REPRESENTATION OF AMERICAN SIGN LANGUAGE
FOR MACHINE TRANSLATION

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ABSTRACT

This dissertation describes an approach to designing a machine translation system that generates a representation of American Sign Language (ASL) from English. ASL uses space and non-manual signals (NMSs) to encode grammatical features such as agreement, negation, wh-questions, etc. Previous computational systems for ASL are typically hindered by static representations of ASL signs, which makes it computationally impractical to represent the large number of possible surface forms for each sign, and by the use of notation systems that cannot represent such variation.

The approach developed here addresses these limitations. The representation of ASL is based on the Move-Hold (MH) model (Liddell and Johnson 1989), a sign notation system that allows for both precision of sign description and predictable variation of surface forms based on grammatical detail. Empty features are used in MH notations of lexical forms, which are instantiated with spatial data during generation.

The generation system is implemented as an LFG correspondence architecture (Kaplan and Bresnan 1982, Kaplan et al 1989). Correspondence functions are defined that convert an English f-structure into an ASL f-structure; build an ASL c-structure from the f-structure; and build the phonetic representation level (p-structure, where spatial and non-manual variations are revealed) from the c-structure.

The concepts presented in this dissertation have been implemented in a software application, *ASL Workbench*. Possible future applications of this work include developing

animated output, tagged corpora for linguistic analysis, and shared lexicons for gloss standardization, among others.

Preface

American Sign Language is the native language spoken by Deaf people[1] in the United States and Canada. Sacks (1989) speculates that there are approximately a quarter of a million pre-lingual deaf people, and about fifteen million post-lingual deaf and hard-of-hearing people in the world today. Sign language is used by many of the members of this population, but also by others: by hearing parents of deaf children; by children of Deaf adults (CODAs); by hearing educators of the Deaf; and others who find themselves in contact with native signers, such as the hearing inhabitants of Martha's Vineyard prior to the latter part of the 20th century (see Groce 1985). Sign language is also used and studied by linguists who are investigating principles of language that are independent of the mode of communication, in an effort to learn more about the species-specific ability to use language.

Sign language is not merely a visual representation of another language, say English, used for convenience by those who cannot hear. It is a natural language, arising in communities of Deaf people just as spoken languages arise in communities of hearing people. It has linguistic structure, idiom, metaphor, etc.; it can represent abstract as well as concrete ideas. As a linguistic medium, it is in no way impoverished or restricted in the type or complexity of ideas that it can convey. And yet, to this day, I encounter people who share the misconception that sign language is a code for English, or that it is a universal language, or that it was constructed by hearing people for the convenience or education of the deaf. Generally, people today are far less aware of the

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[1] Woodward (1972) first proposed the convention of using capital-D "Deaf" to refer to the linguistic and cultural community of deaf people who use sign language, and the word "deaf" with a lower-case "d" to refer to people with the audiological condition of deafness. This convention is adopted here.

issues confronting deaf people than their counterparts of one and even two hundred years ago (cf. Lane 1984, for example). Nevertheless, it is not the goal of this work to address such misconceptions, but to describe an approach to a computational system that is not misguided by them.

Among those who are partially cognizant of the difficulties Deaf people encounter in their contact with the hearing majority, these misconceptions contribute to the belief that current practices, including technology, provide adequate access to information and communication. For communicating over the telephone, we have the TTY (Teletype); for television we have Closed Captioning (CC); for access to information in almost every other medium (books, newspapers, World Wide Web), we have written English. Is this not adequate? Consider the situation in reverse. Imagine that for all hearing people, in order to use any technology or have access to any information (other than face-to-face contact with other hearing people), another language had to be used, say, Latin. Need to talk on the phone? Speak Latin. Need to read the newspaper? Read Latin. Need to write a proposal? Write Latin. Want to go to the movies? Well, forget that, because the Latin captioning technology used on television hasn’t been implemented in the movie theaters yet. And however bad it may seem, it's worse for most Deaf people. At least for the hearing non-Latin speaker, learning to speak Latin is an option. For the Deaf person, while learning to read and write English is possible (as much so as for anyone), learning to speak and understand spoken English is often an insurmountable challenge. It may seem an extreme example, but it is an accurate reflection of the current state of the technologies employed to provide Deaf people with access to information and communication channels: communication is presented visually in English, not in the native language of the community. For hearing people who have become deaf, through natural causes like presbycusis or as a result of injury, these solutions are probably adequate. But for the community of Deaf people, for whom sign language is the native and natural mode of communication, clearly, the current state of affairs is not adequate.

As technology improves, new possibilities will emerge for Deaf people. For instance, the TTY will eventually give way to the videophone, when the bandwidth supports sufficiently high frame rates and the cost is low enough to encourage widespread distribution (or another solution emerges, such as Internet-based video conferencing). High-speed networks such as those being developed for Internet 2 will allow for the development of video-based collections, and video libraries will allow broad access to ASL literature for the first time. And I propose that machine translation and animation technology will allow for the generation of sign language versions of written text. It is this final area of development with which I am concerned here.

Of course, we are a long way from automated machine translation that will generate animated signers. Although machine translation theory and technology have improved much in recent years, it is a field that still faces many challenges, and there are many novel and non-trivial challenges that arise in the context of this project. The most obvious is the need to show the output of such a system as animated sign, of a quality good enough to allow any signer to view and understand the message (and perhaps with sufficiently low bandwidth requirements to allow transmission over computer networks such as the Internet). More fundamental, however, is the task of translating to and generating the ASL to begin with. Linguists have only relatively recently turned their attention to the analysis of sign languages. Dr. William Stokoe at Gallaudet University conducted the original analysis of ASL just 40 years ago. Compare that to the tradition of spoken language linguistics, which has its roots with the ancient Greeks, some 2,000 years ago. Clearly, linguists studying sign language have a lot of catching up to do.

This work is far less ambitious. As a core component of a machine translation system that seeks to generate sign language, this project will address the linguistic requirements imposed by the visual channel (as distinguished from the computational requirements of generating animated output). Given that sign languages use the signing space to encode grammatical information, how does one represent and manipulate this grammatical information in a computational system? Is it even necessary to consider spatial-grammatical relationships, or is an encoding of abstract grammar sufficient? These issues are the focus of the present work.

The system proposed here is intended to translate from written English to ASL, based upon the linguistic properties of ASL. Clearly, there are many potential applications for such a system. Web sites can offer ASL versions of pages, allowing, for instance, news articles to be presented in sign language; computer applications can provide ASL versions of help text, documentation and interface components; ESL applications for Deaf people can be enabled with ASL instructional material; etc. Applications such as these could be designed more quickly and less expensively (both in terms of financial and computing resources) than hiring an interpreter and incorporating video, assuming the translation, performance and animation quality are at least adequate.

There are additional benefits to having machine-readable versions of ASL documents instead of video. Researchers will tag and share documents, allowing for the first time corpus development and analysis of ASL "text." Linguistic analysis can be performed against such a corpus, with appropriate software tools. A concordance of ASL can be developed from such a corpus of ASL documents. Documents of sign can include annotations, which can be used for linguistic description, text searching, etc. The potential benefits to linguists studying sign languages are profound.

The presence of a machine-readable lexicon, one component of the system presented here, will contribute to the standardization of glosses. The current practice in articles which present linguistic analyses of ASL utterances, which is followed almost without exception[2], is to represent signs with English glosses in ASL order, with diacritic marks to show the occurrence of some grammatical information. This practice completely obscures the complexity of the original form, and results in non-replicable linguistic data. Notations such the Move-Hold model described in Liddell and Johnson (1989) certainly pave the way for resolving this particular problem, but as of yet have not received widespread adoption, perhaps due to the necessary complexity of the system. Computer tools that allow the transcription of utterances, and the development and sharing of lexicons and corpora of utterances, have the potential to alleviate these problems.

I want to emphasize that I do not view this kind of technology as an "assistive device" for Deaf people, any more than machine translation to Italian is an assistive device for Italians. Assistive devices are meant to build a bridge between two groups when they are otherwise separated by a disability. The challenges faced by Deaf people are nearly all superficial, artifacts of living in a society where the majority of people are hearing and communicate with spoken language. When a Deaf person and a hearing person (who does not sign) have a need to communicate there is definitely a communication challenge. In my view this is no different from two hearing people who speak different languages who need to communicate: there is a language barrier. In the first scenario it is too easy to ascribe the difficulty in communication to the Deaf person's lack of hearing. But in the second case, when two hearing people who speak different languages need to communicate, who is to blame for the difficulty communicating? Does it even

[2] The American Sign Language Linguistic Research Project (ASL-LRP, http://www.bu.edu/asllrp/), directed by Dr. Carol Neidle of Boston University, is a welcome exception to this practice. They have begun to provide access to video clips of ASL utterances discussed in their work, by using the WWW.

make sense to ask who is to blame? I assert it does not. If it doesn't make sense to ask who is to blame for the two hearing people, why does it make sense to ask who is to blame for the deaf/hearing case? The fallacy of attributing the communication difficulty to the Deaf person is another artifact of viewing ASL as a signed form of English, or as no language at all.

As argued passionately in Lane (1993), the Deaf community is a linguistic minority. When there is not contact between Deaf and hearing communities, Deaf people encounter no such difficulty in communicating. They tell jokes, stories, talk about the weather, their investments, jobs, etc. They need no assistive devices. The TTY is not an assistive device; it addresses the hearing-centric design of the telephone, an inherent shortcoming in the technology, not the user's abilities. In a sense, it is the telephone that is disabled. When high-quality videophones achieve widespread use, TTYs will no longer be necessary. Technology is advancing to the point where it can become Deaf. Deaf/hearing communication over the telephone will still face a language barrier, but this is different from a hearing/hearing language barrier only in the mode of communication.

Acknowledgements

Nearly twenty years ago, a kind patron invited a clumsy but well-meaning busboy to her house to teach him American Sign Language. He had known a few signs, but didn't realize how much he didn't know until she came to the restaurant with her friends, and he tried to talk to them. He introduced himself in sign, but before he could be too proud of himself for his accomplishment, he was lost in a flurry of waving hands, the significance of their gestures lost on his deaf eyes. His discomfort and confusion must have been obvious, for in that moment, rather than rejecting his too-English attempt at communication, she welcomed his effort, and offered him the opportunity to learn from her, and by association, her friends, and by extension, the Deaf community. This serendipitous act of unexpected kindness forever changed his life.

Since then, many people have helped me, directly or indirectly. Some have shared my company as our separate courses followed the same paths for a time, as passengers on a train share a journey to different ultimate destinations. Some played a more direct role, offering me guidance, encouragement and welcome criticism. I am indebted to many people, who I will try to recognize here. Of course, the risk in doing so is in forgetting someone, so I must apologize in advance for those who I may have missed.

I have had many great teachers, and it would not be possible for me to list them all. In particular, however, I want to recognize a few here. Dr. Karl Nicholas was an early inspiration, encouraging me to accomplish more than I thought myself capable of. Nancy Becker's strict style was much needed, and her advice to attend an intensive summer session of ASL instruction at Gallaudet University also proved to be a life-altering event. For at Gallaudet, I met Byron Bridges, a man who impressed me with his creativity and passion. At the time Byron was a graduate student in the department of linguistics and interpreting, and he described for me his research into the many ways grammatical detail can be expressed non-manually in ASL. Motivated by his example, upon returning from Gallaudet I began applying to graduate programs in linguistics, and the following autumn arrived at Georgetown University, naïve and eager. The entire faculty at Georgetown is exceptional, but I would especially like to thank Raffaella Zanuttini for the many unique opportunities she provided me, and my mentor, Cathy Ball, for her endless patience and confidence.

While at Georgetown I also had the good fortune of taking courses at Gallaudet, where I met Scott Liddell and Bob Johnson. Scott's great skill is in applying linguistic knowledge and logical analysis to an unbiased study of language phenomena, resulting in sound but often non-obvious observations. Bob's knowledge of ASL and the field of its study is vast, but perhaps more importantly, he is an incomparable educator. His courses in ASL phonology brought the field to life for me, at a time when I was struggling with spoken language phonology.

I owe an extraordinary debt of gratitude to my wife, Amy, who has been indefatigable in supporting me through the many years of research, software development and writing that this dissertation required.

And finally, to my many friends, Deaf and hearing, who have given me encouragement and inspiration through the years (even if they weren't aware of it), my heartfelt gratitude. It is often said that the Deaf community is guarded against hearing people who try to glimpse or share their culture. Perhaps "suspicious" is the better word. However, if not for one Deaf woman's open and welcoming nature nearly twenty years ago, who knows where that busboy I was then would have ended up. The largest debt I owe goes back the farthest. Thank you, Diane.

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Chapter 1 Introduction

This dissertation describes an approach to designing a machine translation system that generates American Sign Language from written English. The main focus of this paper is the representation of ASL both used in the generation component of the system and as the output. The concepts presented in this dissertation are implemented in a software application called *ASL Workbench*, as a demonstration of their application, and a platform for future work.

Chapter 1 reviews previous work relating to computational linguistics and ASL. Many of these approaches are limited by inadequate notation systems such as ASCII-Stokoe, as well as limited vocabularies. But primarily these approaches are hindered by their static representation of ASL linguistic information and failure to capture spatial-grammatical information and non-manual signals. The current work addresses these limitations. Chapter 1 concludes with an overview of the approach presented here and the components of the machine translation system that are included in the discussion.

Chapter 2 provides background on ASL linguistics (phonology, morphology and syntax) while developing the representation system. In doing so, I define the fragment of ASL for this work. In particular, Chapter 2 notes how ASL uses space to reflect grammatical information such as subject and object agreement, and how this is encoded in the representation system.

Chapter 3 discusses issues related specifically to generation of the representation in a machine translation system. This includes an account of the ASL lexicon and the definition of the transfer and generation functions. In developing a bilingual machine translation system, one must account for the difficulties in accurately conveying a range of expressions from the source to the target language. This consists of issues such as word choice and ambiguity, differing uses of grammatical constructions, and generating an appropriate representation out of a variety of potential choices. Chapter 3 includes a discussion of these issues.

Chapter 4 will present noted areas for further research, and a discussion of potential applications of this technology. Appendix A is a collection of MH notations for signs discussed throughout the dissertation, for the convenience of the reader.

1.1 Previous Work

Other computational systems for sign language have been proposed and/or designed. These include attempts to translate from English to ASL; from ASL to English; and systems for encoding linguistic or other structural information about ASL. Even though not all systems discussed here bear directly on MT generation of ASL, evaluating their respective approaches can be valuable. Sections 1.1.1 - 1.1.4 review extant research in computational systems. Section 1.1.5 provides a brief overview of relevant ASL linguistics, as employed by the prototype machine translation system developed here.

1.1.1 Generating English from ASL

Systems that attempt to generate spoken or written language from ASL have a common difficulty: they must somehow receive as input the positions, movements and shapes of the signer's hands and arms, and translate this into meaningful data. The two approaches discussed here are VR (virtual reality) gloves and video-based image processing.

1.1.1.1 Gloves

Imagine having a device that a signer can wear while signing, which will translate the signs into English (or another spoken language) in real-time. This is the ultimate goal of glove-based approaches. The glove is based upon VR technology, which uses the devices for input to VR modeling environments. At least four separate research projects have investigated glove-based technologies for translating from English to ASL.

The Talking Glove (Kramer and Leifer 1987) converts hand configurations for one-handed fingerspelling into speech. The system is also equipped with voice recognition, which converts speech into text to be shown on an alphanumeric or Braille display. The designers' original goal was to develop a system that can convert Pidgin Signed English (PSE) into English; it has been scaled back to its current form.

Fels (1990) describes Glove-Talk, a prototype system developed at the University of Toronto. Glove-Talk converts gestures made by the hands into text, and the text is passed to a voice synthesizer. The system is limited, however, to 66 root words and requires specialized motions to identify word endings. Thus, the user of Glove-Talk is not using ASL and must have special training to correctly use the glove. The range of expression is severely limited by the small vocabulary.

Vamplew and Adams (1992) extended the Talking Glove project, with the goal of converting Australian Sign Language (Auslan) to English. SLARTI (**S**ign **La**nguage **R**ecogni**ti**on) receives as input information about the hand configuration, focal site, rotation, and movement of the sign. This is an advancement over the Talking Glove and Glove-Talk systems, which use mainly static hand configurations and limited motion in recognizing signs.

Ryan Patterson, a high school student from Grand Junction, Colorado, was the national winner of the 2001 Siemens Westinghouse Science and Technology competition[3]. His entry, the “Sign Language Translator,” is a glove that recognizes hand configurations of the manual alphabet and displays the characters on a screen. The user trains the glove to recognize hand configurations, in much the same way as training a voice recognition system.

1.1.1.2 Image Recognition and Processing

Starner (1991) and Chapman (nd) describe capturing movements in sign language with cameras, applying image recognition techniques and mapping these images to ASL tokens as an approach to developing assistive devices for generating English from ASL. Chapman, for instance, has developed a lexicon based upon Stokoe Notation, and uses a vision system to identify components of a sign (the *tab*, *sig*, and *dez*),

[3] http://www.siemens-foundation.org/science/science_and_technology.htm

which are then used to identify signs in the lexicon. Chapman’s area of focus appears to be image processing more than machine translation or sign language linguistics. For instance, she describes passing these tokens to a “properly configured universal translator program,” which would presumably be able to translate the tokens into any target language. Chapman also identifies as a difficulty the simultaneous nature of a sign’s features compared to the sequential phonemes of spoken language. As discussed below, more recent analyses of sign structure view signs as sequences of segments, analogous to spoken language phonology, and not as simultaneous bundles of features. No indication is given as to the degree of success these programs have achieved.

1.1.2 Generating ASL from English

Lemcke (1997) has developed a Java application for “translating” English to ASL, with a graphical representation of the output. The animations are pre-recorded and sequenced at run-time, and the “translation” from English to sign appears superficial at best. For instance, there is no grammatical marking with non-manual signals, no spatial agreement, no classifiers; in effect, none of the linguistic phenomena that are derived from signed languages’ grammatical use of space. The lexicon is extremely limited, and the system falls back on fingerspelling words it does not recognize, which results, in effect, in English words in English word order.

Seamless Solutions, Inc.[4] describes the development of “Signing Avatars,” visual representations of signers in graphical multi-user virtual environments. The avatars are VRML (virtual reality markup language) objects, pre-recorded and dynamically sequenced with HTML scripts at runtime. Currently, they make use of no linguistic information for ASL. Although this project is not related to machine translation, it demonstrates the potential for machine-generated animation of ASL.

Grieve-Smith (1998, 2000) describes a project called SignSynth, a project closest in spirit to the one described here. SignSynth uses ASCII-Stokoe, an adaptation of Stokoe's (Stokoe and Croneberg 1976)

[4] http://www.concentric.net/~seamless

notation developed by Mark Mandel (1993). SignSynth converts ASCII-Stokoe into VRML, which can then be animated.

In another project, Grieve-Smith (1999) undertakes the machine translation of weather reports from English to ASL. The ASL representations are generated as ASCII-Stokoe notations. Weather reports are used because of the fairly limited variety of language encountered. This system includes both an analysis of the input and generation of the ASCII-Stokoe output.

1.1.3 Systems for Linguistic Representation of ASL

Poizner and Shantz (1982) describe a program written in BASIC for an HP 9830A microcomputer, which can synthesize some aspects of ASL forms. The entire program is included in their article, composed of less that 600 lines of BASIC code. Loomis, et al. (1983) describe a system descended from Poizner and Shantz's, for representing, segmenting, and analyzing movements in sign language.

Cormier (1997) describes an HPSG approach to representing locus agreement in ASL. In the lexicon, verbs are presented as unmarked roots, with no morphological agreement specified. Two types of agreeing verbs are modeled: verbs that agree only with the subject, and verbs that agree with the subject and object. Agreement is represented with indexation, and indexes may be related to coindexes in context to account for continuity of references in a discourse. Although the current proposal is not based upon HPSG, a similar approach to representing verbal agreement features will be described in Section 2.3.2.2.

The American Sign Language Linguistic Research Project (ASL-LRP)[5] is developing a Macintosh application, *SignStream*, for recording linguistic information about signed utterances, and associating the display of the linguistic data with video clips of signers.

Speers (1995) describes the development of a tool, *SL-Corpus*, designed to associate linguistic notations with video clips, similar in spirit to *SignStream*. One notation is based upon Liddell and Johnson (1989); the other notation, developed in Winston (1993), shows additional information relevant for

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[5] http://www.bu.edu/asllrp/

discourse, such as head rotation, eye gaze direction, etc. Although SL-Corpus is deprecated, many of its features are incorporated into tools developed for the current project. For instance, the lexicon maintenance tool (*ASL-LMT)* allows for the development of an ASL lexicon, based on the Move-Hold model. ASL-LMT also includes the ability to test hypotheses about morpheme structure constraints against all signs in the lexicon (Speers 1988).

