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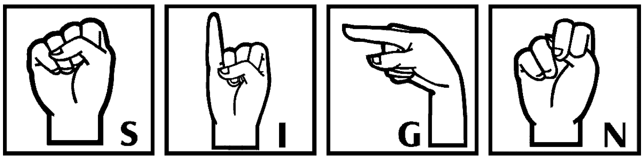

A Formal Description of Sign Language using HPSG

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Karlsruhe, den 26. September 2002

Zusammenfassung

Diese Arbeit untersucht die Phonologie, Morphologie, Syntax und Semantik der Gebärdensprache mit formalen Methoden. Nach der Einführung in die Grundlagen der Linguistik und ihrer Betrachtung der Gebärdensprache, wird die Eingliederung in die logische Struktur der theoretischen Linguistik (nach [Cho75]) vorgenommen. Desweiteren werden die morphologischen und syntaktischen Regeln mit sogenannten "Head Driven Phrasenstrukturgrammatiken" (HPSG, siehe [PS87]) modelliert. Zum Abschluß wird eine Implementierung in dem auf Prolog basierendem System ALE vorgestellt.

Seit William Stokoe 1960 die Bedeutung der Gebärdensprache entdeckte, nimmt das wissenschaftliche Interesse an der Sprache und Kultur der gehörlosen Menschen stark zu. Diese Arbeit soll zu diesem neuen Verständnis beitragen.

Abstract

This work investigates the phonology, morphology, syntax and semantics of Sign Language with formal methods. After introducing the basic principles of linguistics in general and in the specific case of Sign Language, we focus on the integration of Sign Language into the logical structure of linguistic theory [Cho75]. Furthermore we construct the morphological and syntactical rules using "Head-driven Phrase Structure Grammars" (HPSG, [PS87]). Finally an implementation in the Prolog-based system ALE is presented.

Since William Stokoe discovered the importance of Sign Language in 1960, the scientific interest in language and culture of the Deaf people increased strongly. This work wants to contribute to this new understanding.

Contents

1. Introduction

1.1 Sign Language in Context

Sign Language is the natural language used by the Deaf[1] community. Although unique in its phonology, the grammatical structure of Sign Language, i.e. morphology and syntax, is comparable to any other language. As Sign Language developed naturally it differs from region to region, it is then called for example South African Sign Language (SASL), German Sign Language (DGS[2]), American Sign Language (ASL), etc.

When William Stokoe started to teach English at Gallaudet College in 1955 he realized quickly that the Deaf students were using signs differently from what they were tought ([Mah96]). The school forced them to use signed English and to learn lipreading, but the Deaf expierenced big difficulties with spoken languages. They even were regarded as mentally retarded.

Stokoe never believed this dogma and started to investigate the Sign Language with scientific methods. His first publication [Sto60] was groundbreaking, he was the first to describe the signs, introducing an own notation system. This allowed him to work on the first Sign Language dictionary, published 1965 ([Sto65]).

Although his work was accepted immediately by fellow scientists, it took another 38 years until the Deaf themselves accepted this new theory and I. King Jordan, the first Deaf president at Gallaudet, announced: "Deaf people can do anything but hear."

[1] The terms "Deaf" and "Sign Language" are written with capital letters when they refer to the culture of the people (most of them deaf or hard hearing) that use signing as their communication language.

[2] Deutsche Gebärdensprache

Since Stokoes first paper, Sign Language research became a repected field in linguistics. Todays research investigates many aspects of Sign Language, like the grammatical structure, the psycho linguistics and the social status of the Deaf community.

Deaf people experience communication problems in their everyday life. Translation is essential because many Deaf have problems reading and writing the spoken languages. Human translators are very expensive and often not reachable. An automatic translation unit could help here.

The aim of this work is to investigate, how Sign Language can be formalized, so it can be used for computer-based projects, especially for automatic translation from and into Sign Language.

1.2 Formalizing Sign Language

In this first chapter we give an introduction to Sign Language. We also present related work.

The second chapter discusses linguistic theory in general and the phonology and morphology of Sign Language in detail.

We investigate how the general Sign Language structure fits into Chomskys logical structure for natural languages in the third chapter.

The fourth chapter introduces the formal grammar framework HPSG, and we show how Sign Language phonology, morphology, syntax and semantic can be integrated, by implementing grammar fragments.

In the fifth chapter, the conclusion is drawn and a perspective for further work is given.

We add three appendices with an explanation of the Movement-Hold Model, a sample lexicon of South African Sign Language and the final implementation of the HPSG based grammar.

1.3 Related Work

With an increasing interest in Sign Language research, combined with the possibilities of modern computer science, several projects and publications were developed and emerged.

Speers ([dLS02]) wrote his dissertation on the “Representation of American Sign Language for Machine Translation”. He developed a formal framework on ASL linguistics, this includes phonology, morphology and syntax. Translation related issues are discussed as well. For the formalism an extended version of the LFG architecture is used (see section 4.5 for details), while the phonology is based on the Movement-Hold Model (see section 2.2.3). Only parts of his research results could be incooperated into this thesis because they were released only recently. Especially the ASL Workbench, an application for the Movement-Hold Model representation, was used for the lexicon and influenced the phonological approach.

Sáfár and Marshall ([SM01a][SM01b][SM02]) work on the ViSiCAST project, a translation system from English to British Sign Language. For their formal Sign Language representation, HPSG is used and the grammar is implemented utilizing the Prolog based system Ale (see appendix A). For the phonology HamNoSys is used. Unfortunatly the system with its focus on British Sign Language is not convertable to South African Sign Language and core information about the syntactical structure is not published yet. Still this is the most advanced project on Sign Language translation.

An HPSG analysis of ASL agreement is supplied by Cormier ([Cor97]). This work uses the potential of HPSG as a formalism for Sign Language. The agreement is realized with indexation and the importance of the locus is emphasised.

Sagawa, Takeuchi and Ohki published on the description of Sign Language. They implemented it for the translation system from Japanese Sign Language into Japanese ([STO97]). They use a Stokoe based lexicon to recognize the handshape, location and movement from the glove-based input.

A similar project for the recognition of American Sign Language and its translation into English is initiated by Vogler and Metaxas ([VM99]). The system is based on the Movement-Hold Model. Hidden Markov Models are trained to recognize the segmental properties. In this case, video-streaming is used as the input source.

Zhao, Vogler et al. also discuss their prototype for the translation from English to American Sign Language ([Zha00]). Staying with a Stokoe based notation system and transforming English into ASL with Tree Adjoining Grammar, the system focuses more on the technical aspects of the translation and representation.

Grieve-Smith propagates a presentation prototype ([GS02]). The system named SignSynth takes ASCII Stokoe as input and renders a VRML or Web3D based avatar. It has a web frontend and is also used for a English to ASL translation with a specific vocabulary for weather reports.

2. Linguistic Theory

In this chapter we look at the basic terms of general linguistics. We then discuss the phonological and morphological concepts of Sign Language in more detail.

2.1 Linguistic Basics

2.1.1 Linguistic Levels

The organization of a language can be seen as a hierarchy of linguistic levels. Each level contains units that describe the language in a more or less abstract way. The higher levels units can be broken up into smaller units of the lower levels.

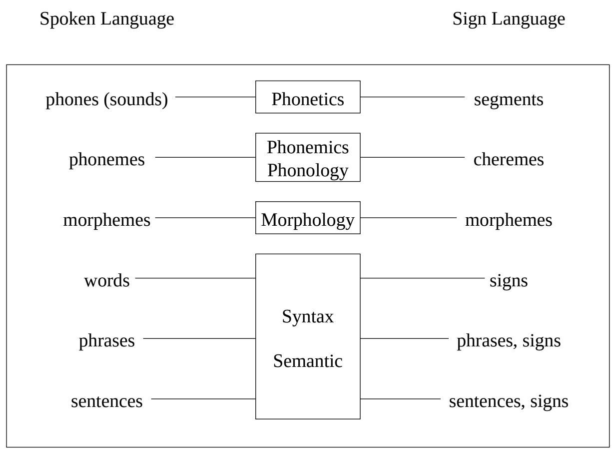


Figure 2.1: The linguistic levels listed from lower to higher.

Figure 2.1 shows an overview of the different levels and the terminology used by both Sign Language and spoken language.

2.1.2 Phonetics

In spoken language the study of the sounds that are used in all languages around the world is called *phonetics*. To make investigation easier the continuous stream of sound is broken up into segmental pieces named *phones*. Generally two types of phones can be distinguished, namely vowels and consonants. The main difference is the flow of air from the lungs that is more interrupted at the production of consonants while it can flow more freely at the production of vowels. Other features of phones are length, stress and tone.

In Sign Language it is difficult to split signs into minimal segments. One attempt was done by Liddell and Johnson who divided signs into units of hold and units of movement that were meant to be analogous to consonants and vowels ([Lid93]). This model is now considered a phonological rather than a phonetic model because the distinction between these two levels for Sign Language is not clearly distinguishable.

2.1.3 Phonology

Different to phones, the individual sounds of a language are called *phonemes*, and their study is called *phonemics* or *phonology*. For example ([CLSP95, p. 81]) the word meaning "water" in Yareba, a language from Micronesia, can be pronounced `[elio]` or `[erio]`. The phones `[l]` and `[r]` do not change the meaning of any word in Yareba, so they represent one phoneme written as `/r/: [r]-[l]`.

An English example is the phoneme `/p/` in the words "spill" and "pill". While "spill" uses the phone `[p`^{h}`]`, "pill" uses `[p]`. In Hindi these phones are two phonemes, while in English they can be swapped without any loss. Thus the phoneme is given as `/p/: [p]-[p`^{h}`]`.

Phonemes are found by looking for *minimal pairs*. A pair of two words forms a minimal pair when

- the two have different meanings, and
- the two words are identical in every way except for just a single sound in the same position in both words.

Although Stokoe [Sto60] introduced the term *cheremes* (from greek $\chi\epsilon\acute{\iota}\rho$ meaning "hand") for the phonological components of handshape, location and movement in Sign Language, in all recent publications the term phoneme is used. Several models try to define phonemes focusing on different aspects of Sign Language. The Hand Tier Model, the above mentioned Movement-Hold Model, the Moraic Model and the Prosodic Model are discussed later on.

2.1.4 Morphology

The smallest meaningful unit is the *morpheme*, and its study is called *morphology*. A word like *unlucky* can be divided into the morphemes *un*, *luck* and *y*, that have a specific meaning unlike the single phonemes which are meaningless.

Each language has rules that describe how morphemes are joined. So while *un-luck-y* is a correctly built form, **luck-un-y*, **y-un-luck* and **un-y-luck* are wrong. Note that ungrammatical forms are marked with an asterisk.

In Sign Language, morphological structure can be found for example in compounds, consisting out of two signs, temporal aspect, where a circular repetitional movement is added to show continuity or the construction of a gerund by adding a fast repeated movement.

2.1.5 Syntax

The higher levels containing the word, phrase and sentence are called the *syntax*.

Words are units with the characteristics

- isolability – a native speaker can break a sentence down to words, and natural speech has many interruptions in the fluent utterance stream,
- mobility – words can be moved within a sentence to form new sentences with different meanings,
- phonological independence – many phonemes have a special pronunciation at the beginning and the end of a word.

Words are classified into *word classes*. The definition of the word classes depends on the specific language, but normally the morphemic pre- and suffixes or the relationship to other words are used. For example, English words with a suffix *-s* and an article *a*, *an* or *the* are called nouns. Important classes for English and Sign Language are nouns, adjectives, adverbs and verbs. But these terms may have a very different meaning in other languages, for example Paamese has only one class for what is called adjective and verb in English ([CLSP95, p. 27]).

A *phrase* is a group of words with a similar behaviour. Tests, whether a group of words is a phrase or not, are substitution by a single word, mobility, the group can be shifted around, conjoinability, groups can be conjoined and others. Three phrases for the English language are:

Noun phrases (NP) consist of a noun, that can have a number of adjectives and a determinater, or of a pronoun. In a more abstract way:

$$\text{NP} \rightarrow \begin{cases} \text{(DET) (ADJ) N} \\ \text{PRONOUN} \end{cases}$$

Prepositional phrases (PP) have a preposition (like on, at, in, etc.) and a noun phrase.

$$\text{PP} \rightarrow \text{P NP}$$

Verb phrases (VP) always contain a verb. However, noun phrases and preposition phrases can be added.

$$\text{VP} \rightarrow \text{V (NP) (PP)}$$

Sentences are units formed from phrases that are a complete utterance themselves and include the features:

· The sentences have a meaning,

· they have an internal structure without refering to other sentences

· and they have an intonation break with a final falling or rising intonation marking the end of the sentence.

2.1.6 Semantics and Pragmatics

The study of meaning is called *semantics*. The main purpose of language is to transport the meaning of idea and thought between two persons. The investigation of semantics is a difficult task because the meaning depends on the subjective intention of the speaker or signer.

Semantics can be divided into grammatical semantics and lexical semantics. The grammatrical semantic is the meaning of whole phrases and sentences added up by the meanings of the words. The lexical meaning focuses on the single word. Every word gets a definition explaining what makes it unique and how it should be used in context.

2.2 Phonology of Sign Language

The phonology of Sign Language is a broad research field. Different to spoken language, the actual structural features needed for the analysis of signed language are still a matter of ongoing debate. The high number of different approaches, some of them discussed here, reflect this.

