Modernizing the WebDSL front-end: A case study in SDF3 and Statix

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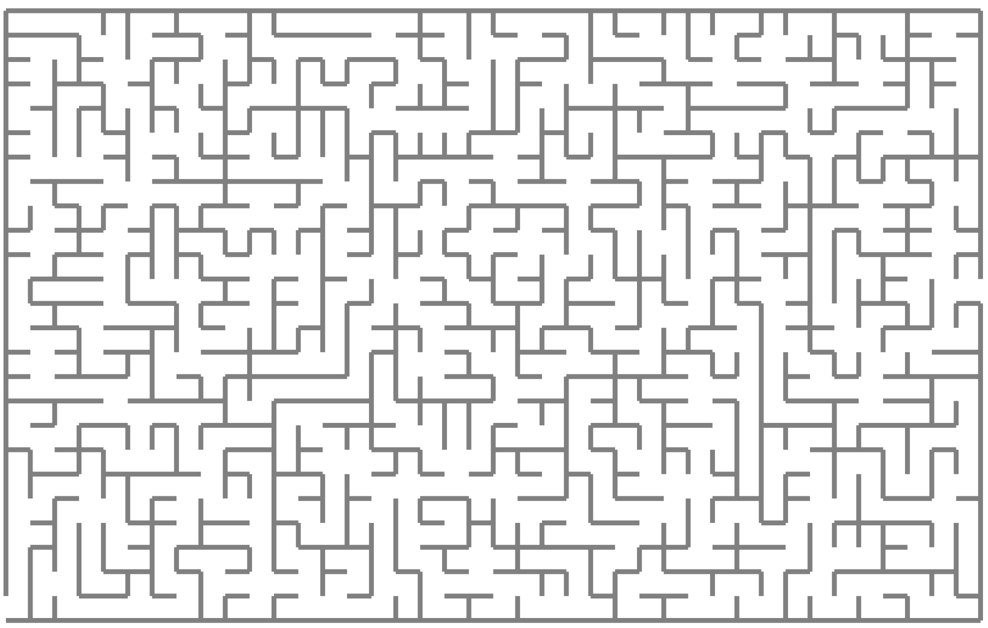

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THESIS

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Abstract

WebDSL is a domain-specific language for web programming that is being used for over ten years. As web applications evolved over the past decade, so did WebDSL. A complete formal specification of WebDSL has been *TO-DO: check if missing or not updated* since its original development. With the introduction of Statix in the Spoofax Language Workbench, a declarative language that generates a typechecker, we made an elegant and practical formal semantics for WebDSL.

Preface

Preface here.

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Delft, the Netherlands
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Chapter 1

Introduction

Computer programming is an essential skill that is increasingly important in diverse disciplines (Rafalski et al. 2019). To this end, many different programming languages exist, each with different properties and advantages. Over time, the popularity of programming languages change and developers tend to have preferences for one language over the other. In addition to preference, the implementation of a language and the tools that come with it can greatly boost the productivity of developers, if done well.

Another key to boost the productivity of software engineers is abstractions. Abstractions allow developers to think in terms closer to the domain rather than the implementation. In other words, the ideal level of abstraction increases the focus on the what, and steers away from the how. In this thesis, we will focus on a *domain-specific language* (DSL). In contrast to a general-purpose language such as Java, C, or Python, a domain-specific language does not intend to provide solutions for problems from all domains, but instead focus on a single domain. This restriction allows for a high level of abstraction in the language itself, in an attempt to boost developer productivity. Examples of popular domain-specific languages are CSS for styling web pages and SQL for efficient database querying.

In this thesis, we are using the domain-specific language *WebDSL* as a large case study for the languages *SDF3* and *Statix*. WebDSL is a domain-specific language for developing web applications, developed and maintained by the Programming Languages research group of the Delft University of Technology.

When inspecting the implementation of a programming language, the process is split up in multiple parts such as parsing, static analysis, code generation and optimization. The parsing, desugaring and static analysis is often called the front-end of a programming language, and this is the part developers face directly. The code generation and code optimization is called the back-end, and is required to make the programming language operational. While the back-end of a programming langauge makes it work, the front-end plays a large role in how developers experience a programming language. Early feedback in the form of good error messages and hints are required to make the interaction with a programming language efficient (Becker et al. 2019).

Because of the language-based approach of WebDSL for encoding domain concepts, many features that would be a library or an external tool in a general purpose language, are linguistically integrated into WebDSL. Examples of such features are fuzzy search and defining the data model. The linguistic integration of these features allows for better consistency checking and more precise error descriptions.

Currently, the WebDSL implementation is composed of multiple definitions in meta-languages supported by the *Spoofax Language Workbench* (Kats and Visser 2010). Spoofax is an environment in which multiple meta-DSLs are used to declaratively specify a programming language. WebDSL is developed in Spoofax. In particular, the WebDSL syntax is defined in SDF2 and the desugaring, typechecking, optimization and code generation is defined in the term transformation language Stratego. In the current Stratego implementation of the WebDSL, the compilation steps are not clearly separated, which poses a threat to the readability and maintainability of the WebDSL language.

Continuous improvement of the Spoofax language workbench has introduced more meta-languages specialized in different parts of the language development chain. In this thesis, we will be modernizing the WebDSL front-end, by using the Spoofax meta-languages SDF3 to specify and disambiguate the syntax from which a parser is generated, and Statix to declare the static semantics from which a typechecker is automatically generated.

1.1 Why WebDSL as case study?

WebDSL is an interesting case study for SDF3 and Statix because of two main reasons. Firstly, WebDSL has a large amount of language features inspired by multiple paradigms of programming languages. As a consequence, the resulting SDF3 and Statix specifications are arguably the largest specifications to date. Accompanied by the large amount of publicly available source code for evaluation purposes, we aim to make observations about the elegancy of the resulting specifications and the scalability of their performance. Since this thesis is a case study, we cannot make general claims about the performance of SDF3 and Statix, but only reveal and analyse results of the WebDSL specification.

Secondly, WebDSL contains language features that have never been modelled in Statix before. Specifically, those features are:

- Bi-directional type extension
- Generated functions and classes
- An unconventional module and scoping system

With the implementation of the above features in Statix, we aim to contribute to assessing whether Statix is capable of modelling the static semantics of all reasonable programming languages.

1.2 Contributions

In this thesis, the following contributions are made.

- We present a modernized WebDSL front-end through an implementation of its grammar in SDF3 and its analysis in Statix and document the challenges of this process.
- We assess the coverage of Statix and SDF3 by attempting to model all language features of WebDSL, evaluating the result on existing test suites, and give qualitative feedback on how to further improve the coverage and increase the elegancy of definitions.
- We assess the performance of Statix and SDF3 by benchmarking the new WebDSL front-end with large codebases of existing applications.

1.3 Outline

The rest of this thesis is structured as follows. In Chapter 2 we describe WebDSL, its features and its current implementation. Next, Chapter 3 and Section 4.1 go in detail about the new implementation of the WebDSL front-end in SDF3 and Statix respectively. The result of this implementation is evaluated in Chapter 5 and compared with related work in Chapter 6. Finally, Chapter 7 concludes this thesis.

Chapter 2

WebDSL

In this chapter, we describe WebDSL. WebDSL is a domain-specific language for developing web applications. The language incorporates ideas from various web programming frameworks and produces code for all tiers in a web application (Groenewegen, Chastelet, and Visser 2020). Ever since its introduction over 10 years ago (Visser 2007), WebDSL has been the subject of many published papers (cite some papers here) and on top of that, is the programming language underpinning several applications used daily by thousands of users. Examples of WebDSL applications include but are not limited to:

- **WebLab**: An online learning management system, used by the Delft University of Technology.
- **conf.researchr.org**: A domain-specific content management system for conferences, used by all ACM SIGPLAN and SIGSOFT conferences.
- **researchr.org**: A platform for finding, collecting, sharing, and reviewing scientific computer science related publications.

TO-DO:

- Paragraph with strong points of WebDSL

The rest of this chapter showcases the different aspects of WebDSL and zooms in on its non-trivial features. First, in Section 2.1 we will describe how WebDSL offers functionality for creating web user interfaces. Next, in Section 2.2 we illustrate how the langauge manages data models. Thirdly, Section 2.3 contains information about WebDSL's solution for access control and in Section 2.4 we highlight interesting aspects of its general-purpose object oriented function code. We concluse this chapter by going in detail about WebDSL's current implementation in Section 2.5.

2.1 User Interfaces

Introduction

2.1.1 Building blocks and Syntax

Domain specific language for web applications -> the UI is how the user interacts with the application.

Page is the entry point, arguments are clean URL parameters.

Templates are reusable components that can be inserted on pages or in other templates.

Short example with three boxes next to each other (WebDSL code left, resulting HTML right, resulting UI bottom):

Functionalities for in example:
- Pages
- Templates
- Navigate
- Text
- Divs
- HTML elements

2.1.2 Request processing and Action Code

With the building blocks of the previous subsection, only static pages can be made.

Need HTML forms and submits to manipulate data.

WebDSL abstracts over the usual manual request processing by using forms, inputs and action code.

Functionalities for in example:
- Form
- Multiple input sorts (boolean, string, text)
- Action with different redirects based on boolean, pass string to new page

2.1.3 Template Overriding and Overloading

2.1.4 Dynamically scoped redefines

2.1.5 Ajax

2.2 Data Model

- Syntax
- Inheritance
- Extending entities

2.3 Access Control

- Syntax
- Inferred visibility
- Nested rules
- Pointcuts

2.4 Functions

- Syntax

- Entities as classes
- Hooks for entity setters
- Extending functions

2.5 Current Implementation

2.5.1 Spoofax Language Workbench

- History
- Goal
- Achievements

2.5.2 Current Implementation of WebDSL

- Large Stratego specification where desugaring, static analysis, optimization and code-generation are interleaved (exaggeration?)
- Side effects using dynamic rules.
- Unexpected consequences of changes due to limited static analysis in untyped setting.

Go over some interesting WebDSL features and how they are implemented:

- Access control
- Template overloading and overriding
- Entity extension

2.6 Modernization goal

- A complete and maintainable SDF3 and Statix specification of WebDSL.
- Gather insight into the capabilities, elegance and performance of SDF3 and Statix.
- (Incrementalization for free leveraging the parallel Statix solver)

Chapter 3

WebDSL in SDF3

Goal: New specification of WebDSL grammar. Stay compatible with all existing WebDSL code; as few breaking changes as possible.

Goal: Large case study for SDF3.

Outline of chapter

3.1 WebDSL Grammar Specification

The current grammar of WebDSL is specified in SDF2, the predecessor of SDF3.

The WebDSL grammar specification consists of <> files with <> productions in total.

Parts of the syntax are deprecated but still mainainted for backwards compatibility reasons.

Some productions added for the sake of autocompletion.

Reason to switch to SDF3:
- Modern spoofax does not support SDF2 anymore?
- SDF3 more performant?

3.2 Introduction to SDF3

Able to declaratively specify the complete syntax of a programming language in SDF3, and a parser, highlighter and pretty-printer gets generated from this specification.

3.2.1 Syntax

- Lexical sorts
- Context-free sorts
- Constructors
- Injections
- Optional sorts
- Repitition

3.2.2 Disambiguation

Possibilities:
- Prefer/avoid annotations on constructors (deprecated)
- Declare priorities of nested constructors
- Reject keywords
- Reject nesting of certain constructors

3.3 Migration from SDF2 to SDF3

There is a tool to migrate SDF2 specifications to SDF3 specifications but it does not work in all cases. Some work needs to be done to prepare the SDF2 specification for the migration, and some work needs to be done on the resulting SDF3 specification to make sure it is as usable as the old SDF2 specification.

3.3.1 Preparing the WebDSL SDF2 definition for migration

The SDF2 to SDF3 migration tool does not accept ″sorts″ sections.

Alternations must be removed from the SDF2 specification. Solution is to introduce a separate sort for the alternation:

Before:
(″B″ | ″C″) -> A cons(″A″)

After:
BorC -> A cons(″A″)
″B″ -> BorC cons(″B″)
″C″ -> BorC cons(″C″)

Restrictions (both context-free and lexical) produce an error during transformation and must be manually copied.

Mixed languages and parameterized imports are currently not supported in SDF3, so WebDSL code cannot be mixed with Stratego/Java code in the new SDF3 syntax definition.

Mixed languages were only used in the compiler, except for HQL which is used in WebDSL code. Fortunately, the HQL syntax is not used elsewhere and could be transformed to be a part of the WebDSL syntax natively.

