Formalizing Argument Structures with Combinatory Categorial Grammar

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Abstract. We present a formalization of the *constructivist* analysis of argument structure in Combinatory Categorial Grammar (CCG). According to the constructivist analysis, often couched in terms of Distributed Morphology (DM), arguments are introduced in the syntax rather than specified by the lexical argument structure of the verb. We argue that formalizing constructivism in CCG not only provides the basis for a model of incremental processing of argument structure but also a principled account for the locality constraints on contextual allomorphy observed in the DM literature.

Keywords: Combinatory Categorial Grammar · argument structure · morphology

1 Introduction

Combinatory Categorial Grammar (CCG) [33] is a lexicalized theory of grammar in which syntactic derivations are carried out by applying a small set of combinatory rules that operate on categories that constituents are associated with. A major advantage of the theory is that it can be directly incorporated into a parsing model as it allows (largely) left-to-right structure building based on the surface string. CCG thus conforms to the Strict Competence Hypothesis, which states that the language processor needs only mechanisms provided by the competence grammar to build structures [33].

The current study deals with a challenge to the analysis of verbal argument structure that is typically employed in CCG. In such an analysis, the argument structure is specified by the category of the verb. For example, (2) is a CCG

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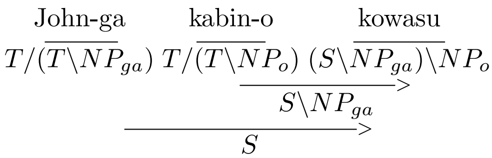
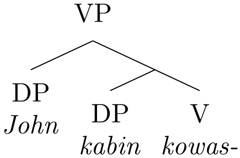
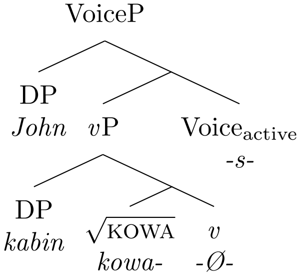
analysis of the Japanese sentence (1) based on [2].[1] Here, the category of *kowasu* 'break' is specified as $S \backslash NP_{ga} \backslash NP_o$, which means that the verb takes two NPs to its left (as indicated by the backslashes; see Sect. 2 for details) marked with nominative case (*ga*) and accusative case (*o*), respectively.

(1) John-ga kabin-o kowasu.
John-NOM vase-ACC break
'John breaks the vase.'

(2)


In mainstream generative grammar, the same line of analysis is realized by assuming that verbs have a list of arguments (θ-grid) as one of their lexical properties, and that list is "projected" to the verb phrase headed by the verb (e.g., [10]). (3a) is such an analysis for the verb phrase in (1).

(3) a.


b.


However, there is an alternative view on argument structure called *constructivism,* often couched in terms of Distributed Morphology (DM) [15]. Constructivism assumes that argument structures are composed in the syntax, rather than in the lexicon. (3b) is a constructivist analysis of (1) based on [30] (also see [16, 26]). In this structure, the root $\sqrt{\text{KOWA}}$ does not have an inherent argument structure. Instead, the internal and external arguments are introduced by functional heads called v and Voice, respectively.[2] In contrast, analyses of the line of (3a) is called *projectionism,* since the lexical argument structure of the verb is projected to the syntax (see [6, 17, 27] for more discussions on projectionism vs. constructivism).

[1] In (2), features irrelevant for the current discussion are omitted. T is a variable ranging over categories.

[2] There is a debate within constructivism over whether the internal argument should be severed from the root. We assume that it should, given that the root can appear without an internal argument (e.g., in deverbal nouns), following [7, 24]. See [17, 18] for arguments against separation of the internal argument from a root.

Constructivism provides a straightforward explanation for why speakers can interpret innovative combinations of verbs and argument structures [6]. For example, native speakers of English can interpret sentences in (4) even if they have never heard of *siren* being used in these particular constructions, as pointed out by [12]. In constructivism, their interpretations derive from the encyclopedic meaning associated with the root $\sqrt{\textsc{siren}}$ and the compositional semantics of the functional heads that give rise to the respective construction (see works such as [6,7,17,22,27] for more arguments in favor of constructivism).

(4) a. The factory horns *sirened* throughout the raid.
b. The factory horns *sirened* midday and everyone broke for lunch.
c. The police car *sirened* the Porsche to a stop.
d. The police car *sirened* up to the accident site.
e. The police car *sirened* the daylight out of me.

The theoretical framework of DM is suitable for constructivism. DM adopts the *single engine hypothesis,* according to which "all computation, whether of small (words) or large elements (phrases and sentences), is syntactic" [1] (p. 738). The single engine hypothesis straightforwardly captures the relation between verbal morphology and its consequence on the syntactic argument structure. At the same time, DM captures the irregularity of such argument-introducing morphology by *late insertion*. Late insertion stipulates that the morphological (and semantic) realization of terminal nodes is determined after the syntactic structure is built and can refer to the syntactic context. In (3b), for example, $\text{Voice}_{\text{active}}$ is realized as -*s*- in the context of the root $\sqrt{\textsc{kowa}}$ (to be interpreted as 'break'); the same head would be realized as -*as*- in the context of $\sqrt{\textsc{her}}$ (to be interpreted as 'reduce') [16,30]. This analysis captures the fact that transitivity morphemes in Japanese are separable from the root (cf. *kowa-re-* 'break.intransitive') but varies depending on the root.

