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Master's thesis

Implementation of a type-safe generalized syntax-directed editor

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Abstract

This is my abstract

Contents

Chapter 1

Introduction

This project explores the implementation of a generalized, type-safe structure editor, based on a proposed calculus[1].

The report is structured as follows:

- The rest of this chapter provides a brief overview of prior work, including structure editors, editor generators and partial evaluation, which are relevant to the project.
- Chapter 2 presents a summary of abstract syntax, as described by Harper[6], which is a central part of the editor calculus proposed by [1], both subjects inherently playing an important role in the implementation of the editor.
- Chapter 3 describes the implementation of the editor, from parsing abstract syntax to generating source code for an editor instance.
- Chapter 4 provides examples of the editor in use for different languages, demonstrating the editor's generic nature.
- Chapter 5 concludes the report, summarizing the project and suggesting future work.

1.1 Prior work

Following is an overview

1.1.1 Structure editors

Structure editors provide a way to manipulate the abstract syntax structure of programs directly, in contrast to writing and editing source code of a program in plain text, which also requires a parser to produce an abstract syntax tree. An early example of this is the Cornell Program Synthesizer by Reps and Teitelbaum[18] in 1981. By using a structure editor, the user can avoid syntax errors and might have a better overview of their source code. Moreover, unfinished blocks of code can be represented by syntactic holes, allowing the programmer to develop a mental model of their code, without getting distracted or blocked by syntax errors.

However structure editors like the Cornell Program Synthesizer[18] allow programmers to create syntactically ill-formed programs. This includes introducing use-before-declaration statements, as the editor cannot manage context-sensitive constraints within the syntax.

In 2017 Omar et al. introduced Hazel[14], a programming environment for a functional language with typed holes, which allows for evaluation to continue past holes which might be empty or ill-formed. The motivation for this work is to provide feedback about a program's dynamic behaviour as it is being edited, in contrast to other programming languages and environments which usually only assign dynamic meaning to complete programs. In other words, the Hazel environment[14] provides feedback on programs, even if they are ill-formed or contain type errors. This is possible by surrounding static and dynamic inconsistencies with typed holes, allowing evaluation to proceed past holes.

The Hazel environment is based on the Hazelnut structure editor calculus, defined by operational semantics, that allow finite edit expressions and inserts holes automatically to guarantee that every editor state has some type.

Hazel itself is not a structure editor, however the core calculus supports incomplete functional programs, also referred to as "holes", which are a central part of the work of Godiksen et. al [4]. They introduced a type-safe structure editor calculus which manipulates a simply-typed lambda calculus with the ability to evaluate programs partially with breakpoints and assign meaning to holes. It also ensures that if an edit action is well-typed, then the resulting program is also well-typed. The editor calculus and programming language have later been used to implement a type-safe structure editor in Elm[**KU-bach-missing-ref**].

1.1.2 Editor generators

A common property of the editor calculi and editors mentioned so far is that they are built to work with only one programming language. The calculi are strongly dependent on the language they can manipulate, and if the language were to change, it could require re-writing the complete editor calculus. A solution to this problem is editor generators.

A few years after presenting the Cornell Program Synthesizer, Reps and Teitelbaum also presented The Synthesizer Generator[17] in 1984, which creates structure editors from language descriptions in the form of attribute grammar specifications.

Another example is the Centaur system[2], which takes formalism described in the Metal language[12], a collection of concrete syntax, abstract syntax, tree building functions and unparsing (a.k.a. pretty-printing) specifications. The abstract syntax is made of operators and *phyla*, where operators label the nodes of the abstract trees and are either fixed arity or list operators. Operators are defined as having *offsprings*, where fixed-arity operators can have offsprings of different kinds, whereas offsprings of list operators must be of the same kind. This concept is formalized by the concept of *phylum*, where *phyla* (plural of *phylum*) are sets of operators, describing what operators are allowed at every offspring of an operator. In other words, phyla constrain the allowed operators in every subtree of either a non-null fixed arity operator or a list-operator. Each operator-phylum relation is used to maintain syntactically correct trees. This definition of operators and phyla in Metal strongly relates to Harper's definition of abstract syntax[6] in the form of sorts, arity-indexed operators and variables. Operators in both definitions represent a node in an abstract syntax tree and having an associated phyla or being arity-indexed serves the same purpose of constraining the possible children of each node, hence maintaining syntactically correct trees.

However, the Centaur system[2] lacks a dedicated type-safe editor calculus. Such a type-safe generalized editor calculus has been proposed by [1], which is a generalization of the work of Godiksen et al. [4]. The generalized editor calculus takes abstract syntax in the form of sorts, arity-indexed operators and variables, as described by Harper[6].

1.1.3 Partial evaluation

One of the goals of this project is to implement a generic syntax-directed editor based on the editor calculus proposed by [1]. Implementing such a generic editor relates to the question of how to balance between generality and modularity, brought up by Neil D. Jones[11] in the context of program specialization. If we are presented with a class of similar problems, such as instantiating a syntax-directed editor for different languages, one might consider two extremes: either write many small, but efficient, programs or write a single highly *parametrized* program which can solve any problem.

The first approach is very modular and has the advantage of allowing the programmer to focus solely on performance for every smaller program, but it has an obvious disadvantage of being hard to maintain. Highly modular programming might also lead to performance overhead in terms of passing data back and forth between programs and converting among various internal representations.

The second approach is general and has the advantage of being easier to document and maintain, due to it being a single program. However, it is arguably not well-performing, as some amount of time needs to be spent interpreting the parameters instead of the actual problem-solving computation.

Using a partial evaluator[10] to specialize a highly parametrized program into smaller, customized versions, is arguably a better solution than both approaches. This way, only one single program requires maintenance, while allowing it to be specialized, taking advantage of program speedup.

The notion of partial evaluation in terms of program specialization[10] includes a partial evaluator, which receives a general program and some static input, resulting in a specialized program that, if specialized in a meaningful way, performs better than the original program. An example provided by Jones is a program computing x^n (program p in listing 1.1), which can be specialized to having $n = 5$ (program p_5 in listing 1.2), unfolding the recursive calls and reducing $x * 1$ to x. Formally, the general program p and static input in_1 are passed to a partial evaluator mix, which outputs a specialized program p_{in_1}, which can take dynamic input in_2 and produce some output. For an illustration of this example, see figure 1.1.

```
f(n, x) = if n = 0 then 1
else if even(n) then f (n/2,x)^2
else x * f(n-1,x)
```

Listing 1.1: Two-input program p

```
f5(x) = x * ((x^2)^2)
```

Listing 1.2: Specialization of program p

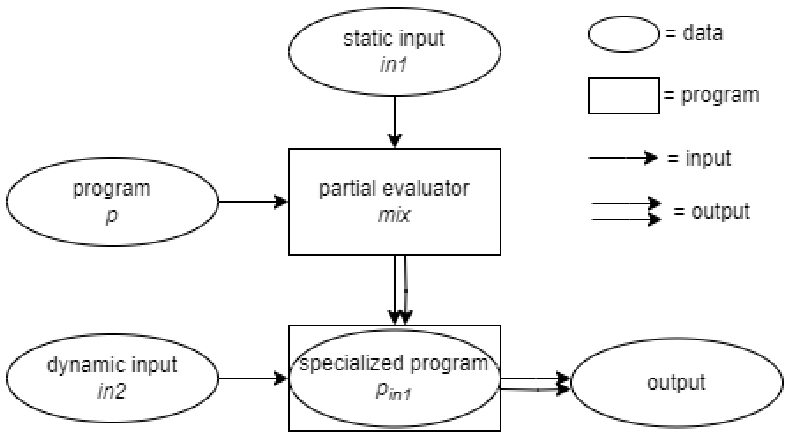


Figure 1.1: Visualisation of partial evaluation of a two-input program

This idea of specialization can also be applied to the implementation of this project, where the static input is the syntax of a language, which if partially evaluated with a general program, results in a specialized program. This program represents a syntax-directed editor instance for the static input's language, which can take dynamic input in the form of editor expressions, resulting in either cursor movement or updates to the target language's program. This can be seen as a curried function with following signature:

$$f : t_1 \to t_2 \to t_3$$

where t_1 is the type of language specifications, t_2 is the type of editor expressions and t_3 is the type of programs. Given a language specification, f produces a new function f' of type $t_2 \to t_3$, i.e., a new function that takes an editor expression and returns a program. Here, f' is an instance of the editor for a specific language.

In other words, the implementation can be specialized given some syntax, potentially skipping the process of parsing syntax and generating source code every time a user wishes to use the same editor instance for some language.

Chapter 2

Background

Following is a summary of the background material which serves as the foundation for the work presented in this project.

2.1 Abstract Syntax

Following is an overview of abstract syntax trees and abstract binding trees, as described by Harper[6]. This has served as the foundation for the work presented in the generalized editor calculus project[1], which inherently also plays an important role in the implementation of this project.

2.1.1 Abstract Syntax Trees

An abstract syntax tree (ast for short) is an ordered tree describing the syntactical structure of a program.

Harper introduces the notion of sorts $s \in \mathcal{S}$, arity-indexed families $\mathcal{O}$ of disjoint sets of operators $\mathcal{O}_\alpha$ of arity α and sort-indexed families $\mathcal{X}$ of disjoint finite sets $\mathcal{X}_s$ of variables x of sort s.

Sorts are syntactical categories which form a distinction between asts.

The internal nodes in an ast are operators o with arity $(s_1, ..., s_n)s$, describing the sort of the operator itself and its arguments.

Leaves of an ast are variables x of sort s, which enforce that variables can only be substituted by asts of the same sort.

Formally, $\mathcal{S}$ is a finite set of sorts. An arity has the form $(s_1, ..., s_n)s$ specifying the sort $s \in \mathcal{S}$ of an operator taking $n \geq 0$ arguments of sort $s_i \in \mathcal{S}$. Let $\mathcal{O} = \{\mathcal{O}_\alpha\}$ be an arity-indexed family of disjoint sets of operators $\mathcal{O}_\alpha$ of arity α. When o is an operator with arity $(s_1, ..., s_n)s$, we say o is an operator of sort s with n arguments, each of sort $s_1, ..., s_n$.

Example 1: Operators

Let us define a set of sorts $\mathcal{S} = \{exp\}$ and an operator $plus \in \mathcal{O}_\alpha$ with arity $\alpha = (exp_1, exp_2)exp$. Then we say that the operator *plus* is an operator of sort *exp* with 2 arguments of sort *exp*.

Having a fixed set of sorts $\mathcal{S}$ and an arity-indexed family $\mathcal{O}$ of sets of operators of each arity, $\mathcal{X} = \{\mathcal{X}_s\}_{s\in\mathcal{S}}$ is defined as a sort-indexed family of disjoint finite sets $\mathcal{X}_s$ of variables x of sort s.

The family $\mathcal{A}[\mathcal{X}] = \{\mathcal{A}[\mathcal{X}]_s\}_{s\in\mathcal{S}}$ of asts of sort s is the smallest family satisfying following conditions:

1. A variable of sort s is an ast of sort s: if $x \in \mathcal{X}_s$, then $x \in \mathcal{A}[\mathcal{X}]_s$
2. Operators combine asts: if o is an operator of arity $(s_1, ..., s_n)s$, and if $a_1 \in \mathcal{A}[\mathcal{X}]_{s_1}, ..., a_n \in \mathcal{A}[\mathcal{X}]_{s_n}$, then $o(a_1; ...; a_n) \in \mathcal{A}[\mathcal{X}]_s$

2.1.2 Abstract Binding Trees

An abstract binding tree (abt for short) is an enriched ast with bindings, allowing identifiers to be bound within a scope.

Operators in an abt can bind any finite number (possibly zero) of variables in each argument with form $x_1, ..., x_k.a$ where variables $x_1, ..., x_k$ are bound within the abt a. A finite sequence of bound variables $x_1, ..., x_k$ is represented as $\vec{x}$ for short.

Operators are assigned a generalized arity of the form $(v_1, ..., v_n)s$ where a valence v has the form $s_1, ..., s_k.s$, or $\vec{s}.s$ for short.

