Thesis for the Degree of Master of Science

Embedded Grammars

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Göteborg, February 2005

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Printed at Chalmers, Göteborg, Sweden, 2005

Abstract

This work explores the use of grammars as integral parts of computer programs and presents a number of tools and methods which facilitate such integration. An embeddable interpreter for the Grammatical Framework (GF) grammar formalism, a compiler from GF grammars to speech recognition grammars, and methods for writing multimodal grammars in GF are described. It is then shown how these tools and methods can be used to build multilingual multimodal dialog systems and precise domain-specific machine translation systems for both spoken and written language.

Contents

Acknowledgments

First and foremost, I would like to thank my supervisor Aarne Ranta for his fantastic help and support. Aarne is always curious and full of ideas, and not afraid to try them out. He helped me to get started with language technology, and he got me involved in the TALK project. Being able to walk into his office any time and discuss whatever I am thinking about has helped me a great deal. Without him I would still be thinking that I should start writing my thesis soon.

I would also like to thank the other members of the TALK project: Peter Ljunglöf — for his work on GF parsing, for interesting discussions in the sauna, and for getting me on TV, Robin Cooper — for his thoughts and enthusiasm, and for occasionally sharing an office with me, David Hjelm — for helping me with the antics of speech recognizers and for discussing strange dialog system hardware ideas, Staffan Larsson — for his ideas on dialog systems, and for drinking whisky with David and me on the bus after we happened to fly to the wrong country, and Ann-Charlotte Forslund and Andreas Wallentin — for being the first victims of the Embedded GF Interpreter.

Thanks are also due to the other members of the Chalmers Language Technology group who make this an interesting and dynamic environment: Harald Hammarström — my new-found office mate and partner in crime, Kristofer Johannisson — for being kind and helpful, Markus Forsberg — for his work on BNFC and for dropping by our office just to talk, Bengt Nordström — for his no-nonsense style and ability to make my demo systems misbehave, Janna Khegai — for showing up with new interesting GF applications and for lending me her desk, though I probably never told her, and Ali El Dada — for agreeing to be my opponent at such short notice.

Much of my work uses ideas from functional programming, even when I am not fortunate enough to program in a functional language. I am grateful to John Hughes and the other great functional programmers in the department for teaching me about this delightful programming paradigm.

Finally, I would like to thank all the students, faculty and staff in the department for their company, for unexpected lunchroom encounters and for making this a great place to work.

This work has been funded by the EU TALK project, IST-507802.

Björn Bringert Chalmers, February 2005

Abbreviations

ABNF	Augmented BNF
API	Application Programming Interface
ATK	Application Toolkit for HTK
BNF	Backus-Naur Form
BNFC	BNF Converter
CCG	Combinatory Categorial Grammar
CFG	Context-Free Grammar
CFGM	Multilingual Context-Free Grammar
DCG	Definite Clause Grammar
EBNF	Extended BNF
GF	Grammatical Framework
GFC	Canonical GF
GFCM	Multilingual Canonical GF
GNU	GNU is Not Unix
GOTTIS	Göteborg Tram Information System
GPL	GNU General Public License
GSL	Nuance Grammar Specification Language
HPSG	Head-Driven Phrase Structure Grammar
HTK	Hidden Markov Model Toolkit
ICL	Interagent Communication Language
IDE	Integrated Development Environment
JFP	The Journal of Functional Programming
JSAPI	Java Speech API
JSGF	JSpeech Grammar Format
LBNF	Labeled BNF
LFG	Lexical Functional Grammar
LKB	Linguistic Knowledge Building
LHS	Left-Hand Side
MCFG	Multiple CFG
OAA	Open Agent Architecture
RHS	Right-Hand Side
TALK	Tools for Ambient Linguistic Knowledge
SLM	Statistical Language Model
SRG	Speech Recognition Grammar
SRGS	Speech Recognition Grammar Specification
XLE	Xerox Linguistics Environment
XML	Extensible Markup Language

Chapter 1

Introduction

A grammar is a definition of a language. By *embedded grammars*, we refer to grammars which are used as parts of computer applications. Grammars can be used to describe both natural languages, such as those spoken and written by humans, and formal languages such as computer programming languages, document markup languages, mathematical language and many others. One may even use grammars to describe what many would not even consider languages, for example drawings and gestures, as long as it is possible to construct a string encoding of the expressions in the language. Thus, any computer program which gets input or produces output in some language could make use of embedded grammars.

We present a system for using embedded grammars written in the *Grammatical Framework* (GF) formalism, some methods and tools for using such grammars, and some example applications which use embedded grammars.

This introduction chapter gives some motivation for why embedded grammars are useful and a short introduction to the GF formalism. The following chapter details the main product of this thesis: the Embedded GF Interpreter. We then describe a method for writing multimodal grammars, that is, grammars which describe more than one mode of comunication, in GF. In chapter 4, the transformation of GF grammars to speech recognition grammars is described. The following chapters give some overview of how to construct dialog systems using the tools presented in this thesis and describe a few example applications which we have developed. Chapter 10 mentions some tools which can be used to aid the development of GF grammars for use in systems such as those described earlier. Finally, some related work is discussed.

1.1 Motivation

Many existing dialog systems and other systems with natural language interfaces employ *statistical language models* (SLMs) for speech recognition and *phrase spotting* for extracting meaning from utterances. This gives robust systems which may be able to accept and extract some meaning even from utterances which fall outside of what the system has been explicitly constructed for. On the other hand, such systems are often not as accurate as one may wish for when presented with utterances within its intended coverage.

Grammars, on the other hand, may be used to get precise semantics for everything within their coverage, but tend to fail completely for unexpected inputs. One conclusion that one might draw is that grammars are suitable for domain-specific or otherwise limited systems. Another approach is to construct hybrid systems which fall back to SLMs and phrase spotting when the grammar fails.

Many existing speech recognition systems support the use of simple context-free grammars for guiding the recognition. On the other hand, parsers which are intended to capture the semantics of a recognized utterance often use a grammar more suited to that task, as opposed to the simpler recognition problem. This means that a complete system may involve one grammar for the speech recognizer, and a separate grammar for parsing. These grammars should ideally be equivalent in their coverage, and must at least be kept in sync during development. It would seem to be more efficient if this could be done automatically, for example by generating one of the grammars from the other.

In addition to parsing, grammars can also be used for *linearization*, the generation of (natural) language strings from some semantic description. Support for linearization is needed in order to do natural language output.

The aim of the work presented in this report is to create tools which simplify integrating grammar-based functionality such as multilingual and multimodal parsing and linearization as well as grammar-aided speech recognition into applications.

1.2 Grammatical Framework

Grammatical Framework (GF) is a grammar formalism based on Martin-Löf type theory [1]. This section is a very short introduction to GF; Aarne Ranta's *JFP* article [2] and the introduction chapter of Peter Ljunglöf's PhD thesis [3] give much more information.

GF makes an essential distinction between *abstract syntax* and *concrete syntax*. The abstract syntax represents the structure or meaning of values in the language, whereas the concrete syntax describes their appearance. The idea is that the abstract syntax is easy to analyze and synthesize in a program, and thus does not contain any irrelevant details or redundancy. The abstract syntax might also be shared between grammars for different languages. The concrete syntax, on the other hand, might be designed for readability or redundancy, or in the case of natural languages, evolved rather than designed. The distinction between abstract and concrete syntax is much used in the field of computer languages, but less so within computational linguistics.

Concrete syntaxes are written as linearization rules for abstract syntax terms. In other words, the grammar writer defines how each function in the abstract syntax is converted to a value in the concrete syntax. Using a concrete syntax, the GF system can both parse input to abstract syntax terms and linearize abstract syntax terms to values in the concrete syntax.

In GF there may be several concrete syntaxes for a single abstract syntax. This may be used to produce output or accept input in any of a number of languages, or to translate between languages. Formal and natural languages might share a common abstract syntax. This can for example be used to translate specifications in some formal language to informal natural language specifications [4].

Another application of multilingual grammars is multilingual syntax editing, where the user edits a document in multiple languages simultaneously by manipulating abstract syntax terms and observing the resulting concrete syntax output for many languages in parallel. This may involve several natural languages [5], or both natural and formal languages [6].

GF is a suitable grammar formalism for general embedded grammars since it is quite powerful while being parsable in polynomial time [3], and since it can be used for both parsing and linearization. As is shown in chapter 4, other necessary grammars such as context-free grammars for external systems can be generated from GF grammars.

Chapter 2

The Embedded GF Interpreter

2.1 Introduction

The GF system is primarily a command line application for working with GF grammars. It has a significant amount of functionality, such as parsing, linearization, computation, syntax editing, morphological analysis, compilation of source grammars to canonical GF grammars, conversion of grammars to various formats, translation and morphology quizzes, etc. GF has been in development for a number of years and has grown quite large. It is well-equipped for testing and working interactively with grammars. However, GF is more complex than necessary to be used with embedded grammars. We have therefore developed an interpreter for compiled GF grammars in the Java programming language, version 1.5 [7]. The goal of the Embedded GF Interpreter is to make a small and fast implementation of the features necessary for building applications to make use of embedded grammars. Thus, any functionality which is only used during the application development has been delegated to the full GF system.

GF itself is still essential for developing embedded grammars, but it need not be included in the finished system. GF is used to compile the source grammars to the various formats used for parsing, linearization and speech recognition by the finished system. This situation can be compared to that for programming languages such as Java, which can be compiled into byte-code. A compiler is used to convert the human-readable and human-writable source code to a simpler form. Users of the program then only need a runtime environment or virtual machine to run the compiled code.

The full GF system is a rather large executable program, requires a Haskell implementation for the given platform and has a large memory footprint. The aim of the Embedded GF Interpreter is to be small, fast and portable. The size of the compiled interpreter is around 250 kilobytes and it should run on any platform which has a Java 1.5.0 Runtime Environment.

Following C.A.R. Hoare's maxim that "premature optimization is the root of all evil", the main principle guiding the implementation of the Embedded GF Interpreter has been to take the simplest and most understandable route available. After testing has revealed bottlenecks which lead to unacceptable performance, selected parts have been optimized.

2.2 Abstract Syntax Terms

Abstract syntax terms are:

- function applications of the form $f A_1 \dots A_n$, where f is a function and $A_1 \dots A_n, n \geq 0$ are abstract syntax terms.
- string constants.
- integer constants.
- meta-variables, written as ?.

Full GF also supports lambda abstractions and bound variables in abstract syntax. This is not yet implemented in the Embedded GF interpreter.

2.3 Parsing

The parser computes a set of abstract syntax trees for a given string input. In the full GF system, parsing is done by using a context-free grammar in which the productions have labels and profiles [3]. GF first computes a Multiple Context-Free Grammar (MCFG) from a GF grammar. The MCFG is then converted to a context-free grammar (CFG). The Embedded GF Interpreter makes use of a CFG produced by the full GF system.

2.3.1 Lexical Analysis

The first step in parsing input is to divide it into tokens. A simple hard-coded lexer divides the input into simple words (non-empty sequences of letters and digits), quoted strings and punctuation. The full GF system allows flags which specify which of a number of hard-coded lexers and unlexers to use. The Embedded GF Interpreter does not support these flags, see section 2.10.1.

2.3.2 CFGM Language

The GF system is used to create a context-free grammar with labeled productions and *profiles* from a GF grammar. The general form of a production is:
$f : C[p] \rightarrow \overline{s}$

The function f is the name of the function that will be used to construct an abstract syntax term for the production. The right-hand side $\overline{s}$ is a sequence of terminals and non-terminals. The profile p is a sequence of sets of integers which determine in which position of the function application each sub-term will be put. The n:th set in the profile contains the indexes of the non-terminals on the RHS which correspond to the n:th argument to the function f. In case of *suppression*, the set for the corresponding function argument will be empty. A set with more than one member means that that function argument is *reduplicated*.

2.3.3 Chart Parsing

The parser is a Kilbury bottom-up chart parser, similar to the chart parser described by Peter Ljunglöf [8]. The algorithm has been modified to support empty rules and to be better suited to implementation in an imperative language.

Below, S is the start symbol of the grammar, A and B are arbitrary non-terminals, α, β and γ are sequences of zero or more terminals or non-terminals, t is a terminal, f is an abstract syntax function, and p is a profile.

First the CFGM grammar is transformed so that all rules with terminals on the RHS have only a single terminal as the RHS. This is done by replacing all terminals in other rules by a category which has a single production with the terminal as the RHS.

The grammar rules are divided into three sets:

- Rules of the form $f : A[p] \to B_1 \dots B_n$, where $n \geq 1$ and $B_1 \dots B_n$ are all non-terminals.
- Rules of the form $f : A[p] \to \epsilon$.
- Rules of the form $f : A[p] \to t$, where t is a terminal. There are three kinds of terminal rules:
  - Constant terminal rules, which match a given string. This can be compared to keywords in programming language grammars.
  - Integer literal rules, which match tokens consisting entirely of decimal digits.
  - String literal rules which match any token which is not an integer literal or matched by any constant terminal rule.

Given a sequence of n input tokens $t_k, 1 \leq k \leq n$, the algorithm constructs the sets $\Delta_{i,j}$ where $0 \leq i \leq j \leq n$. This collection of sets is called a *parse chart*. The sets $\Delta_{i,j}$ contain *dotted rules*, which are grammar rules with a dot indicating how much of the RHS has been matched. We refer to a dotted rule $A \to \alpha \bullet \beta$ in some set $\Delta_{i,j}$ as an *edge* between nodes i and j. Such an edge means that the input sub-sequence consisting of tokens t_{i+1} through t_j has been matched by α. An *active edge* is a dotted rule which does not have the dot at the end of the RHS. A *passive edge* has the dot at the end, and its rule has thus been fully matched.

