FINITE-STATE SIGN LANGUAGE MORPHOPHONOLOGY

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ABSTRACT

FINITE-STATE SIGN LANGUAGE MORPHOPHONOLOGY

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The aim of this thesis is to investigate the computational power required for processing sign language morphophonology. This dissertation focuses on the objective of reducing autosegmental representations and rules defined by three sign language phonology models, namely, Movement-Hold Model (Liddell & Johnson, 1989), Hand-Tier Model (Sandler, 1989, 1990), and Prosodic Model (Brentari, 1998), to finite state machinery. By adopting Autosegmental Phonology framework (Goldsmith, 1976), these models are capable of dealing with both simultaneity and sequentiality observed in sign language phonology and morphology. We suggest algorithms for transforming the autosegmental representations and rules constructed within these three models into state labeled automata of One-Level Phonology (Bird & Ellison, 1994). State labeled automata are known to have regular language power. By this reduction, non-linear representations of sign languages are shown to be serializable.

Keywords: sign language morphophonology, computational phonology, One-Level Phonology, Autosegmental Phonology, simultaneity

ÖZ

SONLU-DURUMLU BİÇİMSEL İŞARETBİRİM BİLİMİ

SEVİNÇ, AYÇA MÜGE
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Bu tezin hedefi biçimsel işaretbirim bilimi için gerekli olan hesaplama gücünü araştırmaktır. Bu tez, Hareket-Duruş Modeli (Liddell ve Johnson, 1989), El-Katmanı Modeli (Sandler, 1989) ve Bürünsel Model (Brentari, 1998) gibi üç işaretbirim bilimi modeli tarafından tanımlanan oto-bölütsel betimlemeleri ve kuralları sonlu durum makinelerine indirgeme amacına odaklanmaktadır. Bu modeller, oto-bölütsel fonoloji çerçevesini (Goldsmith, 1976) benimsediklerinden, işaret dillerinde işaretbirimsel ve biçimsel olarak gözlemlenen hem sıralılığın hem de eş anlılığın üstesinden gelebilmektedirler. Bu modellere ait betimlemeleri ve kuralları tek-seviyeli sesbilimin (Bird ve Ellison, 1994) etiketli durum makinelerine dönüştürmek üzere algoritmalar önermekteyiz. Etiketli durum makinelerinin düzenli dil gücüne sahip olduğu bilinmektedir. Bu indergemeyle işaret dilindeki doğrusal olmayan biçimsel yapının aslında sıralanabilir olduğu gösterilmektedir.

Anahtar Kelimeler: işaret dili biçimfonolojisi, berimsel fonoloji, tek-seviyeli fonoloji, oto-bölütsel fonoloji, eşanlılık

...dedicated to

Feriha Çetin

Nihat & Şirin Sevinç

Emir Candaş Sevinç

...in memory of

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Yunus & Zümriye Sevinç

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LIST OF ABBREVIATIONS

1g	enlarged path
1LP	One-Level Phonology
2LP	Two-Level Phonology
7	seven contour
A	articulator
acc	accelerating
arc	a curved path starts at one location and ends in another location
ASL	American Sign Language
ASR	autosegmental representation
C	Consonant
CCG	Combinatory Categorial Grammar
circle	a curved path which starts and ends in the same location
circling	circling
contact	contacting
DGS	German Sign Language (Deutsche Gebärdensprache))
FA	facing
FSA	Finite State Automaton/Automata
fl	flattening
H	Hold
HC	hand configuration
HS	hand shape
HTM	Hand-Tier Model
HP	horizontal plane
hk	hooking
IF	Inherent Features
ISL	Israeli Sign Language
NS	Japanese Sign Language (Niho Siyuwa)
KSL	Korean Sign Language
L	Location
LIS	Italian Sign Language
long	temporally prolonged
M	Movement

MP	midsagittal plane
MHM	Movement-Hold Model
OP	oblique plane
OR	orientation
PAM	Person Agreement Marker
PF	Prosodic Features
PM	Prosodic Model
POA	place of articulation
POC	point of contact
rel	releasing
rnd	round path
rub	rubbing
SFA	State-labeled Finite-State Automaton/Automata
short	temporally shortened
sm	reduced path
SL	Sign Language
SP	surface plane
SpL	Spoken Language
str	straight path
TİD	Turkish Sign Language (Türk İşaret Dili)
tns	tense
tw	twisting
V	Vowel
VP	vertical plane
wg	wiggling

CHAPTER 1

INTRODUCTION

1.1 Motivation of the Thesis

Sign linguists ask questions of the form "one phonology or two?" (Sandler, 2000), "one syntax or two?" (Lillo-Martin, 2001) or "one grammar or two?" (Lillo-Martin & Gajewski, 2014). They give the obvious answer "one grammar applies for human language, no matter the modality of expression" (Lillo-Martin & Gajewski, 2014, p.387). The reason why they ask these questions is to call attention to the need of capturing the three main modality differences in theories of language: (i) iconicity, (ii) use of space, and (iii) simultaneity.

Iconicity is the resemblance of a symbol (form) to its referent (meaning). Hockett (1960) states that having an arbitrary form-meaning mapping is a design feature of natural languages. Sign languages are more iconic than spoken languages. For this reason, sign languages had not been accepted as full-fledged languages and had been claimed to be pantomime-like communications for many years until the pioneering work of Stokoe (1960) which claimed that signs are composed of meaningless units, such as handshape, location and movement.

Iconicity is observed frequently in sign languages, however, it does not mean that the meaning is always predictable given the form. Klima and Bellugi (1979) carry out some experiments in which they show non-signers some iconic signs and ask them to guess their meanings. These experiments show that it may not be possible to predict the meaning of these signs most of the time. Similarly, when the form of the sign is to be predicted for a given meaning, there may be more than one possible form. For example, if you ask non-signers to predict the sign for tree, they would come up with different forms which all look like a real tree. Hence, there is also arbitrariness observed in parallel to iconicity throughout the cognitive processes of sign generation and recognition.

Use of space is another characteristic specific to sign languages. Referencing, agreement and classifier systems make use of space very frequently. Pronouns are associated with loci in signing space, and there are infinitely many possible locations for these loci. Hence listing all of them in the lexicon is not possible (Rathmann & Mathur, 2002). Similarly agreement verbs have infinitely many different phonological realizations since these verbs incorporate these loci when they are inflected for person.

The last modality difference is the simultaneity. Sign languages are claimed to have a simultaneous phonological organization (Stokoe, 1960; Klima & Bellugi, 1979), whereas most spoken languages are known to have a sequential phonology and morphology. Liddell (1984) and (Sandler, 1989) later argue that phonological organization of signs has also sequential segments. Simultaneity in sign languages is not observed in phonology and morphology but also it is observed in the level of syntax (Liddell, 1980; Neidle, Kegl, MacLaughlin, Bahan, & Lee, 2000; Kremers, 2012), i.e., non-manual markings may accompany constructions such as interrogatives, negation, relative clauses, and topicalization.

In the big picture, the motivation of this thesis is to advocate Combinatory Categorial Grammar (CCG) (Steedman, 2000b) as the one grammar that parses and generates languages from both modalities, and One-Level Phonology (Bird & Ellison, 1994) as the recognizer/generator of the phonological forms in both modalities. We propose One-level Phonology as a framework which is integrable to CCG.

CCG is a linguistic formalism that supports radical representational non-autonomy view (Steedman, 2000b; Crain & Steedman, 1985; Steedman, 2000a). As a radically lexicalized theory, CCG has at its heart a lexicon in which each lexical entry has a phonological form, a syntactic category and a logical form, which are all aligned or 'locked' together. We suggest that phonological form in the lexical entry is filled by state-labeled finite-state automaton (SFA) of One-Level Phonology (Bird & Ellison, 1994).

In the architecture of a lexicalized theory like CCG, the only place where languages differ is the lexicon. Lexicon encodes all the language specific information such as word order, case and agreement. By the integration of One-level phonology to CCG, the lexicon also encodes the information of how morphophonological changes take place in inflectional processes. The information in the lexical entries is projected from the lexicon by the combinatory rules. The set of combinatory rules that apply to all languages is the same. Derivations are driven by syntactic categories, and syntax is phonology-free and semantics-free (Steedman & Bozşahin, In submission). Phonology, semantics, and syntax work in parallel at each step of the derivations ('Rule-to-rule transparency').

CCG's architecture of language together with the 'rule-to-rule transparency' is clearly different than Jackendoff's "tripartite parallel architecture" of language faculty. Jackendoff (1997, 2002) defines phonology, syntax and semantics as separate, generative and autonomous systems which have correspondence rules between them.

Wilbur (2010) claims that iconicity in sign languages suggests that there is a semantics-phonology interface in the sense of Jackendoff (2002) and proposes the **'Event Visibility Hypothesis'**: "In the predicate system, the semantics of event structure is visible in the phonological form of the predicate sign." As an example, Wilbur (2010) claims that telic events which have a conceptual end point, i.e., 'running to the store', have an "End State" which is "signaled by a rapid deceleration of the movement to a stop".

Establishing a direct relation between phonology and semantics predicts that fixed forms would have fixed meanings. However, it is not always the case for sign languages, since it is not always possible to predict the meaning of the signs (Klima & Bellugi, 1979). CCG takes the relation between phonology and semantics as an arbitrary mapping which is coded in the lexical entries. Children learn this mapping in language acquisition phase.

The integration of One-level Phonology and CCG results in a lexical-incremental theory of morphology. We propose a morphemic lexicon in order to handle the boundedness problem[1] observed in agglutinating languages. The lexical entries of a morphemic lexicon are the

[1] Agglutinating languages like Turkish and Korean have recursive morphologies that lead to phonological

morphemes: stems and affixes[2].

When two lexical entries are combined, their syntactic categories, logical forms and phonological forms are also composed in parallel. This combination is driven by the syntactic category. Syntactic categories are combined by combinatory rules of syntax, logical forms by λ-calculus, and phonological forms by the concatenation or intersection of the automata.

For example, English stem 'cat' is a lexical entry whose phonological form is a state-labeled automaton which recognizes/generates 'cat'. Its syntactic category is a noun, and its logical form is the meaning of 'cat'. The plural suffix -s is a lexical entry of English lexicon whose function is to add a plural meaning to the noun it is attached to. In a CCG lexicon of English, the lexical entry of this plural suffix has the following triplet which works in parallel:

- Phonological form: A state-labeled automaton whose function is to make the morphophonological changes on its argument to end up with the plural form of this argument.
- Syntactic Category: A category which looks for a noun to the left. When it finds its argument, the result of combining with the argument is also a noun.
- Logical form: A $\lambda - term$ that adds a plural meaning to the meaning of its argument.

This thesis is in the heart of our motivation of one grammar and one phonology for both modalities, and the scope of this thesis is limited to construct a One-level Phonology for Sign Language. Hence, the main focus of this thesis is the phonological and morphological simultaneity, the topics of iconicity and use of space is left for further study.

1.2 Purpose of the Thesis

The aim of this thesis is to construct a computational morphology for sign language which defines the mechanisms required to generate and recognize signs and their inflected forms. The main question here is whether having a simultaneous phonological organization has an effect on the morphological complexity. This thesis investigates the computational power required for morphological processes in sign languages.

Anderson (2012) investigates "what is complex about the morphology" and argues that morphological complexity depends on the number of elements and the form of realization. He states that overall system complexity of morphology in Eskimo-Aleut depends on the number of derivational and inflectional affixes, which is larger than 500 affixes for Yupik which allows a maximum of 7 affixes in a word, complexity depends on the maximum number of affixation in a word. He argues that syncretism, variation, allomorphy and discontinuous realization such as infixation and circumfixation, would also result in the morphological complexity of the languages.

words which consist of infinite number of morphemes (Bozşahin, 2011; Lee, 1995). Even if there is a limitation on the number of morphemes that people are able to remember or understand because of limited capacity of their memories, these languages have the power for generating phonological words with unbounded number of morphemes. This is called *boundedness problem*.

[2] In a lexical theory of morphology, affixes are lexical entries who has the information of how it is related to its stem. On the other hand, in an inferential theory of morphology, the relations between the stems and affixes are represented in terms of rules.

Aronoff, Meir, and Sandler (2005) state that sign languages have "a rich and complex simultaneous inflectional morphology" and "a relatively simple sequential derivational morphology". They call classifier constructions, verb agreement, and temporal aspect marking as "complex" morphological processes.

Aronoff, Meir, and Sandler (2005) give a morphologically complex sign example which has the following compositional meaning: "he looked at it with relaxation and enjoyment for a long time". In this example, the number of morphemes is taken as a measurement of morphological complexity in American Sign Language (ASL). There are five morphemes realized in this sign: verb stem, subject agreement marker, object agreement marker, temporal aspect marker and non-manual marker which functions as an adverb.

Emmorey (2002) defines classifier constructions as complex predicates that express motion, position, stative-descriptive information and handling information. The classifier constructions are simultaneous combinations of morphemes; each hand's configuration, location and movement may function as a different morpheme. They explain that morphological complexity of classifier constructions owes to their combinatorial productivity: "Different classifiers, relative locations and an array of movement patterns productively enter into a potentially vast number of constructions." In other words, the number of available elements to construct classifiers is large.

Napoli and Sutton-Spence (2010) claim that sign languages allow at most four simultaneous propositions in classifier constructions and argue that this upper limit on the number of propositions may be resulting from the limited capacity of human's visual short-term memory.

The maximum number of morphemes in these examples of morphologically complex signs are up to four to five morphemes (Aronoff, Meir, & Sandler, 2005; Napoli & Sutton-Spence, 2010) which is less than the average number of morphemes in a word in an agglutinating language. We suggest that complexity of a process can be measured by the kind of computational resources it requires, e.g. finite-state mechanisms or push-down mechanisms, rather than its apparent descriptive complexity.

Emmorey (2002) cites the argumentation in Anderson (1992) and Hall (1992) which states non-concatenative morphology such as infixation and circumfixation is rarely observed in spoken languages resulting from its processing complexity associated with the discontinuous elements, and the concatenative morphology is less computationally complex since there is a straight forward mapping between the surface and the underlying forms. However, Emmorey (2002) claims that simultaneous morphology in sign languages is not like infixation or circumfixation in spoken languages, "the morphological processes in sign languages do not interrupt the base form or do not involve discontinuous affixes", and sign languages do not seem to have a difficulty for the morphological parsing as it is the case for non-concatenative morphology in spoken languages.

The natural question is whether morphological complexity results from discontinuous affixation in some spoken languages and simultaneity in sign languages is only apparent. We have seen from spoken languages that all discontinuous and non-concatenative morphological phenomena can be captured by finite-state mechanisms (Roark & Sproat, 2007). We aim to show this holds for the simultaneity in sign languages.

1.3 Objectives of the Thesis

The main objective of this thesis is to show that the reduction of non-linear phonological representations to finite state machinery is possible on three models of sign language phonology, namely, Movement-Hold Model (MHM) (Liddell & Johnson, 1989), Hand-Tier Model (HTM) (Sandler, 1989), and Prosodic Model (Brentari, 1998), all of which incorporate Autosegmental Phonology of (Goldsmith, 1976). In these models, signs are represented as autosegmental representations, and the morphological processes are defined in terms of autosegmental rules.

According to MHM, HTM and PM, we construct autosegmental representations for signs and define rules which encode the changes on these representations when a morphological process takes place. Bird and Ellison (1994) show how principles of Autosegmental Phonology (Goldsmith, 1976) can be translated to a finite-state model, namely, to *One-Level Phonology*. We adopt their transformation methodology to capture the feature geometries developed by these three sign language phonology models and give algorithms for converting autosegmental representations and rules proposed by these three models into SFA of One-level Phonology.

The last objective to be achieved is the design and development of a computational ontology based on the knowledge of sign language phonology models. The aim is to define the temporal semantics behind the autosegmental representations of sign languages. We re-use and extend event-based ontology (Bird & Klein, 1990) to capture the sign language phonology based on MHM.

1.4 Contribution of the Thesis

This thesis makes the following contributions:

- The non-linear phonological representations of sign languages are shown to be reducible to finite-state machines, hence sign language morphophonology is computationally within the expressive power of generalized regular languages in Chomsky's hierarchy of languages (Chomsky, 1956). Hence, the complexity of sign language morphophonology is the same as that of spoken languages.
- The feature geometries defined by sign language phonology models are shown to be serializable, hence the underlying mechanisms of syntax can work independent of the phonological organization of the sign languages.
- An event-based computational ontology for sign language phonology, which is useful for the verification of autosegmental representations by automatically checking the well-formedness conditions, is developed.

1.5 Organization of the Thesis

The outline of the thesis is as follows:

Chapter 2 introduces how spoken language phonology models deal with the linear and non-linear structures. Generative Phonology (Chomsky & Halle, 1968), Two-Level Phonology (Koskenniemi, 1983), Autosegmental Phonology framework (Goldsmith, 1976), and One-Level Phonology (Bird & Ellison, 1994) are presented briefly. Section 2.2 is a general introduction to the simultaneity and sequentiality in sign language phonology and morphology.

Chapter 3 is a survey on the inflectional and derivational morphology in sign languages. It presents inflectional processes such as verb agreement, temporal aspect and pluralization; derivational processes such compounding, nominalization, modifying the adjectives by the affixes which have the meanings of 'characteristically' and '-ISH'; and lastly classifiers. This chapter also brings together the available information on the morphotactics of ASL. Lastly, it presents two studies on computational morphology of sign language: a rule-based morphological analyzer (Shield & Baldridge, 2008) which is constructed for the habitual and continuative aspect in ASL and a two-level computational inflectional morphology model for Spanish Sign Language (Zamorano, 2014).

In Chapter 4, after a general introduction to sign language phonology is presented, three sign language phonology models, MHM, HTM and PM are introduced. Our focus is on how these models represent both the simultaneity and the sequentiality in the autosegmental phonological representations they propose, and how they model inflectional morphological processes such as agreement marking, aspectual marking, nominalization.

Chapter 5 presents how we construct One-Level Phonology for sign languages. We introduce One-level Phonology (Bird & Ellison, 1994) and then in Sections 5.2 , 5.3 and 5.4 we show how we reduce autosegmental representations and rules that are constructed according to MHM, HTM and PM into state labeled automata of One-level Phonology (Bird & Ellison, 1994).

Chapter 6 explains formal *temporal semantics* (Bird & Klein, 1990) attached to the autosegmental rules and representations. It explains how autosegments, tiers, charts and associations are interpreted within One-level Phonology of sign language. It presents an event-based ontology based on MHM which captures both simultaneous and sequential aspects of sign language phonology via temporal relations. This ontology checks the validity of the autosegmental representations of signs based on the well-formedness condition.

Chapter 7 concludes this thesis and presents some future work.

CHAPTER 2

LINEARITY AND NON–LINEARITY

2.1 Spoken Languages

Phonology is the study of how words are composed of meaningless units whereas morphology is the study of how meaningful units come together to form a word. Mostly, spoken languages (SpLs) have sequential phonology and morphology, i.e., phonemes follows phonemes, and morphemes are affixed to the root in a sequential order. By most theories of language, an utterance is usually called a 'surface form', and the representation underlying this utterance is called the 'lexical form' or the 'underlying form'. The kind of phonology/morphology in which the surface form is generated by linear concatenation of the phonemes/morphemes is called *concatenative* or *linear phonology/morphology*.

Concatenative morphology consists of processes such as suffixation and prefixation. As an example of suffixation, we may mention the pluralization of nouns in Turkish which is realized as the addition of -ler/-lar suffix. An example of prefixation is the negation of adjectives in English which is achieved by adding im-/in- prefix. These examples go under some phonological processes, for example, nasal assimilation occurs during English adjectival negation, and vowel harmony effects the suffixation in Turkish. This kind of interaction between morphological and phonological processes during word formation is called morphophonology.

SpLs may have non-linear phonological and morphological processes although non-linearity is not observed as wide spread as linearity. The kind of morphology that changes the shape or the rhythm of the word is called *non-concatenative*[1] morphology.

Non-concatenative morphology contains processes such as ablaut, infixation and suprafixation. An example of ablaut is observed in English tense marking (sing, sang, sung) where there are internal modifications to the phonological base, a similar process is umlaut which is observed in German pluralization (Apfel, Äpfel). Semitic languages and Arabic have a non-linear morphological process of infixation where verbs consist of morphemes that are joined together in a non-concatenative manner. Linear concatenation of {ktb} 'to write' and {a} 'perfect active' in Arabic would result in ungrammatical words: */aktb/ or */ktba/, instead these morphemes are combined to form the words /katab/ *"write + perfective active"* by infixation. Suprafixation is a process observed in tonal language where the meaning of a word may change when a different tone is realized simultaneously with that word.

The following sections introduce some theories of phonology mostly in historical order:

[1] The other names for *non-concatenative morphology* are *non-linear morphology*, *templatic morphology*, *prosodic morphology* and *root-and-pattern morphology*.

Sound Pattern of English (Chomsky & Halle, 1968), Two-Level Phonology (Koskenniemi, 1983), Autosegmental Phonology framework (Goldsmith, 1976) and One-Level Phonology (Bird & Ellison, 1994).

2.1.1 Sound Pattern of English (SPE)

The first theory of generative phonology is presented in *Sound Pattern of English* (SPE). It has been the dominant paradigm in this field for many years. In SPE, Chomsky and Halle (1968) represent a word as a linear sequence of segments which are associated to 'feature bundles' and propose a generative phonological grammar which has rewriting rules of the form X⇒ Y\ A__B. This rule states that string X is rewritten as Y whenever it is preceded by A and followed by B. A and B are called contexts, and they are regular expressions defined over a basic alphabet of segments.

This theory is transformational in the sense that an underlying form is transformed into a surface form according to the rules, intermediate forms may also be produced during this transformation. Rules are applied in a language-specific sequential order.

Although these rewriting rules have the expressive power of context-sensitive grammars[2], C. D. Johnson (1972) observes that phonologists functionally make use of SPE-style phonology in a manner where rules are not applied recursively to its output. C. D. Johnson (1972) demonstrates that a rewrite rule which never applies to its output can be modeled by a finite state transducer (fst)[3]. Independently, Kaplan and Kay (1994) show that SPE-style rewrite rules describe *r*egular relations since each rule is represented by an fst. Heinz (2011a, p.143) claims that Kaplan and Kay's work (1994) indicates that "all phonological patterns are regular".

Generative phonology proposed in SPE is unidirectional, it is capable of word generation, but not of morphological analyzing. If used for analyzing, it would result in multiple possible lexical forms. Kay (1982) suggests that all fsts generated for the rules may be merged into a big fst (by serial composition) which has the functionality of mapping between the lexical and surface form. Since each rule is described by a regular relation and "the regular relations are closed under serial composition, a finite set of rules applying to each other's output in an ordered sequence also defines a regular relation"(Kaplan & Kay, 1994, p.331). By this merge, mapping becomes bidirectional: given a surface form, it would also produce the lexical form. Koskenniemi (1984, p.178) argues that "the size of the merged automaton" would be problematic especially for "languages with complex morphology such as Finnish".

[2] Context-sensitive grammars generate context sensitive languages and the automaton that recognizes a context sensitive language are called a linear-bounded automaton. Context-sensitive languages are labeled as Type-1 in Chomsky hierarchy of formal languages (Chomsky, 1956) which are more powerful than regular languages and context-free languages.

[3] A finite-state transducer is a finite-state automaton whose transitions are labeled with pairs of symbols. Each pair has an input and output symbol. I assume that the reader is at least familiar with the concepts such as automata (Turing, 1950), finite automata (Moore, 1956), regular languages (Kleene, 1956), and Chomsky hierarchy of formal languages (Chomsky, 1956). Fundamental information on regular languages and finite state automata can be found in any book of introduction to theory of computation such as (Hopcroft & Ullman, 1979; Lewis & Papadimitriou, 1998). For a survey of these concepts and finite state transducers, the reader may refer to (Jurafsky & Martin, 2000; Roark & Sproat, 2007).

2.1.2 *Two-Level Phonology/Morphology*

Inspired by the work of Kay (1982), Koskenniemi (1983) introduces a language independent *Two-level Morphology* model which has only the surface form and the lexical form, and no intermediate forms between them. The lexicon level contains the morphophonological representations of words and the phonemic level (surface form) consists of phonemes or letters of alphabet. Instead of rewrite rules of SPE which require a sequential application order, he defines two-level rules which map between the surface form and the lexical form which work in parallel and hence do not require any rule ordering. His approach is different than Kay's approach which composes all fsts into a big fst. Each rule is equivalent to a finite state automaton (fsa) and all automata are working simultaneously on the lexical segments. Hence, rather than a big fst in size, there are a small set of automata in this model. Two-level morphology is bidirectional in the sense that two-level rules are also equally used for synthesizing and analyzing of word forms.

Two-level Morphology expresses the power of *r*egular relations (Kaplan & Kay, 1994). In Two-level Morphology, there are morphological markers which are overt in lexical form but marked as zero in the surface level. Karttunen (2003) notes that two-level rules represent *equal-length-relations* owing to having these zeros. Karttunen (2003) states that the intersection of the equal-length-regular-relations are regular even if regular relations themselves are not closed under intersection.

There has been some argumentation on its computational complexity. Barton (1986) argues that word generation in the Two-level Phonology model takes non-deterministic polynomial time. Heinz (2011b, p.154) puts a similar argumentation in his words: "There is no deterministic algorithm that is guaranteed to compute the surface form from the underlying form for any Two-level Phonology grammar fewer than f(n) steps where f is a polynomial function and n is the length of the underlying form".

Koskenniemi (1983) states that the Two-level Morphology model would need an extension to handle infixation. Kay (1987) was the first to apply the Two-level Morphology to the non-concatenative data of Arabic. In that work, he designs a four-tape machine: fst reads four-strings, one string for the surface form and three strings for each of the autosegmental tiers such as the root tier, the timing tier and the vocalic tier. Bird and Ellison (1994) state that there is no upper limit on the number of autosegmental tiers in principle, hence there is similarly no upper bound on the number of tapes.

2.1.3 *Autosegmental Phonology and Feature Geometry*

Goldsmith (1976) proposes an alternative phonology model to generative phonology. *Autosegmental Phonology* is a multi-tiered phonological model in which similar phonological features are placed on the same tier and different features are placed on different tiers. When features which are employed in autosegmental representations encode information about manner or place of articulation, this framework also explains "how articulators such as tongue, lips, velum and larynx are coordinated" to form a spoken word (Goldsmith, 1976).

Autosegmental phonology (Goldsmith, 1976) is originally developed for modeling phonology of tonal languages. The autosegmental tiers are linear sequences of *autosegments*. For example, in Ngbaka, a tonal language, tense is indicated by specific tones which are placed in a different layer than the root morpheme ‘kpolo’ (Kiraz, 2001). In Figure 2.1, tones such as high pitch ‘H’, low pitch ‘L’ or medium pitch ‘M’ are autosegments on the tone tier, whereas tone bearing units are located in the root tier.

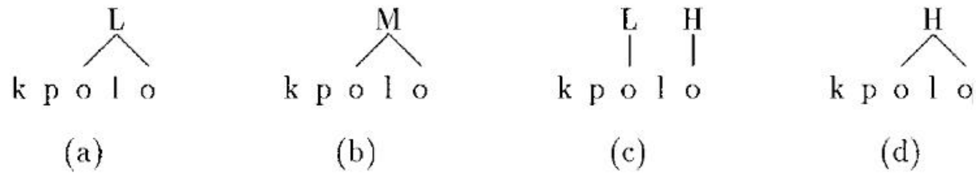

Figure 2.1: Tense marking in Ngbaka (Kiraz, 2001, p.4). H: high pitch, L: low pitch, M:medium pitch.

Temporal relations between autosegments in different tiers are organized with *association lines*. The association of one autosegment in a tier with two or more elements in another tier is called *spreading*. A *chart* is a pair of tiers linked by association lines. Goldsmith (1976) defines the *well-formedness condition* for charts as follows:

(1) Well-formedness Condition:

a. All vowels are associated with at least one tone.

b. All tones are associated with at least one vowel.

c. Association lines do not cross.

Autosegmental phonology framework is also used to model non-linearity in Arabic and the Semitic languages where the root morpheme is discontinuous and there are not clear cut morpheme boundaries as it is in the languages with linear morphology where the morphemes are sequenced one after another. McCarthy (1981) proposes a linguistic model based on Autosegmental Phonology framework (Goldsmith, 1976) where he adopts a feature based system rather than a boundary-based system. McCarthy (1981) extends Autosegmental Phonology by proposing that each tier represents a separate morpheme. In McCarthy’s model, stem consists of three morphemes: root morpheme that contains the consonants in the stem, vocalism morpheme that contains the vowels, and the pattern morpheme that consists of Cs and Vs. In Figure 2.2, there are three morphemes: root morpheme, {ktb} ‘to write’, pattern (template) morpheme, CVCCVC ‘to cause’, and vocalism morpheme, {a} ‘perfect active’. *CV tier* works as a timing skeleton, consonant geminates and long vowels are handled within the patterns of timing skeleton.

To sum up, segmental tier, timing tier and tone tier are some autosegmental tiers defined for explaining the non-linearity in spoken languages. *Tone tier* contains features such as ± high pitch ‘H’ and ± low pitch ‘L’ which show the distribution of tones. These features are assigned to the tone-bearing units of the language as in Figure 2.1. *Segmental tier* contains distinctive features which identify the segments. A segment may consist of binary features such as ± sonorant, ± continuant, ± voice. *Timing tier* contains timing units that define the lengths of segments. CV tier in Figure 2.2 is an example of timing tier.

Following Autosegmental Phonology, Clements (1985) makes a move from feature matrices to a feature geometry. Clements (1985) suggests a hierarchical organization for the distinctive

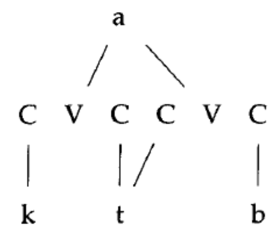

Figure 2.2: Autosegmental tiers for the Arabic verb kattab ‘cause to write’ which has the citation form katab ‘to write’.

features, namely a feature tree, as in Figure 2.3, which he claims to be universal for all spoken languages. In this representation, the features which function “as a whole unit with respect to phonological rules” are grouped together. Root of the feature tree dominates distinctive features that form a segment (C or V), intermediate nodes are called *feature classes* and terminal nodes holds distinctive features. “Feature classes are determined functionally rather than phonetically” (Clements, 1985).

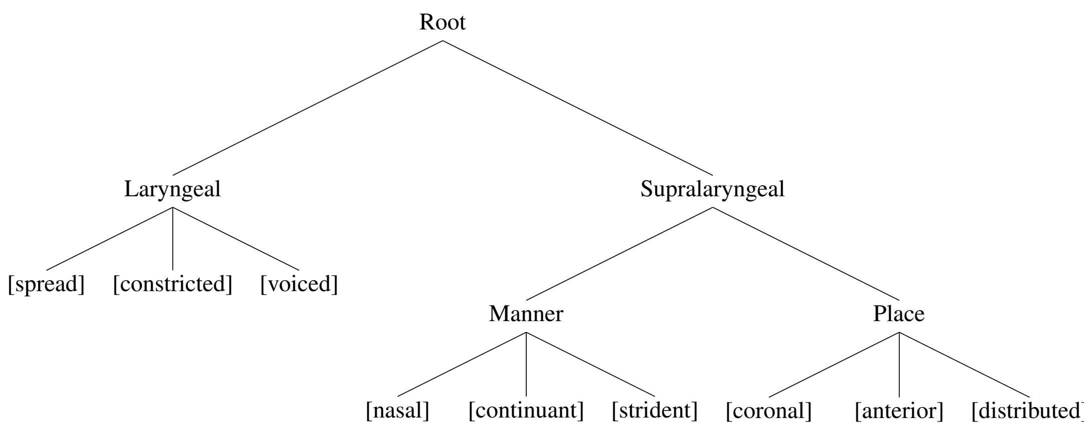

Figure 2.3: Hierarchical feature organization of a segment (Clements, 1985)

Feature Geometry is proposed as an extension to Autosegmental Phonology (Goldsmith, 1976): “Each feature and feature class is represented as a node on a separate autosegmental tier” (Clements, 1985). When there is more than one segment, they form an autosegmental representation as in Figure 2.4. Association lines in the autosegmental representation define which sets of features are realized simultaneously. The feature tree in Figure 2.3 is the side view of the autosegmental representation in Figure 2.4.