While late insertion offers a nice account of such *contextual allomorphy,* it is problematic when a real-time use of language is taken into account. Human sentence processing is known to proceed incrementally from left to right (e.g., [21,34]). However, DM assumes bottom-up structural building (as in Minimalist analyses in general), and this is not just a convention in description. "Late" insertion, along with the phase-based account of context-sensitivity of such insertion, crucially relies on the assumption that syntactic structures are built in a bottom-up manner before any phonological (or semantic) information is supplied. Given the theoretical plausibility of assuming that competence grammar is used in performance in some way [8,9,23,33], such a bottom-up approach bears the burden of explaining how the grammar defined that way can be made compatible with incremental processing [32]. This is the primary motivation of our study: can we capture the constructivist nature of argument structure using a surface-oriented grammar formalism that is compatible with incremental processing? Note that there is some psycholinguistic evidence that the decomposition of argument structure is relevant for real-time processing (e.g., [14,29]).

One preceding study that attempts to rigorously formalize (a fragment of) DM is [35]. This study presents an algorithm that can parse a sequence of out-put forms into a sequence of terminals (i.e., feature bundles) given DM-style contextual insertion rules. The parsing algorithm is fairly complicated, mainly because it has to look ahead of the context on the right side. Also, Trommer's approach is different from ours in that the Vocabulary Insertion mechanism is not integrated into a mechanism to build syntactic structures.

Turning back to the current study, we thus attempt a formalization of the constructivist analysis in CCG, which is claimed to be compatible with incremental structure building. Although analyses in CCG are non-constructivist as mentioned earlier, we will demonstrate that the constructivist analysis can indeed be translated to CCG. We will further argue that such an analysis provides an explanation for an important feature of the constructivist analysis, the locality-sensitivity of contextual allomorphy. We focus on the Japanese verbal morphology as a test case since it has morphological phenomena that are interesting for the current purpose: agglutinative conjugation with a few irregular verbs, and systematic transitivity alternation with overt morphological marking. The rest of this paper is organized as follows. Section 2 presents an analysis of verbal conjugation in Japanese, which serves as the basis for the analysis of transitive alternation presented in Sect. 3. Section 4 discusses extensions of the current analysis to other morphological phenomena, namely infixation and fusion. Section 5 summarizes the study and discusses remaining issues.

2 Segment-Based Analysis of Japanese Verb Conjugation

The current section develops an analysis of Japanese verb conjugation in CCG. An overview of the Japanese verb conjugation paradigm is presented in Table 1. Most Japanese verbs belong to either the five-grade (*godan*) or mono-grade (*itidan*) conjugation class. In the traditional mora-based analysis, the conjugated forms of a five-grade verb are decomposed into an invariant stem (*to-* in the case of 'fly,' shown in Table 1) and an inflectional ending. The inflectional endings share the initial consonant while differing in the vowel: *-ba-, -bi-, -bu-, -be-, -bo-* in the case of 'fly.' Since these syllables belong to the same row in the traditional Japanese syllabary chart, 'fly' is said to belong to the *ba*-row subclass of the five-grade conjugation. Five-grade verbs can also take an euphonic (*onbin*) form, whose inflectional ending does not share the initial consonant with other forms. The mono-grade conjugation is much simpler. Each form consists of an invariant stem and an inflectional ending shared by all mono-grade verbs, and there is no euphonic variation. There are also some irregular verbs, most notably *suru* 'do' and *kuru* 'come.' Below we limit our discussion to the terminal, negation, and euphonic forms, since these three forms are sufficient to illustrate how the stem, the inflectional ending, and subsequent morphemes are concatenated.

We take Bekki's analysis of Japanese verb conjugation in CCG [2] as our starting point. A CCG consists of categorial lexicon which assigns each lexical item a syntactic category and a logical form, and a set of combinatory rules that combine those categories and logical forms to yield new ones. A syntactic category is either a *basic category* such as S or NP, or a *complex category* such

Table 1. An excerpt from the Japanese verb conjugation paradigm. The strings in parentheses are not considered to be part of the conjugated forms but are endings that these forms typically accompany.

	Five-grade		Five-grade	Mono-grade	Irregular
Form	'fly' (*ba*-row)		'write' (*ka*-row)	'see'	'come'
Negative	*toba(nai)*	'do not fly'	*kaka(nai)*	*mi(nai)*	*ko(nai)*
Continuous	*tobi*	'fly, and...'	*kaki*	*mi*	*ki*
Euphonic	*ton(da)*	'flew'	*kai(ta)*	*mi(ta)*	*ki(ta)*
Terminal/Attributive	*tobu*	'fly$_{nonpast}$'	*kaku*	*miru*	*kuru*
Conditional	*tobe(ba)*	'if ... fly'	*kake(ba)*	*mire(ba)*	*kure(ba)*
Imperative	*tobe*	'fly!'	*kake*	*miro*	*koi*

as NP/NP or $(S\backslash NP)\backslash NP$, which is recursively built from basic categories and two types of slashes that indicate the directions of arguments. X/Y means that it takes Y as an argument to its right to yield X, while $X\backslash Y$ means that it takes Y to its left to yield X. The combinatory rules that will be used in the current analysis are listed with their semantics in (5). $X, Y, ...$ range over categories while $a, f, g, ...$ range over λ-terms. $>, <, ...$ are the annotations for the combinatory rules to be used in the derivation trees. Basic categories can also have *features*, indicated by superscripts and subscripts. Features are used to represent information such as case, conjugation class, and inflectional forms.