Example 2: Operators with binders

Let us define a set of sorts $\mathcal{S} = \{exp, stmt\}$ and an operator $let \in \mathcal{O}_\alpha$ with arity $\alpha = (exp_1, exp_2.stmt)stmt$. Then we say that the operator *let* is an operator of sort *stmt* with 2 arguments of sort *exp*, where the second binds a variable of sort *stmt* within the scope of exp_2.

If $\mathcal{X}$ is clear from context, a variable x is of sort s if $x \in \mathcal{X}_s$, and x is fresh for $\mathcal{X}$ if $x \notin \mathcal{X}_s$ for any sort s. If x is fresh for $\mathcal{X}$ and s is a sort, then $\mathcal{X}, x$ represents the notion of adding x to $\mathcal{X}_s$.

A fresh renaming of a finite sequence of variables $\vec{x}$ is a bijection $\rho : \vec{x} \leftrightarrow \vec{x}'$, where $\vec{x}'$ is fresh for $\mathcal{X}$. The result of replacing all occurrences of x_i in a by its fresh counterpart $\rho(x_i)$, is written as $\hat{\rho}(a)$.

Having a fixed set of sorts $\mathcal{S}$ and a family $\mathcal{O}$ of disjoint sets of operators indexed by their generalized arities and given a family of disjoint sets of variables $\mathcal{X}$, the family of abts $\mathcal{B}[\mathcal{X}]$ is the smallest family satisfying following:

1. If $x \in \mathcal{X}_s$, then $x \in \mathcal{B}[\mathcal{X}]_s$
2. For each operator o of arity $(\vec{s}_1.s_1, ..., \vec{s}_n.s_n)s$, if for each $1 \leq i \leq n$ and for each fresh renaming $\rho_i : \vec{x}_i \leftrightarrow \vec{x}'_i$, we have $\hat{\rho}_i(a_i) \in \mathcal{B}[\mathcal{X}, \vec{x}'_i]$, then $o(\vec{x}_1.a_1; ...; \vec{x}_n.a_n) \in \mathcal{B}[\mathcal{X}]_s$

For short, arity-indexed families $\mathcal{O}$ of disjoint sets of operators $\mathcal{O}_\alpha$ and sort-indexed families $\mathcal{X}$ of disjoint finite sets $\mathcal{X}_s$ might be referred to as sets. For example, $o \in \mathcal{O}$ is a shorthand for operator o being part of one of the disjoint sets in the family $\mathcal{O}$.

2.2 Generalized editor calculus

The generalized editor calculus[1] is a generalization of the type-safe structure editor calculus proposed by Godiksen et al.[4], where the editor calculus is able to account for any language given its abstract syntax, in contrast to the calculus in Godiksen[4] et al. which is tailored towards an applied λ-calculus.

2.2.1 Abstract syntax

It is assumed that the abstract syntax is given by a set of sorts $\mathcal{S}$, an arity-indexed family of operators $\mathcal{O}$ and a sort-indexed family of variables $\mathcal{X}$, as described by Harper[6].

Cursors and holes are important concepts in syntax-directed editors, where the cursor represents the current selection in the syntax tree, and holes are missing or empty subtrees.

The calculus proposed by Godiksen et al. [4] has a single term for the cursor and hole in the abstract syntax. For a generalized calculus, it is necessary to add a hole and cursor for every sort in $\mathcal{S}$.

Definition 1: Abstract syntax of a language

The abstract syntax of a language is given by the following:

1. A set of sorts $\mathcal{S}$
2. An arity-indexed family of operators $\mathcal{O}$
3. A sort-indexed family of variables $\mathcal{X}$

Then, for every sort $s \in \mathcal{S}$, the following operators are added to $\mathcal{O}$

1. A $hole_s$ operator with arity $()s$
2. A $cursor_s$ operator with arity $(s)s$

Example 3: Abstract syntax of a simple language

Below is a simple language consisting of arithmetic expressions and local declarations:

Sort	Term	Operator	Arity
$s ::=$	let $x = e$ in s	let	$(e, e.s)s$
$\mid$	e	exp	$(e)s$
$e ::=$	$e_1 + e_2$	$plus$	$(e, e)e$
$\mid$	n	$num[n]$	$()e$
$\mid$	x	$var[x]$	$()e$

In other words, we have sorts:

$$\mathcal{S} = \{s, e\}$$

and we have operators:

$$\mathcal{O} = \{\mathcal{O}_{(e,e.s)s}, \mathcal{O}_{(e)s}, \mathcal{O}_{(e,e)e}, \mathcal{O}_{()e}\}$$

where

$$\mathcal{O}_{(e,e.s)s} = \{let\}$$
$$\mathcal{O}_{(e)s} = \{exp\}$$
$$\mathcal{O}_{(e,e)e} = \{plus\}$$
$$\mathcal{O}_{()e} = \{num[n], var[x]\}$$

Example 4: Introduction of cursors and holes

Given the abstract syntax of a simple language consisting of arithmetic expressions and local declarations (Example 3), it would be extended with following cursor and hole operators:

Sort	Term	Operator	Arity
$s ::=$	$[s]$	cursor_s	$(s)s$
$\mid$	$\llbracket\,\rrbracket_s$	hole_s	$()s$
$e ::=$	$[e]$	cursor_e	$(e)e$
$\mid$	$\llbracket\,\rrbracket_e$	hole_e	$()e$

Editor calculus

The abstract syntax of the general editor calculus (Fig. 2.1) resembles the one from Godiksen et al., the only difference being the lack of an *eval* construct, since the generalized editor only considers the static and structural properties of abstract syntax.

Figure 2.1: Abstract syntax of general editor calculus

$$\begin{aligned} E &::= \pi.E \mid \phi \Rightarrow E_1|E_2 \mid E_1 \ggg E_2 \mid \mathit{rec}\ x.E \mid x \mid \mathit{nil} \\ \pi &::= \mathit{child}\ n \mid \mathit{parent} \mid \{o\} \\ \phi &::= \neg\phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid @o \mid \Diamond o \mid \Box o \end{aligned}$$

Cursorless trees

The notion of cursorless trees is introduced to support a single cursor only being able to encapsulate a single node, hence the rest of the tree being considered cursorless.

Definition 2: Abstract syntax of cursorless trees

The abstract syntax of cursorless trees is given by:

1. The sorts $\hat{\mathcal{S}} = \{\hat{s}\}_{s\in\mathcal{S}}$
2. The family of cursorless operators $\hat{\mathcal{O}}$ is made by adding the operator $\hat{o}$ of arity $(\vec{\hat{s}}_1.\hat{s}_1, ..., \vec{\hat{s}}_n.\hat{s}_n)\hat{s}$ for every $o \in \mathcal{O}$ of arity $(\vec{s}_1.s_1, ..., \vec{s}_n.s_n)s$
3. The family of variables $\hat{\mathcal{X}}$

Cursor Context

A cursor context C holds information about the current tree, up until a context hole, which is filled out by a well-formed tree including the cursor. In other words, the actual cursor is located somewhere in the well-formed tree, but is not part of the cursor context.

Definition 3: Abstract syntax of cursor contexts

The abstract syntax of cursor contexts is given by:

1. The sorts $\mathcal{S}^C = \hat{\mathcal{S}} \cup \{C\}$
2. The family of operators $\mathcal{O}^C = \hat{\mathcal{O}}$ extended with the $[\cdot]$ operator with arity $()C$
3. For every operator $\hat{o} \in \hat{\mathcal{O}}$ of arity $(\vec{\hat{s}}_1.\hat{s}_1, ..., \vec{\hat{s}}_n.\hat{s}_n)\hat{s}$ and for every $1 \leq i \leq n$ the operator o_i^C of arity $(\vec{\hat{s}}_1.\hat{s}_1, ..., \vec{\hat{s}}_i.C, ..., \vec{\hat{s}}_n.\hat{s}_n)C$ to $\mathcal{O}^C$
4. The family of variables $\mathcal{X}^C = \hat{\mathcal{X}}$

Well-formed trees

Well-formed trees are trees with a single cursor, where the cursor is located either at the root or one of the immediate children. The rest of the tree is cursorless, hence being well-formed since it only contains a single cursor.

Definition 4: Abstract syntax of well-formed trees

The abstract syntax of well-formed trees is given by:

1. The sorts $\dot{\mathcal{S}} = \hat{\mathcal{S}} \cup \{\dot{s}\}_{s \in \mathcal{S}}$
2. The family of operators $\dot{\mathcal{O}} = \hat{\mathcal{O}}$ extended with an operator of arity $(\hat{s})\dot{s}$ for every $\hat{s} \in \hat{\mathcal{S}}$
3. For every operator $\hat{o} \in \hat{\mathcal{O}}$ of arity $(\vec{\hat{s}}_1.\hat{s}_1, ..., \vec{\hat{s}}_n.\hat{s}_n)\hat{s}$ and for every $1 \leq i \leq n$ the operator $\dot{o}_i$ of arity $(\vec{\hat{s}}_1.\hat{s}_1, ..., \vec{\hat{s}}_i.\dot{s}_i, ..., \vec{\hat{s}}_n.\hat{s}_n)\dot{s}$ is added to $\dot{\mathcal{O}}$
4. The family of variables $\dot{\mathcal{X}} = \hat{\mathcal{X}}$

Given this, a well-formed abt $a \in \mathcal{B}[\mathcal{X}]$ is any abt that can be interpreted as $C[\dot{a}]$, where C is a cursor context and $\dot{a}$ is a well-formed tree.

2.2.2 Semantics

Reduction rules for editor expressions are presented in Fig. 2.2, substitution in Fig. 2.3 and cursor movement in Fig. 2.4.

Figure 2.2: Reduction rules for editor expressions

$$\text{(Cond-1)}\ \frac{a \models \phi}{\langle \phi \Rightarrow E_1 | E_2, C[a] \rangle \overset{\epsilon}{\Rightarrow} \langle E_1, C[a] \rangle}$$

$$\text{(Cond-2)}\ \frac{a \not\models \phi}{\langle \phi \Rightarrow E_1 | E_2, C[a] \rangle \overset{\epsilon}{\Rightarrow} \langle E_2, C[a] \rangle}$$

$$\text{(Seq)}\ \frac{\langle E_1, a \rangle \overset{\alpha}{\Rightarrow} \langle E_1', a' \rangle}{\langle E_1 \ggg E_2, a \rangle \overset{\alpha}{\Rightarrow} \langle E_1' \ggg E_2, a' \rangle}$$

$$\text{(Seq-Trivial)}\ \frac{}{\langle nil \ggg E_2, a \rangle \overset{\epsilon}{\Rightarrow} \langle E_2, a \rangle}$$

$$\text{(Recursion)}\ \frac{}{\langle \text{rec} x.E, a \rangle \overset{\epsilon}{\Rightarrow} \langle E[x := rec\ x.E], a \rangle}$$

$$\text{(Context)}\ \frac{a \overset{\pi}{\Rightarrow} a'}{\langle \pi.E, C[a] \rangle \overset{\pi}{\Rightarrow} \langle E, C[a'] \rangle}$$

Figure 2.3: Reduction rules for substitution

$$\text{(Insert-op)}\ \frac{}{[\hat{a}] \overset{\{o\}}{\Rightarrow} [o(\vec{x}_1.\llparenthesis\,\rrparenthesis_{s_1}; \ldots; \vec{x}_n.\llparenthesis\,\rrparenthesis_{s_n})]}\ \hat{a} \in \mathcal{B}[\mathcal{X}]_s \text{where } s \text{ is the sort of } o$$

Figure 2.4: Reduction rules for cursor movement

$$\text{(Child-i)}\ \frac{}{[\hat{o}(\vec{x}_1.\hat{a}_1; \ldots; \vec{x}_n.\hat{a}_n)] \overset{child\ i}{\Rightarrow} o(\vec{x}_1.\hat{a}_1; \ldots; \vec{x}_i.[\hat{a}_i]; \ldots; \vec{x}_n.\hat{a}_n)}$$

$$\text{(Parent)}\ \frac{}{o(\vec{x}_1.\hat{a}_1; \ldots; \vec{x}_i.[\hat{a}_i]; \ldots; \vec{x}_n.\hat{a}_n) \overset{parent}{\Rightarrow} [\hat{o}(\vec{x}_1.\hat{a}_1; \ldots; \vec{x}_n.\hat{a}_n)]}$$

Satisfaction rules for the propositional connectives are presented in Fig. 2.5 and modalitites in Fig. 2.6.