Phonological rules such as assimilation, de-linking (deletion) and spreading are defined on these autosegmental representations. An example of an phonological rule defined over the feature geometry in Figure 2.3 is the nasal assimilation rule which states that if a nasal is followed by a consonant then the nasal changes its place of articulation to agree with the following consonant’s place of articulation. Nasal harmony rule is defined as a partial assimilation of the place node as in Figure 2.5. The association line on which there is two parallel lines (=) is deleted and the dotted line is added as the new association.

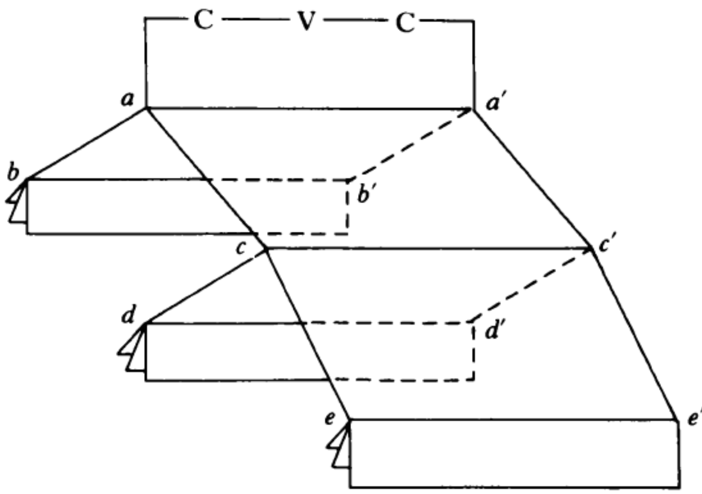

Figure 2.4: Autosegmental tiers in Feature Geometry (Clements, 1985). aa': Root Tier, bb': Laryngeal Tier, cc': Supralaryngeal Tieri, dd': Manner Tier, ee': Place Tier

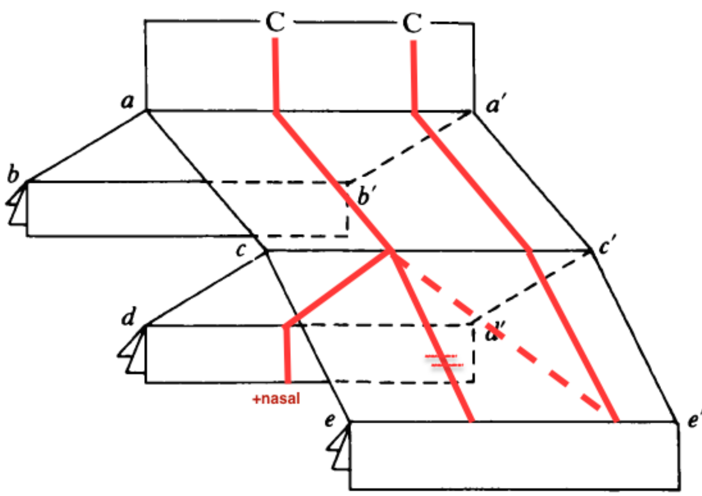

Figure 2.5: Nasal Assimilation Rule (aa': Root Tier, bb': Laryngeal Tier, cc': Supralaryngeal Tier, dd': Manner Tier, ee': Place Tier)

2.1.4 One-Level Phonology

Bird and Ellison (1994) presents a declarative phonology, namely, *One-level Phonology*, which transforms the representations and the rules of Autosegmental Phonology (Goldsmith, 1976) into state labeled automata which are shown to be equivalent to finite-state automata.

It is called "one-level" because there is "only one level of linguistic description" (Bird & Ellison, 1994). In Two-level Phonology, there are two levels: the underlying form and the surface form. These two forms are represented as strings, and the rules as finite state transducers (fsts). In One level Phonology, there is no 'underlying form' - 'surface form' distinction, there is only one form. Autosegmental representations and rules are not also distinguished in

One-level Phonology, they are both represented as SFA. Applying the rule to the representation is achieved by intersecting the automata of the two.

One-level phonology is language independent, it may be applied to autosegmental representations constructed for representing any kind of language such as tonal languages, sign languages, Semitic languages. One-level phonology is explained in greater detail in Chapter 5.

2.2 Sign Languages

2.2.1 Simultaneity

Stokoe (1960) was the first to claim that signs may be divided into meaningless units such as handshape, location and movement. He observed that these phonemes are simultaneously articulated in many signs. In his model there are no segments and no sequentiality. He suggests that two signs that differ by a single unit are minimal pairs. Being minimal is counted as a psycholinguistic evidence for these units to be accepted as phonemes[4]. As cited in (Battison, 1978), there is a fourth unit in addition to the ones above, it is the orientation of the palm.

Klima and Bellugi (1979) claim that phonological organization of signs is mostly simultaneous rather than sequential. Klima and Bellugi (1979) state that hands are slower articulators than vocal organs, and the time required to transmit grammatical information is almost the same in spoken and sign languages. Since simultaneous expression of linguistic elements is faster than linear articulation, sign languages seem to encourage simultaneity over sequentiality because of its slower rate of articulation (Klima & Bellugi, 1979). In addition to this argumentation, Emmorey (2002) explains non-concatenative nature of sign languages with the fact that humans are capable of encoding visuo-spatially distinct information in a parallel fashion.

Simultaneous nature of phonemes also affect morphological processes since handshape, orientation, location and movement components may also function as morphemes. Johnston and Schembri (1999) suggest referring to these components as ‘phonomorphemes’.

Klima and Bellugi (1979) present a detailed study on ASL derivational processes like compounding and inflectional processes like grammatical marking such as temporal aspect, reciprocal, number, distributional aspect, manner and degree. They argue that grammatical inflections are mostly internal modifications to the movement phoneme. Addition of a new morpheme to a sign may be realized as a non-manual marking on the face occurring simultaneously with the sign, a change in the path shape of the movement (circle, elliptical, line, point), a change in the dynamic qualities of the movement, such as manner (hold, continuous, restrained), rate (slow, fast), tension (tense, lax), evenness (even, uneven) or size (elongated, abbreviated) (Klima & Bellugi, 1979).

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[4] Later on, R. E. Johnson and Liddell (2010) argue “minimal pairs are pairs of words that share identical phones in all sequential positions except one”, hence they claim that applying the notion of minimal pairs in a system without segments is problematic.

2.2.2 *Sequentiality*

In an initial investigation on sequential affixation in ASL, Klima and Bellugi (1979) claim that ASL does only have suffixes, which are loan translations from English. Aronoff, Meir, and Sandler (2005) and Aronoff, Meir, Padden, and Sandler (2005) report that there are suffixes for the negative (zero suffix), comparative, superlative and agentive morphemes in ASL, and sense prefixes and a negation suffix in Israeli Sign Language. Kubuş (2008) reports a negation suffix in TİD. All these sequential affixations are stated to have a limited productivity.

Simultaneity in sign languages was not a surprise, however the existence of sequential organizations was well discussed before it was accepted and took its place in the phonological theories. Liddell (1984) shows that majority of signs have a sequence of segments by analyzing the timing data. Liddell and Johnson (1989) formalize that ASL signs are composed of movement and hold segments. Movement is defined as a time segment in which some articulatory features change. On the contrary, hold is defined as a period of time when there is no change. Their formalization, known as *Movement-Hold Model*, is a sign language phonology model based on Autosegmental Phonology (Goldsmith, 1976). Sequential organization proposed in Movement-Hold Model explains the phonological changes in handshape, location, orientation, movement, and non-manual activities that are associated to signs. These changes may be resulting from morphological processes such as person marking, aspectual marking, or may be part of the lexical form of the sign.

Person marking on verbs may either be realized as a change in direction of movement or orientation change or both (Klima & Bellugi, 1979; Fischer & Gough, 1978; Mathur, 2000). The underlying sequential representation proposed by Liddell (1984) explains the incorporation of location morphemes to the verbs during morphological agreement with its arguments. Agreement verbs have a sequence of segments, i.e., HMH, in which Hs may be associated with agreement markers and M is a straight movement.

Sandler (1989) suggests another autosegmental model for phonology, namely *Hand-Tier Model*, which has three main tiers: timing tier that consists of sequential segments such as Locations (L) and movements (M), hand configuration (HC) tier that spreads over this skeleton, and place tier. Sandler (Sandler, 1989, 1990) argues that the temporal segmentation of the sign is required for representing the temporal aspect in ASL. Newkirk (Newkirk, 1998a, 1998b) similarly claims that the representation of continuous aspect and multiple marking on verbs require the existence of sequential segments.

Brentari (1998) proposes a Prosodic Model of sign language phonology which suggests a feature geometry (Clements, 1985). This geometry simply organizes the articulatory features under two branches: inherent features and prosodic features. The inherent features are the stationary features that describe the hand configuration. The prosodic features describe the changes in the articulatory features. For instance, aperture change, setting change, orientation change and path movements are grouped as prosodic features. Movement is not a segment in this model, it is rather described as a change of prosodic features in time, to model this, prosodic features are associated with the time slots.

In summary, phonological organization of the signs is simultaneous, in other words, foundational units such as handshape, location, movement, orientation and non-manuals are synchronously realized. However, there may be a change in one or more of these units within a sign. A morphological process may cause this change, or it may be lexical in nature. These changes signal the need of sequentiality in phonological representations. The relative timing of these changes with respect to each other is another point that the phonological models of sign language shall deal with.

Relying on Autosegmental Phonology (Goldsmith, 1976), both the sequential and the simultaneous facts of sign language phonology and morphology are captured by the phonological models such as Movement-Hold Model (Liddell & Johnson, 1989), Hand-Tier Model (Sandler, 1989) and Prosodic Model (Sandler, 1989).

CHAPTER 3

SIGN LANGUAGE MORPHOLOGY

Morphology is the study of word internal structures. Morphemes are the smallest meaningful units. Units of signs such as handshape, movement, location, orientation, non-manual markings may have meanings, so they may function as morphemes. Sometimes smaller units, i.e., the shape of the movement, or the speed of the movement may also carry meanings.

Inflectional morphology is the study of formation of new variations of the same word by adding grammatical markers such as tense, aspect, person, number, gender and case. Derivational morphology is the study of the formation of a new word from another word(s). Derivation may result in a change of word class but inflection does not. Inflection may be thought as a more systematic process than derivation. The meaning of the inflected form is predictable whereas derivation may result in an idiosyncratic meaning. Meir (2012) claims that inflectional morphology in sign languages is restricted to simultaneity, whereas derivational processes make use of both.

Studies in inflectional morphology of sign languages focus mainly on three topics: person, number, aspect and plurality. The other grammatical markings such as tense, case, gender are mostly lacking or not systematical in sign languages. In most sign languages, there is no case or no gender marking on nouns and personal pronouns (Meir, 2012). Gender marking is only reported for Korea, Japan, and Taiwan Sign Languages (Zeshan, 2009; McBurney, 2002). It is optional so that it is not accepted as a grammatical process (McBurney, 2002).

The question of whether there is tense in sign languages is another topic under discussion. Sutton-Spence and Woll (1999) report some British SL (BSL) verbs to have different forms for past and present tense, however they state that these are different lexical items, and it is not a systematic system of inflection. Jacobowitz and Stokoe (1988) and Zucchi (2009) observe some verbs in ASL and Italian Sign Language (LIS) are inflected by tense markers. Jacobowitz and Stokoe (1988) suggest that "flexion at the wrist, elbow, or shoulder" marks past tense and "extension at these joints" marks future tense in ASL. Zucchi (2009) claims that LIS verbs are associated with simultaneously occurring non-manual markers such as 'shoulder backward' for past tense and 'shoulder forward' for future tense.

Pfau, Steinbach, and Woll (2012) argue that tense does not seem to be a systematic verbal inflection system in sign languages, they say that non-manuals which mark tense cannot be used with the time adverbials simultaneously, hence they conclude that verbs generally "do not inflect for tense, instead tense is generally encoded by time adverbials" such as now, tomorrow, yesterday, today.

Three morphological operations used by sign languages are compounding, affixation, and reduplication (Liddell & Johnson, 1989; Meir, 2012). Reduplication is the repetition of a sign two or three times, where in each repetition the whole sign is simply copied and mostly the movement is shortened. Processes like pluralization, iterative and habitual aspect marking make use of this operation.

Compounding may be sequential or simultaneous in sign languages, i.e., if two signs are linearly composed, it is sequential, if the signer uses one of its hands for signing one sign and the other for signing the other sign, it is simultaneous (Meir, 2012).

Akinlabi (1996) classifies affixation as segmental affixation and featural affixation. Segmental affixes may be phonetically realized on their own, they can be prefixes or suffixes, whereas featural affixes are realized as a featural change on one or more of the segments of the stem. Affixation in sign languages is mostly simultaneous. Whenever a new morpheme is added to a sign by one of these operations, there occurs some changes on the phonological representation of the sign: it may be a change in the features of the movement, a change in the palm orientation, or addition of a non-manual marking (Klima & Bellugi, 1979; Mathur, 2000). For example, continuative aspect marking adds an elliptical shape to the movement of the verb.

Affixation may also be sequential, i.e., adding a new morpheme is realized as adding a new phonological segment to the representation. For example, it may be realized as adding a segment which is associated to a new place of articulation at the initial and/or final parts of the sign. This would result in a change in the direction of the movement as observed in the morphological process of person marking. Another example is the addition of a long tense hold to mark proactive aspect.

Morphology has two branches: inflectional and derivational morphology. Section 3.1 presents topics of inflectional morphology such as person, number, aspect and plurality and Section 3.2 briefly introduces topics in derivational morphology such as compounding, nominalization of the verbs and adjectival derivations. After introducing sign language morphology, we briefly summarize the studies on morphotactics in Section 3.4, and present classifiers that are claimed to be morphologically the most complex structures in sign languages in Section 3.3, and lastly we close the chapter by introducing the work on the sign language computational morphology in Section 3.5.

3.1 Inflectional Morphology

3.1.1 Person

In most sign languages, nouns or personal pronouns are associated with spatial locations, which are then used for referring to these nominals. There is an infinite number of possible locations to which a noun or a non-first person pronoun can be associated (Meier, 1990).

Some verbs are modified to incorporate these locations into themselves, this modification relates the verbs with the nominals. The meaning of the verb is changed when the hand moves in the direction of these spatial locations or and/or the hand changes its orientation towards these locations (Klima & Bellugi, 1979; Fischer & Gough, 1978).

Klima and Bellugi (1979) claim that these verbs are marked for person reference by "indexal inflections" which result in a change in the form of their movement. Similarly, Fischer and Gough (1978) state that "the direction of the motion changes to indicate the location of the arguments" and "in addition to or instead of a change in direction of movement in a verb to show who is doing what to whom, there is also a change in the orientation of the hand(s)".

For example in Figure 3.1, when TİD verb DURDUR 'to stop' is directed to the chest of the signer from a location in space, it means "X stops me", when the movement starts from the chest of the signer and is directed to a location in space, then it means "I stop X". Here, X is a singular non-first person (you/him/her).

In fact, there is an on-going discussion whether the directionality observed in this class of verbs should be called morphological verb agreement or not. A verb that is directed to and/or oriented towards a spatial location for referencing a nominal is called a *"directional verb"* by Fischer and Gough (1978), an *"inflecting verb"* by Padden (1988), an *"agreement verb"* by Meier (1982), Padden (1990), Liddell (1990a), Aronoff, Meir, and Sandler (2005), Sandler and Lillo-Martin (2006), and Mathur and Rathmann (2010) and an *"indicating verb"* by Liddell (2000) and de Beuzeville, Johnston, and Schembri (2009).

Many researchers (Meier, 1982; Padden, 1988, 1990; Liddell, 1990b; Aronoff, Meir, & Sandler, 2005; Mathur & Rathmann, 2012) argue that this phenomenon is to be considered as inflection, namely, person agreement marking, whereas the other camp (Liddell, 2000, 2003; de Beuzeville et al., 2009) argues that it is not verb agreement, and these verbs are "indicating verbs" which are directed to entities in mental spaces.

Meier (1982) argues that these verbs agree with the physical locations which are associated to their arguments. Verb agreement takes place by modifying the movement and/or orientation of the sign to take place at the locus of the first person or non-first person. Locus of first person is the signer's chest and locus for an existing referent is the real world location of the referent, and locus for an absent non-first person is an abstract locus which may be selected from a list of infinitely many different locations. He makes the point that it is not possible to differentiate between the possible loci for the second-person from the possible loci of the third-person. He claims that "there is no linguistic distinction between second- and third-person".

These verbs and pronouns also have infinitely many different phonological realizations because of having infinitely many possible locations. This is often called *listability problem* (Rathmann & Mathur, 2002). Enumerating all these possible phonological realizations for the agreement verbs and pronouns in the lexicon would cause lexicon to be infinite. Mental lexicon is bounded and listable. For humans and even for the machine parsers/generators, an infinite size lexicon would lead to infeasible computational power and memory. There are three different views for how to treat the loci and the listability problem: loci as variables (Lillo-Martin & Klima, 1990), loci as features (Neidle et al., 2000; Kuhn, 2015) and loci as featural variables (Schlenker, 2014).

In (Padden, 1988), it is noted that only a certain group of ASL verbs are inflected for person and number. Padden (Padden, 1988, 1990) classifies ASL verbs into three groups according to their morpho-syntactic features: (i) inflecting, (ii) plain and (iii) spatial. Padden (1988) puts the distinction between these verb classes as follows: Inflecting verbs inflect for person and number. Spatial verbs have markers for location and manner. Plain verbs do not have any markers for person and number, however they are inflected for temporal aspect. Padden's classification is widely accepted in sign linguistics literature (Sandler & Lillo-Martin, 2006; Mathur & Rathmann, 2010), it has been applied to other sign languages, e.g., Israeli SL (Meir,

$_{i}$DURDUR$_{1}$: 'I stop you/him/her.'

$_{1}$DURDUR$_{i}$: 'You/he/she stop(s) me.'

$_{i}$DURDUR$_{j}$: 'He/she stops him/her.

Figure 3.1: DURDUR 'to stop' is a TİD verb which changes both the orientation of the palm and the direction of movement (Sevinç, 2006).

2002), Danish SL (Engberg-Pederson, 2002), BSL (Kyle & Woll, 1985) and TİD (Sevinç, 2006).

Padden (1988) classifies agreement verbs based on the number of arguments involved in agreement as follows: *Single agreement verbs* only agree with the object and they are mostly body-anchored, i.e., the movement of these signs begins at a fixed location on the body. For example, GÖR 'see' is a body-anchored transitive verb which shows single agreement. *Double agreement verbs* agree with both the subject and the object. She also points out that subject agreement markers are optional. She indicates that some inflecting verbs have a sequential order in their morphological structure: a subject agreement marker, a linear movement and an object agreement marker. These verbs are called forward agreement verbs. Backward agreement verbs have the reverse order of morphemes.

Mathur and Rathmann (2012) suggest a featural analysis of agreement in sign languages based on (Padden, 1988, 1990; Neidle et al., 2000). In their analysis, they claim that verbs agree with the subject and the object in their morpho-syntactic features such as person features (+1: first person, -1: non-first person), and number features (+pl:plural, -pl:singular).

Mathur (2000) asks the question of whether a verb's membership to agreement verbs is predictable. Padden (1988) suggests this membership is a lexical property learned by the children during acquisition. Mathur (2000) investigates the effect of phonological and morphological constraints and the animacy factor on this prediction. He argues that agreement applies only to animate arguments, and person marking is realized as either a change only in palm orientation, a change only in direction of movement, or a change in both.

3.1.2 Number and Distributional Aspect

Klima and Bellugi (1979) point out that ASL nouns are optionally marked for plurality and verbs are marked for two (dual) or many (multiple) agents or recipients. Number is marked on verbs by making internal changes in the form of the verb.

a. Dual Marking: Dual inflection marks agreement with either two agents or two recipients. Padden (1988) notes there are two forms for dual marking as below. Both of the forms are used for dual object agreement, and only the second form is possible for dual subject agreement.

    i. The verb is repeated twice where the inflected end points are displaced in the second iteration. Ex: ${}_a\text{GIVE}_b$ ${}_a\text{GIVE}_c$.
    ii. The verb's handshape is copied to the non-dominant hand. Both hands articulate the same movement synchronously or execute the movement twice in sequence. Figure 3.2 shows how dual agreement marking for one-handed sign like GÖR 'see' is realized via the simultaneous execution of the sign with the both hands. When there is exactly two people who see someone, or someone sees exactly two people, the two-handed dual form is signed as in Figure 3.2.

b. Multiple Marking: Collective plurality is marked by an addition of a sweep arc movement, it does not involve any repetitions. The verb is specified by the number of recipients as 'some', 'many' or 'all'. Here, the action is not distributed to each recipient, it is a general unspecified form.

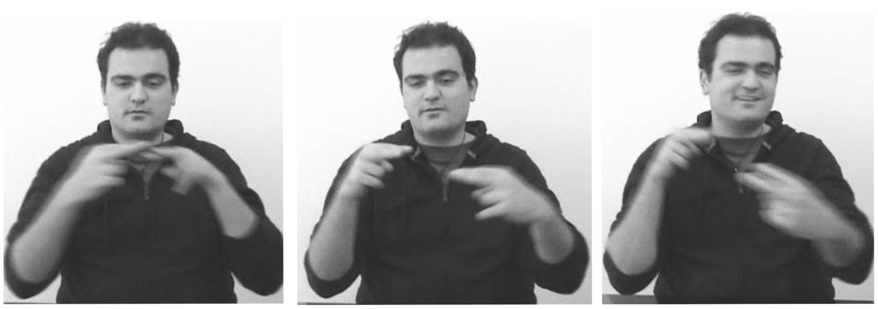
c. Exhaustive Marking: Klima and Bellugi (1979) describe exhaustive marking as a distributional aspect. Actions are distributed to each individual in a group, and they are viewed as a single event. For the meaning 'to each one', the verb is repeated many times in a series along an arc as shown in Figure 3.8.C.

Initial location of GÖR ‘see’ Final location of GÖR ‘see’ $GÖR_{Dual}$

Figure 3.2: Dual number agreement in TİD (Sevinç, 2006).

d. Reciprocal Marking: Klima and Bellugi (1979) indicate that ASL has an inflectional marker which operates on verbs and adds the meaning of ‘each other’ or ‘one another’ to the verb. The sign marked for reciprocity is articulated as a two-handed sign in which the hands are moving simultaneously. The hands are directed and oriented towards each other. The example in Figure 3.3 shows an example of reciprocal and exhaustive marking in TİD. The repetition of the reciprocal sign is caused by its exhaustive distributional meaning. Sign languages seem to exhibit similar reciprocal strategies.

Pfau and Steinbach (2003) report that German Sign Language (DGS) have a reciprocal strategy based on morphological (agreement or plain verb) and phonological (one-handed or two-handed) properties of the sign. For two-handed agreement verbs, reciprocity is marked by the conversion of movement and/or orientation. For one-handed agreement verbs, the strategy is conversion and feature copy onto the non-dominant hand. For plain verbs, there are two strategies: zero marking and insertion of an overt person agreement marker (PAM).



$BAK_{Reciprocal}$

Figure 3.3: Reciprocal and exhaustive marking in TİD. These photographs show the reciprocal and exhaustive marking in the TİD sentence ADAM KADIN VE ÇOCUK BAK which has the meaning “The man, the woman, and the child look at each other (Sevinç, 2006).

3.1.3 Temporal Aspect

Sign languages have a rich inflection system for marking temporal aspect (Klima & Bellugi, 1979; Newkirk, 1998b; Fischer, 1973; Sandler, 1990). In a paper on reduplication, Fischer (1973) defines two methods of reduplication of ASL verbs, namely, fast and slow reduplication, which cannot occur simultaneously. Slow reduplication adds the meaning of "for a long time", where as fast reduplication may add one of the following meanings: "habitually", "many times", "to many people", "to many places", "always". Building upon this early work of Fischer (1973), Klima and Bellugi (1979) study many aspectual markings on both the adjectives and the verbs of ASL. Klima and Bellugi (1979) describe the forms associated with the meanings of protactive, incessant, contuniative, habitual, iterative and resultative aspects for ASL verbs. Aspectual modulations are also observed on adjectivals (Klima & Bellugi, 1979). Table 3.1 summarizes temporal aspect in ASL as shown in Figure 3.4.

Table 3.1: Temporal aspect in ASL: form-meaning relations. Adapted from Klima and Bellugi (1979).

Temporal Aspect	Form	Meaning
Protactive	a long tense hold and no movement	'duration in time'
Incessant	a tiny, tense and uneven movement made rapidly and iterated several times	'incessantly'
Contuniative	a elliptical modulation on the verb with a slow reduplication	'for a long time'
Iterative	reduplicated form, characterized by a tense performance of the movement followed by a slow return to the onset of the sign	'over and over again'
Resultative	a single elongated tense movement which accelerates to a long final hold	'resulting in a completely change of state'
Habitual	reduplication of the sign three times and a transitional movement is inserted between the copies	'regularly'

Aspectual markings are "characterized by dynamic qualities of movement" such as manner (hold, continuous, restrained), rate (slow, fast), tension (tense, lax), evenness (even, uneven), size (elongated, abbreviated) (Klima & Bellugi, 1979), which may also be accompanied with a change in the shape of verb's movement. Change in the shape of movement or in dynamic qualities of movements are realized at the same time with the other phonological units such as handshape. However, to explain the reduplication in habitual and iterative aspect marking and the final hold in resultative form, a phonological model also need to have sequential segments. Hence, for aspectual marking, sign languages use both strategies: simultaneity and sequentiality among phonological units.

3.1.4 Pluralization

Some sign languages use two kinds of reduplication to indicate plurality on nouns (Sutton-Spence & Woll, 1999; Pfau & Steinbach, 2005; Steinbach, 2012):

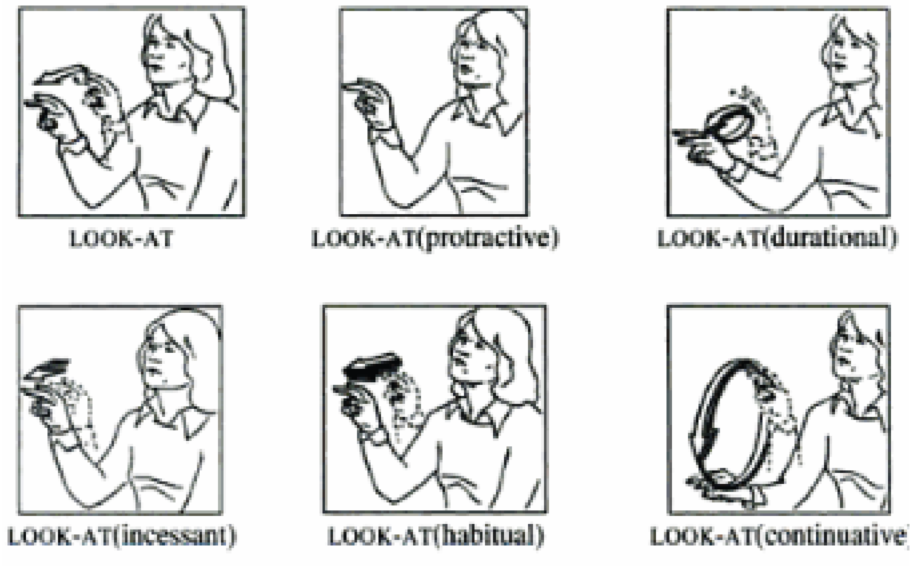


Figure 3.4: Aspectual markings on the verb LOOK-AT (Klima & Bellugi, 1979)

(i) Simple reduplication: Sign is repeated three times at the same location.

(ii) Sideward reduplication: Sign is repeated three times and each repetition is distributed to a different location which is next to the one before.

Steinbach (2012) states that in DGS, body-anchored nouns and signs with complex movements, i.e., signs which have inherent repetition of movement, are not marked for pluralization. It is called "zero marking". He also points out that the signs whose place of articulation is the midsagittal plane are simply reduplicated (e.g., BOOK++), and the signs which are realized at the lateral side are undergo sideward reduplication (CHILDREN, see Figure 3.5).

Figure 3.5: Pluralization of the sign CHILD, which is signed at the lateral side of the dominant hand, is achieved by sideward reduplication. Photographs are taken from the video for CHILDREN sign in the online dictionary https://www.signingsavvy.com/sign/CHILDREN/74/2

3.2 Derivational Processes

3.2.1 Compounds

A compound sign consists of two or more signs. Compounding may be sequential or simultaneous in sign languages, i.e., if two signs are linearly composed, it is sequential, if the signer uses one of its hands for signing one sign and the other for signing the other sign, it is simultaneous (Meir, 2012). The meaning of the compound is not the same as the composition of the meanings of its parts. A compound sign looks more like one-single sign rather than two, because phonological segments are either reduced or deleted while compounding. Compounds are signed in less time than their equivalent phrases (Klima & Bellugi, 1979).

3.2.2 Nominalization

The first work which systematically differentiates nouns from their related verbs is (Supalla & Newport, 1978). They focus on a list of 100 noun-verb pairs each of which contains an instrument and an action performed by that instrument. Some example pairs are chair/sit, bed/go-to-bed and iron/to iron. The handshape, the location and orientation of the signs in a pair are exactly the same. The movement in nouns is reduplicated and restrained; whereas the movement of the related verbs is not. In restrained manner, the muscles of the articulator are more tense and so the hands sign faster. In some sign languages, the verbs are claimed to have a wider and a longer movement than the corresponding nouns (Meir, 2012).

Figure 3.6: Nominalization in TİD. The verb form seen in the left photograph is rapidly repeated in the noun form as seen in the photographs at the right side. Snapshots are taken from the videos for TİD signs OTUR 'to sit' and SANDALYE 'chair' located in http://www.spreadthesign.com/.

Not all verb forms go under this nominalization process. There seems to be some phonological restrictions on the verbs that prohibit them to be nominalized. Brentari (1998) observes that nouns can be derived from verbs by movement reduplication only if the verb has a light syllable in ASL.

Klima and Bellugi (1979) claim that when a trilled movement is added to ASL verbs such as ACT, SWIM, WALK and CHAT, the associated nouns such as ACTING, SWIMMING, WALKING and CHATTING are derived. Trilled movement is a small, quick and repeated movement whose repetitions are uncountable. Padden and Perlmutter (1987) call these nouns "Activity Nouns", and propose "Activity Noun Rule" which states that non-stative verbs become an activity noun by adding a trilled movement.

3.2.3 Derived Adjectives

Padden and Perlmutter (1987) note that the derivational form of 'characteristically adjective' is constructed by adding the adjective a reduplicated circular movement. If adjective is a one-handed sign, the derivational form will be a two-handed sign with an alternating movement on the non-dominant hand. Padden and Perlmutter (1987) also state that the derivational form 'adjective+(ish)' is constructed by adding the adjective a trilled movement. Both the ISH and Characteristic Adjective Rule may apply to other's output.