3.3.2 Manual Tweaking of Generated WebDSL SDF3

Missing and duplicate constructors

In SDF3, the constructors are a much more key part of the productions than in SDF2, where constructors are defined as a `cons("MyConstructor")` annotation on the production. In the WebDSL SDF2 definition, some constructors were missing and there were many duplicate constructors that denoted alternative syntax for the same construct, essentially providing syntactic sugar.

In the newly generated SDF3, duplicate constructors had to be changed, in order for them to be unique. Additionally, missing constructors had to be added, preferably even for injections for a reason we will touch on later in Section 3.4.

Priority chains

To indicate priority amongst context-free productions, both SDF2 and SDF3 use the concept of priority chains, but the SDF2 variant requires a repitition of the production inside the chain, whereas SDF3 uses a reference to the sort with corresponding constructor. This causes the SDF2 priority chains to not be migrated to the SDF3 priority chains.

The only way to tackle this issue is to manually re-enter the priority chains in SDF3.

Transferring comments

Of a lesser importance, but highly recommended for the readability of a syntax definition is the comments, that are parsed as layout and are therefore not tranfered to the generated SDF3 files. Again, there is no way around this and they have to be manually transferred.

Template productions

A major change in SDF3 compared to SDF2 are template productions, that allow for nice pretty printing and syntactic code completion. The productions in the generated SDF3 files are all template productions, but do not have the proper surrounding layout and indentation because there is no way to extract this information from the SDF2 source. This had to be manually added to the generated SDF3 productions where applicable.

Deeply embedding HQL

Previously, the syntax definition of HQL was a standalone definition, and was used in the WebDSL SDF2 through parameterized imports. SDF3 has no support for this feature, so as discussed in Section 3.3.1, the language has to be transformed to be a part of the WebDSL syntax.

Deeply embedding the HQL syntax in the WebDSL syntax causes some errors to arise on duplicate names of sorts and constructors, this had to be fixed manually.

3.4 Preparation for Statix

With the intention to use Statix for implementing the WebDSL static analyses, the grammar sorts and constructors have strict requirements. Statix is a strongly typed language and requires all input to adhere to the declared sorts and constructors.

3.4.1 Sorts and Constructors in Statix

Statix takes an abstract syntax tree as input.

In the signature definition of Statix rules, it must be stated what the input and output sorts are. The implementation of the rules are defined over the constructors that belong to the sorts in the rule's signature.

Demo: Left top a few SDF3 productions, right top an abstract syntax tree, bottom statix sorts, constructors and a few rules.

All sorts and constructors that rules are defined over, have to be defined in the Statix code. In our case, a complete redefinition of all sorts and constructors in the Statix code is necessary to statically analyze the all WebDSL language features.

Unlike SDF3 and Stratego, Statix is statically typed and does not support injections or polymorphism in its constructors, which leaves some abstract syntax trees generated by the parser unable to serve as input for static analysis.

3.4.2 Statix Signature Generator

As mentioned and demonstrated in Section 3.4.1, Statix requires a definition of the constructors and sorts of the language to be analyzed. This definition exists in SDF3, but is not compatible with the Statix semantics since no injections are allowed. To prevent manual redefinition of the sorts in Statix code, the Statix Signature Generator is developped. This tool takes the SDF3 definition as input, and generates importable Statix files that contain the sorts and constructors from the syntax definition. For the Statix Signature Generator to work properly, Additional well-formedness requirements exist for the SDF3 definition.

Explicitly Declare Sorts

The parser generator that takes an SDF3 definition as input, is able to extract the sorts names from productions. Unfortunately, this is not the case for the Statix Signature generator so all sorts used in productions must be declared explicitly in `context-free sorts` and `lexical sorts` blocks.

TO-DO: Find reason and describe here

TO-DO: Example here with before and after with context-free and lexical sort blocks

Injections

With the semantics of Statix' constructors and sorts, it is not possible to model injections.

TO-DO: Example of injection here and impossibility of modelling in Statix

The Statix Signature Generator deals with simple injections (from one sort to one sort) by explicating the injections, making a more verbose version of the constructors and sorts.

TO-DO: Example here of simple injection explicated

Even though this functions properly, it is hard to read in the Statix rules. For this reason, we changed the WebDSL SDF3 to contain less injections by inserting constructors with descriptive names where injections were.

TO-DO: Show result

Optional Sorts

As mentioned in Section 3.2.1, SDF3 has built-in support for optional sorts, resulting in `Some(_)` and `None()` terms.

The resulting terms cannot be translated to Statix signatures, since this would mean a lot of duplicate Some and None constructors belonging to different sorts.

To resolve this challenge, the SDF3 definition must be altered make the Some and None constructors unique per sort. This leads to a much more verbose syntax definition:

TO-DO: Example here with two syntax definitions and resulting ASTs: one with built-in optional sorts, other with verbose optional sorts.

Disambiguation

As mentioned in Section 3.2.1, ambiguous code fragments lead to abstract syntax trees with the `amb(_, _)` term. Similar to optional sorts, this cannot be translated to Statix and therefore it is crucial that the syntax is disambiguated properly.

Next to this, the `prefer` and `avoid` annotations for disambiguation were heavily used in the WebDSL SDF2 definition. The annotations are supported in SDF3, but the support is likely to be dropped in a future release.

For the two reasons listed above, we reimplemented disambiguation through a combination of multiple SDF3 features. This process is explained in Section 3.5.

3.5 Disambiguation

Since the `amb(_,_)` constructor is not declarable in Statix, having an ambiguity in the AST leads to the analysis not executing. This increases the need for disambiguation.

Challenges and solutions:

- Keywords in WebDSL: SDF3 template options not optimal.
- String interpolation: Convert to one String constructor with a list of parts.
- Optional separators: In SDF2 multiple productions could have the same constructor, in SDF3 multiple constructors make for an increase in reject and desugaring rules.
- Optional alias vs. cast expression: use non-transitive priority rule.

3.6 Reflection on SDF3

Chapter 4

WebDSL in Statix

In this chapter, we elaborate on the implementation of the WebDSL static semantics in Statix, using the examples from Chapter 2 as a basis. We start this chapter by introducing the meta-DSL Statix. Once the goal and basics of Statix are stated, we describe the implementation of the type system that is the core of WebDSL. Next, we address and discuss the challenges faced while implementing non-trivial WebDSL features in Statix and lastly we reflect on the developer experience of using Statix to implement static analyses.

4.1 Introduction to Statix

Statix is a constraint-based declarative language for the specification of type systems, introduced in 2018 (Antwerpen et al. 2018). Since then, the meta-DSL Statix has become a part of the Spoofax Language Workbench and allows language developers to implement static analyses to provide language-specific feedback to developers on written code.

A Statix specification consists of rules over terms that define constraints. Additionally, Statix rules build and query a *scope graph* (Neron et al. 2015) that provides a language-agnostic representation of a program. A scope graph consists of nodes and edges that can be used to for example model the lexical scope of variables.

4.1.1 Language Signature

Consider a language consisting of booleans, integers and addition, for which we want to create a type-checker with Statix. First, Statix requires us to declare all types and sorts that we will be using in the rules. These Statix constructor names have to match the constructors of the input term (the AST). The Statix code that declares the sorts and constructors of our example language is shown in Figure 4.1. When writing a Statix specification for a language implemented in the Spoofax language workbench, it is a common practice to have the Statix signature generated from your SDF3 specification by the Statix signature generator (see Section 3.4.2), to prevent code duplication.

```
signature
  sorts
    Application
    Exp

  constructors
    Application : Exp       -> Application
    True        :              Exp
    False       :              Exp
    Int         : string    -> Exp
    Add         : Exp * Exp -> Exp
```

Figure 4.1: Language signature in Statix

So far, our specification consists of two sorts. The `Application` sort defines the entry point of our language, it has one constructor with an identical name. Next, the sort `Exp` describes what expressions are allowed. It has four constructors: the Boolean values `True` and `False`, `Int` which requires an integer literal as subterm, and `Add` which takes two nested expressions as subterms. Examples of valid input according to our defined signature are shown in Figure 4.2.

```
Application(True())                    // true
Application(Int("42"))                 // 42
Application(Add(Int("40"), Int("2")))  // 40 + 2
Application(Add(Int("40"), False()))   // 40 + false
```

Figure 4.2: Valid input terms for the described language

4.1.2 Semantic Types

Not all of the valid input terms according to our signature are well-typed. For example, the last term shown in Figure 4.2 features an addition of the integer literal `40` and the Boolean value `False`. Using Statix' constraint solving capabilities, we would like to give feedback to the programmer that the input is ill-typed.

Given the code in Figure 4.1, our Statix specification does not yet generate any constraints. Constraints that we would like to generate using Statix rules are firstly that a program must be well-typed and secondly, in order for an addition expression to be well-typed, its two subterms must be of integer type.

To reason about the types of expressions and use them in constraints, we must first define them in our specification, as shown in Figure 4.3. To distinguish input sorts and constructors from semantic types that we will use in our constraints, those sorts and constructors are defined in upper-case. With the new `TYPE` sort that has two constructors: `BOOL` and `INT`, we can start generating constraints on input terms.

```
signature
  sorts
    TYPE

  constructors
    BOOL : TYPE
    INT  : TYPE
```

Figure 4.3: Statix signature for Boolean and integer types

4.1.3 Predicates and Rules

Figure 4.4 lists the Statix predicates and rules required to generate the constraints we want to be satisfied in order for a program to be well-typed.

```
 1 rules
 2
 3   applicationOk : Application
 4   applicationOk(Application(e)) :- { T }
 5     typeOfExp(e) == T.
 6
 7   typeOfExp : Exp -> TYPE
 8   typeOfExp(True()) = BOOL().
 9   typeOfExp(False()) = BOOL().
10   typeOfExp(Int(_)) = INT().
11   typeOfExp(Add(e1, e2)) = INT() :-
12     typeOfExp(e1) == INT(),
13     typeOfExp(e2) == INT().
```

Figure 4.4: Statix predicates and rules for typing booleans, integers and addition

The type of all Statix predicates must be explicitly declared, for example the `applicationOk` predicate on **line 3** specifies that all rules of `applicationOk` match exactly one constructor `Application`. An instantiation of the `applicationOk` predicate is on **line 4**. In prose English it would read "An application is well-typed, given that for some type `T`, the expression `e` has type `T`".

The other Statix rule in our small example specification is a *functional predicate*, meaning that it returns a value. All but the last rules of the `typeOfExp` predicate compute a `TYPE` for a given expression, without conditions. The last rule of the example does have two conditions, in prose English it would read "`e1` plus `e2` is of type `INT`, given that `e1` is of type `INT` and `e2` is of type `INT`".

4.1.4 Building and Querying Scope Graphs

When we expand our small example language with let-bindings and we want to add typing rules for this new construct, we come across a new feature in Statix. To facilitate typing rules for name binding, Statix uses *scope graphs* (Neron et al. 2015). Scope graphs are built out of three components: scopes, edges and declarations.

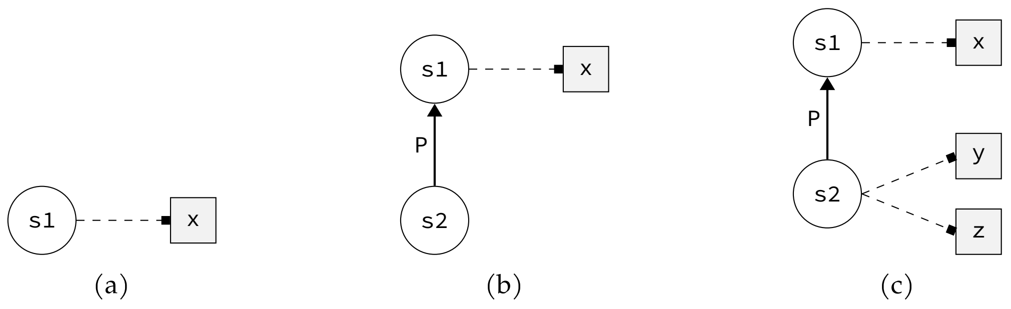


Figure 4.5: Scope graph examples

Figure 4.5 showcases three examples of scope graphs. Figure 4.5a consists of a single scope `s1` with declaration `x` that could be a model of a module with a single global variable `x` declared inside. The second example, Figure 4.5b, consists of two scopes: a root scope `s1` with again a declaration of `x`, and a scope `s2` with an outgoing edge to `s1` labeled `P`. The `P` label is often used to denote the relation of a lexical parent scope. In this example, `s2` could for example model an empty function declared in module `s1`. The last example again has two scopes, with one declaration in `s1` and two declarations in `s2`. This could model the same program as described previously, but now with two local variable declarations inside the function body of `s2`.