We explain the structure that any phonological model must be based on and look further to the models that are able to incorporate such a structure. We also mention the most important notation systems. Of special interest is the Movement-Hold Model, the model of our choice.

2.2.1 Phonological Sign Structures

Every phonological correct model of Sign Language must satisfy the structures given by the forms: One-handed signs, two-handed signs and finger-spelled signs. All signs contain a handshape and a location of articulation. Furthermore most signs have a movement ([Bre98]).

The *path movement* is made by the elbow or shoulder, and it is mostly straight or arc shaped. The *local movement* is made by the wrist, knuckles or finger joints. Several different kinds of local movements can be found, such as zig-zag, circular and wiggling movements by wrist and fingers are possible, as well as handshape changes and rotation movements. The figure 2.2 shows local and path movements.

Most signs are articulated in front of the torso, we refer to this area as *neutral space* or simply $\emptyset$. Still other signs can be in contact with any region of the body or the head, or they are signed near these locations.

The hand configuration can be any easily produced handshape. Every signer has a strong, dominant hand (called H_1) and a weak, non-dominant hand (called H_2). Normally a righthanded person uses his right hand also as strong signing hand.

One-Handed Signs

One-handed signs are always expressed with the strong hand H_1. Figure 2.2 shows two examples.

Two-Handed Signs

We can differentiate among three different types of two-handed signs:

For type-1 signs, both hands are active. The movement can be synchronous or alternating (also called reciprocal), and the handshapes are the

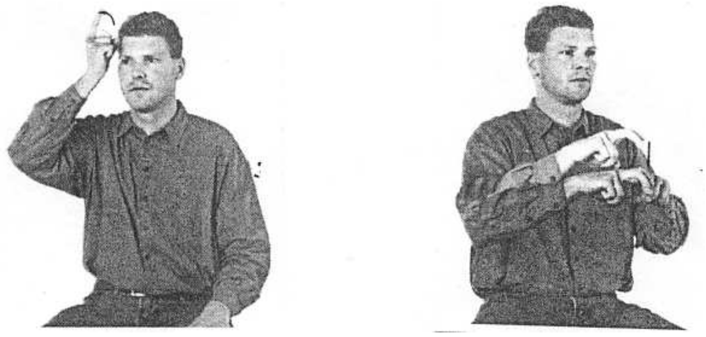


Figure 2.2: UNDERSTAND (left) shows a local movement, SIT (right) shows a path movement in ASL (taken from [Bre98]).

same. However the movements can not be destinct or be articulated in distinct body regions. This applies to all two-handed signs.

For type-2 signs the strong hand is active and the weak is passive, and both have the same handshape.

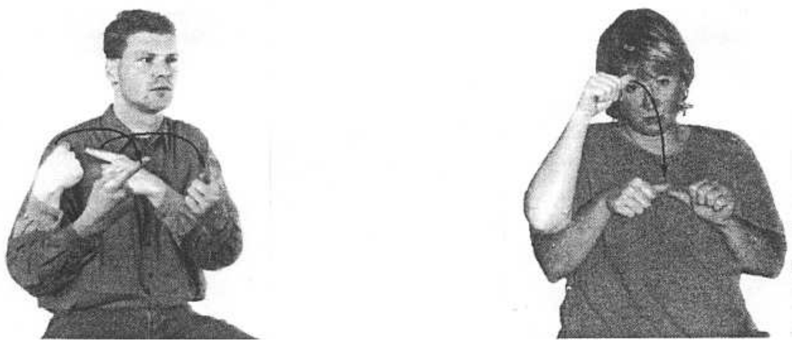


Figure 2.3: SINCE (left) is a type-1-two-handed sign, REMEMBER (right) is a type-2-two-handed sign in ASL (taken from [Bre98]).

For type-3 signs the strong hand is active and the weak one is passive, but they have different handshapes. Other two-handed signs are not very common in South African Sign Language and American Sign Language.

Fingerspelled Borrowings

Signers use an one-handed and a two-handed alphabet that is widely understood all over the world. Fingerspelling can have several functions in different Sign Languages. It can be used for the spelling of proper names or to emphasize words. Some fingerspelled words assimilated and became signs on their own. Such fingerspelled borrowings are quite common in ASL.

Figure 2.4: TOUCH (left) is a type-3-two-handed sign, the right picture shows an impossible two-handed sign (taken from [Bre98]).

2.2.2 The Stokoe Model

Stokoe [Sto60][Sto65] was the first to investigate Sign Language from a linguistic point of view. His work was ground-breaking, and it is still the foundation of most current research on Sign Language linguistics. He divided a sign into three sets of cheremes, avoiding the linguistic term 'phoneme' that we use. The sets represent handshape (called *dez*), the location on the body or in space where the sign is shown (called *tab*) and the movement (called *sig*). In total Stokoe listed only 55 phonemes. Every sign consists of at least one phoneme of each set, which are expressed simultaneously.

As an example the SASL sign glossed YOUR can be expressed as $\emptyset A_{\perp}$ in Stokoe notation. Here $\emptyset$ is the tab symbol for neutral space, A represents the dez phoneme for a fist and $_{\perp}$ is the sig phoneme for the movement away from the body.

2.2.3 The Movement-Hold Model

The Stokoe Model assumes the simultaneous occuring of the phonemes, but in all spoken languages the phonological structure is linear. The *Movement-Hold Model (MH Model)* by Liddell and Johnson ([Lid84] [Lid89] [Lid90]) therefore suggests a sequential division of the sign stream into segments, movements M and holds H.

During movements some aspects of the sign change, while holds are segments where all aspects are in a steady state for ≥ 0.1 second. The segments include all the necessary information needed to describe the handshapes, locations, orientations, non-manual signs (the expression of face and body) and possible movements of the sign, bundled in different tiers.

Holds between two movements are deleted or replaced by non-durable

Segmental Bundle	Timing Unit	H	M	X	M	H
	Contour/Flow		[arc]/[+ant]		[arc]/[-ant]	
	Touch					
	T-Quality					
	M-Quality					
	Local Move't					
Strong Placement	Hand Config	n+1234v+				
	Hand Site	HAND				
	Sprel	[sup]		[inf]		[sup]
	Focal Site	m1CH				
Facing	Hand Site	PA				
	Sprel	[near]				
	Focal Site	MP				
Rotation	Rotation	[neut]/Ext				
Weak Placement	Hand Config					
	Hand Site					
	Sprel					
	Focal Site					
Facing	Hand Site					
	Sprel					
	Focal Site					
Rotation	Rotation					
NMS	NMS					

Figure 2.5: Movement-Hold Model of SIGN

holds named X. This allows the segmentation within a changing movement.

Several projects are based on the Movement-Hold Model, for example those of Speers [dLS02] and Vogler [VM99].

We decided to use the MH Model because of its wide acceptance and its completeness in terms of structure and features. The sequential approach is widely supported, and the discussion is rather about the details of the segmentation. Using the Movement-Hold Model, we built a small lexicon of SASL signs, showing different structured signs. This phonological representation of signs is also used for the HPSG grammar. See appendix A for a full listing of possible features for the MH Model and appendix B for the lexicon.

Example 1: The Movement-Hold Model of SIGN

We analyse the word SIGN that is produced by circling both spread hands at a midline plane two times. In figure 2.5 the Movement-Hold representation of SIGN is shown.

The segmental bundle holds the information about the segmental type (movement or hold), about any possible movements, which includes local movement for hold segments, and whether contact (touch) is made. In the example we have five segments, consisting of two movements and three holds. The hold named `X` is non-durable, so it is used as a fast transition between two movements. The first movement is arc shaped `[arc]` to the anterior side `[+ant]`, the forward direction, while the second is arc shaped `[arc]` to the posterior side `[-ant]`, the backward direction relative to the hand position. No contact is made and no local movement occurs.

The fingers of the strong hand are all opened and spread `n+1234v+`. This code is given by a hand configuration calculator ([dLS02]). In the first segment, the whole hand `HAND` is located above, here called superior `[sup]`, a point in neutral space in front of the chest `m1CH`. The finger tips point away from the body `[neut]`, but the wrist is slightly bent, and it is extended `Ext`.

The hand is facing with its palm `PA` towards a midline plane `MP`, but only stays near the plane `[near]`.

Now during the arcshaped, anterior movement, the hand moves from the superior to the inferior position, below the virtual point `[inf]` and then during the arcshaped, posterior movement again to the superior position `[sup]`.

No non-manual signs are needed.

The sign is still not complete, as further information is vital. So we add the following table:

Structure Building Features	
Alternating Dominance	−
Bidirectional	−
Reduplicated	+
Symmetrical	+
Reciprocal	+

The sign is symmetrical, so the features of the strong hand also apply for the weak hand. It is reciprocal, as the movement of weak hand is the opposite of that of the strong hand. And the sign is reduplicated, as it is repeated at least for a second time.

2.2.4 The Hand-Tier Model

Another segmental phonemic model is the Hand-Tier Model ([San90]). Signs are divided into the two segments *location (L)* and *movement (M)*. L is defined as "a segment that is present when the dominant hand (i.e., the hand that articulates one-handed signs) obligatory reaches [a specific] location in the course of executing a sign"[San89]. In addition, handshape is placed on a separate tier. This gives the handshape a more important role than in the MH Model, and hence it is comparable to the importance of handshape in the Stokoe Model.

The hand configuration tree (figure 2.6) is used for the handshape tier while a similar location tree and a movement tree are used for the LM tier.

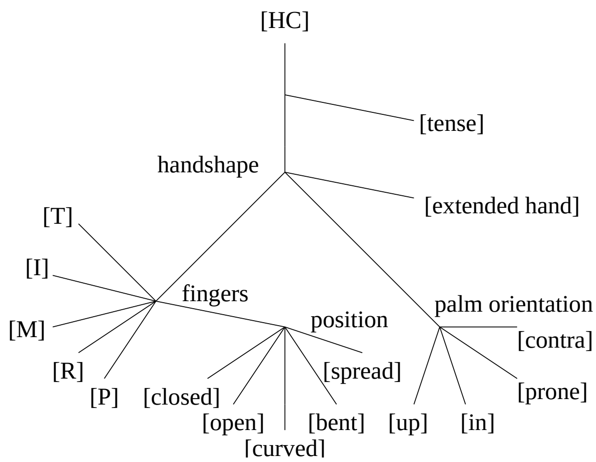


Figure 2.6: The hand configuration tree (taken from [Bre98])

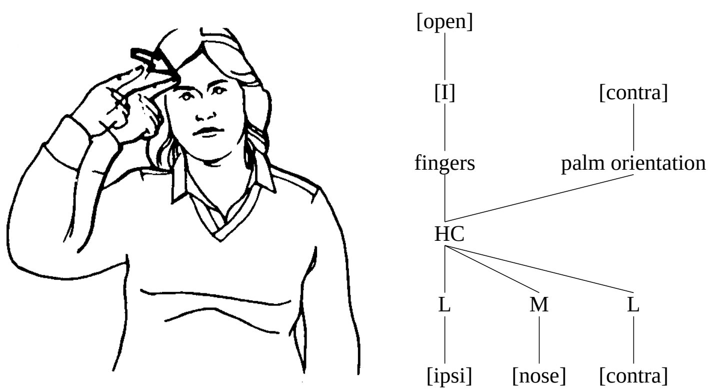


Figure 2.7: FALSE and the Hand-Tier Model of FALSE in ASL (taken from [Bre98])

2.2.5 The Moraic Model

The Moraic Model, also called the μ Model, by David Perlmutter ([Per90]) introduces moras (μ) as a timing unit. A mora is the minimal subsyllabic unit required of a well-formed syllable in spoken languages. In addition the model also includes segments to represent the sign. All path movements belong to the movement segment M, while all locations and non-path movements belong to the position segment P. The moraic timing units can be attached to M and P segments. Furthermore, mora insertion is an operation that attaches a mora to the final segment of a phrase. This stresses a duration of a final M or generates a hold for a final P.

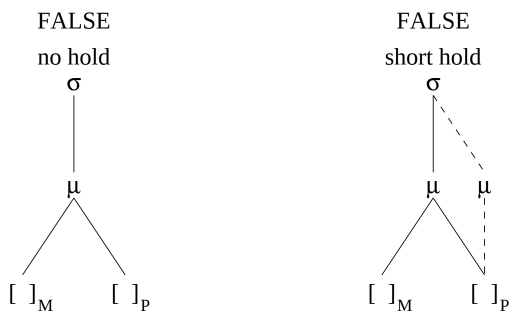


Figure 2.8: The sign FALSE within a phrase (left) and at the end of a phrase with mora insertion (right) (taken from [Bre98])

2.2.6 The Prosodic Model

Based on the previous works of the MH Model and the Hand-Tier Model, Brentari presented the *Prosodic Model* ([Bre98]).

The Prosodic Model distinguishes between *prosodic features* and *inherent features* that are based on separated branches of structure. The definition is as follows:

· Inherent features are only specified once and do not change.

· Prosodic features can change or are realized as dynamic properties.

This implies that all movement features are bundled into one branch, the prosodic branch. Figure 2.9 shows the Prosodic Model representation of FALSE. One problem of the MH Model is the inability to pick out minimal pairs because of the high amount of different phonemes. The Prosodic Model handles this and also introduces moras for syllables construction like the Moraic Model does. However, this is compromised with a high complexity.