3.3 Classifiers

Classifier nouns and predicates are observed in many sign languages. They categorize the real world objects. Classifiers in sign languages seem iconic and gestural since they model the form of these objects. Supalla (Supalla, 1982, 1986) groups ASL classifiers as follows:

i. **Size and Shape Specifiers (SASSes)** describe the size and the shape of an entity. SASS may have hand-parts as different morphemes.

ii. **Semantic classifiers** categorize nouns into classes such as humans, animals, or vehicles. Handshape works as a morpheme for referring the semantic category of the noun.

iii. **Body classifiers** are used to represent an animate entity which has a body or limbs.

iv. **Bodypart classifiers** such as eyes, mouth, or hands can be used as markers to refer to themselves. Limb classifiers refer to the hands or the feet of animals.

v. **Instrumental classifiers** refer to instruments and tools.

Classifier predicates or "verbs of motion" (Supalla, 1986) are considered as morphologically complex signs which are composed of morphemes such as the handshape which specifies the object's semantic type (human, animal, round object, etc.), the movement that describes the motion of the object and the position of the hands which encodes the spatial relations between objects. The classifiers in [i-v] except for body classifiers can take part in classifier predicates.

Classifier predicates are different than the other types of verbs (agreement, plain, spatial) because the handshape functions as a morpheme in this constructions.

Spatial relations may be used to describe the location of an entity with respect to another entity. For example, the meaning "a man with a brown hat is standing next to a tree, facing the tree" is achieved by the sign utterance in Figure 3.7. The predicate in the last photograph (F) in Figure 3.7 have 4 morphemes: two handshape morphemes (a classifier for the man and a classifier for the tree, the position morpheme (BE LOCATED), the facing morpheme. The predicate here is the spatial relation between the locations of the two objects. It is not a frozen lexical item, when 'next to' relation is signed for entities different than tree and man, it would have a completely different form.

In Figure 3.7, we do not observe an overt adposition to indicate the meaning of 'next to', instead this information is transmitted by locating the classifier of the man next to the classifier of the tree. Sign languages are claimed not to have overt spatial adpositions (Pfau & Aboh,

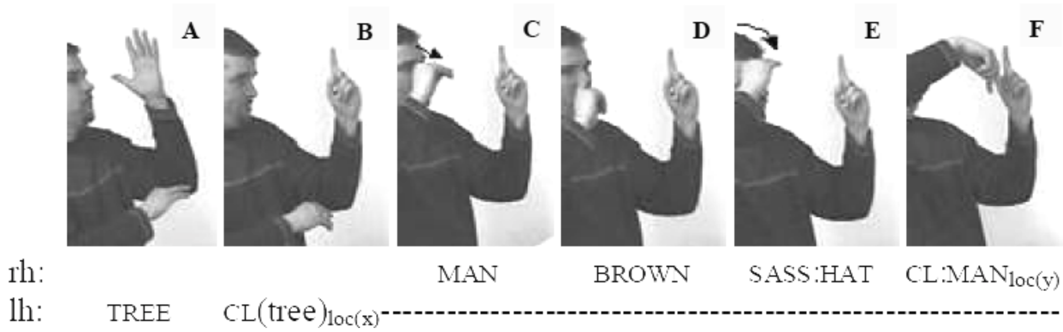


Figure 3.7: In this classifier construction, signer first articulates the sign TREE, then it locates the classifier for the TREE with his left hand. Later, he signs the sequence MAN BROWN SASS:HAT with the right hand while the left hand simultaneously holding the classifier for the tree. In the last photograph, the classifier for man is located next to the tree. Posture meaning ('facing the tree') is given by the orientation of the hand. Example is taken from Pfau and Aboh (2012).

2012), instead the spatial relations between the entities are encoded by using "classifier predicates".

3.4 Morphotactics

Morphotactics is the study of the order of the morphemes in a word. There are not many detailed studies on sign language morphotactics. Even the sign morphology is mostly simultaneous, the order of how morphemes are added is important. Sometimes the order changes the meaning of the inflected form. Some orders may lead to ungrammatical forms.

Emmorey (2002) states the application order of the morphological markers such as temporal aspect and distributional aspect would result in a change in the meaning as expected. Example combinations in 2 are shown in Figure 3.8.

(2) i. GIVE((exhaustive), durational) means "to give to each, that action recurring over time"

ii. GIVE((durational), exhaustive) means "to give continuously to each in turn"

iii. GIVE(((durational), exhaustive), durational) means "to give continuously to each in turn, that action recurring over time"

Sandler (1990) states that if an ASL verb is marked for both habitual aspect and person, there must be an order for inflections: first the person marker, and then the aspect marker. She claims that reduplication in the realization of habitual aspect would take place before person marking if it is not in this order, and it will result in an ungrammatical form where only the first two locations are marked for person in the reduplicated form.

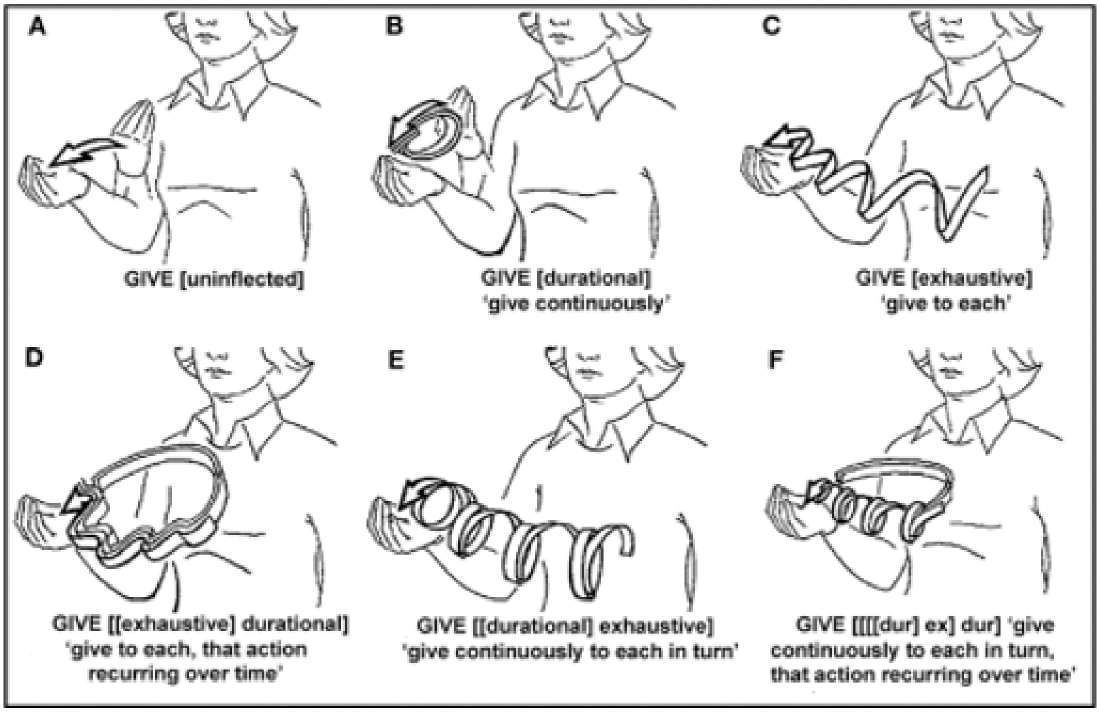


Figure 3.8: Order between temporal aspect and distributional aspect markings in ASL (Klima & Bellugi, 1979).

3.5 Computational Morphology

To best of our knowledge, there are two computational morphology studies dealing with sign language. Shield and Baldridge (2008) implement the first morphological analyzer for a sign language. Jordi Porta and Colas (2012) and Zamorano (2014) propose a two-level computational inflectional morphology model for Spanish Sign Language.

3.5.1 A Morphological Analyzer for Sign Language

Shield and Baldridge's (Shield & Baldridge, 2008) morphological analyzer for sign language use Xerox Finite State Toolkit (Beesley & Karttunen, 2003) to model the phonotactics required for the temporal aspect marking of the verbs in American Sign Language. This analyzer deals with only the two verbal aspect markers, namely contuniative and habitual aspect.

Shield and Baldridge's analyzer (Shield & Baldridge, 2008) has a small lexicon which consists of the underlying forms of five ASL verbs: COOK, FORCE, PLAY, SEE and STUDY (Figures 3.9-3.13).

Each underlying form is represented as a list of values assigned for the parameters such as type, handshape, location, orientation and movement.

i. Sign type: one-handed (1H), two-handed symmetrical (2HS), two-handed dominant (2HD)

Figure 3.9: Citation form of ASL sign COOK

It is a two-handed sign. The handshapes of the both hands are same, it is the 5-handshape. Palm orientation for the dominant hand is “down” and for the non-dominant hand is “up”. The sign is articulated in neutral space. There is twist on the dominant hand. Dominant hand contacts the non-dominant hand. (The photographs are from http://www.lifeprint.com/asl101/pages-signs/c/cook.htm.)

Figure 3.10: Citation form of ASL sign FORCE

It is a two-handed sign. The handshape for dominant hand is C-handshape and non-dominant hand is 5-handshape. Palm orientation of the dominant hand is “out” and it is ‘down’ for the non-dominant hand. The sign is articulated in the neutral space. There is no reduplication and no twist. Dominant hand touches the non dominant hand. (The photographs are snapshots of the video http://www.handspeak.com/word/search.php?wordID=FORCE&submitword=Find.)

ii. Handshape: A, B, C, 5, E, F, G, H, 3, O, R, V, W, X, Y, 8

iii. Location: face, nuet (neutral), torso, neck, shoulders, chest, trunk, upper arm, elbow, forearm, wrist

iv. Palm orientation: up, down, out, in, base

v. Movement: Touch (contact between two hands), Tw (twist: turning the wrist), Reduplication (iteration), Arc, Slow (signing rate slower than normal)

Shield and Baldridge (2008) make use of these parameters to construct rules that model the morphophonological changes occurring when the verbs are marked with these aspectual markers. They represent the underlying forms of these verbs as follows:

$COOK =< T : 2HD, DH : 5down, NDH : 5up, Loc : neut, +Touch, +Tw, -Redup, -Arc, -Slow >$
$FORCE =< T : 2HD, DH : Cout, NDH : 5down, Loc : neut, +Touch, -Tw, -Redup, -Arc, -Slow >$

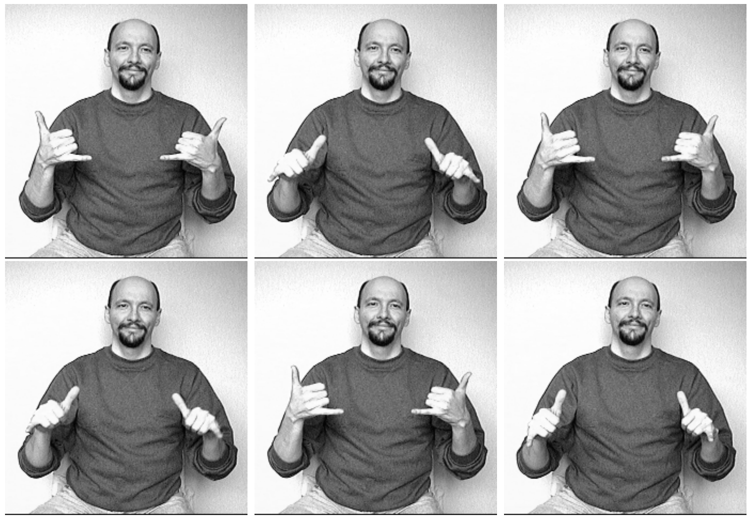


Figure 3.11: Citation form of ASL sign PLAY

It is a two-handed symmetrical sign. The handshape is same for the two hands (Y). The palm orientation for the both hands are “base” . The place of articulation of the sign is neutral space. There is reduplication (2-3 times) within the sign. There is twist on both hands. There is no contact with the body, non-dominant hand, or face. (The photographs are from http://www.lifeprint.com/asl101/pages-signs/p/play.htm.)

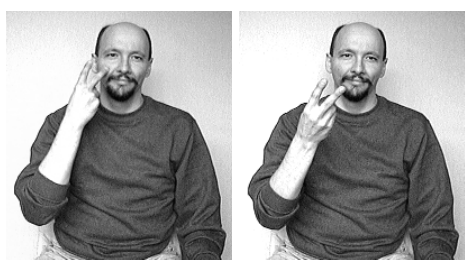


Figure 3.12: Citation form of ASL sign SEE

It is a one-handed sign. There is a local movement. The handshape is V. The palm orientation is “in”. The place of articulation of the sign is the face. There is no reduplication, no twist. There is contact with the face, but no touch to non-dominant hand. (The photographs are from http://www.lifeprint.com/asl101/pages-signs/s/see.htm.)

$PLAY =< T : 2HS, DH : Ybase, NDH : Ybase, Loc : neut, -Touch, +Tw, +Redup, -Arc, -Slow >$
$SEE =< T : 1H, DH : Vin, NDH : none, Loc : face, -Touch, -Tw, -Redup, +Arc, -Slow >$
$STUDY =< T : 2HD, DH : 5in, NDH : 5up, Loc : neut, -Touch, -Tw, -Redup, -Arc, -Slow >$

Shield and Baldridge (2008) define Arc feature as whether or not the sign follows a path through space, so they mark the citation form of SEE as +Arc[1].

[1] Phonological models such as Movement-Hold Model differentiates straight movements from arc movements, i.e. citation form of SEE has a straight movement not an arc movement with respect to that model .

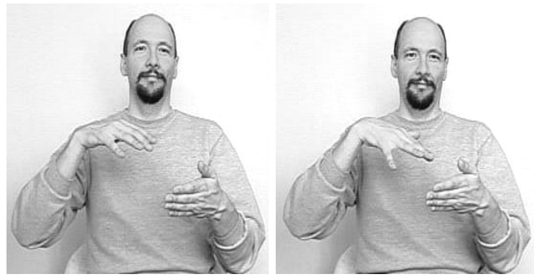


Figure 3.13: Citation form of ASL sign STUDY

It is a two-handed sign. There is a local movement on the dominant hand: wiggling. The handshape is same for the two hands (5). The palm orientation for the dominant hand is "in" and for the non-dominant hand is "up". Sign is articulated in neutral space. There is no reduplication, no twist, no touch. (The photographs are from http://www.lifeprint.com/asl101/pages-signs/s/study.htm.)

They define two rules for the habitual and continuative aspect inflection of verbs:

i. If the verb is inflected for habitual aspect, then add arc and reduplicate (Hab. → +Arc, +Redup).

ii. If the verb is inflected for continuative aspect, then add arc and make the movement longer and slower (Cont → +Arc, +Slow).

For example, when the verbs SEE and STUDY is inflected for continuative and habitual aspect, the resulting surface forms are as follows:

$[SEE_{Hab}] =< T: 1H,\ DH: Vin,\ NDH: none,\ Loc: face, -Touch, -Tw, +\mathbf{Redup}, +\mathbf{Arc}, -Slow >$
$[SEE_{Cont}] =< T: 1H,\ DH: Vin,\ NDH: none,\ Loc: face, -Touch, -Tw, -Redup, +\mathbf{Arc}, +\mathbf{Slow} >$
$[STUDY_{Hab}] =< T: 2HD,\ DH: 5in,\ NDH: 5up,\ Loc: neut, -Touch, -Tw, +\mathbf{Redup}, +\mathbf{Arc}, -Slow >$
$[STUDY_{Cont}] =< T: 2HD,\ DH: 5in,\ NDH: 5up,\ Loc: neut, -Touch, -Tw, -Redup, +\mathbf{Arc}, +\mathbf{Slow} >$

Some features of signs cannot be co-articulated when these inflections occur, hence there are some phonological constraints on the formation of the verbs that are marked for aspect. Shield and Baldridge (2008) put these constraints into their analyzer by adding the following rules:

i. Arc feature cannot be articulated simultaneously on a two-handed symmetrical (2HS) sign like PLAY which has +Tw feature. Hence, the sign loses its +Tw feature when it is inflected for habitual or continuative aspect. They define NoTwistWith2HSArc rule for this case.

   NoTwistWith2HSArc Rule : T:2HS, +Arc → -Tw.

   When PLAY is inflected for continuative aspect, this rule applies, and Tw feature is deleted from the result:

   $[PLAY_{Cont}] =< T: 2HS,\ DH: Ybase,\ NDH: Ybase,\ Loc: nuet, -Touch, -\mathbf{Tw}, +Redup, + Arc, +Slow >$

ii. The signs, which have +Tw feature and a contact with the body or the non-dominant hand, lose +Touch feature when they are inflected for habitual or continuative aspect and an +Arc feature is added to their form. They define NoTouchWithArcTwist rule for this case.

NoTouchWithArcTwist Rule : +Tw, +Arc → -Touch.

When COOK is inflected for habitual aspect, this rule applies, and Touch feature is deleted from the result:

$[COOK_{Hab}] =< T : 2HD,\ DH : 5down,\ NDH : 5up,\ Loc : neut, -\textbf{Touch}, +Tw, +Redup, + Arc, -Slow >$

iii. The non dominant hand is completely dropped when there is reduplication and the non dominant hand has the handshape 5 and orientation down. They define the following rule to handle this case:

NoTouchWoutNDH: if +Redup then 5down → none.

Dropping of the non dominant hand also makes +Touch impossible. They formalize this case with the *NoTouchWoutNDH* rule:

NoTouchWoutNDH : if NDH:none → -Touch.

For example, when habitual aspect is added to the sign FORCE, the result is:

$[FORCE_{Hab}] =< T : 2HD,\ DH : Cout,\ NDH : 5none,\ Loc : neut, -\textbf{Touch}, -Tw, +Redup, + Arc, -Slow >$

Shield and Baldridge (2008) is the first computational analyzer for sign language which only deals with aspect. They use vectors of parameters to represent the underlying forms and they define rules applying on these representations. They do not commit to a particular phonological model such as Movement-Hold Model (Liddell & Johnson, 1989), Hand-Tier Model (Sandler, 1989) or Prosodic Model (Sandler, 1989). Their representation is not autosegmental, it does not involve any sequential segments or and any timing information of the segments, only the parameters like handshape, location, palm and movement are assumed to be simultaneous.

3.5.2 A Two-Level Computational Morphology for Spanish Sign Language

Jordi Porta and Colas (2012) and Zamorano (2014) implement computational morphology for aspectual marking, verbal agreement, entity classifiers and nominalization in Spanish Sign Language (LSE). This system has two levels: a lexical form level which contains the sign's transcription in Hamburg Sign Language Notation System(HamNoSys) (Hanke et al., 2011) and its morphological features (i.e., -sg: singular), and a surface form level which is represented also in HamNoSys. They define rewrite rules for these morphological processes, and compile transducers using the OpenGrm Thrax Grammar Compiler.

HamNoSys[2] is a phonetic transcription system similar to International Phonetic Alphabet (IPA), and it is widely used by sign language generation systems as input to animation of

[2] http://www.signlang.uni-hamburg.de/projects/hamnosys.html

signing avatars (Elliott, Glauert, Kennaway, & Marshall, 2000; Marshall & Safar, 2005). Each symbol in HamNoSys simply describes a handshape, a hand position, a location, a non-manual, an orientations or a movement. Its alphabet is based on Stokoe's notation (Stokoe, 1960) so it is a linear representation in which the symbols are accepted as simultaneous. Besides, HamNoSys reflects sequentiality taking place in the change of handshape, orientation and location. Even if HamNoSys has sequential and simultaneous flavor, HamNoSys is not a detailed representation that shows how these components of the signs are temporally related. In order to capture the morphological changes, HamNoSys has symbols that indicates the modality of movement (fast, slow, tense) and basic repetition information.

CHAPTER 4

SIGN LANGUAGE PHONOLOGY

Stokoe (1960) claims that the smallest meaningless units (phonemes) that signs are composed of are handshape, location and movement. These units are proposed to combine simultaneously in his model. Orientation of the palm is suggested in addition to these parameters (Battison, 1978). SL phonology models aim to construct phonological representations that show the relations between these components, and explain the constraints that apply during sign formation.

Signs are one-handed or two-handed. Battison (1978) classifies two-handed signs into three basic types:

- Type 1: Both hands are moving: Two hands have the same handshape and the same movement (synchronously or alternating). There may or may not be contact with the other hand or the body.
- Type 2: One hand is active and both have the same handshape.
- Type 3: One hand is active and both have different handshapes.

Battison (1978) also proposes a fourth type for the compounds (Type C) which combines the above defined types. He defines two phonological constraints that apply to the lexical two-handed signs: *symmetry* and *dominance conditions*. According to *symmetry condition*, "if two hands move independently, then they have the same location, the same handshape, the same movement (either simultaneously or alternating) and the orientation is either symmetrical or identical". The *dominance condition* is defined as follows: "if two hands have different handshapes, then one of the hands is passive and handshape of this hand is restricted to a set of unmarked handshapes ('B', 'A', 'S', 'C', 'O' '1', '5')". These conditions do not apply to classifier constructions.

Liddell (1984) and Liddell and Johnson (1989) argue that there are also sequential segments in the phonological structure since there may be changes in handshape, location, movement, and orientation parameters. Also, signs may be associated with a sequence of non-manual markings.

Signs mostly have only one handshape, however some signs may have a handshape change. For example, as seen in Figure 4.1, ASL sign LIKE has initially has a open 8 handshape, then the finger configuration is changed at the end of the sign. Liddell and Johnson (1989) claim that for the signs with two handshapes, the ending handshape is not predictable given the initial handshape.

Figure 4.1: Handshape change: The handshape is changed from open 8 handshape to closed 8 handshape. Photographs are taken from the video for the ASL sign LIKE from http://www.spreadthesign.com/.

Sandler (1989) argues that modifications on handshape are limited by the following set of actions: opening, closing, curving, bending or rotating. Lexical signs have "active fingers" which is a fixed set of selected fingers that move or contact body (Mandel, 1981). Sign linguists have not observed other patterns of handshape change other than aperture change.

Every sign is claimed to have one place of articulation. It may be articulated at the body, at the head, on the non-dominant hand, at the arm, or at neutral signing space which is the space in front of the signer's torso that he can reach with his hands (Battison, 1978). Signs may have at most two locations which are located at the same place of articulation. In simple signs, such re-locations are defined in the lexicon. Morphological processes such as compounding and person agreement may give rise to a change in its location. Stokoe's model cannot represent person marking since it only suggest simultaneity, whereas models suggesting sequentiality such as Movement-Hold Model (Liddell & Johnson, 1989) or Hand-Tier Model Sandler (1989) are capable of represent agreement in their models.

Brentari (1998) states that all mono-morphemic signs have a movement: either a path movement (articulated by shoulder or elbow) or a local movement (articulated by wrist or finger joints). Brentari (1998) claims poly-morphemic signs in ASL may have movement combinations such as bidirectional+repeated, unidirectional+repeated and circle+straight, whereas straight+circle combination is not possible for the signs with two internal movements.

Brentari (1998) argues that ASL native signs only allows one orientation change within a syllable. Syllable in SLs is a unit which must contain a movement of any type.

In this chapter, we focus on three sign phonology models: Movement-Hold Model (Liddell & Johnson, 1989), Hand-Tier Model (Sandler, 1989) and Prosodic Model (Brentari, 1998). We choose them among many others since they are based on *"Autosegmental Phonology"* (Goldsmith, 1976) from which they get their explanatory power for representing both sequentiality and simultaneity.[1] In these models, the features which are employed in autosegmental representations carry the information of how articulators such as fingers, palm, thumb, wrist and forearm work together to build a sign from its components.

Movement-Hold Model (MHM) and Hand-Tier Model (HTM) inherit the idea of timing skeletons (McCarthy, 1981). In MHM, segmental tier consists of movements (Ms) and holds (Hs), and HTM makes use of locations (Ls) and Ms in the timing tier. Prosodic Model (PM) does

[1] The reader may refer to (Brentari, 1998) for a review of other sign phonology models.

not label movement as a segment as the other two models, it suggest that there are timing slots (Xs) which are associated to the features which change through movements. Next three sections[2] present how autosegmental representations and rules are defined within these models, and in what ways these models are different, i.e., in their definitions of autosegments, tiers and charts. In these sections, we will show how these models represent the morphological processes such as agreement marking, aspectual marking, nominalization, compounding and formation of classifier constructions.

4.1 Movement-Hold Model

Liddell (1984) and Liddell and Johnson (1989) suggest that ASL signs consist of sequential phonological segments: holds (H) and movements (M). Movement is defined as a time interval in which some articulatory features change and basically in which the hand moves. Hold is a segment in which the articulatory features are in a static state where the hand does not move. They support their claim that signs are sequences of Ms & Hs with the following observations:

(i) There are signs with a local movement (e.g. wiggling of the fingers) in which the local movement does not occur during the initial and final (hold) segments

(ii) There are signs which are accompanied by a non-manual marking only at the initial and final segments of the sign.

Both sequential and simultaneous components of the signs are represented in this model. This phonological model inherits the temporal relationships among the elements of the Autosegmental Phonology framework (Goldsmith, 1976) and also adopts the idea of timing skeletons (McCarthy, 1981), where the skeleton is defined as a sequentially ordered tier of segments consisting of movements and holds.

A segment has five main entries: a major class, a contour of movement, a local movement (a rapidly repeated movement), a quality feature describing temporal or physical quality of the segment, and a contour plane upon which the hand moves. The values of these properties are given in Table 4.1. Liddell (1990b) suggests that both the path movements and the local movements such as wiggling, circling, rubbing, hooking, twisting may be associated to the movement segment in the timing tier. Local movements may also be attached to holds.

In Movement-Hold model (Liddell & Johnson, 1989), there are four articulatory tiers in addition to the segmental tier: hand configuration, place of contact, orientation and facing tiers[3]. Hand configuration tier describes handshape, it is composed of following three articulatory features: forearm involvement, *handshape* and *configuration of fingers*. Place of contact tier describes hand's contact with the body by employing four kinds of features: the *handpart* which touches the body, the *location* on the body which is contacted, *spatial relation* between the handpart and the location, and the *proximity* which describes how proximate the handpart is to the location. Facing is composed of a *handpart* and a *location* where the handpart points to the location. Orientation is made up of a *handpart* and a *plane*, and it indicates which handpart looks towards the ground (HP). Articulatory features are shown in Table 4.2.

[2] Section 4.1 is a partly presented in ESSLLI 2015 Student Session and it is published in online proceedings (Sevinç, 2015).

[3] Non-manual tier is also included in the list of tiers in (Liddell, 1990b)

Table 4.1: The properties that segments carry in Movement-Hold Model

Major class	movement [M] or hold [H]
Contour of movement	straight path [str], round path [rnd], seven contour [7], an arc path [arc], a circular path [circle]
Local movement	wiggling[wg] , circling[circling] , rubbing[rub] , hooking[hk], twisting[tw], flattening [fl], releasing [rel]
Quality features	prolonged [long], shortened [srt], accelerating [acc], tense [tns], reduced path [sm], enlarged path [1g], contacting [contact]
Contour plane	horizontal plane [HP], vertical plane[VP], surface plane [SP], midsagittal plane [MP], oblique plane [OP]

Table 4.2: Articulatory features in Movement-Hold Model

handshape	A, S, 1, !, I, Y, =, >, H, V, K, D, R, r, W, 6, 7 ,8 , F, 9, B, 4, T, N, M
finger configuration	o (open), op(closed),” (hooked), ˆ(flattened)
handpart of contact	RAFI (radial side of the finger(s)), TIFI (tips of finger(s)), PDFI (pads of finger(s))
proximity	p (proximal), m (medial), d (distal), c (contact)
spatial relation	ipsi, contra, over, under, behind, tipward, baseward, toward ulnar side, toward radial side, palmward, backward
location	BH (back of head), CN (chin), TH (top of head), NK (neck), FH (forehead), SH (shoulder), SF (side of forehead), LG (Leg), ST (sternum), NS (nose), CH (chest), CK (cheek), TR (trunk), ER (ear), UA (upper arm), MO (mouth), FA (forearm), LP (Lip), AB (abdomen), JW (jaw)
handpart	IN (inside), PD (pad), BK (back), RA (radial), UL (ulnar), TI (tips), KN (knuckle), BA (base), HL (heel), WB (web), PA (palm)
plane	HP (horizontal plane), VP (vertical plane), SP (surface plane), MP (midsagittal plane), OP (oblique plane)

Figure 4.2 demonstrates the corresponding autosegmental representation of ASL sign LIKE in MHM (Liddell & Johnson, 1989). This sign has HMH sequencing of segments. There is a handshape change which is from open 8 handshape to closed 8 handshape. 8 is a handshape which has all but middle finger open and spread. The location of the sign is the chest. The sign starts with a contact (c) of pads of fingers (PDFI) to sternum (ST) and moves proximal (p) to ST and ahead of it. While moving ahead of the sternum, the tips of the selected fingers (TIFI) touch each other. The palm (PA) faces the surface plane (SP), in other words, the body plane. Orientation is defined as the relation between ulnar (UL) part of the hand and the ground (HP). There is no orientation change. There are no non-manuals accompanying the sign, hence there is no non-manual tier.

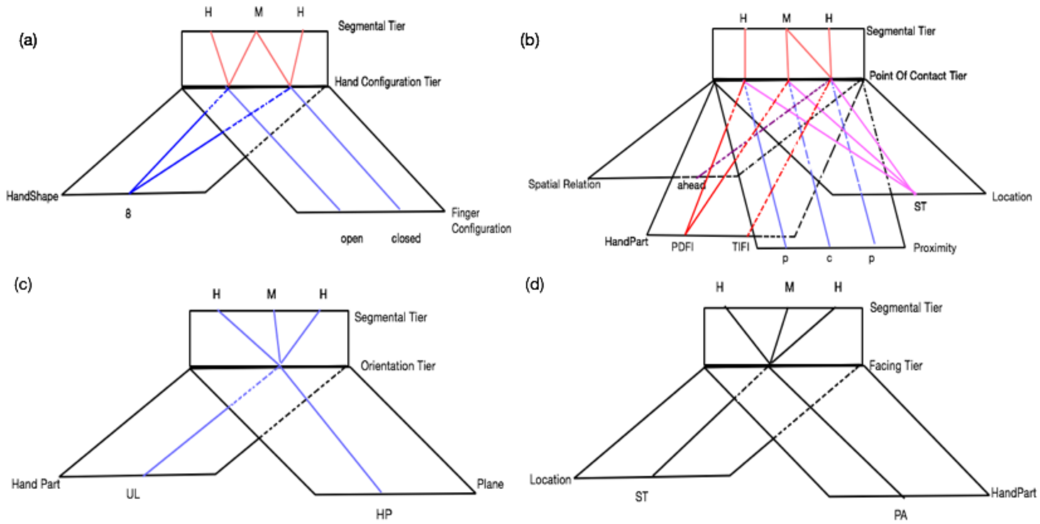


Figure 4.2: Autosegmental representation of ASL sign LIKE in Movement-Hold Model (Liddell & Johnson, 1989). (a) Hand Configuration (b) Place of Contact (c) Orientation (d) Facing.

Liddell (1990b) also suggests a model in which there is a tentative number of tiers, e.g., segmental tier, hand configuration tier, location tier, facing tier, orientation tier, non-manual tier, which are all at the same level in the hierarchy. Segments in the segmental tier are directly associated with these articulatory features in these tiers. He proposes this organization on the grounds that each of these tiers may function as a separate morpheme. As seen Figure 4.4, the tier organization in Figure 4.4 is slightly different than the tier organization in Figure 4.2 (Liddell & Johnson, 1989), where there are four main tiers and the other low level articulatory tiers are dominated by these four tiers.

An annotation of autosegmental representation of ASL sign LIKE is shown in Figure 4.3. It is created by ELAN (Hellwig & Uytvanck, 2005) which is perhaps the most frequently used tool to create, edit, visualize and search annotations for video recordings of sign languages. This annotation aims to present how segmental and articulatory features are associated to the timeline of the video recording of ASL sign LIKE and show how temporal overlap between the elements of the tiers takes place in real time.