(5)
$$\begin{array}{llll}
X/Y : f & Y : a & \Longrightarrow X : fa & (>) \\
Y : a & X\backslash Y : f & \Longrightarrow X : fa & (<) \\
X/Y : f & Y/Z : g & \Longrightarrow X/Z : \lambda x.f(gx) & (>\mathbf{B}) \\
Y\backslash Z : g & X\backslash Y : f & \Longrightarrow X\backslash Z : \lambda x.f(gx) & (<\mathbf{B}) \\
(Y\backslash W)\backslash Z : g & X\backslash Y : f & \Longrightarrow (X\backslash W)\backslash Z : \lambda z.\lambda w.f((gz)w) & (<\mathbf{B}^2)
\end{array}$$

Bekki's analysis formalizes the mora-based analysis described above using CCG. The selection of the appropriate inflectional ending and subsequent morphemes are achieved by annotating categories with features. (6) shows the analysis of *tobanai* 'do not fly.' Here, $S^{v::5::b}_{stem}$ means the stem of a five-grade verb of *ba*-row, and $S^{a}_{term|attr}$ means a terminal (*syusi*) or an attributive (*rentai*) form of an adjective (features in the original work that are irrelevant for the current discussion are omitted).

(6)
$$\begin{array}{ccc}
\text{to-} & \text{-ba-} & \text{-nai} \\
\overline{S^{v::5::b}_{stem}\backslash NP_{ga}} & \overline{S^{v::5::b}_{neg}\backslash S^{v::5::b}_{stem}} & \overline{S^{a}_{term|attr}\backslash S_{neg}}
\end{array}$$
$$\underline{S^{v::5::b}_{stem}\backslash NP_{ga} \quad S^{v::5::b}_{neg}\backslash S^{v::5::b}_{stem}}_{<\mathbf{B}} \;\Rightarrow\; S^{v::5::b}_{neg}\backslash NP_{ga}$$
$$\underline{S^{v::5::b}_{neg}\backslash NP_{ga} \quad S^{a}_{term|attr}\backslash S_{neg}}_{<\mathbf{B}} \;\Rightarrow\; S^{a}_{term|attr}\backslash NP_{ga}$$

A mora-based analysis is a reasonable choice if the application to text data is concerned, given that Japanese orthography is mora-based. However, segment-based analysis allows further generalization for the conjugation system of the language by eliminating the classification by row [4]. For example, *-a-* that appears in *tob-a-nai* is also found in negated forms of other verbs that belong to other rows such as *kak-a-nai* 'do not write' and *yom-a-nai* 'do not read.'

A problem that remains in such a basic segment-based analysis is that the stem thus identified is not stable across the paradigm. The stem for 'fly' can be identified as *tob-* from forms such as *tob-u* 'fly (present)' and *tob-a-nai* 'do not fly.' However, when *tob-* is combined with the past tense morpheme *-ta*, the result is *ton-da* rather than **tob-ta*, which violates the Japanese phonotactics. Such a "change" is regular in the language, and the type of the change is dictated by the final consonant of the stem. In a processing-compatible approach that we are aiming at here, we cannot resort to a rewriting rule such as $b \rightarrow n$ / _ [+past] since the derivation must start from the string as it is observed. Instead, we assume that regularly alternating consonants like *b/n* in *tob-u* vs. *ton-da* are separated from the nonalternating part as an *inflectional consonant* (Ic). *To-* demands *-b-* as its inflectional consonant, and this demand is satisfied in the cases of (7a,b).[3] In (7c), on the other hand, *-n-* overrides that demand by taking $V_5^{stem}/Ic_{b|m|n}$ (a stem whose inflectional consonant has not been realized) as an argument.[4] Note also that, unlike Bekki's analysis, we employ V and S as distinct categories to introduce the distinction between verb phrase and tense phrase, that is usually assumed in the Minimalist syntax.

(7) a.

$$\dfrac{\dfrac{\dfrac{\text{to-}}{(V_5^{stem}/Ic_b)\backslash NP_{ga}} \quad \dfrac{\text{-b-}}{V_5^{stem}\backslash(V_5^{stem}/Ic_b)}}{V_5^{stem}\backslash NP_{ga}}{<}\mathbf{B} \quad \dfrac{\text{-u}}{S_{term|attr}\backslash V_5^{stem}}}{S_{term|attr}\backslash NP_{ga}}{<}\mathbf{B}$$

b.

$$\dfrac{\dfrac{\dfrac{\dfrac{\text{to-}}{(V_5^{stem}/Ic_b)\backslash NP_{ga}} \quad \dfrac{\text{-b-}}{V_5^{stem}\backslash(V_5^{stem}/Ic_b)}}{V_5^{stem}\backslash NP_{ga}}{<}\mathbf{B} \quad \dfrac{\text{-a-}}{V_{neg}\backslash V_5^{stem}}}{V_{neg}\backslash NP_{ga}}{<}\mathbf{B} \quad \dfrac{\text{-nai}}{S^a_{term|attr}\backslash V_{neg}}}{S^a_{term|attr}\backslash NP_{ga}}{<}\mathbf{B}$$

[3] We assume that the inflectional consonant is type-raised as $V_5^{stem}\backslash(V_5^{stem}/Ic_b)$ in the lexicon rather than having a simple category Ic_b and then being type-raised in the derivation. This follows the suggestion of one of the reviewers, who pointed out that the elimination of type-raising rules from the grammar has desirable consequences concerning parsing and long-distance dependencies.