Parsing Algorithm

1. Let $k := 0$.
2. (*Scan*) If $k \geq 1$, then for all rules $f : A[p] \to t_k$, add $f : A[p] \to t_k \bullet$ to $\Delta_{k-1,k}$.
3. For all empty rules $f : A[p] \to \epsilon$, add $f : A[p] \to \bullet$ to $\Delta_{k,k}$.
4. For all passive edges $f' : C[p'] \to \alpha \bullet$ in $\Delta_{j,k}$ where $0 \leq j \leq k$:
   (a) (*Bottom-up predict*) For all rules $f : A[p] \to C\beta$, add edge $f : A[p] \to C \bullet \beta$ to $\Delta_{j,k}$.

(b) (*Combine*) For all active edges $f : A[p] \to \beta \bullet C\gamma$ in $\Delta_{i,j}$, where $0 \leq i \leq j$, add edge $f : A[p] \to \beta C \bullet \gamma$ to $\Delta_{i,k}$.

5. Repeat step 4 until no new edges are added.
6. If $k < n$, then let $k := k + 1$ and go to step 2.
7. Parsing was successful if $f : S[p] \to \alpha\bullet \in \Delta_{0,n}$.

The algorithm uses a bottom-up prediction step in order for it to build all sub-parses even if there is no complete parse. This feature is currently not used, but in the future it could be exploited to produce at least some result even if the entire input cannot be understood. This could for example be useful when combined with syntax editing. The user could type in a phrase which, if not parsed completely, would produce some abstract syntax terms for parts of the input. Using syntax editing, these terms could then be used to construct the full term which the user intended. Another use might be in a dialog system which can ask for clarification of the parts which it did not understand.

Implemented Optimizations

The *Predict* step is optimized by keeping a multimap which maps categories to all the rules which start with that category.

Future Work

The parsing algorithm and its implementation could potentially be optimized in a number of ways:

- The *Scan* step is currently implemented using linear search through the terminal rules. For a grammar with a large number of terminal productions, using a trie to look up terminal productions would improve the algorithmic complexity of this step.
- Each $\Delta_{i,j}$ set could be split into two sets: one for passive and one for active edges. This could make iteration through the sets faster, as no step uses both active and passive edges.
- In step 3 above, edges for all empty rules are added to each of the $n + 1$ sets $\Delta_{k,k}$. The set of such edges is the same for each node and it is independent of the input tokens. Thus this set could be precomputed and shared between the nodes and between invocations of the parsing algorithm.

2.3.4 Tree Building

After a successful parse, we need to build abstract syntax trees for the input. The tree building algorithm uses the chart produced by the parsing algorithm described above. Tree building is done by the mutually recursive functions *buildTree* and *buildTrees* and gives as a result a set of parse trees. To build the set of abstract syntax trees for the entire input we use $\mathit{buildTree}(S, 0, n, \emptyset)$, where S is the start category and n is the number of input tokens.

In order to avoid non-termination with circular grammars, a set of used edges for a given input sub-sequence is kept. No edge can be used more than once for a given sub-sequence, which means that not all possible parse trees are generated. This may seem to be too harsh a restriction, but this decision was made based on the belief that for most applications, cyclic uses of the same rules are not essential for the semantics. Another possible solution to this problem would be to build graphs instead of trees. This might seem to be an elegant solution, but traversing such graphs could lead to non-termination if special care is not taken.

The buildTree Function

The function *buildTree* builds the set of abstract syntax trees in category C for the input between nodes i and j, i.e. for the input consisting of tokens t_{i+1} through t_j.

$buildTree(C, i, j, used)$:

```
1. Let $T := \emptyset$
2. For each passive edge $E = f.C[p] \rightarrow \alpha \bullet \in \Delta_{i,j}$,
   (a) If $\alpha = \epsilon$, then let $T := T \cup \{f\ ?_1 \ldots ?_n\}$, where $?_1 \ldots ?_n$ are fresh meta-variables and $n = length(p)$, i.e. the arity of $f$.
   (b) If $\alpha = t$, where $t$ is a string or integer literal terminal, then let $T := T \cup \{t_j\}$.
   (c) If $\alpha = t$, where $t$ is a constant terminal, then let $T := T \cup \{f\}$.
   (d) If $\alpha = A_1...A_k$ and $E \notin used$, then:
       i. Let $used' := used \cup \{E\}$.
       ii. For each $s \in buildTrees(\alpha, i, j, used')$:
           A. Let $s' := s$ with trees for constant terminals removed.
           B. If there are $c_1 \ldots c_n$ such that $n = length(p)$ and $c_k = unifyAll(\{s'[x] | x \in p[k]\})$, then let $T := T \cup \{f\ c_1 \ldots c_n\}$.
3. Return $T$.
```

Note on Constant Terminals In step 2c above, abstract syntax trees for constant terminals are created. These are just placeholders and are later removed in step 2(d)iiA.

The buildTrees Function

The function *buildTrees* builds a set of sequences of abstract syntax trees for a non-empty sequence of categories $\langle C_1 \ldots C_n \rangle$, where $n >= 1$, using tokens t_{i+1} through t_j.

$buildTrees(\langle C_1 \ldots C_n \rangle, i, j, used)$:

```
1. If $n = 1$, then return $\{\langle h \rangle \mid h \in buildTree(C_1, i, j, used)\}$
2. If $n > 1$, then:
```

```
(a) Let $R := \emptyset$.
(b) For each $k$ such that $i \leq k \leq j$:
    i. Let $H = buildTree(C_1, i, k, used')$, where $used' = used$ if $k = j$
       and $used' = \emptyset$ otherwise.
    ii. Let $T = buildTrees(\langle C_2 \dots C_n \rangle, k, j, used')$, where $used' = used$
        if $k = i$ and $used' = \emptyset$ otherwise.
    iii. Let $R := R \cup \{\langle h, t_1 \dots t_n \rangle \mid h \in H, \langle t_1 \dots t_n \rangle \in T\}$.
(c) Return $R$.
```

Unification

The unification function used in *buildTree* is defined below. In the function definitions, ? is a fresh meta-variable. Note that the unification function is partial.

$$\begin{array}{lcl} unifyAll(\emptyset) & = & ? \\ unifyAll(\{x\} \cup T) & = & unify(x, unifyAll(T)) \end{array}$$

$$\begin{array}{lcl} unify(?, y) & = & y \\ unify(x, ?) & = & x \\ unify(f\ a_1 \dots a_n, f\ b_1 \dots b_n) & = & f\ unify(a_1, b_1) \dots unify(a_n, b_n) \\ unify(s, s) & = & s \\ unify(i, i) & = & i \end{array}$$

Implemented Optimizations

In order to speed up the iteration through the passive edges in step 2 of *buildTree*, the edge sets in the chart keep the edges indexed by their LHS category.

Future Work

The tree building algorithm produces all parse trees at once. Since the number of parse trees may be very large, and we may only be interested in some of them, this can be inefficient. Peter Ljunglöf describes a more efficient way of handling parse forests [3] which could be implemented also in the Embedded GF Interpreter.

2.4 Type Annotation

All meta-variables are annotated with their type. This is a prerequisite for syntax editing. Note that the type annotation only uses non-dependent types, and thus all types are categories. We write a meta-variable ? as ? : C when annotated with the type C. Type annotation of the abstract syntax term T in category C is done by the function $ann(T, C)$, shown below.

$$\begin{array}{lcl} ann(f\ A_1 \dots A_n, C) & = & f\ ann(A_1, C_1)\ \dots\ ann(A_n, C_n) \\ ann(?, C) & = & ? : C \\ ann(s, C) & = & s \\ ann(i, C) & = & i \end{array}$$

Above, f has the type $C_1 \ldots C_n \to C$, s is a string constant, and i is an integer constant.

2.5 Linearization

In GF, *linearization* refers to the inverse of parsing, i.e. the process of producing a string in the concrete syntax from an abstract syntax term.

For linearization, the Embedded GF Interpreter uses a Canonical GF (GFC) grammar, which is produced from a source grammar by the GF system. Canonical GF can be seen as a simple total functional language. This section only considers the sub-language of Canonical GF used for concrete and abstract modules. Canonical GF can also be used to describe some aspects of resource modules, but these are not used directly in linearization.

This section defines the sets of GFC terms and values, a relation $\Downarrow$ which evaluates terms to values and finally how these are used in the linearization of abstract syntax terms.

2.5.1 Canonical GF Term Language

The GFC term language supported by the Embedded GF Interpreter is defined by the EBNF grammar in figure 2.1. This grammar describes the abstract rather than the concrete syntax of GFC; see the LBNF [9] grammar for GFC included in the Embedded GF Interpreter source distribution for the complete grammar.

```
⟨Term⟩  ::=  { (⟨Ident⟩ = ⟨Term⟩)* }
          |   table { (⟨Patt⟩* => ⟨Term⟩)* }
          |   ⟨Term⟩ . ⟨Ident⟩
          |   ⟨Term⟩ ! ⟨Term⟩
          |   < ⟨Ident⟩ ⟨Term⟩* >
          |   ⟨Term⟩ ++ ⟨Term⟩
          |   variants { ⟨Term⟩* }
          |   [ ]
          |   ⟨Token⟩
          |   ⟨Variable⟩
⟨Patt⟩  ::=  ( ⟨Ident⟩ ⟨Patt⟩* )
          |   { (⟨Label⟩ = ⟨Patt⟩)* }
```

Figure 2.1: The set of GFC terms.

In figures 2.1 and 2.2, we use C* to denote a possibly empty sequence of Cs. The ⟨*Token*⟩ category contains ordinary string tokens and *prefix-dependent choice* tokens. Prefix-dependent choice is handled by the unlexer, but is not further described in this thesis. The language described above is a subset of the full GFC language as it lacks higher-order terms as well as wild-card and variable patterns.

2.5.2 Linearization Values

The set of values to which abstract syntax terms can be linearized is shown in figure 2.2.

```
⟨Value⟩  ::=  [ ⟨Token⟩* ]
           |  table { (⟨Patt⟩* => ⟨Value⟩)* }
           |  { (⟨Label⟩ = ⟨Value⟩)* }
           |  < ⟨Ident⟩ ⟨Value⟩* >
           |  variants { }
```

Figure 2.2: The set of linearization values.

2.5.3 Operational Semantics

We define an evaluation relation $\Downarrow$ for evaluating a GFC term to a value. The definition of $\Downarrow$ is shown in figures 2.3 and 2.4. There is no rule for evaluating variables since these are substituted away before evaluation; see section 2.5.4.

Note on Empty Variants

Empty variants are a kind of bottom in the evaluation of GFC terms. Any evaluation which would need to analyze an empty variants value results in empty variants. Empty variants can be used to linearize abstract syntax terms which cannot be represented in a given concrete syntax. For example, in some languages, certain word forms do not exist even though one might expect them to. In Swedish, some adjectives such as *rädd* ("afraid") do not have a neuter form, which makes all phrases which would use this form impossible to construct.

Note on Free Variation

Note that the semantics that we give to free variation mean that we always choose the first alternative. This was done for simplicity and predictability. One possible design decision could have been to make the choice non-deterministic, or to make linearization ambiguous, i.e. to have linearization produce a set of values. In the latter case there are two alternative ways to handle linearization of reduplicated terms. In each linearization, a reduplicated term may be linearized using the same variant for each occurrence. Alternatively, each linearization could contain all combinations of the possible variants. Ljunglöf [3] refers to these interpretations as *intensional disjunction* and *extensional disjunction* respectively and argues that the latter constitutes a strict extension of GF by making the formalism more powerful. The full GF system interprets free variation as extensional disjunction.

2.5.4 Linearization Operator

We use a° to denote the linearization of the abstract syntax term a using a given concrete syntax. The linearization operator $^\circ$ is defined in figure 2.5. In the figure, $t[x = v; \ldots]$ means simultaneous substitution.

Record construction

$$\frac{t_1 \Downarrow v_1 \qquad \ldots \qquad t_n \Downarrow v_n}{\{l_1 = t_1; \ldots; l_n = t_n\} \Downarrow \{l_1 = v_1; \ldots; l_n = v_n\}}$$

Record projection

$$\frac{t \Downarrow \{\ldots; l = v; \ldots\}}{t.l \Downarrow v}$$

Table construction

$$\frac{t_1 \Downarrow v_1 \qquad \ldots \qquad t_n \Downarrow v_n}{\mathit{table}\ T\ \{\overline{p_1} \Rightarrow t_1; \ldots; \overline{p_n} \Rightarrow t_n\} \Downarrow \mathit{table}\ \{\overline{p_1} \Rightarrow v_1; \ldots; \overline{p_n} \Rightarrow v_n\}}$$

Table projection

$$\frac{t \Downarrow \mathit{table}\ \{\ldots; \langle \ldots \mid p \mid \ldots \rangle \Rightarrow v'; \ldots\} \qquad t' \Downarrow v \qquad v \equiv p}{t!t' \Downarrow v'}$$

Parameter construction

$$\frac{t_1 \Downarrow v_1 \qquad \ldots \qquad t_n \Downarrow v_n}{\langle i\ t_1 \ldots t_n \rangle \Downarrow \langle i\ v_1 \ldots v_n \rangle}$$

Concatenation

$$\frac{t \Downarrow [v_1, \ldots, v_n] \qquad u \Downarrow [w_1, \ldots, w_m]}{t ++ u \Downarrow [v_1, \ldots, v_n, w_1, \ldots, w_m]}$$

Free variation

$$\frac{n \geq 1 \qquad t_1 \Downarrow v}{\mathit{variants}\ \{t_1 \ldots t_n\} \Downarrow v}$$

Empty token list

$$\frac{}{[] \Downarrow []}$$

Token

$$\frac{t \text{ is a token}}{t \Downarrow [t]}$$

Figure 2.3: Definition of the GFC term evaluation relation $\Downarrow$.