4.1.1 Morphological Processes in MHM

Movement-Hold Model (Liddell, 1984) was the first model that proposed that signs have sequentially ordered segments, which make it possible to explain the phonological organization of the person marking on verbs. Agreement on verbs are marked either by a change in the direction of movement, or an orientation change, or both. We may also think these phonological changes which occur during person marking are an evidence for the existence of sequential segments in signs.

Body-anchored single agreement verbs such as SEE has a movement starting from a location near the cheek (CK) to the locus of the object, if it is marked for object agreement. Autoseg-

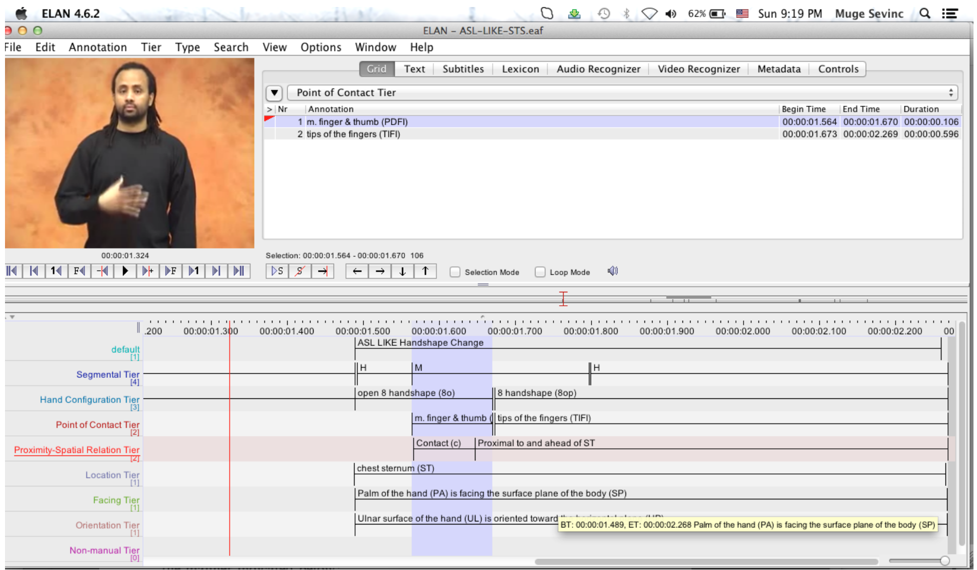


Figure 4.3: Annotation of the phonological representation of ASL sign LIKE in Movement-Hold Model (Liddell, 1990b). Video is from http://media.spreadthesign.com/video/ogv/13/48560.ogv and it is annotated by using ELAN (Hellwig & Uytvanck, 2005).

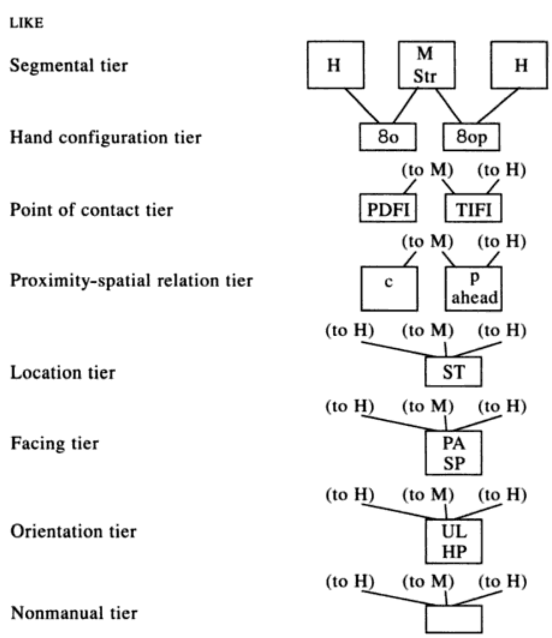


Figure 4.4: The autosegmental representation of ASL sign LIKE in Movement-Hold Model (Liddell, 1990b, p.43).

mental representation of the citation form of ASL sign SEE is shown in Figure 4.5. When it is marked for person, the location morpheme is inserted in the feature bundle, for example for first person object marking, there will be a contact at the sternum (ST) instead of moving ahead of cheek (CK).

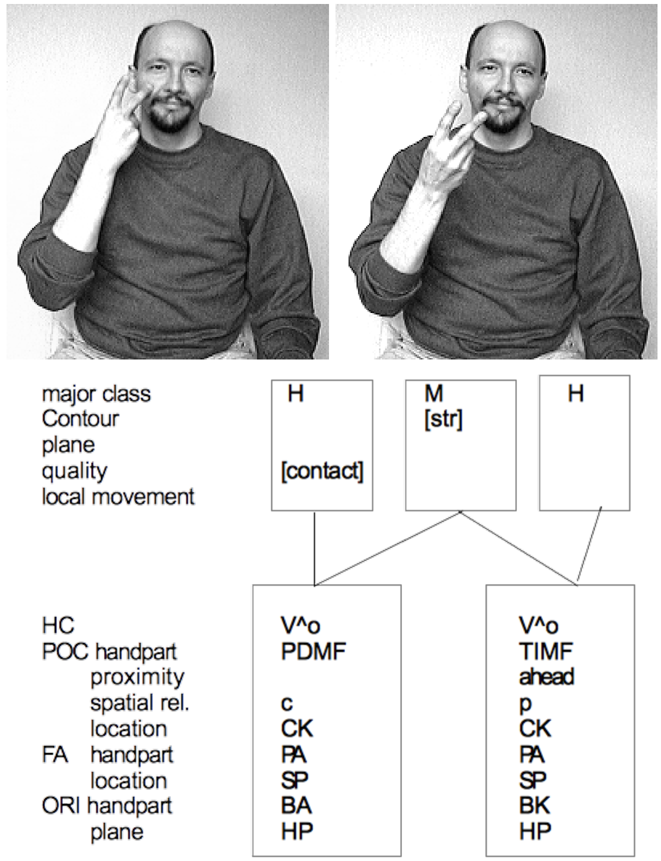


Figure 4.5: Citation form of ASL sign SEE (http://www.lifeprint.com/asl101/pages-signs/s/see.htm) and its autosegmental representation in Movement-Hold Model.

This model defines double agreement verbs as having two different locations, one for the subject and one for the object. These locations are associated with two different hold segments, one at the beginning of the sign and one at the end of the sign. To have a movement segment between these two hold segments means that the hand moves between these two locations. In this representation, this movement segment is also associated with both of the locations. For example, the inflected sign ${}_3$GIVE$_1$ would have a HMH sequence in its timing tier, and the first H and M will be associated with the location for the third person, and the second H and M will be associated with the sternum (ST).

Person marking is achieved by the insertion of some articulatory feature(s) such as location and/or orientation features. This feature insertion is basically a morpheme insertion. For insertion of location and orientation morphemes into the agreement verbs, we define two autosegmental rules as in Figure 4.6: the first rule for the verbs which only change its direction of movement and the second rule for the verbs which only change its orientation. For the verbs that change both, both rules are applied.

For phonological realization of aspectual markings, we need mechanisms such as insertion of features related to the dynamic qualities of movement, insertion of a feature for the shape

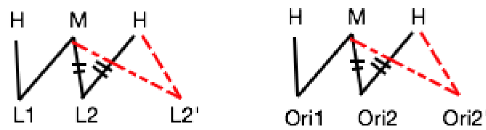


Figure 4.6: Autosegmental rules for object marking of forward agreement verbs in Movement-Hold Model.

of the movement, or reduplication. We will explain these mechanisms on continuative and habitual aspect marking. Based on Movement-Hold Model (Liddell & Johnson, 1989), we first describe the autosegmental representations of the citation verbs and inflected forms, and define the autosegmental rules required for aspect marking. We describe the representations for the same verb list (STUDY, COOK, FORCE and PLAY) as in Shield and Baldridge (2008). The autosegmental representations for these verbs are shown in Figure 4.7.

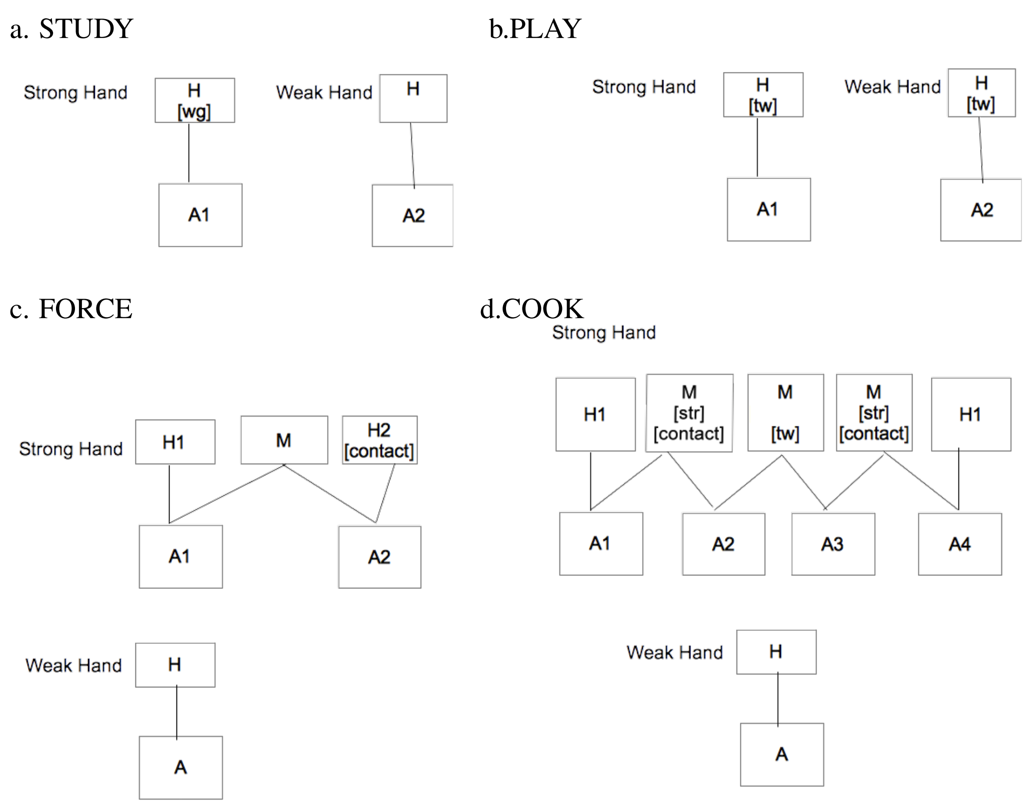


Figure 4.7: Simplified autosegmental representations for ASL signs in Movement Hold Model: STUDY, PLAY, FORCE, and COOK.

We propose a phonological rule for continuative aspect marking within Movement-Hold model and introduce the rule which Liddell and Johnson (1989) propose for the habitual aspect.

In continuative aspect, a movement with an elliptical form is added and the sign is articulated slower. In Movement-Hold model, the parameters of the segments such as "contour of movement" is to be updated as [arc] and "quality feature" as [long]. The autosegmental rule in Figure 4.8 is proposed for the one-handed signs which have HMH and H patterns.

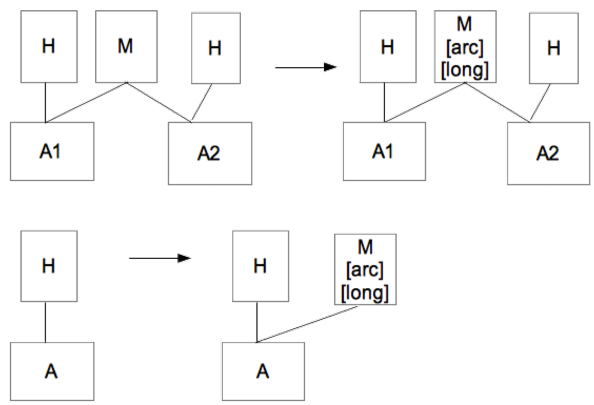


Figure 4.8: Phonological rules for continuative aspect inflection for one handed signs with HMH and H patterns.

Twisting is accepted as a local movement in Movement-Hold model, it is no different than wiggling. However, Shield and Baldridge (2008) state that the sign STUDY contains an internal movement which does not appear to change with the changes in aspectual inflection. The sign PLAY which is a two handed symmetrical sign loses its twisting feature when inflected for continuative aspect. They explain that there cannot be twist and arc at the same time for two handed symmetrical signs. Twisting remains when an arc is added to a two handed asymmetrical sign like COOK. For the signs like PLAY, we apply the rule in Figure 4.9.

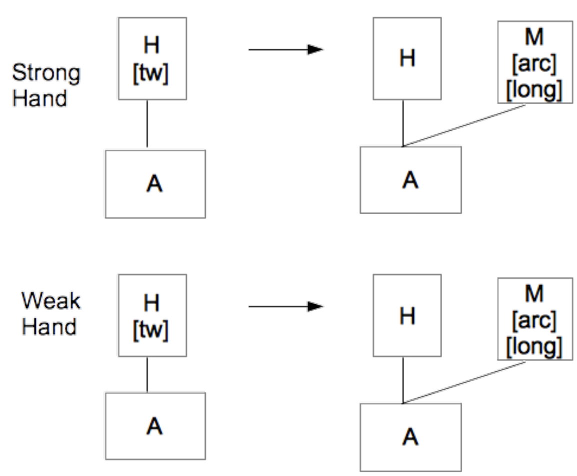


Figure 4.9: A phonological rule for continuative aspect inflection for two handed symmetrical signs which have only a hold segment

Shield and Baldridge (2008) add +Redup feature for habitual aspect inflection. Liddell and Johnson (1989) state that using +Redup as a feature is not adequate, reduplication shall be defined as a process rather than a feature. They define habitual aspect as a reduplication rule as in (3) where srt means shortened movement and 123 stand for HMH sequences. They apply movement epenthesis (4) and hold deletion (5) rules to the output of this habitual aspect rule. Movement epenthesis rule adds movements between two holds which are articulated at different locations. Hold deletion rule moves the holds which are between two movements.

(3)	1 2 3	→	1 2 3	1 2 3	1 2 3	1 2 3	(Reduplication)
			srt	srt	srt	srt	

(4)	1 2 3	→	1 2 3 M	1 2 3 M	1 2 3 M	1 2 3	(Movement Epenthesis)
			srt	srt	srt	srt	

(5)	1 2 3	→	1 2 M	2 M	2 M	2 3	(Hold Deletion)
			srt	srt	srt	srt	

For dual number marking, there are two mechanisms:

i. Repetition of the movement twice but by relocating the second location: we need a combination of three rules defined by Liddell and Johnson (1989), namely, reduplication, movement epenthesis rule, and hold deletion rule for describing the repetition, and relocating will be handled by person marking rules.

ii. Copying the autosegmental representation of the strong hand to the weak hand, the sign becomes two-handed, symmetrical and simultaneous.

For multiple marking, a rule which adds a arc shape to the contour of movement is enough, this process does not involve any repetitions. For exhaustive marking, the rules of repetition plus addition of [arc] feature is required.

Plurality of nouns requires two autosegmental rules for reduplication and feature insertion. Feature insertion rule inserts a new location to explain sideward reduplication.

4.2 Hand Tier Model

Sandler (1989) proposes Hand-Tier Model as an Autosegmental Phonology model whose main tiers are hand configuration (HC), place of articulation (POA) and timing tier. Timing tier consists of sequential segments such as locations (L) and movements (M). Locations replace the holds of Movement-Hold model, they do not need to be stationary like holds, internal movements can be associated to these segments through hand configuration. Locations are the beginning and the ending points of the sign. Figure 4.10 shows an autosegmental phonological representation of a sign.

Sandler (1989) argues that HC is a separate tier that spreads over the timing tier. Under the hypothesis that each tier represents a separate morpheme, they support their argumentation with the morphological evidence that HC functions as a morpheme at least in the classifier

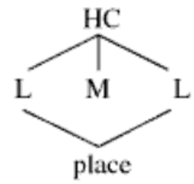


Figure 4.10: Canonical form of a mono-morphemic sign in Hand Tier Model (Sandler & Lillo-Martin, 2006).

constructions. Poizner, Bellugi, and Klima (1990) provide evidence in favor of the claim that HC is a separate formational tier. The evidence comes from a Wernicke-like aphasic patient who makes paraphasias (substitution of a sign with a different sign) specific to handshape. However, Sandler and Lillo-Martin (2006, p.141) state that autosegmental status of HC and POA tiers are phonologically motivated since they are not always morphemes. Each tier may not correspond to a morpheme in the Hand-Tier Model as it is the case for Arabic examples in Figure 2.2.

HC is multiply associated with the movement and the location segments. Battison (1978) indicates that there is only one major body location per morpheme of the simple signs. Sandler (1989) represents this information by multiply associating place with the locations in the beginning and the end of the sign as in Figure 4.10, she calls these associations as *"place harmony"*.

Relying on the theory of feature geometry of Clements (1985), Sandler (1989) proposes a feature tree for HC as in Figure 4.11 and for L as in Figure 4.13. These feature trees are multi-tiered and hierarchical structures, in which the association lines stand for the dominance relation. The terminal nodes of the tree carry two-valued features.

Root of HC tree dominates the handshape node and the feature [tense]. [+Tense] means that the internal movement (handshape change or orientation change) is repeated rapidly. If there is no internal movement, this feature is not used. When there is change but no repetition, then the feature is set to [-tense].

Handshape and orientation are the two major feature classes for HC category. Handshape dominates fingers, palm orientation and [extended hand] feature. Fingers node dominates the features that mark the selected fingers, and the position features which define the fingers configuration. [Extended hand] feature describes how the unselected fingers are positioned. If all fingers are selected, then this slot is empty. If unselected fingers are straight and spread, then it gets [+ext] value. If they are curled to the palm, then it has [-ext].

Palm orientation dominates four features [up], [in], [prone] and [contra]. [+In] refers to a palm which is oriented towards the signers body, [-in] refers to the outward orientation. [+Prone] is used for the flat of the palm facing the ground, [-prone] for its facing up. [+Up] means that the fingertips is pointing up, and [-up] means pointing down. [Contra] feature indicates that the palm is facing the left or the right side. [+Contra] is used for the side of the dominant hand, and [-contra] for the other side.

As seen in Figure 4.11, tiers in HC feature geometry are root, handshape, fingers, position, manner and palm orientation. All the tiers except for the position and palm orientation tiers

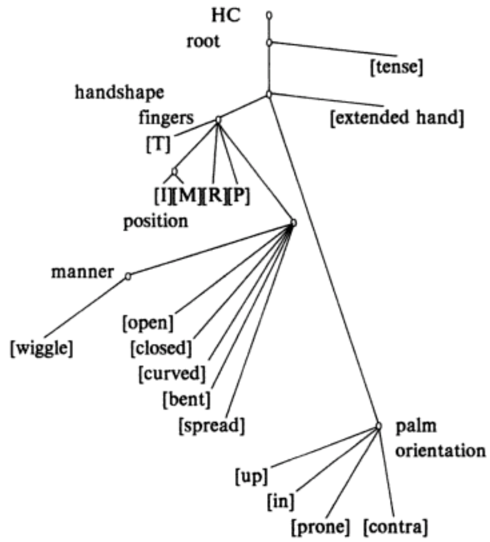


Figure 4.11: Feature tree for hand configuration in Hand Tier Model (Sandler & Lillo-Martin, 2006).

have features occurring simultaneously, i.e., if in the fingers tier have both [+T] and [+I] features, it means that the thumb and the index finger are selected, there is no sequential order relation between these two features. [T],[I],[M],[R],[P] are more like independent tiers. However, Sandler (1989) suggests that position and orientation tiers may have sequential autosegments, i.e., [+open][+closed] means that the fingers were first open, and then closed. Similarly, if there is twisting in the sign, the orientation tier will have two sequential features [+prone][-prone]. In other words, handshape change and orientation change are coded within the position and palm orientation tiers of the HC.

The argumentation that HC is a separate tier has to deal with the signs which undergo a handshape change during their articulation. Mandel (1981) reports that even if the signs change its handshape, the specified fingers in the hand configuration category are still the same. Sandler (1989) claims that handshapes are predictable for these signs with a handshape change, so that having HC twice both for the initial and final locations as in (Liddell, 1990b) is redundant.

The autosegmental representation in Figure 4.12 is suggested for ASL sign LIKE, where there is the 8-handshape with a change from open to closed fingers and the orientation of the hand is towards body [+in]. HC spreads over the LML segments, which means that this handshape change is observed simultaneously while the hand moves from the first location to the second. Unlike Movement-Hold model, HTM does not associate open and closed features directly with the segments in one to one manner.

As shown by the feature geometry tree of location seen in Figure 4.13, location category consists of

i. setting features ([contact])

ii. manner features ([restrained])

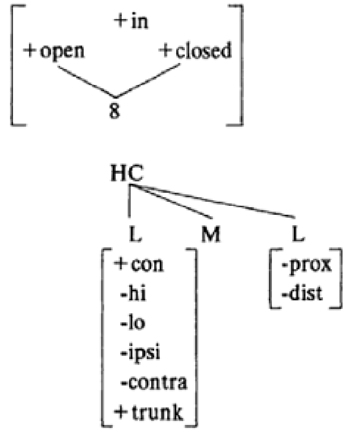


Figure 4.12: Autosegmental representation of ASL sign LIKE in Hand Tier Model. Taken from Sandler (1989, p.25).

iii. place features ([head], [neck], [shoulder], [trunk], [arm], [hand])

Setting features also dominates distance features ([proximal], [distal]), laterality features ([ipsi],[contra]) and height features ([hi],[lo]). Setting, manner and place features are occurring simultaneously in this representation. For every L category, only one place feature can be selected, similarly at most one of each features selected from the distance and laterality features. For height features, if both [hi] and [lo] selected it means in the middle. For simple signs, place harmony is represented as a double association as in Figure 5.18. Compounds do not exhibit place harmony, hence they are associated to different place features in the model. In this feature geometry, no change is encoded, in other words there is no sequentiality coded in any of the tiers.

As indicated before, in verb agreement there is a change either in the direction of movement or in the orientation or both. In this model, change in the direction of movement is represented as a manipulation of the location segments of the verb. Subject and object agreement morphemes are associated with the location segments of the verb. In other words, the locations are associated with a person locus by an autosegmental rule of double verb agreement as shown in Figure 4.14).

The agreement morphemes in the lexicon are specified with location features, e.g., for 1st person, the features are ([+contact], [-high], [-low], [-ipsi], [-contra] and [+trunk]). For example, in Figure 4.15, autosegmental representation of the citation form of ASL sign SEE and the inflected form SEE_1 are shown.

In this model, path movements, in which the hand moves from one location to another, are linked to the segment M in the timing tier. The movements other than the path movements, i.e., rapid movements of the joints such as wiggling, hooking, or handshape change (aperture changes) and changing position of the wrist such as twisting or orientation change, are called internal movements. Internal movements are linked to the hand configuration (HC) category rather than the movement segment (M) as it is the case for MHM. Sandler (1989) also claims that the observation that there are signs which show only handshape change but do not have a path movement (ex: UNDERSTAND) is an evidence for accepting handshape change as an

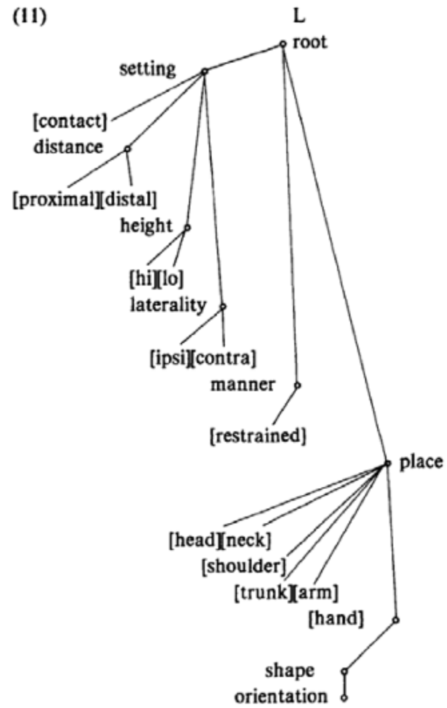


Figure 4.13: Feature tree for location in Hand Tier Model (Sandler & Lillo-Martin, 2006).

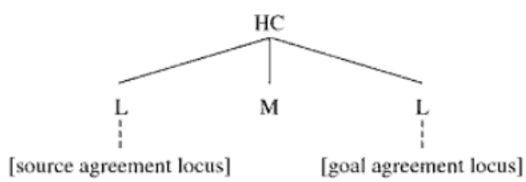


Figure 4.14: Autosegmental rule for verb agreement in Hand Tier Model (Sandler & Lillo-Martin, 2006).

internal movement rather than a path movement.

Movement category has three main features: shape, setting and manner. Values for the shape feature are [+/-arc] (default value is -arc for the straight movement). Circular movements are represented as two arcs. Setting feature has the value [+contact] if the hands touch some specified place. Manner feature [+restrained] means shortened and doubled movement.

Sandler (1990) states that predicative adjectives and verbs are inflected for aspect by changing the shape of the movement or the rhythmic pattern. For example, the manner of movement changes from path movement to arc movement in ASL when the verb is inflected for the contuniative aspect as seen in Figure 4.16a. Inflection by the markers of both agreement and aspect at the same time is possible as seen in Figure 4.16b, since they are affecting different segments.

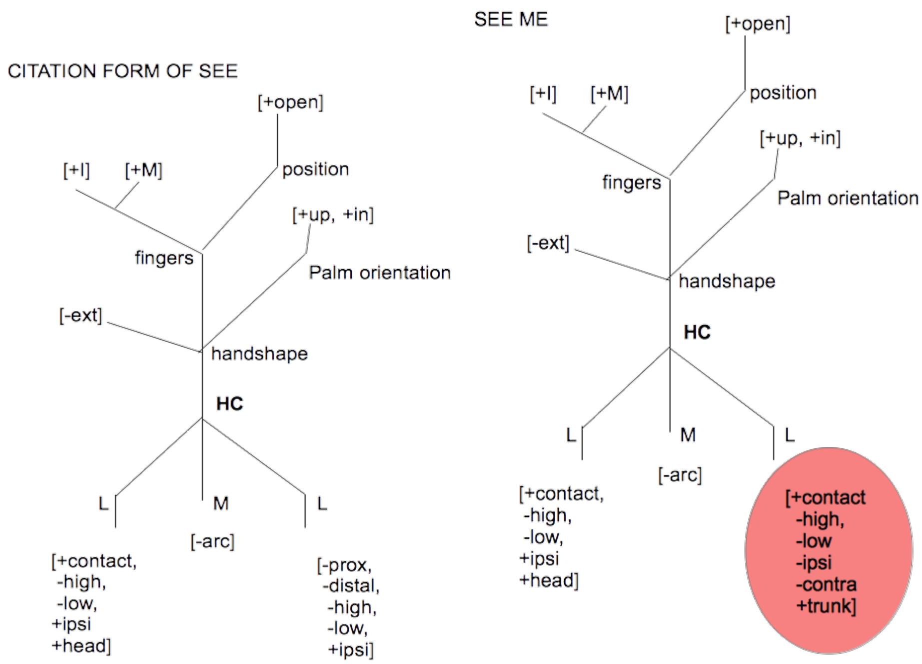
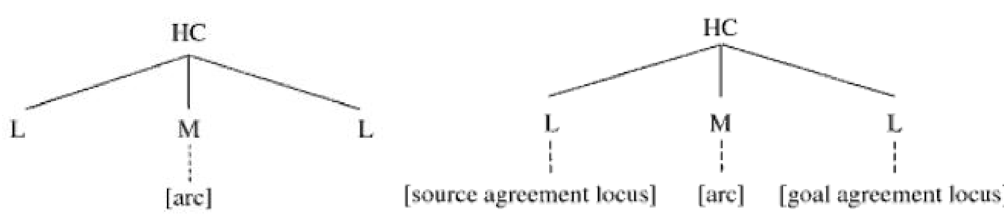


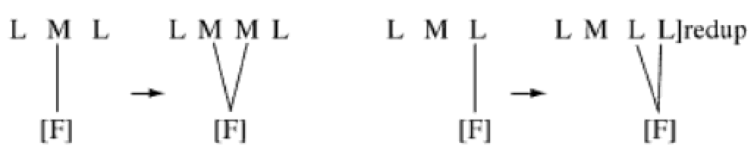
Figure 4.15: Autosegmental representation of the citation form of ASL sign SEE and inflected form SEE_1 in Hand-Tier Model.



a. Durational aspect

b. Verb agreement & Durational aspect

Figure 4.16: Verb agreement and durational aspect marking in ASL (Sandler & Lillo-Martin, 2006).



a. Movement Gemination
in Intensive Aspect

b. Location Gemination
in Contuniative Aspect

Figure 4.17: Aspect as gemination in ISL (Sandler & Lillo-Martin, 2006).

For intensive aspect in ISL, timing of movement segment is lengthened. In the contuniative aspect the final location is geminated as seen in Figure 4.17.

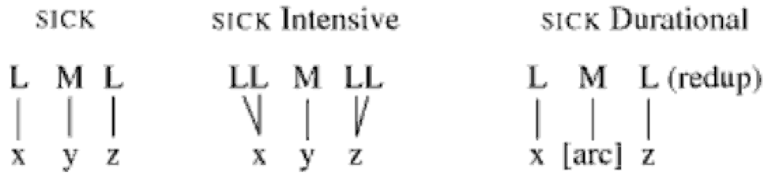


Figure 4.18: Templatic morphology in ASL (Sandler & Lillo-Martin, 2006).

Similarly, intensive aspect in ASL is represented by the LLMLL pattern in Figure 4.18, this pattern functions as a morpheme.

Habitual aspect involves reduplication of the sign three times. Hand-Tier Model (Sandler, 1989) defines the three rules seen in Figure 4.19 for habitual aspect First rule simple triplicates the sign, movement epenthesis rule adds a linking movement between every two location segments if the adjacent two segments are the same, and lastly HC spread rule links this epenthetic movements to the HC category.

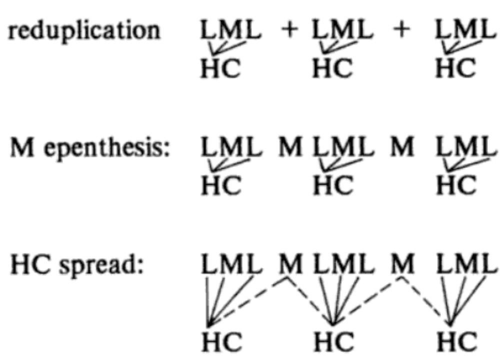


Figure 4.19: Autosegmental rules for habitual aspect (Sandler, 1989)

4.3 Prosodic Model

Brentari (1998) proposes the Prosodic Model (PM) of sign language phonology that has the feature organization shown by the feature tree in Figure 4.20. This is a hierarchical tree in which the features are grouped into feature classes and the root node dominates all the class nodes and feature nodes.

In Prosodic Model, the root node has two main feature classes: Inherent Features (IF) and Prosodic Features (PF). Inherent features are the static properties of the sign, i.e., features regarding articulators (A) and place of articulation (POA), which do not change during sign's production. Prosodic features are the dynamic features that change resulting from the movement of the articulators such as shoulder, elbow, wrist, and finger joints. Brentari (1998) classifies dynamic features under four movements: setting change, path, orientation change and aperture change as shown in Figure 4.24.

