for graph semantics as it requires representing the subject (here you) as the agent of two predicates. Wh-questions are another complex and difficult phenomenon that is handled by CCG derivation. Additionally, figure 7 gives examples of both types of composition: symmetric and non-symmetric.

4.3 Inverse Core Roles and Relative Clauses

AMR provides notation for inverse roles that reverse the usual ordering of a relation. These are indicated with the -of suffix: (a :rel-of b) is equivalent to (b :rel a). This ensures that the graph can be constructed with a single root, and provides a convenient mechanism for expressing derived nominals and relative clauses. For instance, the noun phrases “teacher” and “a person who teaches” both receive the AMR (person :ARG0-of teach-01). If the subject matter is expressed, that is slotted into the :ARG1 of teach-01. This can be handled by treating “teachers” as a predicate of sorts, as seen in the derivation below.

Also below is an illustration of the relative clause paraphrase, “people who teach math”. Here, the relativizer “who” needs to fill the appropriate role of the verbal predicate with its noun head “people”. An inverse role is produced so that person, rather than teach-01, will be the root of the resulting subgraph.

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Note that constructions such as the passive and control are sensitive to a syntactic relation, “deep” subject, not a semantic role per se. Depending on the semantic predicate (PropBank frame) and which other arguments are realized overtly, the subject could be :ARG0 (e.g. “I opened the door”), :ARG1 (“The door opened”), or :ARG2 (“The key opened the door”). The approach described above would thus require some duplication of lexical entries not just for the verb, but also for “by”, control verbs, infinitive “to” for purpose adjuncts, and so forth.
What did you decide to eat yesterday? 

Figure 7: wh-question and control, symmetric and non-symmetric composition: “What did you decide to eat yesterday?” $B_x$ stands for crossing composition, which has the same semantics as composition.

The symmetric application combinator must therefore be aware of inverses: it must match the :ARG0 of with the :ARG0 edge in the operand and effectively merge the two relations. Alternatively, the phrase could be parsed by first symmetrically composing “who” with “teach”, which requires similar handling of the inverse role, and then attaching “math” by application.

4.4 Eventive Nouns and PP Complements

This section will describe an approach to the semantics of eventive nouns, and in the process will illustrate our treatment of prepositional phrase complements (as opposed to adjuncts: §4.1), which in CCG are traditionally given the category PP.

An eventive noun is a noun whose semantics has the form and argument structure of an event. In English, many eventive nouns can be linked to semantic arguments via prepositional phrases, possessives, and light verb constructions, as shown in table 2. AMR uses a canonical form with a predicate (typically based on a verbal paraphrase), treating John decided, John’s decision, and John made a/his decision as semantically equivalent. Despite some work on integrating event nominals and multiword expressions into CCG (Constable and Curran, 2009; Honnibal et al., 2010; de Lhoneux, 2014), we are not aware of any CCG analyses of light verb constructions, which have been studied computationally in other frameworks (e.g., Baldwin and Kim, 2010; Bonial et al., 2014; Ramisch et al., 2018), that gives them semantics equivalent to a content verb paraphrase. We offer such an analysis based on three principles:

1. The event frame is in the semantics of the eventive noun or verb.
2. For any syntactic argument of a noun or verb, the corresponding edge (and free variable) is in the semantics of the noun or verb.
3. Any function word (light verb, ’s, preposition, or infinitival to) that links the eventive noun to its semantic argument has an associated edge (and free variables) in its semantics.

Principle 1 derives from the definition of eventive nouns. Principle 2 is motivated by the mechanics of
Table 2: English eventive nouns shown in three common forms; words in square brackets coordinate additional semantic arguments. (In the AMR corpus, “take pictures” is actually treated superficially with take-01 :ARG1 picture, but we suggest photograph-01 instead.)

| Light Verb Construction | Possessive Form | AMR Predicate |
|-------------------------|----------------|---------------|
| make a decision [about/on] | my decision [about/on] | decide-01 |
| pay attention [to] | my attention [to] | attend-02 |
| make an attempt [to] | my attempt [to] | attempt-01 |
| take a nap | my nap | nap-01 |
| take a picture [of] | — (my picture is not eventive) | photograph-01 (suggested) |

Figure 8: **Light Verb Construction:** “John made a decision on his major”

CCG and graph semantics—function application can only apply to a free variable. Principle 3 is the primary thesis of this analysis of eventive nouns.