The first step in implementing let-bindings in Statix is adding the signature. In addition to the new constructors on **line 3 and 4**, we now introduce an edge label `P` and the relation `var`. The edge labels defined in the constructor provide the set of allowed labels to use in rules later on. The relation `var` on **line 11** specifies that any declaration made under the `var` relation in a scope, maps an identifier to its type.

For illustration purposes, when we want to encode a single scope with two variable declarations, `x` of type `INT` and `b` of type `BOOL`, its scope graph would be as shown in Figure 4.7.

```
 1 signature
 2   constructors
 3     Let : string * Exp * Exp -> Exp
 4     Var : string             -> Exp
 5
 6   name-resolution
 7     labels
 8       P // to denote parent scope
 9
10   relations
11     var : string * TYPE
```

Figure 4.6: Statix signature for let-bindings

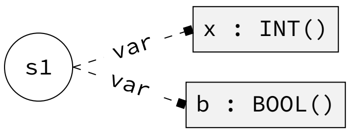


Figure 4.7: A scope graph containing a single scope with two declared variables

In Statix, scopes can be passed around as data. When we are evaluating an expression in our extended language, we now also want to pass the current scope. If the current input term that we are generating constraints for is a let-binding, we want to create a new scope, link it to the previous one, declare the variable in the new scope and evaluate the expression. To generate constraints for a variable expression, we want to query the scope graph and get its type. The Statix rules to reflect this are shown in Figure 4.8.

Figure 4.8 showcases various previously unexplained constructs:

- **Line 4** creates a new scope `s`. This scope is the root scope since it is created once at the start of an application and is not linked to any other scope.
- **Line 7** shows the new signature of the `typeOfExp` functional predicate. Given a scope and an expression, the rules of `typeOfExp` will compute the type of the expression.
- **Line 9-14** gives the typing rule of a let-binding. Given that the let-binding is of form `let x = e1 in e2`, the rule:
  - computes the type of `e1` on line 10;
  - creates a new scope `s_let` on line 11 for the body of the let to evaluate in;
  - declares variable `x` with associated type `T1` in the newly created scope `s_let`;
  - computes the type of `e2` and this is the result of the rule.
- **Line 16-21** holds the implementation of the variable typing rule. It executes a query with the following properties:
  - It only returns entries in the `var` relation (line 17)
  - It may follow zero or more `P` edge labels to other scopes (line 17);
  - It only returns declarations under the same identifier as `x` (line 18);

```
1  rules
2    applicationOk : Application
3    applicationOk(Application(e)) :- { s T }
4      new s,
5      typeOfExp(s, e) == T.
6
7    typeOfExp : scope * Exp -> TYPE
8    // ... previous rules
9    typeOfExp(s, Let(x, e1, e2)) = T2 :- { s_let T1 }
10     typeOfExp(s, e1) == T1,
11     new s_let,
12     s_let -P-> s,
13     !var[x, T1] in s_let,
14     T2 == typeOfExp(s_let, e2).
15
16   typeOfExp(s, Var(x)) = T :-
17     query var filter P*
18               and { x' :- (x', _) == (x, _) }
19               min $ < P
20               and true
21               in s |-> [(_, (_, T))].
```

Figure 4.8: Statix rules for let-bindings

- It prefers local declarations over declarations for which P edges must be followed (line 19);
- Shadowing according to the shadowing rules of line 19 is enabled (line 20);
- The query starts in the passed scope s (line 21);
- The result may only be one declaration (line 21).

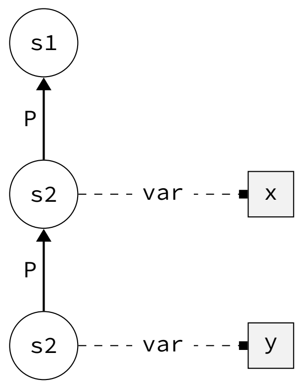
Figure 4.9 shows a possible input and the constructed scope graph after the constraints have been solved.

```
let x = 1 in
  let y = x in
    x + y
```

(a)

```
Application(
  Let(
    "x", Int("1"), Let(
      "y", Var("x"), Add(
        Var("x"),
        Var("y")
      )
    )
  )
)
```

(b)



(c)

Figure 4.9: Constructed scope graph after the example specification solved its contraints

4.2 Encoding the WebDSL Basics

The WebDSL language adheres to a structure similar to many popular programming languages. A WebDSL application consists of multiple files. At the topmost level in a file, there is a module or *unit* declaration. Within a module, multiple *sections* of *definitions* exist, such as pages, templates, entities and functions. A function consists of consecutive *statements* such as variable assignment (`var n := 2`). At the innermost level, these statements contain *expressions* that form the basis the WebDSL type system.

```
rules
  projectOk : scope
  unitOk    : scope * Unit
  sectionOk : scope * Section
  defOk     : scope * Definition
  typeOfExp : scope * Exp -> TYPE
```

Figure 4.10: Predicates that form the basis of the WebDSL Statix specification

To define well-typedness of the mentioned constructs, the Statix predicates as shown in Figure 4.10 form the backbone of the WebDSL Statix specification.

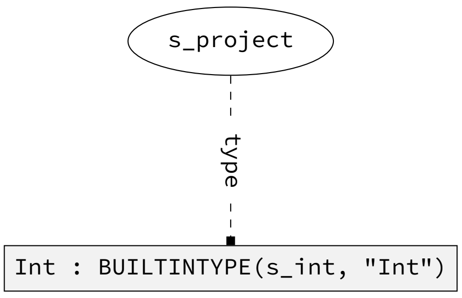
4.2.1 Built-in Types and Constant Expressions

Constant expressions such as strings, integers and booleans form the building blocks of more complication constructs. For reasons explained later (see section Section 4.6.2), a built-in type such as string is not declared as `STRING : TYPE` but instead as `BUILTINTYPE : scope * string -> TYPE`, where the instantiation of the string type is as follows: `BUILTINTYPE(s, "String")`.

These built-in types are declared in a scope that is reachable from almost every location, the project scope, once per analysis. All WebDSL type declarations are made under the `type` relation, which associates the human readable type name with a `TYPE` term: `type : string * TYPE`. The part of the Statix specification to achieve this, and the resulting scope graph are shown in Figure 4.11.

```
projectOk(s_project) :-
  declareTypeBuiltIns(s_project).
  // ...

declareTypeBuiltIns : scope
declareTypeBuiltIns(s) :-
  declareType(s, "Int",
    BUILTINTYPE(new, "Int")).
  // ...

declareType : scope * string * TYPE
declareType(s, name, t) :-
  !type[name, t] in s.
```

(a)



(b)

Figure 4.11: Declaring built-in types in the project scope

To retrieve a built-in type when evaluating a constant expression, we need to query the scope graph and resolve the type associated with the string representation. For example, the typing rules of an integer constant are listed in Figure 4.12. The integer typing rule introduces a constraint

```
typeOfExp(s, Const(Int(_))) = t :-
  resolveType(s, "Int") == [(_, (_, t))].

resolveType : scope * string
  -> list((path * (string * TYPE)))
resolveType(s, name) = ts :-
  query type filter P*
         and { t' :- t' == (name, _) }
         in s |-> ts.
```

```
 1 typeOfExp(s, Const(StringConst(String(str)))) = t :-
 2   resolveType(s, "String") == [(_, (_, t))],
 3   stringPartsOk(s, str).
 4
 5 stringPartsOk maps stringPartOk(*, list(*))
 6 stringPartOk : scope * StringPart
 7 stringPartOk(s, StringValue(_)).
 8 stringPartOk(s, InterpExp(exp)) :- typed(s, exp).
 9 stringPartOk(s, InterpValue(InterpSimpleExp(simple_exp))) :- { T }
10   typeOfSimpleExp(s, simple_exp) == T.
```

Figure 4.14: WebDSL string typing rules

that the scope graph must contain a single type declaration associated with `"Int"` under the `type` relation. The result of the `resolveType` functional predicate on **line 2** should be a list containing one entry, namely the pair that we declared in Figure 4.11. Other WebDSL constant expressions such as booleans, longs and floats have similar typing rules.

The typing of perhaps the most common constant expression, a string, has an additional condition to be well-typed. Because string interpolation is possible, the constructor of a WebDSL string contains multiple parts that may impose additional constraints. A demonstration of the different interpolated parts is shown in Figure 4.13 and the complete typing rules are shown in Figure 4.14. The parts can be a simple string value which imposes no additional constraints, they can be a complete interpolated expression which requires the expression to be typed, or lastly they can be a "simple" expression which is directly inlineable.

```
"Hello world" // value
"Hello ~( 1 + 2 )" // exp
"Hello ~x.y" // simple exp
```

Figure 4.13: WebDSL string interpolation examples

Now that all the typing rules for constants are implemented, typing rules for unary and binary operators are a step towards more complicated expressions. While it might seem trivial, we might require additional construct functional predicates for determining type compatibility or determining the resulting type of an expression.

4.2.2 Variables

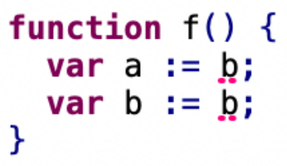
Similar to other imperative languages, WebDSL allows the use of variables to store values. These variables can be defined on multiple levels, such as in the module, within a function or at the top of a page/template definition. Additionally, functions may be embedded in entities, allowing direct access to entity properties as variables without having to prefix it with the `this` keyword.

The basic variable declaration and resolving rules are shown in Figure 4.15. Given a scope `s`, the declaration rule will make a declaration in `s` of variable `x` with associated type `t`.

```
 1 declareVar : scope * string * TYPE
 2 declareVar(s, x, t) :-
 3   !var[x, t] in s,
 4   noDuplicateVarDefs(s, x)
 5     | error $[A variable named [x] already exists in this scope].
 6
 7 resolveVar : scope * string -> list((path * (string * TYPE)))
 8 resolveVar(s, x) = ps :-
 9   query var filter P* /* The filter will be expanded throughout the chapter */
10              and { x' :- x' == (x, _) }
11              min $ < P
12              and true
13              in s |-> ps.
```

Figure 4.15: WebDSL variable declaration and resolving

The implementation of variable typing is similar to the example of let-bindings in Section 4.1.4. One difference between the let-bindings and WebDSL variables is that the introduction of consecutive statements in WebDSL requires a structure that defines declare-before-use semantics, to prevent backwards- or self-references such as shown in Figure 4.16.



```
function f() {
  var a := b;
  var b := b;
}
```

Figure 4.16: WebDSL requires declare-before-use of variables

Figure 4.17 shows how the scope graph is constructed when there are consecutive statements. To catch declare-before-use related errors, a new scope is created for each statement (**line 6 and 7**). When constraints are generated for a constraint (such as on **line 11**), it has access to two scopes. Scope `s` denotes the scope of the current statement. Any scope graph queries will be executed in this scope. Example: the type of this statement is queried starting in scope `s` on **line 12**). Scope `s_decl` denotes the scope of the next statement. Any scope graph declarations will be made this scope. Example: a variable declaration is being made in scope `s_decl` on **line 14**).

Using this tactic, a statement can never access declarations made by itself or by the next statements, it can only access declarations from previous statements.

An example of how this structure influences the building of scope graphs, a visualization of a function, accompanied by the scope graph of its body is shown in Figure 4.18.

Another difference between the let-binding rules from an earlier example and WebDSL variables is the complexity of the shadowing rules. The WebDSL variable shadowing rules which we reverse-engineered from the current compiler and static analysis implementation, state that the same variable identifier may be used multiple times, but never twice in the "environment". Such environments are: module scope, entity properties, functions, templates, etc. If a variable reference has multiple declarations in reach, the closest one according to the shadowing rules will be picked. The regular expression that defines the reachability of variables (left out in **line 9** of Figure 4.15) is shown in Figure 4.19.

The edge label `P` as introduced in Figure 4.17 is the edge label used for linking consecutive statements together. The other edge labels such as complicate this regular expression, and will be will be explained in

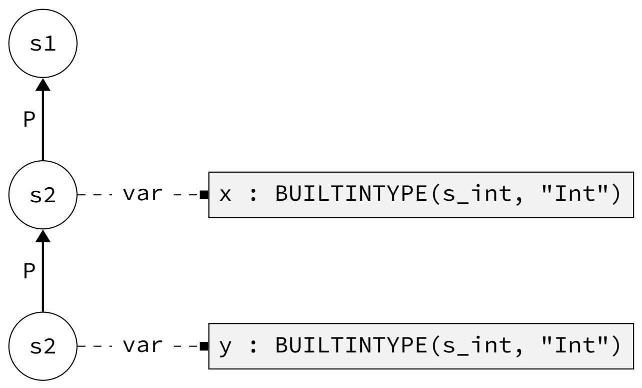
```
P*
F*
(
    (EXTEND? (INHERIT EXTEND?)*)
  | (DEF? (IMPORT | IMPORTLIB)?)
)
```

```
stmtOk : scope * scope * Statement

stmtsOk : scope * list(Statement)
stmtsOk(_, []).
stmtsOk(s, [stmt | tail]) :- {s_decl s_next}
  new s_decl, s_decl -P-> s,
  new s_next, s_next -P-> s_decl,
  stmtOk(s, s_decl, stmt),
  stmtsOk(s_next, tail).

stmtOk(s, s_decl, VarDecl(x, sort)) :- { t }
  t == typeOfSort(s, sort),
  inequalType(t, UNTYPED()) | error $[Unknown type [sort]] @sort,
  declareVar(s_decl, x, t),
  @x.type := t.
```

Figure 4.17: WebDSL statements use different scopes for querying and declaring data from the scope graph

```
function f() : Int {
  var x := 1;
  var y := 2;
  return y;
}
```

(a)



(b)

Figure 4.18: Variable declarations example using a separate declaration scopes

more details in later sections when their use is discussed.