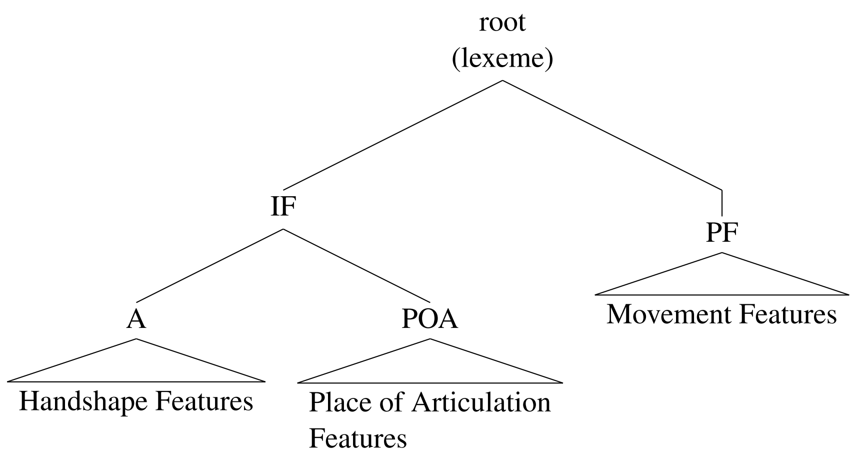


Figure 4.20: Feature Organization of Prosodic Model (Brentari, 1998).

Brentari (1998) states that inherent features are realized simultaneously, whereas prosodic features are realized sequentially. It means that the elements in IF branch, for example A and POA are simultaneous, i.e., the handshape and the location are realized at the same time. Similarly, in Articulatory (A) branch, as seen in Figure 4.21, manual and non-manual articulators are realized at the same time, dominant hand (H1) and non-dominant hand (H2) can act simultaneously. Inherent features spread out the whole lexeme. Since each feature and feature class of the feature geometry is a node on a separate autosegmental tier (Clements, 1985, 2006), every node of IF branch is a separate autosegmental tier, there is no ordering relation between the daughter nodes. PF branch is an autosegmental representation which contains sequential timing slots which are associated with the feature nodes.

Modality differences between spoken and signed languages give rise to the feature geometries with different sets of features. The feature geometry in Figure 4.20 is different than the feature geometry in Figure 2.3 proposed by Clements (1985) for spoken languages because not only it has different set of features, but also there is an organizational difference: the root node identifies a lexeme in Prosodic Model of sign language phonology and a segment in spoken language feature geometry (Clements, 1985).

When the root is a segment, the composition of two or more segments through temporal precedence relation results in the composition of the feature geometry trees for these segments. The phonological rules such as assimilation of segments, spreading and de-linking which take place during this composition can be defined and shown on this resultant autosegmental representation. However, when the root is a lexeme, the composition of two roots may explain the compounding process, but it does not describe the word formation process. In Prosodic Model, the segments are identified by the terminal nodes, and the temporal precedence relation apply only to these units.

4.3.1 Inherent Features

Articulatory features describe the handshape of the lexeme and the accompanying non-manual features (if any). Feature tree of articulators is organized as in Figure 4.21. Brentari (1998) suggests that this tree has an asymmetry, i.e., the nodes such as manual, H1, hand and selected fingers are the heads, whereas the non-manuals, H2, arm and non-selected fingers are dependents. She states that heads are more complex than their dependents. Head features do not change, whereas dependents may be deleted from the representation.

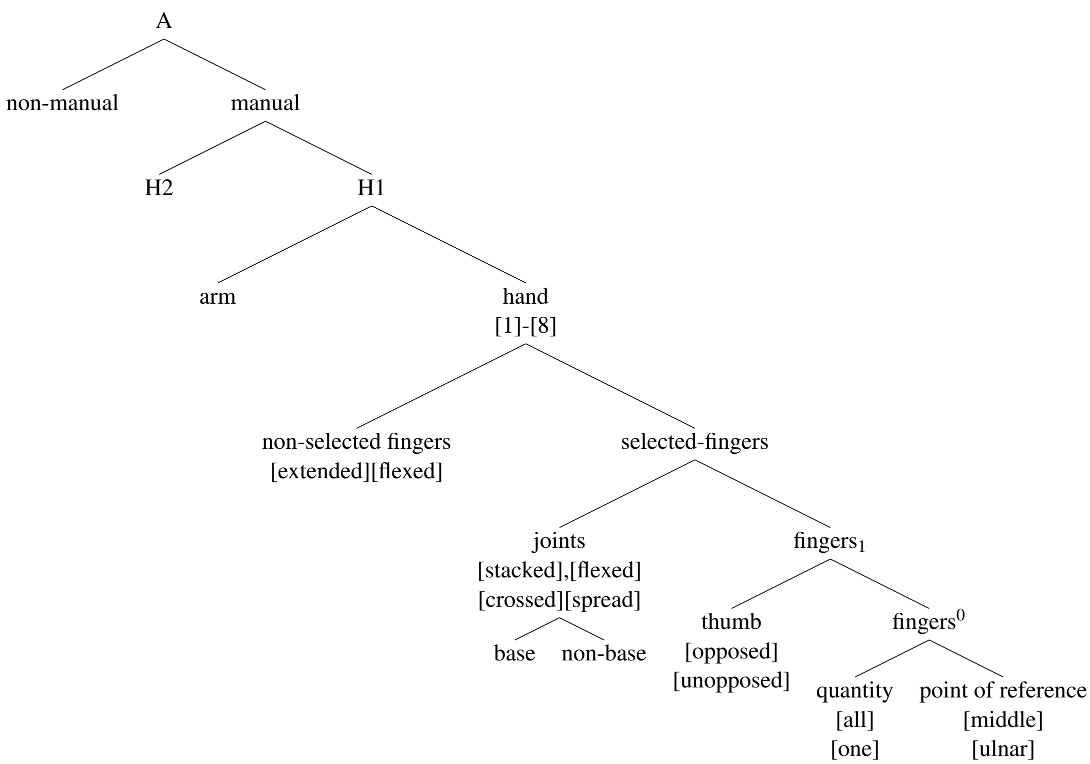


Figure 4.21: Articulatory features in Prosodic Model (Brentari, 1998).

Manual node is the head since manual articulation is obligatory whereas there may be signs with or without non-manual markings. Manual node dominates only the dominant hand (H1 node) if the sign is one-handed. It dominates both the dominant hand (H1) and the non-dominant hand (H2) if the sign is two-handed. H1 is the head and H2 is the dependent, because the handshape or the movement of H2 depends on H1 for some two handed signs.

H1 branches into arm and hand features. Hand node has more branches than arm node, so it is more complex. If the whole forearm is not used during sign's production, then this branch can be deleted. Therefore, hand is the head and the arm is the dependent.

Hand node and its daughters describe the handshape. The features [1]-[8] describe the hand-part used to specify the orientation[4]. Hand node dominates the selected fingers and non-selected fingers. Selected fingers are the fingers which are active, which move or which have a contact with the body. There is a restriction that the set of selected fingers does not change

[4] Same feature set is also used to specify the place of contact on H2. See Table 4.3.

during sign's production. The features of joints, the thumb and the other four fingers are represented in this branch.

The classification of two-handed signs (Battison, 1978) is modeled by PM as shown in Figure 4.22. For a two-handed sign, the manual node has the feature [2-handed]. If this feature is on but H2 node does not dominate anything, then the system copies the features of H1 to H2.

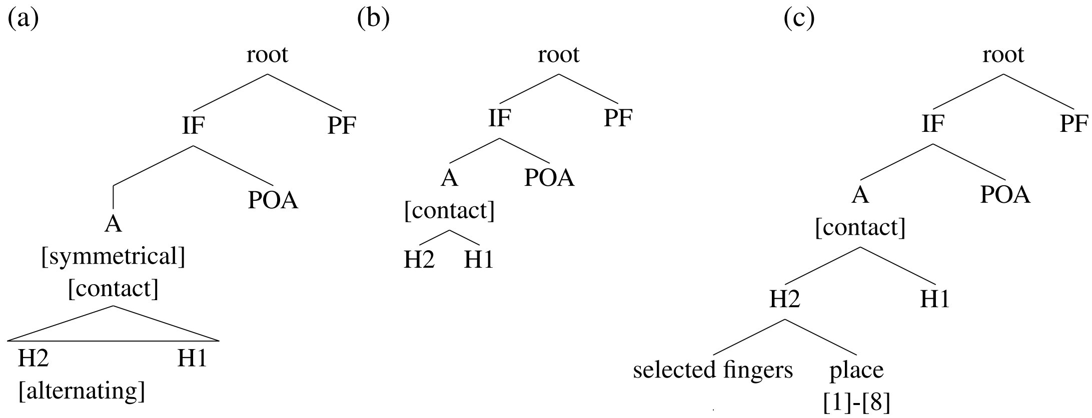


Figure 4.22: Two handed signs in Prosodic Model (Brentari, 1998): (a) Type 1 signs: same handshape, same movement (b) Type 2 signs: passive H2, same handshape (c) Type 3 signs: passive H2, different handshapes.

As shown in Figure 4.22.a, Type 1 signs are two-handed signs where H1 and H2 have the same movement. A-node has the feature [symmetrical] which means that the same parts of H1 and H2 are oriented towards each other. The association line between H1 and H2 means that the system copies the movement features of H1 to H2. Type 1 signs may have a contact with a place of articulation, if it is the case, A-node has the feature node [contact]. These signs may have synchronous or alternating movement, being synchronous is the default, if it is alternating, then H2 node has the feature node [alternating].

For Type 2 signs, H2 does not have a movement so the features [symmetrical] and [alternating] do not exist in Figure 4.22.b. For Type 1 and Type 2 signs, H2 has the same handshape with H1, so H2 node is left empty, Prosodic Model copies the handshape features of H1 to H2.

In Type 3 signs, two hands have different handshapes. In this case, H2 is not empty, it dominates the selected fingers and place nodes as shown in Figure 4.22.c. The possible handshapes for H2 is a restricted set ('B', 'A', 'S', 'C', 'O' '1', '5') for ASL, and they are modeled by the selected fingers branch. Place features [1]-[8] in Table 4.3 are used to describe the place of contact on H2.

In addition to the handshape features (A-node), inherent feature (IF) node dominates place of articulation features (POA node). Place of articulation features are shown in Figure 4.23, x stands for frontal plane (it may be the body plane or any parallel plane), y for horizontal plane and z for midsagittal plane. [contact] feature describes a contact of the dominant hand H1 with a place of articulation. For 2-handed signs, [contact] feature is a daughter of A-node.

There are four major body locations: head, arm, body and H2. For any lexical sign, at most one of these locations is set, the sign is articulated on one of the places described by the place

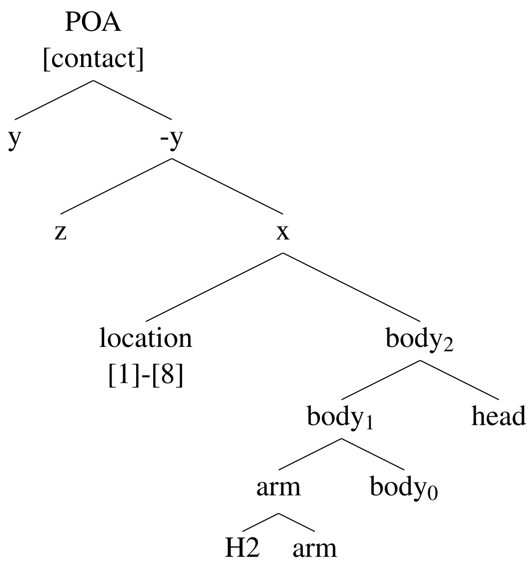


Figure 4.23: Place features in Prosodic Model (Brentari, 1998).

features [1]-[8] for each of these locations in Table 4.3.

Table 4.3: Distinctive place features [1]-[8] in Prosodic Model

	Head	Arm	Body	Hand
[1]	top of the head	upper arm	neck	palm
[2]	forehead	elbow front	shoulder	finger fronts
[3]	eye	elbow back	clavicle	back of palm
[4]	cheek/nose	forearm back	torso-top	back of fingers
[5]	upper lip	forearm front	torso-mid	radial side of selected fingers
[6]	mouth	forearm ulnar	torso-bottom	ulnar side of selected fingers
[7]	chin	wrist back	waist	tip of selected fingers/thumb
[8]	under the chin	wrist front	hips	heel of hand

4.3.2 Prosodic Features

Prosodic Model classifies movements and related features into five levels seen in the hierarchical organization in Figure 4.24: handshape change, orientation change, path, non-manual, setting change.

Prosodic Model labels movements as prosodic units whereas the other two models (MHM and HTM) label them as segments. As shown in the bottom of Figure 4.24, Brentari (1998) proposes that there are at least two phonological timing slots (Xs) that are associated with the movement features. In MHM and HTM, there are sequences of segments such as HMH or LML, which work as timing skeletons.

These slots are defined to be the minimal and concatenative units that refer to the beginnings and the endings of the movements at any level of the hierarchy: handshape change, orientation

PF
[arc],[circle],[straight],[trilled movement]
|
non-manual
|
setting Δ
[ipsi],[contra],[distal],[proximal],[bottom],[top]
|
path
[pivot],[repeat],[tracing],[direction]
|
orientation Δ
[extension],[flexion],[supination],[pronation],[abduction]
|
aperture Δ
[open],[closed]
X X

Figure 4.24: Prosodic features in Prosodic Model (Brentari, 1998, 2012).

change, path, setting change. These units are associated with the prosodic features in a one-to-one and left-to-right manner. This satisfies the well-formedness conditions in (1) defined by Autosegmental Phonology (Goldsmith, 1976).

Figure 4.24 shows that the top node (PF class node) may have two kinds of features: (i) abstract movement shapes and (ii) the trilled movements. The features such as [arc], [circle] and [straight] which are associated with PF node are the abstract movement shape features. They are found in core lexemes, bound affixes or classifier forms.

Brentari (1998) gives the following examples of the morphological processes where the inflected forms have these abstract shapes. The multiple affix, which has the collective meaning 'all of', has an arc form. The iterative aspect has the meaning 'over and over again' and has the form of a repeated and tense straight movement. The apportionative aspect which adds the meaning that 'the actions are distributed over a group' (Klima & Bellugi, 1979) has the form of a circle movement. In the classifier forms, these abstract movement shapes may express the form of a real movement like moving in a circle or a straight path.

Trilled movement (TM) is a secondary movement, it is also called 'local movement' by Liddell and Johnson (1989). TMs are rapidly repeated movements such as wiggling, rubbing, hooking, tremor, nodding, twisting, releasing, closing, pivoting, circling, flattening, releasing and tongue wagging. TM is an articulator-free feature; it does not spread (Brentari, 1998).

Brentari (1998) suggests that TM features can be localized in the related node of PF branch, i.e., wiggling, flattening and hooking are considered as a feature of aperture change (TM:HS), twisting and pivoting as an orientation change feature (TM:O), tremor as a place feature (TM:POA), nodding and tongue wagging as non-manual features (TM:NM), and circling as a path feature (TM:P).

The class nodes dominated by PF node are ordered with respect to the joints used to articulate these movements: setting change (shoulders), path (elbow), orientation change (wrist) and aperture change (finger joints). The earlier the node is in this ordering, the bigger the movement is, and the more sonorous (more visible) the sign is.

Setting Change: Most mono-morphemic signs have only one place of articulation. Possible places of articulation are the body, the head, the non-dominant hand, the arm or neutral signing space (Battison, 1978). The hand may change its position (i.e., contra ↔ ipsi, top ↔ bottom, distal ↔ proximal) within this POA, this is called "setting change" (Brentari, 1998).

Ipsilateral ([ipsi]) is the side of the dominant hand, and the contralateral ([contra]) is the opposite side. [Distal] is a setting, which is far from the body, and [proximal] is a setting, which is more close to the body. [Top] is the upper part of POA, whereas [bottom] is the lower part. Prosodic Model puts POA under IF branch that consists of features that do not change, and setting change under PF branch.

An example of a sign which has a setting change is the sign DEAF as seen in Figure 4.25. The main body location for this sign is the head and its place is the cheek. The dominant hand moves from the top of the cheek to the bottom of the cheek. As shown in the representation of the sign DEAF in Figure 4.25, the head and place feature [4], namely the cheek, are static features that put under IF branch and the setting change from top to bottom is put under PF branch.

The order of these two settings may change (from top→bottom to bottom→top) if the former sign is articulated near to the bottom rather than the top of the cheek, this is known as metathesis. Even if the setting changes look like path movements, Brentari (1998) suggests a test to differentiate them: "if a sign goes under metathesis then it has a setting change not a path movement".

Path Movements: A path movement is realized when H1 (and H2) is moving from one place to another place following a path either on the body or in the neutral signing space. Path movements are realized by the movement of the elbow or the shoulder joints. Brentari (1998) includes the following path features: [direction], [tracing], [pivot], [repeat] and [alternating]. She claims that path features "are needed to explain the systematicity in surface forms that undergo phonological operations". For instance, they are used to explain processes such as compounding and agreement.

[Direction] feature describes a straight path movement that takes place perpendicular to the plane of articulation. When this feature is added, there is no need to use [straight] feature. For the sign CHILD in Figure 4.26, the movement that is made perpendicular to y-plane is a path movement not a setting change from top to bottom, because the order of the settings cannot be changed as a result of metathesis. [Direction] feature is added to the path node to represent this movement in the feature geometry tree as seen in Figure 4.26.

Brentari (1998) employs [direction] feature in the phonological representations of directional (agreement) verbs which express the transfer of a theme between the agent and the patient with a change in the direction of the movement. For the forward agreement verbs in which the direction of movement is from agent to patient, [direction:|>] feature is used. For backward agreement verbs in which the direction of movement is from the patient to the agent, [direction:>|] feature is employed. For the single agreement verbs, [direction] feature is realized with [contact] feature either at the beginning ([direction:|>]) or at the end ([direction:>|]).

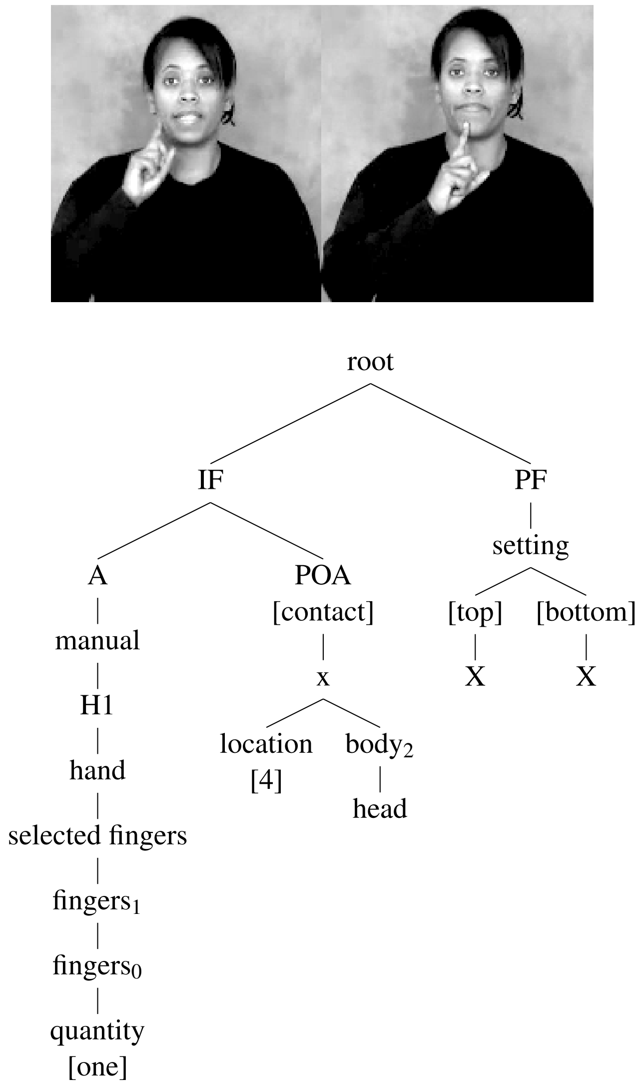


Figure 4.25: Setting change in Prosodic Model (Brentari, 1998). Handshape node (A-node) represents the index finger shape. POA branch describes there is a contact with the head and the place of the contact is the cheek [4]. PF part defines the setting change from the top of the POA to the bottom of it. Photographs are taken from the video for the ASL sign DEAF in the online dictionary http://www.spreadthesign.com/.

Brentari (1998) argues that [direction] feature predicts [contact] feature at the beginning or at the end of the path movement: contact occurs at the point when the movement meets the place. If the movement is a straight movement from a point, [|>] is employed. If the movement is towards to a point, [>|] feature is used.

[Tracing] feature describes a movement that occurs within a plane. This movement may have any shape: an arc, a circle or a straight line. For the signs which have [tracing] feature, [contact] feature is realized during the whole path movement.

[Repeat] feature describes a repeated movement. Brentari (1998) sets down some forms of repeated movements observed in the lexical signs as 90^o '7', 90^o 'X', set$_i$ set$_j$ and 180^o. Some plural nominals may have this repeated movement. For example, ASL sign CHILD as seen in Figure 4.26 has one movement like patting the head of someone short. For making it plural, the movement of the sign CHILD is repeated twice in two different settings (set_i set_j) in the sign CHILDREN as seen in Figure 4.27. This repetition, which is also called "sideward reduplication" by Steinbach (2012), is one of the strategies for making the non-body anchored lateral nouns plural. Brentari (1998) represents sideward reduplication as a setting change, this is not a path movement since the movement may be from [ipsi] to [contra] or vice versa.

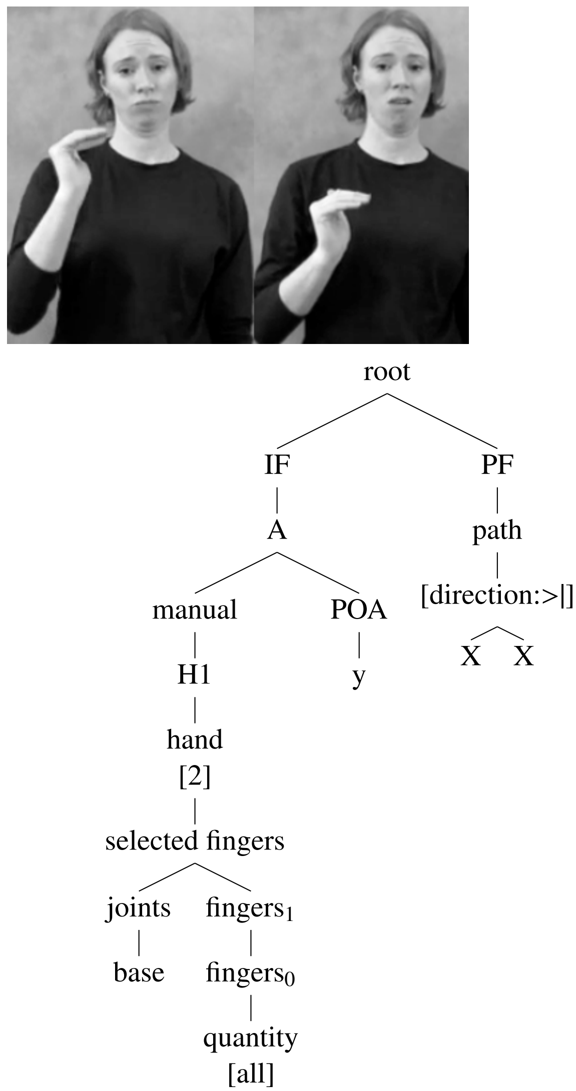


Figure 4.26: Representation of ASL sign CHILD in PM. Handshape is flat open 5-handshape and orientation is defined as the relation between the finger fronts [2] and horizontal plane (y-plane). The downward movement is a path movement, which is described with the direction feature. Photographs are taken from the videos for ASL sign CHILD from the online dictionary http://www.spreadthesign.com/.

Wilbur (2009) suggest to use [repeat] feature for describing the reduplication in nominalization process and habitual aspect marking. For habitual aspect, features [repeat] and [return=tracing:straight] are suggested. [Return] feature describes the epenthetic movement

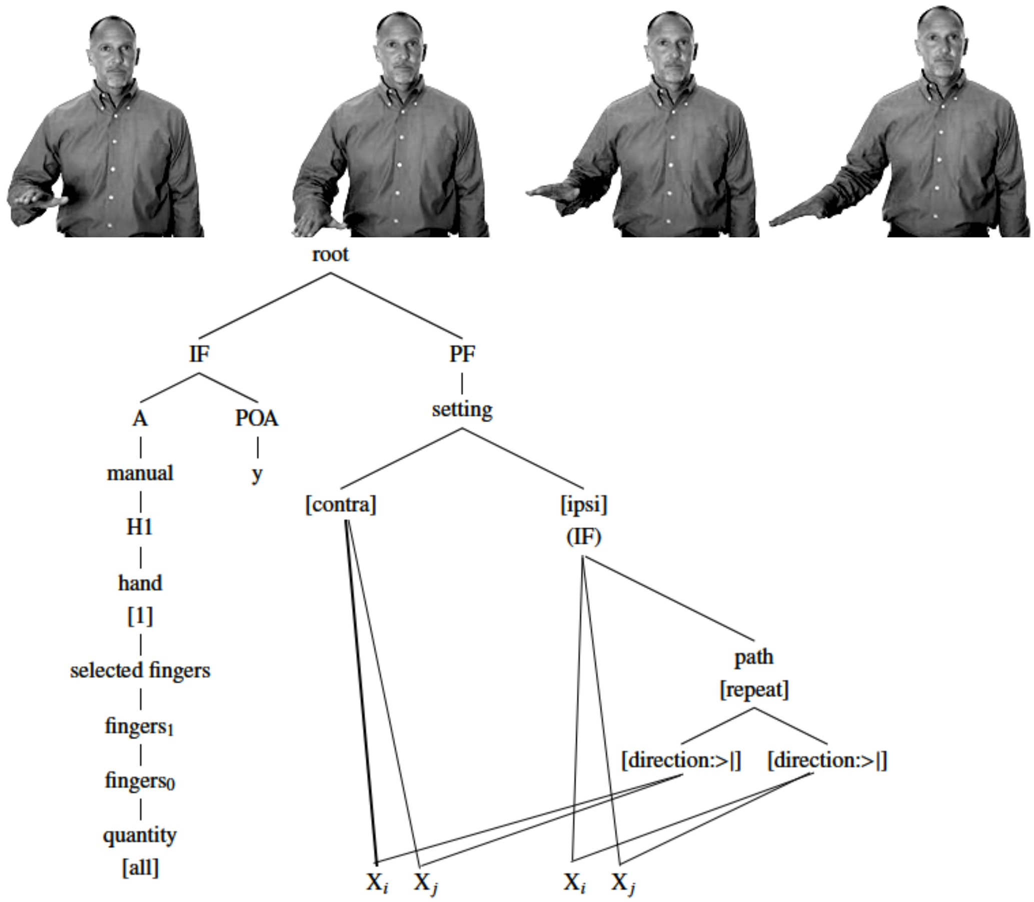


Figure 4.27: Representation of ASL sign CHILDREN in PM. Pluralization is achieved by repeating the movement with a setting change. Photographs are taken from the video for ASL sign CHILDREN in the online dictionary https://www.signingsavvy.com/sign/CHILDREN/74/2.

which occurs between the repetitions of the sign.

[Pivot] is a path movement articulated with a fixed elbow.

[Alternating] feature defines the movement of the two-hands that move at a 180^o phase difference. Brentari (1998) suggests this feature is realized at H2 node, since an alternating two-handed sign may not undergo "Weak Drop" (H2 deletion) and only synchronous Type 1 signs may become one-handed.

Orientation Change: Orientation is defined as a relation between a hand-part and a place of articulation, both of which are in IF branch. For instance, the orientation of ASL sign CHILDREN is defined as having the palm oriented towards horizontal plane as seen in Figure 4.27. The orientation is defined in IF part whereas orientation change is replaced under PF branch. Orientation change is a movement of the wrist. Wrist may have three movements: (i) rotation (supination or pronation), (ii) flexion or extension and (iii) side to side movement (abduction or adduction). The orientation change branch has the features: [supination], [pronation], [flexion], [extension] and [abduction].

Aperture Change: While selected fingers remain the same during sign's production, the handshape may change resulting from an aperture change (i.e., fingers may be opened or closed). Brentari (1998) puts the articulatory features that remain the same, i.e., selected fingers, under IF, and the features such as aperture change into PF as shown in Figure 4.28.

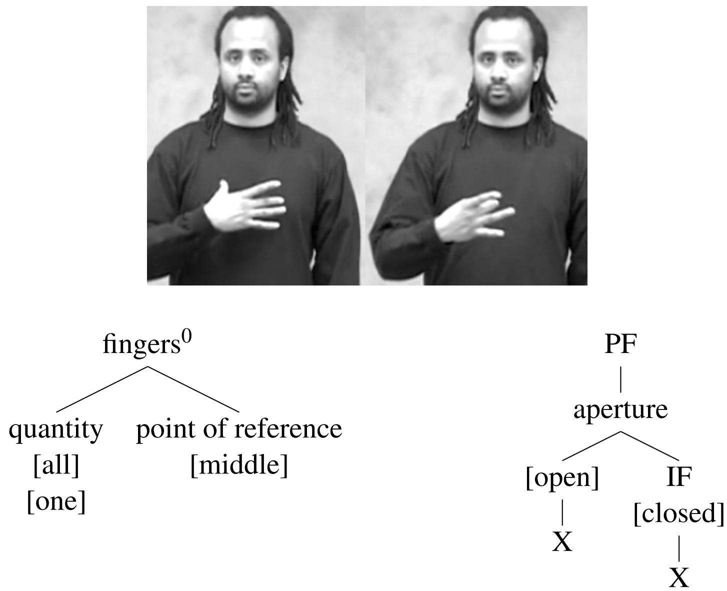


Figure 4.28: Aperture change in Prosodic Model (Brentari, 1998). The '8' handshape is accepted as a stationary feature and it is described in the selected fingers branch. The aperture change is defined under the dynamic features. IF in PF branch represents the closed form of '8' (horny) handshape. Photographs are taken from the video for ASL sign LIKE from the online dictionary http://www.spreadthesign.com/.

CHAPTER 5

ONE-LEVEL PHONOLOGY FOR SIGN LANGUAGE

This chapter shows how we construct One-Level Phonology for sign language based on three autosegmental phonology models of sign language: MHM (Liddell & Johnson, 1989), HTM (Sandler, 1989) and PM (Brentari, 1998). Section 5.1 introduces the basics of One-Level Phonology (Bird & Ellison, 1994) and presents how Bird and Ellison convert autosegmental representations and rules into finite state machinery. In Sections 5.2, 5.3, and 5.4, we show how SFA are constructed for the representations and rules defined within these three models, which have different feature geometries.

5.1 Introduction to One-Level Phonology

One-Level Phonology is a monostratal phonological framework (Bird & Ellison, 1994). Being monostratal means that there is "only one level of linguistic description", there is no distinction such as an underlying form and a surface form. It transforms representations and rules of Autosegmental Phonology (Goldsmith, 1976) into the same linguistic description: state-labeled non-deterministic finite-state automaton (SFA).

SFA is shown to be equivalent to finite-state automaton (FSA) and so it has the expressive power of regular languages (Bird & Ellison, 1994). Applying the autosegmental rule to the autosegmental representation is simply equivalent to intersecting two SFA which are generated for the representation and the rule. Regular languages are closed under intersection (Beesley & Karttunen, 2003, p.54), so the intersection of the two SFA is also an SFA.

Section 5.1.1 briefly gives the definition of an SFA and the operations defined on it. Sections 5.1.2 and 5.1.4 explain how autosegmental representations and rules are transformed into SFA. Section 5.1.3 shows how to convert an Arabic multi-tiered autosegmental representation to SFA. Section 5.1.5 introduces an evaluation of the encoding used in these conversions.