1.1.4 Limitations of previous work

Some limitations inherent in the systems described above will be presented here, in preparation for motivating the current approach.

The VR glove systems are limited by their small vocabularies and nonstandard sign use. Such systems are not readily usable without training, and even trained users will be severely limited in their range of expression. A system designed to be generally usable should not be based upon a nonstandard or specialized lexicon, and should have the ability to interact with the user in a natural, straightforward way.

Chapman (nd) describes a lexicon of ASL for an image recognition system, based upon Stokoe notation. It is likely that Chapman chose Stokoe notation in order to limit the number of tokens that would need to be correctly identified. However, there are several limitations inherent in Stokoe notation.[6] Stokoe notation is a taxonomic representation, not a descriptive system. It does not account for the full range of possible handshapes and signs or movements they contain, such as handshape change. More fundamentally, Stokoe's analysis treated signs as a simultaneous bundle of features that combine to form meaningful units (signs). This differs from analyses of spoken languages, in which features combine to form phonemes, and phonemes combine to form morphemes (meaningful units). However, evidence from sign language makes it clear that signs do contain sequential information, such as the contrast between single-motion verbs and related nouns with repeated motions (such as SIT and CHAIR) (Supalla and

[6] See Liddell and Johnson (1989) for a detailed discussion.

Newport 1978). Most relevant to this discussion, however, is the fact that Stokoe notation cannot represent how ASL uses space to mark subject and object agreement in inflecting verbs (Section 2.3.2.2).

Lemke (1997) and Seamless Solutions Inc. both describe systems that use pre-recorded animations arranged in an appropriate sequence at runtime. The systems, then, are tasked with determining an appropriate sequence for the pre-recorded segments. However, for generating animations of ASL, this approach is seriously limited by the inflexibility of pre-recorded segments. For instance, inflecting verbs change their articulation depending upon the syntactic arguments and their morphological properties. The verb GIVE, for example, will alter its initial and final position to mark subject and object agreement. In order to pre-record this verb, each possible combination of initial and final positions will have to be prepared. Also, the hand configuration for GIVE may change to reflect properties of the object that is being given; each possible combination of initial and final positions must be recorded with each of the possible handshape classifiers for this verb. In addition, non-manual signals that indicate syntactic properties in the sentence (Section 2.6) need to be expressed during the articulation of this sign in an utterance. Each of the combinations of initial and final location, for each of the possible handshape classifiers, must be recorded with each of the possible non-manual signals. Assume for the sake of argument that there are six possible combinations of initial and final positions marking subject and object agreement: I-you; you-me; I-it; it-me; you-it; it-you. If you assume that eighteen classifiers can be used with GIVE and that there are only three non-manual signals that can co-occur with this verb (wh, neg, yes/no), then this collection of possibilities produces 26 x 18 x 3 = 1,404 possible forms, just for one verb. In a system that cannot dynamically generate the utterance, these possibilities must be pre-recorded, or the spatial-grammatical and non-manual characteristics of ASL must be abandoned. Clearly, a system that generates ASL, including the grammatical detail that is communicated through the use of space, must be able to dynamically generate such representations.

Cormier (1997) describes a promising approach based upon HPSG that allows for the specification of agreement features for inflecting verbs. Cormier only discusses locus agreement, or agreement features which are realized as the initial or final place of articulation. However, signs may realize their agreement features in other ways, such as through their orientation (as with UNDERSTAND-EACH-OTHER); both location and orientation (e.g., ASK); etc. In Cormier's system, root verbs in the lexicon are unspecified for the features that represent agreement. This paper will extend this approach to cover all types of agreement.

However, it is not sufficient to identify attributes that need agreement features with null values in the lexicon. Such an approach assumes that all features must be fully specified, even redundantly, and that all empty slots require agreement features. In the system presented here, features are not redundantly specified. Not only must verbs be identified in the lexicon for how they encode agreement (subject and/or object), but they must also indicate which features vary to encode the agreement (location and/or orientation; initial and/or final segments, etc.).

This suggests that in the current system, a token feature must be used to flag attributes that require agreement features. As will be seen in the sections on morphology (2.3) and syntax (2.4) below, we need many empty elements to signal agreement features.

1.1.5 ASL linguistics

The machine translation developed in this dissertation translates from English to ASL. This section will outline some of the major areas of research that influence the representation of ASL.

ASL uses the signing space to encode grammatical detail in an utterance. In order to represent this use of space computationally, one must (a) identify those features that need to be represented; and (b) figure out how to represent them. In order to represent spatial-grammatical features, the machine translation system will make use of Liddell and Johnson’s (1989) Move-Hold (MH) model of sign language transcription. The MH model treats signs as a sequence of segments, in the same way that morphemes in spoken languages are sequences of phonemes. Each sign segment (phoneme) is composed of a set of features that specify the articulation of the sign. The features in the notation vary in ways that are predictable, based on grammatical features in the utterance. The predictability of variation in signs due to grammatical features can be encoded in the representation system through the means of feature variables in root forms of lexical elements.

Chapter 2 reviews both traditional and recent work in sign language linguistics, to determine which features to represent this way in the notation. I will sketch here some of the topics addressed below.

Some signs (e.g., GIVE, PUT) vary their handshape depending upon other arguments in the utterance; these handshapes are called *classifiers*. There is a class of lexical roots, commonly described as *classifier predicates*, that must always combine with classifier handshapes; these are used to describe the movement, location or physical characteristics of objects. The discussion of classifiers and classifier predicates was introduced by Klima and Bellugi (1979), and expanded upon significantly in Supalla (1982), Schick (1985), and Liddell and Johnson (1987).

Many verbs vary their articulation patterns to convey information about *aspect*. Klima and Bellugi (1979) discuss a variety of aspects and their related sign modifications; Aarons et al (1995) provide a more recent account, comparing aspect, lexical tense markers and time adverbials.

Verb agreement, and variations in the articulation of verbs to represent such agreement, has been the focus of much attention. Padden (1988) provides a thorough account of verb types and agreement patterns.

Through several recent publications (see for example Aarons et al 1992, Neidle et al 1997), the ASL-LRP has argued convincingly that *WH-movement* in ASL occurs to the right, *contra* Lillo-Martin (1990) and Petronio and Lillo-Martin (1996).

MacLaughlin (1997) provides a thorough analysis of noun phrases in ASL, arguing for the existence of definite, indefinite determiners and adverbials, in addition to pronouns. MacLaughlin's discussion is extended here to account for possessive noun phrases, numerals and adjectives.

In addition to these specific areas, the machine translation system must be able to account for *non-manual signals* (*NMSs*). These are characteristic facial expressions used in specific syntactic contexts, used to convey grammatical information such as negation, WH-questions, yes/no questions, etc. The prototype machine translation system described here handles both lexical and syntactic NMSs.

1.2 Overview of the Machine Translation System

It is not the goal of this work to produce a complete machine translation system, but rather to identify and develop a methodology for key linguistic and computational components of such a system. While the architecture of a complete system will be sketched, many components will be intentionally excluded.

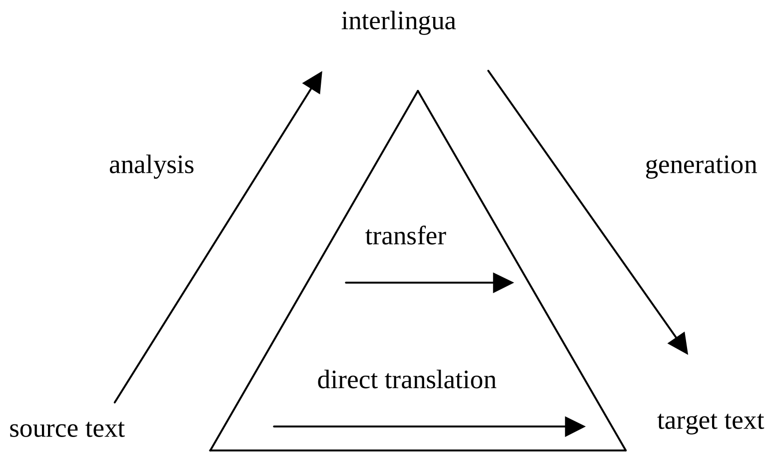

Figure 1-1: MT Pyramid

Figure 1-1 shows a traditional MT pyramid (Hutchins and Somers 1992). A machine translation system takes source text as input and performs some function to produce target text as the output. Early MT systems performed a direct translation, substituting words from a bilingual dictionary and performing superficial surface word order changes. All of the work of the analysis and generation was done in the transfer, a fact that is represented by the length of the line in the pyramid. The other extreme is interlingua at the top of the pyramid. Interlingua represents a language-neutral abstraction that is the output of analysis and the input to generation. In an interlingua-based system, all of the work of translation is based in analysis and generation. In the middle are transfer-based systems, which use a combination of analysis, transfer and generation.

The prototype system presented here is a transfer-based, mono-directional, bilingual human-assisted machine translation system. The source language is American English, and the target language is American Sign Language (ASL). Analysis of the source language is assumed. Generation of the target language will begin with transfer from a hypothesized feature representation of the source language, which is the result of the analysis phase. The representation will contain the linguistic information necessary to generate target structures for a fragment of ASL.

I have described the system above as "human-assisted." In translating from English to ASL, there will be a variety of choices regarding the form of the utterance, which at this time the translation system will not attempt to determine automatically. The system should have the flexibility to express ASL utterances of any possible form, whether the utterance employs simple lexical elements or more complex constructions, such as spatially arranged classifiers. When generating a representation, the system will generate the simpler form. If the translator wishes to employ a different strategy in representing the utterance, the system will allow for the creation of the utterance through interaction.

The overall goal of the system is to create an ASL document from an English document. The ASL document will be viewable using several software applications, which will be developed to show output in various forms, including gloss-based output, linguistic notation, and animated sign (although the software developed for this project does not contain these facilities). The ASL document should support not only viewing ASL, but should also be usable as a corpus for linguistic analysis.

We have reviewed many different approaches to developing computational systems for recognizing, representing and generating ASL. In looking at the limitations of current systems, we have begun to outline the requirements for the representation and generation of ASL that will be developed here. Chapter 2 begins this work by describing the linguistic characteristics of a fragment of ASL, paying particular attention to the grammatical use of space and non-manual signals, and relating these features to the representation system.

1.3 Lexical Functional Grammar

Both the representation developed in Chapter 2 and the transfer and generation functions defined in Chapter 3 are presented in terms of Lexical-Functional Grammar (LFG). This section presents a brief overview of the LFG formalism.

Lexical-Functional Grammar (LFG) was introduced by Kaplan and Bresnan (1982). LFG posits two levels of syntactic representation for every sentence: a constituent structure (c-structure) and a functional structure (f-structure). The c-structure is a phrase-structure tree, encoding dominance and linear precedence relations that represent ordered arrangements of words and phrases in a sentence. The f-structure encodes grammatical relations in the sentence (subject, object, etc.). In Figure 1-2, the c-structure is on the left and the f-structure is on the right.

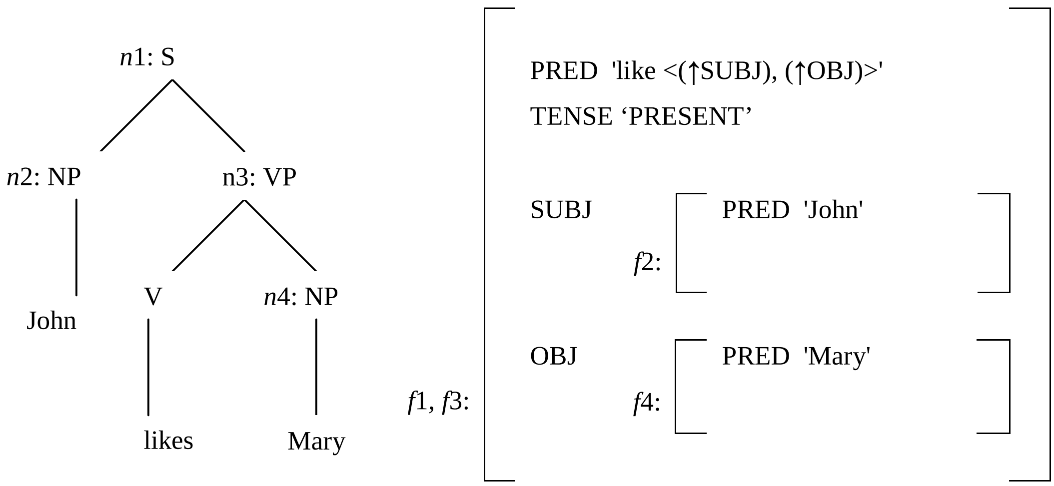

Figure 1-2: Correspondence between c-structure and f-structure

A correspondence function ϕ maps labeled nodes in the c-structure (*n*1, *n*2, etc.) to labeled attribute-value sets in the f-structure (*f*1, *f*2, etc). The grammar of a language is expressed as a set of context-free phrase-structure rules, such as S → NP VP. These hierarchical relations can also be expressed as equations, such as "*n*1 is the mother of *n*2," "*n*3 is the mother of *n*4," etc. LFG uses the function *M* to represent the motherdaughter relationship between two nodes. Thus, these equations can be written more formally as $M(n2) = n1$ and $M(n4) = n3$. Since ϕ represents the correspondence between n and f, these relationships can also be written as equations: $f1 = \phi(n1)$. The subject of the sentence can be expressed as $(\phi(n1)\ \mathrm{SUBJ}) = \phi(n2)$, or equally as $(\phi(M(n2))\ \mathrm{SUBJ}) = \phi(n2)$.

Reference to specific nodes such as $n1$ can be replaced by *, which indicates the node matching a given rule category. The functional description can be generalized to $(\phi(M(*)\ \mathrm{SUBJ}) = \phi(*)$. For convenience, LFG adopts the metavariable $\uparrow$ to refer to the expression $\phi(M(*))$ (the f-structure corresponding to the mother of the current node) and $\downarrow$ to refer to the expression $\phi(*)$ (the f-structure corresponding to the current node). Given these metavariables, the earlier expression $(\phi(M(*)\ \mathrm{SUBJ}) = \phi(*)$ can be shortened to $(\uparrow \mathrm{SUBJ}) = \downarrow$. The phrase structure rules include annotations for grammatical functions using this notation.

1-1	a.	S	$\rightarrow$	NP	VP
				$(\uparrow \mathrm{SUBJ}) = \downarrow$	$\uparrow = \downarrow$
	b.	VP	$\rightarrow$	V	NP
					$(\uparrow \mathrm{OBJ}) = \downarrow$

In addition, functional descriptions can be included in the schemata for entries in the lexicon. ϕ includes these descriptions in the f-structure. The English word *dog*, for instance, could include an expression indicating its number:

1-2.	dog	N	$(\uparrow \mathrm{PRED}) = \text{'dog'}$
			$(\uparrow \mathrm{NUM}) = \mathrm{SG}$

The schemata for a verb includes information about its argument structure in terms of grammatical functions. The schemata for the verb *like* would include the expression $(\uparrow \mathrm{PRED}) = \text{'like} \langle(\uparrow \mathrm{SUBJ}), (\uparrow \mathrm{OBJ})\rangle\text{'}$. For a language, the set of *governable grammatical functions* are those functions that appear in the function assignment lists of lexical predicates. A given lexical entry only mentions a few of the governable functions: it is said to govern the functions that it mentions.

LFG defines grammaticality in terms of the completeness and coherence of f-structures (from Kaplan and Bresnan 1982):

1-3 *Definitions of completeness and coherence*

a. An f-structure is *locally complete* if and only if it contains all the governable grammatical functions that its predicate governs. An f-structure is *complete* if and only if it and all its subsidiary f-structures are locally complete.

b. An f-structure is *locally coherent* if and only if all the governable grammatical functions that it contains are governed by a local predicate. An f-structure is *coherent* if and only if it and all its subsidiary f-structures are locally coherent.

1-4. *Grammaticality condition*

A string is grammatical only if it is assigned a complete and coherent f-structure.

Long-distance dependencies such as WH-questions and topicalization are accounted for in LFG in terms of *functional uncertainty* (Kaplan and Zaenen 1989, Kaplan and Maxwell 1988).[7] The intent of functional uncertainty is to relate the grammatical function of an antecedent with that of its referent, when the grammatical function and syntactic position of the referent is unknown. For instance, the referent for a topic in English can be in the matrix clause, or in an embedded complement:

1-5 a. Mary, John likes.

b. Mary, Bill said that I like.

Mary, Bill said that John believes that I like.

---

[7] This differs from the original formulation of *bounded domination* introduced in Kaplan and Bresnan (1982).

The relationship between the topic *Mary* and the grammatical function of its referent is expressed with the following expression:

1-6. $(\uparrow \text{TOPIC}) = (\uparrow \text{COMP* OBJ})$

The * on the grammatical function COMP indicates that there may be zero or more intervening COMP functions between the TOPIC and its referent.

1-7.
$$\text{S}' \quad \rightarrow \quad \begin{array}{l} \text{NP} \\ (\uparrow \text{TOPIC}) = \downarrow \\ (\uparrow \text{TOPIC}) = (\uparrow \text{COMP* OBJ}) \end{array} \qquad \begin{array}{l} \text{S} \\ \uparrow = \downarrow \\ \end{array}$$

The relationship between the TOPIC and its referent is represented in the f-structure, as shown with the sentence (1-5.a):

1-8
$$\left[\begin{array}{ll} \text{TOPIC} & \left[\text{PRED 'Mary'} \right] \\ & \\ \text{PRED} & \text{'like <(}\uparrow\text{SUBJ), (}\uparrow\text{OBJ)>'} \\ \text{TENSE} & \text{'PRESENT'} \\ & \\ \text{SUBJ} & \left[\text{PRED 'John'} \right] \\ & \\ \text{OBJ} & \end{array} \right]$$

1.3.1 LFG and Machine Translation

As many authors have noted, the functional description and grammatical relations of LFG f-structures makes in this formalism particularly well suited to machine translation (see for example Amores 1992). Kudo and Nomura (1986) use a *description-by-analysis* approach to machine translation transfer. They employ a bi-directional lexicon between the source and target languages, generating target f-descriptions from the source f-structure. The f-descriptions are converted into the target f-structure, similar to the method used during analysis to create the f-structure from f-descriptions created from the c-structure.

An alternative approach is described by Kaplan et al (1989), who apply LFG's *codescription* framework to the task of transfer. They develop a correspondence function τ between the source and target f-structures, and τ' between the source and target s(emantic)-structures. Although this approach is flexible in handling source and target sentences, Sadler and Thompson (1991) demonstrates that Kaplan et al's (1989) approach cannot handle head-switching phenomena, nor do they describe how to handle issues of lexical ambiguity. Wong (1999) provides a good overview of LFG in machine translation.

The preceding section is not a comprehensive review of the LFG formalism, but rather a brief overview. For more detail, see Kaplan and Bresnan (1982), Kaplan and Maxwell (1988), Kaplan and Zaenen (1989), Kaplan et al (1989), and Wong (1999), *inter alia*.

Chapter 2 Representation

This chapter describes the representation system used both within the machine translation system and as output of the system. The representation is constructed by the generation system (discussed in Chapter 3).

Representation will account for various kinds of linguistic data, including syntax, phonetics, discourse elements, and grammatical detail such as agreement, tense and aspect. This type of detail is fairly typical of a non-stochastic approach to machine translation. The important and interesting question is, given the spatial modality of ASL, what types of linguistic information must be included in the representation to accurately and thoroughly generate ASL utterances, making full use of spatial grammatical and non-manual devices? Two central claims motivate this work: that representations of ASL must be dynamically generated; and that they must encode specific spatial information in order to generate well-formed ASL output.

This chapter will describe the phonetic, morphological and syntactic features of ASL that form the basis of the representation[8]. Section 2.1 presents an overview of the components of the representation. Section 2.2 provides an overview of the phonetic transcription system adopted here, the Move-Hold model (Liddell and Johnson 1989), and how it will be used. Section 2.3 describes ASL morphological processes that will affect the representation of signs in the output. Section 2.4 argues for the syntactic representation, describing the relationship between syntactic processes and the phonetic transcription. Section 2.5 describes the system for tracking discourse elements, and the effect of these elements on the representation. Section 2.6 discusses the representation of non-manual signals (NMSs).