Figure 2.5: Satisfaction rules for propositional connectives

$$\text{(Negation)}\ \frac{[\hat{a}] \not\models \phi}{[\hat{a}] \models \neg\phi}$$

$$\text{(Conjunction)}\ \frac{[\hat{a}] \models \phi_1 \quad [\hat{a}] \models \phi_2}{[\hat{a}] \models \phi_1 \wedge \phi_2}$$

$$\text{(Disjunction-1)}\ \frac{[\hat{a}] \models \phi_1}{[\hat{a}] \models \phi_1 \vee \phi_2}$$

$$\text{(Disjunction-2)}\ \frac{[\hat{a}] \models \phi_2}{[\hat{a}] \models \phi_1 \vee \phi_2}$$

Figure 2.6: Satisfaction rules for modalities

$$\text{(At-op)}\ \frac{}{[o(\vec{x}_1.\hat{a}_1; ...; \vec{x}_n.\hat{a}_n)] \models @o}$$

$$\text{(Necessity)}\ \frac{[\hat{a}_1] \models \Diamond ... [\hat{a}_n] \models \Diamond o}{[o(\vec{x}_1.\hat{a}_1; ...; \vec{x}_n.\hat{a}_n)] \models \Box o}$$

$$\text{(Possibly-i)}\ \frac{[\hat{a}_i] \models \Diamond o}{[o(\vec{x}_1.\hat{a}_1; ...; \vec{x}_i.\hat{a}_i; ...; \vec{x}_n.\hat{a}_n)] \models \Diamond o}$$

$$\text{(Possibly-trivial)}\ \frac{[\hat{a}] \models @o}{[\hat{a}] \models \Diamond o}$$

2.2.3 Encoding the generalized editor calculus in an extended λ-calculus

The following sections will show how to encode the generalized editor calculus in a simply typed λ-calculus, extended with pairs, pattern matching and recursion. The notation $[\![a]\!]$ will be used to describe the encoding of an abt a.

The simply typed λ-calculus is first extended with term constants o for every $o \in \mathcal{O}$ excluding cursors and base type s for every sort $s \in \mathcal{S}$. The abstract syntax of this can be seen in Fig. 2.7.

Figure 2.7: Abstract syntax of extended λ-calculus

$$\begin{array}{rcll} & & \text{Terms} & \\ M & ::= & \lambda x : \tau . M & (\mathit{abstraction}) \\ & | & M_1 M_2 & (\mathit{application}) \\ & | & x & (\mathit{variable}) \\ & | & o & (\mathit{operator}) \end{array}$$

$$\begin{array}{rcll} & & \text{Types} & \\ \tau & ::= & \tau_1 \to \tau_2 & (\mathit{function}) \\ & | & s & (\mathit{sort}) \end{array}$$

Abstract binding trees

The types of operators in the λ-calculus can be inferred by their arity. The typing rules for this is provided in Fig. 2.8.

Figure 2.8: Typing rules for λ-calculus operators

$$(\text{T-Operator})\ \frac{o \in \mathcal{O} \text{ and has arity } (\vec{s}_1.s_1, ..., \vec{s}_n.s_n)s}{\Gamma \vdash o : (\vec{s}_1 \to s_1) \to ...(\vec{s}_n \to s_n) \to s}$$

Then, any abt can be encoded in the extended simply typed λ-calculus be the encoding in Fig. 2.9.

Figure 2.9: Encoding of abts

$$[\![o(\vec{x}_1.a_1, ..., \vec{x}_n.a_n)]\!] = o(\lambda \vec{x}_1 : \vec{s}_1.[\![a_1]\!])...(\lambda \vec{x}_n : \vec{s}_n.[\![a_n]\!])$$

Cursor Contexts

Cursor contexts will be represented in the λ-calculus as pairs, hence it is extended to support this notion. The abstract syntax is given in Fig. 2.10.

Figure 2.10: Abstract syntax of extended λ-calculus

$$\begin{array}{lll} & \text{Terms} & \\ M & ::= (M_1, M_2) & \text{(pair)} \\ & \mid \quad M.1 & \text{(first projection)} \\ & \mid \quad M.2 & \text{(second projection)} \end{array}$$

$$\begin{array}{lll} & \text{Types} & \\ \tau & ::= \tau_1 \times \tau_2 & \text{(product type)} \end{array}$$

Reduction rules for projecting the first and second value in a pair are given in Fig. 2.11.

Figure 2.11: Reduction rules for pairs

$$\text{(E-Proj1)} \ \frac{}{(M_1, M_2).1 \to M_1}$$

$$\text{(E-Proj2)} \ \frac{}{(M_1, M_2).2 \to M_2}$$

Typing rules for pairs in the λ-calculus are given in Fig. 2.12.

Figure 2.12: Typing rules for pairs

$$\text{(T-Proj1)} \ \frac{\Gamma \vdash M : \tau_1 \times \tau_2}{\Gamma \vdash M.1 : \tau_1}$$

$$\text{(T-Proj2)} \ \frac{\Gamma \vdash M : \tau_1 \times \tau_2}{\Gamma \vdash M.2 : \tau_2}$$

$$\text{(T-Pair)} \ \frac{\Gamma \vdash M : \tau_1 \quad \Gamma \vdash M_2 : \tau_2}{\Gamma \vdash (M_1, M_2) : \tau_1 \times \tau_2}$$

The actual encoding of cursor contexts can be seen in Fig. 2.13. For short, in the following encodings, the cursor context is also given a type alias $Ctx = s \times s$.

Figure 2.13: Encoding of cursor contexts

$$[\![C[a]]\!] = ([\![a]\!], [\![C]\!])$$

$$[\![[\cdot]]\!] = [\cdot]$$

Atomic Prefix Commands

To encode the atomic prefix commands $\pi \in Apc$, it is necessary to extend the λ-calculus with pattern matching. The abstract syntax of this extension is given in Fig. 2.14.

Figure 2.14: Abstract syntax of extended λ-calculus

$$
\begin{array}{rlr}
M, N & ::= match\ M\ \overrightarrow{p \to N} & \text{(match construct)} \\
p & ::= x & \text{(variable)} \\
 & \mid\ \_ & \text{(wildcard)} \\
 & \mid\ o\ \vec{p} & \text{(operator)} \\
 & \mid\ (p_1, p_2) & \text{(pair)} \\
 & \mid\ .p & \text{(binding)}
\end{array}
$$

The reduction rules for the match construct are given in Fig. 2.15, which uses an auxiliary function *binds* which takes a term M and a pattern p and returns a function of variable bindings, e.g. $[x \to M]$ if a term M can be bound to pattern x, or $fail$ if the term cannot be bound to the pattern.

Figure 2.15: Reduction rules for pattern matching

$$
(E - Match)\ \frac{\sigma_i = binds(M, p_i) \neq fail \qquad \forall j < i.binds(M, p_j) = fail}{match\ M\ \overrightarrow{p \to N} \to N_i\sigma_i}
$$

$$
binds : M \times p \to (Var \to M) \cup \{fail\}
$$

$$
\begin{array}{ll}
binds(M, x) & = [x \to M] \\
binds(M, \_) & = [] \\
binds(o\ a_1\ ...\ a_n,\ o\ p_1\ ...\ p_n) & = binds(a_1, p_1) \circ ... \circ binds(a_n, p_n) \\
binds((M, N), (p_1, p_2)) & = binds(m, p_1) \circ binds(N, p_2) \\
binds(M, .p) & = binds(M, p) \\
binds(\lambda x.M, .p) & = binds(M, .p)
\end{array}
$$

for remaining values in the domain of *binds* the result is defined as $fail$.
$fail$ is defined as the function that always returns $fail$.

The typing rules for the match construct are given in Fig. 2.16.

Figure 2.16: Typing rules for pattern matching

$$\text{(T-Match)}\ \frac{\text{for all } i \text{ satisfying } \sigma_i = binds(M, p_i) \neq fail \qquad \Gamma \vdash N_i\sigma_i : T}{\Gamma \vdash match\ M\ \overrightarrow{p \rightarrow N} : T}$$

With the *match* construct, auxiliary functions for cursor movement (Fig. 2.17) can be defined in terms of matching an abt x against a pattern with some cursor, resulting in a new term. The shorthand $[a]$ is used to represent an abt a being encapsulated with a cursor.

Figure 2.17: Auxiliary functions for cursor movement

$$\begin{aligned}
down &\overset{def}{=} \lambda x : s.\text{match } x \\
&\quad [o(.a_1)...(.a_n)] \rightarrow o(.[a_1])...(.a_n) \\
right &\overset{def}{=} \lambda x : s.\text{match } x \\
&\quad o(.a_1)...(.[a_i])...(.a_n) \rightarrow o(.a_1)...([a_{i+1}])...(.a_n) \\
up &\overset{def}{=} \lambda x : s.\text{match } x \\
&\quad o(.a_1)...(.[a_i])...(.a_n) \rightarrow [o(.a_1)...(.a_n)] \\
set &\overset{def}{=} \lambda a : s.\lambda x : s.\text{match } x \\
&\quad [a'] \rightarrow [a]
\end{aligned}$$

The encoding of atomic prefix commands $\pi \in Apc$ is done in terms of the cursor movement functions in Fig. 2.18. The *child* n is a recursive encoding, where the *right* function is applied on *child* $n-1$, until n becomes 1, where it will be encoded as *down*.

Figure 2.18: Encoding of cursor movement

$$\begin{aligned}
[\![child\ 1]\!] &= down \\
[\![child\ n]\!] &= right\ [\![child\ n-1]\!] \\
[\![parent]\!] &= up \\
[\![insert\ a]\!] &= set\ [\![a]\!]
\end{aligned}$$

Editor expressions

To encode editor expressions $E \in Edt$, it is necessary to introduce recursion and a boolean base type to the extended λ-calculus.

A fix operator (Fig. 2.19) is introduced to support recursion, where E-

FixBeta substitutes the term x in M with another fix operator, hence introducing a layer of recursion.

Figure 2.19: fix operator

$$\text{(E-FixBeta)} \quad \frac{}{fix(\lambda x : T.M) \to M[x := fix(\lambda x : T.M)]}$$

$$\text{(E-Fix)} \quad \frac{M \to M'}{fix\ M \to fix\ M'}$$

The boolean term constants and base types are defined directly in the abstract syntax of the λ-calculus (Fig. 2.20). The patterns p terms have also been extended with the boolean constants, in order to support pattern matching for booleans. For this, the *binds* function has also been extended (Fig. 2.21).

Figure 2.20: Abstract syntax of extended λ-calculus

Terms

$$\begin{array}{lcll} M & ::= & fix\ M & \text{(fixed point of M)} \\ & \mid & \top & \text{(true)} \\ & \mid & \bot & \text{(false)} \\ \\ p & ::= & \top & \text{(match true)} \\ & \mid & \bot & \text{(match false)} \end{array}$$

Types

$$\tau \quad ::= Bool \quad \text{(boolean)}$$

Figure 2.21: *binds* extended with boolean constructs

$$\begin{gathered} binds(\top, \top) = [] \\ binds(\bot, \bot) = [] \end{gathered}$$

Typing rules for fix and booleans can be seen in Fig. 2.22.

Figure 2.22: Typing rules for fix and booleans

$$\text{(T-Fix)} \quad \frac{\Gamma \vdash M : T \to T}{\Gamma \vdash fix\ M : T}$$

$$\text{(T-False)} \quad \frac{}{\bot : Bool}$$

$$\text{(T-True)} \quad \frac{}{\top : Bool}$$

With prior definitions, encoding of editor expressions and context configuration is given in Fig. 2.23.