5.1.1 State Labeled Automata

Bird and Ellison (1994) define state-labeled non-deterministic finite-state automaton (SFA) as a six-tuple $< V, \Sigma, \lambda, \delta, S, F >$ where

V is a finite set of states,

Σ is the alphabet, which consists of a finite set of symbols that are used to label the states,

$\lambda \subseteq Vx\Sigma$ is the labeling relation,

$\delta \subseteq VxV$ is the transition relation, which defines the reachable states from any state,

$S \subseteq V$ is the set of start states, and

$F \subseteq V$ is the set of final states.

Example SFA in Figure 5.1 recognizes the linear string cat. The initial state is pointed by the start symbol and double circle shows that it is a final state.

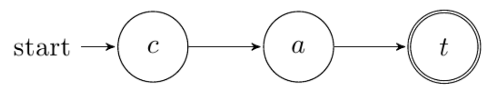


Figure 5.1: An example SFA that accepts the string cat.

SFA is a state machine whose states carry labels. It is different than FSA, which has labels on its arcs. SFA is shown to be equivalent to FSA in computational power (Bird & Ellison, 1994), their "equivalence follows from the equivalence of Mealy and Moore machines[1]", and both have regular language power.

Bird and Ellison (1994) define the following set of basic operations on any two SFA A and B: concatenation ($A + B$), intersection($A \sqcap B$), union($A \sqcup B$), complement($\bar{A}$), Kleene star (A^*) and Kleene plus (A^+). With this set of operations, SFA has the power of generalized regular languages. All these operations are closed under regular languages (Beesley & Karttunen, 2003).

Let A and B be SFA, and L(A) and L(B) be the languages accepted by A and B. Concatenation SFA ($A + B$) accepts concatenation of strings in L(A) with strings in L(B). This SFA has an arrow from each final state of A to the initial states of B. The initial states of this SFA are the initial states of A, and final states are the final states of B. All transitions in A and B are preserved, and also new transitions from final states of A to the initial states of B are added.

Intersection SFA ($A \sqcap B$) accepts L(A) ∩ L(B), which is the language consists of strings that are both accepted by A and B. Union SFA ($A \sqcup B$) accepts L(A) ∪ L(B), which contains strings that are accepted by A, or B or both. Complement SFA ($\bar{A}$) accepts the complement of L(A). SFA for Kleene star (A^*) accepts either the empty string or the concatenation of one or more strings in L(A). SFA for Kleene plus (A^+) accepts the concatenation of one or more strings in L(A).

[1] Input/output symbols are associated with the states in a Moore machine and with the transitions between the states in a Mealy machine.

5.1.2 Autosegmental Representation to State Labeled Automata

One-Level Phonology (Bird & Ellison, 1994) transforms autosegmental representations and rules (Goldsmith, 1976) into SFA. An autosegment having the phonological property P is represented by the SFA in Figure 5.2. A state in SFA is like a point in time, whereas a state with a self loop stands for a possibly extended time interval during which the same property holds. This automaton is equivalent to the regular expression P^+, where $^+$ is the operator for Kleene plus. The reason why such an autosegment is represented as Kleene plus rather than Kleene star is that the phonological property P must be observed at least once.

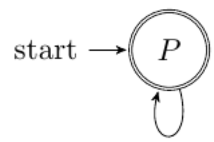


Figure 5.2: An SFA equivalent to an autosegment carrying the property P (Bird & Ellison, 1994, p.65).

Arcs in SFA are unlabeled. An arc has the meaning of immediate precedence. For example, the self loop in Figure 5.2 shows that the state of having property P is immediately preceded by itself, which means that it is an extended interval which carries multiple copies of its defining property P. The arc between the states P and Q in Figure 5.3 means that the autosegment which carries the property P immediately precedes the autosegment which carries the property Q.

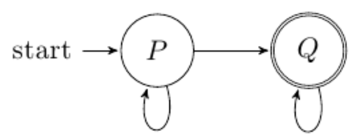


Figure 5.3: An SFA equivalent to an autosegmental tier containing two autosegments which carry the phonological properties P and Q respectively.

Each tier of a chart is represented by an SFA. The association lines between the tiers are interpreted as a temporal overlap relation between the intervals. A chart in the autosegmental representation corresponds to a synchronized SFA. For example, the chart in Figure 5.4 is represented with the SFA in Figure 5.5.

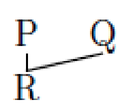


Figure 5.4: A chart containing two tiers. The first tier has two autosegments which carry the phonological properties P and Q, respectively. The second tier has only one autosegment with a phonological property R. P immediately precedes Q. P and Q are associated with R.

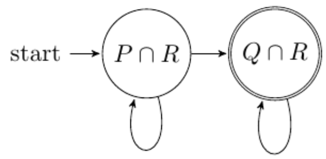


Figure 5.5: The synchronized SFA constructed for the chart containing the tiers PQ and R.

Bird and Ellison (1994) define the following procedure for constructing an SFA given an autosegmental representation:

- **Convert the autosegmental representation to an encoding:**

  Encoding is a format in which each autosegment A in a two-tiered chart is coded as A:n where n is the number of association lines A has. The encodings of the elements in each tier are concatenated in order to form the encoding of the tier. To obtain the encoding of the chart, the encodings of the tiers are intersected.

  For example, the encoding for the autosegmental representation in Figure 5.4 is shown in (6) and written as $(P : 1 + Q : 1) \sqcap R : 2$ where + is the concatenation and $\sqcap$ is the intersection operators.

  (6) P:1 Q:1
  R:2

- **Convert the encoding to a regular expression:**

  In (7), Bird and Ellison (1994) formulates the encoding for an autosegment A, which has n association lines. Bullet (•) is a wildcard, which is a variable that may be replaced with any of the elements of the alphabet.

  (7) $A : n =_{def} s(A) \sqcap a(n)$
  $s(A) =_{def} < A, \bullet >^{+}$
  $a(n) =_{def} < \bullet, 0 >^{*} (< \bullet, 1 >< \bullet, 0 >^{*})^{n}$
  (Bird & Ellison, 1994, p.69)

  Let us apply this conversion to the example in (6): $(P : 1 + Q : 1) \sqcap R : 2$.

  For $P : 1$, we obtain:

  $$P : 1 = s(P) \sqcap a(1)$$
  $$=< P, \bullet >^{+} \sqcap < \bullet, 0 >^{*} < \bullet, 1 >< \bullet, 0 >^{*}$$
  $$=< P, 0 >^{*} < P, 1 >< P, 0 >^{*}$$

  Similarly, for $Q : 1$, we obtain:

  $$Q : 1 =< Q, 0 >^{*} < Q, 1 >< Q, 0 >^{*}$$

  R:2 is defined to be:

  $$R : 2 = s(R) \sqcap a(2)$$

$$=< R, \bullet >^+ \sqcap < \bullet, 0 >^* < \bullet, 1 >< \bullet, 0 >^* < \bullet, 1 >< \bullet, 0 >^*$$
$$=< R, 0 >^* < R, 1 >< R, 0 >^* < R, 1 >< R, 0 >^*$$

In $(P : 1 + Q : 1) \sqcap R : 2$, + is used for the concatenation of two autosegments and $\sqcap$ is the intersection of the two tiers.

(8) $(P : 1 + Q : 1) \sqcap R : 2$
$= (< P, 0 >^* < P, 1 >< P, 0 >^* < Q, 0 >^* < Q, 1 >< Q, 0 >^*) \sqcap$
$(< R, 0 >^* < R, 1 >< R, 0 >^* < R, 1 >< R, 0 >^*)$
$=< P \cap R, 0 >^* < P \cap R, 1 >< P \cap R, 0 >^* < Q \cap R, 0 >^* < Q \cap R, 1 >< Q \cap R, 0 >^*$

- **Convert the regular expression to an SFA:**

  Bird and Ellison (1994) ignore the indices and reduce the notation in (8) to $(P \cap R)^+ (Q \cap R)^+$. This is the projection of the encoding in (6). The corresponding automaton is in Figure 5.5.

5.1.3 Example: Arabic Morphology

Bird and Ellison (1994) serialize the non-linearity in Arabic. In Arabic, the root morpheme is discontinuous. The words consist of three morphemes all of which are represented in different tiers in the phonological organization: the template of the Binyamin, the root, and the vocalism morpheme (McCarthy, 1981). Bird and Ellison (1994) represent each of these three tiers as a separate SFA and their intersection provides the desired inflected form.

For example, the autosegmental representation of the Arabic word *kattab* 'cause to write' in Figure 5.6 has three distinct tiers: vocalism tier (a), CV-tier (CVCCVC) and root tier (ktb). The three SFA that recognize these three tiers are shown in Figure 5.7, 5.8 and 5.9, and the result of intersecting them is shown in Figure 5.10.

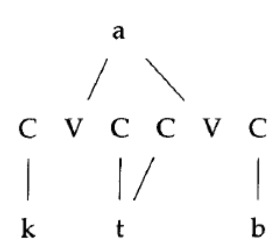


Figure 5.6: Autosegmental representation for *kattab* 'cause to write'

While converting from the ASR of 'kattab' which has multiple charts into SFA, the first step is to transform it into the encoding in Table 5.1. The notation A:x:y:z means that autosegment A has x association lines on the first chart, y associations on the second chart and z associations on the third chart.

There are three charts between these three tiers. The first chart, which connects Tier 1 and Tier 2, associates the V slots with the vocalism morpheme 'a'. The second chart, which connects

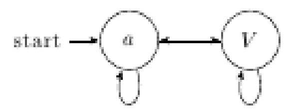


Figure 5.7: SFA that recognizes the vocalism tier

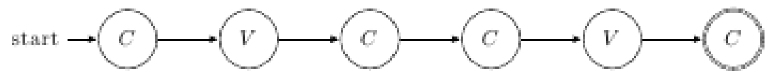


Figure 5.8: SFA that recognizes the CV-tier

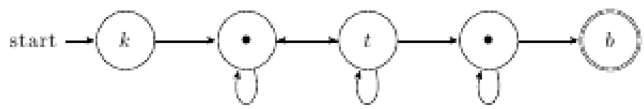


Figure 5.9: SFA that recognizes the root tier

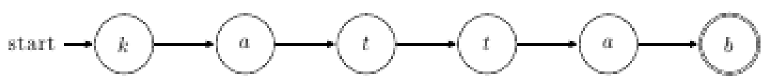


Figure 5.10: Intersection of the vocalism tier, CV-tier and root tier

Tier 2 and Tier 3, has the associations between the C slots and the root morpheme 'ktb'. The third chart consists of Tier 1 and Tier 3 but it has no association lines.

Table 5.1: Encoding for the ASR of the word 'kattab' in Figure (5.6) (Bird & Ellison, 1994, p.85).

Tier 1:			a:2:0:0			
Tier 2:	C:0:1:0	V:1:0:0	C:0:1:0	C:0:1:0	V:1:0:0	C:0:1:0
Tier 3:	k:0:1:0	t:0:2:0	b:0:1:0			

The charts in the autosegmental representation of kattab are shown in Figure 5.11.

The conversion procedure in (7) is updated in order to capture the autosegmental representations which have multiple charts (Bird & Ellison, 1994). The pairs such as $< A, \bullet >$ are replaced with k+1-tuples where k is number of charts. For example, 4-tuples are used for the 'kattab' example which has 3 charts. For every pair of tiers x and y, $a_{xy}(n)$ is defined as in (9), where n is the number of the associations that the autosegment A has on the chart consisting of tiers x and y.

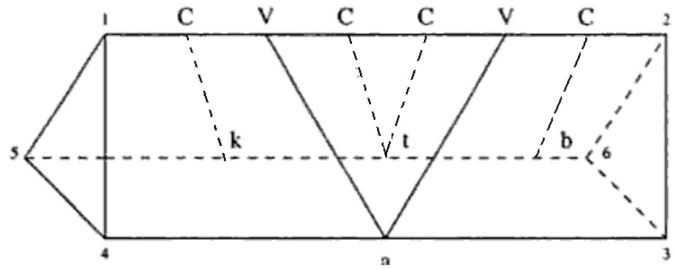


Figure 5.11: An autosegmental representation for the Arabic word 'kattab' (Kiraz, 2001, p.65).

(9) $A : p : q : r =_{def}\ s(A) \sqcap a_{12}(p) \sqcap a_{23}(q) \sqcap a_{13}(r)$

$s(a) =_{def} < a, \bullet, \bullet, \bullet >^{+}$

$a_{12}(n) =_{def} < \bullet, 0, \bullet, \bullet >^{*} \ (< \bullet, 1, \bullet, \bullet >< \bullet, 0, \bullet, \bullet >^{*})^{n}$

$a_{23}(n) =_{def} < \bullet, \bullet, 0, \bullet >^{*} \ (< \bullet, \bullet, 1, \bullet >< \bullet, \bullet, 0, \bullet >^{*})^{n}$

$a_{13}(n) =_{def} < \bullet, \bullet, \bullet, 0 >^{*} \ (< \bullet, \bullet, \bullet, 1 >< \bullet, \bullet, \bullet, 0 >^{*})^{n}$

(Bird & Ellison, 1994, p.71)

The encoding of 'kattab' in Figure 5.6 is the intersection of the tiers in Table 5.1: a:2:0:0 ⊓ [C:0:1:0 + V:1:0:0 + C:0:1:0 + C:0:1:0 + V:1:0:0 + C:0:1:0] ⊓ [k:0:1:0 + t:0:2:0 + b:0:1:0]. By applying the definitions in (9), this encoding is converted into the regular expression kattab and from this regular expression to the SFA in Figure 5.10.

5.1.4 Autosegmental Rule to SFA

Phonologists encode the changes in the descriptions of autosegmental representations by rules. For example, the rule in Figure 5.12 states that "if there is a sequence PQ and P is associated with R, then Q is also associated with R". As seen from this example, autosegmental rules are of the form of logical implication. Hence, they are rewritten as $A \rightarrow B \equiv \neg A \vee B \equiv \neg(A \wedge \neg B)$, where ¬ is 'negation', ∨ is 'logical or', and ∧ is 'logical and'.

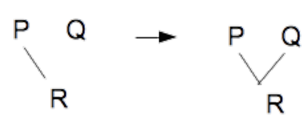


Figure 5.12: An example autosegmental rule

One-Level Phonology (Bird & Ellison, 1994) interpret an autosegmental rule as a logical implication from structural description (SD) to structural change (SC) as in SD→SC. SD shows the description before any manipulation is applied, SC is the representation after the change occurs. These rules are encoded in the form of $\neg(\bullet^{*}(SD \sqcap \neg SC)\bullet^{*})$, where wildcard (•) is any symbol from the alphabet. Here, there is a mapping from 'logical or' (∨) to 'union' (⊔), and from ‘logical and’ (∧) to ‘intersection’ (⊓). For converting the rule in Figure 5.12 to an SFA, Bird and Ellison (1994) assume that there are two charts between these two tiers; one for SD and one for SC. Hence, the rule in Figure 5.12 is expressed with the following SFA.

$$\neg\left(\bullet^* \left[\begin{array}{cccc} \bullet:0^* & P{:}1 & Q{:}0 & \bullet:0^* \\ \bullet:0^* & R{:}1 & & \bullet:0^* \end{array} \sqcap\neg \left[\begin{array}{cccc} \bullet:0:0^* & P{:}1{:}0 & Q{:}0{:}1 & \bullet:0:0^* \\ \bullet:0:0^* & R{:}1{:}1 & & \bullet:0:0^* \end{array}\right]_{SC}\right]_{SD} \bullet^*\right)$$

In the first part of the rule, the structural description is given. Structural description has the encoding for P, Q and R (P:1, Q:0 and R:1) before the rule takes place. This encoding states that only P and R have associations, not Q. In the second part of the rule, the structural change is described. In this part, there are two charts defined, SD and SC. SD chart has only one association (P-R), and SC chart similarly has one association (Q-R). The encoding P:1:0 means that there is one association of P on SD chart and no associations on the SC chart. It means that there is no change, the association between P and Q still exists after the rule applies. The encoding Q:0:1 shows us that there were no associations for Q initially, however one (Q-R) is added by the rule. Lastly, the encoding R:1:1 means that R has an association initially (P-R), and a new association (Q-R) is added by the rule. This encoding is converted to an SFA by using the convergence rules defined for the autosegmental representations such as the ones in (9).

In summary, Bird and Ellison (1994) show that autosegmental rules are transformable into SFA, which is the only representation in One-level Phonology. What follows from this transformation is that application of a rule to a representation is simply intersecting the SFA constructed for the representation and the rule.

5.1.5 Evaluation of the Encoding

Every autosegmental representation, which has an arbitrary number of tiers and has an arbitrary number of autosegments in each of its tiers, is transformable to the encoding of One-Level Phonology (Bird & Ellison, 1994). A tier with one autosegment is represented as one-element-encoding whose only term is this autosegment. A tier with n autosegments is represented as n-element-encoding, whose terms are all concatenated to each other in the order that the autosegments preceded each other in the tier. Hence, the temporal relation of immediate precedence between two autosegments in a tier is represented by the concatenation operation. If one autosegment is added to a tier of n-elements, the encoding for this new tier is constructed by concatenating the n-element-encoding with this element. Hence, any arbitrary-length tier is convertible to this encoding.

When there is only one tier, there is no need for numbering in the terms of the encoding. When a new tier is added and its elements are associated to the older tiers, first the encoding of this new tier is constructed and it is intersected with the others. Then, the number of association lines on the new charts are counted, and these numbers are added to the terms of the encoding. In other words, temporal overlap relation between the tiers is represented by the intersection operator and the numbers in the encoding. Any ASR with an arbitrary number of tiers is convertible to an encoding of intersection of the encodings of all these tiers.

Bird and Ellison (1994) also evaluate their encoding for properties such as being computable and invertible. They state that the encoding is computable since the number of terms in the encoding is exactly equal to the number of autosegments in the ASR. They also claim that it is invertible since ASR can be reconstructed from the encoding. To sum up, for every ASR, there is an equivalent encoding, and this conversion is a complete and invertible process.

5.2 Movement-Hold Model to One-Level Phonology

Movement-Hold Model (Liddell & Johnson, 1989) is an autosegmental phonology model of sign language. Section 4.1 presents how sign language phonology is organized in the autosegmental representations, and how the morphological processes are captures by the autosegmental rules in MHM (Liddell & Johnson, 1989). This section presents how these representations and rules (Liddell & Johnson, 1989) are converted into SFA of One-Level Phonology (Bird & Ellison, 1994). First, we briefly describe how the tiers are organized in MHM, then we show the steps of this transformation.

Liddell and Johnson (1989) do not suggest MHM to have a feature geometry, however from their descriptions we come up with the one in Figure 5.13. Representing MHM's phonological organization as a feature geometry makes it easy to compare it to feature geometries of the other two models of sign language phonology. We discuss how we can adopt the procedures in One-Level Phonology for transforming the representations in sign languages based on these feature geometries.

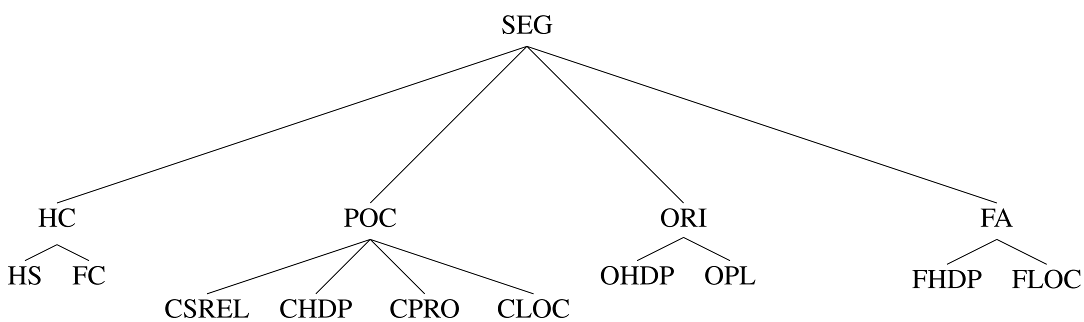


Figure 5.13: Tier organization in Movement-Hold Model (Liddell & Johnson, 1989)

Liddell and Johnson (1989) define segmental tier as the main tier, hence we assume segment (SEG) as the root of the feature organization in Figure 5.13. It consists of segments which are linked to the elements of the other four tiers: hand configuration (HC), place of contact (POC), facing (FA) and orientation (ORI). MHM (Liddell & Johnson, 1989) is an autosegmental model whose typology looks like a book. In this analogy, segmental tier is the spiral of the book and these four tiers are like the pages of the book.

The association lines in Figure 5.13 means that there is a dominance relation between the tiers: HC dominates handshape (HS) and finger configuration (FC). POC has four tiers as its children: Proximity (CPRO), Spatial Relation (CSREL), HandPart (CHDP), and Location (CLOC). ORI dominates handpart (OHDP) and the plane this handpart is oriented (OPL). FA is the mother of handpart (FHDP) and location (FLOC)[2]. The organization in Figure 5.13 is the side view of any autosegmental representation in MHM. Theoretically, it is possible that there are zero or more autosegments in each of these tiers.

Each pair of tiers, which are in a dominance relation in the feature tree in Figure 5.13, is called

[2] This organization may be easily updated to contain non-manual tiers.

a chart. For example , SEG-HC or POC-CSREL pairs are charts. If we traverse the tree in a breadth first manner, we obtain 14 possible charts: (1) SEG-HC, (2) SEG-POC, (3) SEG-ORI, (4) SEG-FA, (5) HC-HS, (6) HC-FC, (7) POC-CSREL, (8) POC-CHDP, (9) POC-CPRO, (10) POC-CLOC, (11) ORI-OHDP, (12) ORI-OPL, (13) FA-FHDP, (14) FA-FLOC[3].

Liddell and Johnson (1989) define segments to have five entries: major class, contour of movement, local movement, quality features, and contour plane. These are mainly articulatory features related to the movement, but Liddell and Johnson (1989) do not define them as separate tiers. Hence, we show segments in the following notation: MajorClass [ListOfFeatures], where the list contains features that do not change and do exist during the whole articulation of the sign. For example, M [long, arc] is a movement segment which is lengthened in time and whose shape is an arc.

The function of feature geometry in Figure 5.13 is to define how the signs are composed of its smaller units. For converting from an autosegmental representation in MHM to an SFA, the feature tree in Figure 5.13 is traversed in a breadth-first manner, and for all the nodes in that order, an encoding is constructed for the node. The nodes of the tree are the tiers of the autosegmental representation.

Figure 5.14 shows how ASL sign LIKE is represented in this model. These four partial representations in the figure show how the tiers come together and form the charts. The association lines show how the autosegments are temporally related to each other. Table 5.2 demonstrates the list of tiers and tier elements that exist in the autosegmental representation of ASL sign LIKE in Figure 5.14. As seen in Table 5.2, there are 15 tiers, the tier elements which are written in quotation marks are articulatory features whose meanings are listed in Table 4.2, and the ones written in capital letters without quotation marks are variables which may be a combination of more than one feature.

The first step of the conversion from the autosegmental representation in Figure 5.14 to the encoding in Table 5.3 is to write encoding for all autosegments in all 15 tiers in Table 5.2 by counting the number of associations of each autosegment in Figure 5.14.

First, each autosegment has assigned an encoding of the form A:n_1:n_2:...:n_k, where A is autosegment, A may be a variable like HC1, or may have a value such as the articulatory features in Table 4.2. In the encoding A:n_1:n_2:...:n_k, k is the number of charts, and n_i is the number of associations that A has on chart i.

The next step is to concatenate the encoding of immediately preceding autosegments to form the encoding of each tier. For example, in Figure 5.14, segmental tier of ASL sign LIKE consists of HMH segments, and it is represented as (H:1:1:1:1:0:0:0:0:0:0:0:0:0:0 + M:2:2:1:1:0:0:0:0:0:0:0:0:0:0 + H:1:1:1:1:0:0:0:0:0:0:0:0:0:0) where '+' sign is used to concatenate the encoding of the segments. Lastly, encoding of the overall autosegmental representation, is the intersection of the encodings of all the tiers as in Table 5.3.

Encoding is used as an intermediate representation to convert an autosegmental representation to a regular expression. Encoding is transformed to a regular expression by using the definitions in (10). In this formulation, all tuples have length k+1, where k is the number of charts, • is a wildcard, all entries of the tuples other than the i^{th} entry are •, i^{th} entry is 0 or 1 as shown in (10). For every chart i, $a_i(n)$ is defined as in (10), where n is the number of the

[3] Normally, there are C(15,2)=105 possible charts among 15 tiers. However, MHM defines only 14 of these charts. There are no associations between the other tier pairs and hence they are not shown in the encodings.

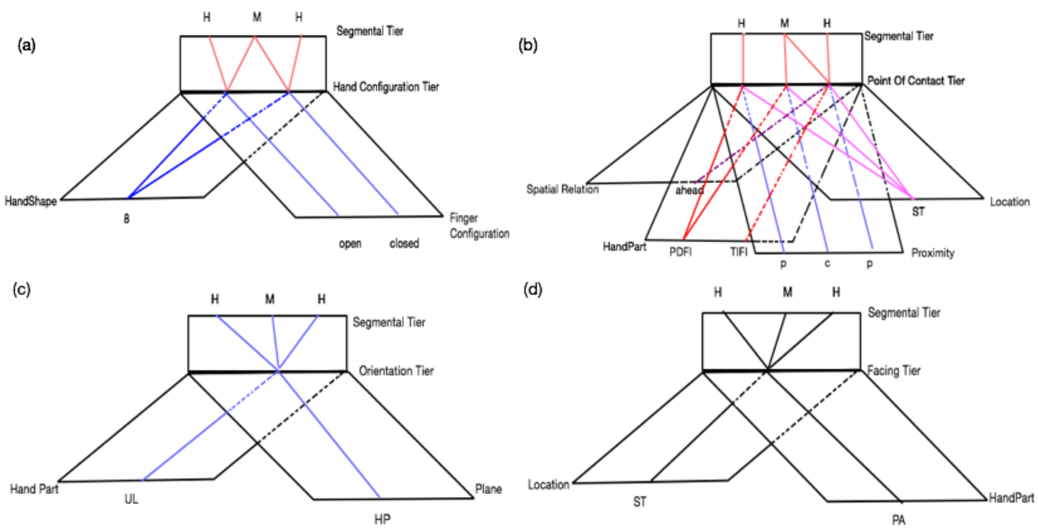


Figure 5.14: Autosegmental representation of ASL sign LIKE in Movement-Hold Model (Liddell & Johnson, 1989). (a) Hand Configuration (b) Place of Contact (c) Orientation (d) Facing.

Table 5.2: Autosegmental tiers and their autosegments for ASL sign LIKE

Tier	Elements		
Tier 1 (SEG):	H1	M	H2
Tier 2 (HC):	HC1	HC2	
Tier 3 (POC):	POC1	POC2	POC3
Tier 4 (ORI):	ORI		
Tier 5 (FA):	FA		
Tier 6 (HS):	‘8’		
Tier 7 (FC):	‘o’	‘op’	
Tier 8 (CSREL):	‘ahead’		
Tier 9 (CHDP):	‘PDFI’	‘TIFI’	
Tier 10 (CPRO):	‘p’	‘c’	‘p’
Tier 11 (CLOC):	‘ST’		
Tier 12 (OHDP):	‘UL’		
Tier 13 (OPL):	‘HP’		
Tier 14 (FHDP):	‘PA’		
Tier 15 (FLOC):	‘ST’		

associations that the autosegment A has on the $chart_i$.

(10)

$$A : n_1 : n_2 : ... : n_k =_{def} s(A) \sqcap a_1(n_1) \sqcap ... \sqcap a_i(n_i) \sqcap ... \sqcap a_k(n_k)$$

$$s(A) =_{def} < A, \bullet, ..., \bullet >^+$$

$$a_1(n) =_{def} < \bullet, 0, \bullet, ..., \bullet >^* (< \bullet, 1, \bullet, ..., \bullet >< \bullet, 0, \bullet, ..., \bullet >^*)^n$$

Table 5.3: This table shows the numbers in each of the terms in the encoding of the autosegmental representation of ASL sign LIKE. Each line corresponds to the tiers in Table 5.2, and there is exactly one numbering for each tier element. These numbers together with the corresponding tier elements in Table 5.2 make up the term. The encoding is (H + M + H) ⊓ (HC1 + HC2) ⊓ (POC1 + POC2 + POC3) ⊓ ORI ⊓ FA ⊓ '8' ⊓ ('o' + 'op') ⊓ 'ahead' ⊓ ('PDFI' + 'TIFI') ⊓ ('p' + 'c' + 'p') ⊓ 'ST' ⊓ 'UL' ⊓ 'HP' ⊓ 'PA' ⊓ 'ST'.

Tier	Numbering		
Tier1	1:1:1:1:0:0:0:0:0:0:0:0:0:0:0	2:2:1:1:0:0:0:0:0:0:0:0:0:0:0	1:1:1:1:0:0:0:0:0:0:0:0:0:0:0
Tier2	2:0:0:0:1:1:0:0:0:0:0:0:0:0:0	2:0:0:0:1:1:0:0:0:0:0:0:0:0:0	
Tier3	0:1:0:0:0:0:0:1:1:1:1:0:0:0:0	0:1:0:0:0:0:0:1:1:1:1:0:0:0:0	0:2:0:0:0:0:1:1:1:1:1:0:0:0:0
Tier4	0:0:3:0:0:0:0:0:0:0:0:1:1:0:0		
Tier5	0:0:0:3:0:0:0:0:0:0:0:0:0:1:1		
Tier6	0:0:0:0:2:0:0:0:0:0:0:0:0:0:0		
Tier7	0:0:0:0:0:1:0:0:0:0:0:0:0:0:0	0:0:0:0:0:1:0:0:0:0:0:0:0:0:0	
Tier8	0:0:0:0:0:0:1:0:0:0:0:0:0:0:0		
Tier9	0:0:0:0:0:0:0:2:0:0:0:0:0:0:0	0:0:0:0:0:0:0:1:0:0:0:0:0:0:0	
Tier10	0:0:0:0:0:0:0:0:1:0:0:0:0:0:0	0:0:0:0:0:0:0:0:1:0:0:0:0:0:0	0:0:0:0:0:0:0:0:1:0:0:0:0:0:0
Tier11	0:0:0:0:0:0:0:0:0:3:0:0:0:0:0		
Tier12	0:0:0:0:0:0:0:0:0:0:1:0:0:0:0		
Tier13	0:0:0:0:0:0:0:0:0:0:0:0:1:0:0		
Tier14	0:0:0:0:0:0:0:0:0:0:0:0:0:1:0		
Tier15	0:0:0:0:0:0:0:0:0:0:0:0:0:0:1		

$$a_i(n) =_{def} < \bullet, ..., \bullet, 0, \bullet, ..., \bullet >^* (< \bullet, ..., \bullet, 1, \bullet, ..., \bullet >< \bullet, ..., \bullet, 0, \bullet, ..., \bullet >^*)^n$$
$$a_k(n) =_{def} < \bullet, ..., \bullet, 0 >^* (< \bullet, ..., \bullet, 1 >< \bullet, ..., \bullet, 0 >^*)^n$$

By applying definitions in (10) to the encoding of ASL sign LIKE in Table 5.3 and reducing them, we get the regular expression in (11).