---

[8] Please note that many of the references in this section, in particular those relating to ASL phonology and morphology, are based upon unpublished work, manuscripts, class notes and personal communication. In particular, the Move-Hold model described in Liddell and Johnson (1989) continues to evolve. This dissertation should not be considered a reference for this material. While I make use of this work, it is not my intention to present it. For more information, the reader is encouraged to contact the authors directly.

2.1 The ASL Representation System

The representation corresponds to an ASL document. A document contains document-level data such as discourse markers, a set of ASL sentences, and document meta-data (such as author, creation date, etc.). Each ASL sentence in the representation contains three levels of information: a functional structure (f-structure); a syntactic tree (c-structure), and a phonetic transcription (p-structure). The p-structure also contains information about non-manual signals, but these are specified lexically or generated syntactically; they do not receive independent representation. Relationships between structural levels are defined in terms of LFG correspondence functions, following Kaplan et al (1989).

2.2 Phonetic Transcription

This section will present a brief overview of the phonetic transcription used in the phonetic structure level of description, the Move-Hold (MH) model (Liddell and Johnson 1989).

2.2.1 Segments

In the MH model, a sign is viewed as a sequence of segments. Each segment is a collection of features that specify information about the articulation of a sign. This is similar to spoken languages, where a phoneme is a collection of features and a morpheme is a sequence of phonemes. Features in a segment are organized into several divisions, shown in Table 2-1:

Segment Divisions	Description
Segmental features	Describes the activity of the hand
Articulatory features	Specifies features of the articulation
Hand configuration	Features of the hand
Placement	The location of the hand and its relationship to that location
Rotation	The orientation of the wrist and forearm
NMS	Lexical non-manual signals

Table 2-1: Feature divisions in a segment

Placement includes a Hand Site (the part of the hand that is salient in the sign), a Spatial Relationship (sprel), and a Focal Site (the placement of the Hand Site). A Focal Site may either be a location on the body (face, arm or torso), or at a spatial location at a specified height. Articulatory features are specified for both the signer's strong hand (the right hand for right-handed signers), and the signer's weak hand for two-handed signs. For each hand, placement features may be specified twice: Placement A and Placement B (Facing). The primary placement features are specified in Placement A. In addition, if a sign is articulated with careful alignment along a plane, rather than with the arms placed comfortably in the signing space, then alignment features are specified in Facing. Thus, the following set of features are used to completely specify a segment:

Segmental features		Timing Unit
		Contour
		Touch
		T Quality
		M Quality
		Local Movement
Strong	Placement	Hand Configuration
		Hand site
		Sprel
		Focal Site
	Facing	Hand Site
		Sprel
		Focal Site
	Rotation	Rotation
Weak	Placement	Hand Configuration
		Hand Site
		Sprel
		Focal Site
	Facing	Hand Site
		Sprel
		Focal Site
	Rotation	Rotation
NMS		NMS

Table 2-2: Full feature specification for a segment

2.2.2 Structure building features

In addition to the features of the segment shown in Table 2-2, a sign may also be specified for structure building features. The application of-structure building features changes the articulatory features of a sign in predictable ways. This simplifies the notation for predictable occurrences of features.

Structure building feature	Description
Reduplication	The complete sequence of a sign's segments is repeated.
Alternating dominance	A sign is reduplicated, and the weak hand assumes the role of the dominant hand.
Symmetrical	Both hands are used, and they have identical articulatory features. Only the features for the strong hand are specified.
Reciprocating	A symmetrical sign where the weak hand and strong hand alternate feature specifications.
Bidirectional	The sign concludes by returning the articulators to the initial place of articulation.

Table 2-3: Structure building features

2.2.2.1 Phonological processes

Phonological processes modify the segments of a sign in predictable ways, in response to phonotactic environments. Such environments arise within signs as a result of the application of-structure building features, and among signs in continuous articulation. As the system generates a representation, phonotactic environments will arise, thus providing the context for the application of these phonological processes.

2.2.2.1.1 Movement epenthesis

When two Hold (H) segments are adjacent, the hand(s) must move from the first H segment to the second. This environment can arise within a sign as the result of the application of-structure building features, and between signs in a sentence. Movement epenthesis inserts a movement segment M (a [-FIXED, -DURABLE] Timing Unit) between the two H segments.

The features of the epenthetic M segment will vary depending upon whether it's within a sign or between morpheme boundaries. When the epenthetic M is between morpheme boundaries (2-1.a), its Contour values are [+DIRECT, -ARC]; it has no values for other skeletal features.

2-1. a. ...H# + #H... => …H M H…

b. #…H H…# => …H M H…

When the epenthetic M occurs within morpheme boundaries (2-1.b), the form of the epenthetic M segment varies depending upon the phonotactic context. If the preceding M segment has a [+ARC] Contour, then the epenthetic M must also have a [+ARC] Contour, and must specify an appropriate value for Flow (examples include CHOCOLATE, SIGN). The generalization is that the return arc occurs in the opposite direction to the preceding M segment's arc.[9] Table 2-4 shows the pattern of the epenthetic M Flow values in this context.

Preceding [+ARC] M	Epenthetic [+ARC] M
[+SUPERIOR]	[-SUPERIOR]
[-SUPERIOR]	[+SUPERIOR]
[+ANTERIOR]	[-ANTERIOR]
[-ANTERIOR]	[+ANTERIOR]
[+IPSILATERAL]	[-IPSILATERAL]
[-IPSILATERAL]	[+IPSILATERAL]

Table 2-4: Epenthetic [+ARC] M Flow values

If the preceding M segment has a [-DIRECT, -ARC] Contour (non-path movement), then an epenthetic M segment must also have a [-DIRECT, -ARC] Contour. In this case, if the preceding M segment has a [+TOUCH] Touch feature, then the epenthetic M must also have a [+TOUCH] Touch feature (e.g., COW, INTERPRET).

If the preceding M segment has a [+DIRECT, -ARC] Contour, then the epenthetic M segment also has a [+DIRECT, -ARC] Contour (e.g., BUSY).

2.2.2.1.2 Hold reduction

[9] Therefore, [+ARC] Contour signs in the lexicon that return to their initial location with the same Flow values are not [+REDUPLICATED].

Liddell and Johnson (1989) observe that when a Hold segment occurs between two Move segments, that Hold segment is deleted, and propose a process of Hold Deletion. The generalization is that signers do not produce signs haltingly, with pauses between each segment, but as a sequence of fluid motions. In the current form of the MH model, Hold Deletion has been replaced with Hold Reduction, in which the non-Motile segment's Timing Unit features shift from [+FIXED, +DURABLE] to [+FIXED, -DURABLE].

2-2. M H M => M X M

2.2.2.1.3 Gemination

When the final segment of one sign has the same features in the articulatory bundle as the initial segment of the following sign, there is no movement epenthesis. In this case, the signs geminate, resulting in a [+ SUSTAINED] Hold. Liddell and Johnson (1989) provide the example of MOTHER followed by REPULSED-BY, as in "mother is repulsed by spaghetti."

	MOTHER	#	REPULSED-BY		
Timing Unit	H		H	M	H
Contour				[str]	
Touch	+		+		
HC	u-1234+v		u-1234+v		
Hand Site	TITH		TITH		
Sprel	[at]		[at]		[ant]
Focal Site	CN		CN		
Rotation	[neutral]		[neutral]		

Table 2-5: Environment for gemination in MOTHER + REPULSED-BY

2.2.2.1.4 Assimilation

Hand configuration features of a sequence of signs may undergo assimilation in fast signing. For instance, the hand configuration of ME is normally [n-1+]. If the following sign is, for instance, INDIAN, the sign ME may be made with the hand configuration for INDIAN, [o-c9"].

2.2.2.1.5 *Metathesis*

Location features for segments of signs may undergo metathesis in some environments. Liddell and Johnson (1989) identify the general structure #X-M-X-M-X-M-X#, as in the sign DEAF, as being susceptible to metathesis. In the sign DEAF, the Focal Site of the initial segment is [CK], and the Focal Site of the final segment is [JW]. ([CK] "cheek" is higher than [JW] "jaw.") In continuous signing, the Focal Site features of the initial and final segments of the sign may undergo metathesis when the preceding sign has a Focal Site near to or the same as the final Focal Site feature of DEAF. For instance, the sign MOTHER as a focal site [CN] "chin," very close to [JW], which may trigger metathesis in continuous signing.

2.2.2.1.6 *Reduction*

Reduction refers to the tendency to move signs to a more central location in the signing space, particularly away from the signer's face. As an example, the sign THINK is normally articulated at the [iFH] Focal Site; it may be reduced to occur at the [CK] Focal Site, or even as low as the [JW] Focal Site.

2.2.3 Preparing to use the Move-Hold Model

The MH model is adopted here due to its sophistication and flexibility. Because MH takes a descriptive approach to sign transcription (rather than a taxonomic approach like Stokoe notation), root forms of signs that vary their form of articulation due to morphological processes or syntactic contexts can be accounted for with precision.

Liddell and Johnson (1989) account for variations in the articulation of root signs by positing under-specified roots called Incomplete S-morphs. An Incomplete S-morph is a morpheme that has missing features; it is incomplete in its specification. The missing features are supplied by another morpheme, called a P-morph. A P-morph is a morpheme that specifies values for features of a segment. The combination of an Incomplete S-morph and an appropriate P-morph will result in a complete morpheme.

Liddell and Johnson (1989) describe Incomplete S-morphs as lexical forms of root signs with empty cells; this is similar to the approach adopted by Cormier (1997). Many, if not most, lexical roots that are complete have empty cells. All one-handed signs will have empty cells for each feature of the weak hand. All signs that to not have phonologically significant alignment will have empty cells for the features of Placement B. The absence of this feature alone is not sufficient to identify an Incomplete S-morph.

There are some legitimate Incomplete S-morphs that need more than empty cells to figure out how to create a complete morpheme. Consider the notation for the sign $_{\text{IX-PRO.2}}$ HELP $_{\text{IX-PRO.1}}$, in Appendix A. With empty cells for the initial and final weak hand Focal Sites, there are many different ways that this Incomplete S-morph can combine with P-morph(s), but only one correct way. A P-morph for the subject or object Focal Site can be inserted in the initial weak hand focal site cell, and spread auto-segmentally. A P-morph for the object Focal Site can be inserted in the initial weak hand Focal Site cell, and a P-morph for the subject Focal Site can be inserted in the final weak hand Focal Site cell. Or, a P-morph for the subject Focal Site can be inserted in the initial weak hand Focal Site cell and a P-morph for the object Focal Site can be inserted in the final weak hand Focal Site cell. While each of these is possible, only the final one is correct. Simply leaving the cell empty is insufficient to determine how to combine P-morphs with the Incomplete S-morphs and create a complete morpheme. This issue will be discussed in more detail in Section 2.3.2.2.

The lexicon will contain root forms of signs, including a gloss, structure building features, and a sequence of segments. Segments will receive a default specification for features, and in some cases empty tokens identifying features that must be supplied during generation to build a fully specified representation. When signs from the lexicon are used in the representation, all structure building features are applied, as well as phonological processes within the segments of the sign and between the signs of a sentence. In addition, the translator will have a great deal of control over the final form of the articulation by modifying the features within segments. Figure 2-1 and Figure 2-2 give examples of lexical entries for the signs EAT (a complete form) and HELP (an incomplete form), respectively.

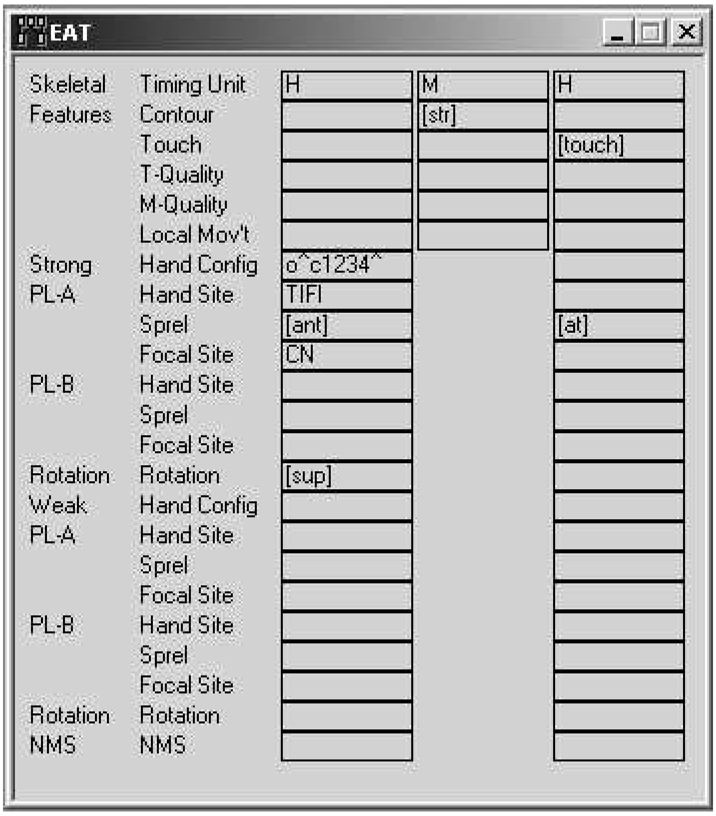

Figure 2-1: Lexical entry: EAT

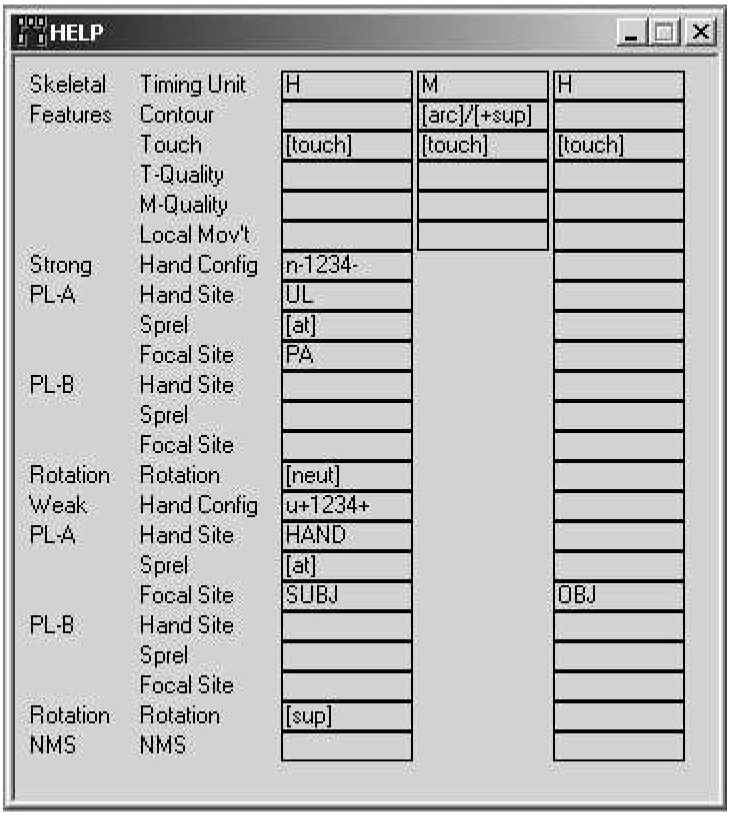

Figure 2-2: Lexical entry: HELP

The next sections describe aspects of ASL morphology (Section 2.3) and syntax (Section 2.4), and in particular how they affect the notation.

2.3 Morphology

As in spoken languages, ASL signs can be divided into units based upon meaning. These morphological units may be bound or free, and may combine with other units in constrained ways. The nature of these units and the processes that constrain their interaction are the focus of this section.

2.3.1 Classifiers

2.3.1.1 Classifier handshapes

Classifiers handshapes are bound morphemes, composed of a specification for the features of a hand configuration. The hand configuration represents characteristics of a referent. Classifiers can be grouped according to the type of characteristics they represent. Klima and Bellugi (1979) discuss Size and Shape Specifier (SASS) classifiers, where the handshape represents and outline of the referent. Supalla (1982) and Schick (1985) both describe Semantic Class and Handle classifiers. Semantic class classifiers represent the referent, such as the [n-12+v] handshape to represent a person; Handle classifiers indicate the shape of the referent in terms of the handshape necessary to handle the object.

Classifier Group	Lexical code	Description
Size and Shape Specifiers (SASS)	SASS	Represent an outline of the referent. Examples include [o"c9"o] *small round*; [o"1234"o] *large round*; [n-1+] *small straight*; and [u-1234+] *large straight*.
Semantic Class	CLASS	Represent the referent as an entity. Examples include [n-12+v] *person*; [u+14+] *airplane*; and [u+12+v] *vehicle*.
Handle	HAND	Represent the shape the hand takes when holding an object or instrument. Examples include [n-1234-] *small round*; and [b^c1234^] *small flat*.

Table 2-6: Classifier Groups

The choice of classifier group depends upon the characteristics of the referent that are relevant to the discourse; different classifiers can represent a noun depending upon the context. Within a given group, though, a noun will generally be represented with the same classifier. For example, in the semantic class group, a person will always be represented by a handshape like [n-1+], and never by the [u+12+v] handshape. Nouns in the lexicon will be provided with a default setting for a classifier from each classifier group.

The handshape for some verbs in the lexicon will depend upon choosing an appropriate classifier for an expression in the sentence. For instance, the indicating verb GIVE will have a different handshape depending upon what is being given. Such verbs will have no handshape defined in their lexical entry; instead, they will have a value of CL:<type>, where "type " refers to the lexical code of one of the classifier groups shown in Table 2-6. The handshape for GIVE, then, is CL:HAND. When used in the representation, the handshape CL:HAND will be replaced with the default Handle classifier for the object noun, and may be modified by the translator.

There are relatively few verbs that obtain classifier handshapes from expressions in the sentence. However, there is a more productive construction that makes wide use of classifier handshapes. These are classifier roots.

2.3.1.2 Classifier roots

Wilbur (1987) discusses the categories of classifier languages presented in Allan (1977), and concludes that ASL is a predicate classifier type language. And indeed, classifiers in ASL are used in many verbal instructions. Sign roots that combine with classifier handshapes are typically referred to as classifier predicates (see for example Supalla 1982, Schick 1985).

However, to incorporate an effective representation of classifiers for this representation system, the traditional notion of "predicate" is not specific enough for this purpose; some classifier constructions are not verbal at all. For the purpose of this discussion, these roots will be referred to as classifier roots instead of predicate roots.

Classifiers and classifier roots combine to form classifier constructions. The location feature in a classifier construction typically indicates a body locus or a spatial locus in the three-dimensional signing space (a Focal Site). This locus may also be used for grammatical marking, such as in verbal agreement.

2.3.1.3 Representing Classifiers and Classifier Roots

Supalla (1982) and Schick (1985) both propose three categories of classifier roots, though their categories differ slightly. These categories include:

<u>Supalla (1982)</u>:

Existence	A single hold segment, indicating the presence of an expression at a location.
Location	And indexing sign, identifying a location as an index for an expression.
Motion	The movement of the hand(s) represents the movement of the referent.

<u>Schick (1985)</u>:

DOT	Incorporates Supalla's (1982) existence and location categories, arguing that the difference between these is merely one of emphasis.
MOV	Corresponds to Supalla's (1982) motion category.
IMIT	Describes the motion of signs that imitates real world activities.

The remainder of this section will describe the classifier roots adopted in this system.

Categories	Description
Description (DESC)	The hands move to describe an object, but the object itself is not moving.
Motion (MOV)	Corresponds to Supalla’s motion category and Schick’s MOV.
Location (LOC)	Corresponds to the Supalla’s location category and Schick’s LOC. The hands move to establish the location of an object, but the movement does not indicate that the object is moving.

Table 2-7: Categories of classifier roots

MOV The MOV root incorporates a SASS classifier handshape and typically involves motion from one location to another. This category also includes Schick's IMIT root, which has the same composition and syntactic distribution. The MOV root is encoded in the lexicon as a spatial verb root with a CL:SASS handshape. Liddell and Johnson (1987) describe this type of root as *process roots*.

LOC LOC is typically composed of a SASS or Handle classifier handshape articulated with a short downward motion serving to identify a position in the signing space with this referent. LOC can be used as a predicate (CAR LOC_a, "The car is here"), but it may also be used within a noun phrase:

t__________________

2-3 CAR BLUE $IX\text{-}ADV_i$, IX-PRO.1 $KICK_i$

"The blue car over there, I kicked it."

In (2-3), IX-ADV uses the SASS classifier for a car [u+12+v], establishing a spatial locus of *i*. The agreeing verb KICK is articulated with the ending location *i*. (See Section 2.4.6 for a discussion of syntactic elements within the noun phrase.)

DESC The descriptive classifier root DESC (also called *stative-descriptive roots* (Liddell and Johnson 1987) *is* used to describe the physical characteristics of an object. As with LOC, DESC roots can be used both as predicates and within a noun phrase.