Figure 2.23: Encoding of editor expressions and context configuration

$$[\![\pi.E]\!] = \lambda CC : Ctx.[\![E]\!](([\![\pi]\!]C.1), C.2)$$

$$[\![nil]\!] = \lambda C : Ctx.C$$

$$[\![E_1 \ggg E_2]\!] = \lambda C : Ctx.[\![E_2]\!]([\![E_1]\!]C)$$

$$[\![\text{Rec } x.E]\!] = fix(\lambda x : (Ctx \to Ctx).[\![E]\!])$$

$$\begin{aligned}[\![\phi \Rightarrow E_1|E_2]\!] = \lambda C : Ctx.&\text{match}([\![\phi]\!]C.1)\\ &\mid \top \to [\![E_1]\!]\ C\\ &\mid \bot \to [\![E_2]\!]\ C\end{aligned}$$

$$[\![\langle E, C[a'] \rangle]\!] = [\![E]\!]\ ([\![a]\!], [\![C]\!])$$

Conditional expressions

To encode conditional expressions $\phi \in Eec$, auxiliary functions *checkboth*, *checkone*, *or*, *and* and *neg* are defined in Fig. 2.24.

Figure 2.24: Auxiliary functions for conditionals

$$
\begin{aligned}
\mathit{checkboth} &\overset{def}{=} \lambda f : (\mathit{Bool} \to \mathit{Bool} \to \mathit{Bool}).\\
&\quad \lambda g : (s \to \mathit{Bool}).\\
&\quad \lambda h : (s \to \mathit{Bool}).\\
&\quad \lambda a : s.\\
&\quad f(ga)(ha)\\[1em]
\mathit{checkone} &\overset{def}{=} \lambda f : (\mathit{Bool} \to \mathit{Bool}).\\
&\quad \lambda g : (s \to \mathit{Bool}).\\
&\quad \lambda a : s.\\
&\quad f(ga)\\[1em]
\mathit{or} &\overset{def}{=} \lambda b_1 : \mathit{Bool}.\lambda b_2 : \mathit{Bool}.\text{match } (b_1, b_2).\\
&\quad (\bot, \bot) \to \bot\\
&\quad (\_, \_) \to \top\\[1em]
\mathit{and} &\overset{def}{=} \lambda b_1 : \mathit{Bool}.\lambda b_2 : \mathit{Bool}.\text{match } (b_1, b_2).\\
&\quad (\top, \top) \to \top\\
&\quad (\_, \_) \to \bot\\[1em]
\mathit{neg} &\overset{def}{=} \lambda b : \mathit{Bool}.\text{match } b.\\
&\quad \top \to \bot\\
&\quad \bot \to \top
\end{aligned}
$$

With the auxiliary functions, the encoding of propositional connectives is given in Fig. 2.25 and the encoding of modal logic is given in Fig. 2.26, which also make use of the *fix* and *match* functions.

Figure 2.25: Encoding of propositional connectives

$$[\![\phi_1 \wedge \phi_2]\!] = \mathit{checkboth}\ \mathit{and}\ [\![\phi_1]\!][\![\phi_2]\!]$$

$$[\![\phi_1 \vee \phi_2]\!] = \mathit{checkboth}\ \mathit{or}\ [\![\phi_1]\!][\![\phi_2]\!]$$

$$[\![\neg\phi]\!] = \mathit{checkone}\ \mathit{neg}\ [\![\phi]\!]$$

Figure 2.26: Encoding of modal logic

$$\begin{aligned}
[\![@o]\!] = {} & \lambda x : \text{smatch}\ x \\
& \quad \mid [o\ \_\ \ldots\ \_] \to \top \\
& \quad \mid \_ \to \bot
\end{aligned}$$

$$\begin{aligned}
[\![\Diamond o]\!] = {} & \mathit{fix}(\lambda f : (s \to \mathit{Bool}).\lambda x : s.\text{match}\ x \\
& \quad \mid [o\ \_\ldots\ \_] \to \top \\
& \quad \mid [\_(\_.a_1, \ldots, \_.a_n)] \to \mathit{or}(\ldots(\mathit{or}(f\ [a_1])(f\ [a_2]))\ \ldots)(f\ [a_n]) \\
& \quad \mid \_ \to \bot)
\end{aligned}$$

$$\begin{aligned}
[\![\Box o]\!] = {} & \lambda x : s.\text{match}\ x \\
& \quad \mid \_(\_.a_1, \ldots, \_.a_n) \to \mathit{and}(\ldots(\mathit{and}([\![\Diamond o]\!]\ a_1)([\![\Diamond o]\!]\ a_2))\ldots)([\![\Diamond o]\!]\ a_n) \\
& \quad \mid \_ \to \top
\end{aligned}$$

Chapter 3

Implementation

This chapter describes the implementation of the type-safe generalized syntax-directed editor. The implementation is ...

3.1 Implementation

3.1.1 Representing Syntax

The generalized editor calculus[1] assumes that it is given an abstract syntax that is represented by a set of sorts $\mathcal{S}$, an arity-indexed family of operators $\mathcal{O}$, and a sort-indexed family of variables $\mathcal{X}$, as per Robert Harper's notation [6].

A criterion for the good solution of this project is also the implementation of being able to pretty-print a program into a concrete syntax. For this, it is also necessary for the user to provide the concrete for a language they wish to edit.

It can be a challenge from the user's perspective to provide a specification based on what the calculus assumes. Therefore, it is ideal for the implementation to provide other means of describing the syntax of a language.

In terms of early examples, Metal[12] has been used in the Mentor[3] and CENTAUR[2] systems. Metal compiles a specification containing concrete syntax, abstract syntax and tree building functions for a formalism F into a Virtual Tree Processor (VTP) formalism, a concrete syntax parser produced by YACC[9] and a tree generator which uses VTP primitives to construct abstract syntax trees.

Another example with the same purpose is Zephyr ASDL (Abstract Syntax Description Language)[19], where the authors have built a tool that converts an ASDL specification into C, C++, Java and ML data-structure definitions. The authors consider ASDL a simpler alternative to other abstract syntax description languages, such as ASN.1[13].

However, both examples have lack of binding mechanisms in abstract syntax in common. This motivates another possibility of defining a specification language for the to-be-implemented generalized editor itself, which can assist the user in describing the syntax. This would also require a parser that can parse the necessary information assumed by the calculus (including binders). Picking this route allows the project to avoid spending time analyzing different tools and developing a workaround for binders.

Specification language

The specification language is chosen to expect some syntactic categories followed by concrete and abstract syntax in BNF notation. Every syntactic category is represented by one or more non-terminals with a term, arity and operator name. The term might refer to other syntactic categories or its own. Each term is the concrete syntax of an operator, while the arity, in combination with the operator name, is a concise representation of the abstract syntax of an operator. The abstract syntax only makes use of the defined syntactic categories and, inspired by Harper[6], binders can be specified in the arity description with a dot ('.'), e.g. $x.s$ specifies that variable x is bound within the scope of s.

From this specification language, it is possible to extract what is assumed by the generalized editor calculus[1]. The set of sorts $\mathcal{S}$ is the set of syntactic categories. For example, a syntactic category $e \in Exp$ can get parsed into a sort s_e. The family of arity-indexed operators $\mathcal{O}$ can be extracted from the BNF notation since each derivation rule represents an operator with a specified arity.

Example 5: Syntax of a small C language

Following is a specification of a subset of the C language[8], per the described specification language.

$$
\begin{aligned}
p &\in \mathit{Prog} & s &\in \mathit{Stmt}\\
vd &\in \mathit{VariableDecl} & fd &\in \mathit{FunDecl}\\
t &\in \mathit{Type} & id &\in \mathit{Id}\\
e &\in \mathit{Exp} & b &\in \mathit{Block}\\
fa &\in \mathit{Funarg} & cond &\in \mathit{Conditional}
\end{aligned}
$$

Sort	Term	Arity	Operator
$p ::=$	fd	$(fd)p$	$program$
$b ::=$	bi	$(bi)b$	$block$
$bi ::=$	vd	$(vd)bi$	$blockdecls$
$\mid$	s	$(s)bi$	$blockstmts$
$\mid$	ϵ	$()bi$	$blockdone$
$vd ::=$	$t\ id$ "=" e ";" bi	$(t, e, id.bi)s$	$vardecl$
$fd ::=$	$t_1\ id_1$ "(" $t_2\ id_2$ ")"	$(t, id.fd,$	$fundecl1$
	"{" b "}" fd	$t, id.b)fd$	
$\mid$	$t_1\ id_1$ "(" $t_2\ id_2$ ","	$(t, id.fd, t,$	$fundecl2$
	$t_3\ id_3$ ") {" b "}" fd	$t, id.id.b)fd$	
$\mid$	ϵ	$()fd$	$fundecldone$
$s ::=$	id "=" e ";"	$(id, e)s$	$assignment$
$\mid$	id "(" fa ");"	$(id, fa)s$	$stmtfuncall$
$\mid$	"return " e ";"	$(e)s$	$return$
$\mid$	$cond$	$(cond)s$	$conditional$
$\mid$	$s\ s$	$(s, s)s$	$compstmt$
$fa ::=$	$t\ id$	$(t, id)fa$	$funarg$
$\mid$	$t\ id$ "," fa	$(t, id, fa)fa$	$funargs$
$cond ::=$	"if (" e ") {" b_1 "} else {" b_2 "}"	$(e, b, b)cond$	$ifelse$
$t ::=$	"int"	$()t$	$tint$
$\mid$	"$char$"	$()t$	$tchar$
$\mid$	"$bool$"	$()t$	$tbool$
$e ::=$	$\%int$	$()e$	$cint[Int]$
$\mid$	$\%char$	$()e$	$cchar[Char]$
$\mid$	$\%bool$	$()e$	$cbool[Bool]$
$\mid$	e_1 "+" e_2	$(e, e)e$	$plus$
$\mid$	e_1 "==" e_2	$(e, e)e$	$equals$
$\mid$	id "(" fa ")"	$(id, fa)e$	$expfuncall$
$\mid$	id	$(id)e$	$expident$
$id ::=$	%string	$()id$	$ident[String]$

'%int', '%char', '%string' and '%bool' are meta-variables representing any parseable integer, character, sequence of characters and boolean constant by the C language.
This subset is chosen as it can represent a C program consisting of only

function declarations at the top level, where one of them might represent a `main` function, the entry point of a C program. The identifier of a function declaration is bound within the following function declarations (e.g. id_1 is bound within *fd* in the *fundecl1* operator).
A limitation of this specification is recursive function calls. Ideally, the identifier in a function declaration is bound both within the function block and the sequence of following function declarations. However, this would result in the same identifier appearing twice in the arity definition. E.g. the arity for the *fundecl1* operator is $(t_1, id_1.fd, t_2, id_2.b)fd$ where id_1 is the identifier of the function, which ideally would be bound in both *fd* (the following sequence of function declarations) and b (the function block).
Another limitation, or something that might seem unnecessary, is having the $blockdone$ and $fundecldone$ operators. They are necessary to allow for a block to end with a $vardecl$ operator and to end a sequence of function declarations with the $fundecl1$ or $fundecl2$ operator. This a pattern that allows operators to bind identifiers within the following terms.

Example 6: Syntax of a small SQL language

Below is the syntax of a subset of the PostgreSQL[5] dialect of SQL:

$$\begin{array}{ll} q \in \mathit{Query} & \\ \mathit{cmd} \in \mathit{Command} & \mathit{id} \in \mathit{Id} \\ \mathit{const} \in \mathit{Const} & \mathit{clause} \in \mathit{Clause} \\ \mathit{cond} \in \mathit{Condition} & \mathit{exp} \in \mathit{Expression} \end{array}$$

Sort	Term	Arity	Operator
query ::=	”SELECT ” id_1	$(id_1, id_2, clause)query$	*select*
	” FROM ” id_2 *clause*		
cmd ::=	”INSERT INTO ” id_1	$(id_1, id_2.query)cmd$	*insert*
	” AS ” id_2 *query*		
id ::=	%string	$()id$	*id*
const ::=	%number	$()const$	*num*
|	” ’%string’ ”	$()const$	*str*
clause ::=	”WHERE ” *cond*	$(cond)clause$	*where*
|	”HAVING ” *cond*	$(cond)clause$	*having*
cond ::=	exp_1 ”>” exp_2	$(exp_1, exp_2)cond$	*greater*
|	exp_1 ”=” exp_2	$(exp_1, exp_2)cond$	*equals*
exp ::=	*const*	$()exp$	*econst*
|	*id*	$()exp$	*eid*

where ’%string’ and ’%number’ and ’%char’ are placeholders for any parsable sequence of characters and numbers by the PostgreSQL language.
This subset is chosen as it can represent simple select queries and insert commands.
Notably, a binder is used in the *insert* operator, where the alias of id_1, specified as id_2 is bound within the sub-query.