Empty variants

$$\frac{}{\mathit{variants}\ \{\} \Downarrow \mathit{variants}\ \{\}}$$

Record projection (empty)

$$\frac{t \Downarrow \mathit{variants}\ \{\}}{t.l \Downarrow \mathit{variants}\ \{\}}$$

Table projection (empty)

$$\frac{t \Downarrow \mathit{variants}\ \{\} \vee t' \Downarrow \mathit{variants}\ \{\}}{t!t' \Downarrow \mathit{variants}\ \{\}}$$

Concatenation (empty)

$$\frac{t \Downarrow \mathit{variants}\ \{\} \vee u \Downarrow \mathit{variants}\ \{\}}{t ++ u \Downarrow \mathit{variants}\ \{\}}$$

Figure 2.4: Rules for the GFC term evaluation relation $\Downarrow$ concerning empty variants.

Function application

$$\frac{lin\ f = \lambda x_0 \ldots x_n \rightarrow t \qquad t[x_0 = a_0^\circ; \ldots; x_n = a_n^\circ] \Downarrow v}{(f\ a_0 \ldots a_n)^\circ = v}$$

Integer constant

$$\frac{i \text{ is a integer} \qquad n \text{ is the decimal string representation of } i}{i^\circ = \{s = [n]\}}$$

String constant

$$\frac{a \text{ is a string}}{a^\circ = \{s = [a]\}}$$

Meta-variable

$$\frac{v \text{ is a string representation of } ? : T}{(? : T)^\circ = \{s = [v]\}}$$

Figure 2.5: Definition of the linearization operator $^\circ$.

Note on Meta-variables

Note that the rule for meta-variables in figure 2.5 is not actually sufficient for all cases. If the linearization type of T is not $\{s : Str\}$, $(? : T)^\circ$ will have the wrong type; see section 2.5.6 for some more information on this topic.

2.5.5 Unlexing

After linearization has produced a list of tokens, the *unlexer* joins the list to create a single output string. A naïve unlexer would simply concatenate the tokens, adding a space character between the tokens. However, this does not produce acceptable strings in most languages. For example, in English there should not be a space before most punctuation characters.

The Embedded GF Interpreter currently uses a fairly simple heuristic for unlexing. We define two subsets of the set of all characters: those which should be preceded by a space (essentially all punctuation, closing brackets and closing parentheses), and those which should not be followed by a space (opening brackets and parentheses). These sets are used to determine whether to add a space between two tokens. The full GF system offers some more freedom in the choice of lexing and unlexing algorithms, see section 2.10.1 for more details.

2.5.6 Future Work

Unimplemented Linearization Features

These features of Canonical GF are not yet implemented in the Embedded GF Interpreter:

- No resource module functionality is implemented, since a resource module is not used for linearization without first producing a concrete module from it.
- The GFC language supports *wild-card patterns* and *variable patterns* in tables. However, since the current GF system always generates fully expanded tables unless specifically told to do these optimizations, support for them in the Embedded GF Interpreter has not yet been implemented.

- *Printnames* are used to give human-readable names to functions. This is useful mainly for syntax editing, which is not yet implemented.
- Tables without patterns, see section 2.10.6, are not implemented yet.
- Higher-order abstract syntax is currently not supported, see section 2.10.5.
- The linearization of meta-variables is incomplete, and there is no support for *lindef* judgments. Such judgments are used to declare a default linearization for a category, i.e. how meta-variables in that category are to be linearized.

Further Optimizations

Replacing Parameters with Integers The linearization algorithm could be optimized by replacing parameters by integers. This can be done since a total ordering of all the parameter values in a parameter type can be easily constructed. This would allow tables to be represented as arrays instead of maps.

Avoiding Left-associated Concatenations In the current implementation, concatenated string lists are not actually concatenated until unlexing time. This is done to enable trees of concatenated lists to be rearranged in order to avoid the $\Theta(n^2)$ behavior which can occur with left-associated concatenations. This rearrangement is, however, not yet implemented.

2.6 Translation

Translation is done by parsing with the source language and linearizing to the destination language. Since parsing may be ambiguous or fail, translation may produce zero or more results.

2.7 Java API

The Java API allows the programmer to call the interpreter directly from a Java program. The Java API supports all functionality, such as grammar loading, parsing, linearization and translation.

The method *createTranslator* in the $TranslatorFactory$ class is used to create a $Translator$ given CFGM and GFCM grammars, and some meta-data. The $Translator$ class has methods for parsing, linearization and translation, which are described below. More documentation is available in the Embedded GF Interpreter API reference [10].

2.7.1 Methods in the Translator Class

The *parse* method takes a language name (the name of a concrete syntax) and an input string. It returns the result of parsing the input string in the given language:

```
Set<Tree> parse(String lang, String text)
```

The *linearize* method takes a language name and an abstract syntax tree and returns the result of linearizing the tree in the given language:

```
String linearize(String lang, Tree tree)
```

The *translate* method takes input and output language names, and a string in the input language, which it translates to a set of strings in the output language:

```
Set<String> translate(String fromLang, String toLang,
                      String text)
```

There are also versions of the parsing and linearization methods which try to use all available concrete syntaxes and return collections of pairs of language name and results:

```
Set<Pair<String,Tree>> parseWithAll(String text)

Set<Pair<String,String>> linearizeWithAll(Tree tree)
```

2.8 Typed Abstract Syntax Trees

The Java API uses generic untyped syntax terms, where there is a single class for functions which uses a string for the function name and an array of child terms. Constructing and analyzing such terms can be quite tedious in Java. An untyped abstract syntax term is constructed thus:

```
new Fun("GoTo", new Tree[]{ new Fun("Chalmers"),
                            new Fun("Valand")});
```

A tool, `Grammar2API`, has been written which creates Java classes for representing a given abstract syntax using typed trees. An abstract class is created for each category, and a concrete class inheriting from that class is created for each function in that category.

There is a Visitor [11] interface for each category, which has methods for each function in the category. Code for converting between typed and untyped trees, as well as typed wrappers around the untyped parsing and linearization methods are also generated. The abstract syntax tree above can be built by simply using the constructors of the generated classes:

```
new GoTo(new Chalmers(), new Valand());
```

2.9 OAA Agent

To allow the GF interpreter to be used in multi-agent systems and from programs written in languages other than Java, an Open Agent Architecture (OAA) [12] wrapper has been written.

OAA is a framework for multi-agent systems. Communication between the agents is done by sending terms in the Interagent Communication Language (ICL), a subset of Prolog. There are OAA interfaces for several programming languages, including Java.

The GF OAA agent has *solvables* (methods) for parsing, linearization, translation, listing languages and grammars. Since OAA uses a unification-based approach to method calls, the GF agent solvables can be used quite flexibly. For example, if the language argument to the parsing solvable is uninstantiated (i.e. it is a variable), all available languages in the given grammar will be tried. The fact that an OAA agent can return multiple solutions to a request is used to return ambiguous parse results. When the language argument is uninstantiated, the parser tries to parse with all available concrete syntaxes.

The solvables are documented in detail in appendix A.

2.10 Future Work

2.10.1 Flexible Lexing and Unlexing

The hard-coded lexer and unlexer might be insufficient for some formal languages, or natural languages with certain lexical features. The full GF system has a similar problem, since while flags in the grammar can be used to specify which of the available hard-coded lexers and unlexers to use, there is no flexible way to give a specification of the lexical features in the grammar. Extending GF to allow specifying lexical rules could solve this problem. Having reversible lexical rules would allow them to be used for both lexing and unlexing. However, it is normally desirable for lexing to be more forgiving than unlexing. For example, the lexer may accept any number of whitespace characters as token delimiters, whereas the unlexer would always use exactly one space. This could be achieved by having separate lexing and unlexing declarations. Another way would be to have one rule for both lexing and unlexing and use some algorithm to make the unlexing rule deterministic. For example, any rule accepting n or more of some character when lexing could produce exactly n characters when unlexing.

2.10.2 Syntax Editing

GF grammars can be used for syntax editing [13, 14]. In order to support this, some functionality for keeping track of the current position and for editing and navigation commands would have to be implemented.

2.10.3 Type Checking

GF abstract syntax terms can be dependently typed. Dependent types are are not used when GF grammars are translated to context-free grammars for parsing. Instead, an over-generating grammar is created, and ill-typed terms may be discarded by type checking after parsing. We have made a preliminary implementation of a slight variation on Thierry Coquand's algorithm for type-checking dependent types [15], but due to lack of time, this has not yet been implemented in the Embedded GF Interpreter.

2.10.4 Computation

GF grammars may contain computation rules. This has not been implemented in the Embedded GF Interpreter yet. Support for computation is necessary for a complete implementation of dependent type checking. It could also be used to move some abstract syntax term computations from the application program into the grammar. For example, if there are several constructions with the same semantics, computation rules could normalize them to a single representation before passing them to the application.

2.10.5 Higher-order Abstract Syntax

In full GF, abstract syntax terms may have function types. Such terms are constructed using lambda expressions and can be used for binding constructs such as universal quantification. Such *higher-order abstract syntax* requires support in the GFC term and value languages and in the GFC interpreter. This has not yet been implemented in the Embedded GF Interpreter.

2.10.6 Reducing GFCM and CFGM File Size

The GFCM and CFGM files produced by the GF system can become rather large for certain grammars. GFCM files are mainly made large because of the fact that all operations are fully evaluated and all tables are fully expanded, including fully qualified parameter patterns for each table entry. The category names in CFGM files are constructed from category, parameter and field names from the original GF grammars. This means that category names can be become quite long. Certain GF grammar features may also cause the number of productions in the generated context-free grammar to explode [3].

For the reasons above, a large number of sub-strings of CFGM and GFCM files are repeated many times, making such files highly compressible. One approach to reducing the size of the files would thus be to compress them using some general purpose text compression algorithm.

Another method could be to change the GFCM and CFGM formats so that they contain less redundant information. The full GF system implements one such optimization where tables can be produced completely without patterns. This can be done since the tables are always fully expanded and a total ordering of the table parameters can be constructed. The GF system can also produce tables with wild-card patterns and variable patterns, both of which may reduce the size of tables. These optimizations are optional in GF, and the grammars produced cannot yet be used by the Embedded GF Interpreter.

Chapter 3

Multimodal Grammars

3.1 Introduction

The most natural method of communication between humans is not always spoken natural language. For example, people may draw maps or point when asked to describe how to get to a certain place. Different modes of communication, such as speech, drawing and pointing are referred to as *modalities*. It will be shown in this chapter how GF grammars can be used to describe other modalities than speech, and how multimodal grammars can be written. Since GF grammars can in themselves only describe strings, we use string encodings for non-string languages.

We distinguish between parallel and integrated multimodality. This distinction is due to Aarne Ranta [16].

3.2 Parallel Multimodality

3.2.1 Introduction

We use the term *parallel multimodality* to describe a situation where all necessary information is available in each of several modalities. For example, driving directions given both as a written description of actions to take and as a route drawn on a map is an instance of parallel multimodality. Figure 3.1 shows an example of parallel multimodality where an abstract syntax term representing a route through a tram network is shown both as a natural language description and a drawing on a map.

3.2.2 Implementation in GF

Parallel multimodality in GF is implemented in the same way as multilinguality. For a given abstract syntax, there is a separate concrete syntax for each modality. In the driving directions example, the abstract syntax would contain some abstract description of the route. There would be one concrete syntax in which the abstract route is linearized to written instructions. Another concrete syntax would create map drawings by using some drawing language. Section 9.5 describes an example of a GF grammar with parallel multimodality.

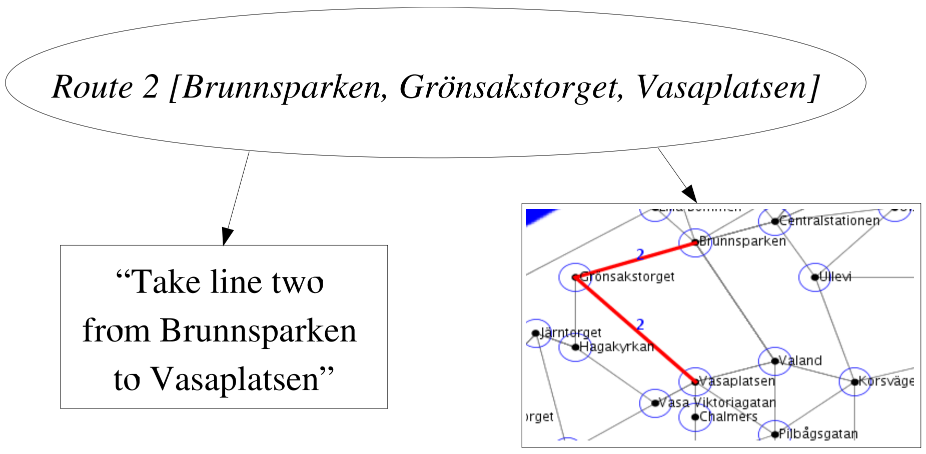


Figure 3.1: An example of parallel multimodality.