2-4 a. CAR DESC

"The car is long."

t__________

b. CAR DESC, IX-PRO.1 BUY

"I bought the long car."

In (2-4.a and 2-4.b), DESC would be articulated with a SASS classifier. The movement of the sign indicates the shape of the object ("car"), not any movement of the car itself. In (2-4.a), the DESC root is acting as a predicate adjective. In (2-4.b), DESC is an adjective describing the noun "car."

Classifier roots do not have a handshape defined in the lexicon. In addition, MOV and DESC roots do not have an initial or final Placement defined in the lexicon. The translator will provide these during generation. The LOC root will have an initial Sprel of [ANT] and a final Sprel of [AT], indicating the indexing motion at a location in the signing space. However, the initial and final Hand Site and Focal

Site features for MOV and DESC will be specified with the empty feature LOC, which will be provided by the translator during generation.   Figure 2-3 shows the lexical entry for the classifier root LOC.

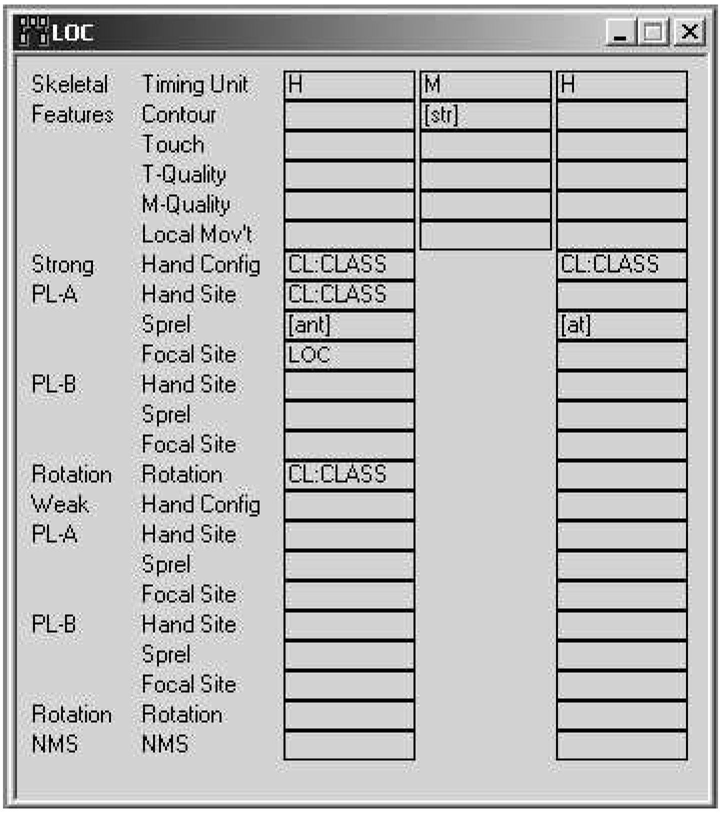

Figure 2-3: Lexical entry: LOC

2.3.2 Inflection

This section will present information about the morphological properties of inflection in ASL. The syntactic properties of these inflectional processes are discussed in Section 2.4.

2.3.2.1 Aspect

Aspect is a grammatical category that conveys information about the state of completion of some action. Klima and Bellugi (1979) introduce the analysis of aspect in ASL; it has received much attention since.

Phonologically, aspect is realized as a predictable change in a sign's features. The type of change is unique for each type of aspect. Aspect is also commonly accompanied by characteristic non-manual signals. Several common types of aspect are discussed below.

Not all lexical elements may be inflected for aspect. In the lexicon, signs that are susceptible to aspect inflection will be so marked for each type of aspect.

Aspect	Description
Continuative	An activity that continues for a long time
Regularly	Regularly, habitually
Frequently	Occurring often

Table 2-8: Examples of aspect in ASL

Several types of aspect described in Klima and Bellugi (1979) are discussed below. For each example, the changes in notation that result from the application of the aspect are noted.

2-5. a. **Continuative**. This aspect is characterized by a repeated, circular movement. The NMS includes a slight tilting back of the head. Examples are ABANDON ^{continuative}, SICK ^{continuative}, and STUDY ^{continuative}.

i. Apply reduplication
ii. Contour => [+ARC], must specify Flow
iii. Touch -> [-TOUCH]
iv. NMS => cont
v. [+REDUPLICATION]

b. **Regularly**. Movement is repeated in a straight line, the head is tilted to the side, and the lips pursed.

i. Apply reduplication
ii. NMS => reg
iii. [+REDUPLICATION]

c. **Frequently**. Tense repetition, the corners of the mouth are lowered. Examples include SICK ^{frequently} and STUDY ^{frequently}.

i. Contour => [+DIRECT, -ARC]
ii. M-Quality => [+REDUCED]
iii. Touch => [-TOUCH]
iv. NMS => freq
v. [+REDUPLICATION]

2.3.2.2 Agreement

There are three broad categories of ASL verbs: those that manifest overt agreement features ("inflecting" verbs, what Liddell (1995) calls "indicating" verbs); those that modify their articulation to indicate location information; and those that show no overt agreement ("plain" verbs) (Padden 1988).

2-6 a. <u>Inflecting/Indicating Verbs</u>
Show person and number agreement
b. <u>Plain Verbs</u>
Do not incorporate agreement inflection
c. <u>Spatial Verbs</u>
Verbs of motion and location (Supalla 1982)

Person agreement involves motion toward the location of the referent (near the signer's body for first person; in the direction of the addressee for second person; toward a spatial location assigned to a referent for third person). Number agreement may be unmarked (singular or collective); or marked for dual, triple, or more than three. Spatial verbs may indicate motion toward or at a location, but do not exhibit the same morphology as person and number agreement (Padden 1988). Inflecting verbs may show person agreement with the subject, the object, or both. Agreement is produced by modifying the sign's location and/or orientation with respect to a locus (typically a spatial locus, but agreement with a body locus, though seldom occurring, is not impossible). For verbs that show subject and object agreement, the verb's agreement features in the first segment will usually indicate the subject, and the agreement features in the final segment usually indicate the object. For inflecting verbs, there are five possible agreement patterns.

Agreement Pattern	Example	Description
Location	HELP	The initial and final Focal Sites indicate subject and object.
Orientation	TEASE	The agreement features are specified in the Facing cluster.
Location and orientation	ASK	Both Placement A and Facing encode agreement features.
Reciprocal	UNDERSTAND-EACH-OTHER	Each hand of a two-handed sign encodes subject and object agreement in the Facing cluster.
Object only	TELL	The final Focal Site indicates the object.

Table 2-9: Agreement patterns

The most commonly discussed agreeing verbs are those that move from a location that indicates the subject, to a location that indicates the object. For these verbs, agreement is encoded in the Placement features for the sign. The sentence $_{\text{IX-PRO.2}}$ HELP $_{\text{IX-PRO.1}}$ is an example. Notably, the agreement features are located in the placement cluster for the weak hand.

Agreement may be included in the sign's orientation, specified in the Facing cluster. See the sample notation for TEASE $_{\text{IX-PRO.3}}$ for an example.

Signs may indicate agreement with location and orientation simultaneously, as in $_{\text{PRO.1}}$ SAY-NO-TO $_{\text{PRO.2}}$ and $_{\text{PRO.1}}$ HATE $_{\text{PRO.2}}$. In these sentences, object agreement is encoded in the strong hand's Placement (location), and subject agreement is encoded in the strong hand's Facing.

In reciprocal signs, agreement features may be fully specified for both hands at the same time. Consider UNDERSTAND-EACH-OTHER, in which the strong hand's Placement (location) indicates the subject and Facing (orientation) indicates the object. Inversely the weak hand's Placement indicates the object, and Facing the subject.

Finally, there are inflecting verbs that only manifest object agreement features; that is, there is no morphological realization of subject agreement. An example of a verb in this category is TELL, in which the Placement features in the sign's final segment indicate the object.

Table 2-10 provides examples of the variety of ways location is used to indicate agreement:

Pattern	Example Sign	Subject Focal Site	Object Focal Site
Location	HELP	Initial Strong Placement	Final Strong Placement
Orientation	TEASE	Initial Strong Facing	Final Strong Facing
Location and Orientation	ASK, SAY-NO-TO	Initial Strong Facing	Initial Strong Placement
Location and Orientation	INVITE	Initial Strong Placement	Initial Strong Facing
Reciprocal, Location and Orientation	UNDERSTAND-EACH-OTHER	Initial Strong Placement Initial Weak Facing	Initial Weak Placement Initial Strong Facing
Object only, Orientation	TELL	--	Final Strong Facing

Table 2-10: Examples of Focal Site in Agreement

Table 2-10 is not taken to be comprehensive of all possible configurations for subjects and objects, strong hands and weak hands, initial and final segments, locations and orientations. But it does demonstrate that the simple approach of identifying the starting location as the subject and ending location as the object is insufficient.

Furthermore, it is not enough to leave the relevant Focal Site features unspecified, as a way of identifying features that need to be specified during generation to indicate agreement. For instance, in the sentence $_{\text{IX-PRO.2}}$ HELP $_{\text{IX-PRO.1}}$, the strong hand's Focal Site does not change, but the weak hand's Focal Site does change. If the values for both Focal Sites were left unspecified, there would be no way to know whether to apply the object's Focal Site features to the verb's strong hand or weak hand.

To accommodate these different agreement patterns in the MT system, an empty Focal Site feature will be used to indicate both the subject and object. These are SUBJ and OBJ, respectively (see Figure 2-2 above)[10]. These features can be used as the Focal Site for both the Placement and Facing clusters, for both strong and weak hands. When encountered during generation, the actual Focal Site features for the sentence's subject and object will replace the empty Focal Site features in the verb. In Chapter 3, these empty SUBJ and OBJ features will be related the grammatical functions of sentential arguments, whose Focal Site features will supply appropriate values for these variables.

Spatial verbs involve movement from, to or at specific locations, but this use of space is distinct from the person and number agreement used by agreeing verbs, described above. For instance, a spatial verb such as PUT will begin and end at different locations depending upon the context. However, unlike GIVE, the initial location does not represent agreement with a subject, and the ending location does not represent agreement with an object. Rather, the initial location of PUT may optionally signify a starting location for the object being put (or may represent a neutral location, if the starting location is undefined or insignificant), and the ending location signifies an ending location (where the item is being put) (Figure 2-4). These locations do not correspond with a Focal Site established for the agent of PUT.

[10] This convention follows Johnson (p.c.), in which variables Σ and Ω are used to represent subject and object, respectively.

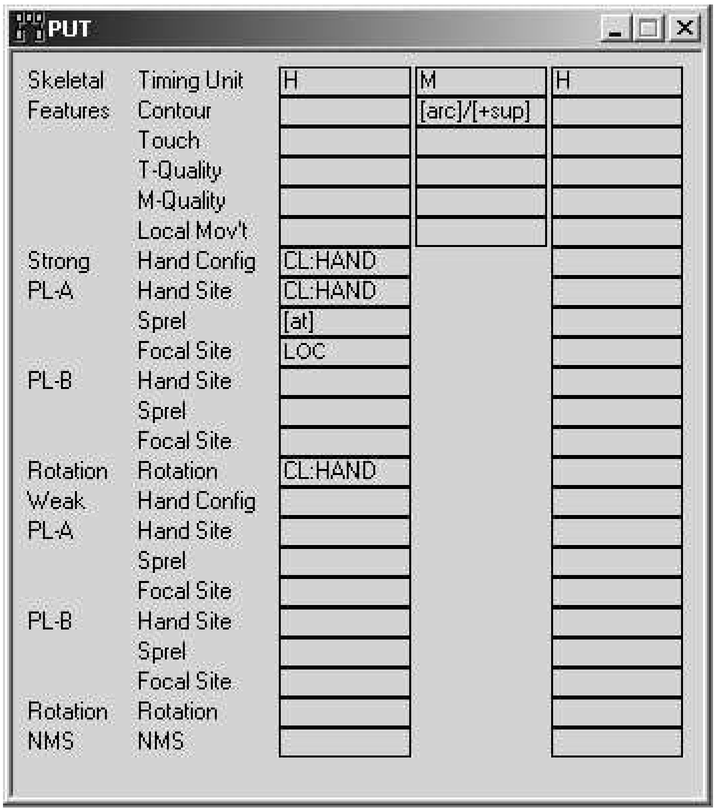

Figure 2-4: Lexical entry: PUT

Spatial verbs that depend upon context in the discourse to determine either a starting or ending location will use the empty feature LOC in their root form in the lexicon. When necessary, the translator will be prompted to provide a Focal Site for these locations.

2.3.3 Plurals and quantification

2.3.3.1 Standard Pluralization

Nouns may be modified by quantifiers to indicate plurals. The existence of the quantifier is all that is required to indicate plurality; there is no additional agreement marking on the noun.

A few nouns in ASL indicate plurality through the process of reduplication (see section 2.2.2), though this is an exception to the general process indicated above. Nouns that are amenable to this process will be marked in the lexicon with a [+ REDUPPLURAL] feature.

2.3.3.2 Numeral Incorporation

Some signs, when pluralized, incorporate the numerals 1-9 into their composition. The segments are unchanged, but the handshape is taken from the numeral. Nouns that undergo numeral incorporation are bound morphemes (Incomplete S-morphs), which must be combined with a numeral (P-morph) to form a complete unit (signs will have a default setting of "1" when an explicit numeral is not present). Signs that undergo numeral incorporation include: YEAR, WEEK, MONTH, DAY, HOUR, MINUTE, YEARS-OLD, DOLLARS, RANK (in a race), HEIGHT, and EXACT-TIME.

For these types of signs, the hand configuration will be lexically encoded with the empty feature NUM. Numeral incorporation will occur during generation, when the empty feature NUM is replaced with the hand configuration of the associated numeral (or [n-1+], if no numeral is present).

2.3.3.3 Pronouns

Pronouns in ASL have different forms for singular and plural, and there is a plurality of plural forms to choose from.

	First person	Second person	Third person	Description
Singular	IX-PRO.1	IX-PRO.2	IX-PRO.3	Identical except for location
Plural	WE	IX-PRO.2	IX-PRO.3	Identical except for location

Table 2-11: Pronouns

The singular forms IX-PRO.n are formed by pointing, with the final location indicating the locus of the referent. First person is signed with the final location at the signer's chest; second person with the final location pointing toward the addressee; and third person with the final location pointing toward the referent (or an index established for the referent). The plural form of IX-PRO.1, listed as WE, is realized as a small arc across the signer's chest; this is the one exception to the patterns shown above. The remaining plurals are formed with a small sweeping action in the direction of the referents, with the same difference between second and third person noted above.

In addition to these forms, pronouns may undergo numeral incorporation, with small changes to the movement segments.

numeral incorporation	First person	Second person	Third person	Description
Dual	2_OF_IX	2_OF_IX	2_OF_IX	Identical except for location
Plural	N_OF_IX	N_OF_IX	N_OF_IX	Identical except for location

Table 2-12: Pronouns with numeral incorporation

Person distinctions are the same as described above. For the 2_OF_IX forms, the signs use the handshape for the number 2 [n-12+v], and the sign moves back and forth between the main referent and the dual referent. For the plural forms, the N in N_OF_IX indicates a numeral from 3 to 9. The sign is made with numeral incorporation, and the movement follows the contour of a small circle in the direction of the included referents. See Section 2.4.6 for more discussion of pronouns.

2.3.4 Other morphological processes

2.3.4.1 Compounding

Some signs are formed as a combination of two other signs, in a process of compounding. When compounding occurs, certain processes may apply to the combined segments of the two signs, listed below (Liddell and Johnson 1986).

Compounding Process	Description
First contact	If there are two or more contact segments in the compound, only the first contact is kept.
Single sequence	Signs which are normally reduplicated drop this feature in compounds; and segments which include local movement drop this featuring compounds.
Weak hand anticipation	The weak hand may anticipate the second sign in the compound. That is, the weak hand will move into position for the second sign concurrently with the articulation of the first sign the compound.

Table 2-13: Compounding processes

Once these processes have been applied, the phonological processes described in Section 2.2.2.1 may also be applied to the segments of the compound. While generation does not automatically employ compounding, it is available as an option within the lexicon.

2.4 Syntax

LFG posits two levels of syntactic representation, the constituent structure (c-structure) and functional structure (f-structure). This section will describe relevant features of ASL syntax in terms of annotated phrase structure rules, c-structures and f-structures, in preparation for the transfer and generation functions defined in Chapter 3.

2.4.1 Word order and phrase structure

Liddell (1980) argues convincingly that underlying word order in ASL is Subject – Verb – Object, and that different surface patterns are the result of regular syntactic processes such as topicalization. The generalization can be represented trivially with the following phrase structure rules, annotated with appropriate grammatical functions:

2-7 a. $$S \rightarrow \underset{(\uparrow \text{SUBJ}) = \downarrow}{NP} \quad \underset{\uparrow = \downarrow}{VP}$$

b.	VP	$\rightarrow$	V	(NP)
				$(\uparrow \text{OBJ}) = \downarrow$

The following sections will build on this initial set of rules.

2.4.2 WH-questions

In ASL, WH -elements can remain in situ, or may optionally occur in a position to the right of the matrix clause (Aarons et al 1992, Neidle et al 1997).

2-8
a. JOHN BUY CAR YESTERDAY

wh ____________________________

b. JOHN BUY WHAT YESTERDAY

wh ____________________________

c. JOHN BUY YESTERDAY WHAT

2-9	a.	S'	$\rightarrow$	S	NP
				$\uparrow = \downarrow$	$(\uparrow \text{Q}) = \downarrow$
					$(\uparrow \text{Q}) = (\uparrow \{\text{COMP, XCOMP}\}^* \text{ GF-COMP})$
					$(\downarrow \text{NMS})$ = 'wh'
	b.	S	$\rightarrow$	NP	VP
				$(\uparrow \text{Q}) = \downarrow$	$\uparrow = \downarrow$
				$(\downarrow \text{NMS})$ = 'wh'	
				$(\uparrow \text{SUBJ}) = \downarrow$	
	c.	VP	$\rightarrow$	V	NP
					$(\uparrow \text{Q}) = \downarrow$
					$(\downarrow \text{NMS})$ = 'wh'
					$(\uparrow \text{OBJ}) = \downarrow$

The rules in (2-9) account for the distribution of WH -elements either rightward (a) or *in situ* (b, c). The functional expression of the WH -element is uncertain, but will be identified in representations of specific sentences. For the sentence (2-8.c), the rule (2-9-a) will apply; the WH -element NP will receive the f-description $(\uparrow \text{Q}) = (\uparrow \text{OBJ})$. The referent of the Q function (the trace of WH -movement in GB theory) does not receive independent representation in the c-structure; that is, there is no empty node in the syntactic tree for the source of WH -movement. The relationship between the Q and its grammatical function OBJ are represented in the f-structure:

2-10

$$\left[\begin{array}{ll} \text{Q} & \left[\begin{array}{l} \text{PRED 'WHAT'} \\ \text{NMS 'wh'} \end{array}\right] \\ & \\ \multicolumn{2}{l}{\text{PRED 'BUY <(}\uparrow\text{SUBJ), (}\uparrow\text{OBJ)>'}} \\ \multicolumn{2}{l}{\text{TENSE 'PAST'}} \\ \multicolumn{2}{l}{\text{ADJUNCTS \{ 'YESTERDAY' \}}} \\ \text{SUBJ} & \left[\begin{array}{l} \text{PRED 'JOHN'} \end{array}\right] \\ & \\ \text{OBJ} & \end{array}\right]$$

The phrase structure rules that encode the referents of a non-*in situ* WH-element show the target grammatical functions as optional:

2-11	a.	S	→	(NP)	VP
				(↑ SUBJ) = ↓	↑ = ↓
	b.	VP	→	V	(NP)
					(↑ OBJ) = ↓

Sentences such as * *LIKE MARY* are ruled out by the completeness condition: the verb '*LIKE <(↑ SUBJ), (↑ OBJ)>*' governs a grammatical function (SUBJ) that is not included in the f-structure of the sentence.

2.4.3 Negation

Sentential negation in ASL can be realized with the lexical element NOT (which must co-occur with the characteristic 'neg' NMS), or may be indicated with the NMS and no lexical element at all.

neg___________
2-12 a. J-O-H-N NOT HUNGRY

neg______
b. J-O-H-N HUNGRY

As discussed by Aarons et al. (1995), Neg must occur after the subject, after any lexical item in AUX, and before any lexical elements in Asp (see below).