(11) $(H1 \cap A1)^+(M \cap A2)^+(M \cap A3)^+(M \cap A4)^+(H2 \cap A4)^+$, where A1-A4 are the following articulatory feature bundles:
A1= HC1 ∩ '8' ∩ 'o' ∩ POC1 ∩ 'PDFI' ∩ 'p' ∩ 'ST' ∩ ORI ∩ 'UL' ∩ 'HP' ∩ FA ∩ 'PA' ∩ 'ST'
A2= HC1 ∩ '8' ∩ 'o' ∩ POC2 ∩ 'PDFI' ∩ 'c' ∩ 'ST' ∩ ORI ∩ 'UL' ∩ 'HP' ∩ FA ∩ 'PA' ∩ 'ST'
A3= HC2 ∩ '8' ∩ 'op' ∩ POC2 ∩ 'PDFI' ∩ 'c' ∩ 'ST' ∩ ORI ∩ 'UL' ∩ 'HP' ∩ FA ∩ 'PA' ∩ 'ST'
A4= HC2 ∩ '8' ∩ 'op' ∩ POC3 ∩ 'TIFI' ∩ 'p' ∩ 'ST' ∩ 'ahead' ∩ ORI ∩ 'UL' ∩ 'HP' ∩ FA ∩ 'PA' ∩ 'ST'

We construct the state labeled automaton in Figure 5.15 from the regular expression in (11). With this step, the conversion from the autosegmental representation in MHM to SFA of One-Level Phonology is finished.

Up to now, we describe how to construct SFA from autosegmental representations in MHM. Now, it is time to transform the autosegmental rules that deal with the morphological pro-

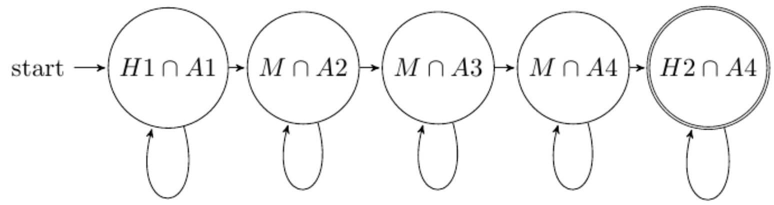


Figure 5.15: SFA transformed from the autosegmental representation of ASL sign LIKE in Movement-Hold Model.

cesses such as verb agreement, temporal aspect, pluralization. For that purpose, we will use the autosegmental representations of the citation verbs and inflected forms, and the autosegmental rules which are defined in Section 4.1. We transform these representations and rules into SFA and take their intersection. We explain the transformation on a simplified version of ASR which is shown in Figure 5.16. In this figure, A1 and A2 represent feature bundles.

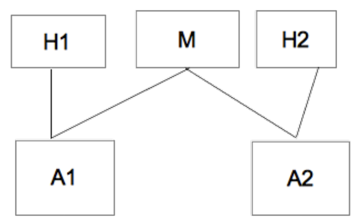


Figure 5.16: The simplified version of autosegmental representation of ASL sign SEE in Movement-Hold Model.

First we transform the autosegmental representation into the encoding form in Table 5.4. We have $(H1 : 1 + M : 2 + H2 : 1) \sqcap (A1 : 2 + A2 : 2)$. Here, + is used for the concatenation of two autosegments and $\sqcap$ is the intersection of the two tiers. Then, we convert this encoding to a regular expression using the definitions in (7).

Table 5.4: Encoding of autosegmental representation of ASL sign SEE. There are two tiers: timing tier and the articulatory tier. Timing tier has the HMH sequence of hold and movement segments, and in the articulatory tier there are two feature bundles A1 and A2.

Tier 1:	H1:1	M:2	H2:1
Tier 2:	A1:2	A2:2	

(i). $H : 1 = s(H1) \sqcap a(1)$

$$=< H1, \bullet >^{+} \sqcap < \bullet, 0 >^{*}< \bullet, 1 >< \bullet, 0 >^{*}$$

$$=< H1, 0 >^{*}< H1, 1 >< H1, 0 >^{*}$$

(ii). $M : 2 = s(M) \sqcap a(2)$

$= < M, \bullet >^{+} \sqcap < \bullet, 0 >^{*} < \bullet, 1 > < \bullet, 0 >^{*} < \bullet, 1 > < \bullet, 0 >^{*}$

$= < M, 0 >^{*} < M, 1 > < M, 0 >^{*} < M, 1 > < M, 0 >^{*}$

(iii). $H2 : 1 = < H2, 0 >^{*} < H2, 1 > < H2, 0 >^{*}$

(iv). $A1 : 2 = < A1, 0 >^{*} < A1, 1 > < A1, 0 >^{*} < A1, 1 > < A1, 0 >^{*}$

(v). $A2 : 2 = < A2, 0 >^{*} < A2, 1 > < A2, 0 >^{*} < A2, 1 > < A2, 0 >^{*}$

(vi). $(H1 : 1 + M : 2 + H2 : 1) \sqcap (A1 : 2 + A2 : 2)$

$= (< H1, 0 >^{*} < H1, 1 > < H1, 0 >^{*} < M, 0 >^{*} < M, 1 > < M, 0 >^{*} < M, 1 > < M, 0 >^{*} < H2, 0 >^{*} < H2, 1 > < H2, 0 >^{*}) \sqcap$

$(A1, 0 >^{*} < A1, 1 > < A1, 0 >^{*} < A1, 1 > < A1, 0 >^{*} < A2, 0 >^{*} < A2, 1 > < A2, 0 >^{*} < A2, 1 > < A2, 0 >^{*})$

$= < H1 \cap A1, 0 >^{*} < H1 \cap A1, 1 > < H1 \cap A1, 0 >^{*} < M \cap A1, 0 >^{*} < M \cap A1, 1 > < M \cap A1, 0 >^{*} < M \cap A2, 0 >^{*} < M \cap A2, 1 > < M \cap A2, 0 >^{*} < H2 \cap A2, 0 >^{*} < H2 \cap A2, 1 > < H2 \cap A2, 0 >^{*}$

When we reduce this regular expression, we obtain $(H1 \cap A1)^{+}(M \cap A1)^{+}(M \cap A2)^{+}(H2 \cap A2)^{+}$. Lastly this regular expression is converted into the state labeled automaton in Figure 5.17.

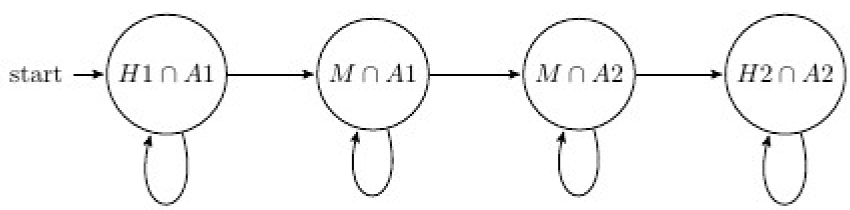


Figure 5.17: SFA that corresponds to the autosegmental representation of ASL sign SEE in Figure 5.16.

Now, we go over some morphological rules and show how they are converted to SFA. We start with the object marking in which only change the direction of movement. In the structural description part of the rule, the holds and the movements are associated with the locations of the citation form, namely L1 and L2. In the structural change part, we show that L2 is replaced with L2'. If this rule was describing an orientation change, then the rule will be exactly the same, only we need to rename L1, L2 and L2' as OR1, OR2 and OR2'.

(12) $\neg\left(\bullet^{*}\left[\begin{array}{ccccc} \bullet : 0^{*} & \text{H:1} & \text{M:2} & \text{H:1} & \bullet : 0^{*} \\ \bullet : 0^{*} & \text{L1:2} & & \text{L2:2} & \bullet : 0^{*} \end{array} \sqcap \neg\left[\begin{array}{ccccc} \bullet : 0 : 0^{*} & \text{H:1:0} & \text{M:1:1} & \text{H:0:1} & \bullet : 0 : 0^{*} \\ \bullet : 0 : 0^{*} & \text{L1:2:0} & & \text{L2':0:2} & \bullet : 0 : 0^{*} \end{array}\right]_{SC}\right]_{SD} \bullet^{*}\right)$

We continue with the conversion of the continuative aspect rules in Figure 4.8 into SFA. The rules are of the form $A \rightarrow B$, so it is equivalent to $\neg A \sqcup B$, and so to $\neg(A \sqcap \neg B)$. Hence, the encoding is written in $\neg(A \sqcap \neg B)$ form. The encoding for the continuative aspect rules in One-Level Phonology are given in (13) and (14). Here, SC stands for structural change and SD for structural description. As seen from these encodings, the continuative rule make a change in the features of the movement segment as arc-shaped and lengthened. The rule in 13) applies to verbs with HMH sequence in their timing skeletons, and the rule in (14) works on the verbs which do not have any movements in their citation forms.

(13) $$\neg\left(\bullet^* \left[\begin{array}{ccccc} \bullet:0^* & \mathrm{H{:}1} & \mathrm{M{:}2} & \mathrm{H{:}1} & \bullet:0^* \\ \bullet:0^* & \mathrm{A1{:}2} & & \mathrm{A2{:}2} & \bullet:0^* \end{array} \sqcap\neg \left[\begin{array}{ccccc} \bullet:0:0^* & \mathrm{H{:}1{:}0} & \mathrm{M[arc,long]{:}2{:}0} & \mathrm{H{:}1{:}0} & \bullet:0:0^* \\ \bullet:0:0^* & \mathrm{A1{:}2{:}0} & & \mathrm{A2{:}2{:}0} & \bullet:0:0^* \end{array} \right]_{SC} \right]_{SD} \bullet^* \right)$$

(14) $$\neg\left(\bullet^* \left[\begin{array}{ccc} \bullet:0^* & \mathrm{H{:}1} & \bullet:0^* \\ \bullet:0^* & \mathrm{A{:}1} & \bullet:0^* \end{array} \sqcap\neg \left[\begin{array}{cccc} \bullet:0:0^* & \mathrm{H{:}1{:}0} & \mathrm{M[arc,\ long]{:}0{:}1} & \bullet:0:0^* \\ \bullet:0:0^* & \mathrm{A{:}1{:}1} & & \bullet:0:0^* \end{array} \right]_{SC} \right]_{SD} \bullet^* \right)$$

In Section sec:MH, MHM claims that reduplication, movement epenthesis, and hold deletion rules are needed for habitual aspect marking. Reduplication in the habitual marking is in fact bounded copying where there is no dependency between the copies. This rule shortens the length of the movements in each of the copies. Reduplication SFA in (15) has the functionality of copying the sign two times and shortening the movement.

(15) $$\neg\left(\bullet^* \left[\begin{array}{ccccc} \bullet:0^* & \mathrm{H{:}1} & \mathrm{M{:}2} & \mathrm{H{:}1} & \bullet:0^* \\ \bullet:0^* & \mathrm{A1{:}2} & & \mathrm{A2{:}2} & \bullet:0^* \end{array} \sqcap \right.\right.$$
$$\neg \left[\begin{array}{ccccccccccc} \bullet:0:0^* & \mathrm{H{:}1{:}0} & \mathrm{M[srt]{:}2{:}0} & \mathrm{H{:}1{:}0} & \mathrm{H{:}0{:}1} & \mathrm{M[srt]{:}0{:}2} & \mathrm{H{:}0{:}1} & \mathrm{H{:}0{:}1} & \mathrm{M[srt]{:}0{:}2} & \mathrm{H{:}0{:}1} & \bullet:0:0^* \\ \bullet:0:0^* & \mathrm{A1{:}2{:}0} & & \mathrm{A2{:}2{:}0} & \mathrm{A1{:}0{:}2} & & \mathrm{A2{:}0{:}2} & \mathrm{A1{:}0{:}2} & & \mathrm{A2{:}0{:}2} & \bullet:0:0^* \end{array} \right]_{SC} \Bigg]$$
$$\left._{SD} \bullet^* \right)$$

Movement epenthesis rule is converted into the SFA in (16) which inserts movements between any two holds.

(16) $$\neg\left(\bullet^* \left[\begin{array}{cccc} \bullet:0^* & \mathrm{H{:}1} & \mathrm{H{:}1} & \bullet:0^* \\ \bullet:0^* & \mathrm{A1{:}1} & \mathrm{A2{:}1} & \bullet:0^* \end{array} \sqcap\neg \left[\begin{array}{ccccc} \bullet:0:0^* & \mathrm{H{:}1{:}0} & \mathrm{M{:}0{:}2} & \mathrm{H{:}1{:}0} & \bullet:0:0^* \\ \bullet:0:0^* & \mathrm{A1{:}1{:}1} & \mathrm{A2{:}1{:}1} & & \bullet:0:0^* \end{array} \right]_{SC} \right]_{SD} \bullet^* \right)$$

A monostratal framework does not admit any kind of deletion rules (Bird & Klein, 1994). By its nature, hold deletion rule cannot be defined in One-Level Phonology. We need to redefine this rule. Hold deletion seems to be possible in the borders of a phonological word. If one word has the pattern ending with an MH and the second word has the pattern starting with an M, this hold will not be deleted unless these two words are forming a new word, as in the case of compounding. In the prosodic word, two holds cannot be adjacent, in these cases movement epenthesis occurs. We may define hierarchical structures for prosodic words (ω) where ωs are associated to holds(H) and movements(M). Instead of the hold deletion rule, an automaton that accepts the words which do not contain MHM patterns, such as H, HM, MH, M^+, M^+H, HM^+, or HM^+H, may be constructed.

5.3 Hand-Tier Model to One-Level Phonology

Hand-Tier Model (Sandler, 1989) is an autosegmental model which has three main tiers as shown in Figure 5.18: hand configuration (HC) tier, place tier, and timing tier (LML). HC is organized as a feature geometry of the features related to handshape, orientation, and internal movement as seen in Figure 4.11. Timing tier has a pattern which consists of location (L) and movement (M) segments. Ls are the starting and ending points of the signs. Location

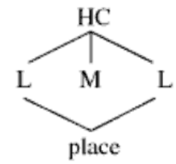


Figure 5.18: Canonical form of a mono-morphemic sign in Hand-Tier Model (Sandler & Lillo-Martin, 2006).

(place) is organized as a feature geometry of location features such as setting, distance, height, manner, and place as seen in Figure 4.13. M is the movement segment to which shape, manner, and setting features are attached.

Transformation of the autosegmental representation in Figure 5.18 to SFA has three steps:

1. Convert autosegmental representation into encoding:

Tier 1:		HC:3:0	
Tier 2:	L:1:1	M:1:0	L:1:1
Tier 3:		place:0:2	

2. Convert encoding to regular expression
   $(HC \cap L \cap place)^{+}(HC \cap M)^{+}(HC \cap L \cap place)^{+}$

3. Convert regular expression to SFA

To make this transformation, we need algorithms to construct SFA for HC tier and SFA for place tier based on the information coded in the feature geometries in Figures 4.11 and 4.13[4]. By traversing the feature tree of Hand Configuration in Figure 4.11 and employing the explanations of Sandler (1989) on this organization, one might have the following fragment of grammar for building the automata for HC tier. Features are written in brackets and they are two valued, i.e., [+F], [-F].

R1. HC = handshape ⊓ [tense]

R2. handshape= fingers ⊓ palm_orientation ⊓ [extended_hand]

R3. fingers= ([T] ⊓ [I] ⊓ [M] ⊓ [R] ⊓ [P]) ⊓ position

R4. position = pos ⊓ manner

R5. manner= [wiggling]

R6. pos = (([open]⊔ [curved]⊔[bent]) ⊓[spread])) ⊔ [closed]) + pos

R7. palm_orientation= ([up]⊔[in]⊔[prone]⊔[contra]) + palm_orientation

[4] Another possible method is to construct an encoding for the whole autosegmental representation, similar to the encoding which is constructed for the autosegmental representation of ASL sign LIKE in MHM in the previous section. In that case, for every autosegment in the sign, there is a term in the encoding, and for every single chart in the feature trees of HC and place, a new number slot is added to every term in this encoding, and the number is determined by counting the associations that the autosegment has on that chart.

Basically the rules R1-R7 define how the hand configuration is composed of its components. R1 states that HC dominates the handshape tier and the feature [tense]. R2 states that handshape tier dominates fingers tier, palm orientation tier and [extended_hand] feature. R3 lists the possible terminal values for fingers tier have and states that the fingers tier dominates the position tier and the selection of fingers (R3 & R4). The terminal values are optional, i.e., if the finger (T:thumb, I:index, M: middle, R:ring, P:pink) is not selected, its feature is not added to the representation.

Sandler (1989) suggests that position tier may also have more than one feature to encode an handshape change. There may be a sequence of pos features as defined by the recursive pos rule R6. The way manner and position of fingers are associated in the feature tree suggests that wiggling spreads over position features (R5). In other words, this model predicts that wiggling should be observed during the change of finger position for example from open to closed.

Sandler (1989) states that when there is an orientation change, it is encoded in the palm orientation tier, hence there may be a sequence of orientations in this tier, i.e., [+up][-up]. Since these changes may be repeated more than once in a sign, we write the rule R7 which is capable of recursively adding more orientations to the sequence by using the concatenation operation.

For constructing an SFA for HC tier, we traverse the feature tree in a depth-first manner, we start with constructing the SFA for the palm orientation tier.

We first check the terminal nodes that the palm orientation dominates (rule R7). If there is no orientation change, only one of the features ([up],[in],[prone],[contra]) is to be selected. In this case, a one-state SFA which recognizes this feature is constructed. If there is an orientation change, then the SFA for the palm orientation is the concatenation of the one-state SFA constructed for each of the orientations in the autosegmental representation.

After we construct the SFA for palm orientation, we pass to rule R6, R5, and R4 in order to construct the SFA which recognizes the position of the fingers. First, if there is no handshape change, a one-state SFA is constructed for the selected position which may be one of the features [open],[closed],[curved],[bent],[spread]. If handshape changes, then the SFA for the position of fingers is the concatenation of the one-state SFA constructed for each of the positions. Second, check whether the representation has [wiggling] feature: if it has this feature then intersect one-state SFA that recognizes this feature, with the SFA constructed for the finger position.

Third step is to construct SFA that recognizes the fingers by intersecting the SFA for the selected fingers and the SFA for finger position (rule R3). SFA for selected fingers is the union of one-state SFA constructed from the terminal nodes ([T], [I], [M], [R],[P]).

In the fourth step, SFA that accepts the handshape is constructed by intersection of the SFA for fingers and the SFA for palm orientation, and one-state SFA for the feature [extended hand] (rule R2).

Last step is the construction of the SFA for HC tier by intersecting of one-state SFA that recognizes the feature [tense] and the SFA for the handshape (rule R1).

When above procedure is applied to the ASR of ASL sign LIKE, the following SFA that recognizes the hand configuration of ASL sign LIKE is constructed: (([+T]⊓[+M])⊓ ([+open] + [+closed])) ⊓ [+in] ⊓ [+ext].

After constructing SFA for HC tier, the next step is to construct SFA for location by traversing the feature tree for location in Figure 4.13. The rules are as follows:

R1. L = setting ⊓ manner ⊓ place

R2. setting= [contact] ⊓ distance ⊓ height ⊓ laterality

R3. manner= [restrained]

R4. place= [head] ⊔ [neck] ⊔ [shoulder] ⊔ [trunk] ⊔ [arm] ⊔ [hand]

R5. distance= [proximal] ⊓ [distal] ⊓ [-proximal, -distal]

R6. height= [hi] ⊔ [lo] ⊔ [-hi,-lo]

R7. laterality = [ipsi] ⊔ [contra] ⊔ [-ipsi, -contra]

The movement features that are associated to M segment are shape, manner, and setting features. Shape feature [+arc] is for arc movements and [-arc] for straight movements. Setting feature is [contact]. Manner feature [restrained] is for fast movement.

Hence, the autosegmental representations are converted to SFA, by first constructing automata for the three tiers HC, timing and place, then just take intersection of them: $HC \sqcap [L + M + L] \sqcap place$.

Up to this point, we describe how the SFA is constructed by converting an autosegmental representation in HTM. Now, we focus on the transformation of autosegmental rules in HTM into SFA. The autosegmental rule for double verb agreement in HTM associates location segments of the timing tier with the source agreement locus (SAL) and goal agreement locus (GAL) as shown in Figure 5.19.

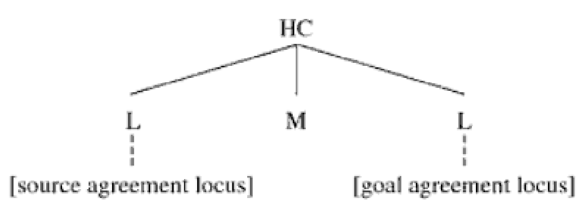


Figure 5.19: Autosegmental rule for verb agreement in Hand Tier Model (Sandler & Lillo-Martin, 2006).

Autosegmental rule for double verb agreement in HTM is converted into the SFA in (17) which adds a new tier into the representation.

(17)
$$\neg\left(\bullet^{*}\left[\begin{array}{ccccc} \bullet:0^{*} & & \text{HC:3} & & \bullet:0^{*} \\ \bullet:0^{*} & \text{L:1} & \text{M:1} & \text{L:1} & \bullet:0^{*} \end{array}\right. \sqcap\neg\left[\begin{array}{ccccc} \bullet:0:0:0:0^{*} & & \text{HC:3:0:0:0} & & \bullet::0:0:0:0^{*} \\ \bullet:0:0:0:0^{*} & \text{L:1:0:0:1} & \text{M:1:0:0:0} & \text{L:1:0:0:1} & \bullet::0:0:0:0^{*} \\ \bullet:0:0:0:0^{*} & \text{SAL:0:0:0:1} & & \text{GAL:0:0:0:1} & \bullet::0:0:0:0^{*} \end{array}\right]_{SC}\right]_{SD}\bullet^{*}\right)$$

The rule SFA for double agreement is multi-tiered, it has two charts, which means that the encoding has four values (1) Chart1 - SD, (2) Chart2 - SD, (3) Chart 1- SC and (4) Chart2 - SC. For example, HC:3:0:0:0 means that HC has 3 associations on the first chart in the structural description, has no associations on structural change. L:1:0:0:1 means that L has one association in the description, and one association is added by the structural change.

The continuative aspect morpheme has the meaning of "for a long time" and the form is adding an [arc] feature to the movement segment as in Figure 5.20. The autosegmental rule for continuative aspect marking in HTM is converted to the SFA in (18):

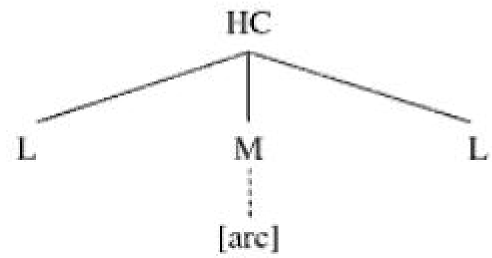


Figure 5.20: Autosegmental rule for continuative aspect marking in Hand Tier Model (Sandler & Lillo-Martin, 2006).

(18) $$\neg\Bigg(\bullet^{*}\Bigg[\begin{array}{ccccc} \bullet:0^{*} & & HC:3 & & \bullet:0^{*} \\ \bullet:0^{*} & L:1 & M:1 & L:1 & \bullet:0^{*}\end{array} \sqcap \neg\Bigg[\begin{array}{ccccc} \bullet:0:0:0:0^{*} & & HC:3:0:0:0 & & \bullet:0:0:0:0^{*} \\ \bullet:0:0:0:0^{*} & L:1:0:0:0 & M:1:0:0:1 & L:1:0:0:0 & \bullet:0:0:0:0^{*} \\ \bullet:0:0:0:0^{*} & & [+arc]:0:0:0:1 & & \bullet:0:0:0:0^{*}\end{array}\Bigg]_{SC}\Bigg]_{SD}\bullet^{*}\Bigg)$$

In HTM, habitual aspect marking is represented by the three rules as seen in Figure 5.21. First rule simple triplicates the sign, movement epenthesis rule adds a linking movement between every two location segments if the adjacent two segments are the same, and lastly HC spread rule links this epenthetic movements to the HC category. The SFA in (19) triplicates the sign. Movement epenthesis and HC-spread rules are converted into one single SFA as in (20).

(19) $$\neg\Bigg(\bullet^{*}\Bigg[\begin{array}{ccccc} \bullet:0^{*} & L:1 & M:1 & L:1 & \bullet:0^{*} \\ \bullet:0^{*} & & HC:3 & & \bullet:0^{*}\end{array} \sqcap \neg\Bigg[\begin{array}{ccccccccccc} \bullet:0:0^{*} & L:1:0 & M:1:0 & L:1:0 & L:0:1 & M:0:1 & L:0:1 & L:0:1 & M:0:1 & L:0:1 & \bullet:0:0^{*} \\ \bullet:0:0^{*} & & HC:3:0 & & & HC:0:3 & & & HC:0:3 & & \bullet:0:0^{*}\end{array}\Bigg]_{SC}\Bigg]_{SD}\bullet^{*}\Bigg)$$

(20) $$\neg\Bigg(\bullet^{*}\Bigg[\begin{array}{cccc} \bullet:0^{*} & L1:1 & L2:1 & \bullet:0^{*} \\ \bullet:0^{*} & HC:1 & HC:1 & \bullet:0^{*}\end{array} \sqcap\neg\Bigg[\begin{array}{ccccc} \bullet:0:0^{*} & L:1:0 & M:0:2 & L2:1:0 & \bullet:0:0^{*} \\ \bullet:0:0^{*} & HC:1:1 & & HC:1:1 & \bullet:0:0^{*}\end{array}\Bigg]_{SC}\Bigg]_{SD}\bullet^{*}\Bigg)$$

5.4 Prosodic Model to One-Level Phonology

Prosodic Model has two main feature classes: Inherent Features (IF) and Prosodic Features (PF) as in Figure 4.20. To construct an SFA for the autosegmental representations in Prosodic

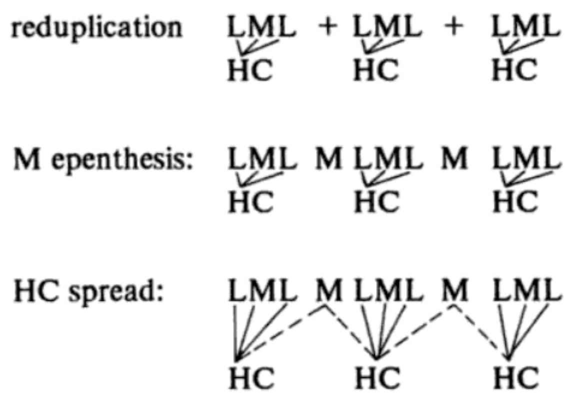


Figure 5.21: Autosegmental rules for habitual aspect (Sandler, 1989)

Model, we suggest to construct two SFA for IF and PF branches and take intersection of the two SFA.

Brentari (1998) states that inherent features are the ones that do not change. They are realized simultaneously, so every node of IF branch is a separate autosegmental tier. There is no temporal sequentiality among the daughter nodes in IF branch. We traverse IF branch in a breadth-first manner, and write the following rules:

R1. IF= A $\sqcap$ POA

R2. A= non-manual $\sqcap$ manual $\sqcap$ [symmetrical]

R3. manual=H2 $\sqcap$ H1 $\sqcap$ [2-handed]

R4. H1= arm $\sqcap$ hand $\sqcap$ ([1] $\sqcup$ [2] $\sqcup$ [3] $\sqcup$ [4] $\sqcup$ [5] $\sqcup$ [6] $\sqcup$ [7] $\sqcup$ [8])

R5. hand= non-selected-fingers $\sqcap$ selected-fingers

R6. non-selected-fingers = [extended] $\sqcup$[flexed]

R7. selected-fingers = joints $\sqcap$ fingers_1

R8. joints= ([stacked]$\sqcup$[flexed]$\sqcup$[crossed]$\sqcup$[spread]) $\sqcap$ (base $\sqcap$ non-base)

R9. fingers_1 = thumb $\sqcup$ fingers_0

R10. thumb = [opposed] $\sqcup$ [unopposed]

R11. fingers_0 = quantity $\sqcap$ point_of_reference

R12. quantity = [all] $\sqcap$ [one]

R13. point_of_reference = [middle] $\sqcap$ [ulnar]

To construct an SFA for IF branch in the Prosodic Model of DESTROY in Figure 5.22, we begin with the terminal nodes. Let us have an SFA that accepts the feature [all], and for brevity just call it [all]. Then, we make use of the rules above to construct an SFA that accepts ASL sign DESTROY. Note that the left-hand sides of the rules are assigned to empty if none of the features on the right-hand side of the rule exists in the autosegmental representation.

1. By rules R12, R11, R9, R7, and R5; SFA for hand= SFA for selected-fingers= SFA of fingers$_0$ = SFA of quantity = SFA of [all]= [all].
2. By rule R4, SFA for H1= [all] $\sqcap$ [1], where [1] is for palm.
3. By rule R3, SFA for manual= H2 $\sqcap$ [all] $\sqcap$ [1] $\sqcap$ [2-handed].
4. By rule R2, SFA for A = H2 $\sqcap$ [all] $\sqcap$ [1]) $\sqcap$ [2-handed] $\sqcap$ [symmetrical]
5. By rule R1, SFA for IF= H2 $\sqcap$ [all] $\sqcap$ [1] $\sqcap$ [2-handed] $\sqcap$ [symmetrical] $\sqcap$ [y-plane]

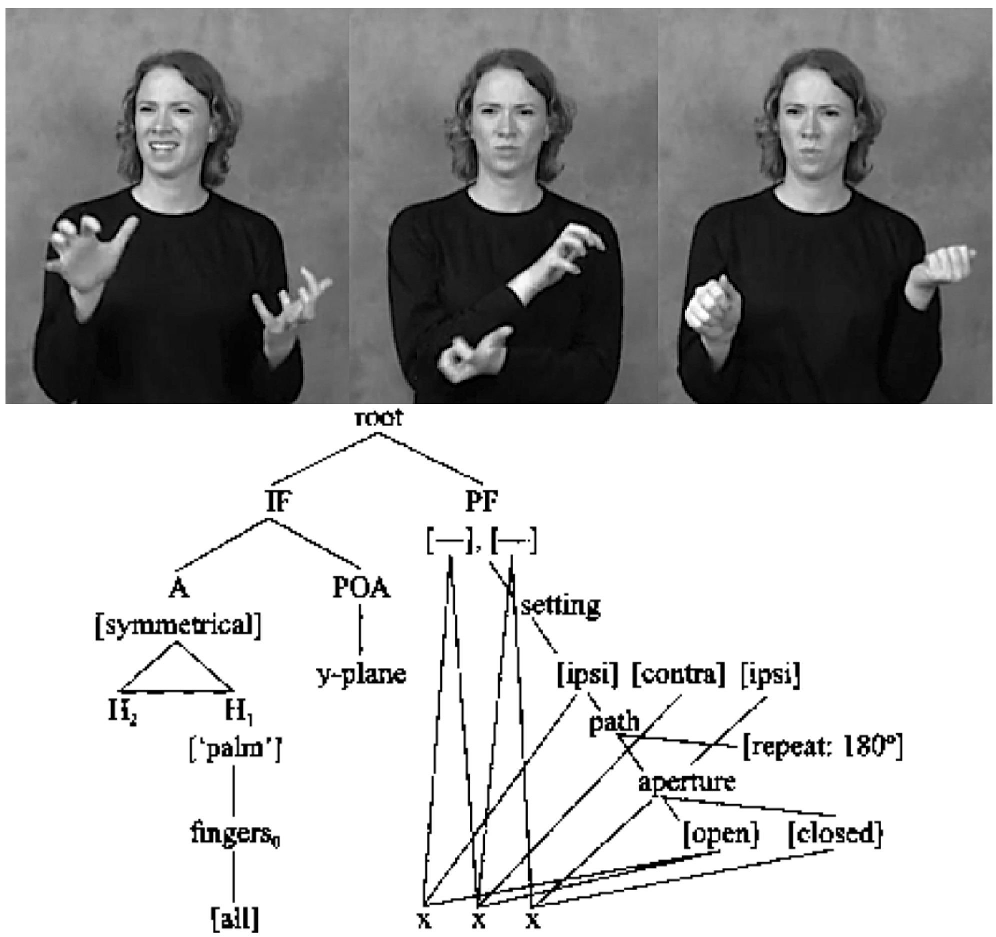


Figure 5.22: Prosodic Model's representation for ASL sign DESTROY (Brentari, 1998, 288). Photographs are taken from the video for DESTROY sign in ASL from the online dictionary http://www.spreadthesign.com/

As the example illustrates, an SFA that recognizes the inherent features (SFA for IF) is constructed by the intersection of all the existing features. This is what we expect, since inherent features are the ones that are realized simultaneously. Transformation of the representation in Figure 5.22 to SFA is completed if we construct an SFA for PF and intersect it with SFA for IF. Prosodic features encode the changes in the sign such as setting change, path, orientation change, and aperture change (Figure 4.24). Prosodic features are realized sequentially, PF branch has sequential timing slots which are associated with the feature nodes.