Figure 4.19 defines what data is reachable from any point in the scope graph, but we also want some restrictions of declarations. The same environment such as function body or an entity definition may never declare the same variable twice. To achieve this, **line 4** of Figure 4.15 uses the helper predicate `noDuplicateVarDefs`. The implementation of this predicate is straight-forward and shown in Figure 4.20. The predicate queries the current scope and checks whether all scopes reachable using only `P` edge labels, results in a list containing only one entry.

4.2.3 Type Compatibility

WebDSL has a notion of type compatiblity. For example, the WebDSL superclass of all entities is conveniently called `Entity`. When assigning a value to a variable that requires type `Entity`, passing an instance of a user-defined entity such as `Person` or `Project` also suffices.

```
noDuplicateVarDefs : scope * string
noDuplicateVarDefs(s, x) :-
  query var filter P*
            and { x' :- x' == (x, _) }
            in s |-> [_].
```

Figure 4.20: The same variable identifier may only be declared once in an environment

```
entity Person {}

function f() {
  var e : Entity := Person{}; // all user-defined entities are compatible with Entity
  var d : Date := now(); // now() produces a value of type DateTime
  var p : Person := null; // null is compatible with many types
}
```

Figure 4.21: Examples of type compatibility in WebDSL

```
typeCompatible : TYPE * TYPE
// By default, two types are not compatible
typeCompatible(T1, T2).
// Same type is always compatible
typeCompatible(T, T).
```

Figure 4.22: WebDSL type compatibility predicate and general rules

In this case, type `Person` is compatible with type `Entity`, but not the other way around. Type compatibility is not limited to entities. For instance, all WebDSL date types (`Date`, `Time`, `DateTime`) are compatible with each other. As a last example, null is compatible with many types. The examples given above are shown in Figure 4.21.

To encode the type compatibility as shown in Figure 4.21 in Statix, we need a predicate that tells us, given two types A and B, if type A is compatible with with B. The signature and its general rules are shown in Figure 4.22.

With only the basic rules from Figure 4.22, we have created the equality (`==`) from Statix in predicate form. The advantage of listing it like this, is that we can now add rules to make it fit the WebDSL type system. To continue the example of `null` being compatible with every type, we can add the rules shown in Figure 4.23 to achieve this. An example of how to use our new `typeCompatible` predicate is also given on **line 8** of Figure 4.23.

Typing of the addition expression

The typing rules for most binary operations such as conjunction is trivial: the resulting value is of boolean type, with the constraint that both operators must be of boolean type. However, the range of values in WebDSL is greater than only natural numbers and booleans. WebDSL supports other numeric types such as `Float`s and `Long`s, as well as string types and multiple subtypes of strings such as `Secret`, `Text` and `WikiText`. The addition operator supports most of these values, and the typing of this operator is not as trivial as boolean conjunction. For example: the addition of two strings results in a string, the addition of a string and an integer results in a string value and the addition of a boolean and a string is not supported.

To calculate the return type of addition, we introduce a functional rule that calculates

```
typeOfExp(_, Null()) = NULL().
typeCompatible(NULL(), _).

// example of usage:
stmtOk(s, VarDeclInit(x, sort, exp), _) :- { sortType expType }
  sortType == typeOfSort(s, sort),
  expType == typeOfExp(s, exp),
  typeCompatible(expType, sortType)
    | error $[Expression [exp] is not of type [sort], got type [expType]] @exp,
  declareVar(s, x, sort),
  @x.type := t.
```

Figure 4.23: Compatibility of the null expression encoded in Statix

```
lubForAdd : TYPE * TYPE -> TYPE
lubForAdd(T1, T2) = lubForAddNumeric(T1, T2).
lubForAdd(t@BUILTINTYPE("String", _), _) = t.
lubForAdd(_, t@BUILTINTYPE("String", _)) = t.

lubForAddNumeric : TYPE * TYPE -> TYPE
lubForAddNumeric(_, _) = UNTYPED().
lubForAddNumeric(t@BUILTINTYPE("Int", _)     , t) = t.
lubForAddNumeric(t@BUILTINTYPE("Long", _)    , t) = t.
lubForAddNumeric(t@BUILTINTYPE("Float", _)   , t) = t.
lubForAddNumeric(t@NATIVECLASS("Double", _) , t) = t.

// implicit widening from int to long
lubForAddNumeric(BUILTINTYPE("Int", _)       , t@BUILTINTYPE("Long", _))    = t.
lubForAddNumeric(t@BUILTINTYPE("Long", _)    , BUILTINTYPE("Int", _))       = t.

// implicit widening from float to double
lubForAddNumeric(t@NATIVECLASS("Double", _) , BUILTINTYPE("Float", _))     = t.
lubForAddNumeric(BUILTINTYPE("Float", _)     , t@NATIVECLASS("Double", _)) = t.
```

Figure 4.24: Least-upper-bound rules for addition

the least-upper-bound of two types: `lubForAdd : TYPE * TYPE -> TYPE`. The implementation of this rule is given in Figure 4.24. The functional rule `lubForAddNumeric` is reused in other contexts, in particular when generating the constraints for comparison with operators such as greater-than, to check if two types are comparable.

4.2.4 Boolean Logic in Statix

So far, most of the WebDSL's static semantics are expressible in Statix. However, the elegance of the Statix definition is sometimes lost due to code duplication. For example, logical negation and disjunction of predicates are not natively expressible in Statix, and require boilerplate code to function. To tackle this challenge, we introduced a notion of explicit boolean results for predicates that are reusable. The implementation in Statix is shown in Figure 4.25. The figure shows a predicate from before (`typeCompatible : TYPE * TYPE`) now changed to return an explicit result: `typeCompatibleB : TYPE * TYPE -> BOOL`. Additionally, we scope

```
signature
  sorts
    BOOL   // used as return values of functional rules

constructors
  TRUE : BOOL
  FALSE : BOOL

rules
  // return a TRUE() or FALSE() value instead of failing/passing constraint
  typeCompatibleB : TYPE * TYPE -> BOOL

  // scope this explicit results in a predicate to avoid having to work
  // with boolean computation everywhere
  typeCompatible : TYPE * TYPE
  typeCompatible(T1, T2) :- typeCompatibleB(T1, T2) == TRUE().
```

Figure 4.25: Boolean computation results in Statix

this boolean result in a predicate `typeCompatible(T1, T2) :- typeCompatibleB(T1, T2) == TRUE().` such that existing references can be left unchanged.

As hinted before, the explicit return values of functional rules open up new possibilities for expressing constraints. One instance of where this is necessary, is expressing the semantics of an equality check in WebDSL. For the expression `A == B` to type check, the types have to be compatible. The naive implementation would be to define the constraint `typeCompatible(T_A, T_B)`. However, type compatibilty is not symmetrical while the equality check should be: `A == B` $\iff$ `B == A`. An example of type compatibilty not being symmetrical is when dealing with entity inheritance (see Section 4.3.1). To properly define the static semantics for the equality expression in Statix, we need the newly defined boolean computation rules. The result is shown in Figure 4.26.

4.2.5 Entities and Properties

Entities form the basis of the type system and data structure in a WebDSL application. Using Hibernate as an object-relational mapping (ORM) tool, instances of entities can be persisted without explicit communication with a database management system. Entities typically have multiple properties which values are persisted, and functions that can be called and will be executed in the scope of the instantiated entity. Entity properties and entity functions together form the entity body declarations.

In the WebDSL type system, entities are declared in the scope of the module they are defined in. An entity is a type in the WebDSL type system, similar to built-in types such as `String` and `Int`. The Statix code to declare entities is shown in Figure 4.27 and an example of a simple program with entity definition plus its scope graph is shown in Figure 4.28.

The `declareType` and `resolveType` rules as introduced in Figure 4.11 need to be updated to work as intended for resolving and declaring entities. To prevent duplicate entity definitions, the `declareType` rule is extended with one additional rule as shown in Figure 4.29. **Line 4** was added to `declareType`, to make sure when you declare a new type or entity, its name is unique.

In addition to the added constraint to the `declareType` rule, we added an optional `DEF` edge label that may be followed when querying the scope graph for a type (**line 9** of Figure 4.29). The `DEF` (short for defintion) is used to link the scope of top-level elements, such as entities and functions, to the module scope. This can be seen in **line 13** of Figure 4.27.

```
or  : BOOL * BOOL
orB : BOOL * BOOL -> BOOL

or(b1, b2) :- orB(b1, b2) == TRUE().

orB(_, _) = FALSE().
orB(TRUE(), _) = TRUE().
orB(FALSE(), TRUE()) = TRUE().

// (e1 == e2)
typeOfExp(s, Eq(e1, e2)) = t :- { T1 T2 }
  t == bool(s),
  typeOfExp(s, e1) == T1,
  typeOfExp(s, e2) == T2,
  or(
    typeCompatibleB(T1, T2),
    typeCompatibleB(T2, T1)
  ).
```

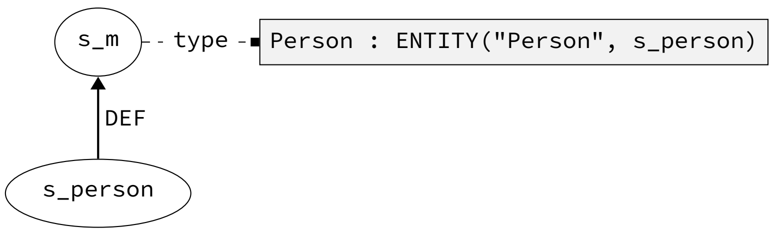
Figure 4.26: Using boolean computation results in Statix for the equality expression

```
signature
  constructors
    // an entity constructor has two subterms:
    // - the entity name
    // - the scope of the entity where all the properties and
    //   functions are declared
    ENTITY : string * scope -> TYPE

rules
  defOk(s_module, EntityNoSuper(entity_name, body)) :- { s_entity }
    // a new scope for the entity is created and linked to the module scope
    // using the `DEF' (for definition) edge label
    new s_entity, s_entity -DEF-> s_module,

    // the new entity is declared as type in the module scope
    declareType(s_module, entity_name, ENTITY(entity_name, s_entity)),

    // finally a helper rule is called that properly handles
    // the entity body definitions (properties, functions, etc.)
    declEntityBody(s_entity, entity_name, body).
```

Figure 4.27: The Statix rules for declaring entities

```
module m
  entity Person {
    // no properties
    // for now...
  }
```

(a)



(b)

Figure 4.28: An example of entity definition in WebDSL

```
declareType : scope * string * TYPE
declareType(s, name, t) :-
  !type[name, t] in s,
  resolveType(s, name) == [(_, (_, t))]
    | error $[Type [name] is defined multiple times] @name.

resolveType : scope * string -> list((path * (string * TYPE)))
resolveType(s, name) = typesOf(ts) :-
  query type filter P* DEF?   // resolving a type may
                              // optionally follow DEF edge label
             and { t' :- t' == (name, _) }
             in s |-> ts.
```

Figure 4.29: `declareType` now shows an error when two types with the same name are declared and `resolveType` may optinally follow a `DEF` edge label

So far, there has been no reason to query for types inside the entity body because we have always worked with empty entities. In practice, entities are filled with properties and functions. **Line 20** of Figure 4.27 calls the `declEntityBody` predicate, of which the implementation is shown in Figure 4.30 and an example of an entity definition with two properties is shown in Figure 4.31.

Entity properties are declared under the variable relation inside the entity scope, such that functions inside entities can reference their own properties without using the `this` prefix. The `this` construct is supported, but not necessary. Declaring properties in this way, allows us to reuse the already existing rules such as those against duplicate definition, without duplicating the code for another relation.

