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

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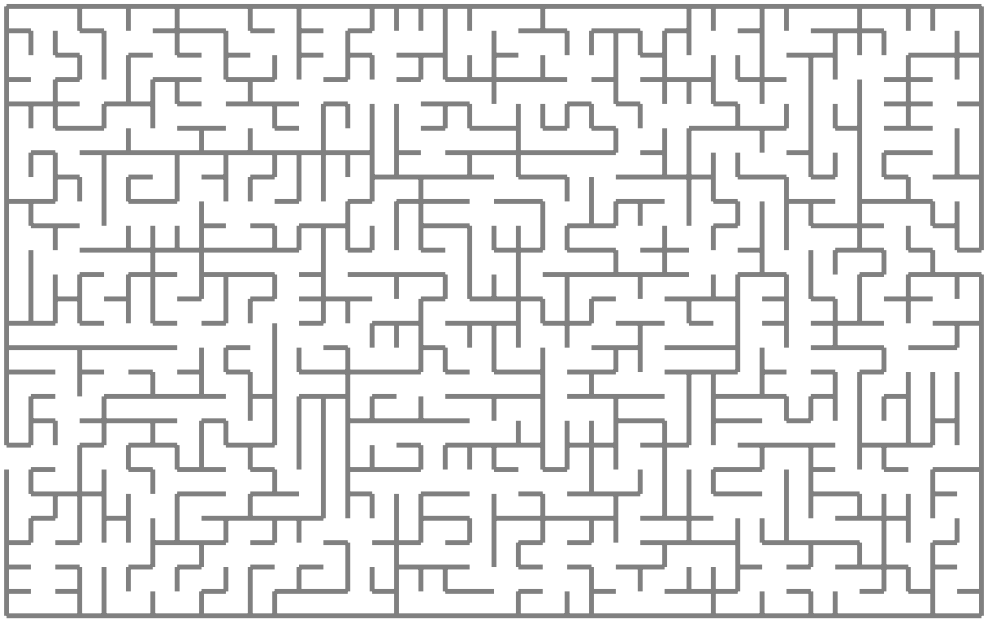

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Modernizing the WebDSL front-end: A case study in SDF3 and Statix

THESIS

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requirements for the degree of

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by

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Cover picture: Random maze.

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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.

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Preface

Preface here.

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Chapter 1

Introduction

Broad Picture

Many different programming languages exist, with many different properties and advantages. (*TO-DO: this is crap, need something better*)

Programming Langauge Front-end Introduction

The implementation of a programming languages can be seperated into two parts: the front-end and the back-end. The front-end is the part of the programming language with which the user interacts (the syntax, early feedback using analysis results) and the back-end is the part that makes the programming language operational (optimization, code generation). While the back-end of a programming langauge makes it work, the front-end defines how a user experiences the programming language (*TO-DO: read papers about this*).

WebDSL

Programming languages are constantly evolving, requiring updates to its specification and implementation. One such language is WebDSL. WebDSL is a domain-specific language for developing web applications, developed at the Delft University of Technology.

Problem Description

Because of its academic nature, many research projects added features to the language, all contributing to the success of existing WebDSL applications. The downside of having many different contributors adding new features, is that the development experience that comes from the front-end leaves much to be desired. (*TO-DO: too harsh?*) Currently, the WebDSL implementation is composed of multiple definitions in meta-DSLs supported by the Spoofax Language Workbench: the syntax is defined in SDF2 and the desugaring, typechecking, optimization and code generation is defined in the term transformation language Stratego. The interleaving of all the latter processes in the same Stratego environment poses a threat to the readability and maintainability of the WebDSL language.

TO-DO: Add something about assessing the usability of SDF3 and Statix for large projects used in practice.

1.1 Contributions

In this thesis, we will be focusing on modernizing the WebDSL front-end, by implementing the syntax definition in SDF3 and the static analyses in Statix and documenting the challenges posed by this process. In this work, the following contributions are made:

- We present a modernized WebDSL front-end through an implementation of its grammar in SDF3 and its analyses in Statix.
- We document the challenges and solutions of implementing the new WebDSL front-end.
- We assess the completeness of Statix and SDF3 by attempting to model all language features of WebDSL.
- We assess the performance of Statix and SDF3 by benchmarking the new WebDSL front-end with large codebases of existing applications.
- We provide qualitative feedback regarding the development experience with SDF3 and Statix.

1.2 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.

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. First, we introduce the meta-DSL Statix. Secondly, we describe the implementation of the simple 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 users with useful hints, warnings and errors.

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.

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. The corresponding Statix code is shown in Figure 4.1.