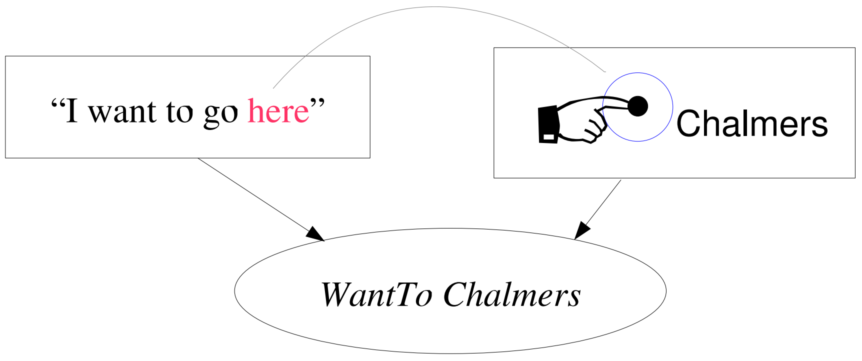


Figure 3.2: An example of integrated multimodality.

3.3 Integrated Multimodality

3.3.1 Introduction

In *integrated multimodality*, the information in each modality contributes to the total information. For example, the utterance "turn left at this intersection" combined with pointing to an intersection on a map gives the complete information. The information from each individual modality is insufficient. Figure 3.2 shows an example of integrated multimodality where a natural language phrase and a pointing gesture together represent an abstract syntax term.

3.3.2 Implementation in GF

Integrated multimodality is implemented by exploiting the fact that GF linearization types are records. An abstract syntax category whose content we would like to represent with integrated multimodality is given a linearization type which is a record with one field for each modality. See section 9.4 for an example of a GF grammar using integrated multimodality.

3.4 Future Work

Currently only speech and click input, and speech and drawing output modalities have been tested. Possibilities for future experiments with other modalities include:

- More advanced drawing modality support. Petri Mäenpää has suggested using GF grammars to describe for example ancient Greek mathematics, where diagrams and text are used together to convey information.
- Drawing input, e.g. “I want to go to this area”.
- User location, e.g. “Switch off the light on my right”.
- Gestures, e.g. “Open that door”.

Chapter 4

Generating Speech Recognition Grammars

4.1 Introduction

In order to improve recognition accuracy, speech recognition engines often use grammars to determine which inputs are to be expected. Speech recognition grammars (SRGs) are often simple context-free grammars. In this application, the grammar is simply used to determine whether a given string belongs to the language or not, the so-called *recognition problem*.

Writing a separate grammar for the speech recognizer, and keeping it in sync with the grammar used by the parser requires some effort. To eliminate this problem, a compiler from the internal CFG [3] format used by GF to some speech generation grammar formats has been implemented.

4.2 Speech Recognition Grammar Formats

There are a number of existing formats for speech recognition grammars:

JSpeech Grammar Format (JSGF)
JSGF [17] is a plain-text language for context-free grammars used in the Java Speech API (JSAPI) [18, 19].

Nuance Grammar Specification Language (GSL)
GSL [20] is a plain-text language for context-free grammars used by the Nuance [21] speech recognizer.

Speech Recognition Grammar Specification (SRGS)
SRGS [22] is a W3C standard for speech recognition grammars. It has two equivalent syntactic forms, Augmented Backus-Naur Form (ABNF) and XML.

4.3 Implementation

The internal context-free grammar for a given concrete syntax is first transformed to a generic simple context-free format for the speech modality:

- Removal of explicit and implicit left recursion by Paull's algorithm [23]. The algorithm does not preserve the structure of the grammar, but as speech recognition grammars are not used to produce parse trees, this is not a problem.
- Removal of productions which use categories in which there are no productions (categories with no productions are often the result of removing non-speech modalities, see section 4.4). This is done by fix-point recursion as each step may create new empty categories.

The generic context-free speech grammar is then converted to either GSL or JSGF and printed. Punctuation is removed before printing, as it is not part of the spoken language, but see section 4.5.2. All upper case characters in tokens are converted to lower case, for the same reason. If the source grammar contains punctuation or upper case characters, the CFGM grammar, which is used for parsing (see section 2.3), will not be able to parse all output from the speech recognizer. This problem could be solved by having GF remove punctuation and capitalization before producing the CFGM grammar, instead of when creating the speech recognition grammar.

Speech recognition grammar compilation has been added to the GF system. The `pg` ("print_grammar") command has been given two additional values for the `-printer` flag: `gsl` and `jsgf`.

4.4 Removing Non-speech Modalities

Since the speech recognition engine is only concerned with the speech modality, all other modalities should be removed from the grammar before producing a speech recognition grammar.

This is not an issue for parallel multimodality, since speech recognition grammars will only be produced for the concrete syntaxes in the speech modality.

In the case of integrated multimodality, some more work is required. Since different modalities are encoded in record fields, we need a way to create a speech recognition grammar just for the speech field. This is achieved by adding new abstract and concrete module which extend the modules for which we wish to create a speech recognition grammar. With the new modules, we add a new (start) category, whose linearization type contains a single string field. The category contains a single function which takes an element of the start category of the original concrete syntax. The linearization of the function keeps just the speech field from the linearization type of the original start category.

4.5 Future Work

4.5.1 Compilation to Finite State Networks

Some speech recognition systems, for example ATK [24], use finite state networks instead of context-free grammars to guide speech recognition. It would be useful to be able to generate finite state approximations of GF grammars for use with such systems. Since finite-state automata are weaker than GF grammars and context-free grammars, the finite state approximation would have to be over-generating.

4.5.2 Automatic Conversion to Spoken Language Forms

The orthography of written language is not always optimal for representing spoken language. For example, punctuation in written language might correspond to various pauses or intonation changes. It might be possible to automatically transform for example punctuation in the given grammar to the corresponding features of the spoken language.

4.5.3 Extended Start Category Concept

If GF were extended to allow the start category to be not just a category, but optionally also a field of the linearization type of a category, stripping non-speech modalities could be done without adding any new modules.

Chapter 5

Building Dialog Systems with Embedded Grammars

Figure 5.1 illustrates the architecture of a multimodal dialog system built using the Embedded GF Interpreter. The Embedded GF Interpreter and the speech recognition grammar compiler are new components developed as part of this thesis. For speech recognition and speech synthesis, existing off-the-shelf components have been used. The following components are specific to the dialog system being created:

- Multimodal GF grammars for input and output.
- A *dialog manager*. The dialog manager can be a simple program written in a general-purpose programming language as in the examples shown later in this thesis, or it can be built using a framework such as Trindikit [25].
- Any domain resources for the specific domain (such as databases, sensors, actuators etc.).
- Any non-speech input devices and their wrappers.

Communication between the components of the system (the solid arrows in figure 5.1) may be done using normal method calls, or within some agent framework. As described in sections 2.7 and 2.9, there is a Java API and an OAA wrapper for the Embedded GF Interpreter.

Note that figure 5.1 does not show a multilingual system. In a multilingual system, there would be one speech recognition grammar, speech recognizer and speech synthesizer per language.

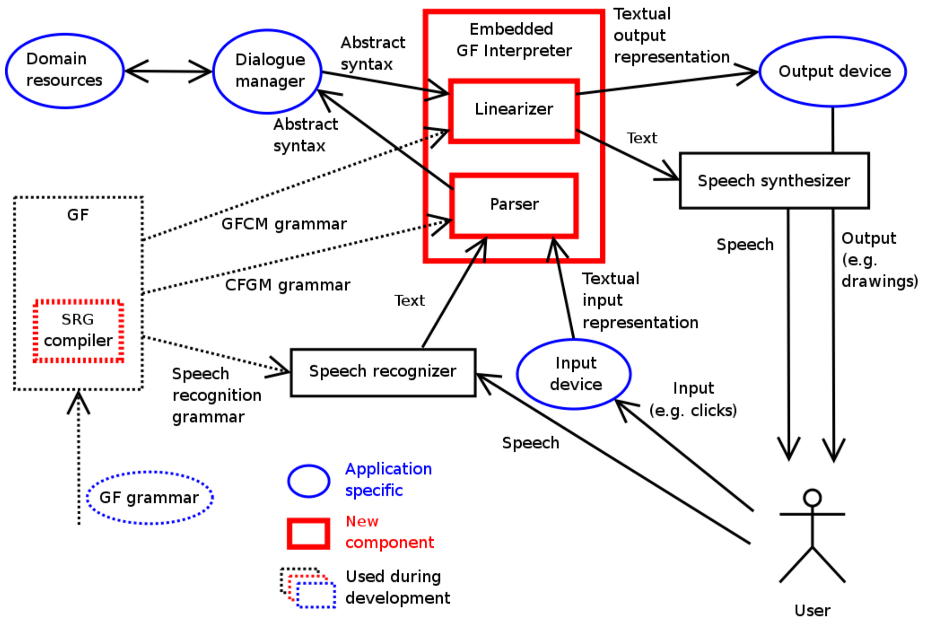


Figure 5.1: Architecture of a multimodal dialog system using the Embedded GF Interpreter.

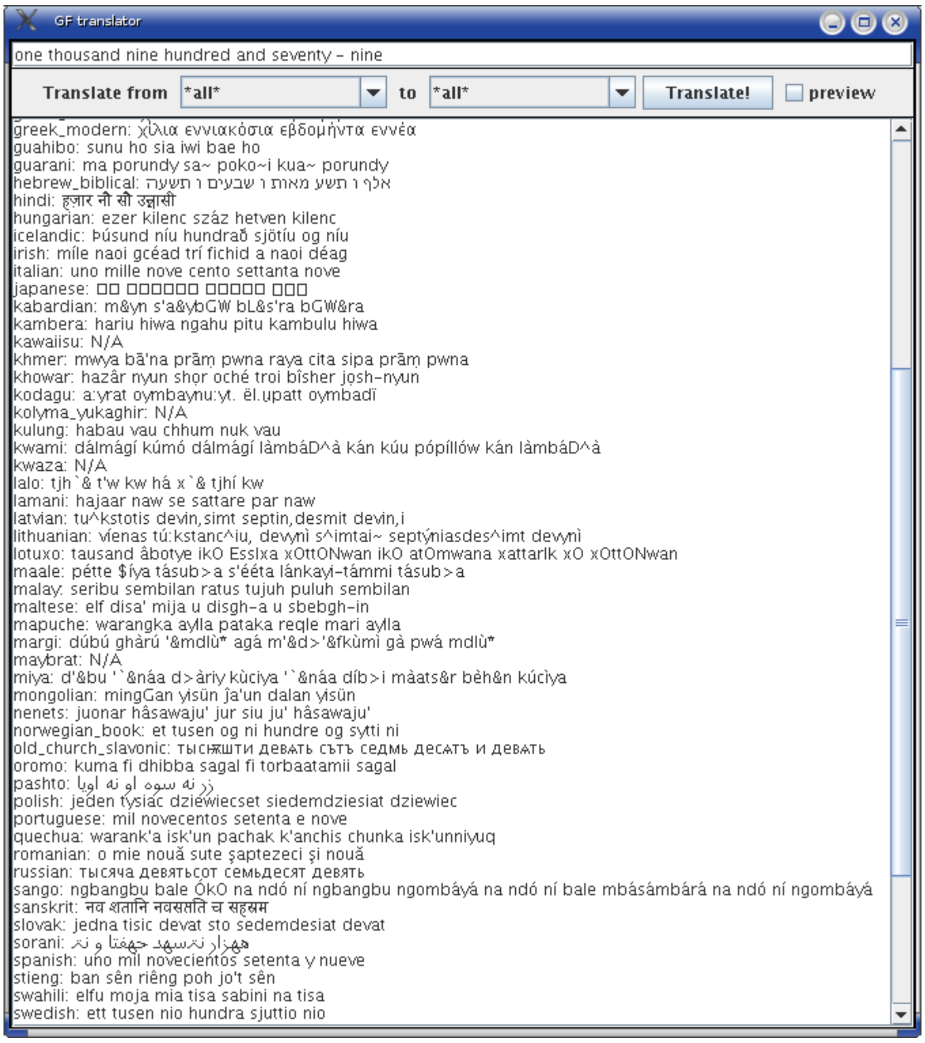
Chapter 6

Example Application: Translation Applet

The translation applet uses GF grammars to perform translation between a number of concrete syntaxes which use the same abstract syntax. The user can specify the input and output languages, or use all available languages.

The applet takes user input and calls the translation function in the Embedded GF Interpreter to translate it to the desired output language(s). If the user opts to use all input languages, all the available parsers are tried. If all output languages are used, a list of linearizations is shown.