2-13 a. VP $\rightarrow$ (Neg) V (NP)
($\downarrow$ NMS) = 'neg' ($\uparrow$ OBJ) = $\downarrow$

2.4.4 Tense and Modals

Discussions of tense and ASL commonly make two claims: that ASL signs with temporal information follow a "timeline," with the area in front of the sign indicating the future and the area behind the signer indicating past (see the discussion of Frishberg and Gough 1973b in Wilbur 1987, and related discussion in Jacobowitz and Stokoe 1988); and that ASL verbs are not inflected for tense (Fischer and Gough 1978, Friedman 1975 and Perlmutter 1991, also discussed in Wilbur 1987, *et alia*). Recently, however, researchers have been providing evidence to challenge these traditional assumptions. For instance, Jacobowitz and Stokoe (1988) re-analyze the notion of a timeline, and furthermore propose that all ASL verbs are overtly infected for tense, though they claim the marking is so subtle that previous analyses have failed to notice the marking. The marking they report is a slight leaning of the body forwards or backwards, indicating future and past tense respectively. Neutral leaning indicates an inflection for present tense.

Aarons et al (1995) distinguish between lexical tense markers and time adverbials. The tense node of an ASL sentence can contain lexical tense markers or modals. Time adverbials can occur before tense, after tense, and as topics. This section describes the distribution of modals, lexical tense markers and time adverbials, and their syntactic representation.

Aarons et al (1995) argue that modals in ASL occupy the T° node, because they have the same distribution as lexical tense markers and occur in the same positions relative to other elements such as negation. The discussion of lexical tense markers is taken to include modals.

Tense occurs after the subject NP and before the VP. If negation is present, tense precedes negation.

neg______________
2-14 JOHN PAST-TNS NOT BUY HOUSE

Some forms of modals and tense markers allow contraction with negation, suggesting these nodes are adjacent.

2-15 a. MUST^NOT
b. CAN^NOT
c. WILL^NOT

A sentence in ASL can contain only one modal or lexical tense marker.

2-16 * JOHN FUTURE-TNS CAN BUY HOUSE

It is possible for tense to co-occur with aspect (though not all combinations are semantically compatible).

2-17 JOHN FUTURE-TNS FINISH/PERF-ASP READ PAPER

Time adverbials, though related to lexical tense markers, show a distinct distribution pattern and variety of articulation. For instance, time adverbials can occur before the subject, between the subject and VP, and sentence-finally.

2-18 a. TOMORROW JOHN BUY CAR
b. JOHN TOMORROW CAN BUY CAR
c. JOHN BUY CAR TOMORROW

Time adverbials can co-occur with modals and lexical tense markers, as in (2-23.b) and (2-24).

2-19 TOMORROW JOHN FUTURE-TNS BUY CAR

Tense elements are restricted in their place of articulation, and cannot occur more than once. Time adverbials are more flexible in their place of articulation and can co-occur with tense elements, which suggests they are in a separate syntactic category.

2-20	a.	VP	→	(AUX)	(Neg)	(Asp)	V	(NP)
					(↓ NMS) = 'neg'			(↑ OBJ) = ↓

The following table shows common modals, lexical tense markers and time adverbials.

Modals	Lexical Tense Markers	Time Adverbials
CAN	FUTURE-TNS	FUTURE-ADV
MUST	PAST-TNS	UP-TO-NOW-ADV
SHOULD	UP-TO-NOW-TNS	NOW
have-to	cs	TOMORROW
MUST	RECENT-PAST-TNS	YESTERDAY
CAN^NOT	USED-TO-TNS	TODAY
MUST^NOT	FORMERLY-TNS	NEVER
	IMMEDIATE-PRESENT-TNS	

Table 2-14: Modals, Tense and Time Adverbials

2.4.5 Aspect

Aarons et al. (1995) describe lexical aspect markers, such as FINISH/PERF-ASP or SUCCEED^{pah}. These lexical elements can co-occur with modals in AUX. Tense precedes aspect, and aspect precedes the verb.

have-to

2-21 TOMORROW J-O-H-N_i MUST TAKE-UP EXAM.
(IX-PRO_i) MUST FINISH/PERF-ASP READ BOOK
"John has to take an exam tomorrow. He must read the book (to completion).
(Aarons et al. 1995, example # 19).

Klima and Bellugi (1979) report on a number of verb modifications that indicate aspect. Liddell and Johnson (1989) discuss the feature of reduplication (see section 2.2.2), and its role in habitual and iterative aspect. These types of verb modifications appear to apply a consistent set of phonological features to verbs when present.

As reported in Klima and Bellugi (1979), not all signs can undergo all types of modulation. For example, signs such as SICK, DIRTY, and AWKWARD can incorporate the continuative aspect, while signs such as PRETTY, UGLY and HARD cannot. Klima and Bellugi speculate that semantic properties of the signs predict whether they incorporate aspect features. For the purpose of this work, however, signs will be specified with features that indicate whether they incorporate aspect features. For instance, the sign SICK will be marked in the lexicon with a [± CONT] feature, indicating that it can incorporate continuative aspect features. In cases where the verb occurs with a [+ CONT] aspect, SICK will incorporate the morpheme for this aspect (see section 2.3.2.1).

2.4.6 Noun phrases

MacLaughlin (1997) discusses the structure of noun phrase in ASL. The data presented by MacLaughlin includes the articulation of index signs (indicated as IX), which include a pointing handshape and motion, and may include various non-manual signals. MacLaughlin observes the following distribution of index signs in ASL:

2-22 JOHN ARRIVE IX_i (adverbial)
"John is arriving over there."

2-23 IX_i ARRIVE (pronominal)

"He/she/it is arriving."

2-24 a. [IX_i MAN] ARRIVE (In a noun phrase)

"The/that man is arriving."

b. [MAN IX_i] ARRIVE

"A man there is arriving."

c. [IX_i MAN IX_i] ARRIVE

"The/that man there is arriving."

MacLaughlin argues that an index IX can function as an adverbial (IX-ADV, as in (2-22)); as a pronominal (IX-PRO, as in (2-23)); and as a definite determiner (IX-DET, as in (2-24.a and c)). She concludes, based on observations of articulatory differences, non-manual signals, co-occurrence with possessives, and number agreement, that the IX occurring before the N is a definite determiner (IX-DET), whereas the IX occurring after the N is an adverbial (IX-ADV). An NP with a pre-nominal IX must carry a definite interpretation, whereas an NP with a post-nominal IX can be [± DEF].

In addition, MacLaughlin identifies two additional (unstressed) indefinite determiners: ONE-DET and SOMETHING/ONE-DET. These determiners must occur before the N, and must carry an indefinite interpretation. MacLaughlin's analysis will be extended here to account also for possessive noun phrases, numerals and adjectives within noun phrases.

2.4.6.1 Possessive noun phrases

ASL uses a lexical possessive marker, articulated as an open, flat hand (n^1234+) with the palm pointing toward the possessor. This will be indicated with the gloss IX-POSS. IX-POSS occurs in the following locations:

2-25 a. IX-POSS SISTER

"His sister"

b. JOHN IX-POSS SISTER
"John's sister"

c. JOHN IX-POSS SISTER TALL
"John's tall sister"

That is, IX-POSS precedes the NP's head noun, but occurs after an N indicating the possessor. This can be generalized as follows:

2-26. NP $\rightarrow$ (NP) Det N
($\uparrow$ POSS) = $\downarrow$

As MacLaughlin (1997) observes, IX-POSS cannot co-occur with IX-DET, which suggests IX-POSS and IX-DET occupy the same syntactic position (Det).

2-27 a. * IX-PRO MEET [IX-DET JOHN IX-POSS FRIEND $]_{DP}$ YESTERDAY

b. IX-PRO MEET [JOHN IX-POSS FRIEND IX-ADV$]_{DP}$ YESTERDAY
"I met John's friend (there) yesterday."

(MacLaughlin 1997, examples #26 and #27)

IX-POSS indicates person agreement with the possessor NP, by moving the hand in the direction of the location identified with the possessor. When IX-POSS exists without an overt possessor NP, its interpretation is that of a possessive pronoun. There is also number agreement between IX-POSS and the possessor. As with IX-DET, IX-POSS adds a [+ ARC] feature to the movement segment to agree with a plural possessor.

2.4.6.2 Numerals

Numerals occur after the determiner and before the N.

2-28 a. THREE SISTER

"three sisters"

b. NP → (NP) (Det) (Num) N

$(\uparrow \text{POSS}) = \downarrow$

MacLaughlin (1997) reports a difference in the articulation of the numeral ONE and the determiner ONE-DET. When ONE is used as a numeral it is slightly stressed, and the palm faces out from the signer (pronated rotation). When ONE-DET is used it does not carry stress, and the palm faces the signer (supinated rotation).

Some ASL nouns allow for numeral incorporation. For instance, the sign THREE-WEEK ("three weeks") is articulated as the sign for WEEK, with the numeral THREE handshape. Typically, signs that allow numeral incorporation only allow it with numbers 1-9.

The following structure is incorporated for numerals in NPs. In order to account for numeral incorporation, nouns in the lexicon are taken to specify a hand configuration of NUM. In the presence of a Num, nouns with this hand configuration feature will undergo numeral incorporation with numerals 1-9. The morphology of numeral incorporation is discussed in Section 2.3.3.2.

2.4.6.3 Adjectives

When adjectives occur within an NP, they occur after the N, but before IX-ADV.

2-29 a. THREE SISTER TALL

"three tall sisters"

b. NP → (NP) (Det) (Num) N (AdjP) (Adv)

$(\uparrow \text{POSS}) = \downarrow$ $\uparrow = \downarrow$

2.4.7 Other types of constructions

2.4.7.1 Relative Clauses

A relative clause is a noun phrase that contains a complement clause, the entire construction performing the role of the noun phrase in the sentence. Liddell (1980) discusses relative clauses in ASL in depth, though the details of this implementation differ from Liddell's analysis.

2-30 a.
$$\overline{\text{MAN YOU MEET YESTERDAY}}^{\,r}\ \text{FUTURE-TNS ARRIVE SOON}$$

b.
$$NP \rightarrow \begin{array}{cc} NP & S \\ (\uparrow \text{REL COMP* GF}) = \downarrow & (\uparrow \text{REL}) = \downarrow \end{array}$$

The expression (↑ REL COMP* GF) = ↓ ensures that the noun is linked to the grammatical function of an argument in the embedded S; since the grammatical function can vary, we use functional uncertainty with the generic GF variable.

Liddell describes the 'r' NMS shown in (2-30.a) as a slight tilting back of the head, raising of the eyebrows and tensing of the upper lip. When generating a sentence with a relative clause, generation will create an NP with a complement S as shown in (2-30.b), with the 'r' NMS.

2.4.7.2 Conjunctions

Conjunctions are lexical elements such as the lexicalized, fingerspelled O-R that conjoin constituents of the same grammatical category. My informants reject the signs AND and PLUS when used as conjunctions, as "Englishy" (not proper ASL). There appears to be at least one other conjunction in ASL, which is used when conjoining more than two constituents. This involves a "counting off" of the elements on the fingers of the weak hand with the index finger of the strong hand. This conjunction will be glossed "CONJ-n", where n indicates the number of elements so far conjoined, from 1-6. CONJ-6 is articulated at an imaginary, 6th finger below the pinky.

Kaplan and Maxwell (1988) describe a mechanism to allow constituent coordination in LFG, allowing for the representation of sets of constituents. In this approach, coordination is represented in the phrase structure rules as follows:

2-31	a.	NP	$\rightarrow$	NP	CONJ	NP
				$\downarrow \in \uparrow$		$\downarrow \in \uparrow$

The rule says that a conjoined noun phrase consists of an NP followed by a conjunction followed by an NP, where the f-structure of each NP is an element of the f-structure that represents their coordination. See Kaplan and Maxwell (1988) for details.

2.4.7.3 Fragments

Throughout Section 2.4, we have been concerned primarily with full sentences. However, in natural discourse it is common for sentence fragments to be used. While the representation strives to follow a well-motivated and consistent theory of grammar, it should also be flexible enough to account for the full range of constructions that can occur in a natural discourse.

The requirements of completeness and coherence (1-3) pertain to individual f-structures. Correspondence between levels of representation does not insist, for example, that every sentence contain a verb; it merely insists that an f-structure contain all and only the grammatical functions listed in the predicate's schemata. In practice, this restricted interpretation permits any complete and coherent f-structure to be handled correctly by the translation system, even if it is not a complete sentence.

2.5 Discourse Elements and Focal Sites

As described in Sections 2.3.2.2, Focal Site features for inflecting and spatial verbs will vary depending upon the spatial coordinates of expressions in the discourse. To facilitate capturing and applying these coordinates, the representation will include a list of all discourse elements encountered during generation.

A discourse element includes a unique index (i, j, k, etc.), the name of the R-expression, and optionally its Focal Site.

Index	R-Expression	Focal Site
i	JOHN	p2AB
j	MARY	%p2AB

Table 2-15: Sample Discourse Elements

When generation encounters an R-expression, the user will be prompted to either select existing discourse element or to create a new one. In some cases, generation requires a discourse element with coordinates. When this happens, the user must either select a discourse element with coordinates or create one with coordinates.

2.6 Non-Manual Signals

There are two types of non-manual signals (NMSs) included in the representation. These are syntactic NMSs created during generation, and lexical NMSs specified in the lexicon. NMSs are not represented independently; rather, they occur as part of lexical items or in specific syntactic contexts.

NMSs that are specified with lexical items are restricted to occur only over the lexical item.

            <u>have-to</u>
2-32. MUST

In (2-32), the sign MUST always occurs with the NMS "have-to" (Aarons et al. 1995). This NMS cannot extend to other signs in the sentence.

                                <u>have-to</u>
2-33 a. J-O-H-N MUST EAT CORN

have-to
b. * J-O-H-N MUST EAT CORN

Other NMSs arise as the result of syntactic environments, such as with WH-questions. It has been postulated that syntactic NMSs occur over the c-command domain of the lexical or functional head, with optional spreading in some cases (Aarons et al 1992, Neidle et al 1996). While generally accurate, the NMS for topicalization ('t') cannot be accounted for using the same mechanism. Both WH-elements and topicalized NPs occur as sisters to the S, but exhibit different behaviors with respect to the spreading of their NMSs.

In LFG terms, NMSs will occur over the constituents that are dominated by the parent of the labeled node containing the NMS feature. This is effectively equivalent to the c-command domain employed by Aarons et al (1992), and thus also fails to account for the difference between topicalized elements and other syntactic configurations that generate non-manual markings, for which I currently have no explanation.

The occurrence of NMSs in the c-structure is achieved with syntactic features expressed in the phrase structure rules. For instance, the 'wh' and 'neg' NMSs are expressed as follows:

2-34	a.	S'	→	S ↑ = ↓	NP (↑ Q) = ↓ (↓ NMS) = 'wh'
	b.	VP	→	(Neg) (↓ NMS) = 'neg'	V …

2.7 Conclusion

This chapter began with two central claims. First, an accurate and well-formed representation of ASL must be dynamic, that is, must allow for a large variation in features of signs, such as handshapes, location, orientation, movement and non-manual signals. With so many different possible forms it is not realistic to encode them all lexically. Second, this representation of ASL must be able to encode how ASL uses space grammatically, as well as accounting for the occurrence and scope of non-manual signals.

The aim of the first claim is to motivate a system that starts with root forms of words in the lexicon and builds context-specific representations of these roots based on phonological, morphological and syntactic processes. This is similar to encoding an English verb root such as "run," and being able to apply features such as tense, person and number agreement to generate a variety of forms: "ran," "runs," "running," and so on. Each separate form does not require a separate lexical entry. In ASL, the number of changes that can apply to roots is so large that it is not practical to encode each form lexically.

The second claim extends this reasoning to argue that instantiated forms of lexical roots must include spatial data. That is, not only should a sign change its form based on linguistic information, but also this must include spatial information that is unique to signed languages.

MH was chosen because of its flexibility to encode spatial information with precision. By adding a number of empty tokens, a wide range of spatial variation can be specified lexically and instantiated dynamically. Chapter 2 presented a review of ASL phonology, morphology and syntax that identified a number of ways in which signs modify their forms.

<u>Classifier handshapes (Section 2.3.1.1)</u>. Verbs that use classifier handshapes do not have a handshape configuration specified lexically. Rather, they will have a token CL:<type>, where <type> identifies which classifier group to select a handshape from. Nouns in the lexicon will contain a default handshape for each classifier group, but the translator can select a different classifier handshape.

<u>Classifier roots (Section 2.3.1.2)</u>. The classifier roots MOV, LOC and DESC each employ empty features for their classifier handshape and Focal Sites.

<u>Aspect (Section 2.3.2.1).</u> Some verbs change the form of their articulation to represent sentential aspect. These changes are predictable, and are described in terms of changes in MH notations. Not all verbs can incorporate aspect features; verbs that do incorporate these features are so marked in the lexicon.

<u>Agreement in inflecting verbs (Section 2.3.2.2).</u> There are five general patterns of how verbs represent agreement with subjects and objects: by modifying location; orientation; both location and

orientation; reciprocals; and object-only location agreement. Subjects and objects are always associated with a Focal Site (either a body locus, or a spatial locus at a specified height). Verbs can use this Focal Site to identify agreement features in a variety of ways, including in the initial or final segment of a sign; in the strong hand's Placement; in the weak hand's Placement; in the strong hand's Facing; and in the weak hand's Facing.

Noun plurals (Section 2.3.3.1). Many nouns indicate pluralization through the process of reduplication. Since not all nouns undergo this process, nouns that do will be marked in the lexicon with a [+REDUPPLURAL] feature.

Numeral incorporation (Section 2.3.3.2). Some nouns incorporate numerals from 1-9 in their handshape to indicate pluralization. These nouns will have a default "1" [n-1+] handshape, and be marked with the empty hand configuration feature NUM in the lexicon.

Pronouns and Determiners (Sections 2.3.3.3 and 2.4.6). These are variations on index signs that involve a movement towards a point in space that establishes or identifies a spatial locus (Focal Site) for the referent. Adding a sweeping motion to the index indicates pluralization.

Non-manual signals (Section 2.6 and throughout). NMSs are Lexical or grammatical variations in facial expressions and body positioning.

With an understanding of the need to encode spatial information and represent signs dynamically, the MH model was selected as the major component of the representation system. Signs in the lexicon include a base MH notation, and undergo phonological processes within and between word boundaries when used in a sentence. MH is extended with empty features for grammatical functions that encode Focal Site features that must be instantiated during generation.

Chapter 3 will address issues involved in generating the representation in the context of a machine translation system. The generation system begins with transfer from an f-structure of English, to the generation of a c-structure syntactic tree of ASL, and then generates the p-structure that encodes grammatical, spatial and non-manual data. The translator will have control over many aspects of how the representation is generated, including selecting appropriate syntactic processes and forms (such as topicalization); morphological elements (such as classifier handshapes); phonological features (such as Focal Sites for predicate roots); and lexical selection.

Chapter 3 Generation

The task of the generation component is to take a representation of some input text and convert it into a well-formed representation of ASL that expresses the same meaning faithfully. An overview of the system architecture implemented in *ASL Workbench* is presented in Section 3.1. The input to the system is a representation of English created by an analysis component. This is an LFG f-structure (Kaplan and Bresnan 1982, Kaplan 1989), described in Section 3.2. Transfer converts the English LFG f-structure to an ASL LFG f-structure by performing two functions: (1) lexical selection from a bilingual transfer lexicon; and (2) assignment of source language (SL) grammatical functions to target language (TL) grammatical functions. The details of this operation are defined in Section 3.3.

Generation (syntactic, morphological, and phonological) follows transfer. Syntactic generation creates constituent structure tree (c-structure), applying language specific phrase-structure rules. Morphological generation applies morphological processes to elements in certain syntactic contexts. Phonological generation applies phonological processes between and among signs in an ASL sentence, represented in a phonetic structure (p-structure). The generation approach is described in Section 3.4.

When translating between two languages, there will be cases where the SL structure is different from the TL structure. These differences are described in the literature as *divergences* (Dorr 1994). Divergences between English and ASL are discussed in Section 3.5.

3.1 System architecture overview

This section outlines the overall architecture of this system as implemented. While certain computational decisions had to be made in order to implement the demonstration system *ASL Workbench* (such as the transfer and generation algorithms), for the most part they are incidental to the generation of the representation developed in Chapter 2.

ASL Workbench implements a transfer module and a generation module. The input to transfer is an English LFG f-structure (see section 3.2). The English f-structure is converted into an ASL f-structure by performing lexical selection and structural correspondence (Section 3.3). The ASL f-structure is used as input to the generation module, which creates an ASL c-structure and p-structure for the sentence (Section 3.4). This architecture is summarized in Table 3-1.