Example 7: Syntax of a small LaTeXlanguage

Below is the syntax of a subset of the LaTeXlanguage:

To make the specification language parseable, a more computer-friendly format is presented in Listing 3.1 in BNF-form. Every syntactic category is expected on its own line, followed by a blank line and all derivations. Each derivation is expected to be a syntactic category, followed by ’::=’ and every term (which acts as the concrete syntax of an operator), arity and operator name, separated with a vertical bar ’—’. Every term, arity and operator are separated with a number-sign ’#’. See figure Fig. 3.1 for an example.

```
<syntax> ::= <synCatList> "\n\n" <synCatRulesList>
```

```

<synCatList> ::= <synCat> "\n" <synCatList> | <synCat>
<synCat> ::= <synCatExp> "in" <synCatSet>

<synCatExp> ::= %string
<synCatSet> ::= %string

<synCatRulesList> ::= <synCatRules> "\n"
                      <synCatRulesList>
                    | <synCatRules>
<synCatRules> ::= <synCatName> "::=" <ruleList>
<ruleList> ::= <rule> "|" <ruleList> | <rule>

<rule> ::= <term> "#" <arity> "#" <operator>
<term> ::= %string
<arity> ::= "(" <arityElementList> ")"
<arityElementList> ::= <arityElement>
                      | <arityElement>
                        <separator>
                        <arityElementList>
<arityElement> ::= %string
<separator> ::= "," | "."
<operator> ::= %string
```

Listing 3.1: The specification language itself in BNF-form

Figure 3.1: Subset of syntax of a small SQL language in a parseable format

```
query in Query
cmd in Command
id in Id
clause in Clause

query ::= " SELECT " id " FROM " id clause # (id,id,
   clause)query # select
cmd ::= " INSERT INTO " id " AS " id query # (id,id.
   query)cmd # insert
```

3.1.2 Code generation versus generic model

Another important thing to consider for the implementation is whether part of the editor's source code should be generated automatically, or if a generic model might suffice.

Automatic generation of source code offers the benefit of directly representing provided operators, along with their arity and sort, within an algebraic data type (referred to as `type` in Elm and `data` in Haskell). This ensures that only well-formed terms can be represented using the algebraic data types.

However, opting for this method might require automatic updates to both the definitions and signatures of some functions. This presents a challenge in ensuring that these functions maintain their intended behavior after the updates.

Example 8: Algebraic data types for a small C syntax

Given example Example 5, one can generate the following custom types in Elm:

```
type alias Bind a b =
    ( List a, b )
type Prog
    = Program FunDecls
type Block
    = Block BlockItems
type BlockItems
    = BlockDecl VarDecls
    | BlockStmts Statements
    | BlockDone
type VarDecls
    = VarDecl Type Id Exp BlockItems
type FunDecls
    = FunDecl1 Type (Bind Id FunDecls) Type (Bind Id
      Block)
    | FunDecl2 Type (Bind Id FunDecls) Type (Bind Id (
      Bind Id Block))
    | FunDeclDone
type Statement
    = Assignment Id Exp
    | StmtFunCall Id Funargs
    | Return Exp
    | Conditional Conditional
type Funargs
    = ArgSingle Funarg
    | ArgCompound Funargs Funarg
```

```
type Funarg
    = Funarg Type Id
type Conditional
    = IfElse Exp Block Block
type Statements
    = SSingle Statement
    | SCompound Statements Statement
type Type
    = TInt
    | TChar
    | TBool
type Exp
    = Num
    | Char
    | Bool
    | Plus Exp Exp
    | Equals Exp Exp
    | ExpFunCall Id Funargs
    | ExpId Id
type Id
    = Ident String
```

The *Bind* type alias is simply a tuple of 2 given type variables, where the first element is a list. This is used to represent binders in the abstract syntax, however with the limitation of only allowing abts of a single sort to be bound.

In contrast, a generic solution without the need for generating new source reduces the risk of syntax errors in the target language for the editor itself. A generic solution involves designing a model capable of holding the necessary information from any syntax. An approach for this is provided in Listing 3.2. However, this approach requires additional well-formedness checks on any given term concerning the syntax.

```
type alias Syntax =
{ synCats : [String]
, operators : [Operator]
}

type alias Operator =
{ name : String
, arity : (Maybe [String], String)
, concSyn : String
}
```

Listing 3.2: Elm Records for storing syntax information

The arity in the Operator type is a tuple, where the first entry is a potential list of identifiers bound within the term in the second element of the tuple.

In Haskell, this corresponds to named fields[7], which have a very similar syntax.

The implementation will proceed with automatic generation of source code, including algebraic data types, due to their advantage in handling ill-formed terms effectively. If given an ill-formed term, it is considered ill-typed by the editor, which poses an advantage over the generic solution requiring thorough checking to ensure that given terms are well-formed.

3.1.3 Generating source code

Elm CodeGen[15] is an Elm package and CLI tool (command-line interface tool) to generate Elm source code. The tool is an alternative to the otherwise obvious (and arguably tedious) strategy of having a source code template, where certain placeholders are replaced with relevant data or code snippets associated with the parsed syntax.

Besides offering the ability to generate source code, it offers offers automatic imports and built-in type inference. Example usage of Elm CodeGen from the documentation[15] is given in Fig. 3.2.

Figure 3.2: Elm CodeGen usage

Following declares an Elm record and passes it to a `ToString` function:

```
Elm.declaration "anExample"
    (Elm.record
        [ ("name", Elm.string "a fancy string!")
        , ("fancy", Elm.bool True)
        ]
    )
    |> Elm.ToString.declaration
```

The above will generate following string:

```
anExample : { name : String, fancy : Bool }
anExample =
    { name = "a fancy string!"
    , fancy = True
    }
```

Using Elm CodeGen offers the advantage of integrating a parser, which, if implemented in Elm as well, can directly produce the data to enable Elm Codegen to produce source files for the editor.

More specifically, the implementation will use the built-in `Parser` Elm library to parse a `RawSyntax` object (Listing 3.3), which is a direct representation of the syntax as specified in the specification language (**??**).

```elm
type alias RawSyntax =
    { synCats : List RawSynCat
    , synCatRules : List RawSynCatRules
    }

type alias RawSynCatRules =
    { synCat : String
    , operators : List RawOp
    }

type alias RawOp =
    { term : String
    , arity : String
    , name : String
    }

type alias RawSynCat =
    { exp : String
    , set : String
    }
```

Listing 3.3: Raw syntax model in Elm

If parsing of the raw syntax is successful, the raw model will be transformed into a separate model built around the `Syntax` type alias (Listing 3.4). Transformations include converting the string-representation of the arity into its own `Arity` type, which is a simple list of tuples, where the first element is a list of variables to be bound within the second element.

```elm
type alias Syntax =
    { synCats : List SynCat
    , synCatOps : List SynCatOps
    }

type alias SynCat =
    { exp : String
    , set : String
    }

type alias SynCatOps =
    { ops : List Operator
    , synCat : String
    }

type alias SynCatOps =
    { ops : List Operator
    , synCat : String
    }

type alias Operator =
    { term : Term
    , arity : Arity
    , name : String
    , synCat : String
    }

type alias Term =
    String

type alias Arity =
    List ( List String, String )
```

Listing 3.4: Syntax model

Having all expected sets of sorts and family of operators, i.e. the abstract syntax extended with *hole* and *cursor* operator $\mathcal{S}, \mathcal{O}$, cursorless trees $\hat{\mathcal{O}}, \hat{\mathcal{S}}$, cursor contexts $\mathcal{S}^C, \mathcal{O}^C$ and well-formed trees $\dot{\mathcal{O}}, \dot{\mathcal{S}}$, the CodeGen package can generate algebraic data types for every sort and its operators and separate them into their own separate modules (files).

Example 9: From specification parser to Elm CodeGen for small C-language

Given the specification in example Example 5, the parser can produce following `Declaration` for the `Statement` algebraic data type in example Example 8:

```
Elm.customType "Statement"
            [ Elm.variantWith "Assignment"
                [ Elm.Annotation.named [] "Id",
                  Elm.Annotation.named [] "Exp" ]
            , Elm.variantWith "StmtFunCall"
                [ Elm.Annotation.named [] "Id",
                  Elm.Annotation.named [] "Funargs"
                     ]
            , Elm.variantWith "Return"
                [ Elm.Annotation.named [] "Exp" ]
            , Elm.variantWith "Conditional"
                [ Elm.Annotation.named [] "
                   Conditional" ] ]
```

This declaration, if passed to Elm CodeGen's `File` function, would generate a source file with following contents:

```
type Statement
    = Assignment Id Exp
    | StmtFunCall Id Funargs
    | Return Exp
    | Conditional Conditional
```

3.1.4 Editor expressions

Having generated all sorts and operators as algebraic data types in Elm, the next step is to implement functionality for manipulating trees. In terms of the editor calculus[1], manipulating an abt involves editor expressions $E \in \mathit{Edt}$ (Fig. 2.1), which include atomic prefix commands $\pi \in \mathit{Apc}$ for abt traversal and modification, and conditions $\phi \in \mathit{Eec}$ for conditional manipulation with respect to modal logic within the encapsulated abt.

Decomposing trees

All editor expressions assume a well-formed abt, which is a tree with exactly one cursor, which cannot be guaranteed by the generated algebraic data types, as every sort has an associated cursor operator.

However, these operations rely on a well-formed abt, which is given by decomposing an abt a into $C[\dot{a}]$, where C is a cursor-context (Definition 3) and $\dot{a}$ is a well-formed abt (Definition 4).

First, it is necessary to know which symbol in the given syntax representation is intended as the starting symbol. Only the syntactic category of the starting symbol would need functions supporting decomposition. In other words, it does not make sense to decompose an abt of some sort which cannot be derived to a well-formed program. This aspect has not been considered yet, and as a temporary solution, a type wrapper called `Base` has been introduced, which has an entry for every syntactic category in the given syntax. For example, see Listing 3.5 for an excerpt of the `Base` type generated for the C language in Example 5.

```
type Base
    = Prog Prog
    | Block Block
    | BlockItems BlockItems
    | VarDecls VarDecls
    | FunDecls FunDecls
```

Listing 3.5: Example of the Base type

This allows for any operator of any sort to be decomposed, although the ideal solution would be having a way to specify the starting symbol in the syntax representation.

The generalized editor calculus[1] defines well-formed trees as abt's with exactly one cursor either as the root or as an argument of the root. However, this definition, in conjunction with the cursor context definition, leads to multiple valid decompositions for an abt in certain scenarios, which is also mentioned in [1]. This can occur when the cursor is located at one of the immediate children of the root. In that case, the cursor context can be interpreted as either the tree where the cursor has been replaced with a context hole, or it can be interpreted as an empty context. For example, consider a small tree created from the syntax given in example Example 6 (including cursor and hole operators) and their two possible decompositions in figure Fig. 3.3.