Figure 6.1 shows the translator applet being used with the numerals grammars [26].



```
one thousand nine hundred and seventy - nine
```

```
greek_modern: χίλια εννιακόσια εβδομήντα εννέα
guahibo: sunu ho sia iwi bae ho
guarani: ma porundy sa~ poko~i kua~ porundy
hebrew_biblical: אלף ו תשע מאות ו שבעים ו תשעה
hindi: हज़ार नौ सौ उन्नासी
hungarian: ezer kilenc száz hetven kilenc
icelandic: Þúsund níu hundrað sjötíu og níu
irish: míle naoi gcéad trí fichid a naoi déag
italian: uno mille nove cento settanta nove
japanese: □□ □□□□□□ □□□□□ □□□
kabardian: m&yn s'a&ybGW bL&s'ra bGW&ra
kambera: hariu hiwa ngahu pitu kambulu hiwa
kawaiisu: N/A
khmer: mwya bā'na prāṃ pwna raya cita sipa prāṃ pwna
khowar: hazâr nyun shọr oché troi bîsher jọsh-nyun
kodagu: a:yrat oymbaynu:yt. ël.ụpatt oymbadï
kolyma_yukaghir: N/A
kulung: habau vau chhum nuk vau
kwami: dálmágí kúmó dálmágí làmbáD^à kán kúu pópíllów kán làmbáD^à
kwaza: N/A
lalo: tjh`& t'w kw há x`& tjhí kw
lamani: hajaar naw se sattare par naw
latvian: tu^kstotis devin,simt septin,desmit devin,i
lithuanian: víenas tú:kstanc^iu, devynì s^imtai~ septýniasdes^imt devynì
lotuxo: tausand âbotye ikO EssIxa xOttONwan ikO atOmwana xattarIk xO xOttONwan
maale: pétte $íya tásub>a s'ééta lánkayi-támmi tásub>a
malay: seribu sembilan ratus tujuh puluh sembilan
maltese: elf disa' mija u disgh-a u sbebgh-in
mapuche: warangka aylla pataka reqle mari aylla
margi: dúbú ghàrú '&mdlù* agá m'&d>'&fkùmì gà pwá mdlù*
maybrat: N/A
miya: d'&bu '`&náa d>àriy kùciya '`&náa díb>i màats&r bèh&n kúcìya
mongolian: mingGan yisün ĵa'un dalan yisün
nenets: juonar hâsawaju' jur siu ju' hâsawaju'
norwegian_book: et tusen og ni hundre og sytti ni
old_church_slavonic: тысѧшти девѧть сътъ седмь десѧтъ и девѧть
oromo: kuma fi dhibba sagal fi torbaatamii sagal
pashto: زر نه سوه او نه اويا
polish: jeden tysiac dziewiecset siedemdziesiat dziewiec
portuguese: mil novecentos setenta e nove
quechua: warank'a isk'un pachak k'anchis chunka isk'unniyuq
romanian: o mie nouă sute şaptezeci şi nouă
russian: тысяча девятьсот семьдесят девять
sango: ngbangbu bale ÓkO na ndó ní ngbangbu ngombáyá na ndó ní bale mbásámbárá na ndó ní ngombáyá
sanskrit: नव शतानि नवसप्तति च सहस्रम
slovak: jedna tisic devat sto sedemdesiat devat
sorani: هەزار نەسهد حهفتا و نۆ
spanish: uno mil novecientos setenta y nueve
stieng: ban sên riêng poh jo't sên
swahili: elfu moja mia tisa sabini na tisa
swedish: ett tusen nio hundra sjuttio nio
```

Figure 6.1: The GF translation applet using the numerals grammars.

Chapter 7

Example Application: Automatic Speech Translation

We have implemented a system for producing domain-specific automatic uni-directional speech translators. The application uses the translation feature of the Embedded GF Interpreter, along with off-the-shelf speech recognition and speech synthesis systems.

An overview of the architecture of the speech translator is shown in figure 7.1. As might be understood from comparing figures 7.1 and 5.1, a speech translator can be seen as a special case of a unimodal dialog system, where the dialog manager is the identity function and the output language is different from the input language.

To use the translation system for a new domain or language pair, all that is needed is a bilingual GF grammar, a speech recognizer for the input language and a speech synthesizer for the output language. The GF system and the speech recognition grammar compiler (see chapter 4) are used to create grammars for the speech recognizer, parser and linearizer. The output of the speech recognizer is translated using the translation function in the Embedded GF Interpreter and the output is fed to the speech synthesizer.

Implementing the speech translator required less than 100 lines of Java code, demonstrating the relative ease with which natural language applications can be developed when using embedded grammars. Of course the real complexity of any useful translator constructed using this system is in the grammars, but writing the grammars is essentially the same as specifying the translation function of the system. The developer does not have to create all the supporting infrastructure.

As fully general speech translation would seem to require artificial intelligence comparable to that of humans, this system cannot be expected evolve into a *Babel fish* [27]. However, for restricted domains where grammars with acceptable coverage can be written, the concept seems promising. So far the system has only been tested with very small grammars, and it might be dangerous to extrapolate from such experiments. For example, if the grammar is ambiguous it can be difficult for the system to present all possible translations in some way understandable to the user, not to mention choosing the right alternative.

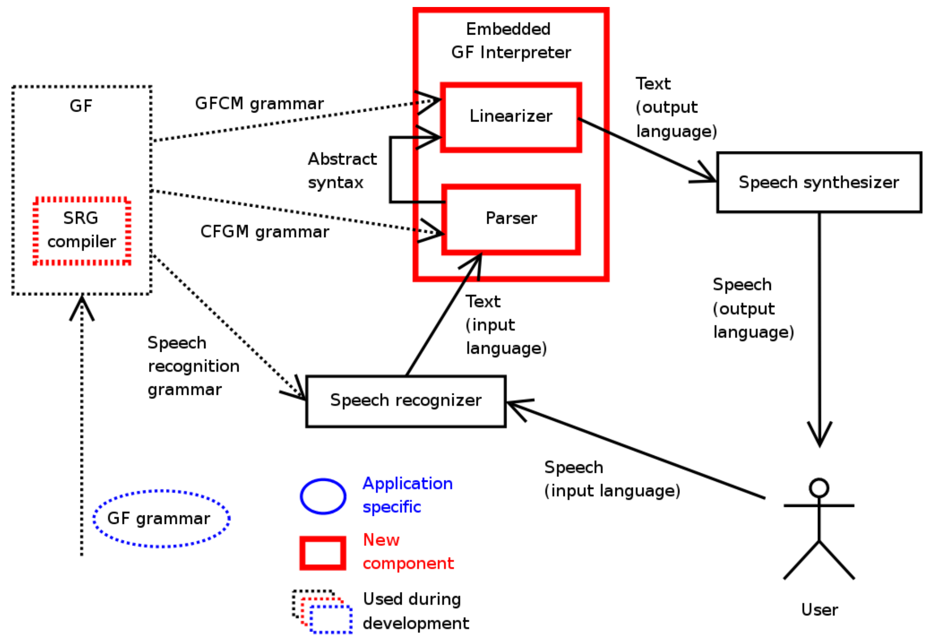


Figure 7.1: Architecture of the GF Speech Translator.

Chapter 8

Example Application: Simple Dialog System

8.1 Introduction

The Hello World dialog system is a very simple multilingual unimodal dialog system. The system accepts the speech inputs “Here you go” and “Thanks”, and responds with “Thanks” and “You are welcome”, respectively. The user may speak in English or Swedish, and the system responds in the same language as the user used.

The purpose of this system is to make a simple dialog system which is small enough to be easily understood. The grammars are extremely basic, but the framework should be sufficient to develop a more sophisticated dialog system. For an example of a larger system, see chapter 9. The grammars used in the application are shown below, and the Java source code is shown in appendix B.

8.2 Grammars

A module graph of the Hello World dialog system grammars is shown in figure 8.1. This module graph has been produced with a module dependency visualization tool developed as part of this thesis. See section 10.3 for a description of this tool and the meaning of the different kinds of nodes and edges in such graphs.

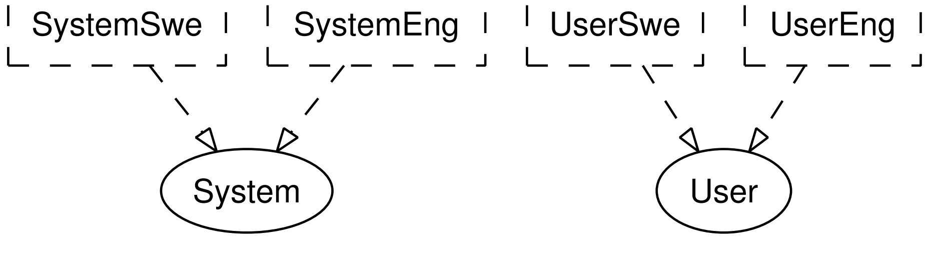


Figure 8.1: Hello World dialog system grammar modules.

8.2.1 User Utterance Grammar

Abstract Syntax

```
abstract User = {
  cat Input ;
  fun HereYouGo : Input ;
  fun Thanks : Input ;
}
```

English Concrete Syntax

```
concrete UserEng of User = {
  flags startcat = Input ;
  lincat Input = { s : Str };
  lin HereYouGo = { s = "here" ++ "you" ++ "go" } ;
  lin Thanks = { s = "thanks" };
}
```

Swedish Concrete Syntax

```
concrete UserSwe of User = {
  flags startcat = Input ;
  lincat Input = { s : Str };
  lin HereYouGo = { s = "varsågod" } ;
  lin Thanks = { s = "tack" };
}
```

8.2.2 System Utterance Grammar

Abstract Syntax

```
abstract System = {
  cat Output ;
  fun Thanks : Output ;
  fun Welcome : Output ;
}
```

English Concrete Syntax

```
concrete SystemEng of System = {
  flags startcat = Output ;
  lincat Output = { s : Str } ;
  lin Thanks = { s = "thanks" } ;
  lin Welcome = { s = "you" ++ "are" ++ "welcome" } ;
}
```

Swedish Concrete Syntax

```
concrete SystemSwe of System = {
  flags startcat = Output ;
  lincat Output = { s : Str } ;
  lin Thanks = { s = "tack" } ;
  lin Welcome = { s = "varsågod" } ;
}
```

Chapter 9

Example Application: Göteborg Tram Information System (GOTTIS)

9.1 Introduction

The Göteborg Tram Information System (GOTTIS) is a demonstration of a multilingual multimodal dialog system. It finds the shortest path through (a subset of) the Göteborg public transportation network. User input consists of spoken queries along with clicks on a map of the transport network. The system responds with spoken instructions and drawings on the network map.

The system is easily adaptable to other transport networks or other systems which can be represented as weighted directed graphs.

The system uses multimodal GF grammars for user and system utterances. The user modalities are speech and map clicks, and the system modalities are speech and drawings on the map. Input and output in all the modalities are handled by multilingual, multimodal grammars. For brevity and clarity, the following sections show English concrete syntax exclusively. For every concrete English module shown below, the application also contains a corresponding module for Swedish concrete syntax.

9.2 Grammar Overview

The user and system grammars are split up into a number of modules in order to make reuse and modification simpler. Overviews of the query and answer grammar modules are shown in figures 9.1 and 9.2, respectively. See section 10.3 for an explanation of module graphs. The following sections show the details of the grammar modules.

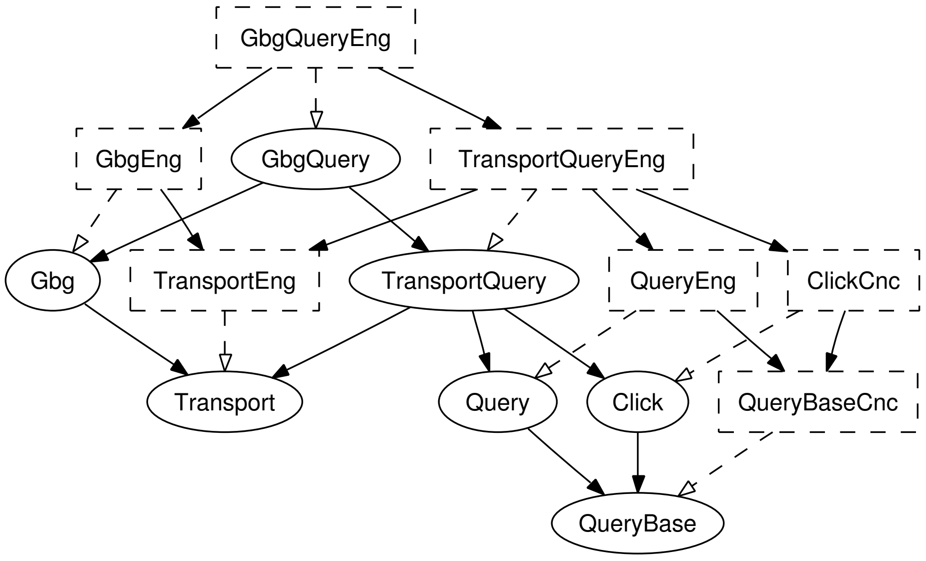


Figure 9.1: Query grammar modules.

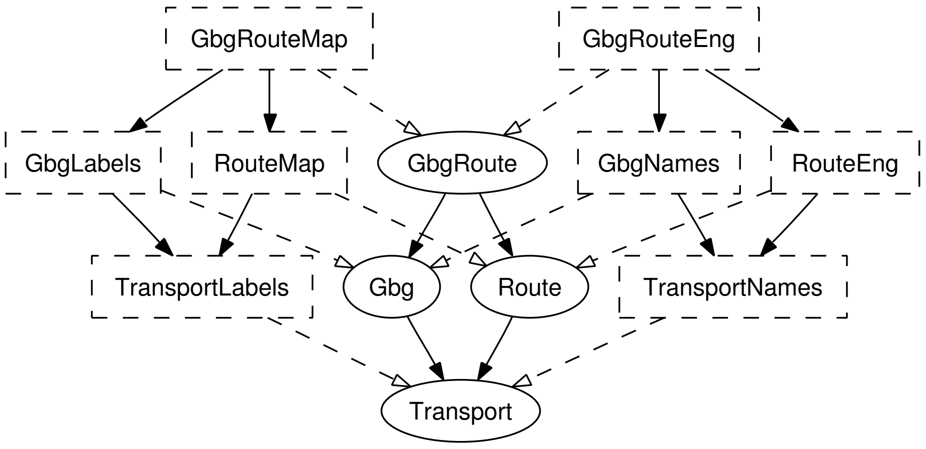


Figure 9.2: Answer grammar modules.

9.3 Transport Network Grammar

The transport network is represented by a set of modules which are used in both the query and answer grammars. Since the transport network is described in a separate set of modules, the Göteborg transport network may be replaced easily.