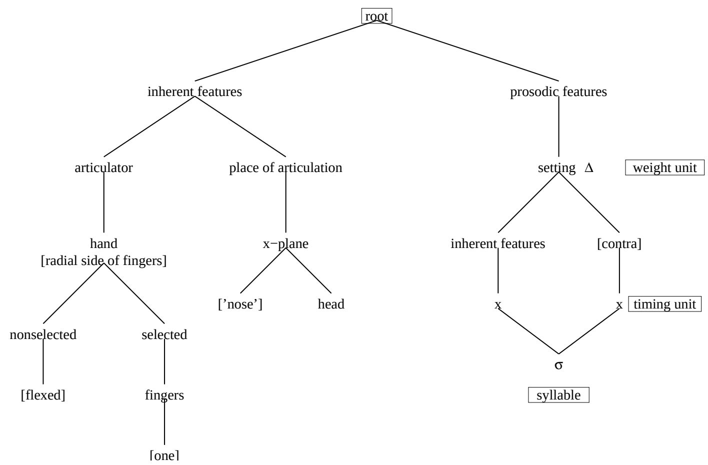


Figure 2.9: Prosodic Model representation of FALSE (taken from [Bre98])

2.2.7 Notation Systems

Stokoe-based Notations

The *ASCII Stokoe notation*[1] transliterates the Stokoe signs into 7-bit ASCII characters. Therefore it is system-independent and is used for dictionaries and email discussions. The SignSynth project[2] by A. Grieve-Smith for translating English text into ASL uses ASCII Stokoe as notation system.

The Hamburg Notation System *HamNoSys* ([Pri89]) is a traditional Stokoe based system. It expands Stokoe by adding further phonemes. HamNoSys is widespread, also because it does not depend on ASL and it is easy to use. The ViSiCAST Project ([SM02]) is based on HamNoSys.

Movement Notations

The movement notations Labanotation[3], Benesh Movement Notation[4] and Eshkol-Wachman Notation[5], were originally designed for dance and ballet. The three most common ones can also be used for any other movement and therefore also for Sign Language, but they are very complex and difficult to implement correctly without simplifying too much.

[1] http://world.std.com/~mam/ASCII-Stokoe.txt
[2] http://www.unm.edu/~grvsmth/signsynth/
[3] http://www.rz.uni-frankfurt.de/~griesbec/LABANE.HTML
[4] http://www.benesh.org
[5] http://ww2.mcgill.ca/Biology/perspage/ew_page.htm

Sutton SignWriting

Other than the first mentioned scientific models, *SignWriting*[6], invented by V. Sutton in 1972, is used for Deaf education and as a writing system for everyday use. It is a movement notation, and for signers it is easy to learn and to use. The differences between SignWriting and the Stokoe model are discussed by J. Martin.[7] SWML, an XML based file format for SignWriting, is also available.[8]

2.3 Morphology of Sign Language

Similar to spoken language, the Sign Language morphology divides the signs into meaningful units.

The morphology of Sign Language is very rich and complex, with differences between the various Sign Language communities. Due to the lack of research into South African Sign Language morphology, the work in this section is based on American Sign Language.

2.3.1 Derived Nominals

Several verbs can transform into nouns by repeating the movement of the verb ([SN78]). Figure 2.10 shows the verb CLOSE-WINDOW with one path movement and the derived noun WINDOW with two path movements.

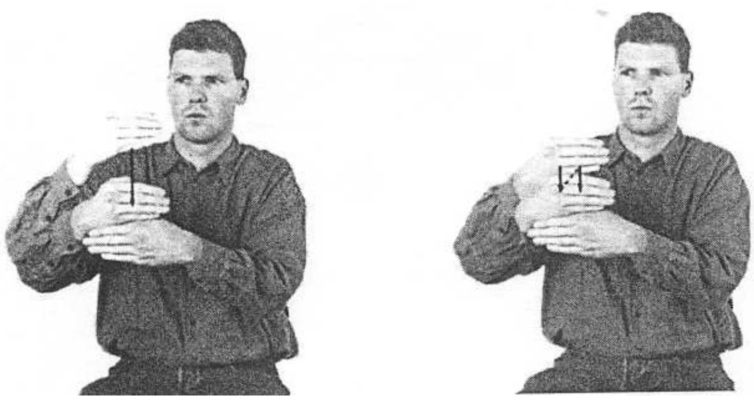


Figure 2.10: CLOSE-WINDOW (left) and WINDOW (right) (taken from [Bre98])

[6]http://www.signwriting.org
[7]http://www.signwriting.org/forums/linguistics/ling008.html
[8]http://swml.ucpel.tche.br

Verbstems with a *trilled movement* are nouns that work like the gerund in spoken languages. The trilled movements are described as "small, rapidly repeated, uncountable movements" [Lid90]. Note that trilled movements belong to the local movements. Figure 2.11 shows READING, the gerund of READ with a trilled movement.

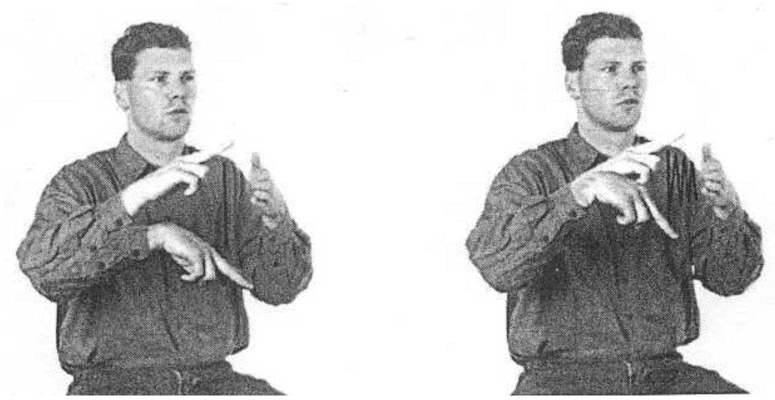


Figure 2.11: READ (left) and READING (right) (taken from [Bre98])

2.3.2 Agreement Affixation

Signs refering to different loci, for example persons or objects, are called *agreement forms*. Several different agreement classes can be found (see figure 2.12):

- Spatial agreement verbs have no or just one final spatial locus.
- Person agreement verbs refer to persons who can be mentioned as subject and/or object of a sentence.
- Mixed spatial and person agreement verbs contain both of the above classes.
- Backward agreement verbs have a grammatical object agreement locus.

2.3.3 Compounds

Compounds are built from at least two signs that can be verbs, nouns and/or adjectives. Some examples are:

- THINKˆSELF consists of a verb and a noun representing the sentence "decide for oneself" (see also figure 2.13).

Figure 2.12: DRIVE-TO (left) is a spatial agreement verb, HELP (middle) a person agreement verb and REQUEST (right) a backward agreement verb (taken from [Bre98]).

· GIRL^MARRY consists of a noun and verb representing the noun "wife".

· GOOD^ENOUGH consists of two adjectives representing the predicate "barely adequate".

Figure 2.13: THINK (left) and SELF (middle) form THINK^SELF (right) (taken from [Bre98]).

2.3.4 Grammatical Aspect

The system of grammatical aspect is complex in Sign Language. For ASL several distributional and temporal aspects with own phonological shape have been reported.

As an example, we list three temporal aspects discussed by Klima and Bellugi ([KB79]):

- The *Continuative Aspect*, an activity that continues for a long time, has a repeated, circular movement and a slight tilting back of the head as a non-manual sign.
- The *Regular Aspect*, an activity or event that is repeated on a regular basis, has a repeated, straight movement and a tilting of the head to the side with pursed lips as non-manual signs.
- The *Frequent Aspect*, an activity or event occuring often, has a tense movement repetition and lowered lips as a non-manual sign.

2.3.5 Classifier Predicates

Whole verb phrases and sentences with several morphemes can be expressed using only one or two syllables. Figure 2.14 shows an ASL sign, which means "two, hunched, upright-beings, facing forward, go forward, carefully, side-by-side, from point a to point b".

Figure 2.14: A polymorphemic sign (taken from [Bre98])

3. The Logical Structure

Noam Chomsky wrote about the logical structure of linguistic theory in 1975 ([Cho75]). We investigated this formalism of the linguistic levels to see whether it is also valid for Sign Language. Several examples illustrate possible applications.

3.1 Linguistic Levels

We first generalize the linguistic levels as described in section 2.1. Every level has its own alphabet Σ of elements called "primes" and ϵ as the identity element. We call Σ^* the set of all strings, whereas a string is a concatenation of primes. Relating to Chomsky[1] [Cho75, p. 105], we define the algebraic structure with concatenation $(\Sigma^*, \circ)$ as follows.

Definition 1 [Sch97, p.183] *For a set of strings Σ^* and a concatenation operation $\circ$ we define the monoid $(\Sigma^*, \circ)$:*

$$x \in \Sigma^* \wedge y \in \Sigma^* \Rightarrow x \circ y \in \Sigma^*$$

$$(x \circ y) \circ z = x \circ (y \circ z)$$

$$x \circ \epsilon = \epsilon \circ x = x$$

The relation between levels can be described as a mapping that we call Φ. Then any string from a high level (e.g. syntax level) can be mapped down

[1]We changed the Chomsky notation in some cases: the alphabet L changed to Σ, the concatenation symbol $\frown$ to $\circ$ and the identity element from U to ϵ (new notation taken from [Sch97]).

to a lower, less abstract level. The lowest level maps into the set of grammatical utterances GU, as a language is not more than a set of grammatical utterances. The structural information about a level is stored in a set of elements called the *L-marker*. Each element of this set is assigned to each grammatical utterance.

Definition 2 [Cho75, p.108] *A* level L *is a system*

$$L = (\Sigma, \circ, R_1, \dots, R_m, \mu, \Phi, \varphi_1, \dots, \varphi_n)$$

whereas

- $R_1, \dots, R_m$ *are* m *classes and relations defined within L, with* R_1 *the identity relation* $=$ *and* $m \in Nat$
- $\mu \subseteq \Sigma^*$ *is the set of L-markers*
- Φ *maps* μ *into the set of grammatical utterances GU*
- $\varphi_1, \dots, \varphi_n$ *express the* n *relations between* L *and other levels, where* $n \in Nat$

We can now construct the phonemic level Pm, the word level W, the level of syntactic categories C and the level of phrase structure P.

3.2 The Phonemic Level Pm

Different to spoken language, where the terms phonetic and phonemic are clearly defined, we already showed that there are several definitions for Sign Language phonology. As Liddell explains in [Lid93], the theory of dividing signs into segments is now accepted, and the current discussion is on the segmentation of the sign stream. Due to the segmentation, it is easy to transfer Chomsky's Axioms for the phonetic level Pn to our phonemic level.

The alphabet Σ^{Pm} is declared as the set of all different[2] segments. We can now specify the properties of the phonemic level by using our general linguistic level definition.

Definition 3 [Cho75, p.158] *The* phonemic level *is the level*

$$Pm = (\Sigma^{Pm}, \circ, =, \mu^{Pm}, \Phi^{Pm}, \varphi_1^{Pm}, \dots, \varphi_n^{Pm}).$$

[2]To distinguish phones in spoken language, minimal pairs are formed. Whether this can be applied to all segmentation models in every detail, is still being investigated.

The L-marker μ^{Pm} stores the structure of the phonemic level, given by the word level W.
The mapping $\Phi^{Pm} : \Sigma^{*Pm} \rightarrow GU$ has the following properties:

- *For all $x \in \Sigma^{*Pm}, x \in$dom$(\Phi^{Pm})$ and for all $g \in GU, g \in$range(Φ^{Pm}), and thus Φ^{Pm} is surjective.*

- *For all $p \in \Sigma^{Pm}$ there exists a set S of defining physical properties, so $\Phi^{Pm}(p)$ is characterized by S.*

- *If $x, y \in \Sigma^{*PM}$, then $\Phi^{Pm}(x \circ y) = \Phi^{Pm}(x) \circ \Phi^{Pm}(y)$ and the sequence of physical specification is (S_x, S_y), whereas S_x and S_y the physical specifications of $\Phi^{Pm}(x)$ and $\Phi^{Pm}(y)$ are.*

- *Let $g_1, g_2 \in GU$. Then $g_1 = g_2$ if there exists exactly one $x \in \mu^{Pm}$ with $\Phi^{Pm}(x) = g_1$ and $\Phi^{Pm}(x) = g_2$.*

Example 2: Movement-Hold Model

First we look at the Movement-Hold Model. The sign stream is divided into segments, movements and holds. There is a finite number of 299 properties for describing the segments [Bre98, p.85]. The physical properties of a prime are given within the MH Model as bundles.

The following table shows the simple representation of the sign THINK in ASL (taken from [Lid84]) with two segments $M, H \in \Sigma^{Pm}$.

	THINK	
Segment	M	H
Type of Segment	Approaching movement	Hold
Handshape	1	1
Orientation	Fingertip toward	Fingertip toward
Location	Forehead	Forehead
Contact	no	yes
Non-manual	—	—

The features of the segments stand for the sets S_M and S_H of physical properties. So for the mapping $\Phi(M \circ H) = \Phi(M) \circ \Phi(H)$ the sequence of physical properties is (S_M, S_H). $\Phi(M \circ H)$ is therefore in Σ^{*Pm}, and THINK is valid on the phonemic level Pm.

Example 3: Syllable Structure in ASL

The second example is based on the Moraic Model (see also section 2.2.5) that divides signs into movements M and positions P. We use Perlmutters explanation in [Per93] for the structure of syllables in American Sign Language. We now use our logical framework to formalize this syllable structure.