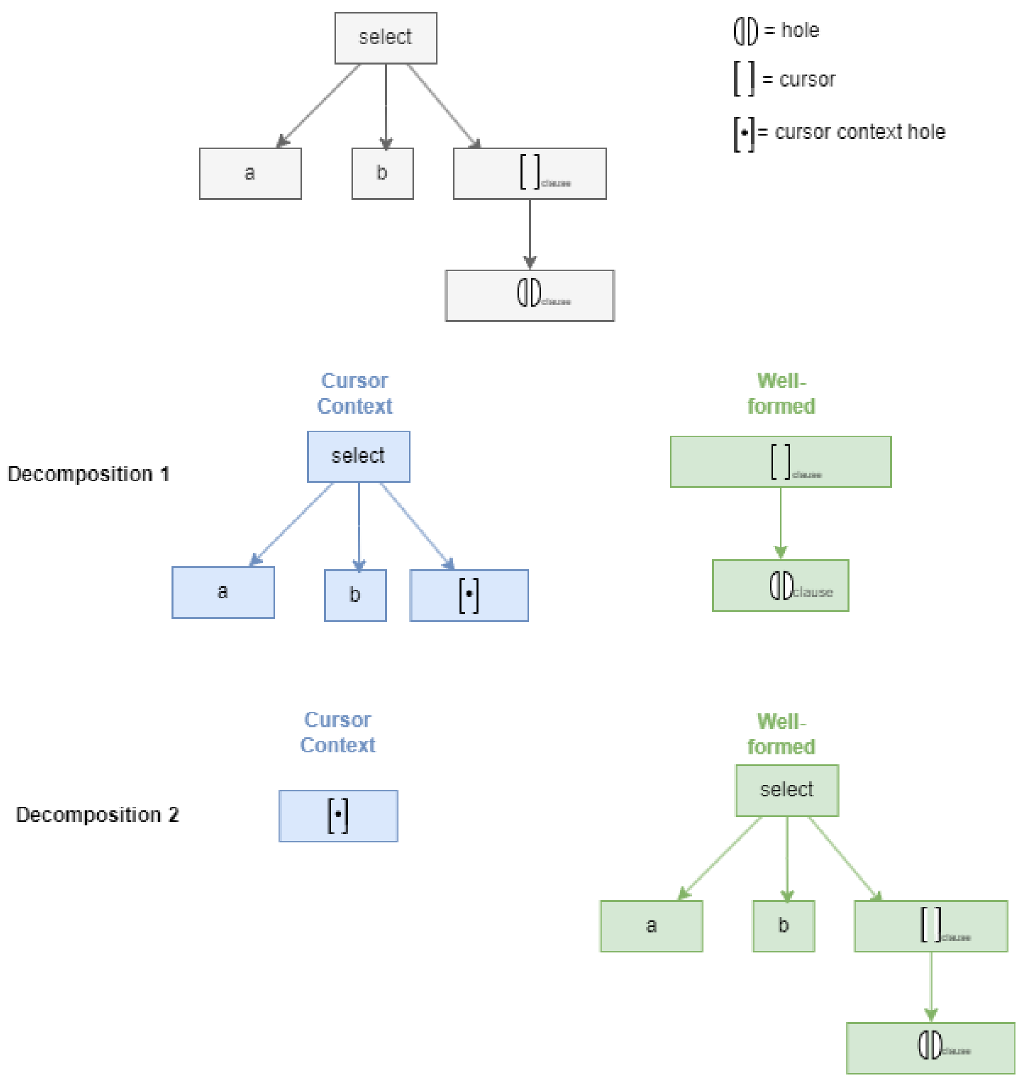


Figure 3.3: Two different decompositions of the same term

In order to generate a decomposition function which works for any sort, it is necessary to specify how we for any term in any sort, can decompose uniquely into a cursor context and well-formed-tree pair.

Unique decomposition of an abt can be defined algorithmically and divided into following sub-tasks:

- Locate the cursor in the tree to be decomposed and generate a path to the cursor
- Generate an abt of sort $s^C \in \mathcal{S}^C$ based on the cursor path

- Generate an abt of sort $\dot{s} \in \dot{\mathcal{S}}$ based on the rest of the tree that was not traversed when generating the cursor context

This way of decomposing an abt always places the cursor at the root of the well-formed tree. This makes it impossible for the cursor to encapsulate the immediate child of the root, making the property 3 in the definition of well-formed trees (Definition 4) redundant. For this reason, the code generation has been revised to only generate an operator of arity $(\hat{s})\dot{s}$ (property 4), representing that the cursor only encapsulates the root of a cursorless abt of sort $\hat{s}$.

The following will explain in more details how the steps above can be done, and how we always get a unique decomposition, as long as the abt to be decomposed is well-formed.

Cursor path

Generating a path to the cursor in the abt of sort $s \in \mathcal{S}$ extended with hole and cursor operators (Definition 1) simplifies the process of generating the cursor context. The path tells us which operator $o^C \in \mathcal{O}^C$ replaces each $o \in \mathcal{O}$. The list can be generated by performing pre-order traversal of the tree to be decomposed, extending the list with every i, representing which argument in an operator of arity $(\vec{s}_1.s_1, ..., \vec{s}_i.s_i, ..., \vec{s}_n.s_n)\mathcal{S}$ was followed to locate the cursor. See Listing 3.6 for pseudocode demonstrating this process.

```
getCursorPath op path =
  case op of
    cursor -> path
    _ ->
      case length op.arity of
        0 -> []
        _ ->
          map ++
            (index_map
              (\i child ->
                getCursorPath child (path ++ [i]))
            op.arity)
```

Listing 3.6: Pseudocode for generating cursor path

The implementation of such a function depends on the set of sorts $\mathcal{S}$ and arity-indexed family of operators $\mathcal{O}$ given by the abstract syntax of a language. The Elm CodeGen package[15] has been used to generate a `getCursorPath` function for a `Base` type (Listing 3.7). The function makes use of the helper function `getBranchList` which is left out for brevity, but its purpose is to generate a case expression for every syntactic category in the given syntax. See Example 10 for an excerpt of the generated `getCursorPath` function for the small C language (Example 5).

```
createGetCursorPath : Syntax -> Elm.Declaration
createGetCursorPath syntax =
    Elm.declaration "getCursorPath" <|
        Elm.withType
            (Type.function
                [ Type.list Type.int
                , Type.named [] "Base"
                ]
                (Type.list Type.int)
            )
            (Elm.fn2
                ( "path", Nothing )
                ( "base", Nothing )
                (\_ base ->
                    Elm.Case.custom base
                        (Type.named [] "Base")
                        (getBranchList syntax)
                )
            )
```

Listing 3.7: getCursorPath function generator

Example 10: Generated cursor path finder function

Following is an excerpt of the generated `getCursorPath` function for the small C language:

```
getCursorPath : List Int -> Base -> List Int
getCursorPath path base =
  case base of
    P p ->
      case p of
        Program arg1 ->
          getCursorPath (path ++ [ 1 ]) (Fd arg1)

        Hole_p ->
          []

        Cursor_p _ ->
```

```
          path
    ...
    Vd vd ->
      case vd of
        Vardecl arg1 arg2 ( boundVars3, arg3 ) ->
          (getCursorPath
            (path ++ [ 1 ])
            (T arg1)
            ++ getCursorPath
                (path ++ [ 2 ])
                (E arg2)
          )
          ++ getCursorPath
              (path ++ [ 3 ])
              (Bi arg3)

        Hole_vd ->
          []

        Cursor_vd _ ->
          path
```

Notable for this example is the `Vardecl` branch, which represents an operator with three arguments, hence the need for three recursive calls to `getCursorPath`. The third argument is deconstructed since it is a binder, although the bound variables are not used in the cursor path generation, as the cursor cannot be in a bound variable.

Cursor context

Having the cursor path, the cursor context can be generated by replacing every operator $o \in \mathcal{O}$ with its corresponding cursor context operator $o^C \in \mathcal{O}^C$, with respect to which argument in the operator was followed to locate the cursor. This is also done by performing pre-order traversal of the tree, but it will stop when the cursor is reached (i.e. when the cursor path is empty) and replace the operator reached with the context hole operator $[\,\cdot\,] \in C$. The rest of the tree which has not been traversed will be passed to the next step, generating the well-formed tree. See Listing 3.8 for pseudocode demonstrating this process.

```
toCCtx op path =
  case path of
    [] -> (context_hole, op)
    pathi :: pathrest ->
      case op of
        cursor -> error "invalid path"
        _ ->
          case length op.arity of
            0 -> error "invalid path"
            _ ->
              case pathi of
                1 ->
                  let (cctxarg1, restTree) =
                      toCCtx op.args[1] rest
                  in
                    (Cctx1_opName cctxarg1
                    , restTree)
                2 ->
                  let clessarg1 =
                      toCLess op.args[2]
                  let (cctxarg2, restTree) =
                      toCCtx op.args[2] rest
                  in
                    (Cctx2_opName clessarg1 cctxarg2
                    , restTree)
                ...
toCLess op =
  case op of
    Cursor _ -> error "not wellformed"
    _ ->
      case length op.arity of
        0 -> CLess_opName
        1 -> CLess_opName
                (toCLess op.args[1])
        2 -> CLess_opName
                (toCLess op.args[1])
                (toCLess op.args[2])
```

Listing 3.8: Pseudocode for generating cursor context

Functions supporting this are generated by Elm CodeGen, and can be seen in Listing 3.9, where a `toCCtx` function is generated for the `Base` type in conjunction with a `toCCtx_s` for every *s* syntactic category in the given syntax, where the algorithm described above is implemented for every sort.

```
createToCCtxFuns : Syntax -> List Elm.Declaration
createToCCtxFuns syntax =
  List.map createToCCtxFun syntax.synCatOps ++
  [ Elm.declaration "toCCtx" <|
    Elm.withType
      (Type.function
        [ Type.named [] "Base"
        , Type.list Type.int ]
        (Type.tuple
          (Type.named [] "Cctx")
          (Type.named [] "Base"))
      ) <|
      Elm.fn2
        ( "base", Nothing )
        ( "path", Nothing )
        (\base path ->
          Elm.Case.custom base
            (Type.named [] "Base")
            (List.map
              (\synCatOp ->
                Elm.Case.branchWith
                  synCatOp.synCat
                  1
                  (\exps ->
                    Elm.apply
                      (Elm.val <|
                      "toCCtx_" ++ synCatOp.synCat)
                      (exps ++ [ path ])
                  )
              )
              syntax.synCatOps
              )
        )
  ]
```

Listing 3.9: toCCtx function generator

Well-formed tree

The well-formed tree is generated by performing pre-order traversal of the rest of the tree that was not traversed when generating the cursor context. This is done by first replacing the cursor with the well-formed operator $\dot{o} \in \dot{\mathcal{O}}$ of arity $(\hat{s})\dot{s}$ indicating that the cursor encapsulates the root of a cursorless abt of sort $\hat{s}$. After this, the rest of the tree is traversed, and every operator $o \in \mathcal{O}$ is replaced with its corresponding cursorless operator $\hat{o} \in \hat{\mathcal{O}}$. See

Listing 3.10 for pseudocode demonstrating this process.

```
toWellformed op =
  let op = consumeCursor op
  in
    case length op.arity of
      0 -> error "not wellformed"
      1 -> Cursor_opName
              (toCLess op.args[1])
      2 -> Cursor_opName
              (toCLess op.args[1])
              (toCLess op.args[2])
      ...

consumeCursor op =
  case op of
    Cursor under -> under
    _ -> op
```

Listing 3.10: Pseudocode for generating well-formed tree

Like when generating functions supporting cursor context, a very similar approach is taken here, and can be seen in listing Listing 3.11.

```
createToWellFormedFun : Syntax -> Elm.Declaration
createToWellFormedFun syntax =
  Elm.declaration "toWellformed" <|
    Elm.withType
      (Type.function
        [ Type.named [] "Base" ]
        (Type.named [] "Wellformed")) <|
      Elm.fn
          ( "base", Nothing )
          (\base ->
            Elm.Case.custom
                (Elm.apply
                  (Elm.val "consumeCursor")
                  [ base ])
                (Type.named [] "Base")
                (List.map
                  (\synCatOp ->
                    branchWith synCatOp.synCat
                        1
                        (\exps ->
                          Elm.apply
```

```
                                        (Elm.val <|
                                          "Root_" ++
                                          synCatOp.synCat ++
                                          "_CLess")
                                        [ Elm.apply
                                          (Elm.val <|
                                            "toCLess_" ++
                                            synCatOp.synCat)
                                          exps
                                        ]
                                  )
                            )
                            syntax.synCatOps
                          )
                    )
```

Listing 3.11: toWellFormed function generator

The cursor context and well-formed tree pair as defined above will decompose any well-formed abt into a unique pair of a cursor context and a well-formed tree.