Note that when a verb or noun takes a PP complement, principles 2 and 3 force both the verb or noun and the preposition to hold the same edge in their semantics. This can be resolved by using symmetric application as described in §3.4. Symmetric application was motivated by type raising, but it also allows semantics to be represented redundantly in more than one word. Here, symmetric application results in a nice analysis—that both the eventive noun or verb and its complement preposition signal *patientness* in eventive noun expressions.

Figure 8 shows the derivation for “decision” in its light verb construction form. In this sentence, “decision” has one syntactic argument and one edge, “on” redundantly represents the same edge as “decide”, and they are merged by symmetric application. In this case, the :ARG0 relation is contained in the light verb “made”. Notice that the semantics of “made” is exactly the same as for ‘s before. Both signal agentiveness. In fact, this strategy can be used to derive the same semantics as expressed with a simple verb form “John decided on his major” or the possessive form “John’s decision on his major”.

With this analysis, the associated light verbs given in table 2 (“make”, “pay”, etc.) as well as possessive ‘s take the semantics :ARG0 :ARG1 and associated prepositions take the semantics :ARG1. In other words, for each eventive noun, either a special light verb or a possessive contributes the agentive semantic relation and (if present) a special preposition or infinitive to may contribute the patient semantic relation, thus allowing derivation of the same AMR regardless of form.

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7We expect that representing certain semantics redundantly—such as :ARG1 in the preposition “on”—in certain multiword constructions will reduce spurious errors as it enforces consistency between different parts of a multiword expression. A simple alternative is to treat every function word in these constructions as having identity ID semantics.

8The category N/NP\/(N/PP<sub>en</sub>) for “on” is suggested by Mark Steedman’s analysis of English prepositions as particles (personal communication) and also maintains the Principle of Functional Isomorphism of §3.1.
5 Discussion

Above, we have laid the foundation for a treatment of CCG-to-AMR parsing that meets a variety of challenges in the syntax-semantics interface. We believe the approach is reasonably intuitive, flowing naturally from CCG syntax, AMR semantics, and the notion of free variables in subgraphs, without the additional need for complicated lambda calculus notation or a highly general graph grammar formalism.

Because AMRs are annotated by humans for raw sentences, rather than on top of a syntactic parse, we cannot expect a CCG parser to elegantly handle the full construction of all AMRs according to compositional rules. Several components of AMR parsing are not part of CCG parsing and will have to be performed as postprocessing steps. These components include NER, time expression parsing, coreference resolution, and wikification, all of which need to be performed after (or before) CCG parsing. Additionally, there is a risk that a CCG lexicon may ‘overgenerate’, producing invalid parses, and additional checking—either in the combinators, or as postprocessing or reranking—may be warranted.

Finally, as pointed out by Bender et al. (2015), AMR annotations sometimes go beyond the compositional ‘sentence meaning’ and incorporate elements of ‘speaker meaning’, though an empirical study of AMR data found the rate of noncompositional structures to be relatively low (Szubert et al., 2018). Beschke and Menzel (2018) give interesting examples of AMR fragments that would be difficult to derive compositionally, e.g., “settled on Indianapolis for its board meeting”, where the AMR attaches Indianapolis as the location of the meeting and the meeting as the thing that was settled on (reflecting the inference \( \text{settle on} \ [\text{LOCATION for ACTIVITY} \Rightarrow \text{settle on} \ [\text{ACTIVITY at LOCATION}]) \).

The way forward for this research will need to involve inducing a data-driven lexicon with AMR graph semantics as described in this paper and apply an existing CCG supertagger or parser to derive full-sentence AMRs, as well as development of postprocessing techniques.

6 Conclusion

We have given the linguistic motivation for a particular method of deriving AMR semantic graphs using CCG. Our specification of AMR subgraphs and CCG combinators ensures a tight correspondence between syntax and semantics, which we have illustrated for a variety of linguistic constructions (including eventive noun semantics, which to the best of our knowledge has not previously been explored for CCG). Future empirical work can make use of this framework to induce CCG lexicons for AMR parsing.

Acknowledgments

References

Anchiêta, R. T. and T. A. S. Pardo (2018, May). Towards AMR-BR: A SemBank for Brazilian Portuguese language. In N. Calzolari, K. Choukri, C. Cieri, T. Declerck, S. Goggi, K. Hasida, H. Isahara, B. Maegaard, J. Mariani, H. Mazo, A. Moreno, J. Odijk, S. Piperidis, and T. Tokunaga (Eds.), Proc. of LREC, Miyazaki, Japan, pp. 974–979.

