Extending the Kahina Debugging Environment by a Feature Workbench for TRALE

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Zusammenfassung

Bei der Entwicklung symbolischer Grammatiken für die Verarbeitung natürlicher Sprache gestaltet sich die Kontrolle der Interaktionen zwischen den implementierten grammatischen Regeln mit steigender Grammatikgröße zunehmend schwierig. Die vorliegende Arbeit leistet einen Beitrag zur Erleichterung der Analyse solcher Probleme am Beispiel des TRALE-Systems, einer Grammatikentwicklungsumgebung, die auf einer getypten Merkmalslogik basiert und vor allem bei der Implementierung von HPSG-Grammatiken zum Einsatz kommt. Nach einer ausführlichen Besprechung bisheriger Ansätze zur interaktiven Grammatikentwicklung wird zunächst ein neuartiges Modul zur kontextabhängigen Anzeige wichtiger Typeninformationen entwickelt und in Kahina, eine bestehende Umgebung für grafisches Debugging, integriert.

Im zweiten Teil der Arbeit wird die Kahina-Umgebung um eine Workbench für Merkmalsstrukturen erweitert. Das Kernstück dieser Workbench bildet ein grafischer Editor für Attribut-Wert-Matrizen, der die rasche Manipulation von Merkmalsstrukturen mittels elementarer Operationen erlaubt, welche die für TRALE wichtige Eigenschaft der vollständigen Wohlgetyptheit erhalten. In der Workbench werden schließlich Operationen auf Merkmalsstrukturen wie Unifikation interaktiv zugänglich gemacht, wodurch wichtige Teilschritte von Parsingprozessen isoliert durchgeführt werden können. Damit ist die Infrastruktur für eine deutlich zielgenauere Analyse problematischer Interaktionen geschaffen.

Abstract

When developing symbolic grammars for natural language processing, with growing grammar size it becomes increasingly difficult to maintain control over the interactions between grammar rules. This thesis strives to develop concepts for facilitating the analysis of such interactions. The new concepts are implemented as tools for the TRALE system, a development environment for typed feature logic which is mainly used for implementing HPSG grammars. After an in-depth discussion of previous approaches to interactive grammar development, a novel concept for displaying context-dependent type information is developed and implemented as a view module for the Kahina graphical debugging environment.

In the second half of the thesis, the Kahina environment is extended by a feature structure workbench. This workbench is built around a graphical editor for attribute-value matrices which supports rapid feature structure manipulation by elementary editing operations that preserve the important property of total well-typedness. In a last step, standard operations on feature structures such as unification are made available through the workbench in an interactive fashion, which makes it possible to execute the central steps of parsing processes in isolation. This functionality allows to analyse problematic interactions in a more fine-grained and goal-oriented manner than with previous tools.

Acknowledgements

It is with great relief that I hand in this thesis. It was written in parallel to the preparations for my final exams in computer science, as a result of my light-headed decision to study three subjects in parallel. This would not have been possible without the support of many people, some of which I wish to mention here.

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Finally, I express my deepest gratitude to my wife, Anna. Without her loving care and unwavering support, I would never have managed to keep up my spirit during the past stressful years. I am glad that we can now happily look forward to calmer times, knowing that we can thrive under virtually any circumstances.

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Chapter 1

Introduction

Current approaches to automated processing of natural language syntax and semantics almost exclusively rely on shallow statistical methods, which have proven to be superior to previous methods on noisy real-life data, especially if performance is taken into account. This trend has led to a deep divide between the methods commonly used in computational linguistics, and the methods of linguistics proper. The deep insights of linguistic theories are considered to be of little use for real-life applications, whereas the tools created by computational linguists become increasingly less interesting to linguists.

This trend has resulted in perils for both sides. Linguists develop elaborate theories on paper, which cover important generalizations and are of central importance for furthering our understanding of language, but they cannot evaluate these theories on a wider range of structures because of a lack of computational tools which would allow them to be intuitively implemented and tested.

On the other hand, modern computational tools for processing natural language almost exclusively rely on surface patterns, which works reasonably well for simple tasks, but does not have much potential for deeper levels of analysis. In particular, integrating linguistic knowledge into such systems is very difficult.

More traditional rule-based methods are clearly more useful for implementing and evaluating linguistic theories, and they make it possible to keep up the goal of deep analysis. However, apart from their weakness in coverage, such symbolic grammars are also very difficult to design. These difficulties are not only caused by the multitude of structures, but also by the notorious tendency of hand-written grammars to get out of hands when attempting to cover a reasonably wide range of linguistic phenomena occurring in natural input.

The chief cause of this are the heavy interactions between rules which tend to grow very quickly with grammar size, and which need to be carefully controlled. This slows down the writing of larger grammars considerably, at some point making it virtually impossible to keep track of all the interactions.

As part of a larger effort to alleviate these difficulties, this thesis introduces some new concepts and tools for making rule interactions more transparent in grammar formalisms based on typed feature structures. This work partially builds on ideas developed for older grammar development environments, mainly during the last burst of work in that area about fifteen years ago.

The test case for these concepts is the development of grammars in the TRALE system, a leading platform for implementing grammars in the framework of HPSG (Head-Driven Phrase Structure Grammar).

In Chapter 2, I give a quick overview of the TRALE environment, and discuss the main issues of grammar development in that system. I then discuss the current state of grammar debugging tools for TRALE, explaining why new advanced debugging methods are desirable for novice and veteran grammar engineers alike.

Chapter 3 gives a short historical overview of advanced tools for grammar engineering, which are mainly evaluated with respect to their methods for visualizing the internals of parsing processes and for exposing central operations to the grammar engineer as interactive tools. In the second half of the chapter, I introduce the Kahina debugging environment which serves as the basis for this work.

Chapter 4 discusses existing tools for signature inspection and visualization, leading to a novel HTML-based signature information system inspired by Javadoc, the leading tool for the documentation of Java classes. At the end of the chapter, I present and discuss an implementation of these ideas as a new Kahina component.

Chapter 5 introduces signature-enhanced AVM (Attribute-Value Matrix) editing as a comfortable way of manually constructing feature structures that can later be used for interactively exploring rule interactions. A set of elementary editing operations is formally developed to the degree that can be implemented. The implementation of these operations results in an editing system that allows the user to freely manipulate parts of feature structures in a point-and-click-fashion while the editing system is responsible for ensuring that the resulting structures always adhere to a signature.

In Chapter 6, the new tools from the previous chapters are integrated into a feature workbench, which exposes important parts of the TRALE parsing process to the user in an interactive fashion. The main design decisions are motivated, focusing on the architectural problems that had to be overcome. The chapter concludes with a discussion of problems and possible extensions to the feature workbench.

Chapter 7 summarizes the main results of the thesis and puts potential usage scenarios for the workbench into a broader context of next-generation grammar engineering.

The appendices contain the source code for the TRALE demo grammar which is used throughout this thesis, and a list of the relevant new interfaces in the Kahina system. The full names of the Java classes mentioned in the text can also be found there.

The ideal reader of this thesis knows the basics of HPSG, has some experience with grammar engineering in a unification-based grammar formalism, and possesses some familiarity with the programming languages Java and Prolog. Experience with the TRALE system is not strictly necessary, but will certainly be helpful for fully understanding the scope and motivation of this work.

Chapter 2

TRALE Grammar Development

In this chapter, I give an overview of the TRALE system that serves as a basis for all the software components which are developed and discussed in this thesis. Section 1 starts with a list of TRALE's features for implementing HPSG grammars, and continues with a comparison to the LKB as the other major platform used for this purpose. Section 2 continues with the challenges of large-scale symbolic grammar engineering in general, elaborating on the key conflict between the generality and the modularity of grammar implementations, and explaining the potential role of debugging technology in remedying these issues. This leads to an in-depth discussion of TRALE's current debugging mechanisms in Section 3, and of the potential benefits of more advanced (graphical) debugging tools in Section 4.

2.1 Basic Principles and Alternative Approaches

The **TRALE** system is a substantial extension to the Attribute Logic Engine (ALE) as described by Carpenter and Penn (1999). It was developed with the goal of facilitating the direct implementation of HPSG grammars in a format that appeals to linguists. The development of TRALE began in the context of the SFB 340 and was continued as part of the MiLCA project (see Meurers et al., 2002). The system has been the subject of continual evolution since then. The most recent (yet somewhat outdated) documentation of TRALE can be found in Penn et al. (2003).

A TRALE grammar consists of a signature and a theory. The **signature** is a type hierarchy which licenses a set of possible feature structures, expressing some general restrictions on their structure. The **theory** then defines further (implicational) constraints on the structures licensed by a signature. This separation closely mirrors the structure of an HPSG grammar, where the signature is used to define possible *sign*s such as *word*s and *phrase*s represented by feature structures, and the theory is used to express rules and principles of grammar, e.g. the Head Feature Principle.

TRALE's type system implements **exhaustive typing**, a principle formalizing an assumption implicit in typical HPSG grammars (such as that of Pollard and Sag (1994)). Exhaustive typing states that objects of a non-maximal type must simultaneously be of one of the subtypes. For instance, there are no *sign*s that are not either *phrase*s or *word*s.

The TRALE constraint language makes it possible to freely define implicational constraints on feature structures, and it offers a formalism for **description-level lexical rules (DLRs)** whose behavior comes very close to the intuitions behind hand-written rules in the format commonly used in the HPSG literature.

The description language is enhanced by a Prolog-style programming language for **definite relations**, allowing commonly used relations such as *append*/3 to be used for expressing type constraints and rules, and a powerful macro mechanism that is especially useful for defining a large lexicon where many entries have common properties.

For efficiency reasons, a TRALE grammar is based on a context-free skeleton defined by **phrase-structure rules**, The categories in these rules are terms of an attribute-value description language, and definite clause goals can be attached to the rules in analogy with Prolog's in-built DCG mechanism.

Taken together, these features permit a rather direct and natural implementation of typical HPSG grammars, although the learning curve especially for users with limited programming experience can be steep, and the powerful formalism leads to efficiency issues that require efficient implementation strategies.

The second leading platform for the implementation of HPSG grammars is the **Linguistic Knowledge Building (LKB)** system. Just like the ALE system underlying TRALE, the LKB is designed as a framework-independent platform for unification-based grammars, although it is most commonly used for type feature structure formalisms such as HPSG.

The LKB has been under development and in use for two decades, most prominently as the primary development platform for the broad-coverage LinGo English Resource Grammar (ERG), as presented in Copestake and Flickinger (2000). Copestake (2002) is the primary documentation for more recent versions of the LKB.

Unlike TRALE, the LKB centralizes all the type information, including all the constraints, in just one file. TRALE enforces some technical constraints on the definable type hierarchies, whereas the LKB takes the liberty of automatically restructuring the types defined by the grammar writer into a more complex hierarchy that fulfills the very same constraints. The LKB can therefore accept a liberal format for type definitions that seems more user-friendly at first sight, but can lead to confusion about the types that are then used internally. TRALE forces the user to think harder about the signature, but then displays computational behavior that is closer to the specification.

Because in the LKB, all constraints must be stated as part of type definitions, they always apply to structures of one specific type. TRALE offers more expressive power by allowing feature structures as complex antecedents in its implicational constraints. This makes it possible to single out classes of linguistics objects that do not correspond to a type, whereas the LKB forces the user to introduce a type distinction even if the corresponding class of objects is only relevant in the context of a single rule.

The LKB clearly lags behind TRALE in faithfulness of implementation for typical grammars developed by linguists. The gap between linguistic theory and the implementation is rather wide, whereas TRALE's advanced features allow grammar implementations to stay notationally and conceptually close to what linguists are used to developing on paper.

But not only for novices in grammar implementation, these disadvantages are compensated for by the fact that the LKB features a window-based graphical interface for user interaction that is chiefly operated using the mouse, whereas TRALE is based on command-style interaction with a Prolog prompt.

For larger grammar implementations, sophisticated test suite facilities are indispensable. Both TRALE and the LKB offer an interface to the [`incr tsdb()`] package by Oepen (2001) for batch parsing. This package can be used to maintain annotated databases of test and reference data, to browse these databases in order to compose suitable test suites, and, most importantly, to collect fine-grained profiling data for evaluating system performance. Such data are very useful for identifying inefficient parts of a grammar implementation.

In a thorough comparison of the two platforms from a grammar writer's point of view, Melnik (2007) considers the graphical user interface to be the core advantage of the LKB over TRALE, especially in the eyes of a not very computer-savvy linguist. Developing an interface for TRALE with comparable characteristics has therefore been the main motivation for the work leading up to this thesis, and the LKB system has been an important source of inspiration.

2.2 The Challenges of Symbolic Grammar Engineering

One of the reasons why rule-based approaches to NLP have suffered a steep decline in popularity is that these approaches failed to include statistical information, leading to low coverage and severe problems with disambiguation. Whereas combinations of rule-based and data-driven models can improve this situation a little, another weakness of symbolic grammar engineering is a lot more difficult to address. Rule-based grammar development traditionally relies on the expert knowledge of an experienced grammar engineer, who needs intimate knowledge of all the grammar components to assess the consequences of modifications. As a grammar grows, the rule interactions become increasingly hard to understand and control, slowing down development considerably. These difficulties are aggravated by the fact that for large-coverage grammars, it is indispensable that multiple persons contribute to grammar development.

From a theorist's point of view, a grammar is only attractive if it expresses all known generalizations on as many levels as possible. The generality of the principles developed in this tradition quickly leads to a situation where rules and constraints are heavily interdependent, leading to all kinds of interactions that a grammar writer must take care of when making even the slightest modification.

Keeping track of such rule interactions is difficult even for the very restricted problem domains usually modeled by theoretical linguists. The interactions between various such insular theories are seldom discussed in the literature, and if they are, the arguments are often rather informal. If one tries to bring such insular solutions together in an implementation, undesired interactions between such theories, which tend to be formulated in as general a fashion as possible in their respective insular context, regularly lead to problems.

From an implementer's point of view, the core problem of linguistic theories can be identified as a lack of modularity. One of the hard lessons learnt in software engineering is that a lack of modularity leads to difficulties in extensibility. Unsurprisingly, these difficulties also turn up in grammar engineering.

For the case of HPSG, Moshier (1997) gives an impressive account of such difficulties. For instance, even a simple principle such as the Head Feature Principle occurs in various incompatible versions in the literature, usually adapted in an ad-hoc manner to block unwanted interactions with a newly developed insular theory.

In an attempt to improve the modularity of HPSG, Moshier fleshes out a strict formalization of HPSG grammars that is based on category theory and strives to abstract away from what he calls the feature geometry of a concrete implementation. This would allow principles to be stated independently, and would force the grammar writer to explicitly control the interactions. Unfortunately, later experience has shown that linguists tend to dislike formal constraints that have good mathematical properties, but cannot be independently motivated on linguistic or cognitive grounds, and detract from their freedom in using a powerful formalism to express generalizations naturally.

To increase modularity, an experienced programmer would want to refactor the grammar according to principles of sound software engineering. Unfortunately, such a refactoring will inevitably destroy many of the generalizations that a linguist would want to see expressed. In grammar engineering, modularity and generality are therefore conflicting goals.

This means that the rule interaction problem is inherent in the grammar engineering task, and cannot be avoided by the use of sophisticated tools. In order to help symbolic grammar engineering deal with these difficulties, one can only develop and provide useful methods for analysing and understanding the interactions more easily. This requires tools which make the interactions more transparent to the grammar implementer, and which provide quick access to explanations for undesired behavior.

2.3 The Current State of Debugging Technology

In grammar development environments such as TRALE or the LKB, any attempt to increase the transparency of internal processes such as rule application presupposes advanced tools for debugging parsing processes. In order to understand the potential of new debugging technology, we need to first have a look at the current state of debugging tools for HPSG implementation.

In the LKB, a strong emphasis is on comprehensive and informative error messages for grammars that violate formal conditions. This helps the novice grammar writer to avoid and correct many mistakes, but users who have had a little experience with the formalism will not any longer run into this kind of problem very often. Instead, especially when writing complex grammars, they will be faced with spurious or missing parses because of subtle errors in rule interactions.

For such debugging tasks, the tools in the LKB are a lot less well-developed. The standard procedure is to look for a short sentence exhibiting the relevant problem, and then to inspect the **parse chart** (a table displaying partial solutions for phrases), exploring the connections between resulting parses and the chart until the problem can be isolated to a small set of phrases. This process can be very time-consuming, and it requires a lot of intuition about the problematic parts of a grammar.

Once the problem is narrowed down, a very useful mechanism for **interactive unification checks** comes into play. The LKB allows the user to select any two structures in its feature structure visualization, and to test whether the information they contain is compatible. If such a unification fails, the user receives explicit feedback on the reasons for failure. For instance, this allows to determine explicitly why lexical entries cannot be combined using some ID schema, or to find out why some principle is violated by a structure. In order to trace the interaction between multiple constraints, intermediate results of successful unifications are used to chain together unification checks.

The TRALE system takes a very different approach to grammar debugging. Just like the LKB, it produces precise error messages in case some formal condition is violated, even though these messages tend to presuppose a little more technical knowledge than their LKB equivalents. The large difference between the systems lies in the tools they offer for understanding internal processes in order to track down erroneous or missing parses.

For such purposes, TRALE features a **source-level debugger** that is implemented on top of SICStus Prolog's debugging facilities. The TRALE interface offers special variants of the predicates for compilation and parsing, that work almost like their standard equivalents except that they expose some of their execution details and give the user interactive control.

The core component of the source-level debugger is roughly based on the **procedure box model** of execution introduced by Byrd (1980), which is also the conceptual basis of the debuggers that come with standard Prolog distributions. The model is built around the concept of **ports**, which is a metaphor for the ways in which the control flow during program execution can pass into and out of embedded boxes that represent invocations of predicates. The TRALE source-level debugger distinguishes only four kinds of ports: call, exit, redo, and fail ports. A **call port** occurs at every initial invocation of a parsing step, and an **exit port** whenever such a step is successfully completed. When ALE backtracks into a step to find more solutions after another choice failed, a **redo port** occurs. The occurrence of a **fail port** indicates that a step could not produce any more solutions. The standard model additionally includes an exception port, for which no equivalent exists in TRALE's source-level debugger.

A **tracer** is in essence a list of port occurrences that grows while computations occur, and allows the user to understand the control flow of a goal execution. A standard tracer prompts the user for confirmation at each port, and allows the user to influence program execution by means of a few standard responses. The **creep** command simply tells the tracer to continue with the next port, **skip** tells it to advance to the next exit or fail port of the current step, **fail** forces the debugger to directly go to the fail port of the current step (possibly manipulating the program outcome), and **leap** has the tracer move forward to the next step matching some criterion defined in ways that vary between systems. The **retry** command forces the tracer back to the call port of the current step, which is only useful if one has lost track of the trace and wants to review a part of the computation, or in case of side effects. Finally, the **abort** command is used to exit the tracing mode. Using these commands, a user can follow the steps of a goal execution, controlling and possibly modifying the control flow to explore alternatives on the way. A tracer is thus a simple tool for **interactive debugging**.

The TRALE source-level debugger expands on this basic functionality by providing links to the source code for each step. If TRALE is started together with an XEmacs (or Emacs) instance, the grammar source code will be displayed in a second window, and at each step the respective code line will get highlighted. Furthermore, the tracer offers a few additional commands that provide a limited degree of interaction with the current parsing state. These options allow the user to switch into a mini-interpreter for exploring the current content of the chart, and to display the feature structure that was established up to this point.

A parse consists of a potentially huge number of steps, causing a tracer to produce very long lists of port occurrences that would be very time-consuming to understand if they were just printed out to the console. It is therefore essential to provide filter mechanisms that can be used by the user to extract few interesting choice points from the large number of steps.

The TRALE source-level debugger offers three basic kinds of filtering. The **leashing** mechanism allows the user to define which steps of the tracing process are merely displayed, and at which steps the tracer pauses and asks for user input. Leashes can be put on a predefined set of eight step types, which makes this type of control rather coarse-grained. To automatize the tracing process further, **auto-skipping** can be enabled on the same step types to define steps whose computation details are not to be displayed, and where the tracing process is to simply continue instead of prompting the user. This can be very helpful for reducing the trace display by hundreds of lines with easily predictable content. The most powerful filtering mechanism are **breakpoints** that can be associated with source code lines either directly via an XEmacs interface, or dynamically by using a special command while tracing. Subsequent leap commands will always only jump over steps until one of the defined breakpoints is reached. As multiple computation steps can be aligned with one line in the source code, a further command is provided for skipping all further steps associated with the current source code line.

In principle, the tracer makes it possible to find out exactly how a parse is computed, and therefore to find the sources of undesirable behavior. However, the tracer component of the source-level debugger has some weaknesses limiting its use. For instance, feature structure unification is treated as an atomic operation. This provides the user with the information that two possibly very large structures could not be unified, but fails to state explicitly why the unification failed, possibly forcing the user into a session of time-consuming manual comparison. Moreover, the source-level debugger does not provide explicit information on how and when constraints and procedural attachments are executed. Given the complexities of TRALE's constraint formalism, this is a severe problem, especially because goals can be suspended until some preconditions are fulfilled, and are then suddenly executed in a delayed fashion. In larger parses, this behavior makes it virtually impossible to infer the current state of execution from the linear representation of the trace.

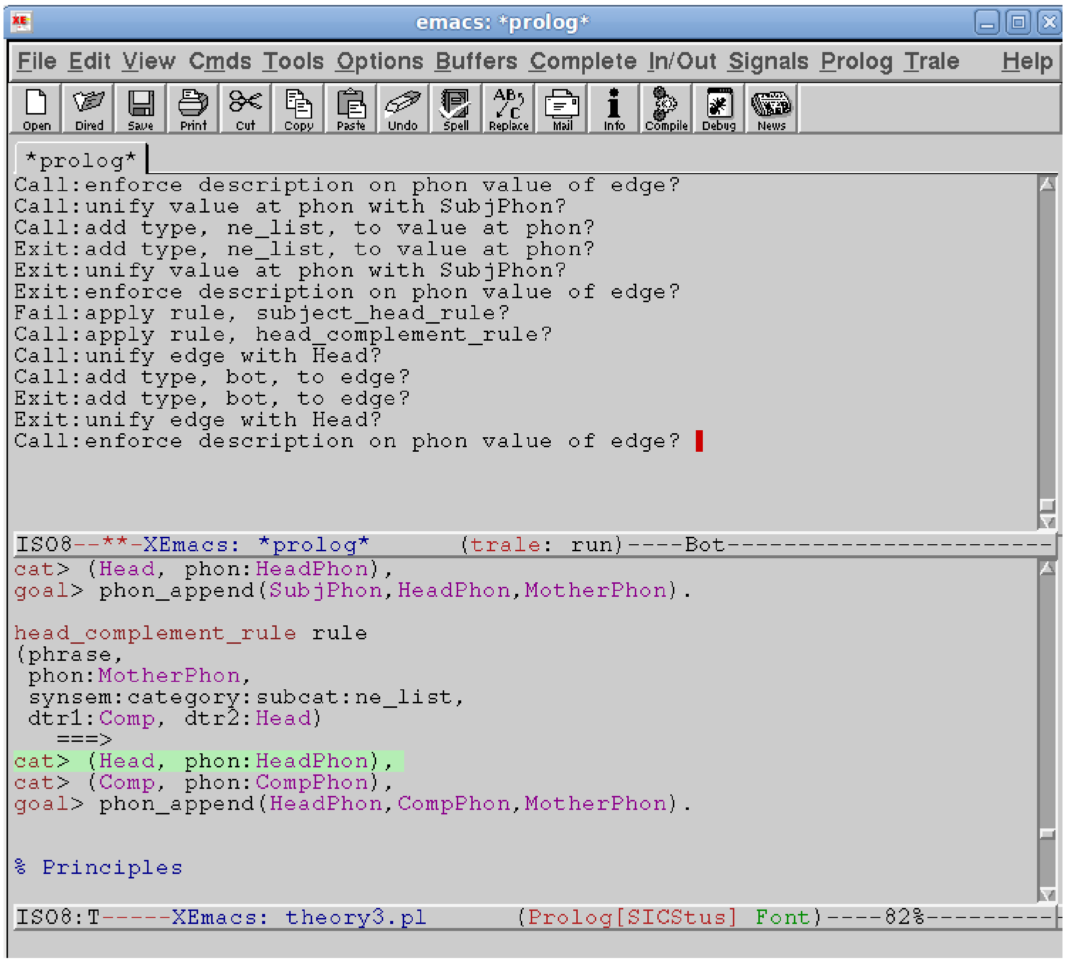
2.4 The Need for Advanced Debugging Tools

Figure 2.1 shows a screenshot of TRALE's old source level debugger as discussed in the previous section. In principle, the trace makes it possible to understand how the procedural boxes are embedded into each other, and thereby the call structure. However, this information is presented in a linear fashion without any visual aid for recognizing the call hierarchy. Unlike in a standard Prolog tracer, not even call depth information or step numbers are provided, which makes it very hard to identify ports that belong to a common procedural box. Without expert knowledge of TRALE's internals, it is therefore impossible to reconstruct the call structure from the trace. A simple indentation of lines to indicate call depth would already be an immense help, but unfeasible for highly recursive programs because of the very limited column width of a typical console window.

While expert users can determine the call structure by careful observation of the linear trace, the tracer does not provide sufficient information about the reasons why computations occur. Especially during backtracking, where the order in which goals are retried does not only depend on the current call stack, but also on the alternatives that have been tried on other paths of the search tree, it is very easy to lose track of the current state of execution. The linear trace becomes even more confusing when cuts come into play, and the lacking information on delayed goals makes the control flow entirely intransparent.

Another severe shortcoming of a tracer is that the tracing decisions are always made locally, without any way to correct errors. If a user erroneously skips a step whose computation details would have been relevant, or makes a small mistake in defining a breakpoint, there is no way to access the missed information other than to abort and restart the tracing process. This behavior forces the user to be very defensive, always erring on the safe side in order to make sure that no relevant information is lost. As a result, traces tend to take a lot longer than they would have to if context information on past steps remained accessible.

The low accessibility of non-local information during tracing is also an issue by itself. If


emacs: *prolog*
File Edit View Cmds Tools Options Buffers Complete In/Out Signals Prolog Trale Help
Open Dired Save Print Cut Copy Paste Undo Spell Replace Mail Info Compile Debug News
prolog

```
Call:enforce description on phon value of edge?
Call:unify value at phon with SubjPhon?
Call:add type, ne_list, to value at phon?
Exit:add type, ne_list, to value at phon?
Exit:unify value at phon with SubjPhon?
Exit:enforce description on phon value of edge?
Fail:apply rule, subject_head_rule?
Call:apply rule, head_complement_rule?
Call:unify edge with Head?
Call:add type, bot, to edge?
Exit:add type, bot, to edge?
Exit:unify edge with Head?
Call:enforce description on phon value of edge?
```

```
ISO8--**-XEmacs: *prolog*        (trale: run)----Bot-----------------------
cat> (Head, phon:HeadPhon),
goal> phon_append(SubjPhon,HeadPhon,MotherPhon).

head_complement_rule rule
(phrase,
 phon:MotherPhon,
 synsem:category:subcat:ne_list,
 dtr1:Comp, dtr2:Head)
  ===>
cat> (Head, phon:HeadPhon),
cat> (Comp, phon:CompPhon),
goal> phon_append(HeadPhon,CompPhon,MotherPhon).


% Principles
ISO8:T-----XEmacs: theory3.pl       (Prolog[SICStus] Font)----82%---------
```

Figure 2.1: TRALE's source-level debugger, embedded in XEmacs.

a user needs to look up some type constraint that is defined in the signature, the usual predicates for feature inspection are not available during tracing. The mini-interpreter for inspection of intermediate results is a very helpful tool, but it visually disrupts the tracing history and requires the user to scroll back and forth a lot in order to assemble the hints on the current execution state after spending some time in it.

Ideally, a grammar developer would want to be able to observe the influence of individual constraints during tracing. Precise information about the points in the parsing process where constraints are applied would also make performance optimizations a lot easier. Unfortunately, the current source-level debugger does not expose this information. Instead, the application of constraints becomes visible through its consequences, usually in the form of a sudden traversal of a description. The source-code highlighting makes this a little less dramatic by at least showing which rule or principle is being applied. But the reasons why a constraint enforcement was triggered at a specific time remain hidden in the depths of the underlying trace.

After this discussion, it should be clear that the TRALE source-level debugger has severe shortcomings, and that any attempt to improve upon its problems holds a lot of promise for the advancement of grammar engineering. Some fixes could more or less readily be made within the framework of a console-based tracer, e.g. by exposing more information on constraint enforcement through details about the underlying Prolog implementation. It would also be possible to store some more step information and to display more information about previous steps on demand. But for reasons that are discussed below, the decision was made to leave XEmacs and/or the console behind in order to construct a debugging system with a Java-based **graphical user interface (GUI)**.

Using a graphical interface for a debugging system is perhaps not an obvious choice. Especially in the Unix community, graphical interfaces have traditionally been criticized for forcing the user to switch between mouse and keyboard input, thereby slowing down proficient keyboard users. Graphical interfaces also tend to respond more slowly to user input, and they invariably suffer from a trade-off of exposing as much functionality as possible while at the same time maintaining a clear design.

These criticisms mostly apply to interfaces that merely provide buttons and menus instead of command-line options, for no other reason than because GUIs are considered visually attractive. In many cases, such interfaces even restrict access to the underlying system, whose original flexibility is often important to advanced users.

In the context of interactive debugging, however, graphical interfaces have genuine advantages. The first of these advantages becomes apparent when we have a second look at the old source-level debugger in Figure 2.1. Complex data structures such as AVMs or trees are hard to represent linearly in a human-readable fashion. While TRALE provides pretty-print predicates for inspecting feature structures on demand, their output is too space-consuming to routinely be displayed as part of a trace. But the trace also gets cluttered when these predicates are used on demand, making the control flow even less traceable. The same problem would affect a more structured trace that provides some visual aid for determining the call hierarchy. Mainly for this reason, SWI Prolog, the leading freely available Prolog implementation, already includes a graphical tracer (Wielemaker, 2003).

The cure to the size problem of human-readable data structure representations is **display parallelism**. Unlike command-line interfaces, GUIs can display various kinds of contextual information at the same time, allowing data structures to be displayed in parallel for comparison, and an uncluttered trace display to be separated from a step detail window. For these reasons, graphical front-ends for console-based debuggers are becoming increasingly common. The DataDisplayDebugger (DDD) by the GNU Project (2011) and KDbg by Sixt (2011) appear to be the most influential such systems in a GNU/Linux context.

For a long time, graphical tools have been used also by advanced users to receive a better bird's-eye overview of complex parsing processes. A case in point is Stefan Müller, the author of the most comprehensive TRALE grammar implementations (see e.g. Müller (2009) and Müller and Ghayoomi (2010) for discussions of implemented fragments of Maltese and Persian). Müller almost exclusively uses a custom graphical chart display for debugging his wide-coverage grammars (personal communication), prefers to look at the source code directly if solutions are missing, and sees little use in the old source-level debugger for his purposes. This chart display plays the role of a visual summary of the parsing process, making good use of shapes like curves and arrows which are difficult to render in a console, but easy to display in a graphical environment.

Human minds tend to be lot better at understanding complex structures which are presented as pictures than at interpreting textual formats. Therefore, graphical view components are superior to consoles whenever non-textual information needs to be presented in a compact and comprehensible fashion. In an area like grammar engineering, where the structures in question quickly become very complex, not making use of this potential in the development of advanced user-friendly tools would be a mistake.

For these reasons, all the tools for facilitating the analysis of rule interactions which are developed in the main part of this thesis will have graphical user interfaces. To motivate the design of these tools, the next chapter takes a look at existing graphical environments for grammar development, and introduces the graphical debugging system which the new tools will be built on.

Chapter 3

Kahina and its Predecessors

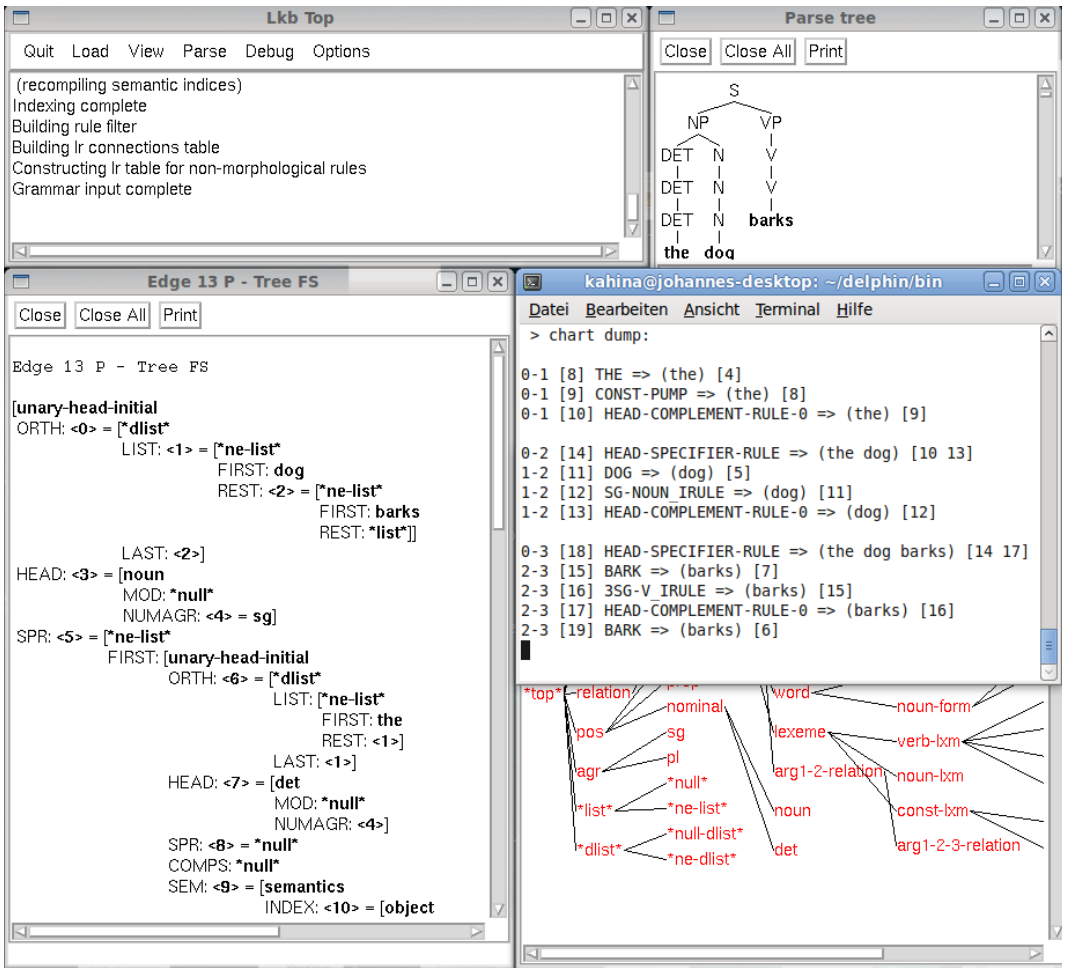
This chapter investigates the use of graphical tools for understanding complex grammars and parsing processes. In the first section, we start out by looking at the visualization components of various successful natural language parsing systems, leading us to the conclusion that graphical approaches to the challenges of grammar engineering have been fruitful in the past, although many of the techniques employed do not directly translate to recipes for the TRALE case.