9.3.1 Generic Abstract Syntax for Transport Networks

The interface for transport network grammars is very simple. Such a grammar simply exports a number of constants in the Stop category.

```
abstract Transport = {
    cat Stop ;
}
```

9.3.2 Generic Concrete Syntax for Transport Networks

The English concrete syntax is equally simple. Languages which inflect proper nouns might need a more complex linearization type for stops.

```
concrete TransportEng of Transport = {
    lincat Stop = { s : Str } ;
}
```

9.3.3 Göteborg Abstract Syntax

The abstract syntax for a given transport network lists the stops.

```
abstract Gbg = Transport ** {
    fun Angered : Stop ;
    fun AxelDahlstromsTorg : Stop ;
    fun Bergsjon : Stop ;
    fun Biskopsgarden : Stop ;
    ...
}
```

9.3.4 Göteborg Concrete Syntaxes

Since names are not normally translated between languages, they introduce a problem for speech recognition. We would like the map to show the names of tram/bus stops in their native orthography. This is done with one concrete syntax:

```
concrete GbgNames of Gbg = TransportNames ** {
    lin Angered = { s = ["Angered"] } ;
    lin Bergsjon = { s = ["Bergsjön"] } ;
    lin Biskopsgarden = { s = ["Biskopsgården"] } ;
    ...
}
```

However, speech recognizers often do not support characters not used in the language which they recognize. Furthermore, some recognizers, such as Nuance [21], do not allow capitals in the recognized text [20]. Therefore, we introduce a different concrete syntax for stop names for each language. In the English syntax, accented characters have the diacritics removed and all letters are converted to lower case.

```
concrete GbgEng of Gbg = TransportEng ** {
    lin Angered = { s = ["angered"] } ;
    lin Bergsjon = { s = ["bergsjon"] } ;
    lin Biskopsgarden = { s = ["biskopsgarden"] } ;
    ...
}
```

Since stop names are also used in the click and drawing modalities, we need an easily machine readable and writable syntax. This is achieved by removing spaces and diacritics from the stop names:

```
concrete GbgLabels of Gbg = TransportLabels ** {
    lin Angered = { s = ["Angered"] } ;
    lin Bergsjon = { s = ["Bergsjon"] } ;
    lin Biskopsgarden = { s = ["Biskopsgarden"] } ;
    ...
}
```

9.4 Multimodal Input Grammars

User input is done with integrated speech and click modalities. The user may use speech only, or speech combined with clicks on the map. Clicks are expected when the user makes a query containing "here" (though "here" might also be used without a click, see section 9.4.4).

Clicks are represented as a list of places that the click might refer to. Normally this is a singleton list containing a single bus/tram stop, but some stops might be close enough that a click could refer to more than one stop. The set might also be empty if the click was not close to any stop.

In the concrete syntax, the click data is appended to the speech input to give the parser a single string to parse. These are some examples using the English concrete syntax:

- "i want to go from brunnsparken to vasaplatsen;"
- "i want to go from vasaplatsen to here; [Chalmers]"
- "i want to go from here to here; [Chalmers] [Saltholmen]"

9.4.1 Common Declarations

The QueryBase module contains declarations common to all input modalities:

```
abstract QueryBase = {
    cat
```

```
        Query ;  -- sequentialized input representation
        Input ;  -- user input: parallel text and clicks
        Click ;  -- map clicks
      fun
        QInput : Input -> Query ; -- sequentialize user input
  }
```

QueryBase has a single concrete syntax since it is language neutral:

```
  concrete QueryBaseCnc of QueryBase = {
      lincat
        Query = { s : Str } ;
        Input = { s1 : Str ; s2 : Str } ;
        Click = { s : Str } ;
      lin
        QInput i = { s = i.s1 ++ ";" ++ i.s2 } ;
  }
```

9.4.2 Click Modality

Clicks are represented by a list of stops that the click might refer to:

```
  abstract Click = QueryBase ** {
      cat
        StopList ; -- a list of stop names
      fun
        CStops : StopList -> Click ;
        NoStop : StopList ;
        OneStop : String -> StopList ;
        ManyStops : String -> StopList -> StopList ;
  }
```

The same concrete syntax is used for clicks in all languages:

```
  concrete ClickCnc of Click = QueryBaseCnc ** {
      lincat
        StopList = { s : Str } ;
      lin
        CStops xs = { s = "[" ++ xs.s ++ "]" } ;
        NoStop = { s = "" } ;
        OneStop x = { s = x.s } ;
        ManyStops x xs = { s = x.s ++ "," ++ xs.s } ;
  }
```

9.4.3 Speech Modality

The Query module adds basic user queries and a way to use a click to indicate a place:

```
  abstract Query = QueryBase ** {
      cat
      Place ; -- any way to identify a place
    fun
      GoFromTo : Place -> Place -> Input ;
      GoToFrom : Place -> Place -> Input ;
      PClick   : Click -> Place ;  -- "here" and a click
}
```

The corresponding English concrete syntax is:

```
concrete QueryEng of Query = QueryBaseCnc ** {
    lincat
      -- speech and click representations of a place
      Place = {s1 : Str; s2 : Str} ;
    lin
      GoFromTo x y = {
        s1 = ["i want to go from"] ++ x.s1 ++ "to" ++ y.s1 ;
        s2 = x.s2 ++ y.s2
      } ;
      GoToFrom x y = {
        s1 = ["i want to go to"] ++ x.s1 ++ "from" ++ y.s1 ;
        s2 = x.s2 ++ y.s2
      } ;
      PClick c = { s1 = "here" ; s2 = c.s } ;
}
```

9.4.4 Indexicality

To refer to her current location, the user can use “here” without a click, or omit either origin or destination. The system is assumed to know where the user is located. Examples of indexical queries in the English concrete syntax include:

- “i want to go from here to centralstationen;”
- “i want to go to valand;”
- “i want to come from brunnsparken;”

These are the abstract syntax declarations for this feature (in the Query module):

```
    fun
      -- indexical "here", without a click
      PHere    : Place ;
      -- "want to come from a" (to where I am now)
      ComeFrom : Place -> Input ;
      -- "want to go to a" (from where I am now)
      GoTo     : Place -> Input ;
```

The English concrete syntax for this is (in the QueryEng module):

```
    lin
      PHere = { s1 = "here" ; s2 = [] } ;
```

```
        ComeFrom x = {
          s1 = ["i want to come from"] ++ x.s1 ;
          s2 = x.s2
        } ;
        GoTo x = {
          s1 = ["i want to go to"] ++ x.s1 ;
          s2 = x.s2
        } ;
```

9.4.5 Ambiguity

Some strings may be parsed in more than one way. Since "here" may be used with or without a click, input with two occurrences of "here" and only one click is ambiguous. The utterance "i want to go from here to here; [Valand]" is an example of such an ambiguous input.

A query might also be ambiguous even if it can be parsed unambiguously, since one click can correspond to multiple stops, for example in the input "i want to go from Chalmers to here; [Klareberg,Tagene]".

The current application fails to produce any output for ambiguous queries. A real system should handle this through dialog management.

9.5 Multimodal Output

The system's answers to the user's queries are presented with speech and drawings on the map. This is an example of parallel multimodality as the speech and the map drawings are independent.

The information presented in the two modalities is however not identical as the spoken output only contains information about when to change trams/buses. The map output shows the entire path, including intermediate stops.

Parallel multimodality is from the system's point of view just a form of multilinguality. The abstract syntax representation of the system's answers has one concrete syntax for the drawing modality, and one for each natural language. The only conceptual difference between the natural language syntaxes and the drawing one is that the latter is a formal language rather than a natural one.

9.5.1 Abstract Syntax for Multimodal Output

The abstract syntax for answers (routes) contains the information needed by all the concrete syntaxes. All concrete syntaxes might not use all of the information. A route is a non-empty list of legs, and a leg consists of a line and a list of at least two stops.

```
  abstract Route = Transport ** {
      cat
        Route; -- route description
        Leg;   -- route segment on a single line
        Line;  -- bus/tram line
        Stops; -- list of at least two stops
      fun
        -- leg followed by a route
      Then : Leg -> Route -> Route ;
      -- single leg
      OneLeg : Leg -> Route ;
      -- leg on a line
      LineLeg : Line -> Stops -> Leg ;
      -- line labelled by a string
      NamedLine : String -> Line ;
      -- stop followed by some stops
      ConsStop : Stop -> Stops -> Stops ;
      -- last two stops
      TwoStops : Stop -> Stop -> Stops ;
}
```

9.5.2 Map Drawing Concrete Syntax

The map drawing language contains sequences of labeled edges to be drawn on the map. The string "drawEdge (6, [Chalmers, Vasaplatsen]); drawEdge (2, [Vasaplatsen, Gronsakstorget, Brunnsparken]);" is an example of a string in the map drawing language described by this concrete syntax:

```
concrete RouteMap of Route = TransportLabels ** {
    lincat
      Route = { s : Str } ;
      Leg = { s : Str } ;
      Line = { s : Str } ;
      Stops = { s : Str } ;
    lin
      Then l r = { s = l.s ++ ";" ++ r.s } ;
      OneLeg l = { s = l.s ++ ";" } ;
      LineLeg l ss =
        { s = "drawEdge" ++ "(" ++ l.s ++ ","
               ++ "[" ++ ss.s ++ "]" ++ ")" } ;
      NamedLine n = { s = n.s } ;
      ConsStop s ss = { s = s.s ++ "," ++ ss.s } ;
      TwoStops s1 s2 = { s = s1.s ++ "," ++ s2.s } ;
}
```

9.5.3 English Concrete Syntax

In the English concrete syntax we wish to list only the first and last stops of each leg of the route.

```
concrete RouteEng of Route = TransportNames ** {
    lincat
      Route = { s : Str } ;
      Leg = { s : Str } ;
      Line = { s : Str } ;
      -- stop list is linearized to its first and last stops
      Stops = { start : Str; end : Str } ;
    lin
```

```
        Then l r = { s = l.s ++ "." ++ r.s } ;
        OneLeg l = { s = l.s ++ "." } ;
        LineLeg l ss =
          { s = "Take" ++ l.s ++ "from" ++ ss.start
                              ++ "to" ++ ss.end } ;
        NamedLine n = { s = n.s } ;
        ConsStop s ss = { start = s.s; end = ss.end } ;
        TwoStops s1 s2 = { start = s1.s; end = s2.s } ;
}
```

9.6 Example Interaction

The user says "I want to go from chalmers to here" and clicks on Frihamnen. This is represented by the input string "i want to go from chalmers to here; [Frihamnen]". From this, the parser produces this abstract syntax representation:

```
QInput (GoFromTo (PStop Chalmers)
                 (PClick (CStops (OneStop "Frihamnen"))))
```

The system responds:

```
Then (LineLeg (NamedLine "6")
     (TwoStops Chalmers Vasaplatsen))
 (Then (LineLeg (NamedLine "2")
       (ConsStop Vasaplatsen
                 (TwoStops Gronsakstorget Brunnsparken)))
  (OneLeg (LineLeg (NamedLine "5")
          (ConsStop Brunnsparken
                    (TwoStops LillaBommen Frihamnen)))))
```

This is linearized to the speech output "Take 6 from Chalmers to Vasaplatsen. Take 2 from Vasaplatsen to Brunnsparken. Take 5 from Brunnsparken to Frihamnen.".

In order to draw the route on the map, the abstract syntax term is also linearized to the drawing instructions "drawEdge (6, [Chalmers, Vasaplatsen]); drawEdge (2, [Vasaplatsen, Gronsakstorget, Brunnsparken]); drawEdge (5, [Brunnsparken, LillaBommen, Frihamnen]);". The map with this output is shown in figure 9.3.

9.7 Multilinguality

Currently, speech input and output in English and Swedish are implemented. The dialog system itself accepts input in either language, but speech recognizers can often only handle a single language at a time.

System output is linearized using the same language as the speech input was in.

Adding support for a new language requires writing concrete syntaxes for the user and system grammars.

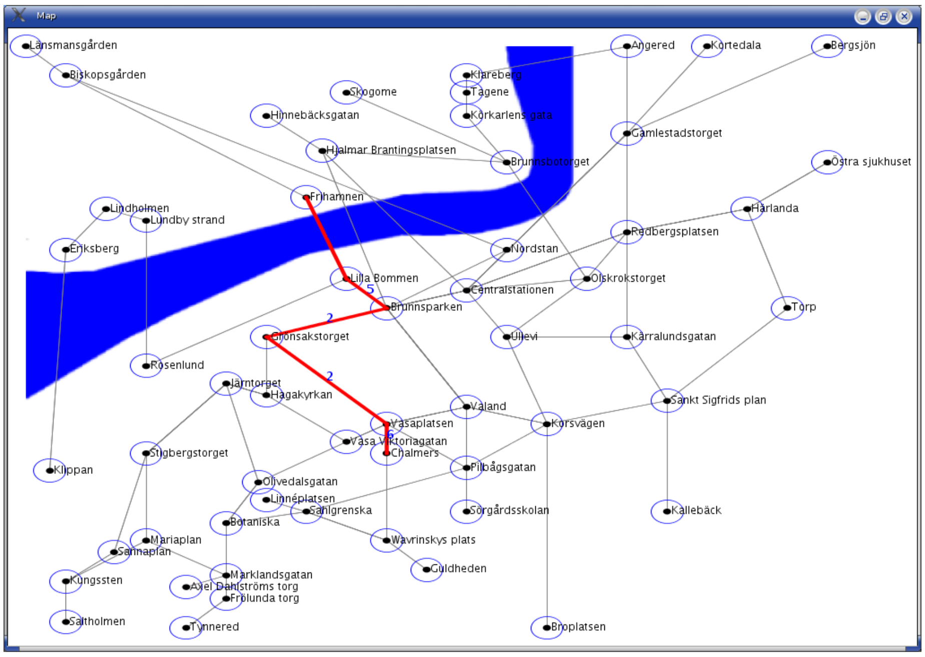


Figure 9.3: The map showing the path from Chalmers to Frihamnen.