When instantiating an entity, the properties declared in the entity body may be given a value in the instantiation expression. To express this in Statix, an entity instantiation first retrieves the scope of the entity. If the scope cannot be retrieved, it means that the entity is unknown at the position of the expression, so either the entity was never declared or it is not imported correctly. Secondly, all instantiated properties must be declared under the `var` relation of the entity scope. An example of the declaration and scope graph of an entity declaration is shown in Figure 4.31. A part of the Statix rules for instantiating entities is shown in Figure 4.32.

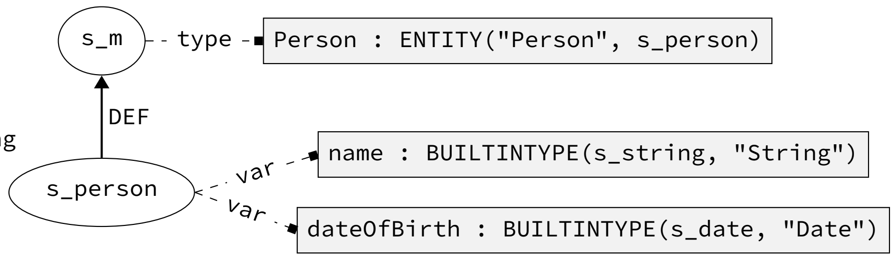
Even though the concepts, rules and approach mentioned in this subsection are present in the Statix specification of WebDSL, we had to simplify the examples and shown Statix rules to hide the extra complexity added concepts such as inheritance, property annotations and type extension. Those concepts will be explained in detail in section Section 4.3 and Section 4.6.

```
declEntityBody maps declEntityBodyDeclaration(*, *, list(*))
declEntityBodyDeclaration : scope * string * EntityBodyDeclaration

// entity property
declEntityBodyDeclaration(s, ent,
    Property(x, propkind, sort, PropAnnos(annos))) :- { sortType }

  // resolve the type of the property
  sortType == typeOfSort(s, sort),

  // there are some restrictions on property types
  sortType != UNTYPED()
    | error $[Cannot resolve type [sort]] @sort,
  sortType != VOID()
    | error $[Property type 'Void' not allowed] @sort,
  sortType != REF(_)
    | error $[Reference type is not allowed in property] @sort,
  isValidTypeForPropKind(propkind, sort, sortType),

  // declare the property as variable in the entity scope
  declareVar(s, x, sortType),

  // use a helper predicate to check for the uniqueness of
  // the property name
  resolveLocalProperty(s, x) == [_]
    | error $[Property [x] of entity [ent] is defined multiple times] @x.
```

Figure 4.30: Statix rules for declaring the entity body

```
module m
  entity Person {
    name        : String
    dateOfBirth : Date
  }
```

(a)


s_m
type
Person : ENTITY("Person", s_person)
DEF
s_person
var
name : BUILTINTYPE(s_string, "String")
var
dateOfBirth : BUILTINTYPE(s_date, "Date")

(b)

Figure 4.31: An example of an entity definition with multiple properties

```
typeOfExp(s, ObjectCreation(x, prop_assignments)) = e :-
  definedType(s, x) == e,
  e == ENTITY(_, _),
  propAssignmentsOk(s, e, prop_assignments).

  propAssignmentsOk maps propAssignmentOk(*, *, list(*))
  propAssignmentOk : scope * TYPE * PropAssignment
  propAssignmentOk(s, ent@ENTITY(e, s_ent),
      PropAssignment(x, exp)) :- { propType expType }
    typeOfProperty(s, ent, x) == propType,
    typeOfExp(s, exp) == expType,
    typeCompatible(expType, propType).
```

Figure 4.32: Statix rules for instantiating an entity

```
signature
  constructors
    PAGE     : string * list(TYPE) -> TYPE
    TEMPLATE : string * list(TYPE) -> TYPE

  relations
    page     : string * TYPE
    template : string * TYPE
```

Figure 4.33: Statix signature for pages and templates

4.2.6 Pages and Templates

The user-inferface of a WebDSL application is built out of *pages* and *templates*. A page defines a path that is able to be requested by the browser while a template is a reusable component that can be part of a page or nested in other templates.

The name of a page must be unique, while a template can be defined multiple times for different argument types (*overloading*), but never multiple times for the same argument types. The statix rules to implement these checks can be found in Figure 4.34 and an example of a module with a page and a template definition is shown in Figure 4.35. In the latter image, the argument type of template `t` is shortened to `String`, instead of its full version `BUILTINTYPE(s_string, "String")`.

Type-checking a page reference is easier than the that of a template, since a page definition cannot be overloaded. In order for a page reference to be well-typed, the page must be defined exactly once, and the types of the passed arguments must be compatible with the parameter types of the page. The Statix rules that ticks those boxes is shown in Figure 4.36. The resolving of templates is similar to that of functions and will be explained later in Section 4.4.

The body of templates and pages consist of so called *Template elements*. The simplest template element is simply a text to be printed on the page. Next to plain text, hyperlinks to other pages can be created using the `navigate` element. If we take Figure 4.35 as basis, an example of a valid navigate call would be `navigate p() { "Go to p" }`. To type-check this, the code from Figure 4.36 can be used. Other examples of template elements are forms, nested template calls, and at the top of a template, variables can be initialized, followed by a block of computational statements that get executed when the template is being loaded.

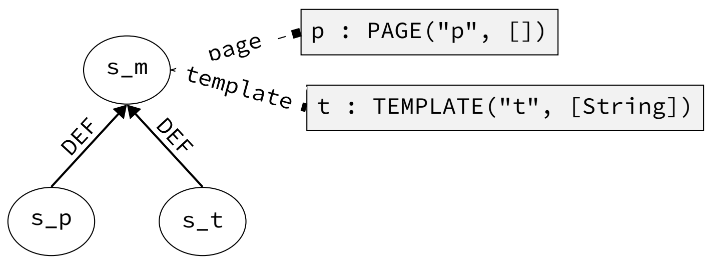
Apart from regular templates, WebDSL also has a notion of Ajax templates. Ajax tem-

```
declarePage : scope * string * list(TYPE)
declarePage(s, p, ts) :-
  !page[p, PAGE(p, ts)] in s,
  resolveTemplate(s, p) == []
    | error $[Multiple page/template definitions with name [p]] @p,
  resolvePage(s, p) == [_]
    | error $[Multiple page/template definitions with name [p]] @p.

declareTemplate : scope * string * list(TYPE)
declareTemplate(s, t, ts) :-
  !template[t, TEMPLATE(t, ts)] in s,
  resolvePage(s, t) == []
    | error $[Multiple page/template definitions with name [t]] @t,
  filterTemplateResultsArgs(resolveTemplate(s, t), ts) == [_]
    | error $[Multiple page/template definitions with name [t] and argument types [ts]] @t.
```

Figure 4.34: Statix rules for declaring WebDSL pages and templates

```
module m
  page p {
    "Hello "
    t("World!")
  }

  template t(s : String) {
    ~s
  }
```

(a)



(b)

Figure 4.35: An example of a module with a page p and a template t

```
pageCallOk : scope * string * list(Exp)
pageCallOk(s, p, args) :- {argTypes ts}
  pageType(s, p) == PAGE(_, ts)
    | error $[There is no page with signature [p]] @p,
  argTypes == typesOfExps(s, args),
  typesCompatible(argTypes, ts)
    | error $[Given argument types not compatible with page definition] @args.

// root page is always accessible from all locations
pageCallOk(_, "root", []).
```

Figure 4.36: Statix rules for type-checking a page reference

plates can be used as building blocks of the user interface, just like regular templates. Additionally, Ajax templates also have a possibility of being replaced on a rendered page without reloading the whole page, for example to refresh the results of a poll on a page. This addition makes Ajax templates useful for more interactive and modern web applications.

Certain action code such as the `replace` and `refresh` statements are only supposed to work on Ajax templates, and not on regular templates. To this end we need to differentiate between them in the scope graph. We have chosen the most trivial way of implementing this, namely adding an additional argument in the type constructor of a template: `TEMPLATE : string * list(TYPE) * BOOL -> TYPE`. The last boolean argument indicates whether the template is an Ajax template or not. When resolving templates we can now resolve only Ajax templates by adding a `TRUE()` to the filter statement of the query.

4.2.7 Functions

In WebDSL, a function is a sequence of statements that perform some sort of computation and can return a value. The type of the return value must be stated in the function header and is part of the signature. The implementation of the declaration and resolving of functions is similar to that of templates, as explained in Section 4.2.6, and therefore will not be repeated here.

An additional characteristic of functions that is similar to templates, is the use of parameters. The parameters with their corresponding types have to be declared statically. The parameters are readable from the function body, but never writable or overridable by a local variable. Additionally, the name of parameters may shadow the name of definitions outside the function such as entity properties or global definitions. To enforce these constraints, we introduce a new edge label `F` for embedding the function scope in their surrounding scope, which is either global or within an entity. Using this new edge label, the shadowing rules can be adjusted to properly check the listed semantics. The result is shown in Figure 4.37 and an example of a WebDSL snippet with the resulting scope graph is shown in Figure 4.38. In the example, parameter `x` of function `f` shadows the globally declared `x`.

Apart from globally declared functions, functions may also be part of an entity. In this case, functions can be called similar to how entity properties are referenced. Lastly, entity functions may have the `static` annotation, which is similar to static class functions in the Java programming language. Static functions may be called without having an instantiated entity.

Possible TO-DO:

- List/explain interesting action code type checking

4.2.8 Access Control

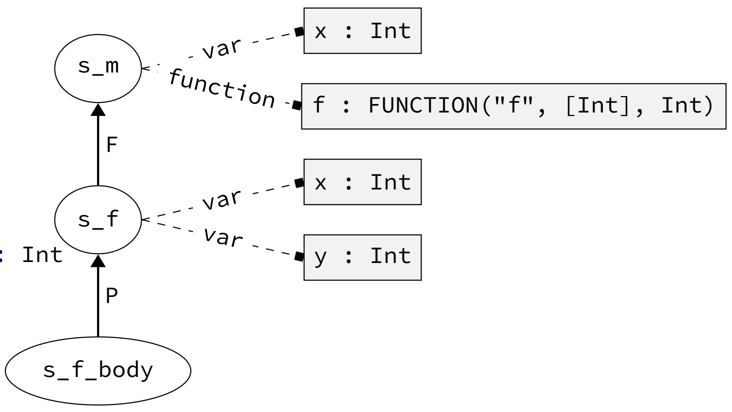
When developing any application that will be used in practice, access control is an important part of the system. It controls which user is allowed to see what data, what actions can be executed. Generally, this is implemented through a log-in system where different user accounts are given different rights. In all popular programming languages, developing a system access control is the responsibility of the developer, either through manual coding or using frameworks and libraries. In WebDSL however, access control is embedded in the language and all pages are protected by default.

Concretely, the developer is able to declare what entity represents a user in the system, and what data the user needs to show to log in. In the rest of the WebDSL code, the globally available security context is extended with the properties `principal` which references the logged in user, and `loggedIn` which is true if the user has logged in. If the developer has not specified what entity represents a user, the security context is available but does not have these properties. An example of WebDSL code with resulting scope graph is shown in

```
functionOk : scope * Function
functionOk(s_outer,
    Function(name, FormalArgs(args), OptSortSome(returnSort), Block(stmts)))
      :- { argTypes returnType s_function s_body }

  // embed the function scope with edge label F
  new s_function, s_function -F-> s_outer,

  // declare parameters in function
  argTypes == typesOfArgs(s_outer, args),
  declareParameters(s_function, zipArgTypes(args, argTypes)),

  // create the function body and generate constraints
  new s_body, s_body -P-> s_function,
  stmtsOk(s_body, stmts, returnType),

  // declare the function in the outer scope
  returnType == typeOfSort(s_outer, returnSort),
  declFunction(s_outer, name, argTypes, returnType).

// resolve variables via P and F edges
resolveVar(s, x) = ps :-
  query var filter P* F*
            and { x' :- x' == (x, _) }
            min $ < P, $ < F,
                   P < F
            and true
            in s |-> ps.

// a definition is only duplicate in a line of P edges
noDuplicateVarDefs : scope * string
noDuplicateVarDefs(s, x) :-
  query var filter P*
            and { x' :- x' == (x, _) }
            in s |-> [_].
```

Figure 4.37: Statix rules for function parameters and variable shadowing

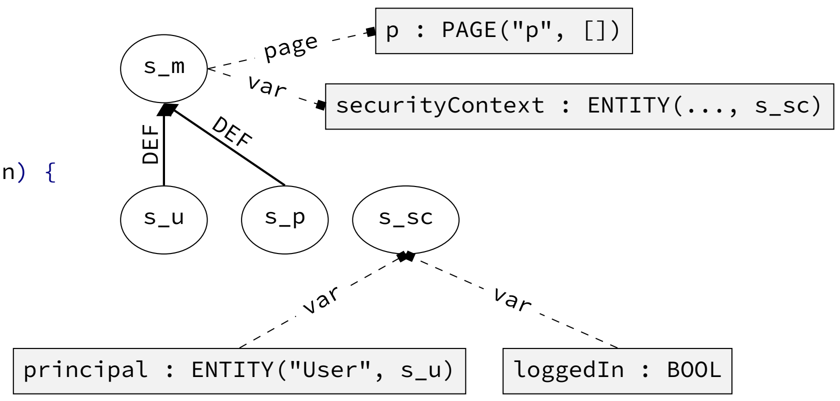
```
module m
  var x : Int := 1

  function f(x : Int, y : Int) : Int
  {
    return x + y;
  }
```



(a) (b)

Figure 4.38: An example of a function with parameters

```
module m
  entity User {
    username : String
    password : Secret
  }

  principal is User
    with credentials
    username, password

  page p {
    if (securityContext.loggedIn) {
      "Welcome!"
    } else {
      "Log in first!"
    }
  }
```



s_m
page
p : PAGE("p", [])
var
securityContext : ENTITY(..., s_sc)
DEF
DEF
s_u
s_p
s_sc
var
var
principal : ENTITY("User", s_u)
loggedIn : BOOL

(a) (b)

Figure 4.39: An example of access control in WebDSL. The entries related to entity `User` are omitted for brevity

Figure 4.39 and the Statix rules used to achieve this are shown in Figure 4.40. In the code for extending the security context with two additional properties, the same mechanics are used as for entity and built-in type extension. An explanation can be found later in Section 4.6.