Section 2 introduces the Kahina debugging environment as a novel tool for visualizing parsing processes, which also attempts to solve some of the problems of current tracer-based Prolog debugging technology in order to make these visualizations useful for TRALE. In Section 3, some parts of the Kahina architecture are discussed in detail, preparing its role as the implementation platform for the new tools developed in later chapters. Section 4 relates the possibilities introduced by Kahina to the capabilities and shortcomings of the console-based source-level debugger.

3.1 Visualization of Parsing Processes in NLP

When investigating ways to visualize parsing processes for HPSG implementations, it is worthwhile to take a closer look at the LKB system, the only HPSG development environment which currently provides a graphical interface. The LKB system uses various windows for displaying result structures as well as grammar information. The screenshot of an LKB session in Figure 3.1 gives the reader a first impression of the system's look and feel.

A core component of any parsing process visualization is a way to give the user access to parse trees and/or parse charts. As we can see in Figure 3.1, the LKB features neat and interactive representations of phrase structure trees, and a solid component for chart visualization. The display of **parse trees** is indispensable for quickly surveying the structures produced for an input sentence, and due to the ubiquity of tree structures in linguistics, they make it particularly easy to spot unexpected behavior. Therefore, even console-based tools without any graphical interface commonly offer some way of producing pictures of parse trees, usually by opening a small window for the purpose, or by using external programs to produce TeX code or image files. Integrated systems such as the LKB tend to make the nodes of a parse tree interactive, using the tree nodes as handles into partial structures. Ideally, by clicking on a node in a parse tree, the user does not only receive more detailed information about the substructure, but also about the parts of the grammar which licensed that structure.



```
(recompiling semantic indices)
Indexing complete
Building rule filter
Building lr connections table
Constructing lr table for non-morphological rules
Grammar input complete
```

```
Edge 13 P - Tree FS

[unary-head-initial
 ORTH: <0> = [*dlist*
              LIST: <1> = [*ne-list*
                           FIRST: dog
                           REST: <2> = [*ne-list*
                                        FIRST: barks
                                        REST: *list*]]
              LAST: <2>]
 HEAD: <3> = [noun
              MOD: *null*
              NUMAGR: <4> = sg]
 SPR: <5> = [*ne-list*
             FIRST: [unary-head-initial
                     ORTH: <6> = [*dlist*
                                  LIST: [*ne-list*
                                         FIRST: the
                                         REST: <1>]
                                  LAST: <1>]
                     HEAD: <7> = [det
                                  MOD: *null*
                                  NUMAGR: <4>]
                     SPR: <8> = *null*
                     COMPS: *null*
                     SEM: <9> = [semantics
                                 INDEX: <10> = [object
```

```
> chart dump:

0-1 [8] THE => (the) [4]
0-1 [9] CONST-PUMP => (the) [8]
0-1 [10] HEAD-COMPLEMENT-RULE-0 => (the) [9]

0-2 [14] HEAD-SPECIFIER-RULE => (the dog) [10 13]
1-2 [11] DOG => (dog) [5]
1-2 [12] SG-NOUN_IRULE => (dog) [11]
1-2 [13] HEAD-COMPLEMENT-RULE-0 => (dog) [12]

0-3 [18] HEAD-SPECIFIER-RULE => (the dog barks) [14 17]
2-3 [15] BARK => (barks) [7]
2-3 [16] 3SG-V_IRULE => (barks) [15]
2-3 [17] HEAD-COMPLEMENT-RULE-0 => (barks) [16]
2-3 [19] BARK => (barks) [6]
```

Figure 3.1: A work session using the LKB system.

While a parse tree merely displays the result of a successful parsing process, a **parse chart** contains more of the information accumulated during a parsing process. Typical chart displays summarize the parsing process by displaying all the constituents that were successfully assigned to structures, including the constituents that later did not become part of a complete parse. Chart displays usually symbolize the spans covered by constituents as **edges** over the input string. The most relevant quality of chart displays for debugging is that they can provide valuable information about unexpected or missing parses. An unexpected parse can often be narrowed down to an unwanted edge for a substructure, while a missing parse is often due to some constituent that was not recognized. Both cases can quickly be identified, making the chart an extremely useful aid in looking for conceptual or notational errors.

A chart is the central data structure for almost all efficient parsing algorithms because it allows partial solutions to be reused. Exposing the chart to the user therefore already provides a lot of essential information about the internals of a parsing process. Parsing algorithms usually fill the chart in a way that only makes it necessary to store positive intermediate results. However, in the case of a missing edge, a user will often be interested in finding out not only that, but also why an expected substructure could not be established. A chart that does not contain what I will call **failed edges** cannot provide interactive access to such information. The LKB is such a case, its chart only provides information about those computations that led to constituents being established. As a result, the information about a parsing process available to the user is quite incomplete, and not only technical details are hidden. Successful and failed edges are of equal importance to a grammar developer.

To find concepts for more complete visualizations, we thus need to look beyond current technology for HPSG implementations. In the rest of this section, we will therefore have a look at the techniques used for visualising parsing processes in other grammar formalisms, starting with closely related formalisms that offer comparable challenges, and then gradually moving away to more distantly related formalisms, for which interesting tools exist.

Another constraint-based grammar formalism that has been used for implementing large grammars is **Lexical-Functional Grammar (LFG)** introduced by Bresnan and Kaplan (1982). For a comprehensive and up-to date introduction to the formalism, the reader is referred to Bresnan (2001). The most advanced freely available system for implementing LFGs is the **Xerox LFG Grammar Writer's Workbench** documented in Kaplan and Maxwell (1996). The system is quite similar to the LKB in both the content of windows and their interactivity. Since syntactic analyses in LFG are separated into the two layers of c-structure and f-structure, the LFG Workbench features separate view components for both layers. The constituent structure is represented by a phrase structure tree, and the functional structure by an attribute-value matrix.

An important difference to the LKB stems from the separation of the parser into a c-structure parsing component and a constraint system that subsequently enforces f-structure constraints, which makes it easy to display legal c-structures for which no valid f-structures could be found, providing more fine-grained feedback about the reasons for a structure to be invalid. The LFG Workbench also provides a chart display, which contains additional edges representing partial matches of the c-structure rules guiding the parsing process. If, for instance, a transitive verb was recognized, but no subsequent constituent qualified as an object, the chart receives an edge with the symbol `/VP`. While this comes a lot closer to providing the desired information on failed edges, it lacks information on c-structure rules that failed to apply because already the first constituent could not be found.

The main asset of the LFG Workbench lies in its advanced mechanisms for explaining why failed edges could not be established, or why no valid f-structure for a given c-structure could be found. For this purpose, all the views offer options for extending the displayed information by invalid or incomplete structures, and selecting such a structure will highlight the parts which were missing in a c-structure rule or which violated some f-structure constraint. While all this is extemely helpful to the grammar developer, the exact way in which f-structure constraints are enforced still remains intransparent. This is not necessarily problematic for debugging, but it means that the LFG Workbench lacks support for grammar optimization, because the order in which the individual constraints are enforced is neither exposed nor manipulable.

A further interesting formalism to investigate is **Weighted Constraint Dependency Grammar (WCDG)**, which is unique in combining hand-crafted constraints with a preference ordering defined by manually assigned weights. Constraints with non-zero weights are defeasible, causing grammaticality to be not any longer a binary feature, but a continuous measure. Parsing becomes a **constraint optimization** problem, in contrast to other constraint-based formalisms that only require constraint solving. This leads to high computational costs, but also allows mere linguistic tendencies to be expressed, making the system robust against extra-grammatical and even ungrammatical input. WCDG was developed by Foth et al. (2004a) to build a large-coverage parser for German. Their grammar consists of about 750 handwritten constraints, and was derived from about 25,000 annotated sentences. The graphical development tools used in this effort are described in Foth et al. (2004b).

The tools of the WCDG system are important in our context because they possess some unique features that make the grammar engineering process very different from other systems. A central dependency tree visualization component works both as a display module for intermediate structures and as an editor that allows to modify parsing results for subsequent **hypothetical evaluation**. In this mode, the parser explains which constraints and which weights prevented it from preferring the user-defined structure, giving the grammar engineer precise information about the rules which would have to be assigned higher or lower weights to achieve the desired behavior.

This is possible because every configuration of dependency arcs and nodes is admissible by default, and the parser uses the constraints only to discard parses under an exclusion paradigm. While in theory, this is also the case for the HPSG formalism, the parsers of both TRALE and the LKB are built around a context-free backbone, and thereby at least partially operate under a licensing paradigm. The resulting difference in efficiency shows in the sluggish performance of the WCDG parser in comparison to these systems. However, for debugging purposes, having a parser that solely operates under the exclusion paradigm turns out to be preferable, since this allows to find out which constraints are violated in an arbitrary structure. Since no other state-of-the-art parser works in this way, the WCDG tools' special features are difficult to emulate in the context of other parsing environments, but they can still serve as an inspiration for future grammar engineering systems.

Going beyond constraint-based approaches, we will next look at visualization tools for **Tree Adjoining Grammar (TAG)**, a mildly context-sensitive grammar formalism that is built on combining trees instead of strings. During structure derivation, tree fragments from a grammar are combined using adjunction (insertion) and substitution operations. Joshi and Schabes (1997) give a comprehensive formal introduction to TAGs and their properties.

The most popular development environment for TAG grammars is formed by the **XTAG tools**, which were created as part of the XTAG project (Doran et al., 1994), a long-term effort to develop a TAG-based wide-coverage grammar for English. Paroubek et al. (1992) give a concise, though somewhat outdated, description of the XTAG graphical development environment. More recent information is available through the XTAG project's website (see University of Pennsylvania, 2011).

The XTAG graphical interface is centered around the manipulation of trees as elementary objects. It includes a graphical tree editor, facilities for exploring both derivation trees and derived trees, and also some support for manipulating simple feature structures (which can be used to enrich nodes in the XTAG formalism). All of these components are used to define grammars in the XTAG system. Unlike in many other systems, grammars are not specified via a text format, but directly in terms of graphical tree structures.

For the visualization of parsing processes, XTAG mainly provides a display of derivation trees, which contain all the essential information about how a tree was derived, and whose nodes are linked to displays of the corresponding elementary trees. This makes the derivation tree display analogous to the source code display for chart edges in TRALE. However, such a display does not expose as much detail about the internal computations, as it causes chart states and especially failed attempts to combine elementary trees to be hidden from the user.

A very interesting property of XTAG, which inspired the development of the feature workbench in Chapter 6, is that it allows to interactively execute tree operations such as adjunction and substitution for manual testing. This mechanism, together with the design as a central buffer of tree structures to which operations can be applied, with the results ending up again in the buffer, makes it possible to emulate entire parsing processes.

A more modern, though less mature, development environment for TAGs is the **Tübingen Linguistic Parsing Architecture (TuLiPA)** presented by Kallmeyer et al. (2008). Unlike the XTAG tools, TuLiPA does not contain tools for graphical editing of TAG grammars. Instead, it relies on the **XMG (eXtensible MetaGrammar)** approach described by Crabbé (2005) for this purpose. However, in comparison to XTAG, TuLiPA's visualization components are more focused on making complete parsing processes transparent, and are much less tuned towards interactive grammar exploration.

As in XTAG, both derivation trees and derived trees are interactively visualized. The elementary trees contributing to a derivation are made accessible as well. The heavily lexicalized nature of typical TuLiPA grammars makes it feasible to also display the structures where some feature clash occurred, highlighting the problematic parts in partially derived structures. The intermediate results after each adjunction or substitution step can optionally be displayed, which makes the parsing processes more transparent than in XTAG, even though TuLiPA lacks facilities for manually executing adjunctions and substitutions.

For even more distant grammar formalisms such as Combinatory Categorical Grammar (CCG) or even plain CFG, a parse chart is usually sufficient because the rules for filling the chart are very local and easy to track. In general, the less complex the categories that need to be grouped into constituents become, and the more dominant simple phrase structure rules become for parsing, the less the user will gain by receiving extensive information about the parser's internal workings.

As statistical approaches to NLP also tend to only rely on local contexts and shun complex interactions for easier model learnability, the few visualization tools are normally just used to quickly survey the consequences that changes in learning parameters have on system behavior. This makes graphical representations for statistical parsing an area unlikely to be of much help for our purposes.

3.2 Introducing the Kahina Architecture

We now turn our attention to **Kahina** (Dellert et al., 2010), a novel debugging framework which developed out of a graphical frontend for TRALE's source-level debugger. The more recent versions of Kahina provide advanced general debugging facilities for logic and constraint programming. The system expands on earlier ideas for graphical Prolog debugging presented by e.g. Dewar and Cleary (1986) and Eisenstadt et al. (1991), and is heavily inspired by SWI-Prolog's GUI tracer (Wielemaker, 2003), which is the most mature visualization tool for Prolog processes currently available.

The Kahina system is built around the concept of the computation step. Representations of such steps can be arranged in global data structures such as control flow graphs, and data of arbitrary type can be assigned to the individual steps. In the case of TRALE, a step is associated with information on the respective operation (e.g. unification, mgs computation, or goal execution), a source code line, and a snapshot of relevant data at that step (e.g. feature structures and variable bindings).

The architecture of the Kahina-based TRALE debugger is sketched in Figure 3.2, as an aid for understanding the somewhat complex relations between the various system components. Kahina as a framework is implemented entirely in Java, and currently consists of about 38.000 lines of code. The Java Swing library is used for the graphical interface code. The entire source code of Kahina and all the components developed in this thesis is distributed under a GPL license via the system's webpage (see Evang and Dellert, 2011).

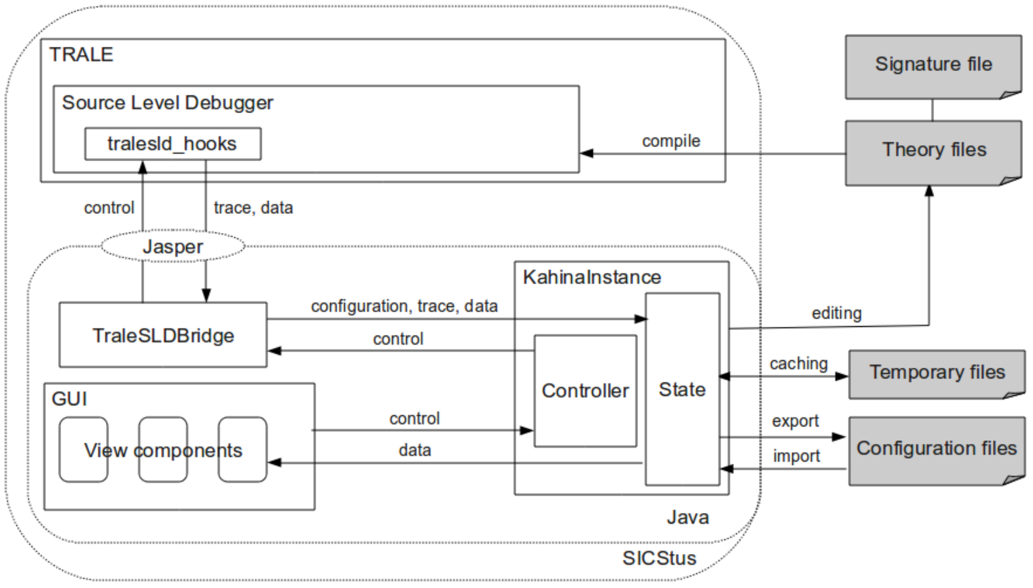


Figure 3.2: Architecture of the Kahina-based TRALE debugger.

A Kahina-based debugger is started by creating a `KahinaInstance` object, which mainly consists of a `KahinaState` and a `KahinaController`, and communicates with a `KahinaGUI`. The `KahinaState` manages a step database containing the step data as well as one or more data structures to model the relations between steps (such as call trees and charts), caching step data into temporary files if they become too large. The `KahinaGUI` includes a window manager coordinating various GUI elements, and it provides functionality for creating and manipulating windows. The `KahinaController` is responsible for message exchange between the various components of the system. Whenever I use the name "Kahina" in this thesis, I refer to this general Java framework.

Kahina can straightforwardly be adapted to a specific application by specifying step types and their relevant content. A **bridge** is then implemented to encapsulate all the traffic between the client application and Kahina. This includes transmitting the step detail information as well as handing back control instructions, such as tracing commands, to the client process. On the client side, the communication with Kahina is usually implemented by adding code for transmitting step data to the bridge, and a control loop that interleaves with the execution process and prompts Kahina for a user command telling it how to proceed.

For both SICStus and SWI-Prolog, the Kahina distribution comes with Prolog libraries that implement both the transmission and the control loop, and which are configured for interaction with a default `LogicProgrammingBridge`. SICStus Prolog communicates with Kahina using the Jasper library (Carlsson et al., 2009, Section 10.43), and for SWI-Prolog, the JPL library (Singleton et al., 2011) is used. Because only a SICStus Prolog version of TRALE is currently available[1], the architecture sketch only mentions the Jasper interface. Both Jasper and JPL spawn and address a Java Virtual Machine (JVM) via the **Java Native Interface (JNI)**, a framework that enables Java code to call and be called by programs and libraries in other languages as native processes that run outside the JVM. The JNI is a lot less stable than other parts of standard Java distributions, so that both Jasper and JPL are considered experimental by the respective developers, and using Jasper is even actively discouraged. In our experience, however, both interfaces are reasonably stable, and they allowed us to

[1]Other versions (e.g. for SWI Prolog) exist, but have not yet been made publicly available.

avoid dealing with separate processes and sockets for inter-process communication. When creating debuggers for systems implemented in Prolog, Kahina's libraries are often sufficient to make client-side adaptations unnecessary, shifting the main focus in creating an advanced debugger to specializing the `LogicProgrammingBridge` for the respective client program.

As the second step in creating a customized debugger, custom data types and specialized views can be added to Kahina's modular data and view models. In the case of TRALE, for instance, we implemented a specialized view component for the chart, and integrated an existing view component for typed feature structures as AVM (Attribute-Value Matrix) representations. We will have a look at the chart display in the next section. The feature structure visualization will be discussed extensively in Chapter 5, since it provides the basis for the feature structure editor.

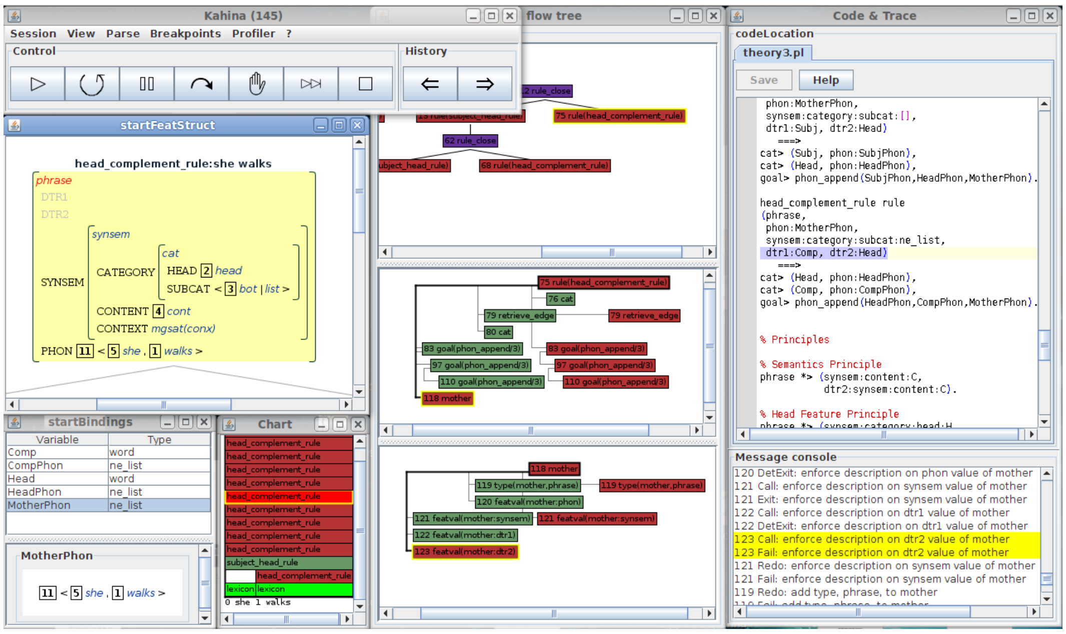
Kahina-based debuggers for several logic programming systems are available through the system's website. The versions for SWI-Prolog and SICStus Prolog are not yet as fully developed as the new TRALE debugger, but they provide an excellent basis for creating Kahina debuggers for other Prolog programs. Because all the functionality specific to logic programming is contained in a separate package (`org.kahina.lp`), the very general core system in `org.kahina.core` can also be used for creating debuggers outside of the logic programming paradigm.

3.3 Visualization and Control Mechanisms in Kahina

When a logic programming system loads its Kahina debugger, it hands over control to the respective bridge, periodically prompting it for tracing instructions. The tracer interface is exposed by a control panel in Kahina's main window, which provides the basic tracing commands of the old source-level debugger as mnemonic buttons that can still be operated by using the old single-key instructions. In reflection of the new possibilities for step data storage, a distinction is made between the operations of skipping and auto-completion. Skipping is directly translated into a skip command for the tracer, discarding the details of the skipped steps, whereas **auto-completion** executes the same skip using a sequence of creep commands, collecting and storing the step information for all intermediate steps. Given the amount of data that needs to be transferred to Kahina in the auto-completion case, it is not surprising that auto-completion is a lot slower than skipping.

A Kahina-based debugger comes with a range of predefined view components, which are either local views intended to visualize the data associated with the currently selected step, or global views that expose some aspect of the overall structure of parsing processes. Kahina allows the user to freely arrange these views into windows, although some useful view and window configurations (called **perspectives**) are distributed with the respective debugger. In the case of TRALE, Kahina currently provides three global and four local views, which I extend by two more global view components in this thesis. Figure 3.3 contains a screenshot of the new TRALE debugger, showing many of the view components that we will talk about in this section.

The views are free to interact via the controller, which allows listeners to register themselves for different message types, and later distributes messages on user interactions or data model changes to all components currently interested in the respective message type. For instance, this makes it possible to dynamically change the step details displayed in the local views when a step is selected in one of the global views.



Variable	Type
Comp	word
CompPhon	ne_list
Head	word
HeadPhon	ne_list
MotherPhon	ne_list

```
 phon:MotherPhon,
 synsem:category:subcat:[],
 dtr1:Subj, dtr2:Head)
   ===>
cat> (Subj, phon:SubjPhon),
cat> (Head, phon:HeadPhon),
goal> phon_append(SubjPhon,HeadPhon,MotherPhon).

head_complement_rule rule
(phrase,
 phon:MotherPhon,
 synsem:category:subcat:ne_list,
 dtr1:Comp, dtr2:Head)
   ===>
cat> (Head, phon:HeadPhon),
cat> (Comp, phon:CompPhon),
goal> phon_append(HeadPhon,CompPhon,MotherPhon).


% Principles

% Semantics Principle
phrase *> (synsem:content:C,
           dtr2:synsem:content:C).

% Head Feature Principle
```

```
120 DetExit: enforce description on phon value of mother
121 Call: enforce description on synsem value of mother
121 Exit: enforce description on synsem value of mother
122 Call: enforce description on dtr1 value of mother
122 DetExit: enforce description on dtr1 value of mother
123 Call: enforce description on dtr2 value of mother
123 Fail: enforce description on dtr2 value of mother
121 Redo: enforce description on synsem value of mother
121 Fail: enforce description on synsem value of mother
119 Redo: add type, phrase, to mother
```

Figure 3.3: A session of the Kahina-based TRALE debugger.

3.3.1 Global Views

The global views currently implemented for TRALE allow the user to interact with a control flow tree, the parse chart, and the source code. We will not discuss the source code editor any further, since it has no importance in the context of the present work.

The heart of the Kahina-based TRALE debugger is the **control flow tree**, which represents the computation steps as nodes and allows the user to select every node in order to retrieve the associated information, which is then displayed in the local views. Each node in the tree is color-coded to mark which port last occurred on the corresponding step. The control flow tree combines two aspects in one view. The **search tree** is symbolized by the macro structure which determines the tree's overall layout, making the backtracking completely transparent. At the same time, the **call tree** can be represented by indentation levels in the linear fragments of the search tree. Together, the two display dimensions contain comprehensive information on the reasons why the steps occurred in which order.

An alternative view mode for the control flow tree is based on a more compact list representation. This **list tree view** puts less emphasis on the search tree by only displaying one branch at a time, but allows the user to switch between alternative branches at each choice point. The resulting less hierarchical structure uses up a lot less screen space, leaving more real estate for other views, or allowing more steps to be displayed at the same time. On the other hand, the global structure of the search tree is not visible any longer, which is a disadvantage if the user wants to find the branches where most steps occurred.

To keep the tree navigable even if it contains thousands of nodes, a **layering mechanism** can be used to separate the tree into meaningful units. User-definable layer deciders classify the nodes into layers that are numbered by importance, where each layer is more important than all the layers with higher IDs, so that layer 0 contains the most important nodes. When computing a tree view at some layer, the nodes of more important layers are treated as **corner-stone nodes**, which define the context boundaries where the tree fragment of the display is pruned. Displays at different layers are connected by a common context node.

Navigation in the tree works by selection, which redefines the context node and causes the displays at all layers to adapt. The effect of the layers can be compared to zoom levels, where the layer decider determines how much detail is visible at each level, and the corner-stone nodes define the boundary of the zoom window.

The **chart display** lists the edges as blocks arranged over the input string. The TRALE parser proceeds by trying to establish edges according to phrase-structure rules in a right-to-left bottom-up fashion, which makes the chart a very helpful component for understanding which structure the parser is currently working on. Chart edges are tightly coupled with the corresponding parsing steps, allowing the user to jump to the relevant position in the control flow tree by selecting a chart edge. This coupling of steps and the chart also works the other way around: whenever the user selects a step in the control flow tree or in the trace-like message console, the chart display highlights the edge that this step contributed to. The highlighting can be configured to also include the descendants and/or the ancestors of the selected edge, providing an intuitive visualization of the edges that contributed to the current edge, or the uses of the current edge in establishing larger constituents.

In addition to the display of all edges that could be established (in green), the chart display allows the user to selectively display all the failed edges (in red) for some phrase-structure rule. The step IDs associated with the failed edges will carry a user directly to a step where the corresponding rule failed, providing direct and detailed access to the reasons why some edge could not be established. However, backtracking often makes it impossible to identify a single step whose failure is responsible for the failure of a superordinate goal. Therefore, while trying to construct an edge, we usually encounter many substeps which fail, but do not prevent the edge from being established. Conversely, if a predicate fails, it usually fails multiple times (once in every branch of the search tree), leading to a confusing proliferation of failed edges on the chart. A few simple heuristics for distinguishing relevant and spurious failures somewhat alleviate this problem, but the conceptual difficulty remains.

3.3.2 Local Views

The local views for TRALE currently display feature structures and variable bindings at the respective ports of the current step. Virtually all the step types that occur during a parsing process amount to a manipulation of **feature structures**, and can therefore most informatively be visualized by an AVM representation of the structures involved. Kahina's approach to feature structure visualization is discussed extensively in Chapter 5. Experience has shown that in comparison to only displaying the substructure that is modified by a step, highlighting it in a larger context structure makes it easier to understand how the different steps contribute to structure manipulation. For instance, when creeping through the complex process of matching a feature structure against a description, this is graphically depicted by parallel highlights closing in on substructures and marking the places were local modifications occur.

In addition to the context structure, the bindings for all the variables used in the definition of the respective predicate are accessible via another view. As variables are bound to feature structures, a **variable bindings** display consists of a list of context variables and a small instance of the feature structure display to present the selected variable's current value in a human-readable fashion.

Both the feature structure and the variable binding views are separated into two windows representing the state before and after the computation step. Because the feature structure display highlights the parts of the context structure that have changed between ports, it implicitly provides a **diff functionality**, which makes it easy to determine the data structure manipulations occurring at every step in the control flow tree.

3.3.3 Breakpoint System

Just like in the old SLD, rapid navigation of a parsing process towards a point of interest requires some functionality beyond the basic tracing commands. For this purpose, Kahina features a powerful **breakpoint system** which, in addition to its obvious use in defining breakpoints, is also used for both pattern search and workflow automation. In addition to putting breakpoints on source code lines as in the old SLD, breakpoints can be defined by pattern matches using regular expressions over step descriptions, or regular tree patterns ranging over substructures of the control flow tree. Such patterns allow to define breakpoints in a very fine-grained manner. For instance, its is possible to single out only those unification steps which involve SYNSEM:CATEGORY values and occur while trying to apply the Head Feature Principle.

All these patterns can be freely combined using boolean expressions, and they can be extended by counters, which in turn can be furnished with numerical constraints. For instance, this makes it possible to define a breakpoint which only fires at every tenth match of some tree pattern. Collections of breakpoints can be administered and edited using a graphical **breakpoint editor**, which includes a tree editor as an intuitive method for defining tree patterns.

The breakpoint system can also be used for searching through the step database, by temporarily defining a breakpoint and running it over the existing control flow tree. The message console will then show all the matches, each line acting as a link for selecting and scrolling to the matching node. All of the patterns that can be used in breakpoint definitions can serve as search patterns in this way.

The standard behavior of a breakpoint is to interrupt leap operations when a situation matching its pattern is encountered. Kahina offers a range of non-standard breakpoint types for **process automation**. For each of the basic tracing commands, a corresponding breakpoint type exists. In analogy to the term *breakpoint*, these are called *skip points*, *creep points*, and *fail points*, and trigger the respective tracing command when their patterns are matched. This automation mechanism can greatly increase the efficiency of debugging, e.g. by telling the tracer to automatically skip over all applications of a phrase structure rule that can safely be assumed to contain no bugs. A **warn point** is a breakpoint with an associated message that is displayed in a pop-up window when the pattern matches. Warn points can e.g. be used to catch infinite recursion when debugging a non-terminating parse, or to provide warnings when a part of the implementation seems particulary inefficient.

This powerful breakpoint system can also be used to emulate the control strategies of the old source-level debugger. Putting a leash on a step type can be emulated by defining a breakpoint with a pattern matching that step type. Of course, the more powerful patterns make the possibilities for leashing a lot more fine-grained than in the old SLD. The same holds for auto-skipping, which corresponds exactly to defining skip points whose patterns match the step types. Finally, the breakpoint mechanism of the old SLD is subsumed by the Kahina breakpoint system because source code line numbers are supported as elementary patterns.

3.4 Discussion

After this quick tour of the Kahina system, we will now see which problems of the old source-level debugger are solved by Kahina, which problems remain unresolved, and also the weaknesses the system currently still has.

One of the most pressing problems of the old SLD, that of determining the current state of execution, can be considered resolved. By the combination of a chart and a control flow graph, the position of each step in the process is in principle completely transparent. The secondary tree dimension based on indentations also allows grasping the call structure much more quickly than before. Although neatly splitting up control flow information into the respective layers without losing too much of the gained transparency turned out to be quite a challenge, already the current approximate solution has proven to be highly useful even for inexperienced grammar implementers.

The fact that all the data associated with the traced steps is stored for later retrieval offers the user the novel option of **post-mortem analysis**, i.e. inspection of computation steps even after they were processed. This means that the user is no longer forced to decide beforehand whether a step can be skipped, and retrace the entire process in case of unexpected behavior. Instead, it is now possible to auto-complete a step, but still inspect the computations involved if the skipping decision was erroneous or too optimistic. Tracing decisions are thus still local, but can to some extent be revised, allowing the user to behave less defensively during debugging.

Interactivity with many windows open at the same time allows the user to configure views according to her information needs. While inspecting a computation step, the control flow diagram, the soure code location, variable bindings as well as input and output feature structures can all be visualized in parallel. This display parallelism has increased the accessibility of non-local information enormously.

Turning to the weaknesses of the Kahina architecture, it comes as no surprise that an interface with this many different views chronically suffers from shortage of screen space. Combining all these views in just one screen leads to a very crowded interface, forcing the user to scroll views and to manipulate window sizes and positions quite frequently. Ideally, a grammar implementer will therefore want to use at least two high-resolution displays. In order to avoid any compromise in the amount of information that can be displayed in parallel, the Kahina window manager provides comprehensive support for distributing windows over several screens, turning this issue more into one of hardware than of design.

A more severe disadvantage is the speed of step data collection, which is partially caused by the need to assemble the feature structures on the Prolog side, but mostly by the delay in every foreign method call via the Jasper interface. As a result, in auto-complete and leap mode (which have evolved to be very popular with users), on a typical machine of this day only the details for about 30 steps per second are transmitted. This low speed is especially disturbing if Kahina is configured to retrieve all the step information even for the tiniest step, not making use of skip points to limit the expensive step detail transmission on points of interest. This makes skip points a core mechanism for an efficient workflow, but they are unfortunately often overlooked by users because their administration is hidden in a submenu. Therefore, it is planned to integrate them more prominently in the user interface.