Local movement is the movement of the fingers or wrist that can occur during path movement. Regarding the Moraic Model, local movement can occur on an M and a P. Figure 3.1 shows the sign TAPE, that consists only of a P and has local movement (finger circling), and the sign GO-UP-IN-FLAMES with local movement (finger wiggling) on an M.

Figure 3.1: TAPE (left) and GO-UP-IN-FLAMES (right), taken from [Per93]

Interesting is now the fact that local movement never occurs on a P preceding or following an M. Figure 3.2 shows an example for such an impossible sequence.

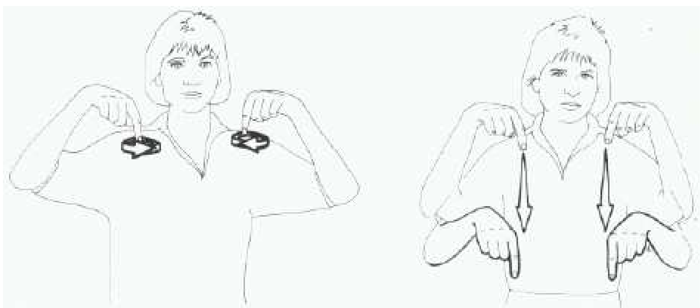


Figure 3.2: Impossible sign, taken from [Per93]

So the following distributions of local movement are possible (with + indicating the presence and − the absence of local movement):

$$\mathrm{P}_{-}\mathrm{M}_{+}\mathrm{P}_{-} \qquad \mathrm{M}_{+}\mathrm{P}_{-} \qquad \mathrm{P}_{-}\mathrm{M}_{+} \qquad \mathrm{M}_{+} \qquad \mathrm{P}_{+}$$

This is the same distribution that is found in spoken languages for vocals and consonants in syllables, when the movements are replaced by vocals and the positions are replaced by consonants. With this investigation we can now formalize the construction of the syllables by using the following definition for the syllable nucleus. The set of M-primes is called Σ_M^{Pm} and the set of P-primes Σ_P^{Pm}, with $\Sigma_M^{Pm} \cup \Sigma_P^{Pm} = \Sigma^{Pm}$.

Definition 4 *The* syllable nucleus $n \in \Sigma^{Pm}$ *for a string* $s \in \Sigma^{*Pm}$, *s containing n, is given by*

- *for* $n \in \Sigma_M^{Pm}$, *n is a syllable nucleus,*
- *for* $n \in \Sigma_P^{Pm}$, *n is not a syllable nucleus, if there is an* $m \in \Sigma_M^{Pm}$ *so that s contains* $n \circ m$ *or* $m \circ n$.

Similar to local movement, handshape change on the handshape tier and orientation change also only take place in the syllable nucleus. While every syllable with an M-nucleus is well-formed, a syllable with P-nucleus needs at least one of the mentioned features.

Definition 5 *For a string* $s \in \Sigma^{*Pm}$ *containing the prime* $n \in \Sigma_P^{Pm}$, *n is a syllable nucleus, if* S_n, *the set of physical properties of n, includes local movement, handshape change on the handshape tier or orientation change.*

All ASL signs have only one or two syllables. But monosyllabic and disyllabic signs can have an M as nucleus, while only monosyllabic signs can have a P as nucleus.

Theorem 1 *Every string* $s \in \Sigma^{*Pm}$ *with a nucleus* $n \in \Sigma_P^{Pm}$ *is monosyllabic, so* $s = n$.

Perlmutter shows that there is no sign with two adjacent P-primes. And because a P can not be followed by an M, the string s must be monosyllabic. The following forms are indeed impossible:

*PP   *PPMP   *PMPP

3.3 The Word Level W

For the word level W we don't have to distinguish between signed and spoken language anymore. In the alphabet Σ^W the vocabulary is stored, while the structure μ^W is given by the syntactic categories. Every word is mapped down to the phonemic level by Φ^W.

Definition 6 [Cho75, p.165] *The* word level *is the level*

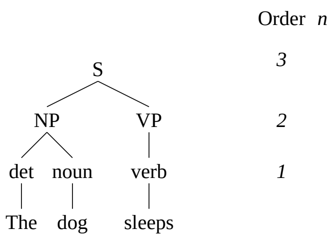
$$W = (\Sigma^W, \circ, =, \mu^W, \Phi^W, \varphi_1^W, \ldots, \varphi_n^W).$$

- *The alphabet* Σ^W *is the set of all words.*
- μ^W *is a set of strings of words which will be defined on the level of syntactic categories.*
- Φ^W *is the mapping* $\Phi^W : \Sigma^{*W} \to \Sigma^{*Pm}$ *with the property* $\Phi^W(x \circ y) = \Phi^W(x) \circ \Phi^W(y)$, *for* $x, y \in \Sigma^{*W}$.

3.4 The Level of Syntactic Categories C

Nouns, verbs, adjectives are all sets of words with similar behaviour within phrases and sentences. We call these sets *syntactical categories.*

Formally, syntactic categories sort words into sets of primes C^n of the order n. The order gives an level of abstraction, thus the order with the largest number of categories is 1. An example for categories of the order 3:



Definition 7 [Cho75, p.166] *Let* C_i^n *be the* i-th category of order n *then the alphabet is*

$$\Sigma^C = \{C_{n_i}^n\}, \text{ where}$$

- $1 \le n \le N$,
- $1 \le n_i \le a_n$ *and*
- $a_1 > a_2 > \ldots > a_N$.

The relation g of generation is applied to the strings of the level of syntactic categories C and the word level W.

Definition 8 [Cho75, p.166] *Let g be the* relation of generation *defined as*

· *if $C_i^n \in \Sigma^C$ and $g(C_i^n, x)$, then $x \in \Sigma^W$,*

· *if $y, z \in \Sigma^{*C}(y, z \neq \epsilon)$, then $g(y \circ z, x)$ iff there are $s_1, s_2 \in \Sigma^W$ such that $x = s_1 \circ s_2$ and $g(y, s_1)$ and $g(z, s_2)$,*

· *for all $C_i^n \in \Sigma^C$, there exists an x such that $g(C_i^n, x)$, and*

· *for all $C_i^n, C_j^n \in \Sigma^C$ and $i \neq j$, there is an x such that $g(C_i^n, x)$ but not $g(C_j^n, x)$.*

The set $Gr_1(W)$ is an approximation to μ^W, the set of grammatical strings of words.

Definition 9 [Cho75, p.166] *A* grammatical sentence form *of order n in terms of a given corpus K (a set of strings of words) is the string $x = C_{a_1}^n \circ \ldots \circ C_{a_m}^n$, such that some y generated by x is in the corpus K. $Gr_1(W)$ is the set of x's, such that for some grammatical sentence form y of order* 1, *$g(y, x)$.*

The L-marker is given by:

Definition 10 [Cho75, p.167] *$M \in \mu^C$ is an L-marker $M \in \mu^C$ if and only if $M = \{C_0, \ldots, C_N\}$, where*

· *C_i is a grammatical sentence form of order i,*

· *$\{x \mid g(C_i, x)\} \subset \{x \mid g(C_{i+1}, x\}, (0 < i < N)$ and*

· *C_0 is a string of words and $g(C_1, C_0)$.*

The mapping Φ^C associates with each μ^C with the string of words C_0. We can now assemble the level of syntactic categories.

Definition 11 [Cho75, p.166] *The* level of syntactic categories *is given by*

$$C = (\Sigma^C, \circ, =, \mu^C, \Phi^C, g).$$

3.5 The Level of Phrase Structure P

Due to the complexity of the phrase structure level P, we shall only give a short, more informal introduction.

Consider the level of phrase structure as

$$P = (\Sigma^P, \circ, =, \mu^P, \Phi^P, \rightarrow^P).$$

The alphabet Σ^P is a set of words like *Sentence (S), Noun Phrase (NP), Verb (V)* etc., called *variables*, but also the words of the word level W. The variables are just names without deeper meaning. We address this arbitrary describtion in the next chapter in the HPSG introduction.

Furthermore the relation $\rightarrow^P$ is used within level P to express the relation between variables and strings. An expression $x \rightarrow^P y$ is called a *rule.*

Axiom 1 [Cho75, p. 175] *The relation $\rightarrow^P$ is irreflexive, asymmetrical, transitive and nonconnected.*

Definition 12 [Cho75, p. 175] $\Sigma^{*\overline{P}}$ *is the set of strings without variables x such that for no y, $x \rightarrow^P y$.*

Examples for $\rightarrow^P$ are

S	$\rightarrow^P$	N $\circ$ VP	or simplified	S	$\rightarrow$	N VP
N	$\rightarrow^P$	HOUSE	or simplified	N	$\rightarrow$	HOUSE

Note that this grammatical structure with only one variable on the left side of $\rightarrow^P$, or more formally, with $x \rightarrow^P y$, where $x \in \Sigma^P \backslash \Sigma^{*\overline{P}}$ and $y \in \Sigma^{*P}$, is called a *Chomsky type 2 grammar* or a *contextfree grammar*[Sch97]. See also definition 13.

The L-marker μ^P is the set of strings out of $\Sigma^{*\overline{P}}$ relating to the *terminal strings.* These are the strings that are derived from S by using the relation $\rightarrow^P$ as a partial ordering with the prime *Sentence (S)* as the first element and the primes of $\Sigma^{*\overline{P}}$ the last elements.

The L-marker μ^P is mapped down to a set containing $Gr_1(W)$ on the word level W with the mapping Φ^P.

Keeping this logical structure in mind, we define a *grammar* as a structure containing the variables, the alphabet, the set of rules and the start variable.

Definition 13 [Sch97, p. 13] *A* grammar *is a 4-tuple* $G = (V, \Sigma, P, S)$, *where*

- *V is the finite set of variables,*
- *Σ is a finite set, the alphabet,*

- *P is the finite set of rules and*
- *$S \in V$ is the start variable.*

Note that V relates to the set $\Sigma^P \backslash \Sigma^{*\overline{P}}$, and Σ relates to the set $\Sigma^P \cap \Sigma^{*\overline{P}}$.

We also have to consider that not all grammatical rules can be expressed with contextfree grammars. Therefore Chomsky introduced the level of transformational analysis, but is beyond our scope.

Example 4: Negative Sentences in ASL

We now show an example for a syntactical rule in ASL. We first introduce a notational simplification, that allows us to mark words with a nonmanual sign. For example $\overline{\text{HOUSE}}^{\text{Neg}}$ refers to the negated word HOUSE combined with a head shake.

Definition 14 *For a grammar $G = (V, \Sigma, P, S)$ and a set of marking symbols Σ_{mark} the* grammar with markings $G_M = (V_M, \Sigma_M, P_M, S_M)$ *is defined as follows:*
For all $m \in \Sigma_{mark}$

$$\Sigma_M = \Sigma \cup \{\overset{m}{\overline{u}}\}, \textit{ for all } u \in \Sigma$$

$$V_M = V \cup \{\overset{m}{\overline{u}}\}, \textit{ for all } u \in V$$

$$P_M = (V_M \cup \Sigma_M)^+ \times (V_M \cup \Sigma_M)^*$$

$$S_M \in V_M$$

We use the following abbreviation for better comprehension:

$$\overset{m}{\overline{u_1 \cdots u_n}} := \overset{m}{\overline{u_1}} \cdots \overset{m}{\overline{u_n}} \quad \textit{for } u_k \in (V \cup \Sigma)^*; n \in Nat; 1 \leq k \leq n; m \in \Sigma_{mark}$$

In ASL the following phrases are grammatically correct:

- JOHN $\overline{\text{NOT}}^{\text{Neg}}$ BUY HOUSE (John is *not* buying a house.)
- JOHN $\overline{\text{NOT BUY HOUSE}}^{\text{Neg}}$ (John is not buying a house.)
- JOHN $\overline{\text{BUY HOUSE}}^{\text{Neg}}$ (John is not buying a house.)

But these phrases are incorrect:

- *JOHN NOT BUY HOUSE

· $*\overline{\text{JOHN NOT BUY HOUSE}}^{\text{Neg}}$

We can describe these sentences with a contextfree grammar:

$$
\begin{array}{rcl}
\text{S} & \rightarrow & \text{N VP} \\
\text{VP} & \rightarrow & \text{V N} \\
\text{VP} & \rightarrow & \overline{\text{NEG}}^{\text{Neg}}\ \text{V N} \\
\text{VP} & \rightarrow & \overline{\text{NEG V N}}^{\text{Neg}} \\
\text{VP} & \rightarrow & \overline{\text{V N}}^{\text{Neg}} \\
\text{N} & \rightarrow & \text{JOHN} \mid \text{HOUSE} \\
\text{V} & \rightarrow & \text{BUY} \\
\overline{\text{N}}^{\text{Neg}} & \rightarrow & \overline{\text{JOHN}}^{\text{Neg}} \mid \overline{\text{HOUSE}}^{\text{Neg}} \\
\overline{\text{V}}^{\text{Neg}} & \rightarrow & \overline{\text{BUY}}^{\text{Neg}} \\
\overline{\text{NEG}}^{\text{Neg}} & \rightarrow & \overline{\text{NOT}}^{\text{Neg}}
\end{array}
$$

4. Formal Representation using HPSG

We describe the structure of the Head-driven Phrase Structure Grammar (HPSG) [PS87][SW99][Mat96] and its application for ASL syntax.