9.8 Component Overview

The application consists of a number of OAA [12] agents:

- Speech recognizer - The Nuance [21] speech recognizer using Nuance-Wrapper [28]. The speech recognition grammar is generated from the GF user grammar.
- Clickable map and path drawing - MapAgent [29], an OAA agent written in Java.
- Parser and linearizer (multilingual and multimodal) - The Embedded GF Interpreter through its OAA interface.
- Shortest path finder - OAA agent written in Java.
- Speech synthesis - FreeTTS [30] over OAA using FreeTTSAgent [31].

9.9 Application Limitations

There is no dialog management in this version. Queries that have do not have exactly one interpretation are not answered. The purpose of this application is to demonstrate use of multimodal and multilingual grammars. Adding dialog management should be orthogonal to this.

There is no handling of departure times, only time between stops. Adding support for this would be relatively straightforward, but would require some effort to support time expressions. The shortest-path algorithm would also need to be changed to take waiting times into account.

The current system is not usable for practical route planning since the Göteborg public transit network description is incomplete and out-of-date.

9.10 Future Work

Whereas we have only investigated the use of drawings for system output (and quite simple ones at that), one could also imagine using them for user input. In the example system, the user could for example circle a number of stops on the map to indicate a set of possible origin or destination stops.

9.11 Conclusions

The system presented in this paper makes the combination of information from different modalities part of the grammar, whereas many other systems do this in a fairly ad-hoc way.

Since GF warns the user (or gives an error message) when the abstract and concrete syntaxes are inconsistent, it is easy to keep the grammars in sync during development.

Automatic generation of speech recognition grammars eliminates the work of writing a separate grammar for the speech recognizer and keeping it consistent with the grammar used by the dialog system.

Chapter 10

Grammar Development Tools

10.1 Introduction

Writing a GF grammar for a new domain or language can be a demanding task, which may require in-depth knowledge both of the domain and of the target language. Large grammars can also be fairly complex and difficult to grasp. If embedded GF grammars are to be useful, it must be feasible to develop new grammars. This chapter discusses some tools aimed at supporting grammar writers.

10.2 Resource Grammars

Resource grammars [13] are general grammars for some language, whose writer is knowledgeable in the grammar of the target language. They contain the syntactic constructs and morphology of the language, along with general purpose vocabulary. Resource grammars can be used by writers of domain-specific grammars to avoid reimplementing the basic machinery of the target language. Resource grammars for a number of languages have already been developed.

10.3 Grammar Visualization

As shown in chapter 9, GF grammars can consist of many modules which may use each other. In order to give an intuition about the relationships between the different modules, a tool for visualizing module dependencies has been developed as part of this thesis. The GF system has been extended to produce a graph description in the DOT [32] language. The `dot` program can then be used to produce images from such descriptions. The module graphs in chapters 8 and 9 (figures 8.1, 9.1 and 9.2) have been produced with this tool.

In the module dependency graphs, nodes with a solid border represent abstract modules and square nodes with a dashed border are concrete modules. Between a concrete module and the abstract module for which it is the concrete syntax, a dashed edge is drawn. Solid edges represent module inheritance for both abstract and concrete modules. Dashed round nodes are resource modules and a dotted edge from one module to another means that the former opens the latter.

10.4 Future Work

10.4.1 Grammar development IDE

For many programming languages, there are development environments which assist the developer in writing programs. Some features inspired by such IDEs may be useful when writing GF grammar. This might include features such as module overviews, code highlighting, support for testing parsing and linearization, documentation browsers, the ability to chose functions from a list of available ones and generation of linearization terms by parsing example strings. Janna Khegai has recently demonstrated [33] a system with some of these capabilities.

Chapter 11

Related Work

11.1 GF Gramlets

The *GF Gramlets* [14] system produces syntax editors in the form of Java applets for a given GF grammar. Gramlets implement syntax editing and linearization using XML representations of GF grammars. While Gramlets and the Embedded GF Interpreter do not share any code, Gramlets provided inspiration for and a hint of the usefulness of writing a general GF interpreter in Java. In the future, we hope to adapt the Gramlets system to use the Embedded GF Interpreter.

11.2 Embedding the Full GF System

Some applications have been written which use the full GF system as a resource. This can be done in two ways, either by communicating with the interactive `gf` program by using pipes [5, 6], or by using the GF Haskell API [34, 35].

11.3 Embedded Context-Free Grammars

Parser generators such as Yacc [36] and Happy [37] are tools for embedding context-free grammars into applications. Such tools normally support only context-free grammars, and are aimed at parsing formal languages. They do generally not support linearization. BNFC [9] is a compiler front-end generator which supports parsing and linearization of context-free languages. Compared to such tools, the main advantages of the work described in this thesis are the power of the GF grammar formalism and the natural support for linearization and multilinguality.

11.4 Attribute Grammars

Attribute grammars [38, 39] are context-free grammars where each symbol has a set of associated attributes. There are semantic rules associated with the productions which define how the attribute values are computed. Whereas embedded grammars as described in this thesis are grammars embedded in programs, attribute grammars can be seen as programs embedded in grammars.

11.5 Prolog Definite Clause Grammars

Many Prolog systems support a grammar notation known as Definite Clause Grammar (DCG) [40]. DCGs are translated into Prolog and can be used for both parsing and generation. Since DCGs can be used directly from Prolog programs, they can be considered examples of embedded grammars. It is possible to write DCGs which use language-independent abstract syntax trees, as demonstrated by the GF-inspired approach presented by Dymetman et al [41].

11.6 OpenCCG

OpenCCG [42] is a Java library which provides parsing and linearization for Combinatory Categorial Grammars (CCG) [43]. Compared to GF, the notion of abstract syntax in CCG is fairly tightly coupled to the concrete syntax [3]. This seems to make it difficult to write multiple concrete syntaxes with the same abstract syntax, something which is essential for the way in which multilinguality is achieved in GF grammars.

11.7 External Grammars Tools

There are a number of stand-alone tools which implement parsing and linearization for different grammar formalisms. While these share some features with the systems described in this thesis, they are often designed for experimenting with writing grammars in their respective formalisms and are seldom meant to be used in an embedded fashion.

Examples of such systems include Linguistic Knowledge Building (LKB) [44] for the Head-Driven Phrase Structure Grammar (HPSG) [45] formalism and Xerox Linguistics Environment (XLE) [46] for the Lexical Functional Grammar (LFG) [47] formalism.

11.8 Multimodal Grammars

Michael Johnston [48] describes unification-based multimodal parsing. His approach is to extend chart parsing to multiple dimensions and to use unification to integrate information from different modalities. The approach described in chapter 3 achieves a similar result by using records along with the existing unification mechanism for resolving reduplication.

11.9 Generating Speech Recognition Grammars

Dowding et al [49] describe generation of context-free speech recognition grammars from unification grammars. The Regulus [50] system is an open source implementation of these ideas.

11.10 Speech Translation

The Verbmobil [51] system is a sophisticated system for speech-to-speech translation. It uses multiple concurrent translation engines, one of which is a semantic transfer engine. Our purely grammar-based system will of course be unlikely to be as robust and accurate as the hybrid approach used in Verbmobil, but the low cost could make it an attractive alternative for some applications.

Chapter 12

Future Work

Many of the previous chapters list future work to be done in their respective areas. This chapter will outline some possibilities for future work on embedded grammars in general.

12.1 Non-human Interaction Grammars

Grammars can be used also for non-human computer interaction tasks, such as communication between system components or with external systems.

Many communication standards and data formats are described by grammars, and it might be feasible to use embedded grammars to implement support for such systems.

Chapter 13

Conclusions

13.1 Contributions

This thesis describes the following contributions to the area of embedded grammars:

The Embedded GF Interpreter An embeddable lightweight interpreter for GF grammars which supports parsing, linearization and translation.

GF to speech recognition grammar compiler A tool for compiling Grammatical Framework grammars to common speech recognition grammar formats to ease integration with speech recognition systems and remove the problem of keeping multiple equivalent grammars in sync.

Grammar module visualization tool A tool for visualizing dependencies between GF grammar modules as directed graphs.

Speech translator A general unidirectional speech translator which translates between any two concrete GF syntaxes which share a common abstract syntax.

Multimodal multilingual dialog system demo A multimodal and multilingual dialog system based on the use of multimodal and multilingual grammars.

The tools we have presented in this thesis make it easy to create complete grammar-based natural language applications, which is demonstrated by the example applications. The GF Speech Translator described in chapter 7 is an extreme example of the power of embedded grammars. The application source code is essentially just glue between existing components. Changing the application to a new domain or language pair only requires new grammars. As the dialog system example in chapter 9 shows, the use of embedded grammars reduces the task of creating a multimodal and multilingual natural language user interface to writing grammars and programs which work on abstract syntax terms.

13.2 Software Availability and Licensing

All stand-alone software written as part of this thesis is available from `http://www.cs.chalmers.se/~bringert/`. The parts integrated into the GF system are available as part of GF from `http://www.cs.chalmers.se/~aarne/GF/`.

All code written as part of this thesis is distributed under the GNU General Public License (GPL) [52].

Bibliography

[1] P. Martin-Löf, *Intuitionistic Type Theory.* Naples: Bibliopolis, 1984.

[2] A. Ranta, "Grammatical Framework, a type-theoretical grammar formalism," *The Journal of Functional Programming*, vol. 14, no. 2, pp. 145–189, 2004.

[3] P. Ljunglöf, *Expressivity and Complexity of the Grammatical Framework.* PhD thesis, Göteborg University, Gothenburg, Sweden, November 2004.

[4] D. A. Burke, "Improving the natural language translation of formal software specifications," Master's thesis, Chalmers University of Technology, Gothenburg, Sweden, December 2004.

[5] J. Khegai, B. Nordström, and A. Ranta, "Multilingual syntax editing in GF," in *CICLing*, pp. 453–464, 2003.

[6] R. Hähnle, K. Johannisson, and A. Ranta, "An authoring tool for informal and formal requirements specifications," in *Fundamental Approaches to Software Engineering* (R.-D. Kutsche and H. Weber, eds.), no. 2306 in LNCS, 2002.

[7] J. Gosling, B. Joy, G. Steele, and G. Bracha, *The Java Language Specification.* Sun Microsystems, Inc., third ed., 2005. Proposed third edition: `http://java.sun.com/docs/books/jls/java_language-3_0-mr-spec.zip`.

[8] P. Ljunglöf, "Functional chart parsing of context-free grammars," *The Journal of Functional Programming*, vol. 14, no. 6, pp. 669–680, 2004.

[9] M. Forsberg and A. Ranta, "The BNF Converter: A high-level tool for implementing well-behaved programming languages," in *NWPT'02 proceedings, Proceedings of the Estonian Academy of Sciences*, December 2003.

[10] B. Bringert, "Embedded GF Interpreter Java API." `http://www.cs.chalmers.se/~bringert/gf/gf-java.html`.

[11] E. Gamma, R. Helm, R. Johnson, and J. Vlissides, *Design patterns: elements of reusable object-oriented software.* Addison-Wesley Longman Publishing Co., Inc., 1995.

[12] D. L. Martin, A. J. Cheyer, and D. B. Moran, "The Open Agent Architecture: A framework for building distributed software systems," *Applied Artificial Intelligence*, vol. 13, pp. 91–128, January–March 1999.

[13] J. Khegai, "Language engineering in Grammatical Framework." Licentiate Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2003.

[14] M. Forsberg, K. Johannisson, J. Khegai, and A. Ranta, "GF Gramlets." `http://www.cs.chalmers.se/~krijo/gramlets.html`.

[15] T. Coquand, "An algorithm for type-checking dependent types," *Science of Computer Programming*, vol. 26, no. 1–3, pp. 167–177, 1996.

[16] B. Bringert, R. Cooper, P. Ljunglöf, and A. Ranta, "Development of multimodal and multilingual grammars: viability and motivation." Deliverable D1.2a, TALK Project, IST-507802, December 2004.

[17] A. Hunt, "JSpeech Grammar Format." W3C Note, June 2000.

[18] Sun Microsystems, Inc., *Java Speech API Programmer's Guide*, October 1998.

[19] Sun Microsystems, Inc., *Java Speech API Specification*, 1998.

[20] Nuance Communications, Inc., Menlo Park, CA, USA, *Nuance Speech Recognition System 8.5: Grammar Developer's Guide*, December 2003.

[21] Nuance Communications, Inc., Menlo Park, CA, USA, *Nuance Speech Recognition System 8.5: Introduction to the Nuance System*, December 2003.

[22] "Speech recognition grammar specification version 1.0." W3C Recommendation, March 2004.

[23] R. C. Moore, "Removing left recursion from context-free grammars," in *Proceedings of the first meeting of the North American chapter of the Association for Computational Linguistics*, pp. 249–255, Morgan Kaufmann Publishers Inc., 2000.

[24] S. Young, *ATK - An Application Toolkit for HTK.* Machine Intelligence Laboratory, Cambridge University Engineering Dept, Trumpington Street, Cambridge, CB2 1PZ, United Kingdom, 1.4.1 ed., July 2004.

[25] S. Larsson and D. Traum, "Information state and dialogue management in the TRINDI dialogue move engine toolkit," *Natural Language Engineering Special Issue on Best Practice in Spoken Language Dialogue Systems Engineering*, pp. 323–340, 2000.

[26] H. Hammarström and A. Ranta, "Cardinal Numerals Revisited in GF." Abstract accepted to Workshop on Numerals in the World's Languages, Dept. of Linguistics Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany, March 2004.

[27] D. Adams, *The Hitchhiker's Guide to the Galaxy.* Pan Macmillan, October 1979.