A further weakness of the current architecture is that it only provides rudimentary support for error handling. If run-time errors happen on the Prolog side (e.g. because of erroneous inputs), the error messages are not yet displayed inside of Kahina, forcing the user to check the console from which TRALE was started. Moreover, Prolog errors often cause the underlying trace in the old SLD to abort, causing Kahina to be disconnected from the underlying tracer, making it unresponsive and forcing the user to restart the process. We plan to fix these problems in the future by extending the bridge interface by another communication channel.

Coming to more TRALE-specific weaknesses, one problem is that delayed goals are still not visualized in a satisfying way. The current version of the Kahina-based debugger uses special nodes in the control flow tree to mark the points where goals are delayed, and the steps that result from the resumption of such a goal are connected to the delay point by a link that can be followed. As a result, the execution of a delayed goal does not any longer cause the user to lose track of the execution state, but it can still be a rather surprising event. This could be improved by displaying the suspended goals in an additional view component, visualizing the conditions for resumption in a transparent way. Attempts will be made to develop such a view component for future versions of Kahina.

Finally, grammar compilation and parsing processes can be started using the debugger's Parse menu, but due to its origin as a mere graphical frontend, Kahina does not yet include any facilities for defining test suites. An option to define projects consisting of grammar files and test parses has a high priority for inclusion in future versions of Kahina. In connection with the introduction of test suites, Kahina's rudimentary profiling facilities will also have to be extended.

Despite the current shortcomings, and even though the Kahina architecture is far from mature, the Kahina-based debugger is stable enough to have replaced the old SLD as the default debugger in recent versions of TRALE. Despite its current lack of documentation, various students (e.g. Nomi Meixner and Anne Brock, personal communication) who implemented or extended grammars for seminar papers at the University of Tübingen, have confirmed it to be very useful in comparison to its console-based predecessor.

Chapter 4

Signature Inspection and Visualization

A core element of a constraint-based grammar is the specification of the structural domain that the constraints apply to. In a typed feature logic system, this is commonly achieved by a signature which considerably restricts the space of allowed feature structures before more complex constraints are enforced.

When getting an overview of a grammar implementation, analyzing the signature is the first step to understanding which linguistic phenomena are covered, and how they are modeled in the grammar. The signature also contains much information on how structures can be manipulated during a parsing or generation process. Unfortunately, signatures are in essence graph structures extended by a rather involved inheritance schema, which makes them hard to grasp especially for the novice user.

This chapter deals with the design of tools for user-friendly signature inspection, where a natural focus lies on useful visualization strategies for the information encoded in a TRALE signature. Section 1 introduces the necessary formal notions as well as a running example. In Section 2, existing approaches to signature visualization are described, leading to a more general discussion of the representation issues in Section 3. Section 4 presents a novel signature visualization approach, which is inspired by Javadoc and implemented as a Kahina view module. The chapter concludes with a discussion of the advantages and problems of the new view module in Section 5.

4.1 TRALE Signatures and the Type System

We begin by formally introducing the type system as implemented in TRALE. The terminology as well as the notation is slightly adapted from Carpenter (1992), whereas information about the variant implemented in TRALE was derived from the ALE User's Guide by Penn et al. (2003).

Definition 4.1.1. *Let Ty be a finite set of symbols called* ***types****, and let $\sqsubseteq$ be an ordering relation on Ty. For $\sigma, \tau \in Ty$, we say that σ* ***subsumes*** *τ or σ* ***is more general than*** *τ iff $\sigma \sqsubseteq \tau$. In that case, we also say that σ is a* ***supertype*** *of τ or that τ is a* ***subtype*** *of σ.*

In applications, the subsumption ordering can often intuitively be understood as expressing degrees of informativity. The more general a type is, the less information it contains. For instance, if we know of a linguistic object that it is a fricative, we also know that it is a consonant, but we have the additional information that it is not a plosive. This could be modeled by a type *consonant* subsuming, among others, the subtypes *plosive*, *nasal*, and *fricative*.

Definition 4.1.2. *A set Ty of types is said to be* ***consistent*** *if they share a common subtype or* ***upper bound*** *σ such that $\tau \sqsubseteq \sigma$ for every $\tau \in Ty$.*

Definition 4.1.3. *A type σ is the* ***least upper bound*** *(or* ***join****) of a subset $S \subseteq Ty$ iff $\forall \tau \in S\ \tau \sqsubseteq \sigma$, and $\sigma \sqsubseteq \upsilon$ for every other $\upsilon \in Ty$ where $\forall \tau \in S\ \tau \sqsubseteq \upsilon$.*

Definition 4.1.4. *A partial order is called* ***bounded complete*** *iff for every set of elements with an upper bound there is a least upper bound.*

Definition 4.1.5. *An* ***inheritance hierarchy*** *is a finite and bounded complete partial order $\langle Ty, \sqsubseteq \rangle$, i.e. a finite set of types where every consistent subset of types has a most general subtype.*

TRALE's type hierarchies are thus in essence acyclic inheritance graphs. An inheritance hierarchy can be defined using a set of **elementary is-a pairs**, defining a relation $\lhd$ that needs to be antisymmetric, but not necessarily reflexive or transitive. The complete subsumption relation $\sqsubseteq$ is then defined as the reflexive transitive closure of $\lhd$. As we shall see, elementary is-a pairs are the entities employed by the user for signature definitions.

Because the tools we develop are designed to present information and options in a format as close as possible to the user's definitions, many of the later formal definitions will rely on the graph structure defined by $\lhd$ instead of its reflexive transitive closure $\sqsubseteq$.

Definition 4.1.6. *An* ***appropriateness specification*** *over an inheritance hierarchy $\langle Ty, \sqsubseteq \rangle$ and a finite set of features Fe is a partial function $A\colon Fe \times Ty \to Ty$ which meets the following conditions:*
*(1) (****feature introduction****): for every $f \in Fe$ there is a most general type $Intro(f) \in Ty$ such that $A(f, Intro(f))$ is defined.*
*(2) (****upward closure****): if for $f \in Fe, \sigma, \tau \in Ty$ and $\sigma \sqsubseteq \tau$, $A(f, \sigma)$ is defined, then so is $A(f, \tau)$, and $A(f, \sigma) \sqsubseteq A(f, \tau)$ holds.*

Intuitively, an appropriateness specification encodes information we have (or postulate) about an object and its relations to other objects if we know about its type. In our phonology example, we could introduce the places of articulation under a type *place* in another part of the type hierarchy and state that that each consonant introduces a feature PLACE whose value is of type *place* by defining $A(\text{PLACE}, consonant) := place$. Upward closure would then ensure that a PLACE value of type *place* is also defined for the subtypes of consonant.

Definition 4.1.7. *A* ***signature*** *is a quadruple $\langle Ty, \sqsubseteq, Fe, A \rangle$ composed of an inheritance hierarchy $\langle Ty, \sqsubseteq \rangle$, a finite set of features Fe, and an appropriateness specification $A\colon Fe \times Ty \to Ty$.*

Throughout this thesis, we will make use of a simple toy grammar to provide us with examples for the theory and implementation of the new tools. The demo grammar is the last introductory example (Grammar 4, Version 3) in Richter (2005). Appendix A contains the signature file for this grammar in TRALE format.

We will not discuss the specifics of this format here, but the reader should notice that it can be conceptualized as pairs defining the $\lhd$ relation, expressing differences that get lost during the closure operation leading to $\sqsubseteq$. The signature defines *bot* $\lhd$ *cont* and *cont* $\lhd$ *arg*, but also *bot* $\lhd$ *arg*, although this last pair would be unnecessary in the definition of a $\sqsubseteq$ relation. As an example of the formalization just introduced, Figure 4.1 contains the complete formal definition of the same signature. Figure 4.2 enhances this by an intuitive visualization which expresses the type hierarchy as well as the appropriateness conditions in a graph. This representation is not entirely intuitive in displaying the bot ("bottom") type at the top, but it adheres to the equally justified convention that supertypes are positioned higher than their subtypes. Using these three representations, the reader will have no difficulty in understanding the signature that will serve as our running example.

$$
\begin{array}{l}
\langle\{\mathit{acc}, \mathit{arg}, \mathit{bin_rel}, \mathit{bse}, \mathit{bot}, \mathit{case}, \mathit{cat}, \mathit{cont}, \mathit{conx}, \mathit{dat}, \mathit{e_list}, \mathit{fem}, \mathit{female_rel}, \mathit{fin},\\
\mathit{first}, \mathit{gender}, \mathit{give_rel}, \mathit{head}, \mathit{index}, \mathit{list}, \mathit{love_rel}, \mathit{masc}, \mathit{more_arg_rel}, \mathit{ne_list},\\
\mathit{nom}, \mathit{nom_obj}, \mathit{noun}, \mathit{number}, \mathit{person}, \mathit{phrase}, \mathit{plur}, \mathit{relations}, \mathit{sign}, \mathit{sing},\\
\mathit{speaker_rel}, \mathit{synsem}, \mathit{think_rel}, \mathit{third}, \mathit{un_rel}, \mathit{verb}, \mathit{vform}, \mathit{walk_rel}, \mathit{word}\},\\
\{(\mathit{acc}, \mathit{acc}), (\mathit{arg}, \mathit{arg}), (\mathit{arg}, \mathit{bin_rel}), (\mathit{arg}, \mathit{female_rel}), (\mathit{arg}, \mathit{give_rel}), (\mathit{arg}, \mathit{index}),\\
(\mathit{arg}, \mathit{love_rel}), (\mathit{arg}, \mathit{more_arg_rel}), (\mathit{arg}, \mathit{relations}), (\mathit{arg}, \mathit{speaker_rel}),\\
(\mathit{arg}, \mathit{think_rel}), (\mathit{arg}, \mathit{un_rel}), (\mathit{arg}, \mathit{walk_rel}), (\mathit{bin_rel}, \mathit{bin_rel}), (\mathit{bin_rel}, \mathit{love_rel}),\\
(\mathit{bin_rel}, \mathit{think_rel}), (\mathit{bot}, \mathit{acc}), (\mathit{bot}, \mathit{arg}), (\mathit{bot}, \mathit{bin_rel}), (\mathit{bot}, \mathit{bot}), (\mathit{bot}, \mathit{bse}), (\mathit{bot}, \mathit{case}),\\
(\mathit{bot}, \mathit{cat}), (\mathit{bot}, \mathit{cont}), (\mathit{bot}, \mathit{conx}), (\mathit{bot}, \mathit{dat}), (\mathit{bot}, \mathit{e_list}), (\mathit{bot}, \mathit{fem}), (\mathit{bot}, \mathit{female_rel}),\\
(\mathit{bot}, \mathit{fin}), (\mathit{bot}, \mathit{first}), (\mathit{bot}, \mathit{gender}), (\mathit{bot}, \mathit{give_rel}), (\mathit{bot}, \mathit{head}), (\mathit{bot}, \mathit{index}), (\mathit{bot}, \mathit{list}),\\
(\mathit{bot}, \mathit{love_rel}), (\mathit{bot}, \mathit{masc}), (\mathit{bot}, \mathit{more_arg_rel}), (\mathit{bot}, \mathit{ne_list}), (\mathit{bot}, \mathit{nom}), (\mathit{bot}, \mathit{nom_obj}),\\
(\mathit{bot}, \mathit{noun}), (\mathit{bot}, \mathit{number}), (\mathit{bot}, \mathit{person}), (\mathit{bot}, \mathit{phrase}), (\mathit{bot}, \mathit{plur}), (\mathit{bot}, \mathit{relations}),\\
(\mathit{bot}, \mathit{sign}), (\mathit{bot}, \mathit{sing}), (\mathit{bot}, \mathit{speaker_rel}), (\mathit{bot}, \mathit{synsem}), (\mathit{bot}, \mathit{think_rel}), (\mathit{bot}, \mathit{third}),\\
(\mathit{bot}, \mathit{un_rel}), (\mathit{bot}, \mathit{verb}), (\mathit{bot}, \mathit{vform}), (\mathit{bot}, \mathit{walk_rel}), (\mathit{bot}, \mathit{word}), (\mathit{bse}, \mathit{bse}), (\mathit{case}, \mathit{acc}),\\
(\mathit{case}, \mathit{case}), (\mathit{case}, \mathit{dat}), (\mathit{case}, \mathit{nom}), (\mathit{cat}, \mathit{cat}), (\mathit{cont}, \mathit{arg}), (\mathit{cont}, \mathit{bin_rel}), (\mathit{cont}, \mathit{cont}),\\
(\mathit{cont}, \mathit{female_rel}), (\mathit{cont}, \mathit{give_rel}), (\mathit{cont}, \mathit{index}), (\mathit{cont}, \mathit{love_rel}), (\mathit{cont}, \mathit{more_arg_rel}),\\
(\mathit{cont}, \mathit{nom_obj}), (\mathit{cont}, \mathit{relations}), (\mathit{cont}, \mathit{speaker_rel}), (\mathit{cont}, \mathit{think_rel}), (\mathit{cont}, \mathit{un_rel}),\\
(\mathit{cont}, \mathit{walk_rel}), (\mathit{conx}, \mathit{conx}), (\mathit{dat}, \mathit{dat}), (\mathit{e_list}, \mathit{e_list}), (\mathit{fem}, \mathit{fem}),\\
(\mathit{female_rel}, \mathit{female_rel}), (\mathit{fin}, \mathit{fin}), (\mathit{first}, \mathit{first}), (\mathit{gender}, \mathit{fem}), (\mathit{gender}, \mathit{gender}),\\
(\mathit{gender}, \mathit{masc}), (\mathit{give_rel}, \mathit{give_rel}), (\mathit{head}, \mathit{head}), (\mathit{head}, \mathit{noun}), (\mathit{head}, \mathit{verb}),\\
(\mathit{index}, \mathit{index}), (\mathit{list}, \mathit{e_list}), (\mathit{list}, \mathit{list}), (\mathit{list}, \mathit{ne_list}), (\mathit{love_rel}, \mathit{love_rel}), (\mathit{masc}, \mathit{masc}),\\
(\mathit{more_arg_rel}, \mathit{bin_rel}), (\mathit{more_arg_rel}, \mathit{give_rel}), (\mathit{more_arg_rel}, \mathit{love_rel}),\\
(\mathit{more_arg_rel}, \mathit{more_arg_rel}), (\mathit{more_arg_rel}, \mathit{think_rel}), (\mathit{ne_list}, \mathit{ne_list}),\\
(\mathit{nom}, \mathit{nom}), (\mathit{nom_obj}, \mathit{nom_obj}), (\mathit{noun}, \mathit{noun}), (\mathit{number}, \mathit{number}), (\mathit{number}, \mathit{plur}),\\
(\mathit{number}, \mathit{sing}), (\mathit{person}, \mathit{first}), (\mathit{person}, \mathit{person}), (\mathit{person}, \mathit{third}), (\mathit{phrase}, \mathit{phrase}),\\
(\mathit{plur}, \mathit{plur}), (\mathit{relations}, \mathit{bin_rel}), (\mathit{relations}, \mathit{female_rel}), (\mathit{relations}, \mathit{give_rel}),\\
(\mathit{relations}, \mathit{love_rel}), (\mathit{relations}, \mathit{more_arg_rel}), (\mathit{relations}, \mathit{relations}),\\
(\mathit{relations}, \mathit{speaker_rel}), (\mathit{relations}, \mathit{think_rel}), (\mathit{relations}, \mathit{un_rel}), (\mathit{relations}, \mathit{walk_rel}),\\
(\mathit{sign}, \mathit{phrase}), (\mathit{sign}, \mathit{sign}), (\mathit{sign}, \mathit{word}), (\mathit{sing}, \mathit{sing}), (\mathit{speaker_rel}, \mathit{speaker_rel}),\\
(\mathit{synsem}, \mathit{synsem}), (\mathit{think_rel}, \mathit{think_rel}), (\mathit{third}, \mathit{third}), (\mathit{un_rel}, \mathit{female_rel}),\\
(\mathit{un_rel}, \mathit{speaker_rel}), (\mathit{un_rel}, \mathit{un_rel}), (\mathit{un_rel}, \mathit{walk_rel}), (\mathit{verb}, \mathit{verb}),\\
(\mathit{vform}, \mathit{bse}), (\mathit{vform}, \mathit{fin}), (\mathit{vform}, \mathit{vform}), (\mathit{walk_rel}, \mathit{walk_rel}), (\mathit{word}, \mathit{word})\},\\
\{\textsc{arg1},\textsc{arg2},\textsc{arg3},\textsc{backgr},\textsc{case},\textsc{category},\textsc{content},\textsc{context},\textsc{dtr1},\textsc{dtr2},\\
\textsc{gender},\textsc{hd},\textsc{head},\textsc{index},\textsc{number},\textsc{person},\textsc{phon},\textsc{subcat},\textsc{synsem},\textsc{tl},\textsc{vform}\},\\
\{(\textsc{arg1}, \mathit{bin_rel}) \mapsto \mathit{arg},\ (\textsc{arg1}, \mathit{female_rel}) \mapsto \mathit{arg},\ (\textsc{arg1}, \mathit{give_rel}) \mapsto \mathit{arg},\\
(\textsc{arg1}, \mathit{love_rel}) \mapsto \mathit{arg},\ (\textsc{arg1}, \mathit{more_arg_rel}) \mapsto \mathit{arg},\\
(\textsc{arg1}, \mathit{relations}) \mapsto \mathit{arg},\ (\textsc{arg1}, \mathit{speaker_rel}) \mapsto \mathit{arg},\\
(\textsc{arg1}, \mathit{think_rel}) \mapsto \mathit{arg},\ (\textsc{arg1}, \mathit{un_rel}) \mapsto \mathit{arg},\ (\textsc{arg1}, \mathit{walk_rel}) \mapsto \mathit{arg},\\
(\textsc{arg2}, \mathit{bin_rel}) \mapsto \mathit{arg},\ (\textsc{arg2}, \mathit{give_rel}) \mapsto \mathit{arg}, (\textsc{arg2}, \mathit{love_rel}) \mapsto \mathit{arg},\\
(\textsc{arg2}, \mathit{more_arg_rel}) \mapsto \mathit{arg}, (\textsc{arg2}, \mathit{think_rel}) \mapsto \mathit{arg},\\
(\textsc{arg3}, \mathit{give_rel}) \mapsto \mathit{arg},\ (\textsc{backgr}, \mathit{conx}) \mapsto \mathit{list},\ (\textsc{case}, \mathit{noun}) \mapsto \mathit{case},\\
(\textsc{category}, \mathit{synsem}) \mapsto \mathit{cat},\ (\textsc{content}, \mathit{synsem}) \mapsto \mathit{cont},\\
(\textsc{context}, \mathit{synsem}) \mapsto \mathit{conx},\ (\textsc{dtr1}, \mathit{phrase}) \mapsto \mathit{sign}, (\textsc{dtr2}, \mathit{phrase}) \mapsto \mathit{sign},\\
(\textsc{gender}, \mathit{index}) \mapsto \mathit{gender}, (\textsc{hd}, \mathit{ne_list}) \mapsto \mathit{bot},\ (\textsc{head}, \mathit{cat}) \mapsto \mathit{head},\\
(\textsc{index}, \mathit{nom_obj}) \mapsto \mathit{index}, (\textsc{number}, \mathit{index}) \mapsto \mathit{number},\\
(\textsc{person}, \mathit{index}) \mapsto \mathit{person},\ (\textsc{phon}, \mathit{phrase}) \mapsto \mathit{ne_list},\\
(\textsc{phon}, \mathit{sign}) \mapsto \mathit{ne_list}, (\textsc{phon}, \mathit{word}) \mapsto \mathit{ne_list},\ (\textsc{subcat}, \mathit{cat}) \mapsto \mathit{list},\\
(\textsc{synsem}, \mathit{phrase}) \mapsto \mathit{synsem},\ (\textsc{synsem}, \mathit{sign}) \mapsto \mathit{synsem},\\
(\textsc{synsem}, \mathit{word}) \mapsto \mathit{synsem},\ (\textsc{tl}, \mathit{ne_list}) \mapsto \mathit{list},\ (\textsc{vform}, \mathit{verb}) \mapsto \mathit{vform}, \}\rangle
\end{array}
$$

Figure 4.1: Demo signature from Appendix A, in formal notation.

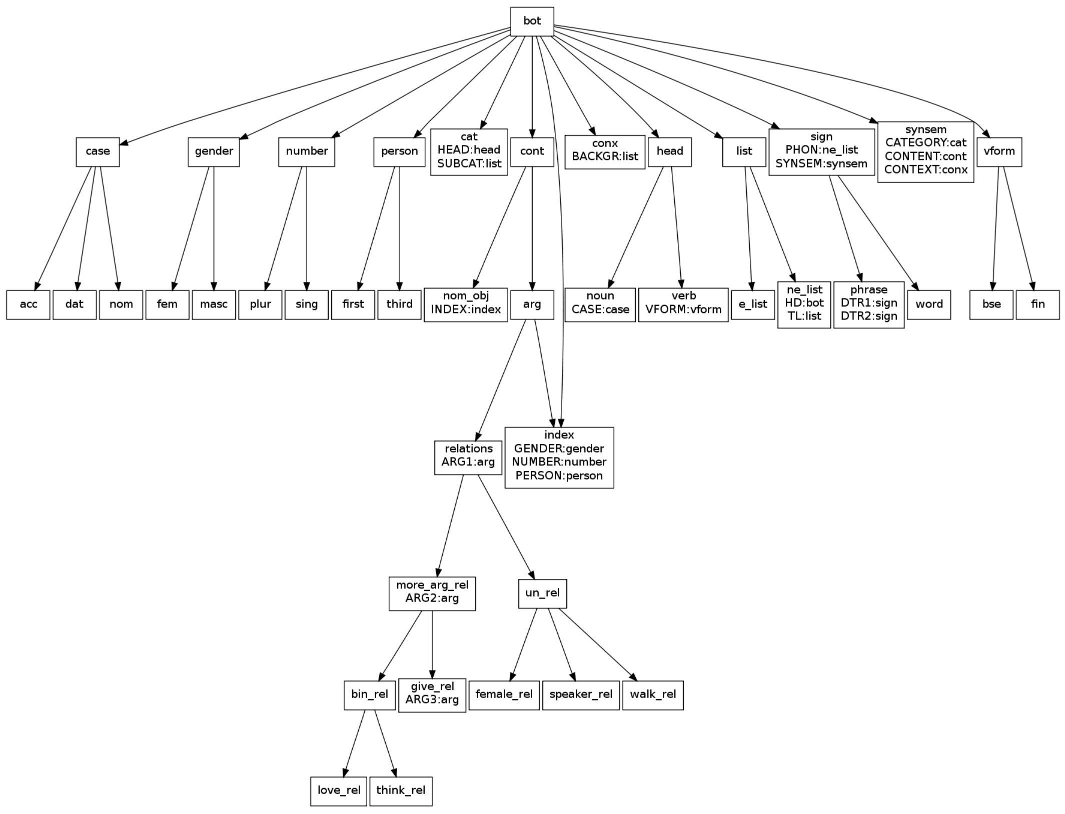


Figure 4.2: Demo signature from Appendix A, visualized as a graph.

4.2 Previous Approaches to Signature Inspection

The example visualization in Figure 4.2 looks nice and comprehensible, but only because it does not show the problems we run into when we try to visualize signatures that go beyond small toy examples. Already an HPSG grammar for a small fragment of English, like that in the appendix of Pollard and Sag (1994), contains more than a hundred types. Depending on the approach to modeling phonetics and semantics, the size of the type hierarchy can easily reach a four-digit number.

An early computational tool for interactively representing the type hierarchy of a typed feature logic was included in the LKB system. Figure 4.3 shows the LKB's display of a type hierarchy belonging to one of its example grammars. Type subsumption relations are indicated with lines in a very compact and rather schematic graph layout. To make such graphs more easily explorable, it is possible to selectively collapse subhierarchies. Specific information about the types' properties is not displayed as part of the graph structure, but instead it is accessible via a context menu option which opens up a separate feature structure view where the entire LKB type definition (which includes constraints, see Section 2.1) is displayed in a textual format.

The Java tool **MorphMoulder (MoMo)**, which was originally presented by Richter et al. (2002) as a tool for teaching the formal foundations of HPSG, and was later extended to description logics in Ovchinnikova and Richter (2007), can also be used as an aid for interactively exploring TRALE signatures. MoMo focuses on visualizing logical relationships between signatures, descriptions and interpretations. A screenshot of MoMo during a work session with our example signature is provided in Figure 4.4.

For the signature information, MoMo uses a text editor window in which a signature file in TRALE syntax can be edited. This format is compact, but not interactive, and does not explicitly represent multiple inheritance or the consequences of upward closure on the appropriateness conditions. MoMo is relevant for the tools we are developing because of the high interactivity of its other components, which allows students to extensively experiment with the formalism. Being able to manually build interpretations and check them for appropriateness against a signature constitutes a valuable aid in thoroughly understanding the formal foundations of HPSG. The facilities can be used to understand which structures are licensed by a given signature, which provides an intuitive handle to the abstract structural constraints it encodes.

The educational focus has negative consequences for MoMo's usefulness as a grammar writer's tool. Structures over a signature are depicted by very colorful and space-consuming graph models, which is important to weaken the erroneous intuition that AVMs were the interpretations of descriptions (while in reality, they are merely a representation format that can be used for descriptions and structures alike), but makes the displays of interpretations corresponding to feature structures as they occur in a grammar implementation really large and hard to understand.

Further pursuing the idea of representing the entire information contained in a signature explicitly in a single view, Ralf Kibiger (2009) implemented a dynamic graph visualization for TRALE signatures. Relying on the open-source Java Graph Visualization Library by JGraph Ltd (2011), the result is conceptually very similar to the visualization in Figure 4.2, but it adds some interactivity. Nodes representing types can be freely rearranged, collapsed and expanded, and the HTML content of the nodes was made editable to allow for annotations and reformatting. In Figure 4.5, a screenshot of Kibiger's visualization component displaying a part of our example signature is shown.

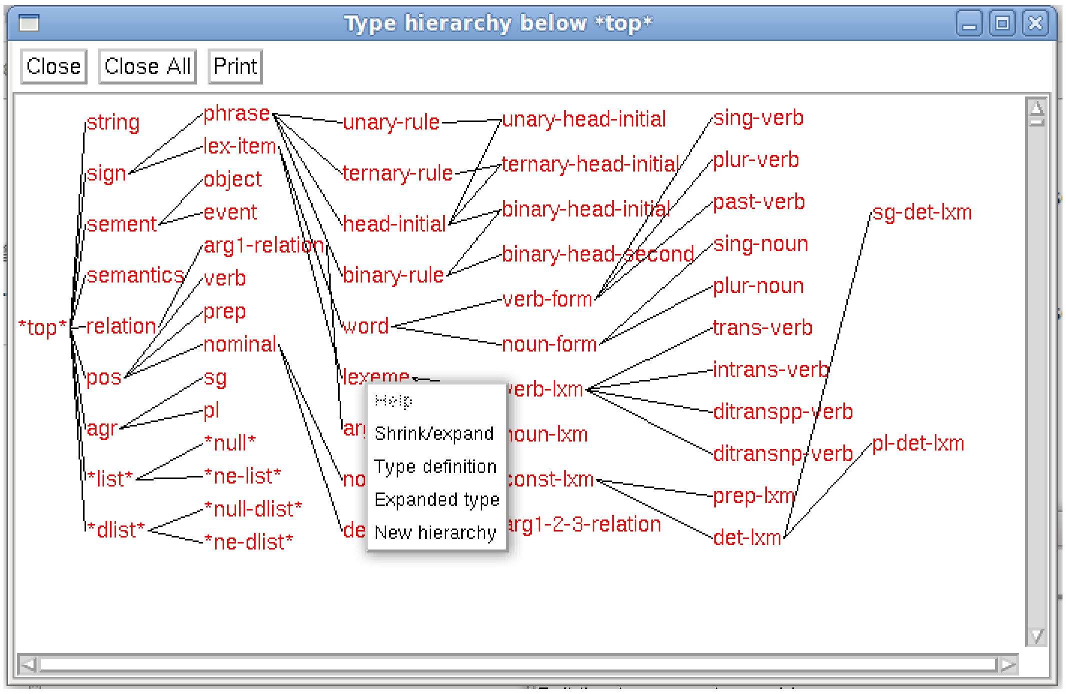


Figure 4.3: LKB type hierarchy view, context menu providing various options.

Unfortunately, the use of a rather heavy-weight explicit graph visualization means that only a fraction of the signature display fits on the screen at a time, and that a lot of display space is wasted due to the rather wide topological structure of typical signatures.[1]

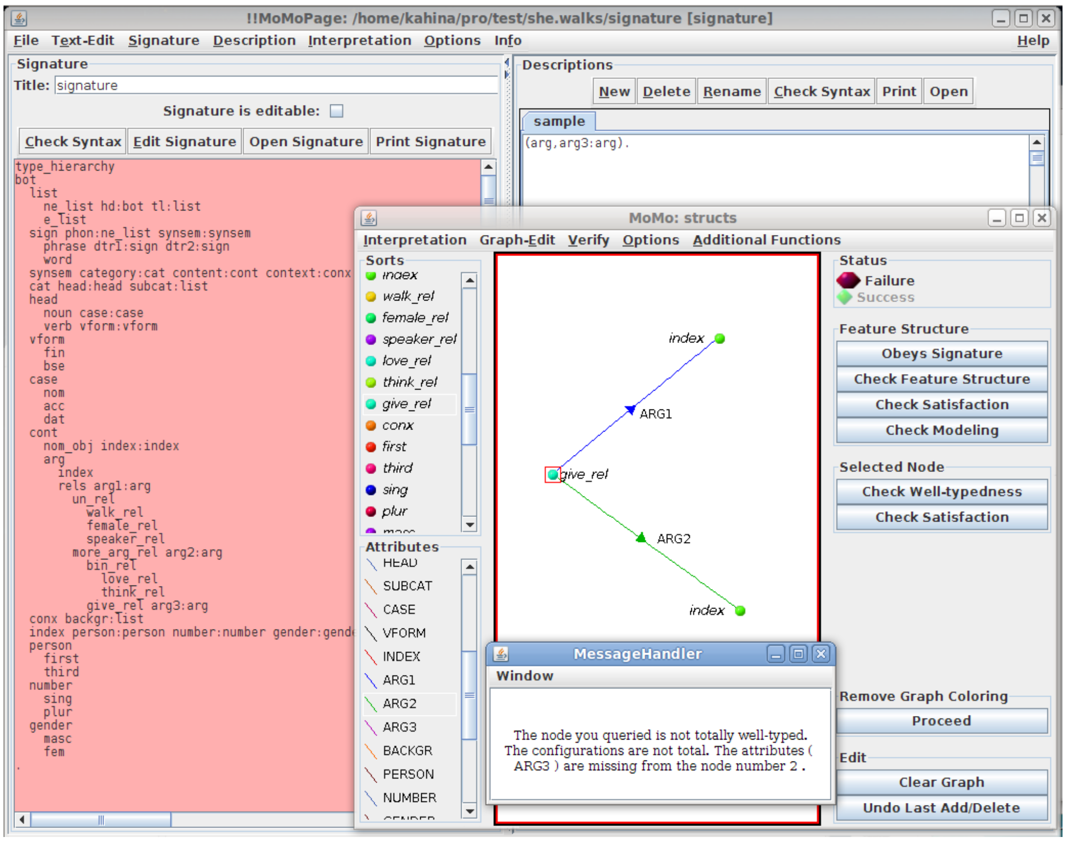
4.3 Issues in Representing Complex Signatures

Historically, research on the visualization of graph structures has focused very much on efficiency. Graph layout algorithms tend to become NP-complete rather fast, and with the computing infrastructure of earlier decades it was not possible to compute an appealing layout for a graph with more than a few nodes in real time. The LKB signature visualization recognizably comes from that age. The layout algorithm consists of a simple topological sort of the type lattice, printing each layer into a column of strings, and crudely drawing lines between the strings to indicate inheritance relations.

As exemplified in Kibiger's visualization module, for today's visualization technology, the main issue is not any longer one of too complex computations. On modern machines, computing a near-optimal layout for a graph consisting of thousands of nodes is perfectly feasible in real time. The problem has shifted to the other side of the keyboard. Nowadays, it is the user's limited capacity of grasping and extracting information from large graph structures that puts a bound on the size of graph structures where visualization makes sense.

Even if the size of the type inheritance structure does not exceed the bounds of what a human can make sense of (and TRALE signatures tend to remain within these bounds, even beyond the toy grammars used for educational purposes), another issue is the lack of screen

[1]Originally, the module was intended for integration with Kahina, but the screen space requirements were much too high for the intended usage as a view displayed in parallel to many other windows. As a result, the idea of representing the entire signature in a single graph was given up, and Kahina stayed without a display module for signature visualization until work on this thesis began.


!!MoMoPage: /home/kahina/pro/test/she.walks/signature [signature]
File Text-Edit Signature Description Interpretation Options Info Help
Signature
Title: signature
Signature is editable:
Check Syntax Edit Signature Open Signature Print Signature
Descriptions
New Delete Rename Check Syntax Print Open
sample
MoMo: structs
Interpretation Graph-Edit Verify Options Additional Functions
Sorts
index walk_rel female_rel speaker_rel love_rel think_rel give_rel conx first third sing plur
Attributes
HEAD SUBCAT CASE VFORM INDEX ARG1 ARG2 ARG3 BACKGR PERSON NUMBER
index
ARG1
give_rel
ARG2
index
Status
Failure
Success
Feature Structure
Obeys Signature
Check Feature Structure
Check Satisfaction
Check Modeling
Selected Node
Check Well-typedness
Check Satisfaction
Remove Graph Coloring
Proceed
Edit
Clear Graph
Undo Last Add/Delete
MessageHandler
Window

```
type_hierarchy
bot
  list
    ne_list hd:bot tl:list
    e_list
  sign phon:ne_list synsem:synsem
    phrase dtr1:sign dtr2:sign
    word
  synsem category:cat content:cont context:conx
  cat head:head subcat:list
  head
    noun case:case
    verb vform:vform
  vform
    fin
    bse
  case
    nom
    acc
    dat
  cont
    nom_obj index:index
    arg
      index
      rels arg1:arg
        un_rel
          walk_rel
          female_rel
          speaker_rel
        more_arg_rel arg2:arg
          bin_rel
            love_rel
            think_rel
          give_rel arg3:arg
  conx backgr:list
  index person:person number:number gender:gend
  person
    first
    third
  number
    sing
    plur
  gender
    masc
    fem
.
```

```
(arg,arg3:arg).
```

The node you queried is not totally well-typed.
The configurations are not total. The attributes (ARG3) are missing from the node number 2 .