Possible TO-DO:

- References to pages and templates
- Wildcards
- Pointcuts?

```
principalDefOk : scope * string * list(string)
principalDefOk(s, ent, properties) :-
  { s_ent entityName credentialTypes t }
  definedType(s, ent) == t@ENTITY(entityName, s_ent),
  principalPropertyTypes(s_ent, properties, ent) == credentialTypes,
  compatibleCredentialTypes(properties, credentialTypes),
  declSecurityContext(s, t, credentialTypes).

compatibleCredentialTypes maps compatibleCredentialType(list(*), list(*))
compatibleCredentialType : string * TYPE
compatibleCredentialType(x, s) :-
  isStringCompatibleType(s).

declSecurityContext : scope * TYPE * list(TYPE)
declSecurityContext(s, principalType, credentialTypes) :-
  { s_extend_security_context }
  new s_extend_security_context,
  declProperty(s_extend_security_context, "securityContext"
    , "principal", principalType),
  declProperty(s_extend_security_context, "securityContext"
    , "loggedIn", bool(s)),
  declareExtendScope(s, "securityContext", s_extend_security_context),
  extendScopes(resolveExtendScope(s, "securityContext")
    , s_extend_security_context).
```

Figure 4.40: Statix rules for declaring the access control principal

4.3 Advanced Entity Features

4.3.1 Inheritance

Linking the Scopes

The implementation of inheritance requires the scope of the sub- and super-entity to be connected such that Statix queries can resolve to declarations from the super-entity when necessary. To achieve this, we introduce an edge label `INHERIT` as shown in Figure 4.41.

First of all, the super-entity refered to in the declaration must refer to an existing entity in the scope graph. Secondly, the new scope belonging to the sub-entity `s_entity` is linked to the scope of the super class `s_super` via an `INHERIT` edge. Finally, some additional constraints are generated to make sure no circular inheritance exists and constraints for the entity body declarations of the sub-entity are generated.

The variable resolving query as listed in Figure 4.43 reflects the addition of the `INHERIT` label. The addition of `INHERIT*` in the query filter makes all variables declared in ancestors reachable, but the shadowing rule as declared after the `min` keyword ensures correct shadowing behaviour, namely that local variables are preferred over variables defined in ancestors.

Overwriting Functions

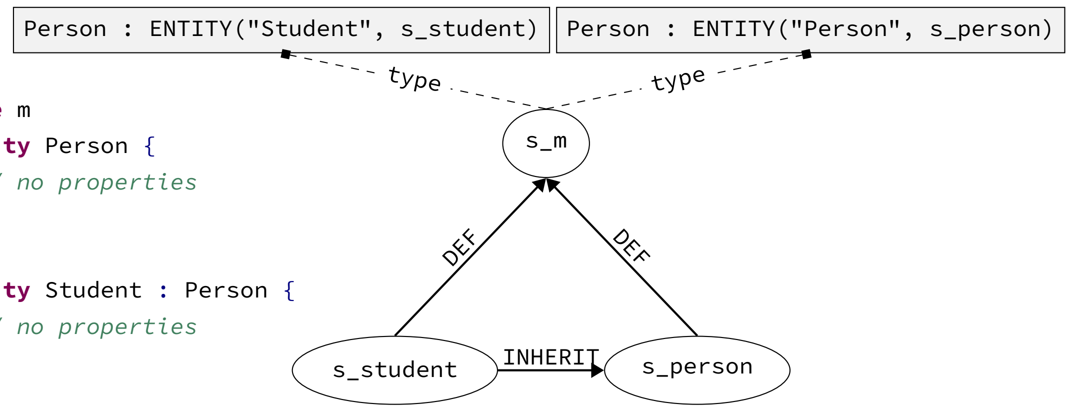
Generally, defining two functions with the same name and same argument types is not allowed in WebDSL. Entity functions are an exception to this such that entity function definitions shadow global function definitions. With the introduction of inheritance there comes

```
signature
  name-resolution
    labels
      INHERIT // inherit edge label for subclasses

rules
  defOk(s_global, Entity(x, super, bodydecs)) :- {s_entity super' s_super}
    resolveEntity(s_global, super) == [(_, (super', ENTITY(_, s_super)))],
    new s_entity, s_entity -INHERIT-> s_super,
    noCircularInheritance(s_entity),
    declEntity(s_global, s_entity, x, bodydecs),
    @super.ref := super'.
```

Figure 4.41: Entity inheritance Statix rules

```
module m
  entity Person {
    // no properties
  }

  entity Student : Person {
    // no properties
  }
```

(a)


Person : ENTITY("Student", s_student)
Person : ENTITY("Person", s_person)
type
type
s_m
DEF
DEF
s_student
INHERIT
s_person

(b)

Figure 4.42: An example of entity definition in WebDSL

```
  resolveVar(s, x) = ps :-
    query var filter P* F* INHERIT*
              and { x' :- x' == (x, _) }
              min $ < P, $ < F, $ < INHERIT,
                         P < F, P < INHERIT,
                                F < INHERIT
              and true
              in s |-> ps.
```

Figure 4.43: The query that specifies what variables can be resolved, updated to reflect entity inheritance

```
// previously (local entity scope only)
resolveEntityFunction(s, x) = ps :-
  query function filter e
                 and { x' :- x' == (x, _) }
                 min
                 in s |-> ps.

// new (allow resolving to ancestors)
resolveEntityFunction(s, x) = ps :-
  query function filter INHERIT*
                 and { x' :- x' == (x, _) }
                 min /* */
                 in s |-> ps.
```

Figure 4.44: Statix rules for allowing entity function calls to resolve to definitions in their ancestors

```
resolveEntityFunction(s, x) = ps :-
  query function filter INHERIT*
                 and { x' :- x' == (x, _) }
                 /* prioritize local scope over inheritance */
                 min $ < INHERIT
                 /* shadow when function name and argument types match */
                 and {
                   (f, FUNCTION(args, _, _)),
                   (f, FUNCTION(args, _, _))
                 }
                  in s |-> ps.
```

Figure 4.45: Statix rules for resolving entity functions that allow overriding

another exception, namely that sub-entities are allowed to override function definitions of their ancestors.

Previously, the resolving of entity functions was done using a query that resolves within the entity scope only. With the introduction of entity inheritance, the path well-formedness over edge labels was changed such that functions from ancestors are also in scope. Changing `filter e` to `filter INHERIT*` accomplishes this. Both the previous and resulting queries are shown in Figure 4.44.

This query definition is adequate when sub-entities do not override functions. When a sub-entity does define a function that is already defined in one of its ancestors, resolving the entity function gives two results while the desired outcome is only one result, namely the overridden function defined in the sub-entity. To tackle this challenge, we defined a Statix anonymous shadowing rule combined with a label order. This ensures that when two functions with the same name and argument types exist, only the most specific (i.e. the least inheritance edges) is returned. This is implemented as shown in Figure 4.45.

Entity Type Compatibility

A perk of having the notion of inheritance in the WebDSL language, is that it allows for better abstraction and less code duplication. An example of this is a function definition,

```
typeCompatibleB(ENTITY(s_sub), ENTITY(s_super)) = inherits(s_sub, s_super).

inherits : scope * scope -> BOOL
inherits(s_sub, s_super) = nonEmptyPathScopeList(ps) :-
  query () filter INHERIT*
           and { s :- s == s_super }
           min $ < INHERIT
           in s_sub |-> ps.

nonEmptyPathScopeList : list((path * scope)) -> BOOL
nonEmptyPathScopeList(_)       = FALSE().
nonEmptyPathScopeList([(_,_)]) = TRUE().
```

Figure 4.46: Statix rules for entity type compatibility that support inheritance

where the argument type is an entity. This function can be called with an argument of the entity type, or one of its sub-entities. To know if the given type is compatible with the required type, we require a predicate that defines this compatibility. We have created such a predicate while implementing general type compatibility in Section 4.2.3, in the form of `typeCompatibleB : TYPE * TYPE -> BOOL`.

With the addition of entity inheritance, we need to expand this definition. To this end, we added the rules as shown in listing Figure 4.46. Given two entity scopes, the `inherits(s_sub, s_super)` predicate returns true when the query has one result. The query in the `inherits` rule requests all paths from scope `s_sub` to scope `s_super` consisting of only `INHERIT` edges. Such a path exists if and only if the entity belonging to scope `s_sub` inherits the entity belonging to `s_super`. An example of a scope graph with entity inheritance is shown in Figure 4.42.

4.3.2 Property Annotations

So far, the Statix specification can validate entities, their properties and their functions. Since the goal is to never manually touch the database specification, we would like to entity properties to be more expressive by for example specifiying default values, or put a constraint on the possible values of a property. WebDSL uses *property annotations* for this. Figure 4.47 shows an WebDSL code of an entity with properties that have annotations.

Many property annotations do not influence the scope graph. An example of this is the `default = <exp>` annotation, where Statix only needs to check whether the given expression is compatible with the property type. For the `length = <exp>` annotation, the same holds, except that the expression must now have type `Int`.

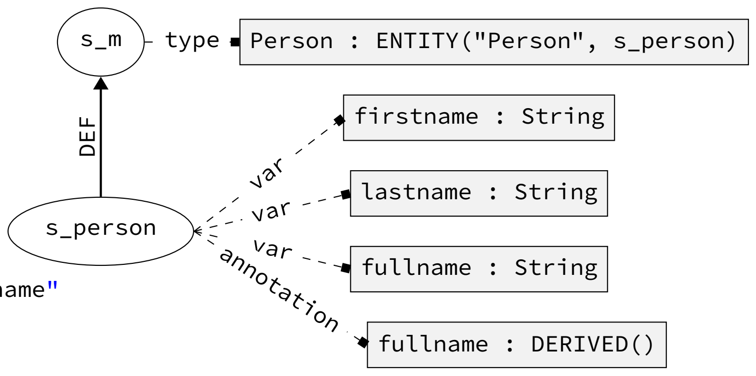
An interesting property to point out is the derived property, as shown in for property `fullname` of the `Teacher` entity in Figure 4.47. While this is not strictly an annotation, it does change something in the scope graph. A derived value can be calculated from other properties of the entity and does not have to be stored. It's value can also not be changed directly. The latter property is something we need to store in the scope graph, such that we can give an error when the developers attempts to assign a value directly to a derived property. For this, a new relation is introduced in Statix, which allows us to declare annotations on properties in the scope of an entity. An example of this is shown in Figure 4.48. When assigning a variable, the left-hand side of the assignment can now be checked for mutability. The implementation of this checks whether the entity property that is referenced on the left-hand side has the `DERIVED()` annotation. To prevent code duplication, we chose to re-use the `DERIVED()` property for function parameters, which can only be referenced but never changed in the function body.

```
module m
  entity Course {
    key : String (default="change-me")
    ects : Float (validate(ects >= 0, "ECTS may not be lower than 0"))
    teacher : Teacher (not null)
  }

  entity Teacher {
    firstname : String
    lastname : String (length = 255)
    courses : [Course] (inverse=teacher)

    temporaryNumber : Int (transient)
    fullname : String := getFullName()

    function getFullName() : String {
      return "~firstname + ~lastname";
    }
  }
```