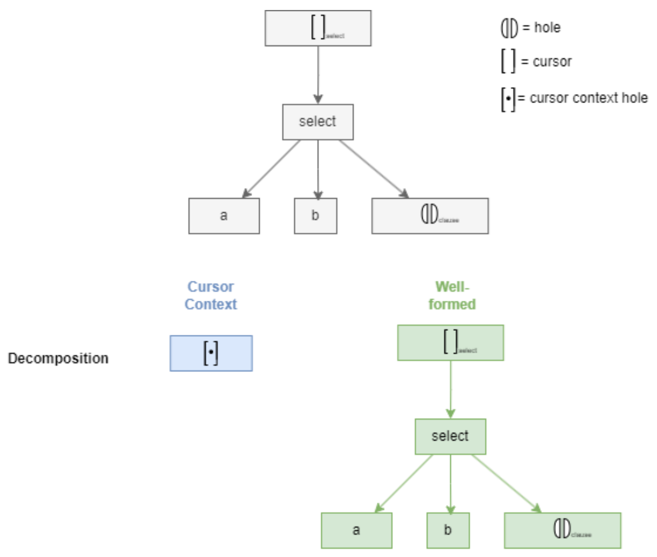
Cursor movement - Child

Cursor movement is a fundamental operation, allowing the editor to move the cursor to a different position, changing the target of editor expressions. This is defined as two operations in the editor calculus in the form of `Child-i` and `Parent` operations (Fig. 2.4).

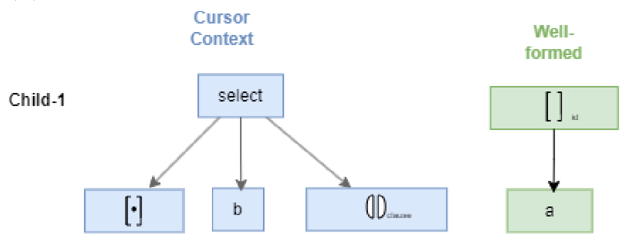
For moving to child i of an operator, a `child` function is generated which takes an integer i and a decomposed tree represented by a tuple of a cursor context and well-formed tree. It returns a new tuple, where the context hole in the cursor context has been replaced with the operator of sort $\mathcal{S}^C$ corresponding to the cursorless operator of sort $\hat{\mathcal{S}}$ under the cursor in the well-formed tree before moving the cursor. The integer i determines which argument of the cursor context operator contains the new context hole. The new well-formed tree is built by wrapping the ith argument of the cursorless operator current root operator in the well-formed tree.

For moving to the parent of the cursor, a `parent` function is generated which takes a decomposed tree and returns a new decomposed tree where the cursor

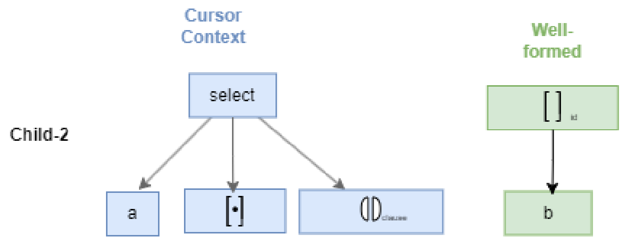
For a visualization of this, see Fig. 3.4 showing the result of applying various `child` operations to a decomposed tree. Pseudocode explaining the overall algorithm is provided in Listing 3.12.



(a) Decomposition of a small SQL program



(b) Applying the `Child-1` operation



(c) Applying the `Child-2` operation

Figure 3.4: Example of cursor movement

```
child(i, (cctx, wellformed)) =
  case wellformed of
    Root_Sort1 underCursor ->
      case underCursor.arity of
        0 -> error "operator has no children"
        1 ->
      case i of
       1 ->
        (replaceCCtxHole cctx i underCursor
         -- X: sort of child
        , Root_SortX underCursor.args[1])
       _ -> error "Invalid child"
    2 ->
      case i of
       1 ->
        (replaceCCtxHole cctx i underCursor
        , Root_SortX underCursor.args[1])
       2 ->
        (replaceCCtxHole cctx i underCursor
        , Root_SortX underCursor.args[2])
       _ -> error "Invalid child"
    ...
  Root_ClessOp2 ->
   ...

replaceCCtxHole cctx i underCursor =
 case cctx of
  CCtxHole ->
   case underCursor arg1 arg2 ... argn of
    Root_Sort1 _ ->
     case i of
      1 -> CCtx1_Sort1 CctxHole ... argn
      2 -> CCtx2_Sort1 arg1 CctxHole ... argn
      ...
    Root_Sort2 _ _ ->
     case i of
      1 -> CCtx1_Sort2 CctxHole ... argn
      2 -> CCtx2_Sort2 arg1 CctxHole ... argn
      ...
    ...
  CCtxOp1 arg1 .. argn ->
   CCtxOp1
    (replaceCCtxHole arg1 i underCursor)
    ...
    argn
  CCtxOp2 args ->
   CCtxOp2
    arg1
    (replaceCCtxHole arg2 i underCursor)
```

```
        ...
        argn
    ...
```

Listing 3.12: Pseudocode for applying child operator

This has been implemented by generating a `child` function which takes an integer i and a decomposed tree, and returns a new cursor context and well-formed tree pair.

Example 11: Generated child function

Following is an excerpt of the generated `child` function for the small C language:

```
child : Int ->
        ( Cctx , Wellformed ) ->
        Maybe ( Cctx , Wellformed )
child i decomposed =
    let
        ( cctx , wellformed ) =
            decomposed
    in
    case wellformed of
        Root_p_CLess underCursor ->
            case underCursor of
                Program_CLess arg1 ->
                    case i of
                        1 ->
                            Just
                                ( replaceCctxHole
                                    i
                                    cctx
                                    (P_CLess
                                      underCursor)
                                , Root_fd_CLess
                                    arg1
                                )

                        _ ->
                            Nothing

                Hole_p_CLess ->
                    Nothing
```

```

          Root_s_CLess underCursor ->
              case underCursor of
                  Assignment_CLess arg1 arg2 ->
                      case i of
                          1 ->
                              Just
                                  ( replaceCctxHole
                                      i
                                      cctx
                                      (S_CLess
                                        underCursor)
                                  , Root_id_CLess
                                      arg1
                                  )

                          2 ->
                              Just
                                  ( replaceCctxHole
                                      i
                                      cctx
                                      (S_CLess
                                        underCursor)
                                  , Root_e_CLess
                                      arg2
                                  )

                          _ ->
                              Nothing
```

Cursor movement - Parent

Moving the cursor to the parent of the cursor is done by first updating the cursor context by moving the context hole a level up, such that the parent of the context hole becomes the new context hole. Then, the parent of the cursor context which has been updated (operator of sort $\mathcal{S}^C$) is inserted as its equivalent well-formed operator (operator of sort $\dot{\mathcal{S}}$) at the root of the well-formed tree.

To visualize this, consider the example already given for the `child` operations, but where applying the `Parent` operation to the tree in Fig. 3.4c would result in the tree in Fig. 3.4a.

The pseudocode for this operation is shown in Listing 3.13. In this pseudocode, the `parent` function first updates the cursor context by calling the `moveCCtxHoleUp` function, which moves the context hole one level up in the cursor context tree. The `moveCCtxHoleUp` function recursively traverses the cursor context based on the cursor context hole's path. When the path contains two elements, we are one level above the cursor context hole's parent, which is then replaced with the new context hole (line 11-14).

When the path contains only one element, the cursor context hole is an immediate child of the root, and in that case it can be replaced directly with the new context hole (line 15).

If the path contains more than two elements, the function recurses further down the cursor context tree, until the grand-parent of the cursor context hole is reached (line 16-28).

Next, the insertAsRoot function is called to insert the removed context as the new root of the well-formed tree. This function adds the prior root of the well-formed tree as an argument to the removed cursor context's equivalent well-formed operator, which is then placed at the root of the well-formed tree. The checks being performed in the `insertAsRoot` function ensure that the insertion is well-formed, i.e. it checks that if an operator of arity $(\vec{\hat{s}}_1.\hat{s}_1, ..., \vec{\hat{s}}_i.C, ..., \vec{\hat{s}}_n.\hat{s}_n)C$ was removed from the cursor context, the root of the well-formed tree must be an operator of sort $(\vec{\hat{s}}_i.\hat{s}_i)\dot{s}$.

```
1  parent((cctx, wellformed)) =
2    let (newCCtx, removed) = moveCCtxHoleUp holepath cctx
3    let newWellformed = insertAsRoot removed wellformed
4    in
5      (newCCtx, newWellformed)
6
7  moveCCtxHoleUp holepath cctx =
8    case holepath of
9      [_,_] -> case cctx of
10                CCtxHole -> error "invalid path"
11                CCtxOp1 arg1 ... argn ->
12                  ((CCtxOp1 CCtxHole ... argn), arg1)
13                CCtxOp2 arg1 arg2 ... argn ->
14                  ((CCtxOp2 arg1 CCtxHole ... argn), arg2)
15     [_] -> (CCtxHole, cctx)
16     _ : restpath -> case cctx of
17                       CCtxOp1 arg1 ... argn ->
```

```
                    let (newCCtx, removed) =
                        moveCCtxHoleUp restpath arg1
                    in
                      ((CCtxOp1 newCCtx ... argn)
                      , removed)
                  CCtxOp2 arg1 arg2 ... argn ->
                    let (newCCtx, removed) =
                        moveCCtxHoleUp restpath arg2
                    in
                      ((CCtxOp2 arg1 newCCtx ... argn)
                      , removed)
    [] -> error "empty path"

insertAsRoot removed wellformed =
  case removed of
    CCtxHole -> error "invalid cctx"
    CCtxOp1_SortY arg1_SortX ... argn ->
      case wellformed of
        Root_SortX underCursor ->
          Root_SortY (CLessOp_SortY underCursor)
        _ -> error "not wellformed"
    CCtxOp2_SortY arg1 arg2_SortX ... argn ->
      case wellformed of
        Root_SortX underCursor ->
          Root_SortY (CLessOp_SortY underCursor)
        _ -> error "not wellformed"
    ...
```

Listing 3.13: Pseudocode for applying parent operator

Substitution

Substitution allow for replacing the abt encapsulated by the cursor with another abt of the same sort, ensuring that well-formedness is maintained. This is defined as the `Insert-op` operation in the editor calculus (Fig. 2.3).

In order to implement this, a function needs to

For this a `substitution` function is generated

Conditional expressions, Sequence, Recursion and Context

Conditional expressions provide a way to perform different operations based on modal logic of the encapsulated abt, such as the @o operator which holds if the cursor is encapsulating the operator o. This is defined as `At-op` along `Necessity`, `Possibly-i` and `Possibly-i` operators in the editor calculus[1] (Fig. 2.6). Conditionals can be connected with logical operators, forming the operators `Negation`, `Conjunction`, `Disjunction-1` and `Disjunction-2` (Fig. 2.5).

Unfortunately, this project has not yet implemented conditional expressions, but it is entirely possible by generating functions for each of the conditional operators, which would take a decomposed tree and return a boolean value based on the modal logic of the encapsulated abt.

Like conditional expressions, sequence, recursion and context operators have not been implemented in this project.