Figure 4.4: Using MoMo to explore the demo signature.

space. While an explicit graph visualization might still be feasible if a user exclusively needs to explore the inheritance graph, in a highly interactive environment such as Kahina, screen space is an important asset that must not be wasted for little information gain.

A **context-dependent** display which only displays the relevant type information in each situation would not only lead to considerable savings in screen space, but an experienced user would also be able to tailor the displayed information to her needs. The idea of visualizing all the signature information at the same time in a single huge graph structure becomes even less attractive in this light.

4.4 A Signature Visualization Module for Kahina

A crucial observation on the way towards new tools for signature inspection was derived from the understanding that a sort hierarchy is not very different from the class inheritance hierarchy of an object-oriented programming language such as Java or C++. Much wisdom on visualization of type hierarchies can be gained from observing industry practice for these widely used languages.

Not surprisingly, class inheritance information is seldom represented by an explicit graph visualization of the entire class hierarchy. Professional software development environments do not include tools for this purpose, an indication that they are considered not informative enough to warrant the expense in computing power and screen space. While graph structures are appealing to the eye, their informativity / screen space ratio makes them unattractive.

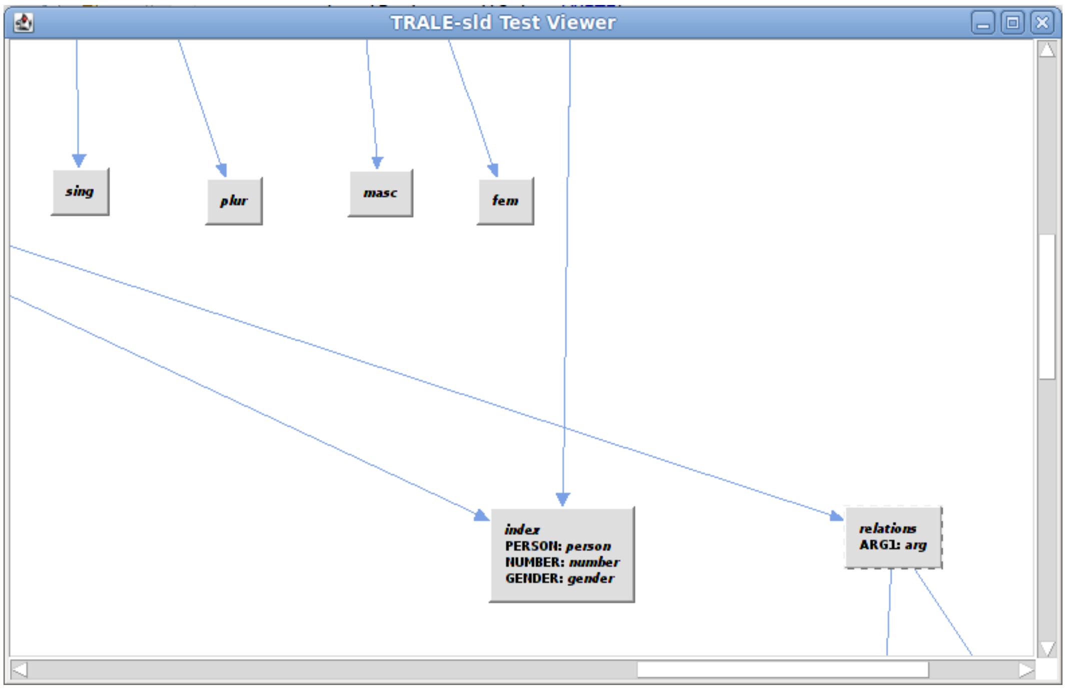


Figure 4.5: Kibiger's signature visualization.

Therefore, it pays to draw inspiration from industry standards for representing complex type and inheritance information. As a result, the signature visualization I will propose is heavily inspired by **Javadoc** (see Oracle Technology Network (2011)), the de-facto standard for documentation of Java classes. Javadoc is essentially a mechanism for compiling code comments in a standardized format into a HTML description page for each class, which are then linked into a coherent and highly structured hypertext document.

Conveniently, the Swing library includes interface components that natively display HTML content. The main challenge in implementing signature visualization in the envisioned way therefore was to faithfully represent the signature in a new Kahina data type called `TraleSLDSignature`, and to fill instances of this class with the type inheritance and feature appropriateness information loaded by TRALE.

The fact that TRALE reads in signatures in two different formats (ALE style being comparatively close to a Prolog specification, and TRALE style, which is used in Appendix A, being more compact but also syntactically more complex) speaks against loading signatures directly from signature files. Instead, I chose to extend the existing Jasper interface used by Kahina to transmit the step information during the debugging process. The extension was relatively straightforward, as direct use of internal TRALE predicates could be made for reading out the signature.[2]

In both approaches, Kahina is oblivious to the format in which the signature was specified, which can be considered a big advantage for modularity. On the other hand, it is not possible to inspect signature files independently of a TRALE instance. If the need arises, it would be relatively straightforward to integrate the corresponding functionality from Kibiger's

[2]As we shall see later, an alternative way of collecting the signature information was used for the standalone test version of the feature workbench, namely a method for extracting the signature from an embedded instance of TRALE. More information about this process can be found in Section 6.6 as part of the discussion of the feature workbench.

visualization module, which includes a parser for TRALE signature files.

We now turn towards the design and implementation of the new signature visualization module. The following bits of information on a given type σ were considered potentially helpful in a variety of usage contexts:

Supertypes. A list of the immediate supertypes of σ, i.e. a list of all types $\tau \in Ty$ where $\tau \lhd \sigma$. This is useful in many situations where just a little more information about a type's position in the hierarchy is needed. In the demo signature, this would be useful for quickly finding out that *think_rel* has the supertype *bin_rel*, showing that thinking is modeled as a type of binary relation.

Subtypes. A list of the immediate subtypes of σ, i.e. a list of all types $\tau \in Ty$ where $\sigma \lhd \tau$. If a user exploring the demo signature wants to see which types of *vform* objects exist, the list of immediate subtypes contains the entries *fin* and *bse*, which answers the question.

Sibling Types. A list of the immediate subtypes of all immediate supertypes, i.e. the type's sister nodes in the type hierarchy. If there is more than one immediate supertype, not all sibling types are sibling nodes in the sense used when talking about trees. In many contexts, this list describes the possible alternative values for a feature. In the demo grammar, the context information for the case value *nom* would show that both *dat* and *acc* are possible alternative case values.

Appropriate Features. A list of all the appropriate features of the type σ together with their value restrictions, i.e. all pairs $(f, A(f, \sigma))$ with $f \in Fe$ where $A(f, \sigma)$ is defined. This list of features that can (or need to) be defined for an object of a type, including the features inherited from supertypes, could be of use in the demo signature to find out that an *index* object groups together information on PERSON, NUMBER, and GENDER.

Feature Introduction. A map from the appropriate features of σ to the types at which the features were introduced, i.e. all pairs $(f, Intro(f))$, or all pairs (f, τ) where $A(f, \sigma)$ and $A(f, \tau)$ are defined and $\tau \sqsubseteq \sigma$, but $A(f, \upsilon)$ is not defined for any $\upsilon \sqsubseteq \tau$. For the demo signature, this map makes explicit why a *word* object defines a SYNSEM feature: it was introduced by the supertype *sign*.

Inheritance Paths. A list of all sequences $(bot = \tau_0, \tau_1, ..., \tau_{n-1}, \tau_n = \sigma)$ where for all $i = 0, \ldots, n-1$ we have $\tau_i \lhd \tau_{i+1}$. These paths are especially useful if a user cannot immediately make sense of a type name. In the demo signature, if the type name *un_rel* is intransparent to a user, the inheritance path $bot \rightarrow cont \rightarrow arg \rightarrow relations \rightarrow un\_rel$ makes it easy to conclude that this encodes a unary relation in the content (i.e. semantic) part of the grammar.

Type Usage. A list of type-feature pairs where values of type σ are appropriate, i.e. all pairs (τ, f) where $A(f, \tau)$ is defined and $A(f, \tau) \sqsubseteq \sigma$. We will later restrict this to only those pairs where in addition, there is no $\upsilon \sqsubseteq \tau$ for which $A(f, \upsilon)$ is defined. In the demo signature, this shows where *list*s can occur: as values of the SUBCAT feature in *sign* objects, of the BACKGR feature in *conx* objects, and of the TL feature in other lists.

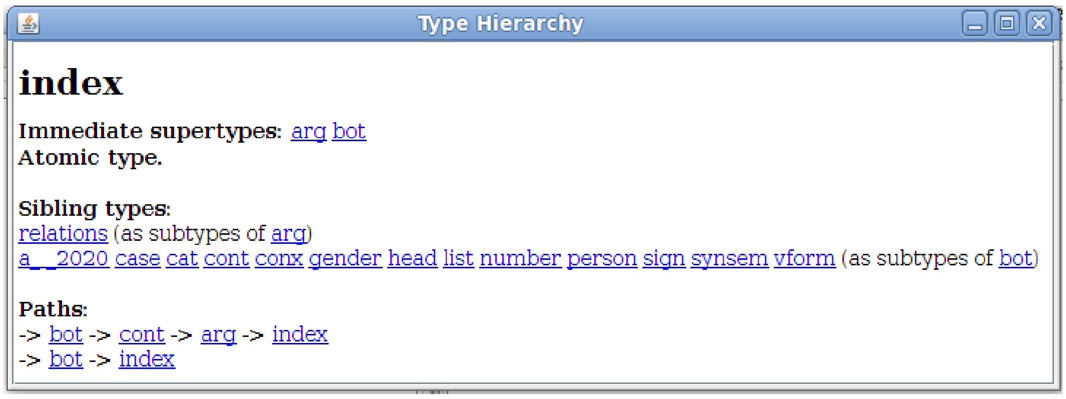
All this information could be integrated into a single HTML document exactly as in Javadoc. However, a Javadoc page is designed to be viewed in a browser, which explains why the resulting large display format is not an issue. This is certainly not the perfect solution for our signature visualization, since it is intended to provide contextual information very similar to an online help system, but with minimal space usage. To achieve this goal, and to retain maximum flexibility, I decided to group the information into three different views, each representing one facet of the information that a user will find relevant:

The **hierarchy view** sums up information about supertypes, subtypes, and sibling types. In the example in Figure 4.6, we can see the only case in the demo signature where multiple inheritance plays a role. The type *index* has the immediate supertypes *arg*, but it is also an immediate supertype of *bot*. The visualization provides links to both supertypes and multiple inheritance paths. In addition, the notion of sibling types has become ambiguous, depending on which supertype we use to determine them. Space provided, the best solution is to express this difference explicitly by providing two lists of sibling types and thereby keeping the desired information easily accessible.

In the **appropriateness view**, the features appropriate for the selected type are displayed together with their value restrictions. This includes appropriateness conditions introduced by upward closure. Feature introduction is expressed in parentheses at the end of each line, stating whether the feature was introduced at the current type, or which ancestor type introduced it. In the example in Figure 4.7, we see that the type *give_rel* has three features encoding its arguments, where ARG1 was introduced already by the ancestor type *relations*, ARG2 was introduced by the supertype *more_arg_rel*, and only ARG3 was introduced by *give_rel*. This display has the advantage that all the appropriate features can be seen at a glimpse without having to trace through a graph structure, while the information why a feature is appropriate is accessible at the same time.

The **usage view** is formatted in a way very similar to the appropriateness conditions, but instead of defining what types of structures can occur as the values of the selected type's features, it displays a list of the places where structures of the selected type can occur. In Figure 4.7, we see usage information for the type *index*. Among others, we can easily find out that *index* objects can be used as INDEX values in objects of type *nom_obj*, and as CONTENT values in *synsem* objects.

These three views can be considered separate information sources, and they are treated as independent views by Kahina's window management system. The separation into three views leads to greater flexibility in the information displayed. A user might be fairly familiar with the inheritance hierarchy, but less so with the appropriateness declarations, or she might consider e.g. the usage information irrelevant. In such cases, being able to freely configure a three-part signature view is an asset. Of course, it is also possible to integrate the three views into one window. This is the configuration in the Kahina-based debugger's default perspective, and it is exemplified in Figure 4.8.



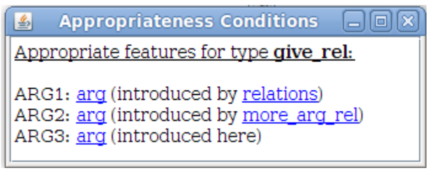
index

Immediate supertypes: arg bot
Atomic type.

Sibling types:
relations (as subtypes of arg)
a__2020 case cat cont conx gender head list number person sign synsem vform (as subtypes of bot)

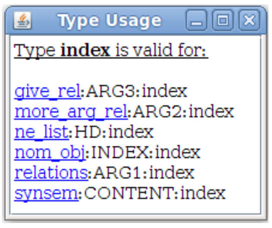
Paths:
-> bot -> cont -> arg -> index
-> bot -> index

Figure 4.6: Hierarchy view component displaying information on the type *index*.



Appropriate features for type **give_rel**:

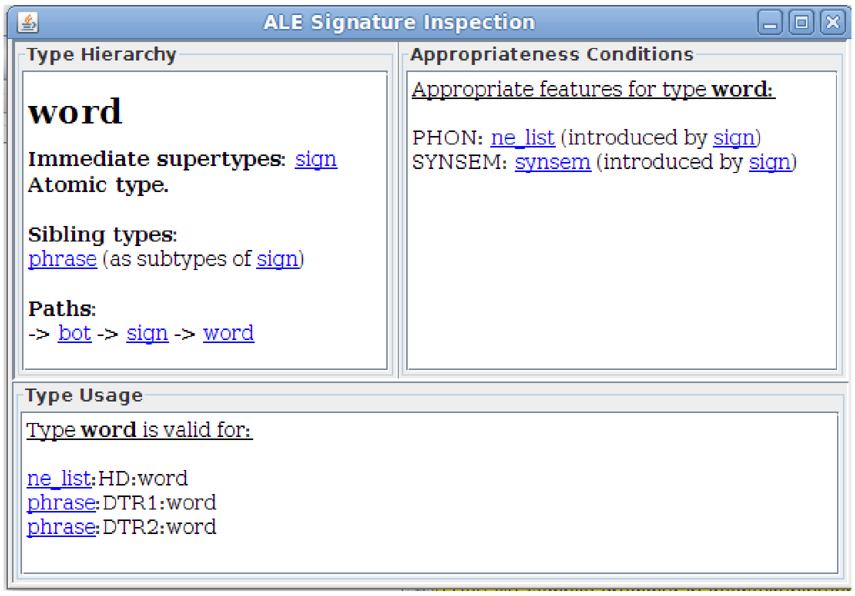
ARG1: arg (introduced by relations)
ARG2: arg (introduced by more_arg_rel)
ARG3: arg (introduced here)



Type **index** is valid for:

give_rel:ARG3:index
more_arg_rel:ARG2:index
ne_list:HD:index
nom_obj:INDEX:index
relations:ARG1:index
synsem:CONTENT:index

Figure 4.7: Appropriateness and type usage view components.



word

Immediate supertypes: sign
Atomic type.

Sibling types:
phrase (as subtypes of sign)

Paths:
-> bot -> sign -> word

Appropriate features for type **word**:

PHON: ne_list (introduced by sign)
SYNSEM: synsem (introduced by sign)

Type **word** is valid for:

ne_list:HD:word
phrase:DTR1:word
phrase:DTR2:word

Figure 4.8: Default configuration of signature view with info on type *word*.

4.5 Discussion

With the new signature view components, the signature information becomes accessible in a very compact and configurable way. The information about the direct neighborhood in the type hierarchy is preserved, and the usage information gives a direct answer to the question which role a type plays in the structures over a signature. While the version presented here is fully functional and very stable, some fine-tuning could be useful for making the HTML formatting more appealing. In addition, some of the taken design decisions might have to be revised in the future.

One such decision concerns the contents of the type usage display. The length of the list of usages is a tradeoff between exhaustivity and conciseness. If we decide to mention every type with an appropriate feature that allows values of the current type, the list explodes even for our small demo grammar (in our example, σ:ARG1:*index* would be mentioned for every single subtype σ of *relations*). To alleviate this problem, I opted for mentioning features only with the types where they were introduced.

Alternatively, one could only mention appropriateness conditions which restrict possible values to the type itself, and not to supertypes. However, the usage information generated in this way turned out to be much less useful. For instance, no usage information at all would be displayed for the type *word*, because *phrase* merely restricts its DTR1 and DTR2 values to be of type *sign*. A somewhat questionable effect of my design decision is that the position *ne_list*:HD is mentioned as a possible usage for every type because the corresponding appropriateness condition does not restrict the HD value at all. This phenomenon is clearly a consequence of the formalism, and it is definitely relevant for implementations, but perhaps this usage that does not at all depend on the selected type should be hidden at least from the advanced user, who will not have to be reminded of the fact that structures of any type can be list elements.

The organization and the amount of information displayed in the current version of the signature view have not been extensively tested for usefulness. It is very likely that some of the displayed information will turn out to be found redundant, whereas other kinds of information will have to be displayed in a more prominent fashion. In the future, one could furthermore experiment with adding additional information, such as a feature structure representing the most general satisfier of the selected type.

Chapter 5

Signature-Enhanced AVM Editing

The objects TRALE is operating on are totally well-typed feature structures over a given signature. Feature structures are used to represent linguistic objects such as words and phrases, and it is the internal structure of such symbols that the rules of a theory constrain. In current systems, feature structures cannot directly be manipulated by the user. They arise as denotations of descriptions in the theory, and they are inspected as the results of parsing processes, but a grammar implementer does not get his hands on the structures directly. Being able to freely manipulate feature structures is not only of use to the novice user getting to grips with the feature logic, but also to the advanced user who e.g. wishes to test the effects of a constraint on some structures that do not come from the lexicon. Providing the user with a handle on these structures amounts to implementing some form of feature structure editing. In this section, we will develop an editing system that makes extensive use of the signature to facilitate and speed up the editing process.

Feature structures over signatures are formally introduced in Section 1, and Section 2 deals with languages for talking about such structures, including the TRALE description language. Section 3 gives an overview of different feaure structure visualizations, and Section 4 discusses existing approaches to feature structure editing. The signature-enhanced editor builds on a small set of elementary editing operations, which are developed formally in Section 5 to the extent that could be implemented. The core of TRALE's variant of feature logic including total well-typedness is accounted for, but certain additional features such as inequations and extensional types are not covered. Section 6 then describes the implementation, which supports all the elementary editing operations, and provides the core component for the feature workbench developed in Chapter 6. The chapter concludes with a discussion of the design decisions taken, and of possible alternatives.

5.1 Feature Structures in TRALE

The formal definition of feature structures and operations on them again stays close to Carpenter (1992), but confines itself to the version relevant for our purposes, which does not cover all phenomena of the variant implemented in TRALE. In particular, it is assumed that feature structures do not contain explicit inequations, and no special treatment is given to types that are declared as extensional in the signature. While these are important parts of the TRALE formalism, they are usually not represented in attribute-value matrices, which we will use as our representation format for feature structures. As we shall see in Chapter 6, inequations and extensionality information cannot yet reliably be retreived from TRALE, motivating me to restrict the formal machinery to only those parts that could actually be implemented.

Definition 5.1.1. *A **feature structure** F over a signature $\langle Ty, \sqsubseteq, Fe, A\rangle$ is a tuple $F = \langle Q, \bar{q}, \theta, \delta\rangle$ where*

- *Q is a finite set of **nodes** rooted at $\bar{q}$,*
- *$\bar{q} \in Q$ is the **root** or head node,*
- *$\theta\colon Q \to Ty$ is a total function (**node typing**), and*
- *$\delta\colon Fe \times Q \to Q$ is a partial function (**feature value**).*

Let $\mathcal{F}$ be the set of feature structures over a given signature $\langle Ty, \sqsubseteq, Fe, A\rangle$.

Note that we do not impose any acyclicity conditions on the graph structure defined by δ. Therefore, feature structures are essentially directed graphs where both the nodes and the edges are labeled, and we will often use the concise graph terminology when talking about them. The value assigned to a node by the typing function θ will also be called the node label, and the tuples $(q, f, \delta(f, q))$ are sometimes referred to and treated as labeled graph edges. What differentiates a feature structure from a general graph is that one of its nodes is designated as the head node, which serves as an entry point to the structure very much like the root node of a tree structure. Starting from this head node, we can develop the notion of a path through a structure, and then define the substructure at a given path. Paths and substructures are formalized as follows:

Definition 5.1.2 (Paths). *A **path** of length n is a sequence of features $\pi = (f_1, \ldots, f_n) \in Fe^n$. The set Fe^* of paths of any length is denoted by Path, the empty path is denoted by ϵ. The feature value function $\delta\colon Fe \times Q \to Q$ is extended to a path-enabled variant $\delta\colon Path \times Q \to Q$ by defining $\delta(\epsilon, q) := q$ and $\delta(f\pi, q) := \delta(\pi, \delta(f, q))$.*

Definition 5.1.3 (Path Value). *In a feature structure $F = \langle Q, \bar{q}, \theta, \delta\rangle$ where $\delta(\pi, \bar{q})$ is defined, the **substructure** $F@\pi = \langle Q', \bar{q}', \delta', \theta'\rangle$ is defined by*

- *$\bar{q}' := \delta(\pi, \bar{q})$*
- *$Q' := \{\delta(\pi', \bar{q}') \mid \pi' \in Path\} = \{\delta(\pi\pi', \bar{q}) \mid \pi' \in Path\}$*
- *$\delta'(f, q) := \delta(f, q)$ if $q \in Q'$, else undefined*
- *$\theta'(q) := \theta(q)$ if $q \in Q'$, else undefined*

The fact that cyclic structures are allowed entails that there can be paths of arbitrary length, and that there can be infinitely many paths addressing the same node in a structure.

As feature structures are to serve as representations of partial information, the next step is to extend the subsumption relation from types to feature structures. This informativity ordering is formally described in the following way:

Definition 5.1.4 (Subsumption). *A feature structure $F = \langle Q, \bar{q}, \theta, \delta\rangle$ **subsumes** another feature structure $F' = \langle Q', \bar{q}', \delta', \theta'\rangle$, written $F \sqsubseteq F'$, iff there is a total function $h\colon Q \to Q'$, called a **morphism**, such that*

- *$h(\bar{q}) = \bar{q}'$*
- *$\theta(q) \sqsubseteq \theta'(h(q))$ for every $q \in Q$*
- *$h(\delta(f, q)) = \delta'(f, h(q))$ for every $q \in Q$ and $f \in Fe$ where $\delta(f, q)$ is defined.*

The subsumption relation allows us to understand **unification**, the most important operation on feature structures, which is commonly interpreted as the combination of the information encoded in two structures. The following definition is a little complex, but the most concise way of formally expressing the intuitive procedure: Traverse the two structures in parallel, recursively unifying the substructures at identical paths, constructing a structure with nodes whose types are the least upper bound of the types at corresponding paths in the original structures. If no least upper bound of two such types exists, the information is inconsistent, causing the unification to fail. If a path only addresses a node in one structure, this node is taken over unchanged.

Definition 5.1.5 (Unification). *For structures $F = \langle Q, \bar{q}, \theta, \delta\rangle$ and $F' = \langle Q', \bar{q}', \theta', \delta'\rangle$ where $Q \cap Q' = \emptyset$, we define an equivalence relation $\bowtie$ on $Q \cup Q'$ as the least equivalence relation where*

- *$\bar{q} \bowtie \bar{q}'$, and*
- *$\delta(f, q) \bowtie \delta(f, q')$ if both are defined and $q \bowtie q'$.*

*The **unification** of F and F' is then defined as $F \sqcup F' := \langle (Q \cup Q')/_{\bowtie}, [\bar{q}]_{\bowtie}, \theta^{\bowtie}, \delta^{\bowtie}\rangle$ where*

- *$\theta^{\bowtie}([\bar{q}]_{\bowtie}) := \bigsqcup\{(\theta \cup \theta')(q') \mid q' \bowtie q\}$ and*
- $\delta^{\bowtie}(f, [\bar{q}]_{\bowtie}) := \begin{cases} [(\delta \cup \delta')(f, q)]_{\bowtie} & if\ (\delta \cup \delta')(f, q)\ is\ defined \\ undefined & otherwise \end{cases}$

if all of the joins in the definition of $\theta^{\bowtie}$ exist, und undefined otherwise.

We take over some properties of the unification operation, which are central for understanding its importance, from Carpenter (1992, Theorems 3.12 and 3.13):

Theorem 5.1.6. *If for $F, F' \in \mathcal{F}$, $F \sqcup F'$ is defined, then also $F \sqcup F' \in \mathcal{F}$.*

Theorem 5.1.7. *If two structures $F, F' \in \mathcal{F}$ have an upper bound in the subsumption ordering $\langle \mathcal{F}, \sqsubseteq\rangle$, then $F \sqcup F'$ is defined, and it is the least upper bound of F and F'.*

These theorems tell us that unification is indeed a (partial) operation on feature structures, and that the notation as $F \sqcup F'$ is justified by analogy with the notation for the join in the inheritance hierarchy, with the interpretation that $F \sqcup F'$ combines the information represented by F and F'.

So far, we have not made use of the appropriateness conditions contained in the A function of the signature. But these conditions put heavy constraints on the set of structures which are legal in the context of TRALE. The decisive property of legal TRALE feature structures is called total well-typedness, which is defined as follows:

Definition 5.1.8. *A feature structure $F = \langle Q, \bar{q}, \theta, \delta\rangle$ is **well-typed** with respect to a signature $\langle Ty, \sqsubseteq, Fe, A\rangle$ iff for $f \in Fe, q \in Q$, whenever $\delta(f, q)$ is defined, $A(f, \theta(q))$ is defined, and $A(f, \theta(q)) \sqsubseteq \theta(\delta(f, q))$. Let $\mathcal{TF}$ be the set of well-typed feature structures.*

Definition 5.1.9. *A feature structure $F = \langle Q, \bar{q}, \theta, \delta\rangle$ is **totally well-typed** with respect to a signature $\langle Ty, \sqsubseteq, Fe, A\rangle$ iff it is well-typed and for $f \in Fe, q \in Q$, when $A(f, \theta(q))$ is defined, $\delta(f, q)$ is defined. Let $\mathcal{TTF}$ be the set of totally well-typed feature structures.*

In essence, total well-typedness means that in a structure of type σ, exactly the features that are appropriate for that type according to the signature must be defined. Totally well-typed feature structures are the objects that we will mainly be operating on.

A feature structure $F \in \mathcal{F}$ is called **typable** if there is a well-typed structure $F' \in \mathcal{TF}$ such that $F \sqsubseteq F'$. For typable structures, we can therefore postulate a function which gives us their most general well-typed extensions:

Definition 5.1.10. *A **type inference** function is a partial function $TypInf\colon \mathcal{F} \to \mathcal{TF}$, where for all $F \in \mathcal{F}$ and $F' \in \mathcal{TTF}$, $F \sqsubseteq F'$ holds iff $TypInf(F) \sqsubseteq F'$.*

Carpenter (1992, Theorem 6.3) shows that such a type inference function exists. The proof is constructive, showing that type inference can be implemented by locally increasing types, and iterating this process until all features and their values are well-typed.

We can take this further by also defining a function that maps well-typed structures into their most general totally well-typed extensions:

Definition 5.1.11. *A **total type inference** function is a total function $Fill\colon \mathcal{TF} \to \mathcal{TTF}$, where $F \in \mathcal{TF}$, $F' \in \mathcal{TTF}$, and $F \sqsubseteq F'$ hold iff $Fill(F) \sqsubseteq F'$.*

Carpenter (1992, Theorem 6.15) shows that such a *Fill* function exists as long as A contains no loops (i.e. there is no type σ such that every structure of type σ must contain another structure of type σ). The function is implemented by iteratively selecting a node q with a type σ such that $A(f, \sigma)$ is defined, but not $\delta(f, q)$, and extending the structure by an arc (q, f, q'), where q' is a new node with $\theta(q') := A(f, \sigma)$.

The two function we just defined can be chained together to build a totally well-typed extension for any typable feature structure. This can be used to define a unification operation which only produces well-typed structures, as shown by Carpenter (1992, Theorem 6.21):

Theorem 5.1.12 (Totally Well-Typed Unification). *If A is loop-free and $F, F', F'' \in \mathcal{TTF}$, then $F \sqsubseteq F''$ and $F' \sqsubseteq F''$ iff $Fill \circ TypInf(F \sqcup F') \sqsubseteq F''$.*

We thus receive the least upper bound of two feature structures in $\mathcal{TTF}$ by first applying the default unification, and then extending the structure by applying first type inference and then total type inference. The *Fill* function will later be an important part of the elementary editing operations on $\mathcal{TTF}$.

5.2 Description and Representation Languages

In their formal representation, feature structures are not very readable to humans. In order to support quick mental processing of feature structures, various more intuitive representation formats have been developed. Some of these formats can be used as mere alternative renditions of a structure's formal definition, whereas other formats make it possible to underspecify some parts of a structure, leading to descriptions that stand for sets of non-equivalent structures.

Feature structures are usually conceived as standing in a model-theoretic connection to such descriptions. Descriptions are the syntactic entities of a feature logic, and feature structures are the elements of their denotations. We will formally introduce the TRALE description language and the satisfiability relation connecting descriptions to their denotations in this section, but we will also show that something like a canonical mapping between structures and descriptions can be established, allowing us to ignore the important formal distinction in large parts of this work.

We start with a few remarks on the nature of the attribute-value matrices which are used to describe feature structures not only in this thesis, but also in the HPSG literature. A large part of the section is dedicated to the TRALE description language and the basics of model theory for feature structures. The section concludes with a formal definition of (a fragment of) the GRISU language, a textual format developed for the communication between TRALE and its feature structure view components (see Section 5.3), which is reused in Kahina as the internal format for storing feature structures.

5.2.1 Attribute-Value Matrices

There is an intuitive correspondence of feature structures to their graphical depiction as **attribute-value matrices (AVMs)**, and as we assume previous exposure to some HPSG literature, we can safely presuppose familiarity of the reader with this correspondence. We will therefore not formalize this correspondence here, but we will later use it when discussing and implementing what we call an editor for feature structures, although on the surface, it serves to manipulate AVM representations.

Figure 5.1 gives an example of this correspondence. It shows the feature structure corresponding to the demo grammar's lexical entry for the verb form *walks* in formal notation, next to the corresponding AVM. Note that the tag in the AVM structure corresponds to the reuse of the node q_{15} in the formal notation, and that the lists enclosed in <> brackets are formally modeled using HD and TL features on structures of type *ne_list*.

AVMs have a special status because they can serve as a representation format for both feature structures and their descriptions. For instance, if an AVM does not map to a totally well-typed structure, it can be interpreted as representing the set of its well-typed extensions.

5.2.2 TRALE Descriptions

Because of its central importance as a representation formalism, we will now formally introduce the TRALE description language. The definitions are again taken from Carpenter (1992), but adapted to reflect the Prolog syntax used in TRALE.

Definition 5.2.1 (**Descriptions**). *The set of descriptions **Desc** over a finite set of types Ty, a finite set of features Fe (both alphanumeric strings starting with a lower-case letter) and a countable set of variables Var (alphanumeric strings starting with an upper-case letter) is the smallest set such that*

- *$Ty \subset Desc$ (i.e. all type names are descriptions),*
- *$Var \subset Desc$,*
- *$f\,\texttt{:}\,\varphi \in Desc$ for all $f \in Fe$, $\varphi \in Desc$,*
- *$\texttt{(}\varphi\texttt{,}\psi\texttt{)} \in Desc$ for all $\varphi, \psi \in Desc$ (conjunction),*
- *$\texttt{(}\varphi\texttt{;}\psi\texttt{)} \in Desc$ for all $\varphi, \psi \in Desc$ (disjunction),*
- *$\texttt{(=\textbackslash= }\varphi\texttt{)} \in Desc$ for all $\varphi \in Desc$ (inequation), and*
- *$\texttt{(}\pi_1\texttt{==}\pi_2\texttt{)} \in Desc$ for all $\pi_1, \pi_2 \in Path$ written as $\texttt{[}f_1\texttt{,}\ldots\texttt{,}f_m\texttt{]}$ (path equation).*

Brackets are liberally handled, based on the following order of precedence: `==`, `:`, `=\=`, `,`, `;`.