4.1 Introducing HPSG

A contextfree grammar (CFG) as described in section 3.5 has two major disadvantages, rules are often massively redundant and the description is arbitrary. We explain these problems and how to deal with them, introducing features, heads and the more complex parts of HPSG.

4.1.1 Features

In example 4 in section 3.5 we had to declare the verbphrase four times and the nouns twice:

$$\mathrm{N} \rightarrow \mathrm{JOHN} \mid \mathrm{HOUSE}$$

$$\overline{\mathrm{N}}^{\mathrm{Neg}} \rightarrow \overline{\mathrm{JOHN}}^{\mathrm{Neg}} \mid \overline{\mathrm{HOUSE}}^{\mathrm{Neg}}$$

This redundancy can not be avoided for any complex grammatical structure. Therefore we introduce *features*. A category is now a complex of grammatical properties, associated with the words. A feature structure can be thought as functions specifying a value for each of a set of functions. For the notation, we use capitalized words and squared brackets:

$$\begin{bmatrix} \mathrm{FEATURE}_1 & \mathrm{VALUE}_1 \\ \vdots & \vdots \\ \mathrm{FEATURE}_n & \mathrm{VALUE}_n \end{bmatrix}$$

The nouns can be enhanced with a feature for negation, this avoids the double declaration. We call the tuple consisting of the word and its features a *lexical entry*. The lexical entries for $\overline{\text{JOHN}}^{\text{Neg}}$ and HOUSE now look as follows:

$$\left\langle \text{JOHN}, \begin{bmatrix} \textit{word} & \\ \text{POS} & \boxed{1}\ \text{noun} \\ \text{NEG} & \text{yes} \end{bmatrix} \right\rangle \left\langle \text{HOUSE}, \begin{bmatrix} \textit{word} & \\ \text{POS} & \boxed{1} \\ \text{NEG} & \text{no} \end{bmatrix} \right\rangle$$

We called the feature structure *word* with the features POS (part of speech) for the wordtype and NEG as a boolean type representing the presence of a negation. The boxed number indicate identical occurances, thus both are nouns.

4.1.2 Heads and Categories

In our example we declared rule (a). Now consider we would change rule (a) to rule (b):

(a) VP $\rightarrow$ V N
(b) VP $\rightarrow$ N S

This is still a correct rule in terms of the CFG formalism, but the the phrase, VP, has an arbitrary name. Of course we want to relate to a verb, if we call the head of a verbphrase VP. In natural language every phrase contains a key property like nounhood, verbhood, etc. with a word of the corresponding syntactical class. This word is called *head*. So the head of (a) is the verb V, (b) does not have a head. Because of the importance of the "headness", we shall capture the properties of the head and transport it to the phrase.

We create a new feature structure called *category*, CAT, that includes the head and the negation feature. The POS feature is not necessary anymore.

$$\begin{bmatrix} \textit{word} & \\ \text{CAT} & \begin{bmatrix} \text{HEAD} & \text{noun} \\ \text{NEG} & \text{yes/no} \end{bmatrix} \end{bmatrix}$$

The headed verbphrase (a) is now given by the following rule, H is the head daughter, while the phrase is the head mother. Both must be unified as stated in the Head Feature Principle.

$$[\textit{phrase}] \rightarrow \text{H} \begin{bmatrix} \textit{word} & \\ \text{CAT} & \begin{bmatrix} \text{HEAD} & \text{verb} \\ \text{NEG} & \text{yes/no} \end{bmatrix} \end{bmatrix} \text{N}$$

Definition 15 (Head Feature Principle HFP) [SW99, p.63] *In any headed phrase, the HEAD value of the mother and the HEAD value of the head daughter must be unified.*

4.2 Basic Syntactical Structures

4.2.1 Subject-Head Rule

Now consider the simple Sign Language sentence JOHN SLEEP. The CFG set of rules is simple:

$$\begin{array}{lll} \text{S} & \rightarrow & \text{N V} \\ \text{N} & \rightarrow & \text{JOHN} \\ \text{V} & \rightarrow & \text{SLEEP} \end{array}$$

The lexical entries are given:

$$\left\langle \text{JOHN}, \begin{bmatrix} \textit{word} & \\ \text{CAT} & \begin{bmatrix} \text{HEAD} & \text{noun} \\ \text{NEG} & \text{no} \end{bmatrix} \end{bmatrix} \right\rangle$$

$$\left\langle \text{SLEEP}, \begin{bmatrix} \textit{word} & \\ \text{CAT} & \begin{bmatrix} \text{HEAD} & \text{verb} \\ \text{SUBJ} & \langle \text{noun} \rangle \\ \text{NEG} & \text{no} \end{bmatrix} \end{bmatrix} \right\rangle$$

Note that the new feature SUBJ describes the subject the verb relates to. By unifying the subject feature of the verb with the head of the noun, the new phrase is generated. Using the feature structure for the noun JOHN and the verb SLEEP and the new feature SUBJ, we can build the structural description tree (see figure 4.1).

The structural description tree consists of the lexical structural description (lexical SD) and the phrasal structural description (phrasal SD).

The lexical SD is a tree diagram with two nodes, the lower node is the first member of the lexical entry tuple, thus JOHN and SLEEP in our example. The upper node consists of the word description, that describes the second member of the lexical entry tuple, or of an extension of the second member, that is, if all or even more information of the second member is present in the extension. In the example the phrase strucure is an extension of the description of the second member of the word tuple.

The mothers and daughters of every local subtree of the phrasal SD include all information of the grammar rule that allows the subtree. Also the subtrees have to unify according to the principles like the HFP. Our example shows the unification of the HEAD values of the phrases and words, the HEAD $\boxed{1}$ of the word must be the value 'noun' while $\boxed{2}$ is unified to 'verb'. The negation is generally unified to 'no'. Note that this allows the phrase JOHN SLEEP but the grammatical correct JOHN $\overset{\text{Neg}}{\overline{\text{SLEEP}}}$ is rejected. To allow this, we change the right-hand branch, see figure 4.2 for details. Now the NEG feature $\boxed{4}$ can be unified to 'no' and 'yes', thus $\overset{\text{Neg}}{\overline{\text{SLEEP}}}$ and SLEEP

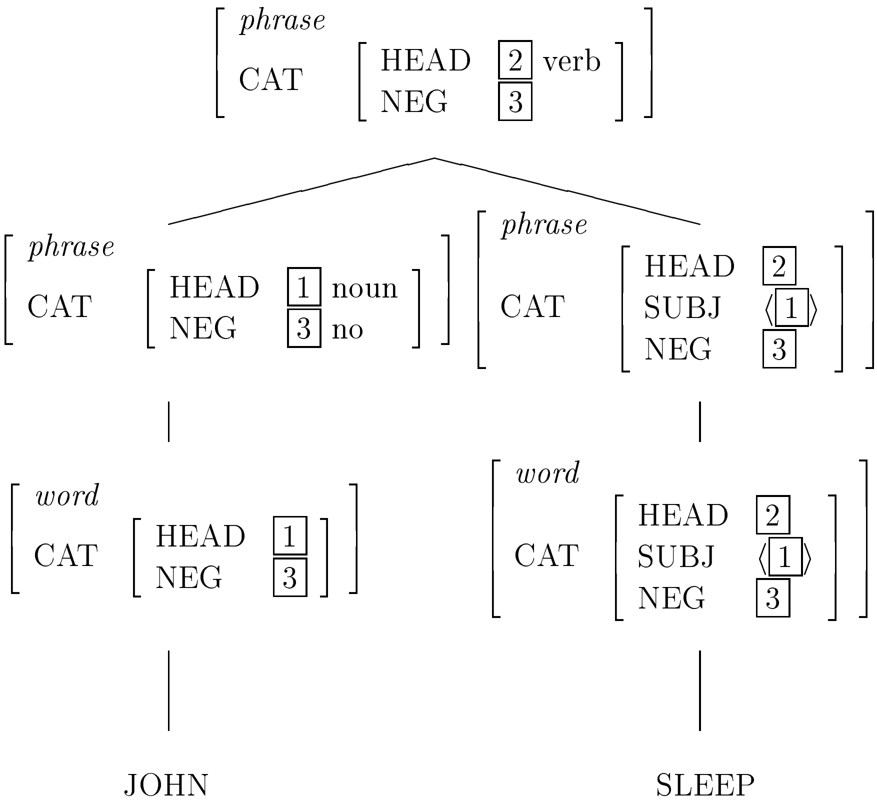


Figure 4.1: The structural description tree for JOHN SLEEP.

are allowed and the entire phrase is negated as well.

4.2.2 Complements Rule

Let us consider the Sign Language sentences showing an intransitive verb without any object (a), a transitive verb with one direkt object (b), and a ditransitive verb with two objects (c). Note that (d) is not possible, the objects are required.

(a) JOHN SLEEP	*(John sleeps)*
(b) JOHN BUY BOOK	*(John buys a book)*
(c) JOHN GIVE SANDY BOOK	*(John gives Sandy a book)*
(d) *JOHN GIVE SANDY	

The corresponding CFG syntactical rules are as expected:

VP $\rightarrow$ V
VP $\rightarrow$ V N
VP $\rightarrow$ V N N

$$\begin{bmatrix} \textit{phrase} & \\ \text{CAT} & \begin{bmatrix} \text{HEAD} & \boxed{2}\ \text{verb} \\ \text{NEG} & \boxed{4} \end{bmatrix} \end{bmatrix}$$

$$|$$

$$\begin{bmatrix} \textit{phrase} & \\ \text{CAT} & \begin{bmatrix} \text{HEAD} & \boxed{2}\ \text{verb} \\ \text{SUBJ} & \langle \boxed{1} \rangle \\ \text{NEG} & \boxed{4} \end{bmatrix} \end{bmatrix}$$

$$|$$

$$\begin{bmatrix} \textit{word} & \\ \text{CAT} & \begin{bmatrix} \text{HEAD} & \boxed{2} \\ \text{SUBJ} & \langle \boxed{1} \rangle \\ \text{NEG} & \boxed{4} \end{bmatrix} \end{bmatrix}$$

$$|$$

$$\text{SLEEP} \mid \overline{\text{SLEEP}}^{\text{Neg}}$$

Figure 4.2: The negation of the verb is unified with its mother, but not the noun.

For HPSG we introduce the *head-complement rule* by adding the new feature complements COMPS to the category structure CAT.

$$\begin{bmatrix} \textit{phrase} & \\ \text{CAT} & [\text{COMPS}\ \langle\rangle] \end{bmatrix} \rightarrow \text{H} \begin{bmatrix} \textit{word} & \\ \text{CAT} & \left[\text{COMPS}\ \left\langle \boxed{1}, \ldots, \boxed{n} \right\rangle\right] \end{bmatrix} \boxed{1} \cdots \boxed{n}$$

Thus, in the lexical entry of a verb, the number of complements must be specified. These are then unified with the complements themself. Note that the phrase never has components, so in the mother the COMPS feature must stay empty. Figure 4.3 explains the verb phrase GIVE SANDY BOOK with the structural description tree.

4.3 Semantics

For adding meaning to words and phrases, we introduce the new feature CONT for content. In the general structure CONT and CAT are combined to the feature LOC (for local) that is explained in the next section.

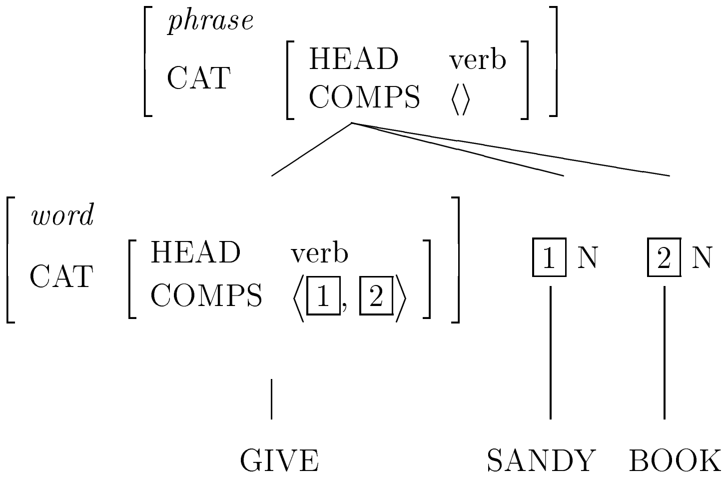


Figure 4.3: The structural description tree explaining the COMPS feature.

$$\begin{bmatrix} \textit{word/phrase} & \\ \text{LOC} & \begin{bmatrix} \text{CAT} & \text{category} \\ \text{CONT} & \text{content} \end{bmatrix} \end{bmatrix}$$

4.3.1 Noun Semantics

To give nouns a grammatical meaning, the two features INDEX and RESTR are used.

The index INDEX takes an unlimited number of atomic values representing references, expressed with lower-case letters. The example (taken from [Mat96, p. 93]) illustrates the usage.

The man likes the book.	INDEX $\boxed{a}$ $\boxed{b}$ likes($\boxed{a}$, $\boxed{b}$)
He often reads them.	often(reads($\boxed{a}$, $\boxed{b}$))

The restrictions RESTR specify the lexical meaning. They tell us, what properties distinguishes a book from other objects. A restriction contains a nucleus NUC with the core properties for the description.

The properties of common nouns are atomic. Hence we use the feature INSTANCE to bind the property to the index of the noun.