[4] Oleg Kiselyov (p.c.) pointed out that the current analysis does not provide a phonological explanation for why b and m corresponds to n, k and g to i, etc., in the euphonic change. Indeed, there are phonological reasons for the historic sound changes that are responsible for those correspondences. However, we remain agnostic about whether such an explanation is needed in the model of the synchronic I-language of a speaker of modern Japanese.

c.

$$\begin{array}{ccc} \text{to-} & \text{-n-} & \text{-da} \\ \hline (V_5^{stem}/Ic_b)\backslash NP_{ga} & V_{euph::d}\backslash(V_5^{stem}/Ic_{b|m|n}) & S_{term|attr}\backslash V_{euph::d} \end{array}$$

$$\frac{(V_5^{stem}/Ic_b)\backslash NP_{ga} \quad V_{euph::d}\backslash(V_5^{stem}/Ic_{b|m|n})}{V_{euph::d}\backslash NP_{ga}}{<}\mathbf{B}$$

$$\frac{V_{euph::d}\backslash NP_{ga} \quad S_{term|attr}\backslash V_{euph::d}}{S_{term|attr}\backslash NP_{ga}}{<}\mathbf{B}$$

The analysis for the mono-grade conjugation under the current approach does not differ from the mora-based analysis of [2] since the morpheme boundaries in this type of conjugation are placed at mora boundaries. Thus, the analyses for *miru* 'see' are as shown in (8). Note the use of a phonologically null item $\emptyset$ that converts a stem into a conjugated form.

(8) a.

$$\begin{array}{cc} \text{mi-} & \text{-ru} \\ \hline (V_1^{stem}\backslash NP_{ga})\backslash NP_o & S_{term|attr}\backslash V_1^{stem} \end{array}$$

$$\frac{(V_1^{stem}\backslash NP_{ga})\backslash NP_o \quad S_{term|attr}\backslash V_1^{stem}}{(S_{term|attr}\backslash NP_{ga})\backslash NP_o}{<}\mathbf{B}^2$$

b.

$$\begin{array}{ccc} \text{mi-} & \text{-}\emptyset\text{-} & \text{-nai} \\ \hline (V_1^{stem}\backslash NP_{ga})\backslash NP_o & V_{neg|cont|euph::t}\backslash V_1^{stem} & S^a_{term|attr}\backslash V_{neg} \end{array}$$

$$\frac{(V_1^{stem}\backslash NP_{ga})\backslash NP_o \quad V_{neg|cont|euph::t}\backslash V_1^{stem}}{(V_{neg|cont|euph::t}\backslash NP_{ga})\backslash NP_o}{<}\mathbf{B}^2$$

$$\frac{(V_{neg|cont|euph::t}\backslash NP_{ga})\backslash NP_o \quad S^a_{term|attr}\backslash V_{neg}}{(S^a_{term|attr}\backslash NP_{ga})\backslash NP_o}{<}\mathbf{B}^2$$

c.

$$\begin{array}{ccc} \text{mi-} & \text{-}\emptyset\text{-} & \text{-ta} \\ \hline (V_1^{stem}\backslash NP_{ga})\backslash NP_o & V_{neg|cont|euph::t}\backslash V_1^{stem} & S_{term|attr}\backslash V_{euph::t} \end{array}$$

$$\frac{(V_1^{stem}\backslash NP_{ga})\backslash NP_o \quad V_{neg|cont|euph::t}\backslash V_1^{stem}}{(V_{neg|cont|euph::t}\backslash NP_{ga})\backslash NP_o}{<}\mathbf{B}^2$$

$$\frac{(V_{neg|cont|euph::t}\backslash NP_{ga})\backslash NP_o \quad S_{term|attr}\backslash V_{euph::t}}{(S_{term|attr}\backslash NP_{ga})\backslash NP_o}{<}\mathbf{B}^2$$

There are two major irregular verbs in Japanese, *suru* 'do' and *kuru* 'come.' The segment-based analysis of these verbs differs from the mora-based analysis since the initial consonant (s and k), which is shared by all the conjugated forms, can be separated out. (9) below shows the analyses for *kuru*. The initial consonant *k-* has the category $V_K^{substem}$ and is selected by the following vowel. A similar analysis is possible for *suru*.

(9) a.

$$\begin{array}{ccc} \text{k-} & \text{-u-} & \text{-ru} \\ \hline V_K^{substem}\backslash NP_{ga} & V_K^{stem::(term|attr)}\backslash V_K^{substem} & S_{term|attr}\backslash V_K^{stem::(term|attr)} \end{array}$$

$$\frac{V_K^{substem}\backslash NP_{ga} \quad V_K^{stem::(term|attr)}\backslash V_K^{substem}}{V_K^{stem::(term|attr)}\backslash NP_{ga}}{<}\mathbf{B}$$

$$\frac{V_K^{stem::(term|attr)}\backslash NP_{ga} \quad S_{term|attr}\backslash V_K^{stem::(term|attr)}}{S_{term|attr}\backslash NP_{ga}}{<}\mathbf{B}$$

b.

$$\begin{array}{ccc} \text{k-} & \text{-o-} & \text{-nai} \\ \hline V_K^{substem}\backslash NP_{ga} & V_{neg}\backslash V_K^{substem} & S^a_{term|attr}\backslash V_{neg} \end{array}$$

$$\frac{V_K^{substem}\backslash NP_{ga} \quad V_{neg}\backslash V_K^{substem}}{V_{neg}\backslash NP_{ga}}{<}\mathbf{B}$$

$$\frac{V_{neg}\backslash NP_{ga} \quad S^a_{term|attr}\backslash V_{neg}}{S^a_{term|attr}\backslash NP_{ga}}{<}\mathbf{B}$$

c.
$$\dfrac{\dfrac{\dfrac{\text{k-}}{V_K^{substem}\backslash NP_{ga}} \quad \dfrac{\text{-i-}}{V_{euph::t}\backslash V_K^{substem}}}{V_{euph::t}\backslash NP_{ga}}{<}\mathbf{B} \quad \dfrac{\text{-ta}}{S_{term|attr}\backslash V_{euph::t}}}{S_{term|attr}\backslash NP_{ga}}{<}\mathbf{B}$$

For reasons of space, we do not attempt to formulate a comprehensive analysis of the entire verb conjugation system of Japanese like [2]. Still, the analyses in (7)–(9) cover the three major classes of verb conjugation in the language, and key phenomena found in the paradigm: segment-level agglutination, stem alternation triggered by a suffix, and irregular conjugation. All of these are done in a surface-oriented manner by careful choice of features for the morphemes involved. As suggested, this ensures that the grammar is compatible with left-to-right processing.