Making the functionality generic

For example, consider the cursor substitution operator (Fig. 2.3), where the editor calculus enforces that operators can only be substituted with operators of same sort. Initially, a straightforward approach involves having a substitution function for each sort $s \in \mathcal{S}$. This approach of course leads an implementer to consider generalization, i.e. how a single function can take any cursor-encapsulated abt and replace it with an operator of the same sort. A solution to this could be using type classes, where we might have a type class called `substitutable` and having an instance for each sort. Having a typeclass is possible in Haskell (Listing 3.14), but typeclasses are not directly supported by Elm. They can however be simulated with Elm records, as shown in the "typeclasses" Elm package[16]. An example of such a simulation is shown in Listing 3.15. This typeclass simulation in Elm has the disadvantage of forcing an explicit reference to the typeclass "instance" in a generic function, in contrast to Haskell. This leads to more verbose code and more source code generation.

```haskell
class Substitutable a where
    substitute :: a -> a -> a

instance Substitutable a where
    substitute _ replacement = replacement

doIntSub :: Int
doIntSub = substitute 1 2
```

Listing 3.14: Haskell typeclass example

```elm
type alias Substitutable a =
    { substitute : a -> a -> a }

substituteAny : Substitutable a
substituteAny =
    { substitute = \_ replacement -> replacement }

substitute : Substitutable a -> a -> a -> a
substitute substitutable expression replacement =
    substitutable.substitute expression replacement

doIntSub : Int
doIntSub =
    substitute substituteAny 1 2
```
Listing 3.15: Elm typeclass simulation example

Chapter 4

Editor Examples

The following will show ...

The following section will show from start to finish, how the implementation can be used to instantiate a syntax-directed editor for the C language (Example 5), SQL (Example 6) and LaTeX(Example 7).

Each section will first show what the computer-friendly and parseable syntax for each language looks like, followed by an excerpt of the generated source code for the editor instance. Finally, a demonstration of the editor in action will be shown using the Elm REPL, where a sample tree built from the generated algebraic data types is manipulated with the generated functions.

4.0.1 C

The syntax for the C language is given in Example 5. The same syntax, but in a more computer-friendly format is given in Listing 4.1.

```
p in Prog
s in Stmt
vd in VariableDecl
fd in FunDecl
t in Type
id in Id
e in Exp
b in Block
bi in BlockItem
fa in Funarg
cond in Conditional

```

```
p ::= fd # (fd)p # program
b ::= bi # (bi)b # block
bi ::= vd # (vd)bi # blockdecls
     | s # (s)bi # blockstmts
     | epsilon # ()bi # blockdone
vd ::= t id \"=\" e; bi # (t,e,id.bi)vd # vardecl
fd ::= t_1 id_1 \"(\" t_2 id_2 \")\" \"{\" b \"}\"
            # (t,id.fd,t,id.b)fd
            # fundecl1
     | t_1 id_1 \"(\" t_2 id_2, t_3 id_3 \")\" \"{\" b
        \"}\"
            # (t,id.fd,t,t,id.id.b)fd
            # fundecl2
     | epsilon # ()fd # fundecldone
s ::= id \"=\" e \";\" # (id,e)s # assignment
     | id \"(\" fa \")\";\" # (id,fa)s # stmtfuncall
     | \"return \" e \";\" # (e)s # return
     | cond # (cond)s # conditional
     | s_1 s_2 # (s,s)s # compstmt
fa ::= t id # (t,id)fa # funarg
     | t id, fa # (t,id,fa)fa # funargs
cond ::= \"if (\" e \")\" \"{\" b_1 \"} else {\" b_2
    \"}\"
            # (e,b,b)cond
            # ifelse
t ::= \"int\" # ()t # tint
     | \"char\" # ()t # tchar
     | \"bool\" # ()t # tbool
e ::= %int # ()e # int[Int] | %char # ()e # char[Char]
     | %bool # ()e # bool[Bool]
     | e_1 \"+\" e_2 # (e,e)e # plus
     | e_1 \"==\" e_2 # (e,e)e # equals
     | id \"(\" fa \")\" # (id,fa)e # expfuncall
     | id # (id)e # expident
id ::= %string # ()id # ident[String]
```
Listing 4.1: Parseable format of C language syntax

When passed the parseable format, the parser will produce the algebraic data types given in Listing 4.2, alongside relevant functions for cursor movement (Listing 4.3) and substitution (Listing 4.4). This makes up in total around 4000 lines of Elm code, so only a small excerpt is shown here, but the full example can be found in the source code repository.

```
type P
    = Program Fd
    | Hole_p
    | Cursor_p P

type S
    = Assignment Id E
    | Stmtfuncall Id Fa
    | Return E
    | Conditional Cond
    | Compstmt S S
    | Hole_s
    | Cursor_s S
...
type P_CLess
    = Program_CLess Fd_CLess
    | Hole_p_CLess


type S_CLess
    = Assignment_CLess Id_CLess E_CLess
    | Stmtfuncall_CLess Id_CLess Fa_CLess
    | Return_CLess E_CLess
    | Conditional_CLess Cond_CLess
    | Compstmt_CLess S_CLess S_CLess
    | Hole_s_CLess
...
type Cctx
    = Cctx_hole
    | Program_CLess_cctx1 Cctx
    | Block_CLess_cctx1 Cctx
    | Blockdecls_CLess_cctx1 Cctx
    | Blockstmts_CLess_cctx1 Cctx
    | Vardecl_CLess_cctx1 Cctx E_CLess (Bind Id_CLess
       Bi_CLess)
    | Vardecl_CLess_cctx2 T_CLess Cctx (Bind Id_CLess
       Bi_CLess)
    | Vardecl_CLess_cctx3 T_CLess E_CLess (Bind Id_CLess
        Cctx)
    ...

type Wellformed
```

```
    = Root_p_CLess P_CLess
    | Root_s_CLess S_CLess
    | Root_vd_CLess Vd_CLess
    | Root_fd_CLess Fd_CLess
    | Root_t_CLess T_CLess
    | Root_id_CLess Id_CLess
    | Root_e_CLess E_CLess
    | Root_b_CLess B_CLess
    | Root_bi_CLess Bi_CLess
    | Root_fa_CLess Fa_CLess
    | Root_cond_CLess Cond_CLess
```

Listing 4.2: Generated ADT for the C language

```
getCursorPath : List Int -> Base -> List Int
getCursorPath path base =
    case base of
        P p ->
            case p of
                Program arg1 ->
                    getCursorPath (path ++ [ 1 ]) (Fd
                       arg1)

                Hole_p ->
                    []

                Cursor_p _ ->
                    path

        B b ->
            case b of
                Block arg1 ->
                    getCursorPath (path ++ [ 1 ]) (Bi
                       arg1)

                Hole_b ->
                    []

                Cursor_b _ ->
                    path
...


parent : ( Cctx, Wellformed ) -> Maybe ( Cctx,
   Wellformed )
parent decomposed =
    let
        ( cctx, wellformed ) =
            decomposed
    in
    case moveCCtxHoleUp cctx (getCctxPath cctx []) of
        Nothing ->
            Nothing

        Just ( newCctx, removedCctx ) ->
            case addParent removedCctx wellformed of
                Nothing ->
                    Nothing

                Just newWellformed ->
                    Just ( newCctx, newWellformed )

...

child : Int -> ( Cctx, Wellformed ) -> Maybe ( Cctx,
   Wellformed )
child i decomposed =
    let
        ( cctx, wellformed ) =
            decomposed
    in
    case wellformed of
        Root_p_CLess underCursor ->
            case underCursor of
                Program_CLess arg1 ->
                    case i of
                        1 ->
                            Just
                                ( replaceCctxHole i cctx
                                    (P_CLess underCursor
                                   )
                                , Root_fd_CLess arg1
                                )

                        _ ->
                            Nothing

                Hole_p_CLess ->
                    Nothing

        Root_s_CLess underCursor ->
            case underCursor of
                Assignment_CLess arg1 arg2 ->
                    case i of
                        1 ->
                            Just
                                ( replaceCctxHole i cctx
                                    (S_CLess underCursor
                                   )
                                , Root_id_CLess arg1
                                )

                        2 ->
                            Just
                                ( replaceCctxHole i cctx
                                    (S_CLess underCursor
                                   )
                                , Root_e_CLess arg2
                                )

                        _ ->
                            Nothing

        ...
```

Listing 4.3: Generated functions for cursor movement for the C language

Listing 4.4: Generated functions for substitution for the C language

Consider Listing 4.5 showing the Elm REPL manipulating a sample program within the language.

```
> example = P <|
|           Program <|
|               Fundecl1
|                   Tint
|                   ( [ Ident "main" ], Fundecldone )
|                   Tint
|                   ( [ Ident "x" ]
|                   , Block
|                        (Blockstmts
|                            (Compstmt
|                                (Assignment (Ident "x")
   (Cursor_e Hole_e))
|                                (Return (Expident (Ident
    "x")))
|                            )
|                        )
|                    )
|
P (Program (Fundecl1 Tint ([Ident "main"],Fundecldone)
   Tint ([Ident "x"],Block (Blockstmts (Compstmt (
   Assignment (Ident "x") (Cursor_e Hole_e)) (Return (
   Expident (Ident "x"))))))))
    : Base

> decomposed = decompose example
(Program_CLess_cctx1 (Fundecl1_CLess_cctx4 Tint_CLess ([
   Ident_CLess "main"],Fundecldone_CLess) Tint_CLess ([
   Ident_CLess "x"],Block_CLess_cctx1 (
   Blockstmts_CLess_cctx1 (Compstmt_CLess_cctx1 (
   Assignment_CLess_cctx2 (Ident_CLess "x") Cctx_hole) (
   Return_CLess (Expident_CLess (Ident_CLess "x"))))))),
   Root_e_CLess Hole_e_CLess)
    : ( Cctx, Wellformed )

> new = parent decomposed
Just (Program_CLess_cctx1 (Fundecl1_CLess_cctx4
   Tint_CLess ([Ident_CLess "main"],Fundecldone_CLess)
   Tint_CLess ([Ident_CLess "x"],Block_CLess_cctx1 (
   Blockstmts_CLess_cctx1 (Compstmt_CLess_cctx1
   Cctx_hole (Return_CLess (Expident_CLess (Ident_CLess
   "x"))))))),Root_s_CLess (Assignment_CLess (
   Ident_CLess "x") Hole_e_CLess))
    : Maybe ( Cctx, Wellformed )

> child 1 (Maybe.withDefault (Cctx_hole, Root_p_CLess
   Hole_p_CLess) new)
Just (Program_CLess_cctx1 (Fundecl1_CLess_cctx4
   Tint_CLess ([Ident_CLess "main"],Fundecldone_CLess)
   Tint_CLess ([Ident_CLess "x"],Block_CLess_cctx1 (
   Blockstmts_CLess_cctx1 (Compstmt_CLess_cctx1 (
   Assignment_CLess_cctx1 Cctx_hole Hole_e_CLess) (
   Return_CLess (Expident_CLess (Ident_CLess "x"))))))),
   Root_id_CLess (Ident_CLess "x"))
    : Maybe ( Cctx , Wellformed )

TODO: substitution example
```
Listing 4.5: Elm REPL demonstration of C language editor

4.0.2 SQL

4.0.3 LaTeX

Chapter 5

Conclusion

This chapter concludes the thesis by summarizing the contributions and discussing future work.

This project was exploratory in nature, aiming to implement a generic editor based on the work of the Aalborg project[1] and other related work.

Only atomic prefix commands have been implemented, including the ability to move the cursor and perform substitutions. This was a necessary first step to implement the remaining editor expressions, which unfortunately were not completed. This however has led to a minimal viable product, which is a program that can instantiate a syntax-directed editor for any language, where basic edits can be performed on the syntax tree directly.

5.0.1 Future work

Editor expressions for the remaining commands should be implemented, this is possible by following a similar approach to the one used for the atomic prefix commands, i.e. by implementing function generators for each command based on its semantics.

Different views is also a feature that could be implemented, allowing for the editor to display the syntax tree in different ways, such as a tree view or string-format (i.e. pretty-printing). The model in the implementation is already designed to hold the concrete syntax of an operator, allowing for pretty-printing to be implemented with relative ease.

There is currently no active use of binders in the editor, leaving out the possibility of potentially checking for use-before-declarations or shadowing. However, the model in the implementation does hold information about binders, making future work on this easier.

Given the generic nature of the editor, it would be interesting to see an implementation in a language with support for typeclasses, such as Haskell. This should allow for a more concise implementation overall, being less rigid than the current implementation, since it relies on references to functions and data types via a low-level interface in the Elm CodeGen package, which refers to them with manipulated strings This is in contrast to typeclass instances, which would allow for a more abstract representation of a tree of any sort.

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