System Function	Data Access
(1) *input* ↓	
(2) TRANSFER • lexical selection • functional correspondence ↓	◄ Transfer lexicon
(3) GENERATION • lexical retrieval • syntactic generation • morphology, phonology • phonetic generation ↓	◄ ASL lexicon ◄ Phrase-structure rules
(4) *output*	

Table 3-1: System Architecture

Details of (1) input, (2) transfer and (3) generation are discussed below.

3.2 Input to the system: functional representation

LFG assigns two levels of representation to a sentence: the c-structure and f-structure. The surface grammatical relations and grammatical functions of the f-structure provide language-independent information about the sentence that is ideally suited to transfer (Amores 1992). The practice of using f-structures as the input to transfer is common (see for example Kudo and Nomura 1986, Amores 1992, Amores and Quesada 1996, Butt and King 1998, Frank 1999, Way 1999, Wong 1999, *inter alia*). This approach is adopted here.

3.3 Transfer

Transfer is defined as the function that converts an English f-structure to an ASL f-structure. Two operations, lexical selection and structural correspondence, work together to create an ASL f-structure. Although transfer does not make use of the representation developed in Chapter 2, this section will describe the approach to transfer implemented in *ASL Workbench*.

Kudo and Numora (1986) use a *description-by-analysis* strategy of lexical functional transfer (LFT) between the SL and TL. After generating an f-structure for an SL sentence, they use a bilingual dictionary with transfer rules to create TL f-descriptions from the SL f-structure. The TL f-descriptions are used to create the TL f-structure, which in turn is used to generate the TL sentence. As Wong (1999) notes, the success of this approach depends on the transfer rules, which can be prohibitively difficult and time-consuming to construct.

Kaplan et al (1989) apply the *codescription* framework of LFG to the problem of machine translation, by proposing a correspondence function τ between the SL and TL f-structures, and τ' between the SL and TL s-structures. Correspondences between SL and TL structures are defined in a bidirectional transfer lexicon. This approach is flexible in handling SL and TL sentences that have different structures. However, as Sadler and Thompson (1991) point out, the codescription approach of Kaplan et al (1989) cannot handle translations involving head-switching phenomena. As Wong (1999) observes, Kaplan et al (1989) do not discuss how to handle problems of lexical ambiguities.

Despite the criticisms of Sadler and Thompson (1991) and Wong (1999), the codescription approach of Kaplan et al (1989) is adopted here, for the purpose of implementing a demonstration system. Amores (1992) notes that LFG literature contains much evidence in favor of both approaches, and the shortcomings of codescription do not bear directly on the issues in generating well-formed ASL structures to be taken up in Section 3.4.

3.3.1 Lexical selection

The purpose of the transfer lexicon is to map SL lexical elements to TL lexical elements[11]. ASL lexical elements are represented as glosses, as in:

3-1. answer → ANSWER

The gloss entry in the transfer lexicon is rather impoverished; it contains no phonetic detail and none of the spatial-grammatical features described in Chapter 2. There is a uniqueness constraint imposed upon entries in ASL lexicon; there will be no ambiguity between an entry selected by the transfer lexicon (or gloss) and the actual lexical element in the ASL lexicon.

There are several well-known challenges to correct lexical selection, which must be addressed by *ASL Workbench*. Some examples are discussed here.

Categorical ambiguity occurs when a single word form has more than one lexical entry, each with different syntactic categories. For instance, the English word *bank* can refer to a financial institution (a noun), or it can refer to the act of turning an aircraft (a verb). Selecting the correct TL form will depend upon identifying the correct syntactic category of the SL form.

Synonymy occurs when a single SL form maps to multiple TL forms of the same syntactic category. For example, the English word *okay* has two equivalents in ASL, one where the radial side of the strong hand brushes the palm of the weak hand (OKAY), and a lexicalization of the fingerspelling O-K.

---

[11] Section 3.3.2 will introduce additional features of the transfer lexicon.

Homonymy refers to the case where two different lexical entries have identical lexical forms. The English word *board* can refer to a piece of wood, or to a group of people. As with categorical ambiguity, selecting the correct TL form will depend upon identifying the correct SL form.

Lexical gaps occur when a lexical element in one language does not have a corresponding lexical element in the other language.

Currently, *ASL Workbench* resolves problems of lexical selection interactively, by presenting the translator with a choice between possible lexical matches. However, lexical gaps require some additional discussion. The transfer lexicon will contain entries only when both SL and TL forms are present for that entry; that is, either a SL gap or a TL gap will result in a missing entry in the transfer lexicon. If the lexical element is a noun, *ASL Workbench* will fingerspell the word. If the lexical element is any other syntactic category, the translation will fail. The translator can then create an appropriate entry in the ASL lexicon if necessary, and create the appropriate entry in the transfer lexicon, to re-attempt the translation.

3.3.2 Mapping grammatical functions

This section will describe the approach taken to map an SL f-structure to a TL f-structure. The approach follows that described by Kaplan et al (1989), by implementing a correspondence function τ between SL and TL f-structures.

3.3.2.1 General description of transfer

As described in Section 1.3, LFG posits two levels of representation, a constituent structure (c-structure) and a functional structure (f-structure). The c-structure includes a phrase-structure tree, encoding an ordered arrangement of sentential constituents in a manner determined by the grammar's phrase-structure rules. The f-structure marks grammatical functions (subject, object, etc.) as combinations of attribute-value pairs (function-argument equalities). LFG employs a correspondence function ϕ that maps a c-structure onto an f-structure. This is illustrated for the sentence *John likes Mary* below.

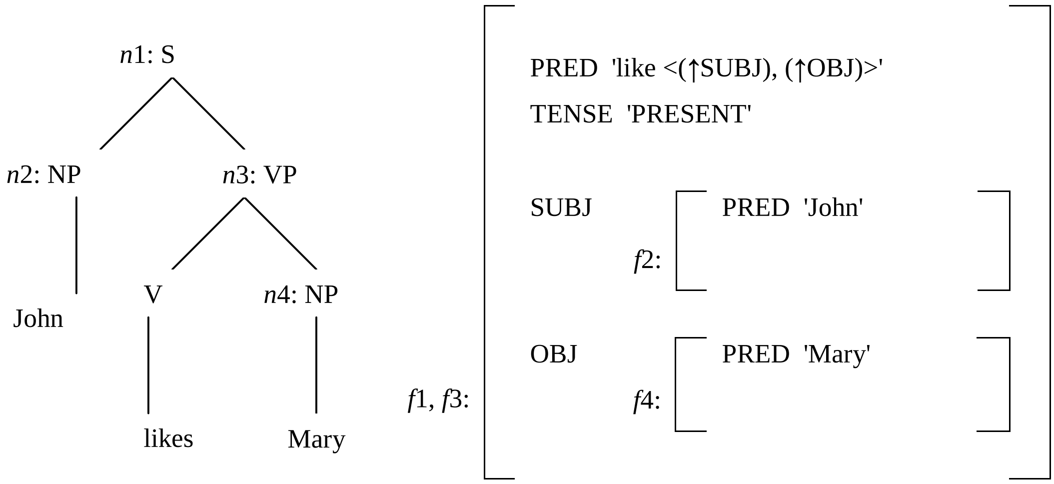

Figure 3-1: Correspondence between c-structure and f-structure

The correspondence function ϕ maps arguments *n* in the c-structure to features *f* in the f-structure. Kaplan et al (1989) describe extensions to the general notion of descriptions and correspondences employed by LFG. Additional types of linguistic information can be represented by additional structure descriptions, achieved with related correspondence functions (Kaplan 1987; Halvorsen 1988; Halvorsen and Kaplan 1988). The notion of multiple levels of linguistic description is referred to as *codescription*. Kaplan et al (1989) extend this notion further, proposing a correspondence function τ that maps an SL f-structure to a TL f-structure.

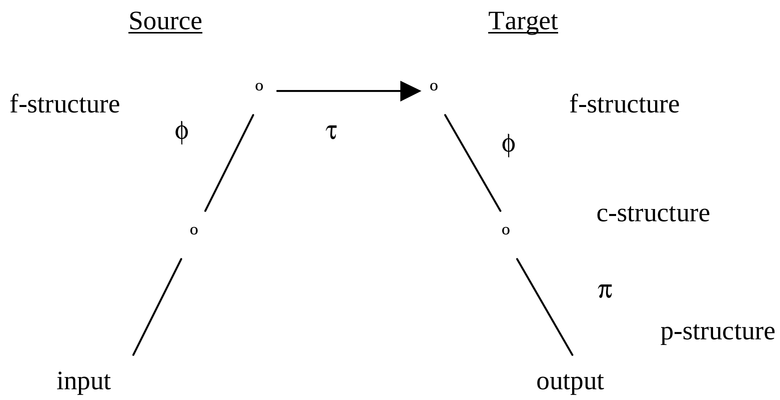

Figure 3-2: Correspondence architecture

The correspondence architecture permits defining SL and TL relations in terms of LFG expressions such as (τ (↑ SUBJ)) = ((τ ↑) SUBJ), mapping the SL subject to the TL subject. Kaplan et al (1989) propose a transfer lexicon that encodes these expressions. They give the example entry to relate the German verb *beantworten* to the French verb *répondre*.

3-2 a. German lexicon

beantworten : V (↑ PRED) = 'beantworten <(↑ SUBJ), (↑ OBJ)>'

b. French lexicon

répondre: V (↑ PRED) = ' répondre <(↑ SUBJ), (↑ AOBJ)>'

c. German – French Transfer lexicon

beantworten: V (↑ PRED) = 'beantworten <SUBJ, OBJ>'

((τ ↑) PRED) = 'répondre<SUBJ, AOBJ OBJ>'

(τ (↑ SUBJ)) = ((τ ↑) SUBJ)

(τ (↑ OBJ)) = ((τ ↑) AOBJ OBJ)

Given the transfer lexicon in (3-2.c) (and appropriate correspondence rules for *Student, étudiant* and *Frage, question*), τ will convert the f-structure in (3-3.a) into (3-3.b).

3-3 a.

$$f1: \left[\begin{array}{ll} \text{PRED} & \text{'beantworten <(}\uparrow\text{ SUBJ), (}\uparrow\text{ OBJ)>'} \\ \text{TENSE} & \text{'PRESENT'} \\ \text{SUBJ} & f2: \left[\begin{array}{ll} \text{PRED} & \text{'Student'} \end{array}\right] \\ \text{OBJ} & f3: \left[\begin{array}{ll} \text{PRED} & \text{'Frage'} \end{array}\right] \end{array}\right]$$

b.

$$\tau1: \left[\begin{array}{ll} \text{PRED} & \text{'répondre <(}\uparrow\text{ SUBJ), (}\uparrow\text{ AOBJ)>'} \\ \text{TENSE} & \text{'PRESENT'} \\ \text{SUBJ} & \tau2: \left[\begin{array}{ll} \text{PRED} & \text{'étudiant'} \end{array}\right] \\ \text{AOBJ} & \left[\begin{array}{ll} \text{PRED} & \text{'á <(}\uparrow\text{ OBJ)>'} \\ \text{OBJ} & \tau3: \left[\begin{array}{ll} \text{PRED} & \text{'question'} \end{array}\right] \end{array}\right] \end{array}\right]$$

3.3.2.2 Application of the transfer architecture

Transfer begins with an LFG f-structure representing an English expression. SL lexical elements are replaced with TL lexical elements, by making a selection from the transfer lexicon as described in Section 3.3.1. Then, the transfer correspondence function τ maps the SL f-structure to a TL f-structure, using τ expressions from the transfer lexicon to map grammatical functions, as described above.

An f-structure is a collection of attribute value pairs. A value may be an atom, or it may be another f-structure. Transfer will process each attribute/value pair in turn. If the value is atomic, transfer will perform lexical selection and generate the target structure through the application of the correspondence function τ. If the value is an f-structure, the algorithm will process the f-structure recursively until all embedded f-structures have been handled. When the matrix f-structure is complete, transfer terminates and generation from the TL f-structure begins.

In performing mapping, there are three types of changes that transfer can make to the TL f-structure: add new grammatical functions, modify existing grammatical functions, or delete existing grammatical functions.

3.3.2.2.1 Adding grammatical functions

In some cases, an SL lexical element does not map directly to a TL lexical element. In this case, additional arguments may be specified for the TL lexical element in the transfer lexicon. For example, the English words *enroll* and *enlist* have no direct correlates in ASL. They map to the ASL term *JOIN*, with the added arguments of *ORGANIZATION* and *MILITARY*, respectively.

3-4 a. join: V (↑ PRED) = 'join<SUBJ, OBJ>'
((τ ↑) PRED) = 'JOIN<SUBJ, OBJ>'
(τ (↑ SUBJ)) = ((τ ↑) SUBJ)
(τ (↑ OBJ)) = ((τ ↑) OBJ)

b. enroll: V (↑ PRED) = 'enroll<SUBJ>'
((τ ↑) PRED) = 'JOIN<SUBJ, OBJ>'
(τ (↑ SUBJ)) = ((τ ↑) SUBJ)
'ORGANIZATION' = ((τ ↑) OBJ)

c. enlist: V (↑ PRED) = 'enlist<SUBJ>'
((τ ↑) PRED) = 'JOIN<SUBJ, OBJ>'
(τ (↑ SUBJ)) = ((τ ↑) SUBJ)
'MILITARY' = ((τ ↑) OBJ)

The sentence *John will enroll tomorrow* is given the English f-structure shown below:

3-5 a.

$$
f1: \left[\begin{array}{ll}
\text{PRED} & \text{'enroll <(}\uparrow\text{ SUBJ)>'} \\
\text{TENSE} & \text{'FUTURE'} \\
\text{ADJUNCTS} & \{\text{'tomorrow'}\} \\
\text{SUBJ} \\ f2: & \left[\begin{array}{l} \text{PRED 'John'} \\ \\ \end{array}\right]
\end{array}\right]
$$

Given the input of 'enroll <(↑ SUBJ)>', the transfer lexicon will return for ASL the lexical element *JOIN*, with the added expressions '(τ (↑ SUBJ)) = ((τ ↑) SUBJ)' and 'ORGANIZATION' = ((τ ↑) OBJ).' The resulting ASL f-structure is:

b.

$$
\tau1: \left[\begin{array}{ll}
\text{PRED} & \text{'JOIN'} \\
\text{TENSE} & \text{'FUTURE'} \\
\text{ADJUNCTS} & \{\text{'TOMORROW'}\} \\
\text{SUBJ} \\ \tau2: & \left[\begin{array}{l} \text{PRED 'JOHN'} \\ \\ \end{array}\right] \\
\text{OBJ} \\ \tau3: & \left[\begin{array}{l} \text{PRED ' ORGANIZATION '} \\ \end{array}\right]
\end{array}\right]
$$

3.3.2.2.2 Changing grammatical functions

SL and TL grammatical functions are not always expressed in the same way. During transfer, SL grammatical functions may be altered to create an appropriate TL representation.

For example, the English verb *go* uses a prepositional phrase to represent a locative argument: *go <u>to</u> the store*. In ASL, the sign *GO* takes a locative argument as the direct object: *GO STORE*. This variation is represented in the transfer lexicon as shown here:

3-6 go: V $(\uparrow \text{PRED}) = \text{'go<SUBJ, TO OBJ>'}$

$$((\tau \uparrow)\ \text{PRED}) = \text{'GO<SUBJ,OBJ>'}$$
$$(\tau\ (\uparrow \text{SUBJ})) = ((\tau \uparrow)\ \text{SUBJ})$$
$$(\tau\ (\uparrow \text{TO OBJ})) = ((\tau \uparrow)\ \text{OBJ})$$

For the sentence *I go to the store*, given a (simplified) SL f-structure like (3-7.a), transfer will create the TL f-structure in (3-7.b).

3-7 a.

$$f1: \left[\begin{array}{ll} \text{PRED} & \text{'go <}(\uparrow \text{SUBJ}), (\uparrow \text{TO OBJ})\text{>'} \\ \text{SUBJ} & \left[\begin{array}{l} \text{PRED 'I'} \\ \text{PERSON } 1 \end{array} \right] \\ f'2: & \\ \text{TO} & \left[\begin{array}{ll} \text{OBJ} & f3: \left[\text{PRED 'store'} \right] \end{array} \right] \end{array} \right]$$

b.

$$\tau 1: \left[\begin{array}{ll} \text{PRED} = \text{'GO <}(\uparrow \text{SUBJ}), (\uparrow \text{OBJ})\text{>'} & \\ \text{SUBJ} & \left[\begin{array}{l} \text{PRED 'IX-PRO'} \\ \text{PERSON } 1 \end{array} \right] \\ \tau 2: & \\ \text{OBJ} & \tau 3: \left[\text{PRED 'STORE'} \right] \end{array} \right]$$

3.3.2.2.3 Deleting grammatical functions

In some cases, a grammatical function that exists in the SL f-structure will be removed from the TL f-structure. An example of this is when the lexical element in the SL f-structure maps to a better, more appropriate ASL lexical element. This is the reverse case of adding grammatical functions, as described in Section 3.3.2.1.

For example, the English sentence *I climb the ladder* would result in the ASL sentence *IX-PRO CLIMB-LADDER*. The SL argument *the ladder* is removed from the TL f-structure. The transfer lexicon is encoded as follows:

3-8 a. climb: V (↑ PRED) = 'climb<SUBJ, OBJ>'
((τ ↑) PRED) = 'CLIMB<SUBJ, OBJ>'
(τ (↑ SUBJ)) = ((τ ↑) SUBJ)
(τ (↑ OBJ)) = ((τ ↑) OBJ)

b. climb: V (↑ PRED) = 'climb<SUBJ, OBJ>'
((τ ↑) PRED) = 'CLIMB-LADDER<SUBJ>'
(τ (↑ SUBJ)) = ((τ ↑) SUBJ)
(τ (↑ OBJ)) = 'ladder'

During lexical selection, these are treated as synonymous terms, and will be resolved through translator interaction as discussed in Section 3.3.1. Correct selection of the entry for CLIMB-LADDER will result in the following SL and TL f-structures:

3-9 a.

$$f1: \left[\begin{array}{ll} \text{PRED} & \text{'climb <}(\uparrow \text{SUBJ}), (\uparrow \text{OBJ})\text{> '} \\ \text{SUBJ} & \\ f2: & \left[\begin{array}{l} \text{PRED 'I'} \\ \text{PERSON 1} \end{array}\right] \\ \text{OBJ} & \\ & f3: \left[\begin{array}{l} \text{PRED 'ladder'} \end{array}\right] \end{array}\right]$$

b.

$$\tau 1: \left[\begin{array}{ll} \text{PRED} & \text{'CLIMB-LADDER <}(\uparrow \text{SUBJ})\text{> '} \\ \text{SUBJ} & \\ \tau 2: & \left[\begin{array}{l} \text{PRED 'IX-PRO'} \\ \text{PERSON 1} \end{array}\right] \end{array}\right]$$

3.3.3 Transfer Grammaticality

It is necessary to ensure that the ASL f-structure created by τ is grammatical. As described in Section 1.3, grammaticality is defined in terms of completeness and coherence.

1-3. *Definitions of completeness and coherence*

c. An f-structure is *locally complete* if and only if it contains all the governable grammatical functions that its predicate governs. An f-structure is *complete* if and only if it and all its subsidiary f-structures are locally complete.

d. An f-structure is *locally coherent* if and only if all the governable grammatical functions that it contains are governed by a local predicate. An f-structure is *coherent* if and only if it and all its subsidiary f-structures are locally coherent.

1-4. *Grammaticality condition*

A string is grammatical only if it is assigned a complete and coherent f-structure.

Under certain conditions the TL f-structure could become ungrammatical. If a SL PRED contains grammatical functions that are not used by the TL PRED, the TL f-structure may be incoherent. If the TL PRED contains grammatical functions that are not a part of the SL PRED, the TL f-structure may be incomplete. In order to prevent this from occurring, constraints must be placed upon the transfer lexicon. That is, τ expressions in the transfer lexicon must be complete and coherent in order to ensure the TL f-structure is complete and coherent as well.

Given an SL PRED *A<SUBJ>* and a TL PRED *B<SUBJ, OBJ>*, the following τ expressions are incomplete:

3-10 A: V ($\uparrow$ PRED) = 'A<SUBJ>'
((τ $\uparrow$) PRED FN) = 'B<SUBJ, OBJ>'
(τ ($\uparrow$ SUBJ)) = ((τ $\uparrow$) SUBJ)

These τ expressions will create an incomplete TL f-structure: *B* will govern the grammatical function *OBJ* that will not be contained in the f-structure.