Figure 4.47: Examples of entity property annotations

```
module m
  entity Person {
    firstname : String
    lastname  : String
    fullname  : String :=
      "~firstname + ~lastname"
  }
```

(a)



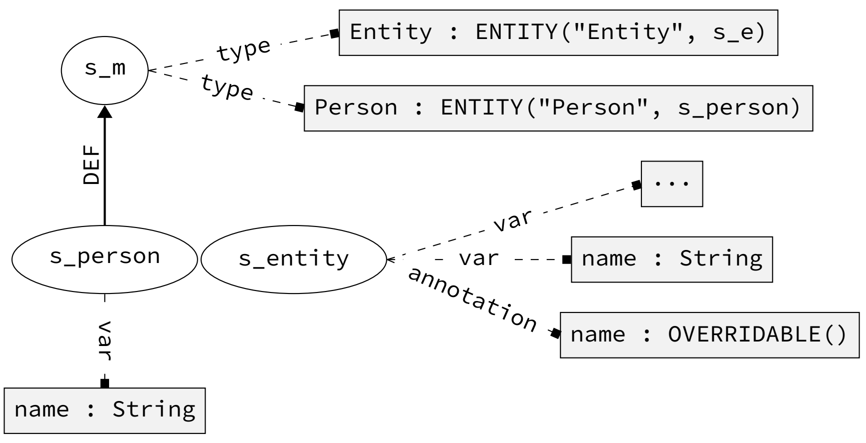
(b)

Figure 4.48: An example of a derived property in an entity

Another interesting annotation to mention, is the `inverse = <var>` annotation as shown for the `courses` property of the `Teacher` entity in Figure 4.47. The inverse annotation is introduced to prevent data duplication in the database. To continue with the example of `Teacher` and `Course` of Figure 4.47, the `Course` table saves the corresponding teacher, and when a teacher is fetched from the database, the `courses` property is instantiated according to the data in the `Course` table. When specifying `inverse=teacher`, the Statix specification has to validate that the entity mentioned in the property type (`Course` in this case) has the `teacher` property, and that the type of that `teacher` property is equal to the type of the entity that the inverse annotation was declared in (`Teacher` in this example). To prevent a situation where none of the two entities is responsible for saving the data, a double inverse annotation is not allowed. To enforce this, another constraint has to be added, namely that the `teacher` property of `Course` does not have an inverse annotation. The only way to reliably check this is to save the annotation `INVERSE()` in the scope graph.

```
module m
  entity Person {
    name : String
  }
```

(a)



(b)

Figure 4.49: An example of overriding the `name` property

4.3.3 Entity Hierarchy and the Name Property

Similar to `Object` in the Java programming language, WebDSL also has a root of the entity hierarchy, namely `Entity`. If a defined entity does not explicitly inherit from another entity, it will automatically inherit from `Entity`. This built-in superclass is convenient to store properties that all entites will have out of the box, such as the property `id` of type `UUID` and the property `created` of type `DateTime`. User-defined entities are not allowed redefine such properties, but they may to edit the values. An exception to this rule is the property `name` of type `String` that all entities have by default, but may be overridden once by sub-entities.

To achieve the overridability, we can re-use the property annotations in the scope graph as explained in previous section. The `name` property of the built-in entity `Entity` gets a `OVERRIDABLE()` annotation declared in the scope of `Entity`, and when attempting to catch duplicate property definitions, we must discard properties from parents that have the `OVERRIDABLE()` property. An example of the overriding is shown in Figure 4.49 and the Statix code to discard overridable properties is shown in Figure 4.50. In the Statix rules, there are now two predicates to prevent duplicates: one for within the entity, and another one to check inherited properties. The difference is rules allows for better error messages, but most importantly allows us to only discard properties with the `OVERRIDABLE()` annotation from inherited properties. At the point of writing this thesis, the built-in name property is the only use case for the `OVERRIDABLE()` annotation and it is not possible to mark a property as overridable by code.

4.4 Function and Template Overloading

Function overloading is the practice of defining multiple functions with the same name, that differ in argument types or in the amount of arguments. Before running the WebDSL program, the compiler determines what instance of the function will be run, based on the types of the function call arguments. WebDSL supports overloading for both functions and templates, and their implementation in the static analysis is the same. The concepts and solutions explained in this section are therefore applicable for both. An example of template overloading is shown in Figure 4.51. In the rest of this section we will talk about functions but the concept is exactly the same for templates.

Overloading complicates the static analysis in two ways. The first and easiest to implement is that functions may now be defined multiple times with the same name, as long as the amount of arguments and argument types do not exactly match. The Statix rules that achieve this are shown in Figure 4.52. The essence of the rules is that all functions with the relevant name are retrieved, and the declarations with argument types exactly matching

```
declProperties maps declProperty(*, *, list(*), list(*))
declProperty : scope * string * string * TYPE
declProperty(s, ent, x, sortType) :-
  validPropertyName(x),
  declareVar(s, x, sortType),
  resolveLocalProperty(s, x) == [_]
    | error $[Property [x] of entity [ent] is defined multiple times] @x,
  noDuplicateVarDefsInSuper(s, x)
    | error $[Cannot override existing entity property [x]] @x.

noDuplicateVarDefsInSuper : scope * string
noDuplicateVarDefsInSuper(s_sub, x) :- { xs nonOverridable }
  resolveProperty(s_sub, x) == xs,
  withoutAnnotation(xs, OVERRIDABLE()) == nonOverridable,
  amountNonOverridableOk(nonOverridable).

amountNonOverridableOk : list((path * (string * TYPE)))
amountNonOverridableOk(_) :- false.
amountNonOverridableOk([]).
amountNonOverridableOk([_]).
```

Figure 4.50: Statix rules for overridable entity properties

```
module m

  entity Animal {
    name : String
  }
  entity Cat : Animal {
    breed : String
  }

  template description(a : Animal) {
    "~a.name"
  }
  template description(c : Cat) {
    "~c.name (Breed: ~c.breed)"
  }
```

Figure 4.51: An example of defining overloaded templates in WebDSL

```
// predicate that defines when there are overlapping function signatures
noDuplicateFunDefs : scope * string * list(TYPE)
noDuplicateFunDefs(s, f, ts) :- { ps }
  resolveFunction(s, f) == ps,
  amountOfFunDeclsWithArgs(ps, ts, 0) == 1.

// helper function for noDuplicateFunDefs that counts the amount
// of functions with a given name and argument types
amountOfFunDeclsWithArgs : list((path * (string * TYPE)))
  * list(TYPE) * int -> int
amountOfFunDeclsWithArgs([], _, n) = n.
amountOfFunDeclsWithArgs([(_, (_, FUNCTION(_, types, _, _))) | tail], types, n)
  = amountOfFunDeclsWithArgs(tail, types, i) :- i #= n + 1.
amountOfFunDeclsWithArgs([_ | tail], types, n)
  = amountOfFunDeclsWithArgs(tail, types, n).
```

Figure 4.52: Statix rules for allowing overloaded function definitions

with the relevant types are counted. The resulting number should be 1, namely the newly declared function.

Now that the static analysis allows for overloaded functions and templates to be defined, the code that typechecks function calls and template calls should be updated to reflect the new changes. The semantics of resolving the correct overloaded function or template are listed below. A practical example of how these rules work is shown in Figure 4.53.

1. Retrieve all function signatures with the matching name from the scope graph
2. Filter the result to end up with function signatures with matching arity (amount of arguments) and compatible argument types.
3. If the filtered result is exactly one signature: this is the function that will be called
4. If the filtered result is more than one signature: choose the signature with the ”most specific” argument types:
    - If there are exactly matching types, always choose this one.
    - Otherwise; count the amount of `INHERIT` edges that have to be taken from the given expression types to the function argument types, and choose the signature with the least total edges taken.

The implementation of resolving the correctly overloaded function according to the listed semantics is shown in Figure 4.54. The essence of the semantics is encoded in the Statix rules, but the brevity and elegancy is lost due to many helper predicates being required to transform the data into the correct forms to perform the queries that calculate the inheritance edges, and filter the function signatures accordingly. Note that the `typeOfFunctionCall` predicate is not specific to functions, because the signature requires a string and a list of expressions, which causes the predicate to be re-usable for resolving template calls.

Possible TO-DO:

- Change implementation to throw an error when an overloaded function is not ”strictly better” than another (e.g. another one has a more specific argument type for at least one of the arguments).

```
module m

  entity Animal {
    name : String
  }
  entity Cat : Animal {
    breed : String
  }

  template description(a : Animal) {
    "~a.name"
  }
  template description(c : Cat) {
    "~c.name (Breed: ~c.breed)"
  }

  page p {
    var a := Animal{ name := "Alice" }
    var c := Cat{ name := "Charlie", breed := "Sphynx" }

    description(a) // will output "Alice"
    description(c) // wil output "Charlie (Breed: Sphynx)"
  }
```

Figure 4.53: An example of referencing overloaded templates in WebDSL

4.5 Placeholders, Actions and Submitting Forms

Forms are the basis of most information systems on the web. WebDSL has linguistically integrated forms through inputs and actions. The static analysis of referencing actions and placeholders is unlike variable referencing, due to their scoping semantics. Actions abd placeholders are defined in pages or templates and may be referred to in the rest of the page or function body. Unlike variables, actions and placeholders do not follow the declare-before-use principle (explained in Section 4.2.2). Actions and placeholders may be defined anywhere in the body, and referenced from anywhere in the body, but there is a twist. Inside the action body, the statements and expressions may reference variables defined in the template or page body, and thus the scope of the action must be linked to the scope of the template of page in some way.

Summarized, actions and placeholders cannot be declared in the scope they are defined in, because that scope follows a declare-before-use regime, but the body of an action must have access to the scope it was declared in. As a solution to this challenge, the Statix rules for declaring a page or template were altered to not only create a scope for its body, but create an additional scope where placeholders and actions will be declared. This scope is passed along such that variables are queryable using the regular function body scope, and querying placeholders and actions is available using the additional scope. An example of an action and its representation in the scope graph is shown in Figure 4.55.

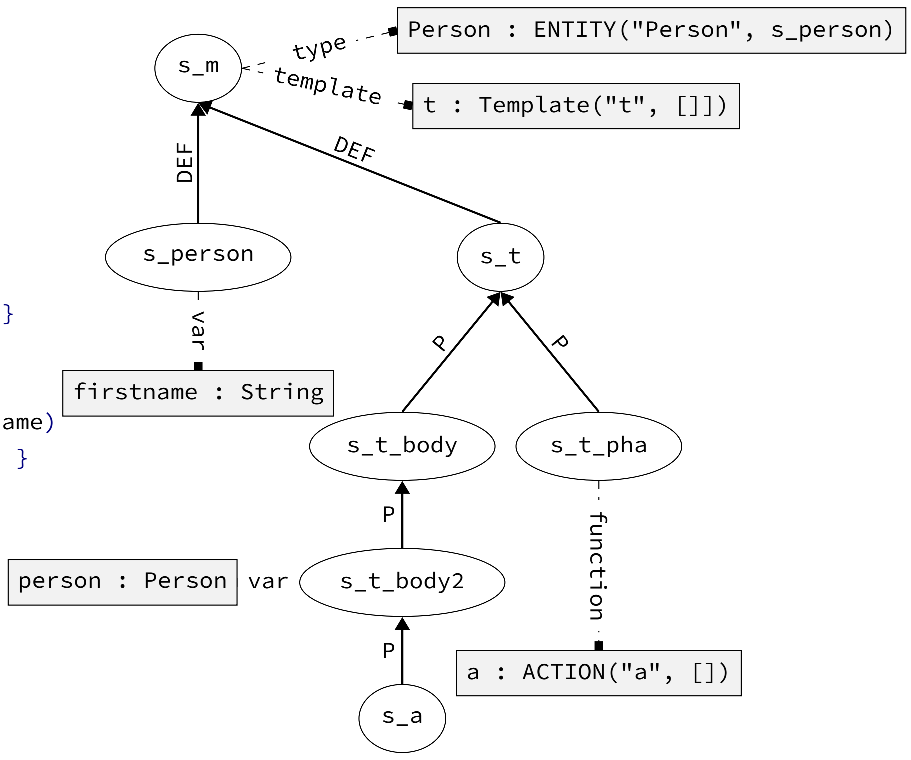
The updated Statix rules for typechecking a page or template definition, and defining actions in shown in Figure 4.56. The Statix rules contain a separate predicate `templateActionOk` where the last boolean parameter indicates whether the action should be declared or not, and this is passed to `optionallyDeclareTemplate`. The declaration is optional because it is possible to create a form with a submit button that defines an action inline; an anonymous

```
typeOfFunctionCall : scope * string * list(Exp)
  * list((path * (string * TYPE))) -> TYPE
typeOfFunctionCall(s, f, args, funSigs) = t :- { argTypes f' result }
  argTypes == typesOfExps(s, args),
  result == mostSpecificSigs(
    argTypes
    , typeCompatibleSigs(funSigs, argTypes
  )),
  [(f', FUNCTION(_, _, t, _))] == result
    | error $[Cannot resolve function [f] with compatible argument types] @f.

// function that gets all functions/templates with matching name
// and compatible argument types
typeCompatibleSigs : list((path * (string * TYPE))) * list(TYPE)
  -> list((string * TYPE))
/* implementation not shown for brevity */

// function that prunes the list of compatible signatures
// to a list of most specific signatures
mostSpecificSigs : list(TYPE) * list((string * TYPE)) -> list((string * TYPE))
// In case no functions are compatible, return empty list
mostSpecificSigs(args, []) = [].
// In case of only one compatible signature, return that
mostSpecificSigs(args, fs@[_]) = fs.
mostSpecificSigs(args, sigs) = mostSpecificSigs_helper(args, sigs,
  matchingSigs(stripRefTypes(args), sigs)).

// helper function for mostSpecificFunSigs that returns
// the exactly matching signatures if they exists,
// else return the most specific (least inheritance) signatures
mostSpecificSigs_helper : list(TYPE) * list((string * TYPE))
  * list((string * TYPE)) -> list((string * TYPE))
mostSpecificSigs_helper(args, sigs, matching) = matching.
mostSpecificSigs_helper(args, sigs, [])       =
  filterLeastInheritanceAmount(
    minOfList(inheritanceAmounts)
    , zipInheritanceAmountWithSig(inheritanceAmounts, sigs)) :-
  inheritanceAmounts == inheritanceAmounts(args, sigs).

// at least ten more helper predicates are not shown that calculate
// the amount of inheritance edges and perform the filtering
```