[28] D. Hjelm, *NuanceWrapper manual.* Göteborg University, Gothenburg, Sweden, June 2004.

[29] B. Bringert, “MapAgent,” December 2004. `http://www.cs.chalmers.se/~bringert/gf/map-agent.html`.

[30] Sun Microsystems, Inc., *FreeTTS Programmer’s Guide*, 2003.

[31] H. Burden, *FreeTTS Agent for OAA.* Göteborg University, Gothenburg, Sweden. `http://www.ling.gu.se/projekt/talk/software/reports/freeTTSAgentReport.%pdf`.

[32] E. Koutsofios and S. C. North, *Drawing graphs with dot.* AT&T Bell Laboratories, Murray Hill, NJ.

[33] J. Khegai, “GF IDE for GF 2.1,” January 2005. `http://www.cs.chalmers.se/~aarne/GF/GF-Doc/GF_IDE_manual/index.htm`.

[34] T. Hallgren and A. Ranta, “An extensible proof text editor,” in *LPAR-2000* (M. Parigot and A. Voronkov, eds.), vol. 1955 of *LNCS/LNAI*, pp. 70–84, Springer, 2000.

[35] D. A. Burke and K. Johannisson, “Translating formal software specifications to natural language — a grammar-based approach,” To be published in proceedings of LACL’05.

[36] S. C. Johnson, “Yacc: Yet another compiler compiler,” in *UNIX Programmer’s Manual*, vol. 2, pp. 353–387, New York, NY, USA: Holt, Rinehart, and Winston, 1979.

[37] A. Gill and S. Marlow, “Happy: The parser generator for Haskell.” `http://haskell.org/happy/`.

[38] D. E. Knuth, “Semantics of context-free languages.,” *Mathematical Systems Theory*, vol. 2, no. 2, pp. 127–145, 1968.

[39] D. E. Knuth, “Correction: Semantics of context-free languages.,” *Mathematical Systems Theory*, vol. 5, no. 1, pp. 95–96, 1971.

[40] “Definite clauses for language analysis,” *Artificial Intelligence*, vol. 13, pp. 231–278, 1980.

[41] M. Dymetman, V. Lux, and A. Ranta, “XML and multilingual document authoring: Convergent trends,” in *COLING, Saarbrücken, Germany*, pp. 243–249, 2000.

[42] “The OpenCCG Homepage.” `http://openccg.sourceforge.net/`.

[43] M. Steedman, “A very short introduction to CCG.” `ftp://ftp.cis.upenn.edu/pub/steedman/ccg/ccgintro.ps.gz`, November 1996.

[44] A. Copestake, *Implementing Typed Feature Structure Grammars.* Stanford, CA, USA: CSLI, December 2001.

[45] C. J. Pollard and I. A. Sag, *Head-Driven Phrase Structure Grammar.* Chicago, IL, USA: University of Chicago Press, 1994.

[46] “Xerox Linguistics Environment project.” `http://www2.parc.com/istl/groups/nltt/xle/`.

[47] R. M. Kaplan, "The formal architecture of lexical-functional grammar," in *Formal Issues in Lexical-Functional Grammar* (J. Maxwell, R. M. Kaplan, M. Dalrymple, and A. Zaenen, eds.), pp. 7–27, Stanford, CA, USA: CSLI, 1995.

[48] M. Johnston, "Unification-based multimodal parsing," in *Proceedings of the 36th conference on Association for Computational Linguistics*, pp. 624–630, Association for Computational Linguistics, 1998.

[49] J. Dowding, B. A. Hockey, J. M. Gawron, and C. Culy, "Practical issues in compiling typed unification grammars for speech recognition," in *Meeting of the Association for Computational Linguistics*, pp. 164–171, 2001.

[50] M. Rayner, B. A. Hockey, and J. Dowding, "An open-source environment for compiling typed unification grammars into speech recognisers," in *EACL*, pp. 223–226, 2003.

[51] W. Wahlster, ed., *Verbmobil: Foundations of Speech-to-Speech Translation.* Springer-Verlag, 2000.

[52] Free Software Foundation, Inc., *GNU General Public License*, June 1991. `http://www.fsf.org/licenses/gpl.txt`.

Appendix A

Embedded GF Interpreter OAA Agent

A.1 Introduction

The Open Agent Architecture (OAA) is "a framework for integrating a community of heterogeneous software agents in a distributed environment".

This document describes the GF OAA Agent included with the Embedded GF Interpreter.

A.2 Running

If the grammar properties file is `test.properties` and the facilitator is running on `$FAC_HOST`, port `$FAC_PORT`, the GF agent is started with:

```
$ java -cp gfc2java.jar:. se.chalmers.cs.gf.oaa.GFAgent \
  /test.properties -oaa_connect "tcp('${FAC_HOST}',${FAC_PORT})"
```

A.2.1 Notes

- The path to the properties file is loaded as a java resource, so the leading slash means to look look at the root of the package hierarchy to find the file in the current directory.
- The following must be on the classpath:
  - OAA 2.3.0 and all its requirements
  - The Trindikit Java library (for the OAAAgent class)

A.3 Solvables

The OAA agent declares these solvables:

- parse (cf. Section A.3.1)
- linearize (cf. Section A.3.2)

- translate (cf. Section A.3.3)
- list_grammars (cf. Section A.3.4)
- list_languages (cf. Section A.3.5)

A.3.1 parse

`parse(Grammar,Lang,Text,Tree)`

Parameters

Grammar The name of the grammar. This is the value of the name parameter in the properties file.

Lang The name of the concrete syntax that should be used for parsing. If Lang is not instantiated, the parser will try all available languages in the given grammar, and return results for each language that the text can be parsed in.

Text The text to parse. Must be instantiated.

Tree The parse tree. Normally not instantiated. The parse tree from the parser is unified with this value. Parse trees are represented as ICL structs.

Examples

- Language given, unambiguous parse:

```
parse(numerals, german, 'drei hundert', Tree)
=>
parse(numerals, german, 'drei hundert',
      num(pot2as3(pot2(pot0(n3)))))
```

- Language uninstantiated, unambiguous parse:

```
parse(numerals, Lang, 'three hundred', Tree)
=>
parse(numerals, english, 'three hundred',
      num(pot2as3(pot2(pot0(n3)))))
```

- Language uninstantiated, parses with several languages to same parse tree:

```
parse(numerals, Lang, 'tre', Tree)
=>
parse(numerals, albanian, tre,
      num(pot2as3(pot1as2(pot0as1(pot0(n3))))))
parse(numerals, danish, tre,
      num(pot2as3(pot1as2(pot0as1(pot0(n3))))))
parse(numerals, italian, tre,
      num(pot2as3(pot1as2(pot0as1(pot0(n3))))))
parse(numerals, norwegian_book, tre,
      num(pot2as3(pot1as2(pot0as1(pot0(n3))))))
parse(numerals, swedish, tre,
      num(pot2as3(pot1as2(pot0as1(pot0(n3))))))
```

- Language uninstantiated, parses with several languages to different parse trees:

```
parse(numerals, Lang, 'tres', Tree)
=>
parse(numerals,catalan,tres,
      num(pot2as3(pot1as2(pot0as1(pot0(n3))))))
parse(numerals,danish,tres,
      num(pot2as3(pot1as2(pot1(n6)))))
parse(numerals,spanish,tres,
      num(pot2as3(pot1as2(pot0as1(pot0(n3))))))
```

A.3.2 linearize

`linearize(Grammar,Lang,Tree,Text)`

Parameters

Grammar The name of the grammar. This is the value of the name parameter in the properties file.

Lang The name of the concrete syntax that should be used for linearization. If Lang is not instantiated, linearizations for all available languages in the given grammar will be returned.

Tree The abstract syntax tree to linearize. Must be instantiated.

Text The linearization of the given tree.

Examples

- Language given:

```
linearize(numerals, english,
          num(pot2as3(pot1as2(pot0as1(pot0(n3))))), Str)
=>
linearize(numerals, english,
          num(pot2as3(pot1as2(pot0as1(pot0(n3))))), three)
```

A.3.3 translate

`translate(Grammar,FromLang,Input,ToLang,Output)`

Parameters

Grammar The name of the grammar. This is the value of the name parameter in the properties file.

FromLang The name of the concrete syntax that should be used for parsing the input text. If Lang is not instantiated, all available languages in the given grammar will be tried.

Input The input text. Must be instantiated.

ToLang The name of the concrete syntax that should be used for linearizing the output.

Output The output text. Normally not instantiated.

Examples

- Input language not given:

```
translate(numerals, Lang, 'tres', english, Str)
=>
translate(numerals,catalan,tres,english,three)
translate(numerals,danish,tres,english,sixty)
translate(numerals,spanish,tres,english,three)
```

A.3.4 list_grammars

`list_grammars(Grammars)`

Parameters

Grammars The list of available grammars.

Examples

- Get all grammars:

```
list_grammars(Grammars)
=>
list_grammars([query,answer])
```

A.3.5 list_languages

`list_languages(Grammar, InputLangs, OutputLangs)`

Parameters

Grammar The grammar to get the languages for. If uninstantiated, there will be one answer for each available grammar.

InputLangs A list of the available input languages for the grammar.

OutputLangs A list of the available output languages for the grammar.

Examples

- Get languages for all grammars (Grammar uninstantiated):

```
list_languages(Grammar, InputLangs, OutputLangs)
=>
list_languages(query,
               ['*all*','GbgQueryEng','GbgQuerySwe'],
               ['*all*','GbgQueryEng','GbgQuerySwe'])
list_languages(answer,
               ['*all*','GbgRouteEng','GbgRouteMap',
                'GbgRouteSwe'],
               ['*all*','GbgRouteEng','GbgRouteMap',
                'GbgRouteSwe'])
```

- Get languages for the query grammar (Grammar instantiated):

```
list_languages('query', InputLangs, OutputLangs)
=>
list_languages(query,
               ['*all*','GbgQueryEng','GbgQuerySwe'],
               ['*all*','GbgQueryEng','GbgQuerySwe'])
```

Appendix B

Java Source Code for a Simple Dialog System

```
import user.*;
import system.*;
import se.chalmers.cs.gf.util.Pair;
import se.chalmers.cs.gf.dialogutil.*;
import se.chalmers.cs.gf.dialogutil.sr.*;
import se.chalmers.cs.gf.dialogutil.tts.*;

import java.util.List;

/**
 *  A very simple demo of a single-modality multilingual dialog
 *  system using GF in Java.
 */
public class SimpleDemo {

        private TextListenerList listeners
            = new TextListenerList();

        private UserMain user;

        private SystemMain system;

        public SimpleDemo(UserMain user, SystemMain system) {
                this.user = user;
                this.system = system;
        }

        /**
         *  Parses the user input, creates system output by
         *  calling answer(), linearizes the system output in the
         *  language that the user used and outputs the answer.
         */
```

```
private void handleInput(String text) {
        // parse the input with all available languages
        List<Pair<String,Input>> inputs =
                user.parseInputWithAll(text);

        // disambiguate the input, do nothing
        // if that fails
        Pair<String,Input> p = disambiguate(inputs);
        if (p == null)
                return;

        // get the unambiguous input
        String inputLang = p.fst;
        Input input = p.snd;

        // figure out answer to user input
        String outputLang = getOutputLang(inputLang);
        Output output = answer(input);

        // linearize and output answer
        String outputText =
            system.linearizeOutput(outputLang, output);
        listeners.fireTextEvent(outputText);
}

/**
 *  Disambiguate parse results.
 *  @return The single umabiguous parse result, if
 *  any. Otherwise null.
 */
private Pair<String,Input>
    disambiguate(List<Pair<String,Input>> is) {
        if (is.size() == 0) {
                System.err.println("No parse");
                return null;
        } else if (is.size() > 1) {
                System.err.println("Ambiguous parse:");
                for (Pair<String,Input> i : is)
                        System.err.println(i.fst + ": "
                                           + i.snd);
                return null;
        }
        return is.get(0);
}

/** Calculates a system output from a user input. */
private Output answer(Input input) {
        return input.accept(new Oracle(), null);
}
```

```
private class Oracle
    implements Input.Visitor<Output,Object> {
        public Output visit(user.Thanks p, Object arg) {
                return new Welcome();
        }
        public Output visit(HereYouGo p, Object arg) {
                return new system.Thanks();
        }
}

/**
 *  Gets the output language to use for a given input
 *  language.
 */
private String getOutputLang(String inputLang) {
        String lang
            = inputLang.substring(inputLang.length()-3);
        return "System" + lang;
}

/**
 *  Add a source of user input, e.g. a dialog box or
 *  a speech recognition engine.
 */
public void addInputSource(TextInput inputSource) {
        inputSource.addTextListener(new TextListener() {
            public void textEvent(TextEvent e) {
                    handleInput(e.getText());
                }
            });
}

/**
 *  Adds a sink to which system output will be sent.
 */
public void addOutputSink(TextListener l) {
        listeners.add(l);
}

public static void main(String [] args)
    throws Exception {
        UserMain user
            = new UserMain("/user.properties");
        SystemMain system
            = new SystemMain("/system.properties");

        SimpleDemo demo = new SimpleDemo(user, system);

        // Get input from a simple dialog
        //demo.addInputSource(new DialogInput());
```

```
                // For Nuance OAA text input
                Recognizer recog
                    = new Recognizer("simpledemo", args);
                demo.addInputSource(new RecognizerInput(recog));

                // Print output to System.err
                demo.addOutputSink(new ConsoleOutput());

                // Speak output with a JSAPI speech synthesizer
                demo.addOutputSink(new JavaSpeechOutput());
        }

}
```