3 Constructivist Analysis of Transitivity Alternation

Having established the basic treatment of Japanese verbal conjugation, we now dig deeper into the decomposition of the stem. Japanese has many pairs of intransitive and transitive verbs (or more precisely, stems) that are morphologically related. Verbs in such a pair share the leftmost morpheme, followed by a suffix that marks the transitivity (sometimes null). We will call the leftmost morpheme *base*. Although it may be more intuitive to call it *root*, that term is reserved for the root in the DM sense, as we will see below. A base and a transitivity suffix constitute a stem in the sense defined in the previous section. An example is shown in (10).

(10) a. Kabin-ga kowa-*re*-ta.
vase-NOM break-INTR-PAST
'The vase broke.'

b. Taroo-ga kabin-o kowa-*s*-ita.
Taroo-NOM vase-ACC break-TR-PAST
'Taroo broke the vase.'

The form of the transitivity suffix is conditioned by the root. [20] classified the pairs into fifteen classes based on the form of the suffixes, as shown in Table 2. An apparent pattern noted in [20] is that suffixes containing *s* always mark transitive, while those containing *r* always mark intransitive. Interestingly, *e* and *Ø* is used to mark both transitive and intransitive, depending on the root.

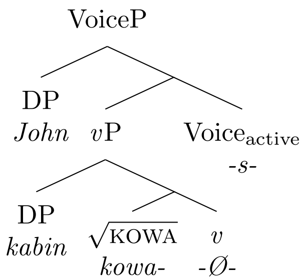
As mentioned earlier, these transitivity morphemes can be analyzed under DM as realizations of different *flavors* of the functional head that determines the transitivity of the verb, often called Voice, as shown in (11) [30] (also see [16, 26]).The *active* Voice introduces an external argument, resulting in a transitive

Table 2. Classification of transitivity alternation [20]. This summary is based on [30].

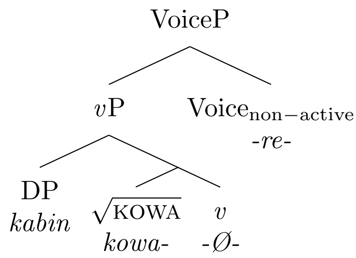
Class	Intransitive	Transitive	Meaning	Class	Intransitive	Transitive	Meaning
1	hag-*e*-ru	hag-∅-u	'peel'	9	tok-*e*-ru	tok-*as*-u	'melt'
2	ak-∅-u	ak-*e*-ru	'open'	10	nob-*i*-ru	nob-*as*-u	'extend'
3	ham-*ar*-u	ham-*e*-ru	'fit'	11	ok-*i*-ru	ok-*os*-u	'get up'
4	tunag-*ar*-u	tunag-∅-u	'connect'	12	abi-∅-ru	abi-*se*-ru	'pour'
5	ama-*r*-u	ama-*s*-u	'remain'	13	obi-*e*-ru	obi-*yakas*-u	'frighten'
6	kowa-*re*-ru	kowa-*s*-u	'break'	14	kom-*or*-u	kom-*e*-ru	'fill'
7	ka-*ri*-ru	ka-*s*-u	'borrow/lend'	15	toraw-*are*-ru	toraw-*e*-ru	'catch'
8	her-∅-u	her-*as*-u	'decrease'				

structure.[5] The *non-active* Voice, on the other hand, does not introduce an external argument, resulting in an intransitive structure. The transitivity morphemes are regarded as realizations of the respective Voice head. In DM terms, they are inserted to the Voice head after the syntactic structure is built, and the specific morpheme is determined by looking at the syntactic context where the target morpheme is situated. The morphological insertion rules for the active Voice, for example, look like (12a). These rules consist of three parts: the target of insertion ($\text{Voice}_{\text{active}}$), the morpheme to be inserted (*-s-, -as-, -os-, ...*), and the local context that restricts the application of the rule, the classification of the root in this case. Similarly, the semantic interpretation for the active Voice is inserted by the rule (12b). Note that this analysis is able to capture the implicational relation that holds between *John broke the vase* and *the vase broke*, as one of our reviewers pointed out; the shared semantics is represented by the *v*P.

(11) a. (=3b)



b.



(12) a. $\text{Voice}_{\text{active}} \rightarrow \textit{-s-} \;/\; \sqrt{}_{class::(v|vi|vii)}\text{—}$

$\rightarrow \textit{-as-} \;/\; \sqrt{}_{class::(viii|ix|x)}\text{—}$

$\rightarrow \textit{-os-} \;/\; \sqrt{}_{class::xi}\text{—}$

$\vdots$

b. $\text{Voice}_{\text{active}} \rightarrow \lambda P.\lambda x.\lambda e.P(e) \wedge causer(x)(e)$

[5] [30] argues that there are two flavors for the active Voice head that appears in Japanese transitive verbs, which introduce a Causer and Agent respectively. We put aside this point for now and focus on the transitive-intransitive contrast. We note however that this analysis can be easily implemented in the current framework by assuming distinct semantics for each flavor.