The lexical entry for the common noun BOOK gives an example:

$$\left\langle \text{BOOK}, \begin{bmatrix} \textit{word} \\ \text{LOC} \begin{bmatrix} \text{CAT} \begin{bmatrix} \text{HEAD} & \text{noun} \\ \text{NEG} & \text{no} \end{bmatrix} \\ \text{CONT} \begin{bmatrix} \text{INDEX} & \boxed{\text{a}} \\ \text{RESTR} & \left\langle \begin{bmatrix} \text{NUC} \begin{bmatrix} \text{BOOK} \\ \text{INSTANCE}\ \boxed{\text{a}} \end{bmatrix} \end{bmatrix} \right\rangle \end{bmatrix} \end{bmatrix} \end{bmatrix} \right\rangle$$

A proper noun does not have any restrictions, so JOHN is represented as follows:

$$\left\langle \text{JOHN}, \begin{bmatrix} \textit{word} \\ \text{LOC} \begin{bmatrix} \text{CAT} \begin{bmatrix} \text{HEAD} & \text{noun} \\ \text{NEG} & \text{no} \end{bmatrix} \\ \text{CONT} \begin{bmatrix} \text{INDEX} & \boxed{\text{a}} \\ \text{RESTR} & \langle\rangle \end{bmatrix} \end{bmatrix} \end{bmatrix} \right\rangle$$

4.3.2 Verb Semantics

The lexical entries use the indices for the subject and complements, and for the semantic relations as well. For example look at the sentence:

HE LIKE BOOK *(He likes the book.)*

LIKE refers to the subject HE, that we call LIKER, and to the object BOOK, called LIKEE. The lexical entry for LIKE with all features:

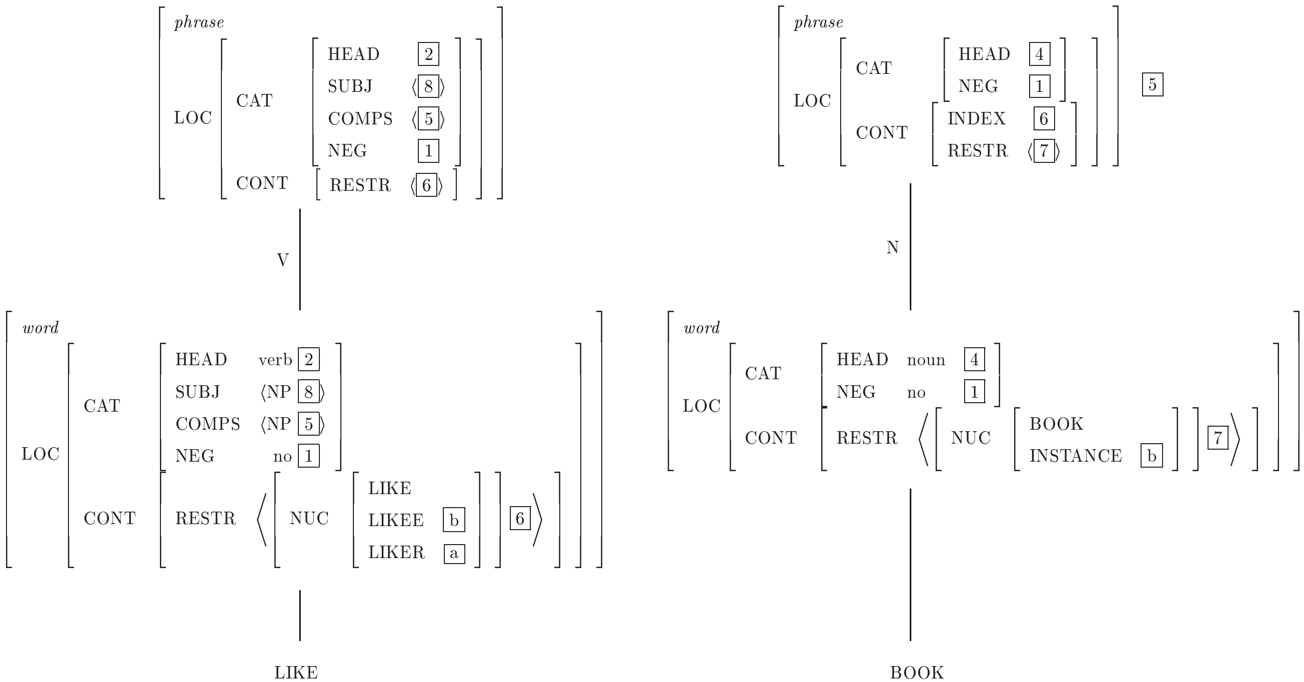
$$\left\langle \text{LIKE}, \begin{bmatrix} \textit{word} \\ \text{LOC} \begin{bmatrix} \text{CAT} \begin{bmatrix} \text{HEAD} & \text{verb} \\ \text{SUBJ} & \langle \text{NP}\ \boxed{1} \rangle \\ \text{COMPS} & \langle \text{NP}\ \boxed{2} \rangle \\ \text{NEG} & \text{no} \end{bmatrix} \\ \text{CONT} \begin{bmatrix} \text{RESTR} \left\langle \begin{bmatrix} \text{NUC} \begin{bmatrix} \text{LIKE} \\ \text{LIKER}\ \boxed{1} \\ \text{LIKEE}\ \boxed{2} \end{bmatrix} \end{bmatrix} \right\rangle \end{bmatrix} \end{bmatrix} \end{bmatrix} \right\rangle$$

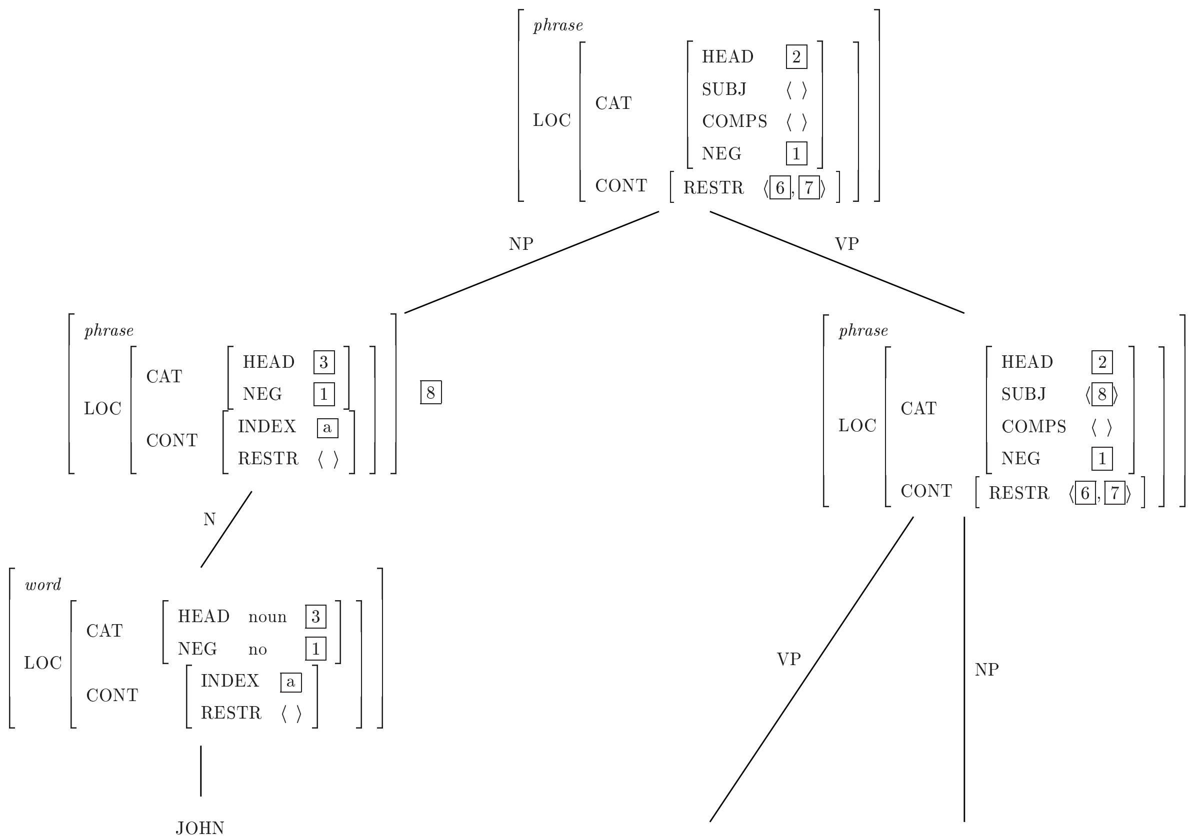
4.3.3 The Semantic Principle

The semantic principle unifies the content of a mother with the head daughter's content.

Definition 16 (Semantic Principle) *In any headed phrase, the CONT value of the mother and the CONT value of the head daughter must be unified.*

The diagram shows the structural description tree for the sentence JOHN LIKE BOOK *(John likes the book).* Note the unification of the content, especially the restrictions.


phrase
LOC
CAT
HEAD 2
SUBJ ⟨8⟩
COMPS ⟨5⟩
NEG 1
CONT
RESTR ⟨6⟩
V
word
LOC
CAT
HEAD verb 2
SUBJ ⟨NP 8⟩
COMPS ⟨NP 5⟩
NEG no 1
CONT
RESTR
NUC
LIKE
LIKEE b
LIKER a
6
LIKE
phrase
LOC
CAT
HEAD 4
NEG 1
CONT
INDEX 6
RESTR ⟨7⟩
5
N
word
LOC
CAT
HEAD noun 4
NEG no 1
CONT
RESTR
NUC
BOOK
INSTANCE b
7
BOOK


phrase
LOC
CAT
HEAD 2
SUBJ ⟨ ⟩
COMPS ⟨ ⟩
NEG 1
CONT
RESTR ⟨6, 7⟩
NP
VP
phrase
LOC
CAT
HEAD 3
NEG 1
CONT
INDEX a
RESTR ⟨ ⟩
8
phrase
LOC
CAT
HEAD 2
SUBJ ⟨8⟩
COMPS ⟨ ⟩
NEG 1
CONT
RESTR ⟨6, 7⟩
N
word
LOC
CAT
HEAD noun 3
NEG no 1
CONT
INDEX a
RESTR ⟨ ⟩
JOHN
VP
NP

4.4 Lexical Entries

4.4.1 Phonology

To complete our lexical entries with all major features, we also have to consider the phonology of the words and phrases. Therefore the PHON feature is used. For a word, the list of the segments and their physical properties can be used, when relating to a segmental phonological model. But also a Stokoe-based model like HamNoSys can be implemented by supplying a list of the phonemes. An example for a PHON feature using the Movement-Hold Model could look like this:

$$\begin{aligned}\text{PHON } \langle & [\text{HOLD, } \textit{handshape, location, } \ldots\textit{, non-manual signs}]\,, \\ & [\text{MOVEMENT, } \textit{movement contour, } \ldots]\,, \cdots \rangle\end{aligned}$$

For the phrase, all PHON features of the underlying words are combined.

Definition 17 (Phonological Principle) *In any well-formed phrase structure, the mother's PHON value is the sum of the PHON values of the daughters.*

4.4.2 General Architecture

As mentioned in the last section, we still have to motivate the introduction of the local feature LOC. Look at the following two questions (the wh-marking expresses the non-manual sign for wh-questions, like WHAT, WHO, WHY, etc.):

(a) $\overline{\text{JOHN GIVE SANDY WHAT?}}^{\text{wh}}$ *(What is John giving to Sandy?)*

(b) $\overline{\text{*JOHN GIVE BOOKS SANDY WHAT?}}^{\text{wh}}$ *(*What is John giving books to Sandy?)*

Obviously question (a) is missing a noun phrase, but it is still a correct sentence. Even worse, question (b), with the noun phrase included, is wrong. To handle these so-called long-distance dependencies, the NONLOCAL feature is needed. It builds a dependency tree, and it is a replacement for Chomskys transformational analysis (see chapter 3.5). For more detailed information on long-distance dependencies, please refer to the literature [Mat96][SW99].

In the complete architecture the local and the non-local features are combinded to the overall SYNSEM feature. The identifier *sign* represents *word* and *phrase* combined and is not to be confused with the Sign Language signs.

$$\begin{bmatrix} \textit{sign} & \\ \text{PHON} & \langle \ldots \rangle \\ \text{SYNSEM} & \begin{bmatrix} \text{LOC} & \begin{bmatrix} \text{CAT} & \text{category} \\ \text{CONT} & \text{content} \end{bmatrix} \\ \text{NONLOCAL} & \text{non-local} \end{bmatrix} \end{bmatrix}$$

4.4.3 Lexical Rules

To reduce further redundancy in the lexicon, lexical rules are used to derive lexical entries from the basic lexical entries, called the *lexemes*.

Definition 18 [SW99, p. 185] *A lexical rule $X \Rightarrow Y$ produces the lexical entry Y from the lexeme X by copying all features, with the exceptions:*

- *If a feature F has different values in X and Y, then the input and output entries have different values for F.*
- *A value v for a feature F in X, that is not specified for F in Y, is applied for F in Y.*
- *A value v for a feature F in Y, that is not specified for F in X, then the input value for F in X is unified with v.*

As an example, we produce negated lexical entries from our lexemes without negation. Already negated lexemes like $\overset{\text{Neg}}{\overline{\text{NOT}}}$ should be ignored.