Note that all path equations can also be expressed by using two instances of a variable. Descriptions are important because they constitute the format in which TRALE expects arguments to user-level predicates, and they are the basis for the language that TRALE theories are written in. We formally introduce the semantics of descriptions by means of the **satisfaction** relation between descriptions and feature structures:

Definition 5.2.2 (**Satisfaction**). *For each feature structure $F = \langle Q, \bar{q}, \theta, \delta \rangle$ and variable assignment $g\colon Var \to Q$, $\vDash_g \subset \mathcal{F} \times Desc$ is defined as the least relation such that*

- *$F \vDash_g \sigma$ if $\sigma \in Ty$ and $\sigma \sqsubseteq \theta(\bar{q})$,*
- *$F \vDash_g \texttt{X} \in Var$ if $g(\texttt{X}) = \bar{q}$,*
- *$F \vDash_g f\,\texttt{:}\,\varphi$ if $F@f \vDash_g \varphi$,*

$\langle\{q_0, q_1, q_2, q_3, q_4, q_5, q_6, q_7, q_8, q_9, q_{10}, q_{11}, q_{12}, q_{13}, q_{14}, q_{15}, q_{16}, q_{17}, q_{18}, q_{19}, q_{20}, q_{21}, q_{22}, q_{23}, q_{24}\},$
$q_0,$
$\{q_0 \mapsto \mathit{word},\ q_1 \mapsto \mathit{ne\_list},\ q_2 \mapsto \mathit{walks},\ q_3 \mapsto \mathit{e\_list}, q_4 \mapsto \mathit{synsem},\ q_5 \mapsto \mathit{cat},\ q_6 \mapsto \mathit{verb},\ q_7 \mapsto \mathit{fin},\ q_8 \mapsto \mathit{ne\_list},\ q_9 \mapsto \mathit{synsem},\ q_{10} \mapsto \mathit{cat},\ q_{11} \mapsto \mathit{noun},\ q_{12} \mapsto \mathit{nom},\ q_{13} \mapsto \mathit{list},\ q_{14} \mapsto \mathit{nom\_obj},\ q_{15} \mapsto \mathit{index},\ q_{16} \mapsto \mathit{gender},\ q_{17} \mapsto \mathit{sing},\ q_{18} \mapsto \mathit{third},\ q_{19} \mapsto \mathit{conx},\ q_{20} \mapsto \mathit{list},\ q_{21} \mapsto \mathit{e\_list},\ q_{22} \mapsto \mathit{walk\_rel},\ q_{23} \mapsto \mathit{conx},\ q_{24} \mapsto \mathit{e\_list}\},$
$\{(\text{PHON}, q_0) \mapsto q_1, (\text{SYNSEM}, q_0) \mapsto q_4, (\text{HD}, q_1) \mapsto q_2, (\text{TL}, q_1) \mapsto q_3, (\text{CATEGORY}, q_4) \mapsto q_5,$
$(\text{CONTENT}, q_4) \mapsto q_{22}, (\text{CONTEXT}, q_4) \mapsto q_{23}, (\text{HEAD}, q_5) \mapsto q_6, (\text{SUBCAT}, q_5) \mapsto q_8,$
$(\text{VERB}, q_6) \mapsto q_7, (\text{HD}, q_8) \mapsto q_9, (\text{TL}, q_8) \mapsto q_{21}, (\text{CATEGORY}, q_9) \mapsto q_{10},$
$(\text{CONTENT}, q_9) \mapsto q_{14}, (\text{CONTEXT}, q_9) \mapsto q_{19}, (\text{HEAD}, q_{10}) \mapsto q_{11}, (\text{SUBCAT}, q_{10}) \mapsto q_{13},$
$(\text{CASE}, q_{11}) \mapsto q_{12}, (\text{INDEX}, q_{14}) \mapsto q_{15}, (\text{GENDER}, q_{15}) \mapsto q_{16}, (\text{NUMBER}, q_{15}) \mapsto q_{17},$
$(\text{PERSON}, q_{15}) \mapsto q_{18}, (\text{BACKGR}, q_{19}) \mapsto q_{20}, (\text{ARG1}, q_{22}) \mapsto q_{15}, (\text{BACKGR}, q_{23}) \mapsto q_{24}\}\rangle$

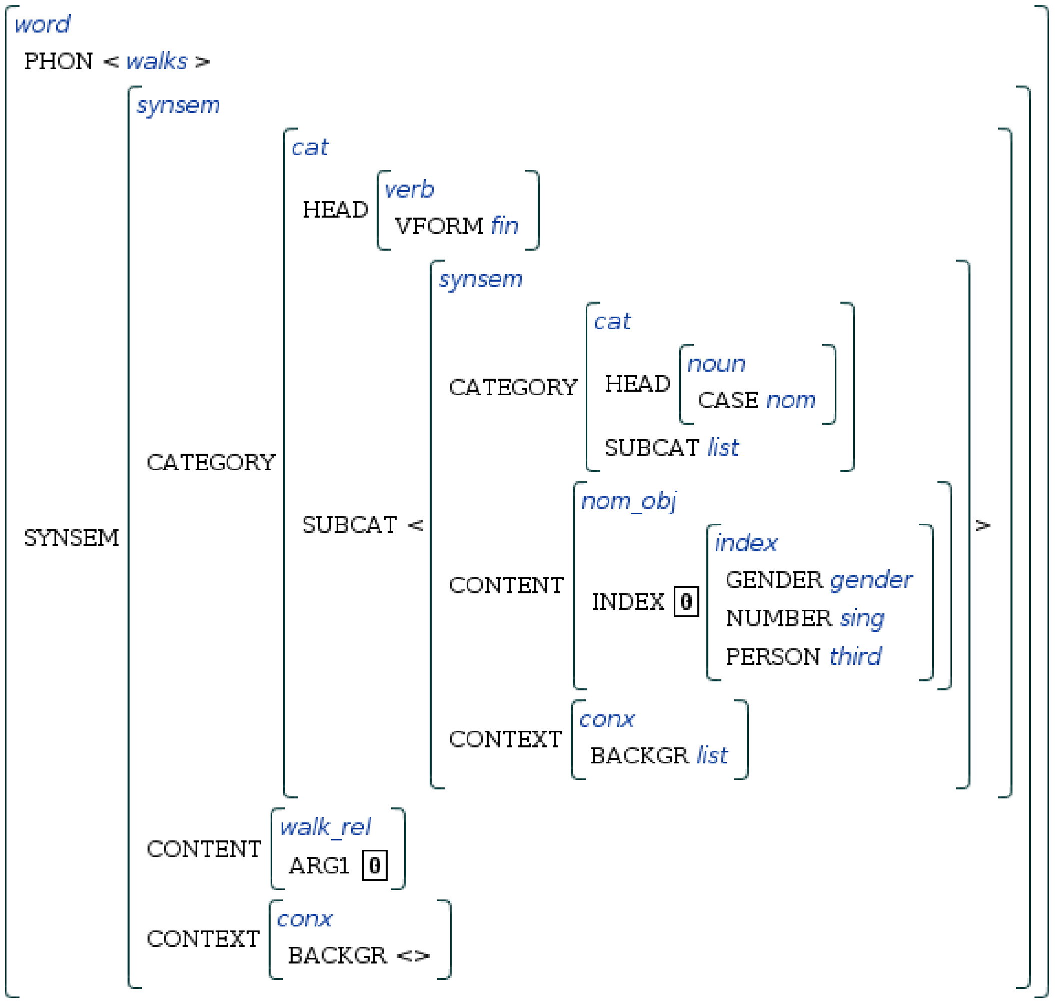


Figure 5.1: The lexical entry for *walks* in formal notation, and as an AVM.

- $F \models_g$ `(`φ`,`ψ`)` *if there is an extension h of g with $F \models_h \varphi$ and $F \models_h \psi$,*
- $F \models_g$ `(`φ`;`ψ`)` *if $F \models_g \varphi$ or $F \models_g \psi$,*
- $F \models_g$ `(=\=` φ`)` *if it is not the case that $F \models_g \varphi$*
- $F \models_g$ `(`π_1`==`π_2`)` *if $\delta(\pi_1, \bar{q}) = \delta(\pi_2, \bar{q})$.*

For each feature structure $F = \langle Q, \bar{q}, \theta, \delta \rangle$, the satisfaction relation $\models$ is then defined as the union of the $\models_g$ relations for all possible variable assignments $g\colon Var \to Q$.

For a description φ, we define $Sat(\varphi) := \{F \in \mathcal{F} \mid F \models \varphi\}$. Using this set, we introduce the usual semantic properties for formulae of a logic:

Definition 5.2.3 (Logical Notions). *For descriptions $\varphi, \psi \in Desc$, we say that*

- *φ is **satisfiable** if and only if $Sat(\varphi) \neq \emptyset$*
- *φ is **valid** if and only if $Sat(\varphi) = \mathcal{F}$*
- *φ and ψ are **logically equivalent** if and only if $Sat(\varphi) = Sat(\psi)$*

We define the set ***NonDisjDesc*** as the set of descriptions that do not make use of the `(;)` connective. An important result about our variant of feature logic is that if a non-disjunctive description is satisfiable, it is guaranteed to have a **most general satisfier (MGS)**. The MGS can be treated as the description's canonical model. Carpenter (1992, Theorem 4.5) proves the existence of a function mapping each satisfiable non-disjunctive description to a unique MGS:

Theorem 5.2.4 (Non-Disjunctive Most General Satisfier). *There is a partial function $MGSat\colon NonDisjDesc \to \mathcal{F}$ such that $F \models \varphi$ iff $MGSat(\varphi) \sqsubseteq F$.*

We can use the $Fill$ and $TypeInf$ functions to extend an MGS into a totally well-typed MGS. This result was again proven by Carpenter (1992, Theorem 6.21):

Theorem 5.2.5 (Totally Well-Typed MGS). *If A is loop-free, then for non-disjunctive descriptions $\varphi \in Desc$ and totally well-typed feature structures $F \in \mathcal{TTF}$, we have $F \models \varphi$ iff $Fill \circ TypInf(MGSat(\varphi)) \sqsubseteq F$.*

If a description is disjunctive, the MGS is not unique any more, but we potentially get multiple most general satisfiers. As we shall see, MGSs have important properties for our usage scenario. Most importantly, they allow us to canonically describe feature structures up to equivalence by descriptions, as stated in Carpenter (1992, Theorem 4.6):

Theorem 5.2.6 (Describability). *For every feature structure F, there is a description $\varphi \in NonDisjDesc$ such that $F \sim MGSat(\varphi)$, i.e. $F \sqsubseteq MGSat(\varphi)$ and $MGSat(\varphi) \sqsubseteq F$.*[1]

In Figure 5.2, we come back to our lexical entry, this time in the form of a description string with the property that its MGS is indistinguishable from the feature structure defined in Figure 5.1. This example should make it plausible to the user that Theorem 5.2.6 does indeed hold, and provide the reader with intuitions on how the translation from a feature structure F to a description with $F = MGSat(\varphi)$ can straightforwardly be implemented.

The Describability Theorem provides a way to state more precisely the relation between AVMs and feature structures assumed in this thesis. AVMs can be seen as an alternative syntax for non-disjunctive descriptions, and therefore also of their MGSs. Whenever we see

[1]Due to the way in which the description language is defined here, there are in fact infinitely many such descriptions. To see this, note that every description φ can e.g. be extended to `(X,`φ`)` for infinitely many variables `X` not occurring in φ, all with the same MGS as φ.

```
(word,
 phon:[(a_ walks)],
 synsem:(category:(head:vform:fin,
                   subcat:[(category:(head:case:nom),
                            content:index:(X,
                                           person:third,
                                           number:sing)
                                          )]),
         content:(walk_rel,
                  arg1:X),
         context:backgr:[])).
```

Figure 5.2: A description whose MGS is our lexical entry for *walks*.

an AVM, we can interpret it as the MGS of the corresponding description, and whenever we want to access a feature structure, it will be exposed to us in the form of the AVM canonically describing it. Based on this correspondence, we use the notions of an AVM and a feature structure interchangeably, only depending on whether the graphical aspect or the data structure aspect is more prominent.

5.2.3 The GRISU interchange format

The GRISU format is the third format for describing feature structures that is highly relevant for our purposes because it is used to store and represent AVMs throughout the infrastructure presented in this thesis. It is a text format, but unlike descriptions, it represents feature structures directly as visualized. This means that there is no satisfaction relation between GRISU strings and feature structures, but GRISU strings stand directly for AVMs, even including some specialized layout information.

The GRISU format was introduced by the Grisu tool (see below) as an interchange format, and it has been used as the glue language between TRALE and its AVM visualization components for a long time, but it seems to never have been formally defined. Given its role as the central representation format for feature structures in the toolchain that we are about to develop, it is advisable to close this gap. The following definitions use the Greek alphabet for variables over strings, "=" to denote string equality, and the infix operator "." to denote string concatenation.

Definition 5.2.7 (GRISU terms). *The set of GRISU terms $\mathcal{GRT}$ is the smallest set where*

- `(S.`n`.(.`m`."`.τ`.").`$\varphi_1 \dots \varphi_n$`.)` $\in \mathcal{GRT}$ *for $n, m \in \mathbb{N}_0$, where τ is an alphanumeric type name and $\varphi_1 \dots \varphi_n$ is a sequence of **feature value terms*** `(V.`n`."`.φ`."`.σ`.))`, *where $n \in \mathbb{N}_0$, $\sigma \in \mathcal{GRT}$, and φ is an alphanumeric feature name (**AVM terms**),*
- `(#.`n`. .`i`.)` $\in \mathcal{GRT}$ *for $n, i \in \mathbb{N}_0$ (**tag terms**), and*
- `(L.`n`.`$\sigma_1 \dots \sigma_m$`.)` $\in \mathcal{GRT}$ *for $n \in \mathbb{N}_0$ and $\sigma_1, \dots, \sigma_m \in \mathcal{GRT}$ (**list terms**).*

Note that feature value terms do not themselves belong to the set of GRISU terms, but can only occur as parts of AVM terms. The correspondence of GRISU terms to the corresponding AVMs is fairly obvious and will only be stated informally here. An AVM term stands for a structure of type τ with feature-value pairs corresponding to the feature value terms $\varphi_1, ...\varphi_n$. A feature value term represents a feature with name φ whose value is the structure corresponding to the term σ. A tag term directly corresponds to a reentrancy tag, where i

is the number that will be displayed on the tag.

The special terms for lists might be a little surprising, given that lists are encoded as AVMs according to the signature. However, lists are much easier to interpret when displayed as comma-separated sequences of AVMs enclosed by chevrons $\langle\rangle$ or brokets $< >$, as is common practice in AVM representations on paper. The same feature is supported by AVM visualization modules, which explains the special symbol for encoding $\langle\sigma_1 \ldots \sigma_m\rangle$.

Note that the integers represented by the symbols n and m have not been given any meaning. They were once used to number the nodes in a traversal order, but the newer generation of visualization tools does not interpret these node IDs any more, making them essentially obsolete parts of the AVM encoding that can be filled with arbitrary integer values.

Definition 5.2.8 (GRISU strings). *A GRISU string is a sequence $\pi.\sigma.\rho$, where*

- *the **preamble** π is of form $\pi =$*`!newdata"`α`"` *for some alphanumeric string α,*
- *the **structure term** is a GRISU term $\sigma \in \mathcal{GRT}$, and*
- *the **target list** ρ is a (possibly empty) sequence of strings of the form* `(R.`n`.  .`i`.`σ`.)`*, where $n, i \in \mathbb{N}_0$ and $\sigma \in \mathcal{GRT}$.*

The reader will have noticed that the previously defined terms did not provide any way to encode structures below tags. An important property of the GRISU format is that these shared structures are not stored at the places where they occur, but in a list of bindings at the end of a GRISU string, where they are indexed by the corresponding tag IDs. In the entries of this target list, i is an integer occurring in a tag term either in the structure term, or in some target structure from the target list (since reentrancies can be nested). Again, the n value is only there for historic reasons, and can be an arbitrary integer. The α value is a string which determines the display name for the structure in visualization tools.

Further parts of the original GRISU syntax can be used to to define list tails and tree fragments. These syntactic elements are supported by all visualization tools which understand GRISU, and they occur quite often in the context structures visualized by Kahina during interactive debugging. However, including list tails and trees in the above definitions would have made these much more complex, and they are not relevant in the context of this thesis. Therefore, I opted for formally defining only a subset of the GRISU syntax that will reliably be processed by the new components.

In Figure 5.3, our running example of a feature structure is displayed in GRISU format. As an exchange format that was not intended for manual editing, it does not allow any whitespace or newlines, which makes it rather hard for humans to read. The example uses indentations to make the rather straightforward structure transparent, but these indentations would have to be removed in a legal GRISU file.

The Kahina system internally stores feature structures in GRISU format. In the debugger, directly storing GRISU strings for the huge number of feature structures that spring from an entire parsing process would be much too space-consuming. Therefore, Kahina contains a compression library for GRISU strings, and the Kahina-based debugger uses temporary files for intermediate storage of compressed feature structures. In our context, the few feature structures that a user will want to edit manually can easily be stored in memory, so feature structure compression does not need to concern us here.

```
!newdata"grisu"
(S1(0"word")
  (V2"phon"
    (L3
      (S5(4"walks"))
    ))
  (V6"synsem"(S8(7"synsem")
    (V9"category"(S11(10"cat")
      (V12"head"(S14(13"verb")
        (V15"vform"(S17(16"fin")))))
      (V18"subcat"
        (L19
          (S21(20"synsem")
            (V22"category"(S24(23"cat")
              (V25"head"(S27(26"noun")
                (V28"case"(S30(29"nom")))))
                (V31"subcat"(S33(32"list")))))
            (V34"content"(S36(35"nom_obj")
              (V37"index"(#38 0))))
            (V39"context"(S41(40"conx")
              (V42"backgr"(S44(43"list"))))))
        ))))
    (V45"content"(S47(46"walk_rel")
      (V48"arg1"(#49 0))))
    (V50"context"(S52(51"conx")
      (V53"backgr"(L54)))))))
(R55 0(S57(56"index")
  (V58"gender"(S60(59"gender")))
  (V61"number"(S63(62"sing")))
  (V64"person"(S66(65"third")))))
```

Figure 5.3: The lexical entry for *walks* in GRISU format

5.3 Visualizing Feature Structures

In principle, feature structures can be visualized in a number of ways. The MorphMoulder discussed in the context of signature visualization in Section 4.2 visualizes feature structures as graphs, strongly emphasizing the difference between structures and their descriptions.

The AVM format is very compact and very familiar to linguists. Its most severe disadvantage is that AVMs are basically just a specialized tree visualization, which is why token identity must be expressed using tags, whereas in the graph approach, identities are a lot more intuitively visible.

Components for visualizing (descriptions of) feature structures as AVMs have been standard components of unification-based grammar development systems for at least two decades. The typed feature structure visualization component of the LKB produces a layout that is only remotely similar to the AVM representations used in the HPSG literature. However, it goes beyond a mere formatted text output in providing very useful interactivity, as can be seen in Figure 5.4. Using a context menu, substructures can be shrunk and expanded in order to focus the display on relevant structures. The menu also allows the user to manually apply lexical rules, to display the type hierarchy for the type of a node, or to select substructures for a unification check. If the LKB is used in Emacs mode, it also provides an option for displaying the associated source code.

The LKB visualization can be considered a compromise between closeness to the AVM displays in the literature, and ease of implementation. For grammar developers who want to cite examples on paper, the LKB offers an option to output feature structures in a TeX format using some LaTeX macros that produce a rather nice AVM representation. However, this is merely an export option. For user interaction, the LKB uses a visualization format for which no such export option is offered, indicating that the developers themselves do not consider it pretty enough for being printed.

An early graphical development environment that could be used with TRALE was the Prolog-based **Hdrug** system by van Noord and Bouma (1997). Hdrug contains visualization modules for various types of linguistically relevant data such as syntax trees and charts. Among these is a visualization of typed feature structures, which is conceptually closer to the AVM layout in books. However, this visualization is not very configurable, and it also lacks the interactivity of its LKB equivalent. Moreover, restrictions of the underlying canvas library make this display aesthetically displeasing by today's standards.

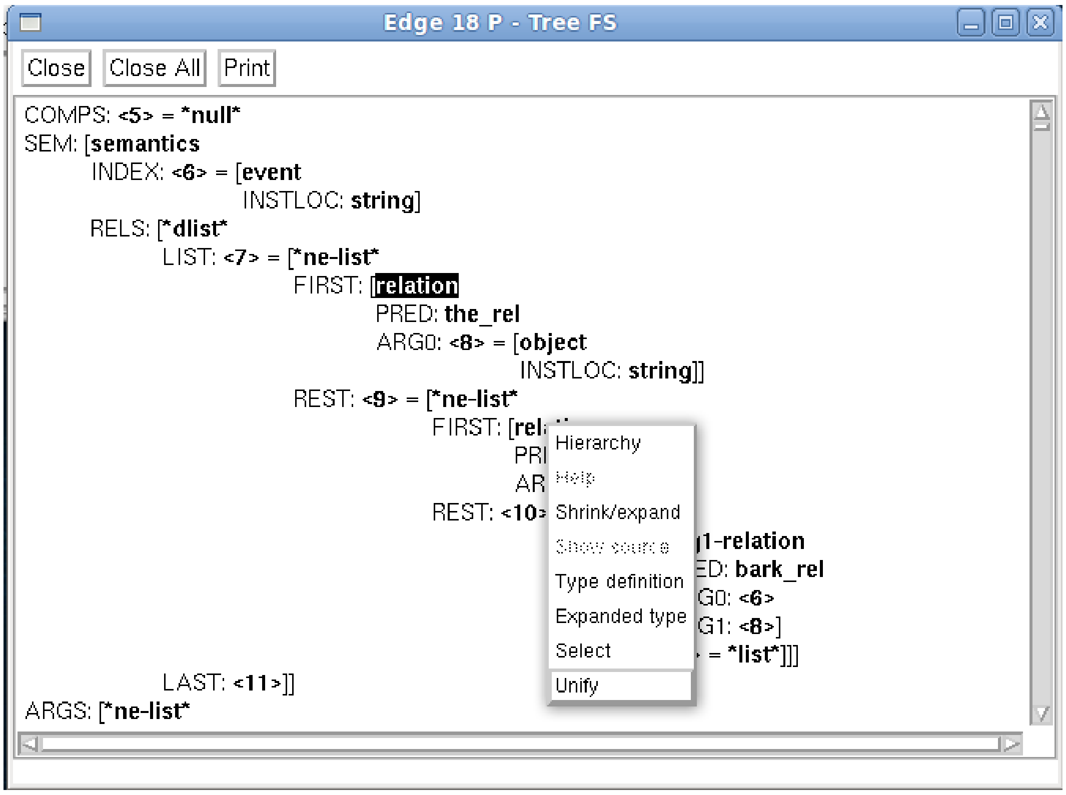
The first modern AVM visualization tool for TRALE was the **Grisu** tool by Wunsch (2003). Grisu can be started in three different modes: together with TRALE, in a remote mode for communicating with a TRALE instance via a network, and in a standalone version. The main window contains a list of displayable structures, and it offers options for importing and exporting AVM data. Whenever a connected TRALE instance successfully parses a sentence, the result structures are passed to Grisu as AVMs, causing the parses to show up in the main window. By selecting items in the structure list, display windows for feature structures can be opened. By default, the AVM visualization is already very close to the style found in HPSG books, and it can be further customized by a variety of options. Grisu was distributed with newer versions of TRALE since 2003. For legal reasons, a slightly updated version of Grisu was later released under the name GRALE, and has been included in TRALE versions since 2008.

The AVM visualization tool **Gralej** by Lazarov et al. (2010) is a re-implementation of GRALE in Java. Gralej implements roughly the same display functionality as the GRALE system, but it adds export options for a variety of formats such as SVG and Postscript, and the Java platform makes it a lot more easy to deploy on a server. Gralej has been TRALE's default AVM visualization component since 2010.

For Kahina, which is also implemented in Java and furthermore builds on the same GUI libraries, Gralej was the obvious choice as a library for AVM visualization. In the current architecture, the class `VisualizationUtility` contains convenience methods for converting instances of `TraleSLDFS` (Kahina's data type for TRALE feature structures) into a Gralej AVM display panel that can directly be integrated into a view. For the AVM editor described in Section 5.5, Gralej also provides the display component onto which the editing functionality is layered.

5.4 Interactive Feature Structure Editing

A few interactive feature structure editors for grammar engineering already exist. The most advanced implementation seems to be **FEGRAMED** by Kiefer and Fettig (1995), which offers powerful display capabilities comparable to those of Gralej, and enhances those by elementary editing functionality. It is possible to add and delete vertices, to add and modify feature-value pairs, and to copy and paste substructures. The FEGRAMED editor allows



```
COMPS: <5> = *null*
SEM: [semantics
        INDEX: <6> = [event
                      INSTLOC: string]
        RELS: [*dlist*
                 LIST: <7> = [*ne-list*
                               FIRST: [relation
                                        PRED: the_rel
                                        ARG0: <8> = [object
                                                     INSTLOC: string]]
                               REST: <9> = [*ne-list*
                                             FIRST: [rel
                                                      PRI
                                                      AR
                                             REST: <10>
                                                                 1-relation
                                                                 ED: bark_rel
                                                                 G0: <6>
                                                                 G1: <8>]
                                                                 = *list*]]]
                 LAST: <11>]]
ARGS: [*ne-list*
```

Figure 5.4: LKB feature structure visualization with context options.

the user to freely enter text for type and feature names, as well as to remove and add arbitrary feature-value pairs.

While these completely free editing capabilities are necessary in an editor that is designed to be system-independent, they are not very appropriate for an AVM editor that is tightly integrated with a feature logic system. Free text input for types and feature names not only introduces the risk of typos and other inconsistencies, but it is also likely to waste editing time by requiring potentially long type and feature names to be input.

If we build AVMs over a predefined set of type and feature symbols, only providing the user who manipulates some node of a feature structure with a choice between these symbols seems more adequate. To further narrow down the number of sensible editing options at each node, the type hierarchy can be used to introduce a notion of modification locality.

The **GraDEUS** grammar development system, which is best described by Ohtani (2005, pp. 42-51), allows debugging through selective application of grammar principles to feature structures. GraDEUS includes a typed feature structure editor for manipulating lexical entries. It does not allow free modification of type and feature names, but relies on local type modifications instead.

The available documentation about the GraDEUS system is very sparse, and the system seems to never have been made accessible outside the project that it was developed for. Concluding from the little information that can be gained from related publications, the GraDEUS feature structure editor seems to support elementary type shifting operations determined by a type hierarchy, which would make the system much more appropriate than

FEGRAMED for feature structure manipulation in a graphical debugger.

In the context of grammar engineering, we usually deal with feature structures over a signature with appropriateness conditions. This means that most of the feature structures that can be constructed using an editing mechanism such as that of FEGRAMED or GraDEUS will not adhere to the signature, as none of its structural constraints is enforced during structure editing. The only way to enforce adherence to a signature would be to check for the appropriateness conditions after each editing step. Most editing operations, even those that would ultimately lead to a legal structure, would then however lead to illegal structures, causing the user to be confronted with error messages all the time, even if the editing steps make sense on the way to an appropriate structure.

This does not only cause problems in the shape of confusing feedback, but is also detrimental to editing economy. In our sample signature, if we introduce a structure of type *synsem*, there is no way this structure could not define values for the features CATEGORY, CONTENT, and CONTEXT. In current feature structure editors, all three additional feature-value pairs would have to be introduced by hand, although it is perfectly clear that they will have to be introduced eventually in order to arrive at a totally well-typed structure.

5.5 Signature-Enhanced Feature Structure Editing

The principal idea leading towards a more user-friendly editor is to make sure that the edited AVM structure adheres to the signature at any point, adding additional structure where it is needed, and allowing only such operations that do not destroy the total well-typedness of the structure. An approach following this principle, which we will call **signature-enhanced editing**, avoids or at least alleviates the problem of generating illegal structures, and it has the potential to speed up feature structure editing tremendously.

We start by formalizing basic editing operations that do not enforce any appropriateness conditions, roughly corresponding to the operations implemented in the GRADEUS system.

One obvious such operation is **type specialization**. Intuitively, this means moving some type in a feature structure down exactly one layer in the type hierarchy, making the structure more specific or more informative. Formally, this can be defined as follows (recall that $\lhd$ denotes the immediate subtype relation):

Definition 5.5.1 (**Type Specialization**). *The operation of **type specialization** is the partial function **spz**: $\mathcal{F} \times Path \times Ty \to \mathcal{F}, (\langle Q, \bar{q}, \theta, \delta \rangle, \pi, \tau) \mapsto \langle Q, \bar{q}, \theta', \delta \rangle$, defined iff $\theta(\delta(\pi, \bar{q})) \lhd \tau$, where θ' is just like θ except that $\theta'(\delta(\pi, \bar{q})) = \tau$.*

The inverse operation of type specialization is **type generalization**. Here, we move up exactly one layer in the type hierarchy, making the structure more general or less informative.

Definition 5.5.2 (**Type Generalization**). *We call **type generalization** the partial function **gez**: $\mathcal{F} \times Path \times Ty \to \mathcal{F}, (\langle Q, \bar{q}, \theta, \delta \rangle, \pi, \tau) \mapsto \langle Q, \bar{q}, \theta', \delta \rangle$, defined iff $\tau \lhd \theta(\delta(\pi, \bar{q}))$, where θ' is just like θ except that $\theta'(\delta(\pi, \bar{q})) = \tau$.*

A further useful editing operation is **type switching**, which changes the type of a structure to one of its sibling types. Though it can be composed of one specialization and one generalization, we will treat it like an elementary operation.

Definition 5.5.3 (**Type Switching**). *We call **type switching** the partial function **swi**: $\mathcal{F} \times Path \times Ty \to \mathcal{F}, (\langle Q, \bar{q}, \theta, \delta \rangle, \pi, \tau) \mapsto \langle Q, \bar{q}, \theta', \delta \rangle$, defined iff there is a $\upsilon \in Ty$ such that $\upsilon \lhd \tau$ and $\upsilon \lhd \theta(\delta(\pi, \bar{q}))$, where θ' is just like θ except that $\theta'(\delta(\pi, \bar{q})) = \tau$.*

To add additional nodes to a structure, it must be possible to add feature-value pairs to a node. This is the task of the **feature introduction** operation, which enlarges the structure at some path π by a new node q_{new}, accessible via some feature f, such that q_{new} is of type *bot*, meaning that nothing is known about it.

Definition 5.5.4 (**Feature Introduction**). *We call **feature introduction** the partial function **fin**:* $\mathcal{F} \times Path \times Fe \to \mathcal{F}, (\langle Q, \bar{q}, \theta, \delta \rangle, \pi, f) \mapsto \langle Q', \bar{q}, \theta', \delta' \rangle$, *where for a* $q_{new} \notin Q$, $Q' := Q \cup \{q_{new}\}$, θ' *is just like* θ *except that* $\theta'(q_{new}) = bot$, *and* δ' *is just like* δ *except that* $\delta'(f, q@\pi) = q_{new}$.

The opposite of feature introduction is **feature removal**, which would be somewhat weak if we formalized it as the exact inverse of feature introduction, restricting it to removing single nodes only. A more powerful version is harder to define because it can cause the loss of more than one node, but it makes more sense in an editor to be able to remove the entire structure under some node. Formally, it is easiest to treat the possibly complex consequences of a substructure removal on reentrancies by just removing the relevant entry from the δ relation, and then to rebuild it using only the nodes that remain accessible. This rebuild process can conveniently be expressed via the @ operator from Definition 5.1.3.

Definition 5.5.5 (**Feature Removal**). *We call **feature removal** the partial function **fre**:* $\mathcal{F} \times Path \times Fe \to \mathcal{F}, (\langle Q, \bar{q}, \theta, \delta \rangle, \pi, f) \mapsto F'@\epsilon$ *where* $F' := \langle Q, \bar{q}, \theta, \delta' \rangle$ *and* δ' *is just like* δ *except that* $\delta'(\pi, f)$ *is undefined.*

So far, we can modify nodes in, add new nodes to, and remove nodes from feature structures. This set of operations would suffice if we were dealing with mere tree structures. However, since feature structures are in fact graphs, we also need the option to add links leading to existing nodes. Stated in terms of paths, we need **identity introduction** to introduce path identities, making use of unification to combine the nodes at the identified paths:

Definition 5.5.6 (**Identity Introduction**). *The operation of **identity introduction** is the partial function **itr**:* $\mathcal{F} \times Path \times Path \to \mathcal{F}$, $(\langle Q, \bar{q}, \theta, \delta \rangle, \pi_1, \pi_2) \mapsto F'@\epsilon$, *defined if* $F_u = \langle Q_u, \bar{q}_u, \theta_u, \delta_u \rangle := F@\pi_1 \sqcup F@\pi_2$ *is defined, where* $F' := \langle Q \cup Q_u, \bar{q}, \theta \cup \theta_u, \delta' \rangle$, *and* δ' *is just like* $\delta \cup \delta_u$ *except that* $\delta'(\pi_1, \bar{q}) := \bar{q}_u =: \delta'(\pi_2, \bar{q})$.

The opposite operation to identity introduction is **identity dissolval**. This operation is sometimes necessary to arrive at an acyclic structure, and it is again somewhat difficult to formalize because it leads to a copying of substructures:

Definition 5.5.7 (**Identity Dissolval**). *The operation of **identity dissolval** is the partial function **ids**:* $\mathcal{F} \times Path \to \mathcal{F}$, $(\langle Q', \bar{q}, \theta, \delta \rangle, \pi) \mapsto F'@\epsilon$, *defined if* $F@\pi$ *exists, where* $F_c := \langle Q_c, \bar{q}_c, \theta_c, \delta_c \rangle$ *is a copy of* $F@\pi$ *such that* $Q_c \cap Q = \emptyset$, *and* $F' := F_c$ *if* $\pi = \epsilon$, *otherwise* $F' := \langle Q \cup Q_c, \bar{q}, \theta \cup \theta_c, \delta' \rangle$, *where* δ' *is just like* $\delta \cup \delta_c$ *except that* $\delta'(\pi, \bar{q}) := \bar{q}_c$.

Note that this operation creates copies of all nodes accessible from $F@\pi$, also dissolving all identities where one node is inside and the other one outside of $F@\pi$. Formally, this is an arbitrary decision whose effects could be remedied by a sequence of identity introductions. In practice, this variant of identity dissolval is much easier to implement, and it still leads to intuitive editing behavior.

Our next step is to develop a set of elementary operations that do not destroy total well-typedness. As we shall see, this will also redundantize operations for explicit feature introduction and removal. To formalize these new elementary operations, we first need a new auxiliary operation which enforces total well-typedness. Because this operation must be able to re-establish total well-typedness after an elementary type generalization, it is convenient to introduce another auxiliary operation which removes features that should not be defined according to the appropriateness conditions.