The structures in (11) can be translated in CCG straightforwardly as follows:6

(13)

$$
\begin{array}{ccc}
\text{kowa-} & \text{-Ø-} & \text{-s-} \\
\hline
R_{vi} & (V_{base::\{1\}}\backslash NP)\backslash R_{\{1\}} & (V^{stem}_{5::s}\backslash NP)\backslash V_{base::(v|vi|vii)} \\
\lambda e.kowa(e) & \lambda P.\lambda x.\lambda e.P(e) \wedge theme(x)(e) & \lambda P.\lambda x.\lambda e.P(e) \wedge causer(x)(e)
\end{array}
$$

$$
\frac{}{\begin{array}{c} V_{base::vi}\backslash NP \\ \lambda x.\lambda e.kowa(e) \wedge theme(x)(e) \end{array}} <
$$

$$
\frac{}{\begin{array}{c} (V^{stem}_{5::s}\backslash NP)\backslash NP \\ \lambda x.\lambda y.\lambda e.kowa(e) \wedge theme(x)(e) \wedge causer(y)(e) \end{array}} <\mathbf{B}
$$

(14)

$$
\begin{array}{ccc}
\text{kowa-} & \text{-Ø-} & \text{-re-} \\
\hline
R_{vi} & (V_{base::\{1\}}\backslash NP)\backslash R_{\{1\}} & V^{stem}_{1}\backslash V_{base::vi} \\
\lambda e.kowa(e) & \lambda P.\lambda x.\lambda e.P(e) \wedge theme(x)(e) & \lambda P.\lambda e.P(e)
\end{array}
$$

$$
\frac{}{\begin{array}{c} V_{base::vi}\backslash NP \\ \lambda x.\lambda e.kowa(e) \wedge theme(x)(e) \end{array}} <
$$

$$
\frac{}{\begin{array}{c} V^{stem}_{1}\backslash NP \\ \lambda x.\lambda e.kowa(e) \wedge theme(x)(e) \end{array}} <\mathbf{B}
$$

In these structures, the leftmost element is the root, as indicated by the category R. It is also specified as belonging to the class 6, written vi, following the classification of the root shown in Table 2. The middle element corresponds to the v head in the DM analysis. It selects a root and introduces an NP as the internal argument. It also inherits the class of the root by the *variable* $\{1\}$. The rightmost element corresponds to the Voice head. It selects a verb phrase with the appropriate class feature, introduces the external argument if it is active, and results in a verb stem.

This analysis exemplifies how contextual allomorphy can be treated in CCG, and provides further insights about the nature of allomorphy. The correct morphological form is obtained because the Voice morpheme with the appropriate sound (e.g., -*s*-) selects the base of the appropriate class. Thus, contextual allomorphy is reduced to mere selection. The allomorphs should be listed in the lexicon, as shown below.

(15)

$$
\begin{array}{l}
\text{-}s\text{-} \vdash (V^{stem}_{5::s}\backslash NP)\backslash V_{base::(v|vi|vii)} : \lambda P.\lambda x.\lambda e.P(e) \wedge causer(x)(e) \\
\text{-}as\text{-} \vdash (V^{stem}_{5::s}\backslash NP)\backslash V_{base::(vii|ix|x)} : \lambda P.\lambda x.\lambda e.P(e) \wedge causer(x)(e) \\
\text{-}os\text{-} \vdash (V^{stem}_{5::s}\backslash NP)\backslash V_{base::xi} : \lambda P.\lambda x.\lambda e.P(e) \wedge causer(x)(e) \\
\vdots
\end{array}
$$

In the list (15), the same logical form and similar categories are repeated. It is apparently less elegant than the DM analysis (12), where the logical form appears only once. Yet we can achieve the same level of abstraction in CCG as in DM by defining a function á la [2] that maps a class feature to a transitivity morpheme, as shown in (16). Then the set of lexical items in (15) are defined succinctly as (17).

(16) $$f(c) \stackrel{def}{=} \begin{cases} \textit{-s-} & (c = v, vi, vii) \\ \textit{-as-} & (c = viii, ix, x) \\ \textit{-os-} & (c = xi) \\ \vdots & \end{cases}$$

(17) For any $c \in dom(f)$,
$f(c) \vdash (V_{stem} \backslash NP) \backslash V_{base::c} : \lambda P.\lambda x.\lambda e.P(e) \wedge causer(x)(e)$

Note that the use of feature inheritance is independently justified by adjunction facts. For example, the fragments *[reads papers]*$_{S\backslash NP_{+3sg}}$ and *[read papers]*$_{S\backslash NP_{-3sg}}$ should require a third-person-singular and non-third-person-singular subject respectively, and the categorial specifications of the fragments do this job. A modifier like *carefully* is able to modify both, but the number specification of the verb phrase must be maintained. This is achieved by assigning a variable category $S\backslash NP_{\{1\}}\backslash(S\backslash NP_{\{1\}})$ to *carefully*. Otherwise we would need two almost identical lexical entries for every adverb that adjoins to verb phrases. Thus, although it is a powerful mechanism, the need for feature inheritance by variables is undeniable.

Another interesting implication of the selection-based account of allomorphy concerns the locality constraints on the context that determines the choice of the allomorph. In the DM literature, it has been pointed out that the choice of the allomorph to be inserted to a given terminal node is conditioned by its local context [1,5,26,28]. In other words, insertion rules can only 'see' a certain local context. Linear (string) adjacency has been suggested to be relevant, although there are also cases where strict adjacency is not required [28]. Limitation based on phase-based cyclic spell-out [11] has also been proposed [25]. Consider the Japanese transitivity alternation paradigm again. The phonological realization of the active/non-active Voice is conditioned by the root. The root and the Voice are not adjacent but intervened by a phonologically null v. Still, the insertion to the Voice head can consult the feature of the root, as evident from the paradigm shown in Table 2. Conversely, when the v head is visible, the insertion to the Voice head seems to be unable to consult the root. In Japanese, for example, verbs can be formed by suffixing *-m-* to an adjectival root. This *-m-* can be analyzed as realization of v [30]. (18) shows the analyses for *huka-m-e-ru* and *huka-m-ar-u* 'deepen,' which share the root with the adjective *huka-i* 'deep.'