Given an SL PRED *A<SUBJ, OBJ>* and a TL PRED *B<SUBJ>*, the following τ expressions are incoherent:

3-11 A: V $(\uparrow \text{PRED}) = \text{'A<SUBJ, OBJ>'}$

$((\tau \uparrow) \text{ PRED FN}) = \text{'B<SUBJ>'}$

$(\tau (\uparrow \text{SUBJ})) = ((\tau \uparrow) \text{ SUBJ})$

$(\tau (\uparrow \text{OBJ})) = ((\tau \uparrow) \text{ OBJ})$

These τ expressions will create an incoherent TL f-structure: the f-structure will contain the grammatical function *OBJ* that is not governed by the predicate *B*.

The LFG notions of completeness and coherence can be extended to apply the necessary constraints on the transfer lexicon. To prevent ungrammatical TL f-structures from being created by τ, requirements of τ completeness and τ coherence are imposed in the system:

3-12. *Definitions of τ completeness and τ coherence*

a. An entry in the transfer lexicon is τ *complete* if and only if it contains all of the governable SL grammatical functions that the SL predicate governs and all of the governable TL grammatical functions that the TL predicate governs.

b. An entry in the transfer lexicon is τ *coherent* if an only if all of the governable SL grammatical functions that it contains are governed by the SL predicate and all of the governable TL grammatical functions that it contains are governed by the TL predicate.

The conditions in (3-12) ensure that each side of the mapping in the transfer lexicon is complete and coherent. Note that the conditions are sufficiently weak to allow for divergences (Section 3.5). For example, in the case of *GO*, the transfer rules shown in (3-6) contain different arguments in the SL and TL.

3-6 go: V (↑ PRED) = 'go<SUBJ, TO OBJ>'

((τ ↑) PRED) = 'GO<SUBJ, OBJ>'

(τ (↑ SUBJ)) = ((τ ↑) SUBJ)

(τ (↑ TO OBJ)) = ((τ ↑) OBJ)

3.4 Generation

The generation function takes an ASL f-structure and creates a c-structure, using the LFG correspondence functions ϕ' (f-structure to c-structure) and π (c-structure to p-structure). This section will describe the mechanics of this operation. In addition to the straightforward application of LFG correspondences and multiple levels of syntactic representation, generation must also account for non-manual signals and spatial-grammatical information in ASL, as described in Chapter 2.

3.4.1 From c-structure to f-structure

Following Kaplan et al (1989) and others, the ASL f-structure is taken as input to the generation function. The first task of generation is to create an ASL c-structure, establishing the linear precedence and dominance relations of the output. Many authors describe this process in terms of the correspondence function ϕ (e.g., Kaplan et al 1989, Amores 1992, Amores and Quesada 1996, Frank 1999, Way 1999). However, as described in Kaplan and Bresnan (1982) the mechanics of ϕ are stated in very precise terms, as a process that creates an f-structure from a set of feature descriptions, these f-descriptions created from the c-structure. Creating a c-structure from a f-structure is a different process. This reverse process cannot simply be the reverse of ϕ, or ϕ^{-1}. Because ϕ can be many-to-one, ϕ^{-1} can be one-to-many; given an f-structure *f* it is not necessarily clear what the target c-structure node *n* would be. That ϕ generates a c-structure from an f-structure using the grammar rules of the target language is tacit in works such as those cited above. In order to distinguish the c- to f-structure correspondence of analysis from the f- to c-structure correspondence of generation, here I will label the latter process ϕ'.

From a computational perspective, ϕ' is implemented in *ASL Workbench* as a top-down, depth-first process. During generation, spatial information will be obtained for arguments in the discourse. New arguments will be added to the discourse element list, with focal sites provided by the translator where necessary. This spatial data will be added to the c-structure, and made available to the phonetic representation.

As an illustration of this process, the f-structure for the sentence *BOY SEE GIRL "the boy sees the girl"* will be converted to a c-structure using the ϕ' correspondence function[12].

3-13

$$\tau1, \tau3: \left[\begin{array}{ll} \text{PRED 'SEE <(}\uparrow\text{ SUBJ), (}\uparrow\text{ OBJ)>'} & \\ \text{TENSE 'PRESENT'} & \\ \text{SUBJ } \tau2: & \left[\begin{array}{l} \text{PRED 'BOY'} \\ \text{NUM SG} \end{array} \right] \\ \text{OBJ } \tau3: & \left[\begin{array}{l} \text{PRED 'GIRL'} \\ \text{NUM SG} \end{array} \right] \end{array} \right]$$

The relevant phrase structure rules for the f-structure in (3-13) are shown below:

3-14	a.	S	$\rightarrow$	NP	VP
				$(\uparrow \text{SUBJ}) = \downarrow$	$\uparrow = \downarrow$
	b.	VP	$\rightarrow$	V	NP
					$(\uparrow \text{OBJ}) = \downarrow$
	c.	NP	$\rightarrow$	(Det)	N

[12] Because the translation system does not maintain a discourse model, it does not attempt to determine the type of r-expressions in the sentence. This limitation is not intrinsic to the approach, but rather is an artifact of the limited focus of the dissertation.

Generation will begin with the first phrase structure rule, S → NP VP, and build this tree. The S node will receive the variable *n*1, the correspondence of the first f-structure variable, τ1. The NP node contains the expression (↑ SUBJ) = ↓, which can be read, "the mother's SUBJ is the current node." The SUBJ role will be taken from the τ1 f-structure and built as the NP node, assigning in the variable *n*2, corresponding to τ2 from the f-structure. Taking the NP rule NP → (Det) N, ϕ' looks for a Det in τ2 but doesn't find one. Since Det is optional, the rule continues to the N node. ϕ' will look for a PRED in the τ2 f-structure, and check the lexical entry for that PRED to ensure that it is the same syntactic category as the current node, N, which will match the entry for BOY. The schemata of the lexical entry for BOY will be added to the current node, and the N node will terminate with the lexical entry for BOY.

When the lexical element BOY is retrieved from the lexicon, *ASL Workbench* will prompt the translator to either identify this r-expression with an existing discourse element, or create a new discourse element. This interaction is prompted for every nominal PRED encountered during ϕ'. The translator can at this time supply a Focal Site for this expression, or leave it blank. The Focal Site is added to the current node, as the expression (↓ FS) = 'fs', where 'fs' is the Focal Site for the current element. For instance, if BOY is associated with the Focal Site 'p2AB', the expression is instantiated as (↓ FS) = 'p2AB.'

Returning to the S rule, ϕ' will access the expression for the VP node, ↑ = ↓, or "the f-structure of the current node's parent is equal to the f-structure of the current node." This equivalence expression causes ϕ' to look for a second variable assignment to the current f-structure, which is τ3. ϕ' will build the VP tree as the child of S, and assign it the variable *n*3 using the f-structure τ3 and the expression ↑ = ↓ from the phrase structure rule. Following the remaining phrase structure rules to completion, the following c-structure is generated:

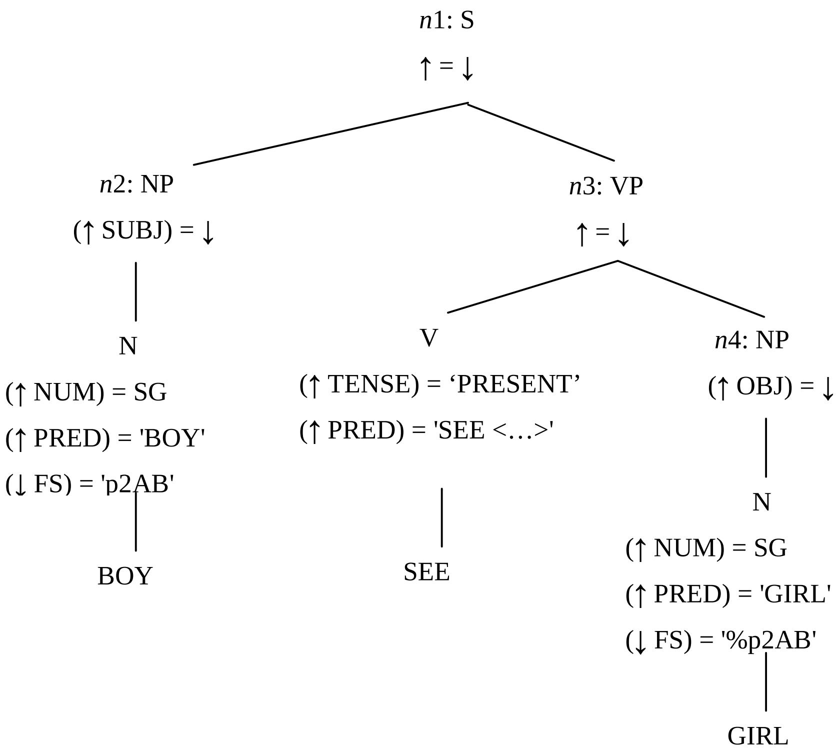

Figure 3-3: Generated c-structure

3.4.2 From c-structure to p-structure

The final step in generation is to build the phonetic structure (p-structure) from the c-structure. The p-structure is built using the phonetic notation system described in Section 2.2, the MH model. To generate the p-structure from the c-structure, an additional correspondence function is defined, **π**. **π** builds the p-structure using the MH notation for lexical elements obtained from the lexicon. In addition, **π** must account for phonological processes, spatial information, and non-manual signals.

The notion of adding a phonetic level of structural description to the codescription and correspondence architecture of LFG is not novel. Butt and King (1998) describe just such an approach for spoken languages, mapping from c-structure to p-structure. The present approach differs in that the features of p-structure, encoded in terms of Liddell and Johnson (1989), are particular to signed languages.

The c-structure represents a linear ordering of lexical elements. π will build the p-structure in a three-step process: (1) for each lexical element (following the linear precedence established in the c-structure), obtain the phonetic features for the lexical element, and add them to the p-structure (applying phonological processes); (2) if the phonetic features contain empty features for agreement, instantiate the empty features from the c-structure using the following equation: (* GF) = (*M*(*) GF FS); and (3) assign non-manual signals.

In the first step, the sequence of segments from the current lexical element will be added to the p-structure. If a sign already exists in the p-structure, apply phonological processes between the signs (Section 2.2.2.1).

In the second step, check the sign's segments for the existence of empty features. Each feature has a name that corresponds to the grammatical function of the argument that contains the required Focal Site features. For example, the predicate 'SEE <(↑ SUBJ), (↑ OBJ)>' has an empty feature OBJ in the final Placement Focal Site. For that feature, construct the equation (* OBJ) = (*M*(*) OBJ FS). This is read, "the current node's OBJ feature is equal to the mother of the current node's OBJ's FS feature." Note, the general equation (* GF) = (*M*(*) GF FS) does not make use of the LFG metavariables ↑ and ↓; these refer to the related f-structures, which do not contain the required information. In the c-structure in Figure 3-3, the function *M*(V) refers to the VP node, and (*M*(V) OBJ) refers to the object NP node, "GIRL." (*M*(V) OBJ FS) returns the value "%p2AB", or the Focal Site associated with the object noun. This Focal Site is assigned to the verb's empty OBJ Focal Site, indicated by the empty feature OBJ in the sign notation. This process is repeated until all empty features in the notation are assigned values.

In the third step, non-manual signals are generated. If the sign has a lexical NMS (such as "pah" or "have-to"), the NMS occurs over the lexical element. These NMSs are phonetic, and appear in the sign's notation; they are not syntactic, and so do not occur in the c-structure. For syntactic NMSs (those that appear in the c-structure), the scope of (* NMS) (the current node's NMS) occurs over all nodes dominated by *M*(*).

The results of the application of the π correspondence function on the c-structure in Figure 3-3 are shown in Table 3-2. Unused features have been removed for brevity.

BOY			#	SEE			#	GIRL		
H	M	X	M	X	M	X	M	X	M	H
	str		str				str		str	
								t		
o^1234^		o^c1234^		n-12+v				u^1234-		
RA				TIFI				RATH		
[at]		[ant]		[at]				[at]		[ant]
TH				EY				eJW		
						TIFI				
						[points to]				
						%p2AB				
[pro]				[sup]						

Table 3-2: Example p-structure

3.4.3 Generation Grammaticality

The notions of completeness and coherence that determine grammaticality in LFG are conditions on f-structures. In the context of translation, it is also necessary to make statements about the grammaticality of the generated c-structures, and in this case, the generated p-structures. To prevent the grammar from creating ungrammatical c-structures, requirements of ϕ' grammaticality are defined as such:

3-15. *Definitions of* ϕ' *completeness and* ϕ' *coherence*

a. A c-structure is ϕ' *complete* if and only if all of the non-empty grammatical functions in the f-structure are related to grammatical functions in the c-structure by ϕ'.

b. A c-structure is ϕ' *coherent* if and only if all grammatical functions in the c-structure are related to grammatical functions in the f-structure by ϕ'.

The rule stated in (3-15.a) prevents the grammar from leaving non-empty elements in the f-structure unaccounted for in the c-structure. The rule stated in (3-15.b) prevents the grammar from attempting to create c-structure branches that do not have any corresponding elements in the f-structure.

Similarly, conditions on grammaticality must be imposed upon generated p-structures. To prevent the grammar from generating ungrammatical p-structures, requirements of π completeness and π coherence are introduced.

3-16. *Definitions of* π *completeness and* π *coherence*

a. A p-structure is π *complete* if an only if all the lexical elements in the c-structure are related to lexical elements in the p-structure by π; and, all grammatical function variables in the p-structure are instantiated with values.

b. A p-structure is π *coherent* if and only if all of the lexical elements in the p-structure are related to lexical elements in the c-structure by π.

As noted above, the process of replacing empty features in p-structure notations must continue until all empty features are instantiated with values. The rule of π completeness formalizes this requirement.

The grammaticality condition stated in (1-4) can be extended to cover ϕ' and π.

3-17. *Grammaticality Condition (revised)*

A translated string is grammatical if and only if it is assigned a complete and coherent f-structure, a ϕ' complete and ϕ' coherent c-structure, and a π complete and π coherent p-structure.

3.5 Divergences

Divergence in a machine translation system refers to differences between input and output forms that must be accounted for (Dorr et al 1994, Dorr 1994). Dorr (1994) provides in inventory of divergence types, while developing a framework for accounting for them during translation. While the mechanics of responding to divergences in the ASL MT system may differ from Dorr's framework, the description of divergence categories will be used to describe divergences that are specific to the case of translation from English to ASL.

3-18. Thematic divergence. The grammatical functions and thematic roles of arguments are different between SL and TL. For example, while English has both *borrow* and *lend*, ASL has the single sign BORROW which is used in both cases.

a. You borrow from me / I lend to you.

b. (IX-PRO.1_i) $_i$BORROW$_j$ (IX-PRO.2_j).

One way to account for this type of divergence is to include two different lexical elements in ASL, one for BORROW and one for LEND. The difference between these two lexical elements would be in the encoding of subject and object Focal Sites. However, this ignores the fact that these really are the same lexical element.[13]

3-19. Structural divergence. This corresponds to the transfer function of modifying grammatical functions in the f-structure, discussed in Section 3.3.2.2.2. In structural divergence, an SL grammatical function is realized as a different grammatical function in the TL.

a. John goes [to the store]$_{PP}$

b. JOHN GO [STORE]$_{NP}$

3-20. Conflational divergence. In a conflational divergence, arguments or adjuncts are incorporated into the action of the verb. One type of conflational divergence between English and ASL occurs when an English verbs object is incorporated into the verb itself, as in (3-9) above.

a. John climbs the ladder.

b. JOHN CLIMB-LADDER

[13] More research needs to be done to determine whether thematic divergence is limited to inflecting verbs such as BORROW.

Another type of conflational divergence occurs when aspect is incorporated into the articulation of the verb.

c. John is regularly sick.

d. JOHN SICK $^{\text{I:Regularly}}$

3-21. Deflational divergence. This is the opposite case from conflational divergence, and is not discussed by Dorr (1994) or Dorr et al (1994). This corresponds to the case of adding grammatical functions, as described in Section 3.3.2.1.

a. John will enroll tomorrow.

b. TOMORROW JOHN JOIN SCHOOL

3-22. Lexical divergence. In lexical divergence, the syntactic category of an element stays the same, but a different SL and TL lexical elements are used.

a. John goes crazy.

b. JOHN (BECOME) CRAZY

3-23. Categorial divergence[14]. This type of divergence refers to the case when the same SL and TL lexical element is used, but it is a different syntactic category.

a. I have [pity $]_{NP}$ for you.

b. (IX-PRO.1_i) [$_i$PITY$_j$ $]_{VP}$ (IX-PRO.2_j)

[14] Dorr (1994) also discusses two types of head-switching divergence, in which the syntactic category of an SL lexical element is different from the syntactic category of the TL lexical element. These include promotional head-switching divergence, in which an adverb phrase becomes a verb phrase; and demotional head-switching divergence, in which a verb phrase becomes an adverb phrase. I assume here that these are cases of categorial divergence, and do not give them separate treatment.

3.6 Conclusion

This chapter has described an approach to generating representations of ASL in a machine translation system. The correspondence architecture of LFG has been extended, following Kaplan et al (1989), with a transfer correspondence function τ, which converts an SL f-structure into a TL f-structure. To build an appropriate c-structure from the TL f-structure, a reverse correspondence function ϕ' is defined, which makes use of the TL phrase structure rules to build the syntactic tree. During ϕ', Focal Sites for grammatical functions such as SUBJ and OBJ are obtained through interaction with the translator, and added to the discourse element list and c-structure. An additional level of description is generated, a p-structure that encodes phonetic details of an utterance; the p-structure is generated using the correspondence function π. During the application of π, phonological processes are applied, and agreement features and non-manual signals are instantiated.

The use of the LFG formalism of *codescription*, or multiple levels of description for a single utterance, provides a natural approach for the representation of different kinds of grammatical information for ASL. Correspondence functions between these levels of description are defined using standard LFG expressions, simplifying the articulation of such functions and reducing the burden that would be required to motivate non-standard extensions to the LFG architecture. In particular, defining the f-structure to c-structure correspondence ϕ', a well-formed c-structure can be constructed using extant phrase-structure rules and LFG expressions. The elegance of this approach is highlighted by the observation that such a grammar becomes reversible in the context of machine translation (Frank 1999).

Many simplifying assumptions had to be made to limit the scope of this work, such as the existence of an English analysis component. Many larger issues such as discourse structure and text planning have been left out completely, but may be fruitful areas for future development.

Chapter 4 Conclusion: Future work and related issues

4.1 Future work

In order to focus on the central issues of this thesis, that is, what a representation of ASL for machine translation would look like and how it is generated, many essential but peripheral parts of the system have been excluded. This section will outline these components.

4.1.1 Analysis

The generation of ASL described in Chapter 3 begins with transfer from a hypothesized LFG f-structure of English. The English analysis component must include semantic analysis, the target of which is this LFG f-structure. In performing an analysis of English, several well-known problems in machine translation must be addressed (Dorr et al. 1998).

Syntactic ambiguity arises when a single surface string can have multiple syntactic representations. In English, this occurs in many contexts such as the location of prepositional phrases and coordination. For example:

4-1. "One morning I shot an elephant in my pajamas. How he got in my pajamas I don't know."

- Julius "Groucho" Marx

The humor in (4-1) lies in the syntactic ambiguity of the first sentence. The reader assumes *in my pajamas* is adjoined to the verb *shot*, but the second sentence makes it clear that it is adjoined to the DP *an elephant*.

In many machine translation systems it is not necessary to resolve all issues of syntactic ambiguities. Hutchins and Somers (1992) refer to this as "structure preservation," when the SL structure pre-determines the TL structure. This works when both SL and TL sentences share the same ambiguity; that is, the joke works in both languages. In ASL, however, prepositional phrases are often realized as classifier root constructions or as features of inflecting verbs, which does not share the syntactic ambiguity of English. Thus the English analysis system must resolve these ambiguities.

Lexical ambiguity arises when an SL word has homophonous meanings and the TL uses different lexical elements for at least two of these meanings. For instance, the English word *book* can refer both to the thing that you read or to the act of securing a reservation. In ASL, these are different signs (e.g., BOOK, RESERVE). The English analysis system must select the correct lexical element.

Semantic ambiguity refers to ambiguities that extend beyond syntactic and lexical ambiguities. There are different types of semantic ambiguity. Polysemy occurs when one word has different but related meanings, and at least two of these means are represented by different TL words. For example, *kill (a person)* vs. *kill (a light)*. Metonymy occurs when one has a word or phrase refers to something else (such as *the Crown* referring to lands governed by England). If the TL would use the referent rather than the SL expression, this ambiguity must be resolved by the translation system.