Definition 5.5.8 (**Purge operation**). *The total function* $Purge\colon \mathcal{F} \to \mathcal{F}$ *is recursively defined in the following way:*

- $Purge(F) := Purge(F, \emptyset)$
- $Purge(F = \langle Q, \bar{q}, \theta, \delta\rangle, A) := \begin{cases} cmb_{|Fe|}(\bar{q}, \times_{f \in Fe} PurgeVal(f, F, A \cup \{\bar{q}\})) & if\ \bar{q} \notin A \\ \langle \emptyset, \bar{q}, \emptyset, \emptyset\rangle & if\ \bar{q} \in A \end{cases}$
- $PurgeVal(f, \langle Q, \bar{q}, \theta, \delta\rangle, A) :=$
  $\begin{cases} cmb_2(\bar{q}, Purge(F@f, A), Link_f) & if\ \delta(f,\bar{q})\ and\ A(f,\theta(\bar{q}))\ are\ defined \\ & and\ A(f,\theta(\bar{q})) \sqsubseteq \theta(\delta(f,\bar{q})) \\ \langle \emptyset, \bar{q}, \emptyset, \emptyset\rangle & otherwise \end{cases},$
  where $Link_f := \langle \{\bar{q}\}, \bar{q}, \langle\langle \bar{q}, \theta(\bar{q})\rangle\rangle, \langle\langle (f,\bar{q}), \delta(f,\bar{q})\rangle\rangle$.
- $cmb_n(\bar{q}, \langle Q_1, \bar{q}_1, \theta_1, \delta_1\rangle, \ldots, \langle Q_n, \bar{q}_n, \theta_n, \delta_n\rangle) :=$
  $\langle Q_1 \cup \cdots \cup Q_n, \bar{q}, \theta_1 \cup \cdots \cup \theta_n, \delta_1 \cup \cdots \cup \delta_n\rangle @\epsilon$.

Intuitively, the *Purge* function recursively descends into the structure by attempting to follows arcs labeled with all possible feature names, removing all arcs whose features are not appropriate for the types of their start nodes, and then rebuilding the substructures to only include the nodes that are still accessible from their head nodes. The set A is used to keep track of the visited nodes in order to ensure termination on cyclic structures.

Theorem 5.5.9. *For every* $F \in \mathcal{F}$, $Purge(F) \in \mathcal{TF}$.

Proof. We observe that no part of the *Purge* operation introduces any new nodes or arcs to the structure, and that the type assignment θ is not modified except that entries may be removed. Therefore, for any $F = \langle Q, \bar{q}, \theta, \delta\rangle \in \mathcal{F}$ and $Purge(F) =: F' = \langle Q', \bar{q}', \theta', \delta'\rangle$ we have $Q' \subseteq Q$, $\theta' \subseteq \theta$, and $\delta' \subseteq \delta$. Now assume that there is a feature structure F for which $F' = Purge(F) \notin \mathcal{TF}$. Then, by the definition of well-typedness, there must be a $f \in Fe$ and a $q \in Q'$ for which $\delta'(f,q)$ is defined, but either ① $A(f,\theta'(q))$ is undefined or ② $A(f,\theta'(q)) \not\sqsubseteq \theta'(\delta'(f,q))$. Let π be the path from $\bar{q}'$ to q (which exists because the outermost part of *Purge* is an application of $@\epsilon$, leaving only nodes reachable from $\bar{q}'$ in Q'). As $\delta'(f,q) \in Q'$, there must have been a recursive call to $PurgeVal(f, F@\pi, A)$ such that both $\delta(f,q)$ and $A(f,\theta(q))$ were defined, and $A(f,\theta(q)) \sqsubseteq \theta(\delta(f,q))$. As both $\delta(f,q)$ and $\delta'(f,q)$ are defined, $\delta' \subseteq \delta$ means that $\delta(f,q) = \delta'(f,q)$. Therefore $q \in Q' \subseteq Q$ and $\theta' \subseteq \theta$ imply $\theta(q) = \theta(q')$ and $\theta'(\delta'(f,q)) = \theta(\delta(f,q))$. But this means that $A(f,\theta'(q)) = A(f,\theta(q))$ is defined, leading to a contradiction in case ①, and that $A(f,\theta'(q)) \sqsubseteq \theta'(\delta'(f,q))$, leading to a contradiction in case ②. □

Note that the *Purge* function is very different from the *TypInf* function of Definition 5.1.10. Both turn any typable feature structure into a well-typed structure, but they achieve this by different means. *TypInf* can only switch the types of nodes, and *Purge* may only remove arcs and their substructures. *TypInf* leaves the graph structure unchanged, but modifies node labels to enforce appropriateness conditions, whereas *Purge* leaves the node labels intact, instead achieving the same goal by pruning the graph structure. *Purge* is more powerful because it can coerce any structure (not just typable ones) into well-typedness, whereas *TypInf* is less invasive, but undefined for structures that are not typable.

For the editor, enforcing well-typedness via *TypInf* is not attractive because it can modify types, competing with the user for whom the types are also the pivot points for determining the structure. For instance, applying *TypInf* after *gez* will often revert that operation, which would be utterly confusing for the user, and it would make parts of the structure space inaccessible. *Purge* behaves a lot more aggressively, but it does not touch these pivot points for orientation, and it allows to define a function that can coerce any structure into a totally well-typed version:

Definition 5.5.10 (**TTF enforcement**)**.** *The operation of* ***TTF enforcement*** *is the function* ***ttf***: $\mathcal{F} \to \mathcal{TTF}$ *defined by* $ttf := Fill \circ Purge$.

Together with the fact that $Fill$ is a total function from $\mathcal{TF}$ into $\mathcal{TTF}$, Theorem 5.5.9 immediately tells us that ttf enforces total well-typedness as intended. The ttf function makes $\mathcal{TTF}$-invariant versions of the elementary editing operations easy to express:

Definition 5.5.11 (**TTF Type Specialization**)**.** *The operation of* ***totally well-typed type specialization*** *is the partial function* ***ttSpz***: $\mathcal{TTF} \times Path \times Ty \to \mathcal{F}$ *defined by* $ttSpz := ttf \circ spz$ *where* spz *is defined, and undefined otherwise.*

Definition 5.5.12 (**TTF Type Generalization**)**.** *The operation of* ***totally well-typed type generalization*** *is the partial function* ***ttGez***: $\mathcal{TTF} \times Path \times Ty \to \mathcal{F}$ *defined by* $ttGez := ttf \circ gez$ *where* gez *is defined, and undefined otherwise.*

Definition 5.5.13 (**TTF Type Switching**)**.** *The operation of* ***totally well-typed type switching*** *is the partial function* ***ttSwi***: $\mathcal{TTF} \times Path \times Ty \to \mathcal{F}$ *defined by* $ttSwi := ttf \circ swi$ *where* swi *is defined, and undefined otherwise.*

Definition 5.5.14 (**TTF Identity Introduction**)**.** *The operation of* ***totally well-typed identity introduction*** *is the partial function* ***ttItr***: $\mathcal{TTF} \times Path \times Path \to \mathcal{F}$ *defined by* $ttItr := ttf \circ itr$ *where* itr *is defined, and undefined otherwise.*

Definition 5.5.15 (**TTF Identity Dissolval**)**.** *The operation of* ***totally well-typed identity dissolval*** *is the partial function* ***ttIds***: $\mathcal{TTF} \times Path \to \mathcal{F}$ *defined by* $ttIds := ttf \circ ids$ *where* ids *is defined, and undefined otherwise.*

After defining these operations, we now have to show their $\mathcal{TTF}$-invariance. Because $ttSwi$ can be seen as a combination of a $ttGez$ and a $ttSpz$ operation, this amounts to proving the following theorem, which is analogous to a correctness proof for a logical calculus:

Theorem 5.5.16. *Each value of* $ttSpz$, $ttGez$, $ttItr$, *and* $ttIds$ *is in* $\mathcal{TTF}$ *or undefined.*

Proof. Consider the case of $ttSpz$. If for some $F \in \mathcal{F}$, $\pi \in Path$, and $\sigma \in Ty$, $spz(F, \pi, \sigma)$ is defined, then $ttSpz(F, \pi, \sigma) = ttf(spz(F, \pi, \sigma)) \in \mathcal{TTF}$ because ttf is a total function from $\mathcal{F}$ to $\mathcal{TTF}$. If, on the other hand, $spz(F, \pi, \sigma)$ is undefined, then by definition $ttSpz(F, \pi, \sigma)$ is undefined as well. The same argument applies to the other operations. □

We started out with the intention of defining operations that make the entire space of TTF structures easily and comfortably accessible. Given the constrained nature of the four elementary operations, we need to make sure that they are enough to create every TTF structure. This is analogous to showing the completeness of a logical calculus, and is expressed by the following theorem:

Theorem 5.5.17. *For any two totally well-typed feature structure* $F_1, F_2 \in \mathcal{TTF}$, *there is a sequence of instances of* $ttSpz$, $ttGez$, *and* $ttItr$ *producing* F_2 *from* F_1.

Proof. We give an algorithm for constructing such a sequence for arbitrary $F_1, F_2 \in \mathcal{TTF}$ by first reducing F_1 to the trivial structure, and then extending the trivial structure to F_2. 1) We construct a finite sequence of applications of the $ttGez$ operation which produces the trivial structure $\langle\{q\}, q, \{q \mapsto bot\}, \emptyset\rangle$ out of $F_1 = \langle Q_1, \bar{q}_1, \theta_1, \delta_1\rangle$. The acyclicity of the type hierarchy gives us a finite sequence $bot = \tau_n \lhd \tau_{n-1} \lhd \cdots \lhd \tau_1 \lhd \tau_0 = \theta(\bar{q}_1)$ of types. We build a sequence of structures F_1^i via $F_1^1 := F_1$ and $F_1^{m+1} := ttGez(F_1^m, \epsilon, \tau_m)$. For each $m < n$, $gez(F_1^m, \epsilon, \tau_m)$ is defined because $\tau_{m+1} \lhd \theta(\delta(\epsilon, \bar{q}_1)) = \tau_m$. By Definition 5.5.12, $ttGez(F_1^m, \epsilon, \tau_m)$ is then defined as well $\Rightarrow$ all the F_1^i up to F_1^{n+1} are defined. We show that F_1^{n+1} is the trivial structure. By n applications of Theorem 5.5.16, we know that $F_1^{n+1} \in \mathcal{TTF}$. The head type of F_1^{n+1} is bot, for which no features are appropriate. Any arcs or nodes other than $\bar{q}_1$ would thus be removed by the last application of $Purge$.

2) We show that F_2 can be produced from the trivial structure $F_2^0 := \langle\{q\}, q, \{q \mapsto bot\}, \emptyset\rangle$ by a sequence of applications of *ttSpz* and *ttItr*. To construct the sequence F_2^i, we recursively construct a copy of F_2 in a depth-first fashion following the arcs labeled $f \in Fe$ in alphabetical order. A mapping $A\colon Q \to Path$ of visited nodes to their paths is maintained to handle the reentrancies and to ensure termination. Whenever at a path π, we reach a node q for which $A(q)$ is already defined, we define $F_2^{i+1} := ttIdt(F_2^i, \pi, A(q))$, which is defined because the paths already led to the same node in F_2. If $A(q)$ is not yet defined, we specialize the type of q via a series of *ttSpz* operations that is constructed analogously to the *ttGez* sequence in 1), until we reach $\theta_2(q)$, and define $A(q) := \pi$. All the arcs and nodes added by the *Fill* part of *ttSpz* must have been present in F_2 because it is totally well-typed. The recursion visits all the reachable nodes in F_2 because *Fill* already introduced all the appropriate features when we arrive at a node. The *Purge* part of *ttItr* and *ttSpz* is never needed, but it does not remove any structure that has been established either, because for each arc $(q, f, \delta(f, q))$ the condition $A(f, \theta(q)) \sqsubseteq \theta(\delta(f, q))$ under which $PurgeVal$ does not discard the arc is fulfilled. $\square$

Note that the *ttIds* operation was not needed for this proof. The other three elementary operations suffice to connect the entire space of totally well-typed structures. However, it is clear that the sequences constructed in this proof differ from the sequences by which a user would want to process structures. *ttIds* is often a very convenient operation, and other $\mathcal{TTF}$-invariant operations might be added to the formalism for the same reason.

Taken together, the two last theorems tell us that the new set of elementary editing operations ensures that only totally well-typed structures can be produced. This editing scheme makes use of the entire available information about the type system, greatly facilitating the manual generation of those feature structures which are useful for interactive debugging.

5.6 Implementing the Signature-Enhanced Editor

In this section, I present my implementation of a signature-enhanced AVM editor which implements the elementary editing operations on totally-well typed structures developed in the previous section. To display AVMs, I use the Gralej visualization component which is already integrated in Kahina. An important design goal is to be minimally invasive, i.e. to make as few changes as possible to previous code. Specifically, any changes to the Gralej code are avoided, and especially, no dependency of the Gralej library on Kahina classes is introduced. This requires some overhead in the implementation, but results in a nicely modular system.

Extending Gralej is complicated by the fact that it was primarily designed to be a stand-alone display module. The view panel is based on a hierarchy of `Block` objects which represent and render graphical entities in the display, whereas the underlying AVM is represented by a data model building on `IEntity` objects. The problem now is that once a structure has been parsed from a GRISU string, its view becomes unalterable. While it is possible to access and modify the `IEntity` objects in the data model after the structure was displayed, there is no way that these changes would be reflected in the view because the `Block` structure cannot be manipulated, and it is impossible to generate `Block`s directly from `IEntity` objects. In fact, the only way to generate `Block`s and thereby to alter and rebuild an AVM view is to parse a new GRISU string.

This means that editing has to be implemented by generating GRISU strings from modified `IEntity` objects. Unfortunately, Gralej's monodirectional nature also has consequences for the input and output languages it supports. Whereas Gralej operates on GRISU as input language, it does not provide an option to export modified AVMs in that format. Instead, the only textual formats that Gralej supports as output languages are the TRALE description language and a custom more human-readable GRISU variant for debugging purposes. The solution was to write an auxiliary method that can traverse any Gralej entity to generate corresponding GRISU strings, which can then be fed back to Gralej for display. The editing operations could thus be implemented to operate directly on Gralej `IEntity` objects.

The diagram in Figure 5.5 gives an overview of the resulting architecture. The elementary editing operations on `IEntity` objects are implemented in the `GraleJUtility` class, a collection of static methods which are modeled after the formal definitions. The methods take an `IEntity` object, one or two paths, and possibly a type name as parameters, and return an `IEntity` object that may be a modified variant of the original, or a newly constructed `IEntity`. Bits of the input structure are systematically reused, but all calling methods can treat the results as if they were newly constructed `IEntity` objects. Helper methods (most importantly, `fill` and `purge`), make the implementation modular. Both editing operations and helper methods sometimes need type information, for which they can query a `TraleSLDSignature` object as already used for modeling signatures in Chapter 4. A full list of the methods in `GraleJUtility` can be found in Appendix C.

To make the editing operations accessible in an intuitive way via the AVM visualization, I opted for using a context menu. When double-clicking onto a node in the AVM, a context menu pops up giving access to all the possible editing operations involving the path to that node. The three kinds of elementary type manipulation are accessible via submenus containing type lists that represent all the valid options. Especially for type switching, some computations are necessary to only offer valid options.

In Figure 5.6, we see an example of a totally well-typed type specialization. The structure on the left is the minimal totally well-typed structure of type *synsem*. The context menu was opened for the *cont* value of the CONTENT feature, which we cannot generalize (because the appropriateness conditions say that the value needs to be of a type subsumed by *cont*), causing the generalization submenu to be deactivated. The specialization menu contains the immediate subtypes of *cont*, and we select a specialization to *nom_obj*. The result is displayed on the right: the appropriateness conditions demand that a totally-well typed structure of type *nom_obj* define the feature INDEX with a value of type *index*, which in turn is required to define a GENDER, a NUMBER, and a PERSON, for whose value types no features are appropriate, causing the *Fill* operation to terminate. The result is again a totally well-typed structure, as predicted by Theorem 5.5.16.

For the identity removal operation, it is fortunate that token identities are explicitly expressed in AVMs as tags. Tags provide context objects to which identity removal can be applied very intuitively. If the user double-clicks on a tag, only the option to dissolve the identity expressed by that tag is offered. Implementing the operation was complicated by the

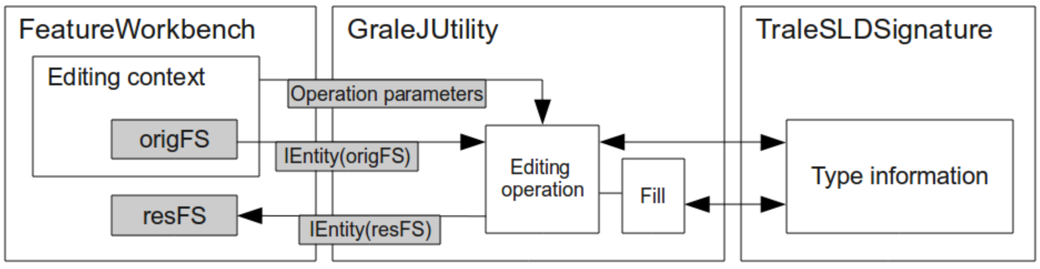


Figure 5.5: Architecture of the signature-enhanced editor.

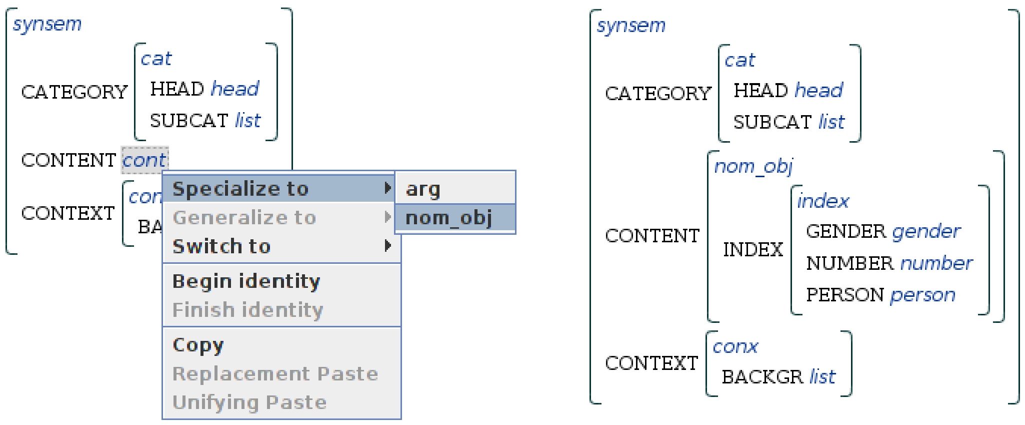


Figure 5.6: Specializing a *cont* object to a *nom_obj*.

need to keep track of the reentrancies in the structure. Handling all cases robustly requires a complete traversal of the structure in a preparation step, assembling lists of identified paths indexed by their tag numbers. Those lists are then used to determine whether the dissolved identity linked two or more paths. In both cases, a copy of the target structure replaces the tag at the context node. If the tag was contained in the original structure only twice, the second occurrence of the tag is removed as well. Keeping track of the reentrancies in this way introduces quite some overhead, but does not cause any trouble with responsiveness even for very large structures.

In Figure 5.7, we see an example of the identity dissolval operation. The structure on the left is a part of the lexical entry for the personal pronoun *I*, where SYNSEM:CONTENT:INDEX is structure-shared with the argument of a *speaker_rel* entry in the SYNSEM:CONTEXT:BACKGR list. The result of dissolving this path identity is displayed on the right: the *index* structure is copied to both paths, and the tags are removed. The resulting AVM reflects the fact that the structures at the two paths are not token-identical any more.

Identity introduction was made accessible in a way similar to the manner in which unification is accessible in the LKB: providing the option to select one node using the context menu, and adding an option to subsequently activated context menus to identify the context node with the one last selected.

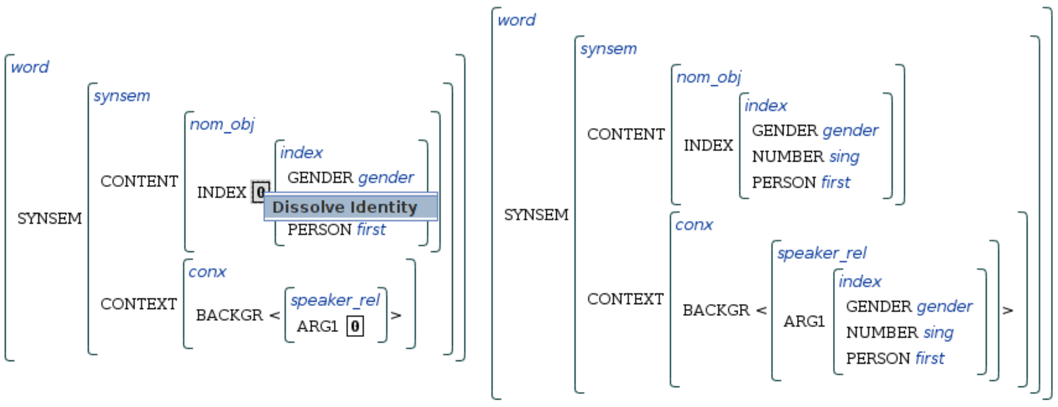


Figure 5.7: Dissolving an identity.

In Figure 5.8, we see how an identity can be reintroduced into the result of Figure 5.7. The left side displays the situation where the ARG1:NUMBER value of the *female_rel* object on the background list has already been selected as the first argument of the identity introduction using the "Begin Identity" context option. In the second step, the "Finish Identity" option is used to mark the SYNSEM:CONTEXT:INDEX:NUMBER value as the second argument, and to effectuate the identity introduction. In the result on the right side, in accordance with the conventions governing AVM representations, the two paths are linked by a new tag, and the common structure is only displayed once.

The implementation of identity introduction requires bookkeeping to keep track of the interactions between path identities. Moreover, the definition shows that the operation makes use of unification in order to combine the substructures below the nodes. While unification had no effect in the example just discussed, unifying two arbitrary feature structures is not a trivial operation if reentrancies are to be treated correctly. which requires techniques such as variable renaming. In AVM representations, where the problematic structure identities are only reflected by tags with common IDs, variable renaming is not easy to implement, which makes a direct implementation of unification on `IEntity` objects very unattractive. Instead, the feature structures are compiled into a format which explicitly stores path equivalence classes. A simple unification algorithm along the lines of Definition 5.1.5 was implemented on this format, yielding a collection of paths which can be used to construct the MGU `IEntity`. This naive implementation with the added conversion overhead would be useless if many unifications were needed, but it is clearly fast enough for an operation that is only triggered now and then by user interaction, given that it does not have any recognizable detrimental effect on responsiveness.

Since the weaker variants of the editing operations had to be implemented as helper methods for the totally well-typed variants, it was easy to define a set of different editing modes, mainly to make the editor attractive for educational purposes. At the moment, the signature-enhanced AVM editor supports a **free mode** that does not enforce any appropriateness conditions, but adds context menu options for feature introduction and removal, a **TF mode** which enforces the appropriateness conditions to the degree that the structures become well-typed, and the default **TTF mode**, which fully implements the totally well-typed editing operations, leading to an editing system with the closure and completeness properties proven in Theorems 5.5.16 and 5.5.17.

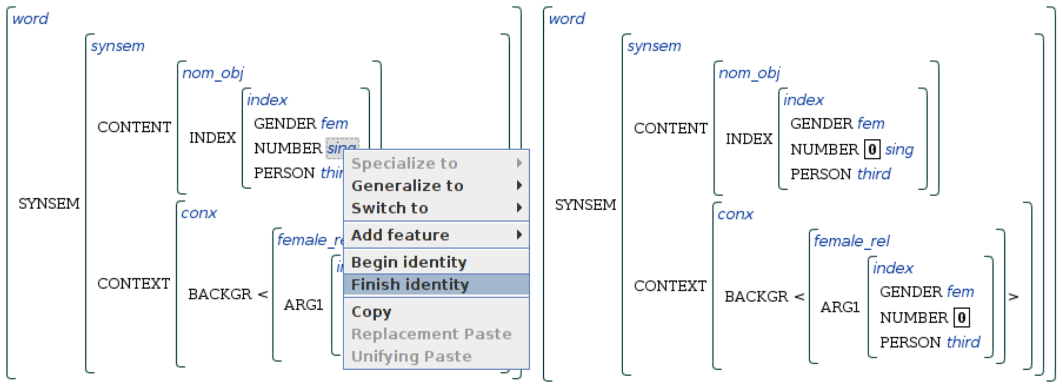


Figure 5.8: Second step of an identity introduction.

5.7 Discussion

Some functionality of the editor goes beyond the formal specification in Section 5.5, and therefore deserves to be mentioned here. For instance, an essential component for any editing system is some kind of replication functionality, which is usually provided in the form of copy and paste operations. This functionality has been added to the editor in the context of the feature workbench, and is discussed in Section 6.5.

The treatment of **atoms** is another issue which could be abstracted away in the formalism, but becomes relevant in the implementation. A TRALE type hierarchy is always assumed to include all possible strings as atomic types in an infinite subhierarchy. This subhierarchy is implicitly present in any signature, and therefore need not (and cannot) be explicitly defined. Atoms commonly occur in values of the PHON feature, where they serve to avoid the explicit modeling of phoneme sequences, which is very similar to the treatment of phonetics e.g. in Pollard and Sag (1994), and is also beneficial to processing efficiency. To provide the editor with support for these atomic types, the context menu for structures was extended by options for specializing structures of type *bot* to arbitrary atoms, for changing the string of an atom, and for generalizing atoms to *bot*.

Some of the decisions made in the editor's implementation might also require justification. To start with a problem of the interface design, a context menu might not be considered the ideal choice for making identity introduction available, because this operation does not influence only a single context node, but the user has to select two paths for unification. There are at least two other standard ways to bring two elements together in a visualization. Possibly the most intuitive way would have been to drag one element onto the other one, but this variant was impossible to implement without heavy modifications to the Gralej code. A second possibility would have been to allow the selection of multiple nodes, and then to have a button next to the visualization for identifying all selected nodes. This variant was the simplest to extend to identification of more than one path, but felt too different from the ways to effectuate the other operations.

Internally, the implementation of the TTF type modification operations on feature structures was complicated by the fact that the `IEntity` data structure represents feature structures in a way very different from the formal definition. This especially concerns the handling of reentrancies, which had to receive careful special treatment. For example, if a substructure containing a tag is removed, but the target is still referenced from outside the removed structure, this other tag must be replaced by the target. If the same tag occurred more than twice, the situation is again different. Moreover, lists needed to receive a special treatment in virtually every method. Whereas the signature defines lists to be objects like any other, without any formal difference to other types, any data model for an AVM visualization will of course contain special data structures for representing lists. Although underlyingly, a list with one element is just a structure of type *ne_list* with the element as HD value and an *e_list* object as TL value, this is not the way the AVM representation handles them. Type switching a non-empty tail to an empty list has the effect of deleting a number of entries from the tail of a list, and this and similar operations should be accessible via the context menu. The current solution is to treat the < and > elements of the lists, and also the separating commas, as context nodes exposing a special set of editing options. Internally, the methods are implemented to treat the `IList` objects which are used to represent lists in the data model exactly like the equivalent structures where heads, tails, and empty lists are explicitly expressed.

Finally, an alternative option for generating the needed GRISU strings from `IEntity` objects would have been to convert the description language output into a temporary theory which licenses only structures satisfying the description, to compile that theory with a TRALE instance, and then to use this instance for generating a GRISU string out of the most general satisfier of *bot*. This variant was implemented and tested using the infrastructure from Chapter 6, where an auxiliary TRALE instance is made accessible for other purposes. The approach failed mainly because TRALE does not support constraints on *bot*, meaning that the head type of the description has to be extracted (or inferred) for use as the constraint antecedent, which is not possible for arbitrary description language expressions given only the signature information.

With the current implementation, the concept of signature-enhanced editing is realized in a powerful and mature tool for rapid AVM editing. The editing economy is much improved over FEGRAMED and GraDEUS due to the $\mathcal{TTF}$-invariant editing operations which make full use of the signature information to avoid superfluous editing steps. The confusing error messages about unappropriate or missing features on the way to totally well-typed structures are avoided, and the user can be sure to navigate only within the space of totally well-typed structures, prducing only structures that could in principle occur during parsing processes.

The implemented editor could easily be turned into a standalone component for exploring type hierarchies. Unlike the signature visualization component in Chapter 4, the editor does not merely present the signature information in a nicely formatted way, but it gives the opportunity to interact with a signature by directly exploring its semantics, providing hands-on experience with the licensed structures. It is easy to imagine that this will make the editor attractive for teaching the basics of feature logic, especially given that the concepts can be introduced in a gradual fashion by going through the editing modes. This use case is similar to the main area of application intended for MoMo (see Section 4.2). MoMo has the advantage that it maintains a clear distinction between descriptions and their denotation, whereas the signature-enhanced editor builds on an intuitive correspondence between AVMs and feature structures. Introducing feature logic with the editor has the advantage that it operates on AVMs and larger signatures from the start, whereas the conceptual leap from explicit graph structures over tiny toy signatures to AVMs over HPSG signatures is rather large in the case of MoMo.

These possibilities could make the editor an attractive tool also for experienced grammar developers. When a grammar developer is confronted with a previously unseen grammar or needs to refresh his memory of an older grammar, being able to play around with the licensed structures is a valuable tool for quickly understanding the signature. In the next chapter, this concept of an environment for exploring signatures is extended to entire grammars. The feature workbench, which also makes it possible to explore the effects of the theory in an interactive fashion, is at the same time a more ambitious use case for the editor.

Chapter 6

The Feature Workbench

In this last core chapter, the new viewing and editing components developed in the previous chapters are integrated into a common user interface, which is then connected to the existing Kahina-based debugging architecture. The purpose of the resulting component, which I call a **feature workbench**, is to free feature structures from their role as mere parts of the step details that are displayed when a step is inspected. Instead, operations such as unification and MGS computation, which are important elements of the parsing process, are made available to the user as tools, making it possible to experiment freely with the structures that were originally only accessible as unalterable representations of parsing results. The envisioned workflow for the workbench is to quickly construct AVMs out of elementary building blocks, and only then to check the consequences of the theory in order to see whether the constructed AVM is ruled out, licensed as is, or enriched by additional structure.

Such a workbench holds some promise for novice users who still have to familiarize themselves with the feature logic. If the structures licensed by a given signature can be interactively explored and appropriate structures can be built up via signature-enhanced editing, the consequences of changes to the signature and the theory can quickly be grasped and tested out without first having to integrate the interactions of interest into a toy grammar.

But a feature workbench also holds a lot of potential for advanced users. First-time readers of a complex grammar can quickly get a feel for the licensed structures and rule interactions, and they can make useful modifications much sooner than if they would have to think of sentences to parse in order to explore the interactions of interest.

From the viewpoint of user-friendliness, it is desirable to integrate the feature workbench with the Kahina-based TRALE debugger presented in Chapter 3. Such an integration allows the user to store and modify feature structures encountered during the parsing process, offering immediate and interactive answers to such questions as whether a given parsing step would not have failed if the input structures had looked somewhat differently.

My prototype implementation of the feature workbench is presented in a gradual fashion. Apart from questions of interface design, there is a strong focus on software engineering issues, due to the necessity of running and maintaining a secondary TRALE instance under the hood. Section 6.1 introduces more conceptual detail and a first very basic design, and Section 6.2 explains how the secondary TRALE instance is handled. Section 6.3 presents the approach taken to elementary building blocks, and Section 6.4 describes how the basic operations were implemented and made accessible. The implementation of a copy and paste mechanism for feature structures is the subject of Section 6.5.

A standalone version of the workbench is presented in Section 6.6, and the integration with the Kahina-based debugger is discussed in Section 6.7. The result is a quite stable workbench, but the complexities of the architecture as well as weaknesses of the underlying software components leave a few gaps that were impossible to fill in the time available for this work. Section 6.8 discusses these problems along with possible alternatives to the design decisions taken. The chapter concludes with some remarks on possible future extensions and enhancements in Section 6.9.

6.1 Basic Concepts of the Workbench

A **workbench** is a common metaphor for a clever arrangement of tools for manipulating objects of some type. The term originally denotes a specialized piece of furniture that is designed to provide an optimally efficient working environment to an artisan. Such a workbench typically consists of a table plate to which heavy tools as well as appliances for fixing workpieces can be mounted, and cleverly devised storage facilities which provide easy access to frequently used tools and materials.

In computing, the workbench, understood as an array of tools which serve to efficiently combine or modify data of a certain type, has been a fruitful metaphor in the design of interactive systems. A word processor can be seen as a simple example of such a digital workbench. The workpieces are the documents, search and formatting options are frequently used and therefore readily accessible tools, and spell checkers and style sheet editors are the equivalents of typical appliances.

The XTAG tools (see University of Pennsylvania, 2011), which were also briefly discussed in Chapter 3, constitute an archetypal workbench for tree structures. The tools are built around a hierarchical buffer of tree structures that express different types of information. Among these are the elementary and auxiliary trees which constitute TAG grammars, but optionally also the derivation trees that represent parsing processes, and the derived trees resulting from such processes. The provided tools are centered around operations on these trees, and include a tree editor for specifying grammars as well as inspection and output modules for derivation trees and derived trees. This tree workbench has been an important inspiration for the feature workbench because it continues to serve as the backbone of a popular grammar development environment.

Designing a feature structure workbench for the same purpose involves thinking about the kinds of operations on feature structures that are likely to be most useful in the context of unification-based grammar engineering. The signature-enhanced AVM editor from Chapter 5 provides the central editing component. Making the construction of larger structures more comfortable requires access to larger building blocks such as minimal appropriate structures of a given type, and the structures representing lexical entries.

After constructing or modifying a feature structure with the signature-enhanced editor, a user will often want to know whether the structure just defined corresponds to an element in the interpretation of a theory, i.e. whether it is not only totally well-typed, but also does not violate any constraints. This can be achieved by computing the most general satisifier not only against the signature, but also against the theory. The result of this **theory MGS** computation also includes the consequences of all the constraints on the structure, making it an important tool for understanding and testing complex grammar implementations.

Unification plays the central role as the method for combining information from many feature structures into one, and for testing whether a description in the theory matches some structure. When a particular parsing step failed, finding the explanation almost always entails analyzing one or more unifications. Functionality for testing such unification steps in isolation gives the user a direct handle on the question whether a parsing step would also have failed if the input structure had been slightly different. It therefore enables an alternative debugging workflow that is not based on a loop of tracing, editing, and reparsing, but on retrieving, manipulating and testing local information to determine the changes necessary in special cases, and only then getting back to the grammar in order to see how these changes can be implemented. This comes close to the hypothetical evaluation workflow of the WCDG system discussed in Section 3.1.