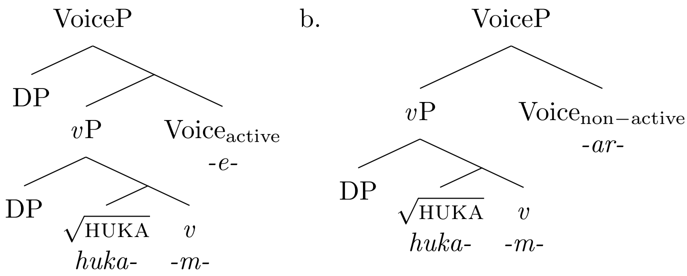
(18) a.


Table 3. An excerpt from the conjugation paradigm of the Greek verb for 'eat,' adopted from [28]. Only the first person singular form is shown.

	Active		Non-active	
	Nonpast	Past	Nonpast	Past
Imperfective	tró-o	é-trog-a	tróg-ome	trog-ómun
Perfective	fá-o	é-fag-a	fago-th-ó	fagó-th-ik-a

Crucially, de-adjectival verbs formed by *-m-* belong to the same alternation class, as evident from forms such as *tuyo-m-e-ru/tuyo-m-ar-u* 'strengthen,' *yowa-m-e-ru/yowa-m-ar-u* 'weaken,' and *taka-m-e-ru/taka-m-ar-u* 'heighten.'[6] This conforms to the suggestion in the DM literature that phonological adjacency is relevant to determine the local context for contextual allomorphy.

However, [28] points to an apparent exception to the locality constraint based on string adjacency in Greek verb conjugation. In Greek, suppletive and irregular alternations of verb stems are conditioned by the *combination* of aspect and voice, as shown in Table 3. Two suffixes can be attached to the stem, and both of them are sensitive to the same voice and aspect features. Thus, *fagóthika* 'eat.nonactive.perfective.past' can be decomposed as *fagó-th-ik-a*, and the first three morphemes are all associated with the non-active voice and the perfective aspect. This means that the insertion of *fagó* to the root must be able to see the features that also contribute to the insertion of *ik,* although *th* intervenes between them. Giving up the decomposition and assuming *fagóthik* to be a single morpheme would miss the generalization that *th* and *ik* appears quite regularly across the Greek verb conjugation. [28] proposes to relax the locality constraint on contextual allomorphy by grouping terminal nodes into 'spans' and let insertion see the adjacent span, rather than the adjacent (non-empty) node, as its context.

The current selection-based approach provides a natural explanation for such complex nature of locality constraints on contextual allomorphy without relying on bottom-up structure building, late insertion, or the notion of span. In CCG, combinatory rules can be applied only for linearly adjacent elements (Principle of Adjacency; [33] p.54). It would then follow that selection-based contextual

[6] Apparent counterexamples to this pattern include *ita-m-e-ru/ita-m-u* 'ache' and *kurusi-m-e-ru/kurusi-m-u* 'suffer.' The intransitive forms of these verbs do not have *-ar-*, unlike the verbs mentioned in the main text. These counterexamples are probably only apparent. While the *-ar-* verbs illustrate a change of state of the subject, *ita-m-u* is stative, and *kurusi-m-u* takes an Experiencer as the subject. Arguably, therefore, these verbs differ in the argument structure and include a third Voice head other than what we call non-active here (cf. [3,13]). Then the difference in the forms is expected. A reviewer pointed out *yuru-m-e-ru/yuru-m-u* 'loosen' as another counterexample; it actually forms a triplet with another intransitive form *yuru-m-ar-u*. A similar explanation may also apply to this case, although the semantic difference between the two intransitive forms is not very clear and seems to be subject to individual variation among native speakers.

allomorphy is only sensitive to linearly adjacent elements. But the feature inheritance mechanism we introduced earlier could circumvent this restriction without any limit: in a string ABC, if B selects A and inherits some of its features, and C selects B, then C is virtually sensitive to A's features. The question is therefore how feature inheritance should be constrained. One possible answer is to postulate a principle that categories must be motivated either semantically or phonologically. A related proposal has been made by Steedman:

(19) *The Principle of Categorial Type Transparency*
For a given language, the semantic type of the interpretation together with a number of language-specific directional parameter settings uniquely determines the syntactic category of a category. ([33], p.36)

That is, categories must be motivated only by semantic types and directionality parameters. This is clearly too strict for the current analysis, since our *class* feature is not motivated semantically. To include morphological considerations in the motivation for categorization, we revise (19) as follows.

(20) *The Principle of Categorial Type Transparency, revised*
For any constituent, the semantic type of the interpretation, the morphological class of the entire string, and a number of language-specific directional parameter settings uniquely determine the syntactic category of the constituent.

The intuition is that if B inherits features on A, they must be semantically or morphologically meaningful for the constituent AB (or BA). In the case of transitivity alternation, *kowa-Ø* is allowed to inherit the morphological class feature of *kowa-* since *-Ø-* is the identity element and thus *kowa-Ø* is morphologically indistinguishable from *kowa-*. Conversely, a morphologically visible element blocks inheritance of the morphological feature of the root. This is the case with the Japanese de-adjectival verbs formed by *-m-*. Since *huka-m-* is morphologically different from *huka-*, it cannot inherit the features from *huka-*. On the other hand, if the feature in question is semantic rather than morphological, what is relevant is not the morphological visibility of the intervening element but rather the semantic congruity. In the case of Greek verb stem alternation, the stem, voice, and aspect are all predicates of the event. In other words, each of them adds information to constrain the set of events that the verb denotes. Therefore features that modify the event can be inherited from the stem up to the aspect element.