$\text{HOUSE} \Rightarrow \overset{\text{Neg}}{\overline{\text{HOUSE}}}$
$\text{SLEEP} \Rightarrow \overset{\text{Neg}}{\overline{\text{SLEEP}}}$
$^{*}\overset{\text{Neg}}{\overline{\text{NOT}}} \Rightarrow \overset{\text{Neg}}{\overline{\overset{\text{Neg}}{\overline{\text{NOT}}}}}$

The lexical rule for this generation copies all features except for the negation NEG.

$$\left\langle \boxed{1}, \begin{bmatrix} \textit{word-lexeme} \\ \text{LOC}\,[\text{CAT}\,[\text{NEG no}]] \end{bmatrix} \right\rangle \Rightarrow \left\langle \boxed{1}, \begin{bmatrix} \textit{word} \\ \text{LOC}\,[\text{CAT}\,[\text{NEG yes}]] \end{bmatrix} \right\rangle$$

4.5 HPSG in Context

HPSG is not the only grammar framework available today. Our choice was HPSG because of it's high popularity and the availability of the implementation system ALE. Other structures are also suitable, like the following:

4.5.1 Transformational Grammar

Chomskys transformational grammar ([Cho75]) is able to handle complex syntactic constructions by first building a tree with normal contextfree grammar and then transform it into different trees. For example, an English passive sentence is derived from the active part by tree transformation.

4.5.2 The Standard Theory

Based upon the tranformational grammar by Chomsky, Katz and Postal ([KP64]) improved it by allowing the use of recursive phrase structure rules and, more important, adding semantic components. The initial tree in the derivation of the sentence represents all necessary information while the words and phrases are located on the final tree.

4.5.3 Lexical Functional Grammar

The Lexical Functional Grammar (LFG) ([Bre82]) uses tree structures and relational concepts. The two main features are the functional structure, used mainly for agreement, and the constituent structure, which is similar to the final tree in the Standard Theory. LFG does not use transformations. Speers ([dLS02]) uses the LFG framework for his Sign Language representation.

5. Conclusion

In this work, we presented a formal framework for Sign Language. We discuss now, what has been done and what work lies ahead for the future.

First we had a view on the linguistic theory of Sign Language and on current topics of Sign Language research. We discussed several phonological models in general and the Movement-Hold Model in detail. The small lexicon of signs in South African Sign Language revealed how the Movement-Hold Model works. The morphology of American Sign Language was introduced too.

Using our knowledge of the linguistic levels, we were able to investigate how Chomskys logical structure for linguistic theory applies for Sign Language. An example about syllable construction in American Sign Language was shown and contextfree grammars were introduced.

The problems with the redundant rules and arbitrary names of contextfree grammars motivated the usage of a modern grammar architecture, HPSG. We introduced heads and features, syntactical and semantical rules and lexical entries and implemented them using the Prolog-based system ALE. Finally more complex rules were shown and other grammar systems were considered.

Using this gained experience for computational methods, we are now able to implement customized grammar fragments, complete with the corresponding phonological basis. This allows translation, analysation and presentation of Sign Language with the computer as utility.

For the translation to or from Sign Language, the grammar is needed to build correct sentences. Several existing tools can be used as a parser for the spoken language or to construct translation trees. These can be linked to our Sign Language grammar in HPSG. Note that first the linguistic research for the targeted Sign Language must be done. Investigations on the morphology and syntax are necessary, and a lexicon containing the essential vocabulary needs to be assembled. Deaf people should be involved during the planing and implementation of the project, not only as a reference and for testing. They should be consulted for finding the right goals of such a project.

Technically, the grammar should be enhanced. The very complex morphology of American Sign Language but also the syntax needs more consideration. Long-distance dependencies should be implemented and more features supplied.

Such a grammar would allow the linguist to analyse the common and different aspects of Sign Languages in depth. Translation systems for two Sign Languages would help to understand the historical and cognitive development of Sign Language and how it fits into the universal grammar system.

Finally a presentation system is needed for Sign Language output. Our framework, based on the Movement-Hold Model, but flexible enough for any other model as well, supplies all necessary data needed for the correct visualization. This should be an avatar system, capable to show all handshapes, movements and non-manual signs.

Looking ahead, we hope that better equipment, deeper understanding and more basic research on Sign Language improves the quality of life for the people of the Deaf community. In return, we shall learn more about a very wonderful language, Sign Language.

A. The Movement-Hold Model

The features of the Movement-Hold Model introduced by Liddell are described according to the Lexicon Maintenance Tool by Speers.

The features are divided into the segmental bundle, the strong hand (H_1), the weak hand (H_2) and the non-manual features. Structure building features give additional information.

The possible parameters of the various features in detail:

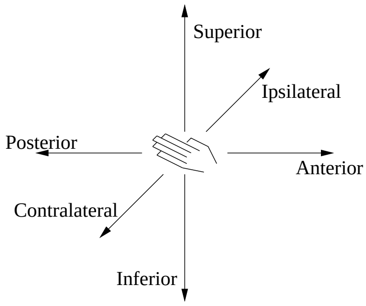
Segmental Bundle

The mobile timing unit determines, whether the segment is a movement (M, D) or a hold (H, X). Note, that the movement units (M, D) only have the segmental bundle tier.

Timing Unit		
`M`	Move	mobile timing unit [-Fixed, -Durable], also needs a contour.
`D`	Move	mobile, durable timing unit [-Fixed,+Durable]
`H`	Hold	[+Fixed, +Durable]
`X`	Hold	non-mobile, non-durable timing unit [+Fixed,-Durable]

The contour of a movement can be straight, arc-like or a local movement without a path. The properties of the arc have to be specified in detail, while the local movement is a feature itself.

Contour	
`Straight`	[+Direct,-Arc] Straight movement
`Arc`	[-Direct,+Arc] Arc-shaped movement
`Non-path`	[-Direct,-Arc] Local movement



Arc Contour	
`[+Superior]`	Upwards
`[-Superior]`	Downwards
`[+Anterior]`	Forwards
`[-Anterior]`	Backwards
`[+Ipsilateral]`	To the ipsilateral side
`[-Ipsilateral]`	To the contralateral side

If a contact occurs on a segment, touch is used.

Touch	
`[+Touch]`	A contact occured

If a segment is significantly shorter or longer, temporal quality is used.

Temporal Quality	
`Sustained`	Longer duration
`Clipped`	Shorter duration

Similar, if a segment has enlarged or reduced movement, movement quality applies.

Movement Quality	
`Enlarged`	Enlarged movement
`Reduced`	Reduced movement

Several local movements are possible. See section 3.2 for syllables construction in ASL based on the investigation of local movement in the Moraic Model.

Local Movement	
`Oscillating`	Further information required
`Zig`	Zig-zag movement
`Circle`	Circular movement
`Progressive`	Progressive handshape change
`Wiggle`	Wiggling movement

Oscillating Movement	
`[hc]`	Oscillating handshapes
`[rot]`	Oscillating rotations (orientations)
`[spat]`	Oscillating locations

Strong/Weak Hand Features

The features of the configuration, placement and pointing of the hand can be applied to both the strong (dominant) and to the weak (non-dominant) hand.

The hand configuration is computed with the help of a hand configuration calculator. Note that if the forearm is included, then the rotation features for the wrist apply to the whole forearm. Metacarpal exclusion instead means the exclusion of changing the wrist. The following features are to be considered:

Hand Configuration	
Fingers to select	Index, Middle, Ring and Pinky
Finger extension	Open, Flat, Hooked or Closed, Rounded optional
Finger interaction	Radial Stacking, Ulnar Stacking, Crossed and Spread
Thumb configuration	Unopposed, Opposed, Beneath, Lateral or Neutral
Thumb extension	Open, Flat, Hooked or Closed
Thumb contact	Contact, Under Contact or none
Forearm included	yes or no
Metacarpal exclusion	yes or no

For the placement the hand site, the spatial relations and the focal site are important.

Figure A.1 shows the possible hand sites.

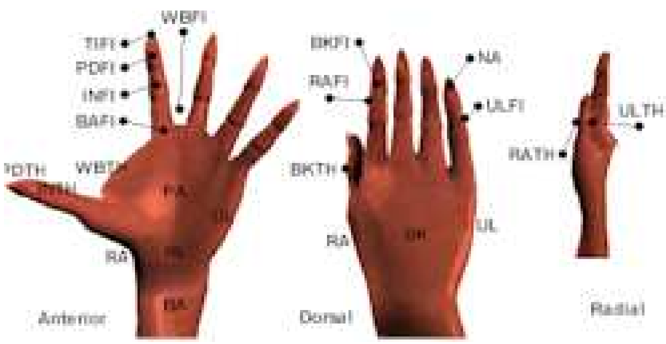


Figure A.1: Possible hand sites (taken from the Lexicon Maintenance Tool)

The spatial relations define the relation to the focal site.

Spatial Relations	
[at]	At a locus
[contra]	Contralateral removal from a [-Manual] locus
[ipsi]	Ipsilateral removal from a [-Manual] locus
[ant]	Anterior removal from a [-Manual] locus
[post]	Posterior removal from a [-Manual] locus
[sup]	Superior removal from a [-Manual] locus
[inf]	Inferior removal from a [-Manual] locus
PA->	Removed in the direction of the palm
BK->	Removed in the direction of the back of the hand
BA->	Removed in the direction of the base of the hand
TI->	Removed in the direction of the tip
RA->	Removed in the direction radial side
UL->	Removed in the direction ulnar side

The focal site informs about the place in space, at the body, at the head or on the hand, where the sign is to be articulated. The position can be either given by its spatial coordinates including the height or by the name of the bodypart. Figure A.2 shows the possible head and body locations, figure A.1 the possible hand locations and the following tables the spatial coordinates.

Spatial Coordinates			
Medial	0	1	2
Proximal	0	1	2

Height	
FH	Forehead
NK	Neck
ST	Sternum
CH	Chest
AB	Abdomen
	Unspecified

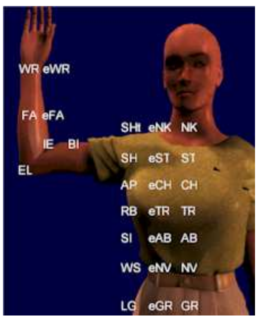


Figure A.2: Head and body locations (taken from the Lexicon Maintenance Tool)

To determine, where the hand is facing to, the already mentioned hand site features are used. Furthermore the spatial relations now state if the hand is pointing to a plane or are near a plane. For example within the sign SIGN, both hands are near the midline plane.

Spatial Relations	
	Unspecified
`Points`	Points to a plane
`Near`	Near a plane

The focal site gives a selection of possible plains.

Focal Site	
`[HP]`	Horizontal Plane
`[VP]`	Vertical Plane
`[SP]`	Surface Plane
`[MP]`	Midline Plane
`[OP]`	Oblique Plane

The rotation of the hand is given by the listed properties. Figure A.3 explains the terms pronated and supinated.

Rotation
Unspecified
Pronated
Neutral
Supinated
Hyper-pronated

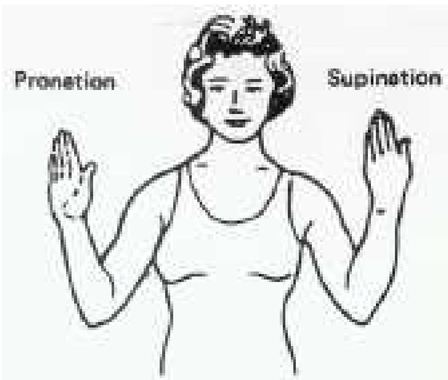


Figure A.3: Pronation and supination (taken from [Bre98])

The flexion and abduction of the wrist also have to be specified. Note that if the feature “Forearm included” in the hand configuration is selected, the wrist properties apply for the whole forearm. Figure A.4 explains the use of these features.

Wrist Flexion
Wrist Flexed
Wrist Extended
Wrist Flexion Neutral

Wrist Abduction
Wrist Abducted
Wrist Adducted
Wrist Abduction Neutral

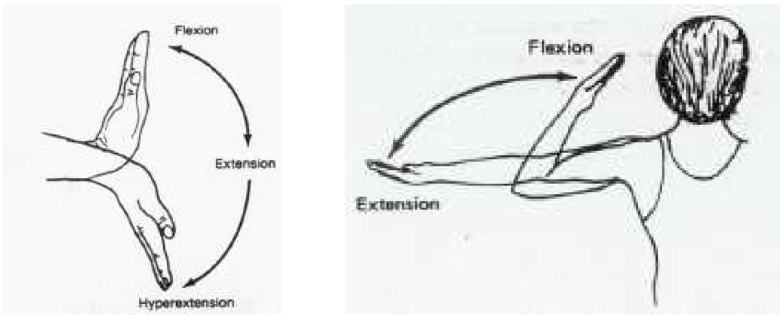


Figure A.4: Flexion and extension of the wrist and forearm (taken from [Bre98])

The non-manual signs (NMS) are an integral part of Sign Language. A sign articulated without its facial expression might not be understood. We give a small (incomplete) list:

Non-Manual Signs
Aspiration
Lip press
Mouth open
Nod
Pucker
Shake head
Suck

The structure building features give further insight about the nature of a sign. They are applied to the given segments.