The starting point for the implementation of the feature workbench is a simple window consisting of a list of feature structures and an instance of the signature-enhanced feature structure editor from Chapter 5. Each feature structure on the workbench is stored under a unique string ID, which is automatically generated from the structure in a meaningful way, but can be freely modified by the user to make structures more easily identifiable. The alphabetically sorted list of these string IDs is used to select feature structures for editing, which are then loaded into the editor. Internally, all feature structures are stored as AVMs in plain GRISU format, and whenever the user edits a feature structure, the underlying GRISU string is replaced.

This prototype layout, designed to leave as much space to the feature structure visualization as possible, is exemplified in Figure 6.1. Building on this basic layout, all the advanced functionality discussed in the following sections was made accessible via the menu bar or by means of context menus.

Facilities for exporting and importing individual structures as well as entire workbench contents are another essential basic component of the workbench. For individual structures, export works by simply dumping the corresponding GRISU strings into files, and import works by prompting the user for a new structure ID and then just as simply reading the GRISU string from a file. These single-structure actions are accessible through items in the feature structure menu. This also allows to generate GRISU strings using other tools, and to import the resulting structures into the workbench. Alternatively, it is possible to save and restore entire collections of feature structures into workbench files, where the GRISU strings are wrapped into a simple XML-based format together with their IDs. The corresponding interface options are accessible via a workbench menu.

6.2 Managing an Auxiliary Trale Instance

The workbench's core functionality is to make the basic operations of the parser freely accessible to the user. Implementing these operations directly on `IEntity` objects as in the signature-enhanced editor is not feasible because of the very complex nature of the constraints expressed in theory files. In fact, such an effort would amount to a reimplementation of the entire TRALE system. The operations can be made accessible at a much lower cost by using the Jasper interface for embedding a second TRALE instance into a Java object called the `AuxiliaryTraleInstance`.

The Jasper library comes in two parts: one is a SICStus library called `library(jasper)` for managing a JVM, which was used for building the Kahina-based TRALE debugger. The other part is a Java package called `se.sics.jasper` that can be used for controlling a SICStus Prolog instance, and was therefore the obvious choice for implementing the `AuxiliaryTraleInstance`. Getting TRALE to run in an embedded SICStus runtime is complicated by the fact that the TRALE system is not started as a Prolog program, but via a shell script that configures the execution environment before starting SICStus and loading

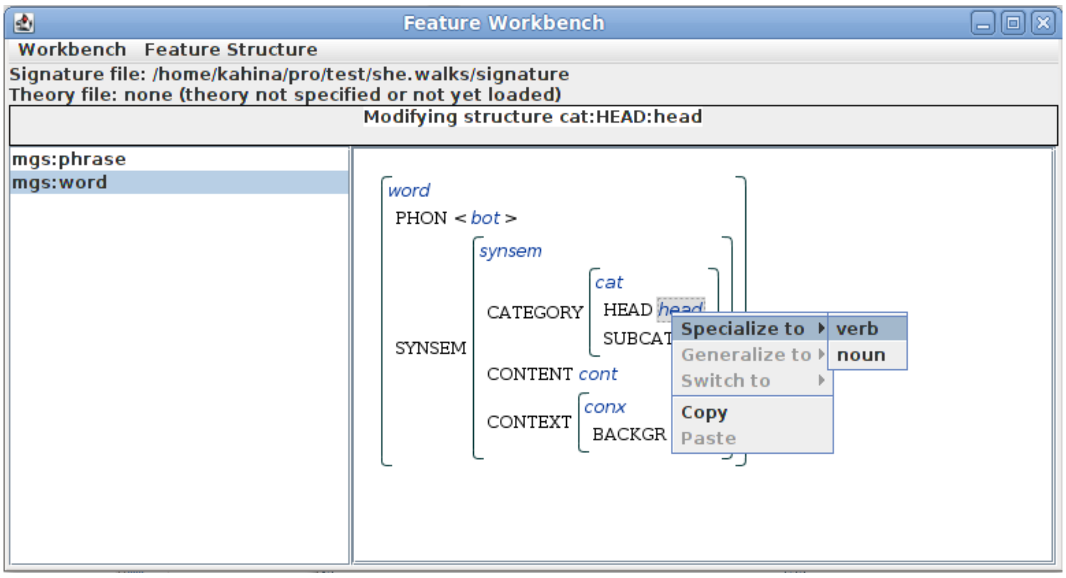

Feature Workbench
Workbench Feature Structure
Signature file: /home/kahina/pro/test/she.walks/signature
Theory file: none (theory not specified or not yet loaded)
Modifying structure cat:HEAD:head
mgs:phrase
mgs:word
word
PHON < bot >
SYNSEM
synsem
CATEGORY
cat
HEAD head
SUBCAT
CONTENT cont
CONTEXT
conx
BACKGR
Specialize to
Generalize to
Switch to
Copy
Paste
verb
noun

Figure 6.1: Workbench prototype with embedded signature-enhanced editor.

TRALE proper. Since the JVM's `ProcessBuilder` class can be used to set up a modified environment, it is possible to emulate the relevant parts of the TRALE startup script by setting appropriate environment variables.

The methods in `se.sics.jasper` responsible for constructing and querying the Prolog instance are not thread-safe. To avoid the complications of external synchronization, Jasper therefore only allows calls from the thread that created the `SICStus` object. Usually, the `AuxiliaryTraleInstance` is called in response to some user interaction via the GUI, but Swing event handling code always runs in a special thread called the event dispatch thread, which is not the thread where the `SICStus` object is created. Therefore, the `AuxiliaryTraleInstance` needed to be implemented as a separate thread which is accessible as a class combining utility methods for controlling the embedded TRALE instance. Inter-thread communication was implemented in a producer-consumer pattern using a synchronized interchange object. On the upside, letting the embedded TRALE instance run in a separate thread has the benefit of making full use of a second CPU core to perform the necessary computations on the Prolog side.

With this architecture it is possible to call TRALE predicates from inside Kahina, and also to retrieve solutions for such remote queries. However, TRALE's user-level predicates (such as `mgsat/1` for determining the most general satisfier of a description) cannot be used as queries binding solutions to variables, but only for printing out the resulting feature structures to the console in a human-readable format. This side-effect output of TRALE predicates needs to be transferred back into Java.

The adopted solution is to mimick the internals of these predicates and intercept the resulting feature structure, using existing GRISU generation code to output the structure in GRISU format to a temporary file, and to read this file back into the `AuxiliaryTraleInstance` object once it has completed the Prolog query.[1] This procedure works in principle, but the GRISU generation part causes problems.

[1]Simply dumping and retrieving the console output is not an attractive option because no tools for automatically parsing TRALE's pretty-print format for feature structures exist, and implementing such a parser would be very difficult, given that the format is not designed to be machine-readable.

For efficiency reasons, TRALE's so-called portraying code is heavily interleaved with the pretty-printing code for structure output, which means that the feature structures are not explicitly computed before output starts. In effect, this required much of the almost 500 lines of intricate Prolog portraying code to be reproduced and adapted for GRISU output into an alternative output stream. Kilian Evang accomplished a large portion of this task as part of the Kahina-based TRALE debugger, where such a method is needed to retrieve the feature structures after each computation step. Evang's code could easily be reused to output the result structures into temporary GRISU files.

Another problem with GRISU generation is that some nodes in the pretty-printed feature structures are annotated with expressions of the form *mgsat*(*type*) to save screen space. However, the structures on a workbench should be as explicit as possible, which makes such shorthands problematic. Fortunately, this shorthand notation occurs only in situations where the substructure was not influenced by any constraint, which permits an expansion using signature information only. As the appropriateness conditions are already encoded and accessible in a `TraleSLDSignature` object, existing code for enforcing these conditions could be reused, namely the *Fill* implementation in `GraleJUtilities` that is used in the totally well-typed mode of the signature-enhanced editor (see Section 5.5). The implementation only required some additional glue code which generates an `IEntity` object for a type, to which only the *Fill* method has to be applied in order to receive an `IEntity` object representing the desired MGS.[2]

This makes it possible to replace the *mgsat*(*type*) shorthands by the corresponding full structures in a **post-processing** step. To avoid the cost of parsing the entire structure into an `IEntity` object using Gralej, this is done by converting the desired MGS `IEntity` into GRISU, and exchanging the structure via a simple surface replacement in the GRISU string.

The workbench interface was extended to display status information about the embedded TRALE instance, such as whether a grammar was compiled, which signature and theory files are currently loaded, and error information in case the initialization or the compilation went wrong. The possibility to include theory as well as signature information was added to the XML format for workbench files in order to permit quick checks whether the currently compiled signature is compatible with a workbench that is being loaded.

6.3 Type MGSs and Lexical Entries as Building Blocks

To quickly create feature structures over a given signature from scratch, it will be useful to have access to a set of elementary building blocks. If we want to create a feature structure of a given type, it makes sense to start with a skeleton which then only needs to be refined. The feature structure representation of the most general satisfier of a type can be useful as such a skeleton. We call such a structure a **type MGS**, and offer them as elementary building blocks for the workbench.

For these computations, one could of course simply use the `AuxiliaryTraleInstance` from the last section, given that the architecture allows us to call `mgsat/1` remotely. However, this would implement a notion of type MGS which is not optimal for the purposes of the workbench because it compromises the desired transparency of the interactions. Using the theory

[2]TRALE also allows descriptions to be attached to types in signatures files. These **type constraints** are not enforced by the *Fill* method, so shorthands are resolved correctly only in their absence. Type constraints are not commonly used in grammar implementations, and enforcing them would amount to reimplementing the entire constraint system. Therefore, it would seem wiser to invest additional development time into finding out how to suppress MGS shorthands.

for type MGS computation causes the constraints to be applied already during construction, leaving it unclear which properties of the structure are consequences of the signature, and which parts were caused by the constraints in the theory.

Constructing type MGSs in the desired sense is possible without using an embedded TRALE instance. In fact, we can achieve this just like in the previous section when replacing shorthand descriptions of the form *mgsat*(*type*). The type MGSs are exactly the structures we generated there, allowing the code to be reused.[3]

The elementary building blocks are accessible to the user via the feature structure menu in the workbench's menu bar, along with all other operations that lead to the addition of feature structures to the workbench. The design of the submenu for type MGS computation is exemplified in Figure 6.2. The menu is organized in a hierarchy which mirrors the elementary is-a relations defined in the signature, forming a tree of menu entries that corresponds to the unfolded inheritance graph. A special top-level entry in the type menu is reserved for generating atoms (see Section 5.5). Activating this menu item opens up an input box where the atom string can be specified.

Apart from combining and modifying type MGSs, the user will want to construct linguistic signs by hand in order to test their satisfiability, or to explore the interactions between lexical entries and the theory. The obvious elementary building blocks for such endeavors are the feature structures of type *word* that are used to represent lexical entries.

To create feature structures for lexical entries, we use the `AuxiliaryTraleInstance` class developed in the last section. Figure 6.3 describes the architecture used for retrieving these structures. A lexicon string is given to the `AuxiliaryTraleInstance` thread for processing, which immediately hands it on as an argument to a query of the `lex/1` predicate. The embedded TRALE instance is configured to hand the result in the internal TRALE format over to the portraying methods implemented by Evang, and the resulting GRISU output is stored in a temporary file. This output is subsequently read in by the `AuxiliaryTraleInstance`, post-processed as described in Section 6.2, and stored in the result field of the synchronized exchange object. The feature workbench is informed about the completion of retrieval, collects the GRISU string, and adds the new feature structure to the workbench. The new entry is automatically selected, prompting a use of Gralej for a new visualization in the editor window.

Lexical entries are selected from a menu which is generated whenever a grammar is compiled, by having the `AuxiliaryTraleInstance` call the `lex/1` predicate with a variable, and collecting the solutions. The current version of this menu simply lists all the lexical entries defined in the grammar, grouping entries with identical PHON values together.

6.4 Providing MGS and MGU Computation as Tools

The main purpose of the `AuxiliaryTraleInstance` is to implement theory-dependent operations on feature structures. The `se.sics.jasper` package allows to recursively construct complex Prolog terms such as TRALE descriptions. This mechanism could rather straightforwardly be used to emulate the existing description output of Gralej, yielding another utility method which reliably constructs `SPTerm` objects representing description terms. The

[3]Compiling an empty auxiliary theory and applying `mgsat/1` on a description containing only the type of interest would produce exactly the same structure, and we would get the appropriateness-enforcing functionality for free. However, reliably discarding a compiled theory and recompiling an empty theory in the embedded TRALE distance turned out to be difficult and slow, especially if the original theory has to be recompiled for the next operation.

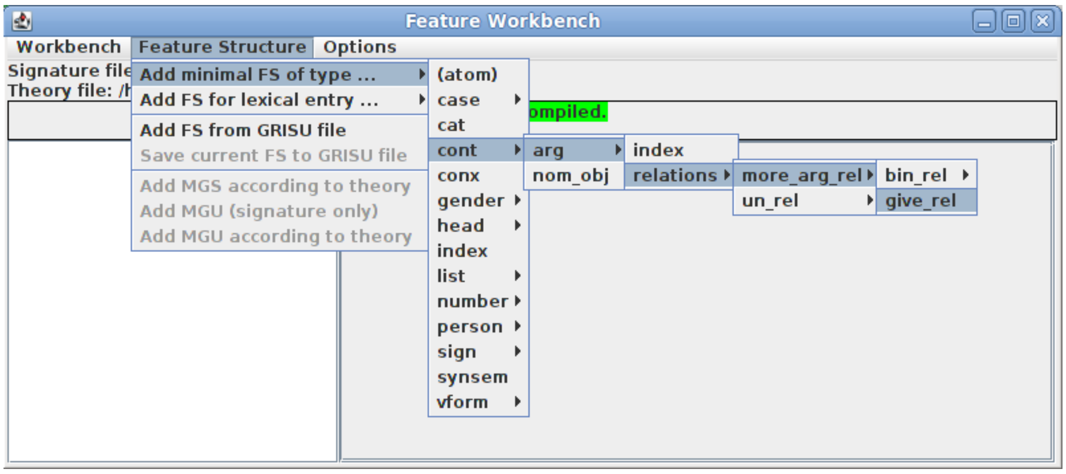


Figure 6.2: Example of the hierarchical menu for type selection.

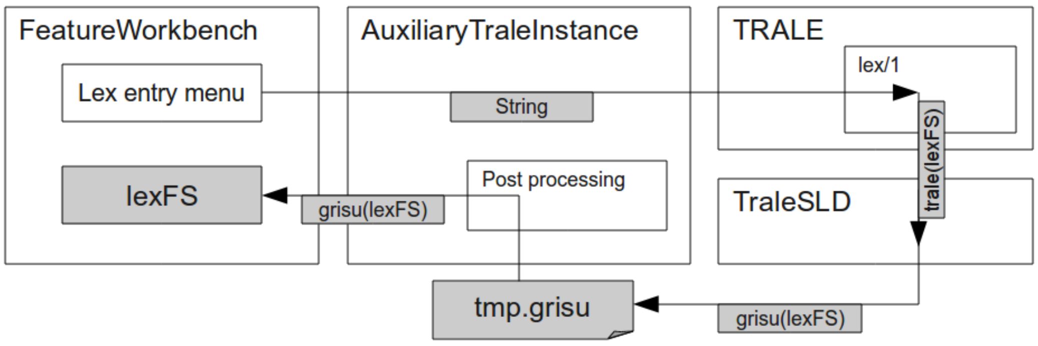


Figure 6.3: Architecture for retrieving lexical entries.

resulting architecture for theory MGS computation (see Figure 6.4) is very similar to the one used for retrieving lexical entries. The difference is that the argument for the TRALE predicate is no longer a simple lexicon string, but a complex `SPTerm` containing a canonical description of the feature structure that we wish to compute the MGS for. Getting the output back into the workbench works exactly as in the lexicon case.

The sketched approach to MGS computation might seem rather complex at first, but it works surprisingly fast. On my machine (an AMD Athlon X2 4850e, i.e. two CPU cores at 2.5 GHz each), the time for Gralej parsing a GRISU string into an `IEntity`, generating an `SPTerm` for the corresponding description, then using the TRALE process running in the `AuxiliaryTraleInstance` to compute the desired MGS and put it out in GRISU format to a file, reading that file back into Java, and finally having Gralej parse the resulting GRISU string to compute the display, sums up to only about 45 ms. This is clearly responsive enough for an interactive editor.

To make this operation accessible to the user, another item was added to the feature structure menu. This item is active if exactly one structure on the workbench is selected, and a theory was compiled by the embedded TRALE instance. Instead of replacing the old feature structure with the ID string α, the MGS is added as a new structure $mgs(\alpha)$, which is automatically selected and displayed in the editor. Unlike in the case of elementary editing operations, the workbench thus does not discard the input to an MGS computation. This is useful because MGS computation is a complex operation, which can be understood better if, by default, we allow the input to be reinspected.

In Figure 6.5, we can see the consequences of the new theory MGS operation on the type MGS of *phrase*. The Semantics Principle and the Head Feature Principle defined in the theory both lead to the introduction of one reentrancy. This example demonstrates that the distinction between the contributions of the signature and the theory is kept up by separating type MGS and theory MGS computation. The information on the left contains all that is known about a *phrase* object fulfilling the appropriateness conditions of the demo signature. The constraints defined in the theory only apply during the theory MGS operation, allowing the user to see clearly what they do.

The key step in exposing basic elements of TRALE parsing processes is to provide a way to manually execute the unification operation. Previously, we have already used a weak variant of unification that only uses the signature, and can therefore be computed without resorting to the `AuxiliaryTraleInstance`. This will henceforth be called **signature unification**, and is equivalent to the MGU operation on `IEntity` objects implemented for the signature-

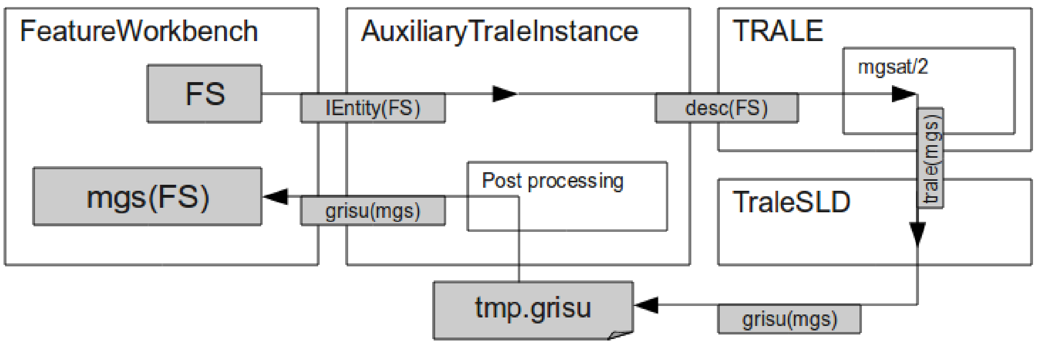


Figure 6.4: Architecture for theory-based MGS computation.

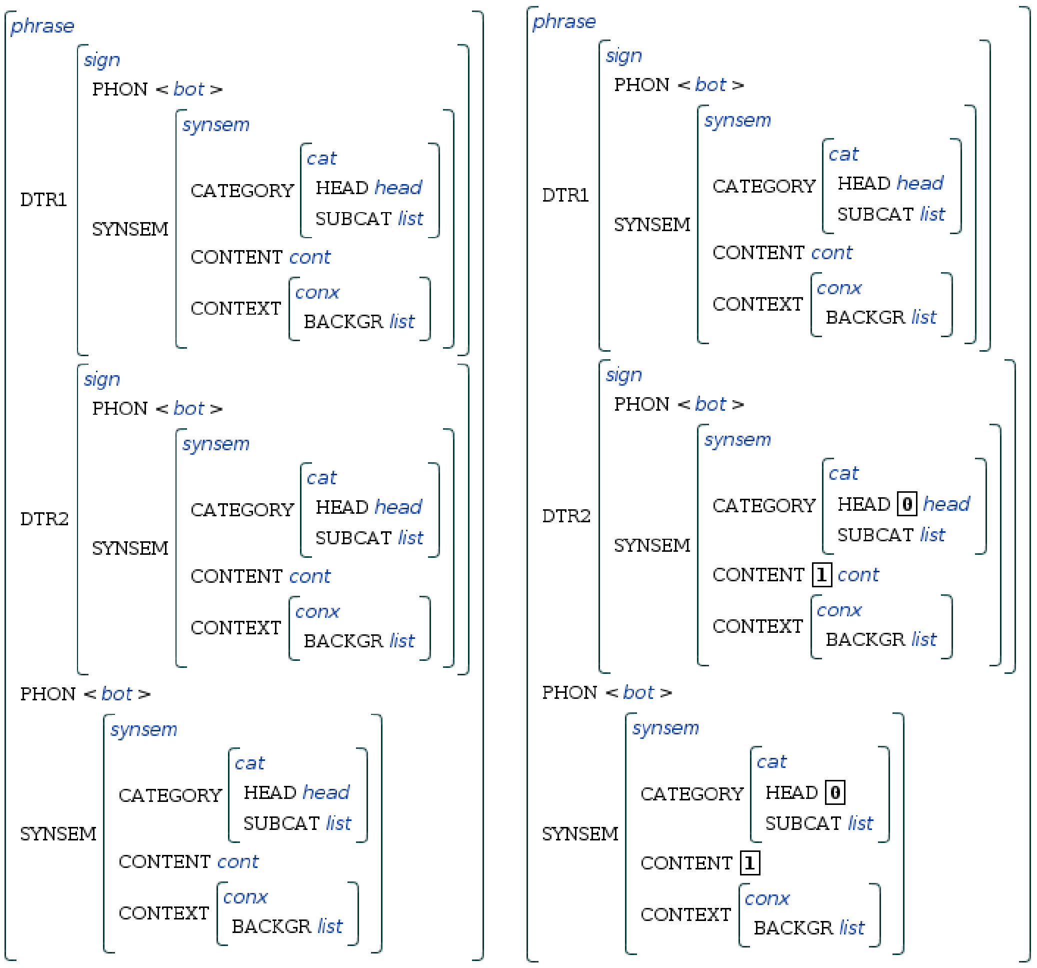


Figure 6.5: Executing the theory MGS operation on the type MGS of *phrase*.

enhanced editor as described in Section 5.5. This operation was made available via another item in the feature structure menu that is active if exactly two entries in the list of feature structures are selected. In analogy to the implementation of the theory MGS operation, in case of success the result of unifying two feature structures with IDs α_1 and α_2 is added to the workbench under the ID $mgu(\alpha_1, \alpha_2)$.

To distinguish it from signature-only unification, the type of unification forming the core of TRALE, which factors in the constraints defined in the theory, will henceforth be called **theory unification**. Implementing the theory MGU operation and making it accessible to the user only required trivial modifications to the infrastructure for theory MGS computation. The difference is that two feature structures have to be converted to description `SPTerms`. The two descriptions are then connected via the "**,**" connective representing a conjunction. The resulting architecture for theory unification is detailed in Figure 6.6.

The small size of our grammar makes it difficult to demonstrate the usefulness of theory unification, but it is possible to illustrate the difference between signature and theory MGU. Figure 6.7 displays two feature structures that we want to unify using both methods. The results of signature and theory unification are displayed next to each other in Figure 6.8.

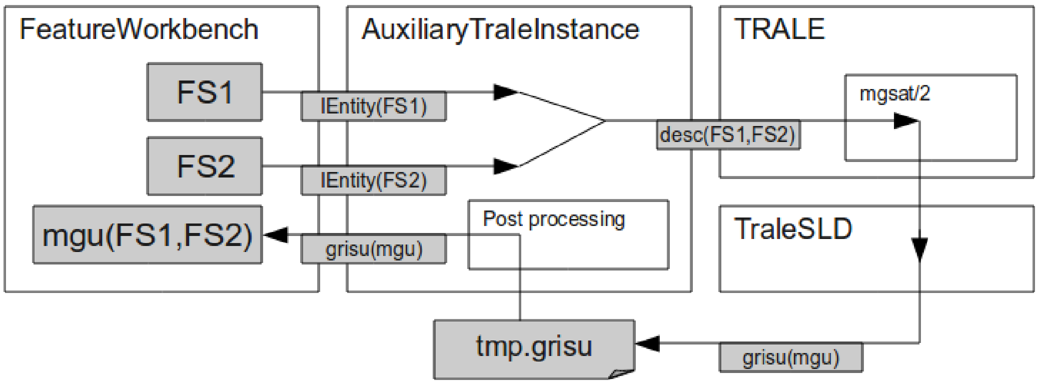


Figure 6.6: Architecture for theory unification.

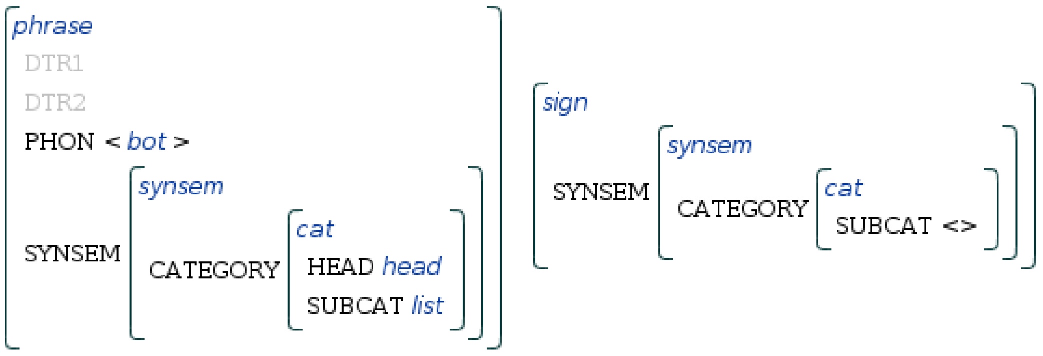


Figure 6.7: The input structures for the unification example.

The signature MGU is the result of unification exactly as specified in Definition 5.1.5, demonstrating that the two structures are compatible according to the signature. The theory MGU can be seen as the result of applying the constraints from the theory to the signature MGU. In our example, the Subcategorization Principle appends the DTR1:SYNSEM value to the DTR2:SYNSEM:CATEGORY:SUBCAT list, the Head Feature Principle unifies the values at SYNSEM:CATEGORY:HEAD and DTR2:SYNSEM:CATEGORY:HEAD, and the Semantics Principle unifies the values at SYNSEM:CONTENT and DTR2:SYNSEM:CONTENT.

Since the empty list is unified into the resulting phrase's subcat list, the signature MGU also fulfills the antecedent of the subject head rule. During a parsing process, this phrase structure rule would enforce the `phon_append` relation, causing the phrase's PHON value to become the concatenation of the daughters' PHON values. Because phrase structure rules are not treated like other constraints by the TRALE system, this append relation is not enforced by the theory MGU operation.

6.5 Composition via Copy and Paste

Up to this point, feature structures were generated from elementary building blocks via elementary editing operations. Signature-enhanced editing makes this process reasonably fast, but a user will still often be forced to execute repetitive sequences of such operations. As in any editor for complex structures, there is a need to provide the user with options for structure reuse. For this, the workbench adopts a standard mechanism by allowing the user to copy and paste substructures.

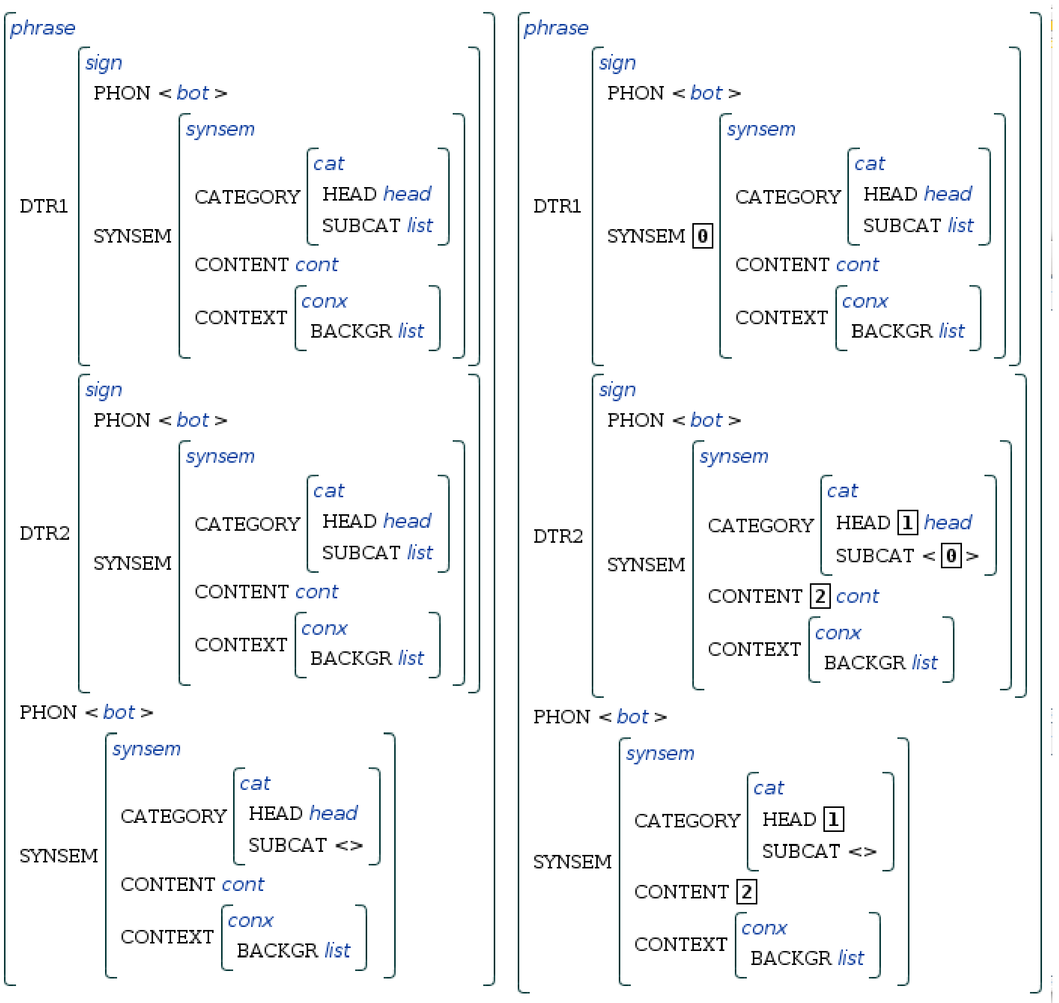


Figure 6.8: Comparison of the signature MGU (left) and the theory MGU (right).

The **copying** operation was easy to implement because the Gralej methods for handling mouse clicks on display panes provide access to the associated `IEntity` objects, which only have to be copied over into a clipboard. This clipboard was simply implemented as a buffer variable that the copied `IEntity` is assigned to. A copy option was also added to the list of structures, allowing structures to comfortably be duplicated.

The **pasting** operation is conceptually a little more difficult than in the case of a string editor or a tree editor. The type hierarchy and the appropriateness conditions make certain structures incompatible, meaning that not every structure can be pasted at every place. Furthermore, at least two different notions of pasting a feature structure at some node in another structure make sense.

The first variant tries to combine the information already present at the node with the information contained in the pasted structure, and can therefore be called **unifying paste**. The name already tells us how this operation is implemented: the substructure at the node into which we paste and the buffered structure that gets pasted are signature-unified, and the result replaces the node into which we paste. If the unification fails, we simply refuse to execute the paste operation, leaving the structure in the clipboard to be pasted elsewhere.

The other variant, which discards the information already present at the node, can be called **replacement paste**. This operation is of course less constrained than unifying paste, but the node at which we paste still has to fulfill conditions. Especially, the type of the pasted structure must be an appropriate value for the feature under which we paste it. For instance, a *case* object should not be allowed to be pasted as the DTR1 value of a *phrase* object.

An important issue in both cases is the treatment of reentrancies in the buffered structure. If a structure already contains a tag with some integer ID, and the structure in the clipboard also contains tags with the same ID, then a naive paste operation introduces spurious path identities that were not part of either structure. This is also necessary for correctly implementing unification of `IEntity` objects, and is resolved by applying **alpha conversion** (variable renaming) to the second argument. The unifying paste relies on a correct implementation of unification and therefore already handles this situation. However, the replacement paste operation must be preceded by an explicit alpha conversion, for which the corresponding part of the unification code can be reused.

Both pasting operations were made accessible via the context menu for nodes in feature structures. The two pasting options are only active if a buffered structure is in the clipboard. Lists again receive special treatment by allowing the buffered structure to be pasted as a new list element, permitting contents to be pasted into lists without overwriting or unifying with an existing list element. A paste option was also added to the list of structures, allowing the contents of the clipboard to be added to the workbench as a new structure.

6.6 The Standalone Feature Workbench

The resulting version of the feature workbench is already a useful tool for grammar inspection, provided that it has access to a `TraleSLDSignature` and an `AuxiliaryTraleInstance`. While both of these can come from a TRALE process from which a debugger instance was started, it is also possible to start an `AuxiliaryTraleInstance` thread, to tell it which grammar to compile, and then to extract the relevant `TraleSLDSignature` from the embedded TRALE instance. To achieve this, a recursive signature readout can be performed by systematically generating and executing signature-related queries. This readout method was implemented and wrapped into a method of the `AuxiliaryTraleInstance`, which builds a `TraleSLDSignature` object, but takes some time to execute.

If the user is allowed to control which theory (and signature) is loaded and serves as the basis for the editing steps, the workbench can be used without running an instance of the Kahina-based TRALE debugger. This leads to a lean **standalone workbench** application which only relies on a few Kahina core classes for feature structure data and window management, but does not need to communicate with a Prolog tracer.

In order to make this workbench more flexible, options were provided for loading only a signature file, for compiling different theories and for recompiling the current theory e.g. after changes were made to the source files. All this functionality could straightforwardly be added to the workbench, because the necessary operations are accessible as user-level predicates in the embedded TRALE instance. The feature workbench menu was extended by menu items for all these interactions, including theory and signature recompilation.