Figure 4.54: Statix rules for resolving overloaded function calls

```
module m

entity Person {
  firstname : String
}

template t {
  var person := Person{}

  form {
    input(person.firstname)
    submit a() { "Save" }
  }

  action a() {
    person.save();
    return p();
  }
}
```

(a)



(b)

Figure 4.55: An example of defining and referencing actions

action in some sense. The anonymous inline action definition can now be type-checked by re-using the `templateActionOk` predicate.

The Statix rules which implement the placeholders and actions code behave correctly because of Statix' scheduling algorithm as first described by in the original Statix paper (Antwerpen et al. 2018) and further characterized by Rouvoet et al. (Rouvoet et al. 2020).

4.6 Type Extension

4.6.1 Entity Extension

4.6.2 Built-in Type Extension

4.7 Generated Definitions

4.8 Module system

4.9 Pre-analyzed built-in library

4.10 Reflection on Statix

- Repeat reasons for using Statix
- What worked out as intended?
- What did not work as intended?
- What are the workarounds?

```
defineTemplateOk(s, DefineTemplate(mods, t
    , FormalArgs(args), _, elements))
  :- {fargTypes s_template s_pha s_body}
  new s_template, s_template -DEF-> s,
  argTypes == typesOfArgs(s, args),
  declareParameters(s_template, zipArgTypes(fargs, argTypes)),
  new s_pha, s_pha -P-> s_template,    // scope for placeholders and actions
  new s_body, s_body -P-> s_pha,       // scope for template body
  declareTemplate(s, t, argTypes, isAjaxTemplate(mods)),
  overriddenElementExists(s, Template(), t, isAjaxTemplate(mods)),
  templateElementsOk(s_body, s_pha, elements).

templateElementOk(s, _, s_pha
  , Action2TemplateElement(Action(_, a, FormalArgs(args), Block(stmts))))
  :- templateActionOk(s, s_pha, a, args, stmts, TRUE()).

templateActionOk : scope * scope * string
  * list(FormalArg) * list(Statement) * BOOL
templateActionOk(s, s_pha, a, args, stmts, declare)
  :- {s_fun s_fun_body argTypes}
  new s_fun, s_fun -P-> s,
  argTypes == typesOfArgs(s, args),
  declareParameters(s_fun, zipArgTypes(args, argTypes)),
  new s_fun_body, s_fun_body -P-> s_fun,
  optionallyDeclareAction(s_pha, a, args, argTypes, declare),
  stmtsOk(s_fun_body, stmts, PAGE(_, _)).

optionallyDeclareAction : scope * string * list(FormalArg) * list(TYPE) * BOOL
optionallyDeclareAction(_, _, _, _, FALSE()).
optionallyDeclareAction(s, a, args, ts, TRUE())
  :- declareAction(s, a, args, ts).
```

Figure 4.56: Statix rules for declaring actions

- Recommendations for improving Statix

Chapter 5

Evaluation

In this chapter we evaluate the newly introduced SDF3 and Statix specifications for WebDSL. The new specifications have two concrete use-cases, namely serving as a case study for SDF3 and Statix, and being used on a daily basis by WebDSL developers. For both purposes it is useful to gather information about how the specifications behave in various situations. As a result of the case study, we want to show strengths and weaknesses of SDF3 and Statix based on information from the specifications, and for the WebDSL developers we would like to decide whether the new specifications are ready to be used in practice.

For both specifications, we will evaluate their correctness and performance on existing test suites, as well as WebDSL code that is used in practice. Then, we conclude this chapter by discussing the usability of the modernized implementation in practice.

5.1 Evaluating the WebDSL SDF3 Specification

Evaluating the SDF3 specification of the WebDSL grammar is done in two parts: its correctness and its performance in terms of generated parse tables and their run time. In this section we will use the current implementation of the WebDSL grammar in SDF2 as the reference grammar for correctness and performance.

5.1.1 Correctness

In this thesis we do not formally prove the correctness of the new grammar. Instead, we parse test suites that are intended for the current SDF2 specification and parse open source WebDSL applications that are used in practice.

The test suite consists of 231 WebDSL snippets, ranging from single expressions to complete functioning applications. To re-use this test suite for the SDF3 specification, we converted the snippets into SPT tests and the result is that all of the 231 snippets parse succesfully.

Upon closer inspection of the original test suite, while converting it to an SPT test suite, we concluded it was not a complete test suite of all syntax constructs but mostly contained syntax fragments which were problematic in the past to serve as a regression test suite. For the sake of completion, we decided to extend the SPT test suite, leading to a new total of 1118 SPT tests, where the newly added test have an expected AST result, instead of only expecting the snippets to parse correctly.

In addition to the test suite, we used two open-source WebDSL applications for verifying that the new parser generated from the SDF3 specification does not suddenly fail or see ambiguities in existing applications:

- **YellowGrass:** A tag based issue tracker similar to GitHub Issues, complete with access control and used daily by WebDSL developers. YellowGrass consists of 54 WebDSL files plus 20 WebDSL library files and 1 standard library file, coming to a total of 12.898 lines of code spread over 75 files.

- **Reposearch:** A source code search engine that helps to find implementation details, example usages, etc. Reposearch consists of 16 main files, 19 library files and 1 standard library file, totalling at 8.722 lines of code spread over 36 files.

The result of parsing both applications with the new parser generated with the SDF3 specification is that no ambiguities were found.

One thing to note in discussing correctness of the WebDSL SDF3 completeness is that, while the results are promising, the SDF3 specification has introduced many new sorts and constructors for disambiguation purposes, and to comply with the Statix Signature Generator expectations. The effect of this change is that the resulting ASTs were not compared and we can therefore not guarantee correctness of the disambiguation, other than the subjective confidence gained from handpicking snippets and comparing the ASTs manually.

5.1.2 Performance

The performance of a parser of a programming language is essential due to the rest of the compilation chain depending on its output. A requirement to use the parser generated by the new SDF3 specification in practice, is that its run time should not increase substantially.

Grammar specifications in SDF2 and SDF3 are not interpreted directly. Both formalisms generate a parse table, which is interpreted by the parser implementation JSGLR. JSGLR is an implementation of SGLR parsing in Java, used within the Spoofax Language Workbench. Because of this architecture, it is insightful to inspect the generated parse tables and highlight the differences, as well as comparing the run times of both parsers on the test suite and existing applications.

Parse table from	States	Gotos	Max gotos per state	Actions	Max actions per state
SDF2	10.449	179.454	510	62.127	107
SDF3	12.866	244.688	821	525.728	2.491

Table 5.1: Data about the size of the parse tables generated from the SDF2 and SDF3 grammar specifications.

TO-DO:

- Explain statistics in table
- Write about setup: jsglr2evaluationsuite, PC specs, JMH, config
- Parse analysis test suite files with both SDF2 and SDF3, show difference in timings
- Parse YellowGrass and RepoSearch with both SDF2 and SDF3, show difference in timings

5.1.3 Usability

5.2 Statix

- Defining correctness in absence of a formal specification
- How correct is the implementation WebDSL

- Explain correctness
- Edge cases

5.2.1 Correctness

- Analysis test suite: expect to pass all
- Analyze YellowGrass and Reposearch, expect 0 errors
- Explain differences

5.2.2 Performance

- Analyze analysis test suite files with both Stratego and Statix analysis, show difference in timings
- Analyze YellowGrass and Reposearch with both Stratego and Statix analysis, show difference in timings

5.2.3 Usability

- Lack of user-friendliness of the error messages generated by Statix
- Can the WebDSL Statix specification be used as formal specification?
- Maintainability of the codebase

Chapter 6

Related work

6.1 Statix Case Studies

6.1.1 A Constraint Language for Static Semantic Analysis Based on Scope Graphs

LMR (Language with Modules and Records)

- Module system
- Definitions (nominal records, functions, variables, etc)
- Expressions
- Constants

6.1.2 Scopes as Types

Simply-typed Lambda Calculus with Records

- Records
- Structural subtyping

Featherweight Java

- Classes
- Nominal subtyping

System F

- Parametric types
  - Solved by lazily duplicating the parametric type structure when an instantiation is made with a concrete type

6.1.3 Knowing when to ask: sound scheduling of name resolution in type checkers derived from declarative specifications

Java (subset)

- Packages and imports

    - Solved remote extension by using a mixin-pattern: compilation units query for all other compilation units within the same package and make their types accessible by adding import edges.

Scala (subset)

- Accessibilty of definitions: local definitions are available in the surrounding scope, whereas imported definitions are available in the subsequent scopes.
    - This also implements forward referencing
    - Possible inspiration for WebDSL action name resolution

6.1.4 LMR/Rust

- Imports that do influence their own resolution (unordered imports).

6.2 Subjects to investigate

- MPS CodeRules
    - Constraint programming for
- https://github.com/JetBrains/mps-coderules

6.3 Papers to investigate

- Type errors for the IDE with Xtext and Xsemantics
    - https://www.degruyter.com/document/doi/10.1515/comp-2019-0003/html
    - 2019, journal Open Computer Science
    - Implements typechers for two small languages with the Xtext language workbench
    - Describes what to pay attention to when implementing a typechecker (error recovery, useful error messages, etc.)
    - Key difference: This thesis contains a larger case study and is written in Spoofax meta-languages
- Xbase: implementing domain-specific languages for Java
    - https://dl.acm.org/doi/abs/10.1145/2480361.2371419
    - 2012, GPCE '12 (Generative Programming and Component Engineering)
- Migrating custom DSL implementations to a language workbench (tool demo)
    - https://dl.acm.org/doi/abs/10.1145/3276604.3276608
    - 2018, SLE '18 (Software Language Engineering)
- The State of the Art in Language Workbenches
    - https://link.springer.com/chapter/10.1007/978-3-319-02654-1_11
    - 2013, SLE '13 (Software Language Engineering)
    -

- Evaluating and comparing language workbenches: Existing results and benchmarks for the future
  - https://www.sciencedirect.com/science/article/pii/S1477842415000573
  - 2015, journal Computer Languages Systems & Structures
- Towards a Spreadsheet-Based Language Workbench
  - https://ieeexplore.ieee.org/abstract/document/9643797
  - 2021, MODELS-C '21 (Model Driven Engineering Languages and Systems Companion)
- Language Workbench Support for Block-Based DSLs
  - https://core.ac.uk/download/pdf/301639649.pdf
  - 2018, BLOCKS+ in SPLASH '18 (Systems, Programming, Languages and Applications: Software for Humanity)

Chapter 7

Conclusion

7.1 Future work

- Use analysis results for back-end
- Incrementalization in back-end?

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Acronyms

AST	abstract syntax tree
DSL	domain-specific language

Appendix A

A