Artzi, Y., K. Lee, and L. Zettlemoyer (2015, September). Broad-coverage CCG semantic parsing with AMR. In Proc. of EMNLP, Lisbon, Portugal, pp. 1699–1710.

Baldwin, T. and S. N. Kim (2010). Multiword expressions. In N. Indurkhya and F. J. Damerau (Eds.), Handbook of Natural Language Processing, Second Edition, pp. 267–292. Boca Raton, FL: CRC Press, Taylor and Francis Group.

Banarescu, L., C. Bonial, S. Cai, M. Georgescu, K. Griffitt, U. Hermjakob, K. Knight, P. Koehn, M. Palmer, and N. Schneider (2013, August). Abstract Meaning Representation for sembanking. In Proc. of the 7th Linguistic Annotation Workshop and Interoperability with Discourse, Sofia, Bulgaria, pp. 178–186.
Bender, E. M., D. Flickinger, S. Oepen, W. Packard, and A. Copestake (2015, April). Layers of interpretation: on grammar and compositionality. In *Proc. of IWCS*, London, UK, pp. 239–249.

Beschke, S. and W. Menzel (2018, June). Graph Algebraic Combinatory Categorial Grammar. In *Proc. of *SEM*, New Orleans, Louisiana, pp. 54–64.

Björklund, H., F. Drewes, and P. Ericson (2016). Between a rock and a hard place – Uniform parsing for hyperedge replacement DAG grammars. In A. Dediu, J. Janoušek, C. Martín-Vide, and B. Truthe (Eds.), *Language and Automata Theory and Applications*, Lecture Notes in Computer Science, pp. 521–532.

Bonial, C., M. Green, J. Preciado, and M. Palmer (2014, April). An approach to ‘take’ multi-word expressions. In *Proc. of the 10th Workshop on Multiword Expressions*, Gothenburg, Sweden, pp. 94–98.

Chiang, D., J. Andreas, D. Bauer, K. M. Hermann, B. Jones, and K. Knight (2013, August). Parsing graphs with hyperedge replacement grammar. In *Proc. of ACL*, Sofia, Bulgaria, pp. 924–932.

Clark, K., M. Luong, C. D. Manning, and Q. Le (2018, November). Semi-supervised sequence modeling with cross-view training. In *Proc. of EMNLP*, Brussels, Belgium, pp. 1914–1925.

Clark, S. and J. R. Curran (2004, July). Parsing the WSJ using CCG and log-linear models. In *Proc. of ACL*, Barcelona, Spain, pp. 103–110.

Constable, J. and J. Curran (2009). Integrating verb–particle constructions into CCG parsing. In *Proc. of the Australasian Language Technology Association Workshop 2009*, Sydney, Australia, pp. 114–118.

Courcelle, B. and J. Engelfriet (2012, June). *Graph Structure and Monadic Second-Order Logic: A Language-Theoretic Approach*. Cambridge University Press.

de Lhoneux, M. (2014, August). CCG parsing and multiword expressions. http://arxiv.org/abs/1505.04420.

Flanigan, J., S. Thomson, J. Carbonell, C. Dyer, and N. A. Smith (2014, June). A discriminative graph-based parser for the Abstract Meaning Representation. In *Proc. of ACL*, Baltimore, Maryland, USA, pp. 1426–1436.

Groschwitz, J., M. Lindemann, M. Fowlie, M. Johnson, and A. Koller (2018, July). AMR dependency parsing with a typed semantic algebra. In *Proc. of ACL*, Melbourne, Australia, pp. 1831–1841.

Hockenmaier, J. and M. Steedman (2007, August). CCGbank: A corpus of CCG derivations and dependency structures extracted from the Penn Treebank. *Computational Linguistics* 33(3), 355–396.

Honnibal, M., J. R. Curran, and J. Bos (2010, July). Rebanking CCGbank for improved NP interpretation. In *Proc. of ACL*, Uppsala, Sweden, pp. 207–215.

Jones, B., J. Andreas, D. Bauer, K. M. Hermann, and K. Knight (2012, December). Semantics-based machine translation with hyperedge replacement grammars. In *Proc. of COLING 2012*, Mumbai, India, pp. 1359–1376.