During signature-enhanced editing, an elementary decision such as a type specialization can have large consequences for the overall structure. This is potentially confusing especially for the novice user, so it is helpful to provide contextual information on the reasons for the changes triggered by elementary editing operations. To better explain the consequences of editing operations, the signature visualization components developed in Chapter 4 were added to the standalone workbench in a second window, which helps the user to understand these effects by displaying context-dependent type information.

While various inspection and manipulation tasks are performed, there is almost always a context structure with a **context type** at the center of interest. During editing, this would be the type of the structure being modified, but it can also be the type of a newly loaded feature structure, or one of the types causing the failure of a MGU computation.

The signature visualization can be run in an **interactive mode**, where it always displays the type information for the context type, and is updated whenever the context type changes. In this mode the user automatically receives some information of relevance for the editing decisions, without having to spend time consulting external sources of information.

On the other hand, a signature view with information that changes after every selection or edit is potentially confusing or even annoying, especially when the user needs information beyond the context type. Depending on the usage scenario, the user might want to directly control the information displayed in the signature view, using the signature view more like a separate **help system** while inspecting structures.

As the main task of the signature visualization in the standalone workbench is to display information in parallel with the editor component, it is set to the interactive mode by default.

6.7 Integration with the Kahina-based SLD

The feature workbench was originally intended not as a standalone tool, but as an extension to the Kahina-based TRALE debugger. The main advantage of this variant over the standalone version is that any structure displayed in the debugger is then accessible to the workbench, supporting the workflow of making minimal changes to intermediate structures in order to examine interactions.

The flexible nature of the Kahina platform made it easy to integrate the standalone workbench into the debugger, though some time had to be invested into developing a reliable concept for message exchange. The workbench was integrated as an additional global view component, but it had to be given a status slightly different from the other global views.

The `AuxiliaryTraleInstance` it controls makes it a rather heavy-weight component that should not be duplicated, so the new category of a unique global view (for which only one instance may exist) had to be added to the Kahina architecture.

The signature visualization was added to the default debugger as a normal global view component. In the prototype, the signature view is put into help system mode when structures outside of the workbench are inspected, but in accordance with the considerations from Section 6.6, it switches to the interactive mode when used in parallel with the feature structure editor.

In order to permit copying feature structures from the non-editable views to the workbench, a class deriving from the standard Gralej display panel was extended to add a one-item context menu for the purpose. The workbench's clipboard was made addressable via the `KahinaController`, allowing copied structures to be transmitted from the debugger's display components to the workbench via newly introduced event types.

6.8 Unresolved Issues of the Prototype

The workbench implementation sketched in this chapter still has some problems that detract from its usefulness. This section deals with those issues that result from weaknesses of the adopted architecture and of the underlying software components. The discussion also covers design alternatives and possible solutions to these issues.

One problem is that the structures generated by Evang's portraying code do not contain all the relevant information. In particular, the **residue**, a set of relations which is passed to the pretty-printing code along with a feature structure for display, is not evaluated during conversion. The residue contains information on both path inequations and relational descriptions such as `append/3` relations between nodes. Gralej includes view components for displaying both components of a residue, but Evang's code does not cover their resolution. This issue must unfortunately remain unresolved for now, because the time that would have been necessary for furrowing into the undocumented internals of the ALE code by far exceeded the time available for this work.

Another issue is the lack of feedback when theory unification fails. In the case of signature unification, the naive implementation of unification on `IEntity` objects generates very useful and transparent error messages that can be displayed in a message panel. Unfortunately, there is currently no way to receive detailed information on failed theory MGU operations, because the embedded TRALE instance is configured to output its error messages to a console. Addressing this problem would also require massive changes to the ALE system.

One would expect that the combination of copying, pasting, and theory MGS computation suffices to emulate complete parsing processes. Consider the case of *she walks* in our demo grammar. First, get the elementary building blocks by generating the type MGS for *phrase*, and retrieving the feature structures for the lexical entries *she* and *walks*. Then, copy and paste the lexical entries into the DTR1 and DTR2 values of the *phrase* object. Running the theory MGS operation over this structure and applying the `subject_head_rule` from the theory would lead to a complete parse for the sentence. However, as discussed in Section 6.4, the special status of phrase structure rules in TRALE as opposed to other constraints prevents the PHON values of the daughter nodes from being appended to yield the mother's PHON value. Therefore, the MGS operation shows whether the structure is licensed, but it does not apply the phrase structure rules. I consider this the most severe shortcoming of the workbench in comparison to the envisioned functionality. In principle, it is possible to add support for manually applying phrase structure rules, but this will again require intimate knowledge and possibly severe modifications of the ALE system's internals.

Further problems of the prototype are rooted in some parts of the software architecture that have evolved to be rather unprincipled ad-hoc solutions. For instance, relying on Gralej's internal format for feature structure manipulation turned out to be cumbersome in many places (especially in reentrancy handling), and developing an easier-to-manipulate feature structure representation format encoding only the properties relevant for editing could be cleaner. On the other hand, this would introduce additional overhead for translations to and from the Gralej format for display, further adding to the already considerable architectural complexity.

One of the strengths of the current design is that not a single change to the Gralej source code had to be made. The prototype therefore not only clearly fulfills the goal of not introducing any dependency on Kahina intro Gralej, but it also keeps the entire editing logic on the Kahina side, keeping Gralej clean and easy to use for display-only purposes.

Unfortunately, these advantages in modularity come at a cost. The editor shows some jerky behavior caused by the fact that it was implemented using only a thin layer of interaction logic on the existing view component, sometimes exposing viewer-specific functionality that has some potential of confusing the user. For example, the context menus in the editor are opened via a click on the left mouse button, whereas the more intuitive right mouse button gives access to a Gralej-specific context menu that has no purpose in the editor. These effects could be removed with some effort, but more principled ways of handling the interface between the editing and display components might be more promising as a foundation for a more stable system.

The current implementation of the integrated workbench relies on an architecture which compromises stability. Integrating the workbench and thereby the `AuxiliaryTraleInstance` with the Kahina-based SLD leads to an architecture where a SICStus process runs within a JVM that is created as part of another SICStus process. The main problem in this situation is the low-level Jasper interface between the SICStus processes and Kahina's Java classes. The two-layer SICStus Prolog memory manager is separated into a top layer providing standard memory allocation methods, and a bottom layer which constitutes the interface to the underlying operating system. SICStus is normally able to use the whole virtual address space, but some of its memory blocks are address-constrained, forcing them to fit within an architecture-specific memory range (for instance, 256 MB on most 32-bit platforms). Some of these address-constrained blocks are necessary for startup. Therefore, if one SICStus instance is already running, the required memory range tends to be unavailable for starting a second SICStus instance. On many variants of Linux, setting the environment variable `PROLOGMAXSIZE` to a value lower than 256 MB does away with the problem, but unfortunately, this depends rather much on the system architecture and configuration, and cannot be relied on in a system for wide deployment. The integration of the feature workbench with the Kahina-based debugger could only be implemented and tested using this environment variable as a temporary solution.

Even though the standalone workbench reliably runs without such tricks, it is not without problems either. TRALE is designed to be started from the directory where the grammar files reside, which carries over to the embedded instance. Handing on theory file paths that point to other directories is therefore difficult, and still leads to mysterious errors. For the moment, the feature workbench therefore needs to be started from the grammar file directory, which again requires careful control of the Java environment. In a release version of the feature workbench, this configuration effort will have to be minimized.

Altogether, the current version of the feature workbench can only be assigned the status of an early prototype, unlike the much more mature software components discussed in Chapters 4 and 5. Nevertheless, as we have seen, it includes the bulk of the functionality envisioned for a feature workbench.

6.9 Discussion

In this section, the workbench prototype is examined once again from a less implementation-specific perspective. The focus therefore is on architectural design decisions that are not directly connected to the underlying components. Some remaining conceptual gaps in the current user interface are discussed along with ideas how they could be filled. The chapter concludes with a perspective on how the architecture could be further developed.

Aside from the caveats concerning system stability, the current workbench prototype is fully functional. It can be used to store feature structures of interest during a parsing process, and it allows the user to use these structures as starting points for exploring the constraint interactions in the grammar. Small changes can be made to see whether constraints and appropriateness conditions are still fulfilled, and the consequences of total well-typedness are a lot more transparent than before, because they are separated from the consequences of the constraints in the theory. This often makes it possible to quickly narrow down the reasons for undesired behavior to one part of the grammar specification.

Having full-blown MGS computation available from the user interface opens up possibilities for further accelerated editing, as one could use an auxiliary theory over a custom signature to fill in underspecified details, leading to a type of editing macros. For instance, by defining a type *np* and a theory expanding this to a skeleton structure for an HPSG representation of a noun phrase, one could simply create a structure of type *np* during editing, and then call the theory MGS operation to flesh this out. Such a macro mechanism could speed up feature structure processing even more.

To reduce complexity, the current version of the editor displays feature structures very explicitly, tending to clutter a lot of screen space with information that is often not very relevant to the user. The adopted policy of always resolving structures of form *mgsat(type)* has certainly not improved the situation. It is very probable that in practice, one will need to provide automated collapsing facilities, expanding *mgsat(type)* only on demand, and allowing the user to define patterns for uninteresting detail to be hidden.

The current simple menu listing all the lexical entries can only be a temporary solution for toy grammars, since we will want to cover theories that define a wide range of lexical entries. In the future, lexical entries should therefore be selected via a selection window which allows keyboard input as well as selecting an entry from a browsing component representing the entire space of lexical entries. Furthermore, TRALE includes a mechanism for specifying **lexical rules**, which are especially important for avoiding redundancy in grammars for morphologically rich languages. One will therefore want to add functionality that provides access to these rules. Ideally, this would include the option of manually applying lexical rules in order to generate derived lexicon entries, and also to inspect the consequences of lexical rules in a way similar to the the implemented operations on feature structures.

The current version of the feature workbench puts considerable strain on the Kahina architecture, and it is not easy to get to run on every platform because of various environment variables and even some operating system-specific behavior. As a result, we have a Java system that heavily depends on a well-configured installation of a specific version of SICStus Prolog, correct versions of about a dozen libraries on the classpath, as well as certain properties of the respective memory management system. For a wider deployment of the system, the architecture will have to be made more robust against changing circumstances. Whereas running the standalone feature workbench in parallel to Kahina can be an acceptable workaround in case of memory management problems, a more integrated system with less unstable interfaces would be highly attractive.

Two approaches seem to be feasible in order to achieve a more robust architecture. One possibility would be to forfeit the Jasper interface and rely on inter-process communication via sockets instead. This would be closer to the principles of pragmatic software engineering, but it would require substantial changes to large parts of the implementation, and it would probably result in a noticeable decline in performance as well as interface responsiveness.

Alternatively, one could integrate Kahina with a Java Prolog engine that has all the features and is optimized enough to run the TRALE system with reasonable response times. While current implementations are not quite at that level of performance yet, it is not unlikely that e.g. JIProlog by Chirico (2011) will fulfill these requirements in the near future. Without the Java-Prolog interface as a bottleneck, this approach could lead to much better performance and open up new possibilities for even more interactivity in grammar development.

A possible future extension of the standalone workbench would include a bridge-like interface to a second embedded TRALE instance which also supports debugging of parses. Much of the existing `TraleSLDBridge` code could be reused for this bridge, only the Prolog-side interface would have to be restructured. The workbench could thereby serve as a basis for a **control-inverted** variant of the current Kahina-based TRALE debugger, where the Kahina-based debugger would not any longer be started from the TRALE console. Instead, Kahina would turn into a complete frontend which can create embedded TRALE instances to execute parses. This would also help to solve the problem that phrase structure rules are not enforced by the theory MGS and MGU operations, meaning that hypothetical evaluation via partial reparses could be fully supported.

Chapter 7

Conclusion and Outlook

In this last chapter, the results of the thesis are summarized and put into a broader context. Section 1 recapitulates the main results with a focus on the newly developed software components, and Section 2 presents desirable future extensions and improvements of this new infrastructure. Section 3 discusses the contribution of this work to remedying the issues of grammar engineering discussed in Chapters 2 and 3. This discussion extends to a more abstract perspective on the significance of this work for symbolic NLP systems in general. Section 4 then gives an overview of future developments of the Kahina environment, and explains how they relate to the work done in this thesis.

7.1 Overview of the New Infrastructure

The first part of this thesis was devoted to the current state of the art in symbolic grammar engineering. Chapter 2 introduced the traditional auxiliary tools for grammar development in the TRALE system, which are centered around a console-based source level debugger and therefore focussed on exposing the internals of parsing processes. Chapter 3 investigated the graphical tools offered by other grammar development platforms to support large-scale engineering, which enable a more interactive debugging workflow, but do not give access to the same amount of detail. Kahina, a new architecture for graphical debugging in NLP, demonstrates how the advantages of both approaches can come together in a graphical source level debugger. Building on the Kahina architecture, four major new pieces of grammar engineering infrastructure for the TRALE system were developed in this thesis.

In Chapter 4, a signature view component inspired by Javadoc was developed in order to give quick access to all the relevant information contained in a TRALE signature, which includes both the type hierarchy and the appropriateness conditions. In contrast to previous approaches, the visualization does not attempt to render the entire type hierarchy as a graph structure, but presents the information as a collection of very compact linked hypertext documents. The component is very economical in its use of screen space, making it attractive for deployment as part of larger systems.

The feature structures previously occurring only as results of parsing processes have been made efficiently manipulable by the introduction of a signature-enhanced AVM editor in Chapter 5. The editor supports multiple editing modes which differ in the extent to which appropriateness conditions are enforced. The strictest editing mode is based on a set of operations which enforce total well-typedness. Formal results in Section 5.5 show that the entire space of totally well-typed structures over a given signature is accessible via these operations, and that only totally well-typed structures can be produced.

The next important piece of new infrastructure is the `AuxiliaryTraleInstance` class, which is run as a separate thread to give a Kahina instance (or in fact, any Java program) control over an embedded TRALE instance, thereby providing a platform for using TRALE functionality within a Java program. The `AuxiliaryTraleInstance` class currently provides convenience methods for computing most-general satisfiers and unifiers against a theory, for retrieving lexical entries, and for retrieving signature information.

Finally, all the new components were combined into a feature workbench in Chapter 6. The workbench is built around a collection of feature structures that can be constructed from scratch via the signature-enhanced editor, assembled from elementary building blocks that are extracted from the embedded TRALE instance, or imported from GRISU files. Elementary steps of TRALE computations (unification and MGS computation) are offered as manually executable operations on feature structures. All of these operations are made accessible in a signature and a theory variant, allowing the user to inspect the consequences of appropriateness conditions and constraints in separation. During structure manipulation, the new signature view component acts as a help system that provides information on the types being modified. The workbench prototype can be used as a standalone tools, but it was also integrated with TRALE's Kahina-based debugger, allowing structures from the debugger's feature structure and variable binding views to be copied into the workbench.

7.2 Possible Extensions and Improvements

Already in the original Kahina, handling errors on the Prolog side is a problem. To receive feedback for erroneous input, the user is forced to look at the console from which Kahina was started. In case the error has caused the tracer to abort, Kahina has to be restarted, leading to loss of the stored step information. Error handling within the `AuxiliaryTraleInstance` is even less satisfactory because the embedded SICStus instance is not started from a console, which leaves no way at all to receive error feedback. Fortunately, errors on the Prolog side have less dire consequences than during tracing because every user action only leads to one query on the embedded TRALE prompt, whose failure does not disrupt the embedded TRALE instance and allows the `AuxiliaryTraleInstance` to proceed. However, channeling the invisible console output produced by the embedded TRALE instance back into the workbench would still be a very useful extension. In addition to improved error handling, this would also make it possible to give precise feedback in case a theory MGU computation fails.

Instead of only showing the consequences of the signature and of the theory separately, one could further increase the modularity of grammar inspection and debugging by making it possible to dynamically activate or deactivate elements of the theory. This would give access to the influence of individual rules and constraints on feature structures. Selective application could easily be implemented by generating an auxiliary theory out of the selected rules and constraints, and compiling this auxiliary theory before computing theory MGSs and theory MGUs. Generation of such auxiliary theories would not even require a sophisticated parser, but it could be done rather superficially by identifying the line spans belonging to rule headings, and assembling impoverished theories out of such line spans.

This could also lead to a much improved feedback mechanism. A grammar engineer will often know exactly which feature structure the grammar is supposed to license as the representation of a word or a phrase. As discussed in Chapter 3, even with a graphical debugger it is difficult to answer the question why exactly a desired structure is not licensed. This task could be made much easier by running individual rules or rule sets on a constructed feature structure, and receiving feedback on which constraints the structure violates. With the infrastructure developed for this thesis, this kind of a feedback mechanism is no longer out of reach, and would only require a few more weeks of development effort.

Once the current state of the system has somewhat matured, it could be worthwhile to think about future innovative uses of the interactive feature structure editor. From the perspective of a linguist, being able to define rules and principles of an HPSG grammar in a format close to the AVM notation would be a huge advantage. The TRALE description language is not particularly difficult to learn, but it requires the user to often switch mentally between a specification format and an output format. These two representations could be unified by offering a graphical rule editor based on the implemented AVM editing functionality. Exclusively offering a graphical editor for stuctures and rules as in the XTAG system has turned out far too restrictive for advanced users. However, providing the novice user with the alternative option of specifying constraints and lexical entries graphically could be a huge step forward in the endeavor to motivate HPSG researchers to implement and verify their theories. What once was only intended as a debugger would then be extended to a full-blown graphical development environment.

7.3 Relevance to Grammar Engineering

The prototype of the feature workbench is already a useful tool for analyzing and understanding rule interactions in complex TRALE grammars. While a graphical debugger like the Kahina-based SLD for TRALE is important for understanding in detail what happens during parsing processes, the debugger workflow gives the user only very indirect access to the rule interactions. The workbench gives a grammar implementer the opportunity to test rule interactions without needing to embed them into a parsing run, which makes it a lot easier to observe their effects. The integration of the workbench with the debugger allows the user to alternate between the two workflows, analysing problems that are detected during parsing in the workbench, and testing the solutions developed with the help of the workbench by parsing sentences with the debugger.

From a wider perspective, making it easier to explore rule interactions has a lot of potential for advancing linguistic theories. The insularity problem of grammars developed on paper can best be remedied by large-scale implementations, which are the closest one can get to putting a comprehensive theory to the test. Advanced tools for detecting rule interactions make such implementations a lot more fruitful for the theorist because grammar optimization can be performed closer to the linguistic concepts than using a classical debugger. This promises to help because a linguist is usually not interested in the internals of a system's parsing algorithm, but he is well-trained to think declaratively in terms of rules.

The new possibilities for symbolic grammar engineering which could result from more mature implementations of this workbench philosophy might one day contribute to a renaissance of linguistic knowledge in natural language processing. Furthering the understanding of rule interactions might help to bring symbolic grammar engineering into a position where larger grammars become easier to develop, perhaps even competing with purely statistical methods in terms of useful coverage.

In this thesis, techniques and tools were mainly developed in the context of implementing theories of syntax, but the infrastructure could be of equal value to the study of semantics. For formalisms such as MRS (Minimal Recursion Semantics) by Copestake et al. (2005) or LRS (Lexical Resource Semantics) by Richter and Sailer (2004), which encode semantic information in feature structures, the workbench is useful already in its present form because it allows to efficiently construct terms in these formalisms. A lot more could be gained by an adapted workbench which exposes not only unification and MGS computation as tools, but also complex operations specific to the respective formalism, e.g. composition and resolution in the case of MRS. To test the correctness of entries in a semantic lexicon, it would then no longer be necessary to start a parsing process, and the interactions e.g. between lambda terms, which tend to be even more complicated than those between syntactic rules, could be determined much more efficiently. This could speed up the development of semantic databases, making a small contribution to the advancement of wide-coverage deep semantics.

7.4 Future Work

An interesting development in the context of Kahina is that it is currently being adapted to a second typed feature logic grammar implementation system. QType, developed at the University of Düsseldorf, has been in internal use there for many years, but it is still not publicly available. The QType system serves as our test case for evaluating whether the Kahina architecture is as flexible as intended. The core components have proven to be very robust against QType's peculiarities, and convenience functionality is currently being added to the resulting Kahina-based QType debugger, with the goal of achieving about the same level of integration as with TRALE.

For this purpose, Kilian Evang has already implemented a translation module from QType's internal feaure structure format to GRISU, allowing Gralej to be used for elegant feature structure visualization here as well. It will be interesting to see with how much effort the new feature structure editor as well as the feature workbench can be adapted to QType's version of typed feature logic.

If this turns out to work as smoothly as we hope, it would be feasible to extend Kahina by an interface for plugging in implementations of custom feature logic variants, possibly arriving at a system that could also be applied to the needs of e.g. the LFG community, with the potential of offering an alternative and more modern graphical interface for the somewhat dated Xerox Workbench (see Kaplan and Maxwell, 1996).

A task that could not be accomplished within the scope of this thesis is the evaluation of the new tools under real-life conditions. The first people confronted with the new version of Kahina will probably be the next generation of Tübingen students of grammar engineering. These students are doubtlessly going to have many suggestions for improving the prototype. The user interfaces are especially likely to receive a lot of streamlining and workflow improvements based on this feedback.

In a second phase, Kahina should then be presented to experienced TRALE users in order to evaluate its fitness for large-scale applications. Given our experiences with presenting previous prototypes of Kahina to this clientele, it seems that convincing these users to experiment with a new version of the Kahina-based debugger would not be difficult. The valuable feedback from these long-time TRALE users would then help Kahina to realize its potential as a next-generation grammar development environment.

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Appendix A

The demo signature

The following signature is used as the running example throughout this thesis. It originally belongs to the last introductory example (Grammar 4, Version 3) in Richter (2005). Here, the signature is presented in TRALE signature file format, whereas Figures 4.1 and 4.2 show it in other formats.

```
type_hierarchy
bot
  list
    ne_list hd:bot tl:list
    e_list
  sign phon:ne_list synsem:synsem
    phrase dtr1:sign dtr2:sign
    word
  synsem category:cat content:cont context:conx
  cat head:head subcat:list
  head
    noun case:case
    verb vform:vform
  vform
    fin
    bse
  case
    nom
    acc
    dat
  cont
    nom_obj index:index
    arg
      index
      relations arg1:arg
        un_rel
          walk_rel
          female_rel
          speaker_rel
        more_arg_rel arg2:arg
          bin_rel
            love_rel
            think_rel
          give_rel arg3:arg
  conx backgr:list
  index person:person number:number gender:gender
  person
    first
    third
  number
    sing
    plur
  gender
    masc
    fem
```

Appendix B

The demo theory

The following theory file is used for the examples in the discussion of the feature workbench in Chapter 6. Together with the demo signature from Appendix A, it originally constitutes the last introductory example (Grammar 4, Version 3) in Richter (2005).

```
% Grammar 4c
% ==========

% specifications for the GRALE output display
hidden_feat(dtr1).
hidden_feat(dtr2).

% specify signature file
signature(signature).

% lexical entries

i ---> (word,
        phon:[(a_ i)],
synsem:(category:(head:case:nom,
                            subcat:e_list),
                  content:(index: (X,(person:first,
                                      number:sing))),
                  context:(backgr:[(speaker_rel,arg1:X)]))).

me ---> (word,
         phon:[(a_ me)],
 synsem:(category:(head:case:(acc;dat),
                             subcat:e_list),
                   content:(index: (X,(person:first,
                                       number:sing))),
                   context:(backgr:[(speaker_rel,arg1:X)]))).

she ---> (word,
          phon:[(a_ she)],
  synsem:(category:(head:case:nom,
                            subcat:e_list),
                  content:(index: (X,(person:third,
                                      number:sing,
                                      gender:fem))),
                  context:(backgr:[(female_rel,arg1:X)]))).

her ---> (word,
          phon:[(a_ her)],
  synsem:(category:(head:case:(acc;dat),
                             subcat:e_list),
                   content:(index: (X,(person:third,
                                       number:sing,
                                       gender:fem))),
                   context:(backgr:[(female_rel,arg1:X)]))).

milk ---> (word,
           phon:[(a_ milk)],
   synsem:(category:(head:noun,
                            subcat:e_list),
                   content:(index:(person:third,
                                   number:sing)),
   context:backgr:[])).

walk --->  (word,
            phon:[(a_ walk)],
   synsem:(category:(head:vform:fin,
                             subcat:[(category:(head:case:nom),
                                      content:index:(X,
                                                     person:first,
                                                     number:sing)
                                                     )]),
                   content:(walk_rel,
                            arg1:X),
   context:backgr:[])).

walks --->  (word,
             phon:[(a_ walks)],
     synsem:(category:(head:vform:fin,
                             subcat:[(category:(head:case:nom),
                                      content:index:(X,
                                                     person:third,
                                                     number:sing)
                                                     )]),
                   content:(walk_rel,
                            arg1:X),
   context:backgr:[])).

love ---> (word,
           phon:[(a_ love)],
   synsem:(category:(head:vform:fin,
                             subcat:[(category:(head:case:nom),
                                      content:index: (X,
                                                      person:first,
                                                      number:sing)),
                                     (category:(head:case:acc),
                                      content:index: Y)]),
                   content:(love_rel,
                            arg1:X,
                            arg2:Y),
   context:backgr:[])).

loves  ---> (word,
             phon:[(a_ loves)],
     synsem:(category:(head:vform:fin,
                             subcat:[(category:(head:case:nom),
                                      content:index: (X,
                                                      person:third,
                                                      number:sing)),
                                     (category:(head:case:acc),
                                      content:index: Y)]),
                   content:(love_rel,
                            arg1:X,
                            arg2:Y),
   context:backgr:[])).

give ---> (word,
           phon:[(a_ give)],
   synsem:(category:(head:vform:fin,
                             subcat:[(category:(head:case:nom),
                                      content:index: (X,
                                                      person:first,
                                                      number:sing)),
                                     (category:(head:case:acc),
                                      content:index: Y),
                                     (category:(head:case:dat),
                                      content:index: Z)]),
                   content:(give_rel,
                            arg1:X,
                            arg2:Y,
                            arg3:Z),
   context:backgr:[])).

gives --->  (word,
             phon:[(a_ gives)],
     synsem:(category:(head:vform:fin,
                             subcat:[(category:(head:case:nom),
                                      content:index: (X,
                                                      person:third,
                                                      number:sing)),
                                     (category:(head:case:acc),
                                      content:index: Y),
                                     (category:(head:case:dat),
                                      content:index: Z)]),
                    content:(give_rel,
                            arg1:X,
                            arg2:Y,
                            arg3:Z),
     context:backgr:[])).
```

```
think  --->  (word,
              phon:[(a_ think)],
      synsem:(category:(head:vform:fin,
                               subcat:[(category:(head:case:nom),
                                       content:index: (X,
                                                       person:first,
                                                       number:sing)),
                                       (category:(head:vform:fin,
 subcat:[]),
                                       content: Y)]),
                    content:(think_rel,
                             arg1:X,
                             arg2:Y),
    context:backgr:[])).

thinks --->  (word,
              phon:[(a_ thinks)],
      synsem:(category:(head:vform:fin,
                               subcat:[(category:(head:case:nom),
                                       content:index: (X,
                                                       person:third,
                                                       number:sing)),
                                       (category:(head:vform:fin,
 subcat:[]),
                                       content: Y)]),
                    content:(think_rel,
                             arg1:X,
                             arg2:Y),
    context:backgr:[])).


% phrase structure rules
subject_head_rule rule
(phrase,
 phon:MotherPhon,
 synsem:category:subcat:[],
 dtr1:Subj, dtr2:Head)
   ===>
cat> (Subj, phon:SubjPhon),
cat> (Head, phon:HeadPhon),
goal> phon_append(SubjPhon,HeadPhon,MotherPhon).

head_complement_rule rule
(phrase,
 phon:MotherPhon,
 synsem:category:subcat:ne_list,
 dtr1:Comp, dtr2:Head)
   ===>
cat> (Head, phon:HeadPhon),
cat> (Comp, phon:CompPhon),
goal> phon_append(HeadPhon,CompPhon,MotherPhon).
```

```
% Principles

% Semantics Principle
phrase *> (synsem:content:C,
   dtr2:synsem:content:C).

% Head Feature Principle
phrase *> (synsem:category:head:H,
   dtr2:synsem:category:head:H).

% Subcategorization Principle
phrase *> (synsem:category:subcat:PhrSubcat,
           dtr1:synsem:Synsem,
           dtr2:synsem:category:subcat:HeadSubcat)
goal
   append(PhrSubcat,[Synsem],HeadSubcat).


% Goal definitions

phon_append([],[],[]) if !, true.
phon_append([],[H|T1],[H|T2]) if phon_append([],T1,T2).
phon_append([H|T1],L,[H|T2]) if phon_append(T1,L,T2).


append(X,Y,Z) if
   when(  ( X=(e_list;ne_list)
%         ; Y=e_list
%         ; Z=(e_list;ne_list)
              ),
            undelayed_append(X,Y,Z)).

undelayed_append(L,[],L) if true.
undelayed_append([],(L,ne_list),L) if true.
undelayed_append([H|T1],(L,ne_list),[H|T2]) if
  append(T1,L,T2).


app(L,[],L) if true.
app([],(L,ne_list),L) if true.
app([H|T1],(L,ne_list),[H|T2]) if
  app(T1,L,T2).
```

Appendix C

Overview of relevant Java classes

Full names of cited classes

Full class name	**Description**
`gralej.blocks.Block`	Root class of AVM view model.
`gralej.om.IEntity`	Root class of AVM data model.
`gralej.om.IList`	Representing lists in the AVM data model.
`java.lang.ProcessBuilder`	Java class for creating operating system processes.
`org.kahina.core.KahinaInstance`	Central object of a Kahina debugger.
`org.kahina.core.KahinaState`	Root class for step databases.
`org.kahina.core.control.KahinaController`	Central class for message exchange.
`org.kahina.core.gui.KahinaGUI`	Root class of GUI definitions for applications.
`org.kahina.lp.bridge.LogicProgrammingBridge`	Bridge for communication with logic programming systems.
`org.kahina.tralesld.bridge.AuxiliaryTraleInstance`	Access to the auxiliary TRALE instance.
`org.kahina.tralesld.bridge.TraleSLDBridge`	Bridge for communication with a TRALE instance.
`org.kahina.tralesld.data.workbench.FeatureWorkbench`	Data model for the contents of a workbench.
`org.kahina.tralesld.data.fs.TraleSLDFS`	AVMs (wrapper for GRISU strings).
`org.kahina.tralesld.visual.fs.GraleJUtility`	Operations on `IEntity` objects.
`org.kahina.tralesld.visual.fs.VisualizationUtility`	Convenience methods for displaying `TraleSLDFS`s.
`org.kahina.tralesld.visual.workbench.FeatureWorkbenchView`	View model for feature workbench.
`org.kahina.tralesld.visual.workbench.FeatureWorkbenchViewPanel`	Feature workbench GUI.
`se.sics.jasper.SICStus`	Wrapper for the SICStus emulator, interaction code.
`se.sics.jasper.SPTerm`	Root class for Java representation of Prolog terms.

Static methods in `org.kahina.tralesld.visual.fs.GraleJUtility`

Method	Comment
`IEntity changeAtom(IEntity e, List<String> path, String atom, TraleSLDSignature sig)`	swi for atoms
`IEntity delta(IEntity e, List<String> path)`	δ (generalized)
`void fill(IEntity e, TraleSLDSignature sig)`	$Fill$
`IEntity fin(IEntity e, List<String> path, String ty, IEntity val, TraleSLDSignature sig)`	fin (+ paste)
`IEntity fre(IEntity e, List<String> path)`	fre
`IEntity generalizeAtom(IEntity e, List<String> path, TraleSLDSignature sig)`	gez for atoms
`IEntity getType(IEntity e)`	θ
`IEntity gez(IEntity e, List<String> path, String ty, TraleSLDSignature sig)`	gez
`String gralejToGrisu(IEntity e)`	conversion into GRISU
`IEntity grisuToGraleJ(String grisu)`	import from GRISU
`IEntity ids(IEntity e, List<String> path)`	ids
`IEntity itr(IEntity e, List<String> p1, List<String> p2, TraleSLDSignature sig)`	itr
`void purge(IEntity e, TraleSLDSignature sig)`	$Purge$
`IEntity replacePaste(IEntity e, List<String> path, IEntity pasted, TraleSLDSignature sig)`	replacement paste
`IEntity sigMGS(String ty, TraleSLDSignature sig)`	signature MGS
`IEntity sigMGU(IEntity e1, IEntity e2, List<String> p1, List<String> p2, TraleSLDSignature sig)`	signature MGU
`IEntity spz(IEntity e, List<String> path, String ty, TraleSLDSignature sig)`	spz
`IEntity swi(IEntity e, List<String> path, String ty, TraleSLDSignature sig)`	swi
`void ttf(IEntity e, TraleSLDSignature sig)`	ttf
`void typInf(IEntity e, TraleSLDSignature sig)`	$TypInf$
`IEntity unifyPaste(IEntity e, List<String> path, IEntity pasted, TraleSLDSignature sig)`	unifying paste

Methods of `org.kahina.tralesld.bridge.AuxiliaryTraleInstance`

Method	**Comment**
`boolean compileGrammar(String fileName)`	lets the embedded TRALE instance compile a grammar file; true if successful
`String descToMgsGrisu(String descString)`	computes the theory MGS of a description string; in GRISU format
`void discardGrammar(String fileName)`	lets the embedded TRALE instance discard the compiled grammar
`String entsToMguGrisu(IEntity e1, IEntity e2)`	computes the theory MGU of two AVMs; in GRISU format
`String entToMgsGrisu(IEntity e)`	computes the theory MGS of an AVM; in GRISU format
`TraleSLDSignature getCurrentSignature(IEntity e)`	extracts the current signature from the embedded TRALE instance
`String getLemmata()`	returns the lemmata of the current theory separated by colons
`TraleSLDSignature getSignature(String fileName)`	extracts a signature from a signature file using the embedded TRALE instance
`String lexEntryGrisu(String lemma)`	retrieves the first lexical entry for the lemma; in GRISU format
`void run()`	starts the embedded TRALE instance (during initialization)