So far, our specification consists of two sorts. The `Program` 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 lastly `Add` which takes two nested expressions as subterms. Examples of valid input according to our defined signature are shown in Figure 4.2.

```
signature
  sorts
    Program
    Exp

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

Figure 4.1: Language signature in Statix

```
Program(True())
Program(Int("42"))
Program(Add(Int("40"), Int("2")))
Program(Add(Int("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 we would like to generate using Statix rules, are that a program must be well-typed and 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. The type of every Statix predicate must be explicitly declared, for example: `programOk : Program` declares that the predicate named `programOk` matches exactly one instantiation sort Program. An instantiation of the `programOk` predicate is on the line below the signature. In prose English it would read "A program is well-typed, given that for some type `T`, the expression `e` has type `T`". The other Statix rule of 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`".

```
rules

  programOk : Program
  programOk(Program(e)) :- { T }
    typeOfExp(e) == T.

  typeOfExp : Exp -> TYPE
  typeOfExp(True()) = BOOL().
  typeOfExp(False()) = BOOL().
  typeOfExp(Int(_)) = INT().
  typeOfExp(Add(e1, e2)) = INT() :-
    typeOfExp(e1) == INT(),
    typeOfExp(e2) == INT().
```

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

4.1.4 Building a Scope Graph

4.1.5 Querying the Scope Graph

4.2 Encoding the WebDSL Basics

4.2.1 Constant Expressions

- Typing rules
- Type compatibility

4.2.2 Variables

- Declaration and resolving
- Prevent duplicates
- Declare before use
- Shadowing

4.2.3 Entities and properties

- Declaration and resolving
- Prevent duplicates
- Parameters

4.2.4 Functions

- Declaration and resolving
- Prevent duplicates
- Parameters

4.2.5 Pages and Templates

- Declaration and resolving

4.3 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 listing *TO-DO*.

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

Declarations of sub-entities will generate constraints as shown in listing *TO-DO*.

```
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'.
```

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.

Previously, the resolving of variables was done using the query as shown in listing *TO-DO*

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

The new query in listing *TO-DO* reflects the addition of the `EXTEND` label. The addition of `INHERIT*` in the query filter makes all variables declared in ancestors reachable.

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

Overwriting Functions

Generally, overwriting functions 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 another exception, namely that sub-entities are allowed to overwrite function definitions of their ancestors.

Previously, the resolving of entity functions was done using the query as shown in listing *TO-DO* below.

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

With the introduction of entity inheritance, the path well-formedness over edge labels should be tweaked such that functions from ancestors are in scope. Changing `filter e` to `filter INHERIT*` accomplishes this. The resulting query is in listing *TO-DO* below.

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

This query definition works perfectly when sub-entities do not overwrite 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 we would like only one result, namely the overwritten 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 listing *TO-DO*.

```
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.
```

Entity Type Compatibility

A great perk of having inheritance in a language is writing code for that works for super-entities, and then executing this code with sub-entities. To know if the given entity type is compatible with the required entity type, we require a predicate that defines this compatibility. We have created such a predicate while implementing general type compatibility in subsection *TO-DO*, 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 *TO-DO*. 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`.

```
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().
```

4.4 Entity Extension

4.4.1 Built-in Type Extension

4.5 Function and Template Overloading

4.6 Module system

4.7 Pre-analyzed built-in library

4.8 Reflection on Statix

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

Chapter 5

Evaluation

In this chapter we will evaluate the results of the work done in this thesis. First we will assess the correctness of the modernized WebDSL front-end by defining what correctness means in absence of a formal specification and evaluating accordingly. Next, we will share, inspect and reason about the performance of the new parser and static analyses. Lastly, we conclude this chapter by discussing the usability of the modernized implementation in practice.

5.1 Correctness

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

5.2 Performance

- Explain metrics and methods
- Results
- Discuss results

5.3 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 Statix and SDF3 codebase

Chapter 6

Related work

6.1 Papers

- Static consistency checking of web applications with WebDSL (Hemel, Groenewegen, Kats, Visser). JSC 2011.
  - Importance of early feedback to developer.
  - Different inconsistencies that can be checked and how they are often checked.
  - Importance of linguistic integration to enable consistency checking at compile time.
  - How WebDSL is designed to enable early reporting of inconsistencies.
- Links: Web Programming Without Tiers (Cooper, Lindley, Wadler, Yallop). FCMO 2006.
  - Introduces the Links programming language.
  - Links generates all tiers of web application: client-side HTML and JavaScript, server-side OCaml and SQL for the database.
  - Links tackles the impedance mismatch problem of different input/output provided and expected by the different tiers.
  - Links is a strict, typed, functional language with all state saved in the client-side.
- Ur/Web: A Simple Model for Programming the Web (Chlipala). POPL 2015.
  - Introduces the Ur/Web programming language.
  - Similar to Links, Ur/Web is a functional programming language that generates code for all tiers of a web application.
  - Ur/Web introduces encapsulation and simple concurrency.
  - Encapsulation: treating key pieces of web applications as private state (?).

6.2 Papers to investigate

- Evolution of the WebDSL runtime
  - About the evolution of a programming language
  - Contains WebDSL details
  - Key difference: This thesis focusses on front-end of the WebDSL language, not the back-end

- Scopes as Types
  - About declaratively specifying static semantics
  - Contains Statix details and case studies
  - Key difference: This thesis contains a larger case study with more language constructs and different (practically motivated) requirements

Maybe?:

- Type errors for the IDE with Xtext and Xsemantics
  - https://www.degruyter.com/document/doi/10.1515/comp-2019-0003/html
  - 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

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