In sum, the current selection-based approach to contextual allomorphy provides an account for the apparent complexity of the locality constraints on allomorphy in terms of constraints on feature inheritance. Only features that are semantically or morphologically meaningful for the entire constituent can be inherited, and can therefore constrain the choice of the allomorph that selects that constituent. While this account is in line with some of the observations in the DM literature that we discussed here, its empirical plausibility must be tested in a wide range of data in the future.

Table 4. The non-future verb conjugation paradigm of Chamorro, adopted from [19].

	'fly'	'stay'	'stand up'
Singular	gumupu	sumaga	kumuentos
Plural	manggupu	mañaga	manguentos

4 Extensions

Beside transitivity alternation, a characteristic feature of the current analysis is the use of a class of categories that serves for a morphological, but not semantic purpose. We postulated the inflectional consonant category *Ic* to capture the euphonic alternation between *tob-* and *ton-* (see Sect. 2). Such a morphological category opens a new way to analyze complex morphological phenomena that go beyond simple concatenation of strings. We briefly discuss an extension of this approach. [19][7] proposes to augment Categorial Grammar with a set of "transformational" morphological operations to capture phenomena such as infixation, circumfixation, reduplication, metathesis, umlaut, and so on. We do not have space to discuss all of these phenomena, but let us consider the case of infixation and fusion in Chamorro discussed by [19]. The relevant facts are summarized in Table 4.

The non-future singular form can be analyzed as involving infixation of *-um-*, while the plural form can be analyzed as prefixation of *man-,* followed by a fusion of the n and the first consonant of the stem in the case of *mañaga* (the initial s is fused with n). [19] proposes to deal with such cases with operations specifically designed for them, which involve a destructive rewriting of the stem. In the current analysis, however, standard composition rules and a class of purely morphological categories C suffice. In the case of *saga* 'stay,' *-aga* requires *s-* on its left, but this requirement is intervened by *-um-* in the singular (21a), and overridden in the plural (21b). Note the resemblance to the analysis of the Japanese euphonic alternation between *tob-* and *ton-* discussed earlier.

(21) a.

$$\dfrac{\dfrac{\dfrac{\text{s-}}{C_s}\quad\dfrac{\text{-um-}}{(V_{sg}/(V_{sg}\backslash C_{\{1\}}))\backslash C_{\{1\}}}}{V_{sg}/(V_{sg}\backslash C_s)}<\quad\dfrac{\text{-aga}}{V\backslash C_s}}{V_{sg}}>$$

[7] We thank Yusuke Kubota (p.c.) for suggesting [19] as relevant to the current discussion. Another work that deals with morphology with Categorial Grammar is [31], also suggested to us by Yusuke Kubota. The central idea of the work is that morphological operations are functions, and such functions can take another function as their argument. Although many interesting cases discussed there are out of the scope of the current study since they involve suprasegmentals, we believe the approach pursued here — viewing morphemes as functions that take other morphemes, which can be functions themselves — is in line with [31]'s intuition.

b.
$$\dfrac{\dfrac{\dfrac{\text{ma-}}{(V_{pl}/V_{pl})/C_n} \quad \dfrac{\text{-ñ-}}{(V_{pl}/(V_{pl}\backslash C_s))\backslash((V_{pl}/V_{pl})/C_n)}}{V_{pl}/(V_{pl}\backslash C_s)}{<} \quad \dfrac{\text{-aga}}{V\backslash C_s}}{V_{pl}}{>}$$

Although this analysis is preliminary and is by no means meant to cover all the relevant morphosyntactic and semantic facts of the Chamorro verb conjugation, it should be sufficient to demonstrate that the current version of CCG, augmented with morphological categories and feature inheritance, is powerful enough to capture morphological phenomena which go beyond simple concatenation. A topic for future work is therefore to explore the potential of the current approach in a broader range of morphological phenomena.

5 Concluding Remarks

We proposed a formalization of the constructivist analysis of verbal argument structure in CCG, in which argument structure is composed in the syntactic derivation, rather than specified in the lexicon. Such a formalization should provide a basis for a constructivist model of argument structure processing since CCG allows incremental, left-to-right structure building. We argued that such an analysis is not only possible but also provides an explanation for the locality constraints on contextual allomorphy observed in the DM literature based on the locality of selection. This explanation is attractive since it reduces contextual allomorphy to the matter of selection, a more fundamental mechanism that is undeniably essential to language.

As both of our reviewers correctly pointed out, a fundamental issue in constructivist analyses is how to constrain the set of argument structures that are allowed with a particular root. In the current framework, possible combinations of argument structures (i.e., argument-introducing items) and roots are defined by features that these items have. To capture the fact that *tabe-* 'eat,' for example, can be combined with the phonologically null transitive morpheme but not with a pronounced transitive morpheme or an intransitive morpheme, one can assign to the root *tabe-* some feature(s) to be selected by the appropriate morpheme. One reviewer suggested that this would be just a 'notational variant' of the projectionist analysis, where *tabe-* is inherently specified as $V\backslash NP\backslash NP$. One possible argument in favor of the constructivist analysis of *tabe-* is that it explains why the first argument is associated with the theme (what is eaten) and the second with the agent (eater). Under the current approach, this fact is explained by hierarchical organization of the argument-introducing elements, which are dictated by features on these categories. The constructivist analysis also enables the role of the arguments to be specified compositionally, rather than lexically (especially the agent role; cf. [22]). Further research is needed to distinguish these two views on empirical grounds.

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