Structure Building Features	
Alternating Dominance	+/−
Bidirectional	+/−
Reduplicated	+/−
Symmetrical	+/−
Reciprocal	+/−

B. SASL Lexicon

Overview of all included signs:

I
I-NOT-UNDERSTAND
I-UNDERSTAND
MY
NAME
NIGHT
SIGN
UNDERSTAND
WORK
YES
YESTERDAY

I

Segmental Bundle	Timing Unit	H	M	H
	Contour/Flow		[str]	
	Touch			[touch]
	T-Quality			
	M-Quality			
	Local Move't			
Strong Placement	Hand Config	n-1+		
	Hand Site	TIFI		
	Sprel	[ant]		[at]
	Focal Site	ST		
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[sup]/Flx		
Weak Placement	Hand Config			
	Hand Site			
	Sprel			
	Focal Site			
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation			
NMS	NMS			

Structure Building Features	
Alternating Dominance	–
Bidirectional	–
Reduplicated	–
Symmetrical	–
Reciprocal	–

I-NOT-UNDERSTAND

Segmental Bundle	Timing Unit	H	M	H
	Contour/Flow		[str]	
	Touch	[touch]		
	T-Quality			
	M-Quality			
	Local Move't		[prog]	
Strong Placement	Hand Config	n-1234-		n-1+
	Hand Site	BAFI		
	Sprel	[at]		BK->
	Focal Site	TM		p2FH
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[neut]		
Weak Placement	Hand Config			
	Hand Site			
	Sprel			
	Focal Site			
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation			
NMS	NMS			Head Shake

Structure Building Features	
Alternating Dominance	–
Bidirectional	–
Reduplicated	–
Symmetrical	–
Reciprocal	–

Comments: See also I-UNDERSTAND and UNDERSTAND.

I-UNDERSTAND

Segmental Bundle	Timing Unit	H	M	H
	Contour/Flow		[str]	
	Touch	[touch]		
	T-Quality			
	M-Quality			
	Local Move't		[prog]	
Strong Placement	Hand Config	n-1234-		n-1+
	Hand Site	BAFI		
	Sprel	[at]		BK->
	Focal Site	TM		p2FH
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[neut]		
Weak Placement	Hand Config			
	Hand Site			
	Sprel			
	Focal Site			
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation			
NMS	NMS			Nod

Structure Building Features	
Alternating Dominance	–
Bidirectional	–
Reduplicated	–
Symmetrical	–
Reciprocal	–

Comments: See also I-NOT-UNDERSTAND and UNDERSTAND.

MY

Segmental Bundle	Timing Unit	H	M	H
	Contour/Flow		[str]	
	Touch			[touch]
	T-Quality			
	M-Quality			
	Local Move't			
Strong Placement	Hand Config	n-1234-		
	Hand Site	PA		
	Sprel	[ant]		[at]
	Focal Site	ST		
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[neut]		
Weak Placement	Hand Config			
	Hand Site			
	Sprel			
	Focal Site			
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation			
NMS	NMS			

Structure Building Features	
Alternating Dominance	–
Bidirectional	–
Reduplicated	–
Symmetrical	–
Reciprocal	–

NAME

Segmental Bundle	Timing Unit	H	M	H
	Contour/Flow		[str]	
	Touch	[touch]	[touch]	
	T-Quality			
	M-Quality			
	Local Move't		[prog]	
Strong Placement	Hand Config	o^1^		o^c1^
	Hand Site	RAFI		
	Sprel	[at]		BK->
	Focal Site	LP		
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[neut]		
Weak Placement	Hand Config			
	Hand Site			
	Sprel			
	Focal Site			
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation			
NMS	NMS			

Structure Building Features	
Alternating Dominance	–
Bidirectional	–
Reduplicated	–
Symmetrical	–
Reciprocal	–

NIGHT

Segmental Bundle	Timing Unit	H	M	H
	Contour/Flow		[arc]/[-ipsi]	
	Touch			
	T-Quality			
	M-Quality			
	Local Move't			
Strong Placement	Hand Config	/n-1+		
	Hand Site	HAND		
	Sprel	RA->		[at]
	Focal Site	mOCH		
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[pro]/AbdN		Add
Weak Placement	Hand Config			
	Hand Site			
	Sprel			
	Focal Site			
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation			
NMS	NMS			

Structure Building Features	
Alternating Dominance	−
Bidirectional	−
Reduplicated	−
Symmetrical	+
Reciprocal	−

Comments: Due to the feature “Symmetrical”, the information for the weak hand is not needed.

SIGN

Segmental Bundle	Timing Unit	H	M	X	M	H
	Contour/Flow		[arc]/[+ant]		[arc]/[-ant]	
	Touch					
	T-Quality					
	M-Quality					
	Local Move't					
Strong Placement	Hand Config	n+1234v+				
	Hand Site	HAND				
	Sprel	[sup]		[inf]		[sup]
	Focal Site	m1CH				
Facing	Hand Site	PA				
	Sprel	[near]				
	Focal Site	MP				
Rotation	Rotation	[neut]/Ext				
Weak Placement	Hand Config					
	Hand Site					
	Sprel					
	Focal Site					
Facing	Hand Site					
	Sprel					
	Focal Site					
Rotation	Rotation					
NMS	NMS					

Structure Building Features	
Alternating Dominance	−
Bidirectional	−
Reduplicated	+
Symmetrical	+
Reciprocal	+

Comments: Due to the feature “Symmetrical”, the information for the weak hand is not needed.

UNDERSTAND

Segmental Bundle	Timing Unit	H	M	H
	Contour/Flow		[-path]	
	Touch	[touch]	[touch]	[touch]
	T-Quality			
	M-Quality			
	Local Move't		[osc]/[hc]	
Strong Placement	Hand Config	n-1234-		n-1+
	Hand Site	BAFI		
	Sprel	[at]		
	Focal Site	TM		
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[neut]		
Weak Placement	Hand Config			
	Hand Site			
	Sprel			
	Focal Site			
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation			
NMS	NMS			

Structure Building Features	
Alternating Dominance	−
Bidirectional	−
Reduplicated	+
Symmetrical	−
Reciprocal	−

Comments: See also I-NOT-UNDERSTAND and I-UNDERSTAND.

WORK

Segmental Bundle	Timing Unit	H	M	H
	Contour/Flow		[str]	
	Touch	[touch]		
	T-Quality			
	M-Quality			
	Local Move't			
Strong Placement	Hand Config	/n+1234+		
	Hand Site	UL		
	Sprel	[at]		RA->
	Focal Site	m1CH		m1ST
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[neut]/Add		
Weak Placement	Hand Config	/n+1234+		
	Hand Site	RAFI		
	Sprel	[at]		
	Focal Site	m1CH		
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[neut]/Add		
NMS	NMS			

Structure Building Features	
Alternating Dominance	−
Bidirectional	−
Reduplicated	+
Symmetrical	−
Reciprocal	−

YES

Segmental Bundle	Timing Unit	X	M	X
	Contour/Flow		[-path]	
	Touch			
	T-Quality			
	M-Quality			
	Local Move't		[osc]/[rot]	
Strong Placement	Hand Config	n-1234-		
	Hand Site	HAND		
	Sprel	[at]		
	Focal Site	m1ST		
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[pro]/FlxN		Flx
Weak Placement	Hand Config			
	Hand Site			
	Sprel			
	Focal Site			
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation			
NMS	NMS			

Structure Building Features	
Alternating Dominance	–
Bidirectional	–
Reduplicated	–
Symmetrical	–
Reciprocal	–

YESTERDAY

Segmental Bundle	Timing Unit	H	M	H
	Contour/Flow		[str]	
	Touch			
	T-Quality			
	M-Quality			
	Local Move't			
Strong Placement	Hand Config	/n+1234-		
	Hand Site	HAND		
	Sprel	[at]		RA->
	Focal Site	m2ST		
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation	[neut]/FlxN		Flx
Weak Placement	Hand Config			
	Hand Site			
	Sprel			
	Focal Site			
Facing	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rotation			
NMS	NMS			

Structure Building Features	
Alternating Dominance	–
Bidirectional	–
Reduplicated	–
Symmetrical	–
Reciprocal	–

C. Implementation in ALE

Our grammar fragment was implemented in ALE ([Mat96]), a grammar system based on Prolog. ALE supports all features and structures of HPSG.

We show parts of our program, the type hierarchy is given first, then the lexical entries, the lexical rules, the syntactical rules and finally the principles.

The Type Hierarchy

As a reminder, the general type hierarchy looks like this:

$$\begin{bmatrix} \textit{sign} & \\ \text{PHON} & \langle \ldots \rangle \\ \text{SYNSEM} & \begin{bmatrix} \text{LOC} \begin{bmatrix} \text{CAT} & \text{category} \\ \text{CONT} & \text{content} \end{bmatrix} \\ \text{NONLOCAL} \quad \text{non-local} \end{bmatrix} \end{bmatrix}$$

Let us introduce the type hierarchy. In ALE all features belong to the type `bot`.

```
bot sub [sign, synsem, loc, non_loc, cat, cont,
         head, list, features, boolean, neg, ind].
```

The feature SIGN holds the phonology as a list and the SYNSEM part.

```
sign sub []
    intro [phon:list,
           synsem:synsem].
```

All syntactical subfeatures of SYNSEM and a boolean type are introduced:

```
synsem sub []
    intro [loc:loc,
           non_loc:non_loc].

non_loc sub [].

loc sub []
    intro [cat:cat,
           cont:cont].

cat sub []
    intro [head:head,
   subj:list,
   comps:list,
   neg:boolean].

head sub [noun, verb].

  noun sub [].
  verb sub [].

boolean sub [yes, no].

  yes sub [].
  no sub [].
```

The type hierarchy for the CONT feature is slightly more complex than introduced because of the feature PSOA (state of affairs), following the suggestions of the book.

```
% --------------  Semantic types

cont sub []
     intro [index:ind,
  restr:set_psoa].

% ---------------------- nom_obj

nom_obj sub []
```

```
        intro [index:ind,
               restr:set_psoa].

%  ----------------------- ind

ind sub [].

% ----------------------- psoa

psoa sub []
     intro [nucleus: qfpsoa].

%----------- qfpsoa def taken from hpsg.pl in ALE

qfpsoa sub [property,un_relation, bin_relation, tri_relation].

property sub [book]
   intro [instance:ref].
      book sub [].

un_relation sub [snore].

snore sub []
   intro [snorer:ref].

bin_relation sub [like].

like sub []
   intro [liker:ref,
          likee:ref].

tri_relation sub [give].

give sub []
  intro [giver:ref,
         givee:ref,
         gift:ref].
```

The phonological features do not need a complex hierarchy. This list is not complete, it just shows the idea.

```
features sub [move, hold, one_o_minus, rafi, prox, ipsi,
```

```
      contra, non_manual_negation].

  move sub [].
  hold sub [].
  one_o_minus sub [].
  rafi sub [].
  prox sub [].
  ipsi sub [].
  contra sub [].
  non_manual_negation sub [].
```

The Lexical Entries

Some lexical entries are shown here. The phonological list is not provided. Note the `@np`, it refers to a macro containing the features for the noun phrase category.

```
%% ---- Proper Nouns

john ---> phon:[],
  @np,
  synsem:loc:cat:neg:no.

%% ---- Nouns

house ---> phon:[],
   @np,
   synsem:loc:cat:neg:no.

dog ---> phon:[],
 @np,
 synsem:loc:cat:neg:no.

%% ---- Verbs

buy ---> phon:[],
 synsem:loc:cat:(head:verb,
 subj:[@np],
 comps:[@np],
 neg:no).
```

```
sleep ---> phon:[],
   synsem:loc:cat:(head:verb,
   subj:[@np],
   comps:[],
   neg:no).
```

Lexical Rules

Our lexical rule for the negation has a **> standing for the ⇒ relation. All features stay, except for the NEG feature. Note also that the NON-MANUAL-NEGATION feature is added to the phonological list. The `neg_` string is added to the name of the lexical entry, so `john` becomes `neg_john` representing the marking.

```
negate lex_rule
    (phon:Phon,
     synsem:loc:cat:(head:Head,
     subj:Subj,
     comps:Comps,
     neg:no))
  **>
    (phon:[Phon,non_manual_negation],
     synsem:loc:cat:(head:Head,
     subj:Subj,
     comps:Comps,
     neg:yes))
  morphs
    X becomes (neg_,X).
```

Syntactical Rules

This is the subject-head rule. The SUBJ is unified with the entry of the subject-daughter SubjDtr. The goals are the principles, that are the unification of the head of the mother and it's daughter and the concatenation of the phonological features.

```
subject_head rule
(Mother, phon:ConcatPhon, synsem:loc:cat:(subj:[],
  comps:[],
  neg:no))
```

```
===>
cat> (SubjDtr, phon:Phonem1, synsem:loc:cat:neg:no),
cat> (HeadDtr, synsem:loc:cat:(subj:[SubjDtr],
       comps:[],
       neg:_),
      phon:Phonem2),
goal> (head_feature_principle(Mother, HeadDtr),
      append(Phonem1, Phonem2, ConcatPhon)).
```

Principles

These are the above mentioned principles. Only if the two parameters of the head-feature principle can be unified, is the principle true. The append principle concatenates two features to a list and returns true.

```
head_feature_principle(synsem:loc:cat:head:Head,
       synsem:loc:cat:head:Head) if true.

append([],Xs,Xs) if
    true.
append([H|T1],L2,[H|T2]) if
    append(T1,L2,T2).
```

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