Kingsbury, P. and M. Palmer (2002, May). From TreeBank to PropBank. In *Proc. of LREC*, Las Palmas, Canary Islands, pp. 1989–1993.

Koller, A. (2015, April). Semantic construction with graph grammars. In *Proc. of the 11th International Conference on Computational Semantics*, Volume IWCS 2015, London, UK, pp. 228–238.

Lewis, M., K. Lee, and L. Zettlemoyer (2016, June). LSTM CCG Parsing. In *Proc. of NAACL-HLT*, San Diego, California, USA, pp. 221–231.
Lewis, M. and M. Steedman (2014, October). A* CCG parsing with a supertag-factored model. In Proc. of EMNLP, Doha, Qatar, pp. 990–1000.

Li, B., Y. Wen, L. Bu, W. Qu, and N. Xue (2016, August). Annotating The Little Prince with Chinese AMRs. In Proc. of LAW X – the 10th Linguistic Annotation Workshop, Berlin, Germany, pp. 7–15.

Lyu, C. and I. Titov (2018, July). AMR parsing as graph prediction with latent alignment. In Proc. of ACL, Melbourne, Australia, pp. 397–407.

Migueles-Abraira, N., R. Agerri, and A. D. d. Ilarraza (2018, May). Annotating Abstract Meaning Representations for Spanish. In N. Calzolari, K. Choukri, C. Cieri, T. Declerck, S. Goggi, K. Hasida, H. Isahara, B. Maegaard, J. Mariani, H. Mazo, A. Moreno, J. Odijk, S. Piperidis, and T. Tokunaga (Eds.), Proc. of LREC, Miyazaki, Japan, pp. 3074–3078.

Misra, D. K. and Y. Artzi (2016, November). Neural shift-reduce CCG semantic parsing. In Proc. of EMNLP, Austin, Texas, pp. 1775–1786.

Peng, X. and D. Gildea (2016, June). UofR at SemEval-2016 Task 8: Learning Synchronous Hyperedge Replacement Grammar for AMR parsing. In Proc. of SemEval, San Diego, California, USA, pp. 1185–1189.

Peng, X., L. Song, and D. Gildea (2015, July). A Synchronous Hyperedge Replacement Grammar based approach for AMR parsing. In Proc. of CoNLL, Beijing, China, pp. 32–41.

Ramisch, C., S. R. Cordeiro, A. Savary, V. Vincze, V. Barbu Mititelu, A. Bhatia, M. Buljan, M. Candito, P. Gantar, V. Giouli, T. Güngör, A. Hawwari, U. İnurrieta, J. Kovalevskaïté, S. Krek, T. Lichte, C. Liebeskind, J. Monti, C. Parra Escartín, B. Qasemizadeh, R. Ramisch, N. Schneider, I. Stoyanova, A. Vaidya, and A. Walsh (2018, August). Edition 1.1 of the PARSEME Shared Task on Automatic Identification of Verbal Multiword Expressions. In Proc. of the Joint Workshop on Linguistic Annotation, Multiword Expressions and Constructions (LAW-MWE-CxG-2018), Santa Fe, New Mexico, USA, pp. 222–240.

Rozenberg, G. (1997). Handbook of Graph Grammars and Comp., Volume 1. World scientific.

Steedman, M. (2000). The Syntactic Process. Cambridge, MA: MIT Press.

Szubert, I., A. Lopez, and N. Schneider (2018, June). A structured syntax-semantics interface for English-AMR alignment. In Proc. of NAACL-HLT, New Orleans, Louisiana, pp. 1169–1180.

Wang, C., B. Li, and N. Xue (2018, June). Transition-based Chinese AMR parsing. In Proc. of NAACL-HLT, New Orleans, Louisiana, pp. 247–252.

Wang, C., S. Pradhan, X. Pan, H. Ji, and N. Xue (2016, June). CAMR at SemEval-2016 Task 8: An extended transition-based AMR parser. In Proc. of SemEval, San Diego, California, USA, pp. 1173–1178.

Xue, N., O. Bojar, J. Hájič, M. Palmer, Z. Urešová, and X. Zhang (2014, May). Not an interlingua, but close: comparison of English AMRs to Chinese and Czech. In N. Calzolari, K. Choukri, T. Declerck, H. Loftsson, B. Maegaard, J. Mariani, A. Moreno, J. Odijk, and S. Piperidis (Eds.), Proc. of LREC, Reykjavik, Iceland, pp. 1765–1772.