Prosodic Model describes six charts between which are the timing tier and the following six tiers: PF tier, non-manual tier, setting change tier, path tier, orientation change tier and aperture change tier. The encoding of an autosegment A is written as A:n1:n2:...:n6 where; n1 is the number of associations A has on chart (timing tier, PF tier), n2 is the number of associations A has on chart (timing tier, non-manual tier), n3 is the number of associations A has on chart (timing tier, setting change tier), n4 is the number of associations A has on chart (timing tier, path tier), n5 is the number of associations A has on chart (timing tier, orientation change tier), and n6 is the number of associations A has on chart (timing tier, aperture change tier).

For reducing PF branch into an SFA, we start with the timing slots that are the terminal nodes among which there is the temporal precedence relation. Then, we apply the procedure of transforming to SFA in three steps as usual. To be able to easily understand how the encodings are written, we re-draw the feature geometry in Figure 5.22 as the autosegmental representation in Figure 5.23.

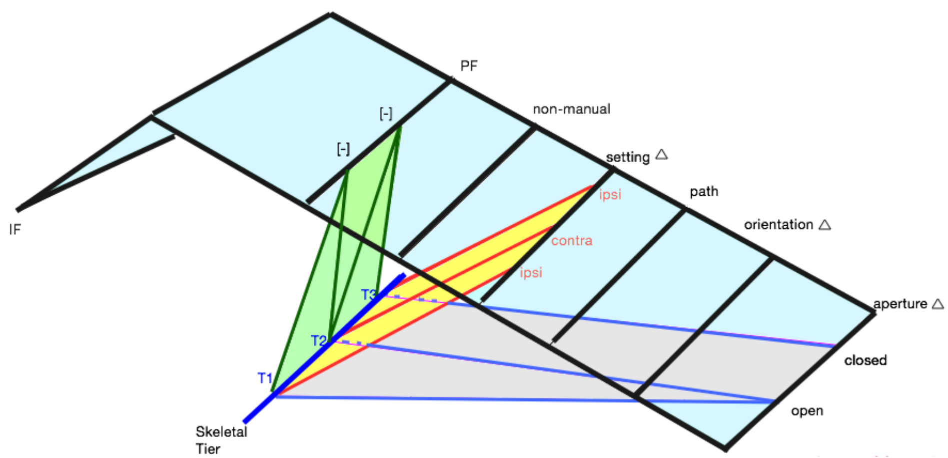


Figure 5.23: A 3D autosegmental representation for Prosodic Model: ASL verb DESTROY has a two straight paths [-][-] in PF tier, [ipsi][contra][ipsi] sequence on setting change tier, and [open][close] sequence for the aperture change tier. These three tiers are associated to the timing slots T1, T2 and T3 on the skeletal tier.

Steps for constructing the SFA for PF:

1. Convert PF branch into encoding. For each element on these tiers, by counting the associations on the above mentioned charts, obtain an encoding of the form A:n1:n2:..:nk, where k is the number of charts.

Skeletal Tier:	T1:1:0:1:0:0:1	T2:2:0:1:0:0:1	T3:1:0:1:0:0:1
PF Tier:	$[-]_1$:2:0:0:0:0:0	$[-]_2$:2:0:0:0:0:0	
Non-manual Tier:			
Setting Change Tier	[ipsi]:0:0:1:0:0:0	[contra]:0:0:1:0:0:0	[ipsi]:0:0:1:0:0:0:0
Path Tier			
Orientation Change Tier			
Aperture Change Tier	[open]:0:0:0:0:0:2	[closed]:0:0:0:0:0:1	

Concatenate the elements in each tier using the operator of concatenation '+', build the encoding of the tier. To obtain the overall encoding of the PF branch, intersect (⊓) the encodings of the tiers. (T1:1:0:1:0:0:1 + T2:2:0:1:0:0:1 + T3:1:0:1:0:0:1) ⊓ ($[-]_1$:2:0:0:0:0:0 + $[-]_2$:2:0:0:0:0:0) ⊓ ([ipsi]:0:0:1:0:0:0 +[contra]:0:0:1:0:0:0 +[ipsi]:0:0:1:0:0:0:0) ⊓ ([open]:0:0:0:0:0:2 + [closed]:0:0:0:0:0:1).

2. Convert encoding into regular expression by using definitions in (10).

3. Convert regular expression into state labeled automata

To construct the final SFA for the prosodic model we intersect the two SFA for IF and PF branches.

CHAPTER 6

EVENT-BASED ONTOLOGY FOR SIGN LANGUAGE PHONOLOGY

This chapter[1] presents an ontology, which analyzes the domain of sign language phonology based on Movement-Hold model (Liddell & Johnson, 1989), as a case study of re-using event-based ontology of Bird and Klein (1990). This ontology specifies how signs are composed of meaningless units, namely phonemes. By extending event-based ontology (Bird & Klein, 1990) to sign language, we assign appropriate meanings to autosegmental representations, and capture both simultaneous and sequential aspects of sign language phonology via temporal relations, and construct a mechanism that checks well-formedness of signs.

The general purpose of developing this ontology is to share the common understanding of the structure of phonological representations among researchers from different fields such as computational linguistics, machine translation, lexicography and sign linguistics, and to make this information accessible to software agents for computational processing and analysis.

We construct an event-based ontology (Bird & Klein, 1990) based on only MHM (Liddell & Johnson, 1989) as a case study of giving appropriate meanings to autosegmental representations of signs. We prefer MHM (Liddell & Johnson, 1989) because it has a rich phonetic transcription system in addition to being an autosegmental phonology model which encodes the timing among the autosegments. It is equivalently possible to develop similar ontologies based on the other two models: HTM (Sandler, 1989) and PM (Brentari, 1998) .

This temporal ontology for sign language is based on time intervals, and it has the power of interpreting the relations between the autosegments as temporal relations. Having an ontology based on a phonological model, it is possible to test the assumptions made by this model, and to check if these assumptions are consistent. This ontology is useful for checking the well-formedness of autosegmental representations of the signs.

Bird and Klein (1990) design an ontology that assigns interpretations to the representations in Autosegmental Phonology (Goldsmith, 1976). The autosegmental representations, which are transformed into *state labeled automata* by *One-level Phonology* (Bird & Ellison, 1994), are assigned a formal *temporal semantics* (Bird & Klein, 1990). In this temporal semantics, autosegments are accepted as *extended time intervals* associated with phonological properties (features or gestures). Event, which is the interpretation of an autosegment, is the basic unit in this ontology. Hence, this semantics is also called *"event-based ontology"* (Bird & Klein,

[1] Chapter 6 is presented in ESSLLI 2015 Student Session and it is published in online proceedings (Sevinç, 2015).

1990).

An autosegmental tier which has a set of autosegments in a linear order is interpreted as a *melody* which has an ordered set of events. The linear order among autosegments is interpreted as *temporal precedence* relation among the intervals of the events. Association lines between autosegments on different tiers are interpreted as *temporal overlap* relation (Bird & Klein, 1990). *Phonological event structure* is the interpretation of an autosegmental representation which consists of multiple tiers. It has a set of melodies and two sets of pairs of intervals to indicate precedence and overlap relations.

In the rest of this chapter, we explain the class hierarchy in Figure 6.1[2] and introduce properties of these classes, relations among them, and axioms defined over these relations. This ontology is developed in Web Ontology Language (OWL) and Semantic Web Rule Language (SWRL) by using Protégé editor[3]. In Table 6.1, all relations in in Figure 6.1 are listed and information such as domain, range and OWL object property characteristics are given.

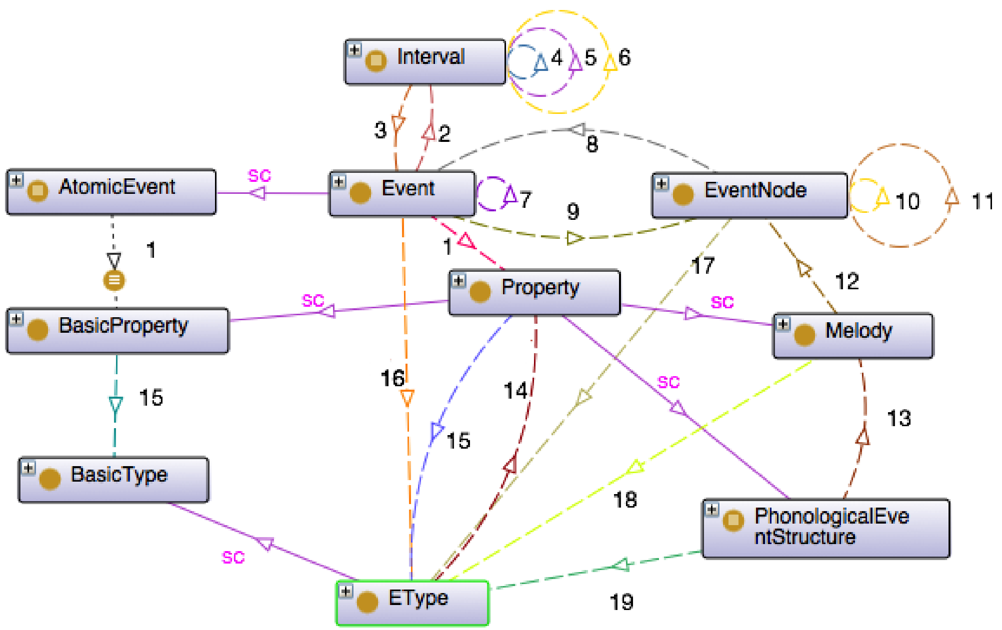


Figure 6.1: Class hierarchy for event-based ontology (Bird & Klein, 1990).

We organize the following sections as to explain the main classes: events, melodies, and phonological event structures. Based on MHM (Liddell & Johnson, 1989), we construct a knowledge base by deciding what an event, a melody or a phonological event structure is in this model, and what kind of phonological properties basic events have and lastly which basic types these properties have.

2 'sc' stands for subClassOf. Enumerated relations are explained in Table 6.1.

3 http://protege.stanford.edu/

Table 6.1: Relations in event based ontology of sign language. F:functionality, IF:inverse functionality, T:transitivity, S: symmetry , AS: asymmetry, R:reflexivity, and IR: irreflexivity. PES stands for PhonologicalEventStructure, xImmPrecedes is shortened form of xImmediatelyPrecedes.

#	Relation Name	Source Concept	Target Concept	F	IF	T	S	AS	R	IR
1	eHasProperty	Event	Property	☑	☐	☐	☐	☑	☐	☑
2	eHasInterval	Event	Interval	☑	☐	☐	☐	☑	☐	☑
3	iIntervalOf	Interval	Event	☐	☑	☐	☐	☑	☐	☑
4	iImmPrecedes	Interval	Interval	☑	☑	☐	☐	☑	☐	☑
5	iPrecedes	Interval	Interval	☐	☐	☐	☐	☑	☐	☑
6	iOverlaps	Interval	Interval	☐	☐	☐	☑	☐	☐	☐
7	eImmPrecedes	Event	Event	☑	☑	☐	☐	☑	☐	☑
8	nHasEvent	EventNode	Event	☑	☑	☐	☐	☑	☐	☑
9	eEventOf	Event	EventNode	☑	☑	☐	☐	☑	☐	☑
10	nImmPrecedes	EventNode	EventNode	☐	☐	☐	☐	☐	☐	☐
11	nHasNextNode	EventNode	EventNode	☑	☑	☐	☐	☑	☐	☑
12	mHasEventSet	Melody	EventNode	☑	☑	☐	☐	☑	☐	☑
13	pesHasMelody	PES	Melody	☐	☐	☐	☐	☑	☐	☑
14	tTypeOf	EType	Property	☐	☑	☐	☐	☑	☐	☑
15	pHasType	Property	EType	☑	☐	☐	☐	☑	☐	☑
16	eHasType	Event	EType	☐	☐	☐	☐	☐	☐	☐
17	nHasType	EventNode	EType	☐	☐	☐	☐	☐	☐	☐
18	mHasType	Melody	EType	☐	☐	☐	☐	☐	☐	☐
19	pesHasType	PES	EType	☐	☐	☐	☐	☐	☐	☐

6.1 Event

Event is the interpretation of an autosegment. Bird and Klein (1990) define an *event* (E_θ) as "an ordered pair $< \iota, \pi_\theta >_\theta$ consisting of an interval (ι) and a property (π_θ)". The type of event is same as the type of its property, θ.

We define eHasInterval relation to attach events an *extended time interval* and eHasProperty to associate events with some *phonological property*. iIntervalOf is inverse of eHasInterval. Self loops on Interval node in Figure 6.1 represent iImmediatelyPrecedes, iPrecedes and iOverlaps relations.

We include three subclasses under Property class: BasicProperty, Melody and PhonologicalEventStructure. Basic properties correspond to features or gestures; i.e., for spoken languages, they are things like phonemes, tones, demisyllables and articulatory features. Based on MHM (Liddell & Johnson, 1989; Liddell, 1990b), we define 14 subclasses of BasicProperty class as in Table 6.2. We add individuals to each subclass by using the values of segmental and articulatory features in Table 4.1 and Table 4.2 which are defined by MHM (Liddell & Johnson, 1989).

Atomic event is an event with a basic property. AtomicEvent is defined as a subclass of Event as follows: "Event that eHasProperty exactly 1 BasicProperty". Some examples of atomic events are E$_1$=$< \iota_1, 8_{hs} >_{hs}$, E$_2$=$< \iota_2, o_{fc} >_{fc}$. E$_1$ is an atomic event which has the property '8 handshape' which is associated with interval ι_1. E$_2$ has the property 'open finger configuration' which is realized in interval ι_2.

Melody class has an ordered set of events (mHasEventSet) and PhonologicalEventStructure has a set of melodies (pesHasMelody). EventSet is implemented as a linked list whose elements are represented by the EventNode class. Each EventNode has an event (nHasEvent) and a next node (nHasNextNode). Definition of event is recursive (Figure 6.1), but it is not cyclic (Bird & Klein, 1990).

This ontology is all typed. Property has a type (pHasType) and Etype is the type of a property (tTypeOf). The type of the property may be a basic type, or a set of basic types or a set of set of basic types (Bird & Klein, 1990). The set of basic types is determined on the basis of the phonological properties that the language has. For our ontology based on MHM (Liddell & Johnson, 1989), we insert 13 individuals of BasicType class all of which are defined to be the types of basic properties (Table 6.2). We relate each basic property with a basic type by defining it as an equivalent class of "BasicProperty and pHasType value X", where X is one of the basic type values in Table 6.2.

Table 6.2: BasicProperty subclasses and their corresponding BasicType individuals

BasicProperty	BasicType	BasicProperty	BasicType
HC-HandShape	hs	NMM-LIPS	nmm
HC-FingerConfiguration	fc	HandPart	hdp
POC-Proximity	cpro	Plane	pl
POC-SpatialRelation	srel	SEG-LocalMovement	lm
POC-HandPart	chdp	SEG-Quality	qm
LOC-MajorBodyLocation	loc	SEG-ContourOfMovement	cm
LOC-SigningSpaceLocation	loc	SEG-MajorClass	mc

The type of event is same as its property's type, eHasType is defined as a composite relation "eHasProperty o pHasType". Type of melody is same as the type of its events, and type of phonological event structure is the set containing the types of its melodies. mHasType and pesHasType are also composite relations.

6.2 Melody

Melody is the interpretation of a tier in an autosegmental representation. The order among autosegments in a tier is defined in terms of "temporal precedence" relation. Formally, Bird and Klein (1990) define a *melody* τ as "a pair $< E, \prec^o >_{\{\theta\}}$ consisting of an *event set* (E) and immediate precedence relation ($\prec^o$)." All the elements of the event set have the same type θ. $\prec^o$ is defined over the event set E as follows:

For any events $x, y \in E$, x immediately precedes y ($x \prec^o y$) iff $x \prec y$ and there is no $z \in E$ such that $x \prec z \prec y$. This relation is

(i) asymmetric: $\forall xy.x \prec^o y \leftrightarrow \neg(y \prec^o x)$

(ii) irreflexive: $\forall x.\neg(x \prec^o x)$

(iii) intransitive: $\forall x.(x \prec^o y \wedge y \prec^o z) \rightarrow \neg(x \prec^o z)$.

In our ontology, iImmediatelyPrecedes is defined on Interval class and marked as asymmetric and irreflexive as in Table 6.1. iPrecedes is defined as a super property of iImmediatelyPrecedes in the object property hierarchy. We define temporal relations among events (eImmediatelyPrecedes, ePrecedes and iOverlaps) based on their counterparts defined on intervals. Similarly, these temporal relations between event nodes in the melody are defined based on relations of their events.

Bird and Klein's definition is equivalent to an ordered list of events. Rather than having a set, we prefer to define melody as a list. In OWL, there is "no built in support specifically for sequences or ordering" (Drummond et al., 2006). Hence, we implement melody as a linked list following (Drummond et al., 2006). Melody has the relation mHasEventSet which directs it to first EventNode in the linked list. We define EventNode class as having two main relations: nHasEvent and nHasNextNode. The last node is marked with a subclass of EventNode class, MaxNode, which is defined to have no next node. The next node is defined to have the same type as current node in the SWRL rule: "nHasNextNode(?en1, ?en2), nHasType(?en1, ?t1), nHasType(?en2, ?t2) → SameAs (?t1, ?t2)". Variables in SWRL start with the ? symbol.

Melody may have events, or may be empty. EmptyMelody is equivalent to Melody class with a maximum cardinality restriction of having zero event: "Melody and (mHasEventSet exactly 0 EventNode)". We define AtomicMelody as a melody whose events are all atomic: "Melody and (mHasEventSet some (EventNode and (nHasEvent only AtomicEvent)))". An example of an atomic melody is the interpretation of the aperture change from open (o) to closed (op) finger configuration in Figure 4.4. $\tau = << \iota_1 : o_{fc} >, < \iota_2 : op_{fc} >>, \prec^o >_{\{fc\}}$, where $\prec^o = \{< \iota_1, \iota_2 >\}$.

In an event-based ontology based on Movement-Hold model (Liddell, 1990b), some other examples of possible melodies are the interpretations of H, M, HMH, $HM_1M_2M_3H$ on segmental tier, where Ms and Hs are segments. For instance, a simplified interpretation of HMH is $\tau = << \iota_1 : H_{mc} >, < \iota_2 : M_{mc} >, < \iota_3 : H_{mc} >>, \prec^o >_{\{mc\}}$, where $\prec^o = \{< \iota_1, \iota_2 >, < \iota_2, \iota_3 >\}$ and *mc* is type of SEG-MajorClass property.

Melodies are not always atomic in Movement-Hold model, subclasses of Melody such as SegmentalMelody, HandConfigurationMelody, FacingMelody, PointOfContactMelody and OrientationMelody are complex in the sense that they have an event set whose members have phonological event structures as their properties.

6.3 Phonological Event Structure

Autosegmental representations are interpreted as phonological event structures. "A *phonological event structure* $\mathcal{R}$ is a triple $< \{\tau_{\theta_1}, ..., \tau_{\theta_n}\}, \prec, o >_{\{\theta_1,...,\theta_n\}}$ where $\{\tau_{\theta_1}, ..., \tau_{\theta_n}\}$ is the set of melodies in the event structure", $\prec$ and o are *precedence* and *overlap* relations (Bird & Klein, 1990). Melodies in an event structure have different types. A melody in an event structure may be empty. The association lines between the tiers are represented by temporal overlap relation.

We define two subclasses of PhonologicalEventStructure class: SegmentCProperty and ArticulatoryCProperty. SegmentCProperty defines the properties of segmental events. ArticulatoryCProperty is either FacingCProperty, HandConfigurationCProperty, OrientationCProperty, or PointOfContactCProperty. These four classes define the properties of the events in the four main melodies described by Movement-Hold model(Liddell & Johnson, 1989). For example, events on Hand Configuration melody are defined to have two basic properties: handshape (hs) and finger configuration (fc). We define HandConfigurationCProperty as "PhonologicalEventStructure and (pesHasMelody exactly 1 (AtomicMelody and (mHasType value fc))) and (pesHasMelody exactly 1 (AtomicMelody and (mHasType value hs)))."

The axioms in [A1]-[A5] are the minimal set of axioms which hold for overlap (o) and precedence ($\prec$) relations .

A1. $\forall x.xox$

A2. $\forall xy.xoy \rightarrow yox$

A3. $\forall xy.x \prec y \rightarrow \neg(y \prec x)$

A4. $\forall xy.x \prec y \rightarrow \neg(xoy)$

A5. $\forall wxyz.(w \prec x) \wedge (xoy) \wedge (y \prec z) \rightarrow (w \prec z)$

iOverlaps is a reflexive, non-transitive and symmetric relation. We declare reflexivity for Interval class as equivalent to 'iOverlaps some Self' (A1). We check only the box of symmetry (A2) for iOverlaps as in Table 6.1. iPrecedes is a transitive, asymmetric and irreflexive relation, however we only check the boxes of asymmetry (A3) and irreflexivity as in Table 6.1, because OWL has the limitation of not having transitive property with irreflexive and asymmetric property. We satisfy transitivity by inserting the SWRL rule "iPrecedes(?x, ?y), iPrecedes(?y, ?z) → iPrecedes(?x, ?z)". For irreflexivity of iPrecedes, we insert the SWRL rule "iPrecedes(?x, ?y) → DifferentFrom (?x, ?y)" (A3). iPrecedes and iOverlaps are defined to be disjoint (A4). In a similar manner, we define temporal relations eOverlaps, ePrecedes and eImmediatelyPrecedes. A5 defines well-formedness condition that states that association lines do not cross. We rephrase well-formedness condition in (1) to make it usable for signs and compatible with the terminology of Hold-Movement model (Liddell & Johnson, 1989).

(21) Well-formedness condition for Sign Language

a. All articulatory events are associated with at least one segment.

b. All segments are associated with at least one articulatory event.

c. Association lines do not cross.

For first condition in (21), we define ArticulatoryEvent as "Event that (eHasProperty some ArticulatoryCProperty) and (eOverlaps min 1 Segment)" and add a SWRL rule: "ArticulatoryEvent(?e), Event(?e2), eOverlaps(?e, ?e2), DifferentFrom (?e, ?e2) → Segment(?e2)". Condition 2 is handled in the same manner. We define Segment as "Event that (eHasProperty some SegmentCProperty) and (eOverlaps min 1 ArticulatoryEvent)", and insert the rule: "Segment(?e), Event(?e2), eOverlaps(?e, ?e2), DifferentFrom (?e, ?e2) → ArticulatoryEvent(?e2)". For third condition, we add the rule: "ePrecedes(?w, ?x), eOverlaps(?x, ?y), ePrecedes(?y, ?z), DifferentFrom (?x, ?y), DifferentFrom (?y, ?z), DifferentFrom (?z, ?w) → ePrecedes(?w, ?z)".

6.4 Summary and Conclusions

In this chapter, we present how we developed a computational event-based ontology depending on the terminology of Movement-Hold model (Liddell, 1990b) which is an autosegmental model that it can represent both simultaneity and sequentiality. This ontology assigns interpretations to the autosegmental representation. Three main classes are defined for giving semantics to autosegments, tiers, and charts: event, melody and phonological event structure. Also temporal precedence and overlap relations are defined among events. We implement this event-based ontology for sign language phonology by using Protégé which is a free, open source ontology editor. It is useful for making inferences about the validity of signs by checking the well-formedness conditions defined by Autosegmental Phonology.

CHAPTER 7

CONCLUSION AND FUTURE WORK

This thesis focuses on simultaneity, which is one of the three main modality differences that theories of language should capture together with the use of space and iconicity. Phonological organization of signs are claimed to be simultaneous (Stokoe, 1960; Klima & Bellugi, 1979), however relatively newer sign language phonology models claim that there are also sequential segments (Liddell & Johnson, 1989; Sandler, 1989; Brentari, 1998). Sign languages make use of morphological operations such as segmental affixation, featural affixation and reduplication very frequently for inflectional morphological processes such as temporal aspect marking, pluralization, person marking and number marking. The phonological realizations of these operations have both simultaneous and sequential aspects.

This thesis investigates whether simultaneity in phonology and morphology of sign languages has an effect on the computational power required for processing morphophonology. For this purpose, we first define the autosegmental representations of signs in three sign language phonology models: Movement-Hold Model (Liddell & Johnson, 1989), Hand-Tier Model (Sandler, 1989) and Prosodic Model (Brentari, 1998). We then define or reuse the pre-defined autosegmental rules, which describe the morphological processes, within these phonological models. MHM, HTM, and PM propose different feature organizations, hence offer different autosegmental representations.

The main objective of the thesis is to show that the autosegmental representations and rules, that are offered by these three sign language phonology models, are reducible to finite state machines. To achieve this objective, we define procedures for these transformations from representations and rules into the state labeled automata (SFA) of One-level Phonology (Bird & Ellison, 1994). SFA are known to be equivalent to finite state automata, and hence they have generalized regular language power. Hence, this thesis shows us that the simultaneity in the phonology and morphology of sign languages does not lead to more or less complexity than spoken languages. The computational power required for sign language morphophonology is the expressive power of generalized regular languages in the Chomsky hierarchy of languages(Chomsky, 1956).

One-level Phonology (Bird & Ellison, 1994) has only one level of linguistic description, hence there is no distinction as surface form and lexical form. All the representations and rules are transformed into the same linguistic object, SFA. This property makes One-level Phonology (Bird & Ellison, 1994) integrable to a strongly lexicalized theory like Combinatory Categorial Grammar (Steedman, 2000b). This integration results in a lexical-incremental theory of morphology.

A morphology based on autosegmental representations and rules is simply an inferential one. By the conversion of these representations and rules into SFA and SFA's integration to CCG, we reach to a lexical-incremental theory of morphology, in which the lexical entries of the lexicon are the morphemes. Morphemes may be stems or affixes. In a lexicon of a sign language, the affixes may be featural or segmental. Lexical entry of a stem has an SFA which recognizes this stem. Lexical entry of an affix contains an SFA which is constructed from the corresponding autosegmental rule(s). If a morpheme requires to make more than one change over the stem, i.e. there are more than one rule to apply, then the intersection of the SFA of these rules is put in the lexical entry.

Radical lexicalization requires the seriation of the phonological representations. If phonological representations and rules defined for various different languages, i.e., tonal languages, agglutinating languages, sign languages, languages with non-linear morphology like Arabic, are all serializable; in other words, if they can be converted to the same finite state machinery, then one grammar parses and generates these languages, and in this case, we can conclude that syntax works independently of how the phonology is organized in these languages. That is to say, phonology does not determine syntax. After serialization of feature geometry of sign languages, we are at a point where one grammar, CCG, parses and generates languages from both modalities. In the scope of the thesis, our focus is on the phonology, we leave the demonstration of its integration to CCG for further research.

For any kind of computational analysis on recorded signs which are mostly stored in video format, a notation system is needed. One of the most popular notation systems for sign language is Hamburg Notation System (HamNoSys). HamNoSys is also used by sign language generation systems as input to animation of signing avatars (Elliott et al., 2000; Marshall & Safar, 2005). In the implementation of computational morphology for Spanish Sign Language, Jordi Porta and Colas (2012) and Zamorano (2014) use HamNoSys transcriptions in the surface and lexical forms. HamNoSys is a phonetic transcription system based on Stokoe's notation (Stokoe, 1960). It represents the sign as a linear sequence of symbols. Symbols represent handshapes, hand positions, locations, non-manuals, orientations and movements. This representation is also said to be multi-tiered since the symbols in the representation are accepted to be simultaneous. Even if HamNoSys has sequential and simultaneous flavor, it is not a detailed representation that shows how these components of the sign are temporally related.

In this thesis, we propose a computational morphology model for sign language which defines the mechanisms required to generate and recognize signs and their inflected forms, and we suggest to integrate it to a strongly lexicalized theory like CCG. This work is based on phonological models rather than a phonetic transcription system like HamNoSys. In this work, we transform autosegmental representations and rules to finite state automata.

Phonetics is about physical properties of speech sounds or signs. It studies the low-level physiological production and perception of manual and non-manual signals. It does not capture the alternations or the changes which occur when the sign is inflected (Mathur, 2000). On the other hand, phonology has abstract representations and defines patterns and rules on these abstractions.

For example, all of the three sign language phonology models (MHM, HTM and PM) have multi-tiered representations which encode the temporal 'overlap' and 'precedence' relations among the autosegments. Hence, phonological models are better representatives of simultaneity and sequentiality than phonetic transcription systems. These temporal relations are easily mapped to 'concatenation' and 'intersection' operations defined over state labeled automata.

These phonological models define rules to encode the morphophonological changes which take place on the autosegmental representations during inflectional processes. Similarly, these rules are also easily converted to automata. Transformation is easily handled by interpreting the autosegmental rule as a logical implication from structural description to structural change, and by using the mapping from 'logical or' and 'logical and' to 'union' and 'intersection' operators (Bird & Ellison, 1994). These conversions are possible since these models are defined over abstract representations. Our explanation is compatible with the main proposal of cognitive science: cognitive processes operate on representations.

In this thesis, we also develop a computational ontology that assigns a temporal semantics to the autosegmental representations of signs based on MHM (Liddell, 1990b). We re-use and extend the event-based ontology of (Bird & Klein, 1990) to cover autosegmental representations defined by MHM (Liddell & Johnson, 1989; Liddell, 1990b) and show how the terminology of this model is expressed within an event-based ontology. For that, we define the basic properties and relations for sign languages, which are apparently very different from the ones for spoken languages.

Event-based ontology is applicable to various kinds of languages such as tonal languages, Arabic, and sign languages. With this ontology, the autosegmental representations, which are transformed into *state-labeled automata* by *One-level Phonology* (Bird & Ellison, 1994), are assigned a formal *temporal semantics* (Bird & Klein, 1990). Autosegments are accepted as events, and the temporal relations among autosegments are defined. By extending this ontology to sign languages, we point that spoken and signed languages are more similar at a higher level of abstraction, the relations between the phonological events are universal, and the same terminology is used for all languages.

Mainly, this event-based ontology of sign phonology makes the domain knowledge accessible to machines. The most important point about this ontology is that it is possible to make inferences about validity of autosegmental representations of signs. Given all the relations and properties defined for the sign, this ontology can decide whether this sign is valid with respect to the well-formedness conditions of Autosegmental Phonology.

In order to make this computational morphology system as a part of a language generation system, annotations of many autosegmental representations are needed to be prepared based on these phonology models. This annotation task would be time consuming since these representations are very loaded and error-prone if the annotations are not standardized. If the number of annotators is relatively large, the annotation task can be accomplished in a shorter time. For this purpose, as a future work, this ontology may be integrated to ELAN to make annotators use the same restricted terminology based on a specific sign language phonology model. Ontology based annotation makes the task faster and more error-free[1].

[1] Ontology-based annotation is an idea suggested by ONTO-ELAN project (Chebotko, Lu, Fotouhi, & Aristar, 2009), however their terminology is not relevant to the topic of phonology.

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International Conference Publications

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Thesis

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