4-2 a. While driving, John hit a tree.

t

b. JOHN DRIVE, TREE$_a$ MOV$_a^{CL:u+12+v}$

"John was driving, the car hit a tree."

In (4-2.a), the subject of *hit* is *John*. In (4-2.b), the classifier root MOV incorporates the classifier handshape for a car (u+12+v).

Contextual ambiguity occurs when the reference of an SL constituent is ambiguous. For example, 4-3. The factories make sports cars. They are fast.

In (4-3), *they* could refer to either *the factories* or the *sports cars* they make.

Because ASL uses space to indicate agreement, such references are non-ambiguous. In the current implementation, such referential ambiguities are resolved by the translator, who must select an appropriate referent from the list of discourse elements or add a new discourse element to the list.

4.1.2 Output Representation

The current output file created by the ASL generation system is only viewable within this system. Because of this, the data is only useful to someone who understands ASL syntax in the manner presented here, and the phonetic notation of the Move-Hold model. In order to be more generally useful several different software applications could be developed to render the data in a variety of formats. In anticipation of this, the source code that describes the file format of the ASL document has been developed separately from the generation software. This approach is similar to the ASL lexicon, which is used both by the lexicon maintenance tool (*LMT*) and the generation software (*ASL Workbench*).

Several different output representations are envisioned. These include, for example, Stokoe notation (Stokoe and Croneberg 1976) and SignWriting.[15] The ultimate goal, however, is to represent utterances in the ASL document with a dynamically generated animation of an ASL signer. With this innovation, documents that are translated to ASL using *ASL Workbench* would be accessible to anyone who knows ASL (depending upon the quality of the translation and of the animation).

[15] http://www.signwriting.org/

4.2 Related Issues

This dissertation defines a computational representation of ASL, and explores the use of this representation in machine translation. There are many other interesting and useful potential applications of this representation system other than machine translation. This section will outline some of these.

4.2.1 Corpus Linguistics

A valuable source of data for linguist looking to understand some phenomenon of language is a corpus: a set of documents in that language that demonstrate real-world language use (Sinclair 1991). This differs significantly from the practice of making grammaticality judgments, often done by the linguist. Because ASL is generally not written (with notable exceptions like Sign Writing, which are not in widespread use) no such corpus exists.

Corpora are typically augmented with linguistic data that are of use to linguists. This can include part-of-speech tagging, identification of constituent structures, anaphoric reference resolution, etc. A variety of software applications read this data and present it in a way that is useful to the linguist. An example of one is a concordancer, which finds instances of selected words and shows the surrounding context (referred to as a "key word in context" (KWIC) concordance).

Valuable enhancements to the ASL document generated by *ASL Workbench* would be to allow for the encoding of tags (such as parts of speech and constituent structure), and software to search and display these tags, show a concordance, word frequency counts, etc.

4.2.2 Gloss Standardization

It is a convention in linguistic work on ASL to represent ASL signs and utterances as upper case English words, called glosses. The details of this convention are not independently defined, and so many researchers redefine the convention to their specific purpose (for example, in representing spatial locations for spatial and inflecting verbs, person and number of pronouns, fingerspelled words, etc.). Non-manual signals are typically represented with lines above the utterance to indicate the scope and a label to indicate which NMS is being used. But even here there is variation: some researchers put the label to the right and others to the left; some use dotted lines to indicate optional spreading, etc.

Furthermore, unless the author describes a sign in detail a chosen gloss may in fact be ambiguous between multiple signs. While providing glosses is widely accepted (and will probably continue due to the relative convenience), it is a painfully imprecise method for encoding linguistic detail.

The Move-Hold model of Liddell and Johnson (1989) could do much to address these limitations. A gloss can be related to a phonetic transcription of the sign in question, making it clear which sign is intended (as is done in this dissertation). I believe one reason the Move-Hold model has not received widespread adoption is its necessary complexity. There are a great many features, and it can be difficult or cumbersome to use and display.

Software such as the ASL Lexicon Maintenance Tool (*ASL-LMT*) (Speers 1988) can help the situation. First, it can lower the barrier to adoption of MH by relieving the user of the burden of remembering all of the various features and their meanings. Dialog boxes show lists of available features and their descriptions, making it easier to use the system correctly.

Second, a core set of ASL signs can be made publicly available, along with the software, which can be cross-referenced by others. A researcher using glosses can either refer to pre-existing glosses, or can use the software to create their own notations. The gloss lexicon can be made publicly available and shared so that readers can easily view phonetic transcriptions of the glosses. For instance, all of the signs used in this dissertation are available as a custom LMT lexicon.[16]

4.2.3 Applications

The representation and generation systems described in this research are only the first steps toward a practical machine translation system for ASL. The eventual goal is have a complete HAMT system, including SL analysis and dynamically synthesized animations of TL output. This section will hypothesize

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[16] http://www.bigfoot.com/~dspeers/cl/

about potential (non-academic) applications of such technology that can serve to reduce the burden of living in a society that largely ignores the challenges faced by Deaf people every day.

<u>Software help documents</u>.
Operating system and application software could include ASL versions of their documentation.

<u>Web pages</u>.
Web sites such as news sites, online catalogs, research reports, customer service centers, etc., could provide information in ASL for Deaf visitors.

<u>E-books</u>.
The ASL equivalent of books on tape.

<u>Automatic Teller Machines (ATMs)</u>.
Bank machines could offer instructions, information about bank services, personal account details, error messages, etc., to Deaf users.

<u>Information Kiosks</u>.
In locations such as airports, museums, tourist attractions, etc., ASL versions of information could be made available for Deaf visitors.

<u>Personal assistants</u>.
Software applications like Microsoft Agent demonstrate the utility (and entertainment value) of interacting with your computer in a more natural way. An agent character that speaks ASL would make this technology available to Deaf users.

Classroom instruction / distance learning.

Teachers who don't speak ASL who nonetheless must prepare lectures for Deaf students could prepare ASL versions of the lectures for the students. Another educational application might include distance learning, where materials are prepared ahead of time and distributed over the Internet.

Alternative to Closed Captioning.

Closed captioning, while making television broadcasts and movies more accessible to Deaf viewers, does not present information in what is the native language for many Deaf people. Dynamically generated animations of ASL signers could be made available as alternatives to closed captioning, more cheaply than hiring and videotaping an ASL interpreter.

Relay.

When a Deaf and hearing person need to communicate over the telephone, one option they have is to use the relay, in which a hearing operator with a TTY intermediates. With real time translation, the relay could be replaced with Internet chat, where text is translated to ASL for the Deaf user.

E-mail.

Email is the asynchronous equivalent of Internet chat.

Test instructions and questions.

When a clear understanding of test instructions and questions is important, such as when getting a driver's license, Deaf people may be at a disadvantage. Providing ASL versions of instructions and questions may temper these everyday challenges.

Appendix A Sample Sign Notations

This appendix contains MH notations for a number of signs referenced within the text above.

B-1: ASK

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	n-1+		n-1"
	Hand Site	BKFI		
	Sprel	[at]		[ant]
	Focal Site	MO		
PL-B	Hand Site			TIFI
	Sprel			[points to]
	Focal Site			OBJ
Rotation	Rot	╥		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

Additional Notes:

Only object agreement.

B-2: BUSY

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow		[touch]	
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	b-1234+		
	Hand Site	BA		
	Sprel	TI →		BA →
	Focal Site	RA		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	╖		
	Wrist Extension	[+ext]		
	Wrist Abduction			
Weak PL-A	Hand Configuration	b-1234+		
	Hand Site	HAND		
	Sprel	[at]		
	Focal Site	m0CH		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	╖		
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	+
	Recip	-
	Redup	+
	Sym	-

Additional Notes:

B-3: COW

SKEL	Timing Unit	H	M	H
	Contour		[-path]	
	Flow	[touch]	[touch]	[touch]
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	u+4+v		
	Hand Site	TITH		
	Sprel	[at]		
	Focal Site	TM		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	ㅠ		F
	Wrist Extension	[+flx]		[+ext]
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

<u>Additional Notes:</u>

B-4: CHOCOLATE

SKEL	Timing Unit	H	M	X	M	H
	Contour		[arc]		[arc]	
	Flow		[+ipsi]		[-ipsi]	
	Touch	[touch]	[touch]	[touch]	[touch]	[touch]
	T-Quality					
	M-Quality					
	Local Movement					
Strong PL-A	Hand Configuration	o"1234"o				
	Hand Site	ULTH				
	Sprel	[at]		UL →		[at]
	Focal Site	BK				
PL-B	Hand Site					
	Sprel					
	Focal Site					
Rotation	Rot	ㅠ				
	Wrist Extension	[+ext]				
	Wrist Abduction					
Weak PL-A	Hand Configuration	b-1234+				
	Hand Site	HAND				
	Sprel	[at]				
	Focal Site	m0CH				
PL-B	Hand Site					
	Sprel					
	Focal Site					
Rotation	Rot	ㅠ				
	Wrist Extension					
	Wrist Abduction					
NMS	NMS					

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	+
	Sym	-

Additional Notes:

B-5: DEAF

SKEL	Timing Unit	H	M	X	M	X	M	H
	Contour		[str]		[str]		[str]	
	Flow			[touch]				[touch]
	Touch							
	T-Quality							
	M-Quality							
	Local Movement							
Strong PL-A	Hand Configuration	n-1+						
	Hand Site	RAFI						
	Sprel	[ant]		[at]		[ant]		[at]
	Focal Site	CK				JW		
PL-B	Hand Site							
	Sprel							
	Focal Site							
Rotation	Rot	ㅠ						
	Wrist Extension	[+ext]						
	Wrist Abduction							
Weak PL-A	Hand Configuration							
	Hand Site							
	Sprel							
	Focal Site							
PL-B	Hand Site							
	Sprel							
	Focal Site							
Rotation	Rot							
	Wrist Extension							
	Wrist Abduction							
NMS	NMS							

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

<u>Additional Notes:</u>

Subject to metathesis.

B-6: EAT

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			[touch]
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	o^c1234^		
	Hand Site	TIFI		
	Sprel	[ant]		[at]
	Focal Site	CN		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	ᒪ		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

Additional Notes:

B-7: GIVE

SKEL	Timing Unit	H	M	H
	Contour		[arc]	
	Flow		[sup]	
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	CL:SASS		
	Hand Site	HAND		
	Sprel	[at]		
	Focal Site	SUBJ		OBJ
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	ᒪ		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

Additional Notes:

B-8: HATE

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	o^c8^		o^8^
	Hand Site	TIFI		
	Sprel	[at]		[ant]
	Focal Site	SUBJ		
PL-B	Hand Site	PA		
	Sprel	[points to]		
	Focal Site	OBJ		
Rotation	Rot	Ш		
	Wrist Extension	[+ext]		
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	+

Additional Notes:

Subject is in Placement, object is in Facing.

B-9: HELP

SKEL	Timing Unit	H	M	H
	Contour		[arc]	
	Flow		[+sup]	
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	u+1234-		
	Hand Site	UL		
	Sprel	[at]		
	Focal Site	PA		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	Ⅎ		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration	u-1234+		
	Hand Site	HAND		
	Sprel	[at]		
	Focal Site	SUBJ		OBJ
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

<u>Additional Notes:</u>

Subject in Weak PL-A Focal Site [1],

Object in Weak PL-A Focal Site [-1]

B-10: INTERPRET

SKEL	Timing Unit	H	M	H
	Contour		[-path]	
	Flow			
	Touch	[touch]	[touch]	[touch]
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	o^c9^		
	Hand Site	TIFI		
	Sprel	[at]		
	Focal Site	m0CH		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	ᅲ		Ⅎ
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	+
	Redup	+
	Sym	+

Additional Notes:

B-11: MOTHER

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			[touch]
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	u+1234+v		
	Hand Site	TITH		
	Sprel	[ant]		[at]
	Focal Site	CN		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	ㅠ		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	+
	Sym	-

<u>Additional Notes:</u>

B-12: PUT

SKEL	Timing Unit	H	M	H
	Contour		[arc]	
	Flow		[+sup]	
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	CL:SASS		
	Hand Site	HAND		
	Sprel	[at]		
	Focal Site	LOC		LOC
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	ㅠ		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

<u>Additional Notes:</u>

Locative verb, doesn't include subject/object agreement.

B-13: SAY-NO-TO

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	o+12^		o+c12^
	Hand Site	TIFI		
	Sprel	[ant]		[at]
	Focal Site	OBJ		
PL-B	Hand Site	BK		
	Sprel	[points to]		
	Focal Site	SUBJ		
Rotation	Rot	ㅠ		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

<u>Additional Notes:</u>

Subject in Strong Facing Focal Site [1]

Object in Strong Placement Focal Site [1]

Note: [ant] => [at] won't work when the subject is not IX-PRO.1.

B-14: SEE

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	n-12+v		
	Hand Site	TIFI		
	Sprel	[at]		[ant]
	Focal Site	EY		
PL-B	Hand Site			TIFI
	Sprel			[points to]
	Focal Site			OBJ
Rotation	Rot	F		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

Additional Notes:

Object agreement in Placement-B.

B-15: SICK

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			
	Touch			+
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	u+8"º		
	Hand Site	TIFI		
	Sprel	[ant]		[at]
	Focal Site	FH		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	Ⅎ		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration	u+8"º		
	Hand Site	TIFI		
	Sprel	[ant]		[at]
	Focal Site	ST		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	Ⅎ		
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

<u>Additional Notes:</u>

B-16: SICK Continuative

SKEL	Timing Unit	H	M	X	M	X	M	H
	Contour		[arc]		[arc]		[arc]	
	Flow		[+sup]		[-sup]		[+sup]	
	Touch							
	T-Quality							
	M-Quality							
	Local Movement							
Strong PL-A	Hand Configuration	u+8"º						
	Hand Site	TIFI						
	Sprel	[ant]		[at]		[ant]		[at]
	Focal Site	FH						
PL-B	Hand Site							
	Sprel							
	Focal Site							
Rotation	Rot	Ⅎ						
	Wrist Extension							
	Wrist Abduction							
Weak PL-A	Hand Configuration	u+8"º						
	Hand Site	TIFI						
	Sprel	[ant]		[at]		[ant]		[at]
	Focal Site	ST						
PL-B	Hand Site							
	Sprel							
	Focal Site							
Rotation	Rot	Ⅎ						
	Wrist Extension							
	Wrist Abduction							
NMS	NMS	cont						

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	+
	Sym	-

<u>Additional Notes:</u>

Translator will supply Flow values.

B-17: SICK Frequently

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			
	Touch			
	T-Quality			
	M-Quality		[reduced]	
	Local Movement			
Strong PL-A	Hand Configuration	u+8"º		
	Hand Site	TIFI		
	Sprel	[ant]		[at]
	Focal Site	FH		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	Ⅎ		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration	u+8"º		
	Hand Site	TIFI		
	Sprel	[ant]		[at]
	Focal Site	ST		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	Ⅎ		
	Wrist Extension			
	Wrist Abduction			
NMS	NMS	freq		

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	+
	Sym	-

Additional Notes:

B-18: SIGN

SKEL	Timing Unit	H	M	H
	Contour		[arc]	
	Flow		[-ant]	
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	n-1^		
	Hand Site	HAND		
	Sprel	[sup]		[inf]
	Focal Site	m2CH		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	⊓		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	+
	Redup	+
	Sym	+

<u>Additional Notes:</u>

B-19: STUDY

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			
	Touch			
	T-Quality			
	M-Quality			
	Local Movement		[wg]	
Strong PL-A	Hand Configuration	b^1234+v		
	Hand Site	TIFI		
	Sprel	PA->		[at]
	Focal Site	PA		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	ㅠ		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration	u+1234+		
	Hand Site	HAND		
	Sprel	[at]		
	Focal Site	p0AB		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	ㅛ		
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	+
	Sym	-

<u>Additional Notes:</u>

B-20: STUDY Continuative

SKEL	Timing Unit	H	M	H	M	H	M	H
	Contour		[arc]		[arc]		[arc]	
	Flow		[+ant]		[-ant]		[+ant]	
	Touch							
	T-Quality							
	M-Quality							
	Local Movement		[wg]				[wg]	
Strong PL-A	Hand Configuration	b^1234+v						
	Hand Site	TIFI						
	Sprel	PA->		[at]		PA->		[at]
	Focal Site	PA						
PL-B	Hand Site							
	Sprel							
	Focal Site							
Rotation	Rot	ㅠ						
	Wrist Extension							
	Wrist Abduction							
Weak PL-A	Hand Configuration	u+1234+						
	Hand Site	HAND						
	Sprel	[at]						
	Focal Site	p0AB						
PL-B	Hand Site							
	Sprel							
	Focal Site							
Rotation	Rot	ㅛ						
	Wrist Extension							
	Wrist Abduction							
NMS	NMS	cont						

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	+
	Sym	-

Additional Notes:

Translator will supply Flow values.

B-21: STUDY [Frequently]

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			
	Touch			
	T-Quality			
	M-Quality		[reduced]	
	Local Movement		[wg]	
Strong PL-A	Hand Configuration	b^1234+v		
	Hand Site	TIFI		
	Sprel	PA->		[at]
	Focal Site	PA		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	ㅠ		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration	u+1234+		
	Hand Site	HAND		
	Sprel	[at]		
	Focal Site	p0AB		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	ㅛ		
	Wrist Extension			
	Wrist Abduction			
NMS	NMS	freq		

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	+
	Sym	-

Additional Notes:

B-22: STUDY [Regularly]

SKEL	Timing Unit	H	M	X	M	X	M	H
	Contour		[str]		[str]		[str]	
	Flow							
	Touch							
	T-Quality							
	M-Quality							
	Local Movement		[wg]				[wg]	
Strong PL-A	Hand Configuration	b^1234+v						
	Hand Site	TIFI						
	Sprel	PA->		[at]		PA->		[at]
	Focal Site	PA						
PL-B	Hand Site							
	Sprel							
	Focal Site							
Rotation	Rot	┬┐						
	Wrist Extension							
	Wrist Abduction							
Weak PL-A	Hand Configuration	u+1234+						
	Hand Site	HAND						
	Sprel	[at]						
	Focal Site	p0AB						
PL-B	Hand Site							
	Sprel							
	Focal Site							
Rotation	Rot	└┴						
	Wrist Extension							
	Wrist Abduction							
NMS	NMS	reg						

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	+
	Sym	-

Additional Notes:

B-23: TELL

		H	M	H
SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow	[touch]		
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong PL-A	Hand Configuration	n-1^		
	Hand Site	TIFI		
	Sprel	[at]		[ant]
	Focal Site	CN		
PL-B	Hand Site			TIFI
	Sprel			[points to]
	Focal Site			OBJ
Rotation	Rot	F		
	Wrist Extension			
	Wrist Abduction			
Weak PL-A	Hand Configuration			
	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

Additional Notes:

B-24: THINK

SKEL	Timing Unit	H	M	H
	Contour		[str]	
	Flow			[touch]
	Touch			
	T-Quality			
	M-Quality			
	Local Movement			
Strong	Hand Configuration	n-1^		
PL-A	Hand Site	TIFI		
	Sprel	[ant]		[at]
	Focal Site	TM		
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot	F		
	Wrist Extension			
	Wrist Abduction			
Weak	Hand Configuration			
PL-A	Hand Site			
	Sprel			
	Focal Site			
PL-B	Hand Site			
	Sprel			
	Focal Site			
Rotation	Rot			
	Wrist Extension			
	Wrist Abduction			
NMS	NMS			

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

Additional Notes:

B-25: UNDERSTAND-EACH-OTHER

SKEL	Timing Unit	H	M	X	M	H
	Contour		[nonpath]		[nonpath]	
	Flow					
	Touch					
	T-Quality					
	M-Quality					
	Local Movement					
Strong PL-A	Hand Configuration	n-1-		n-1+		n-1-
	Hand Site	BK				
	Sprel	[at]				
	Focal Site	E-SUB				
PL-B	Hand Site	PA				
	Sprel	[points to]				
	Focal Site	E-OBJ				
Rotation	Rot	ㅠ				
	Wrist Extension					
	Wrist Abduction					
Weak PL-A	Hand Configuration	n-1-		n-1+		n-1-
	Hand Site	BK				
	Sprel	[at]				
	Focal Site	E-OBJ				
PL-B	Hand Site	PA				
	Sprel	[points to]				
	Focal Site	E-SUB				
Rotation	Rot	ㅠ				
	Wrist Extension					
	Wrist Abduction					
NMS	NMS					

Structure Building Features	AltDom	-
	Bidir	-
	Recip	-
	Redup	-
	Sym	-

Additional Notes:

S1 and S2 refer to Focal Sites for the two subjects.

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