

UNIVERSITY OF BERGEN
DEPARTMENT OF INFORMATICS

Making a template query language for EcmaScript

Author: Rolf Martin Glomsrud

Supervisor: Mikhail Barash

Informal advisor: Yulia Startsev



UNIVERSITETET I BERGEN
Det matematisk-naturvitenskapelige fakultet

June, 2024

Abstract

Lorem ipsum dolor sit amet, his veri singulis necessitatibus ad. Nec insolens periculis ex. Te pro purto eros error, nec alia graeci placerat cu. Hinc volutpat similique no qui, ad labitur mentitum democritum sea. Sale inimicus te eum.

No eros nemore impedit his, per at salutandi eloquentiam, ea semper euismod meliore sea. Mutat scaevola cotidieque cu mel. Eum an convenire tractatos, ei duo nulla molestie, quis hendrerit et vix. In aliquam intellegam philosophia sea. At quo bonorum adipisci. Eros labitur deleniti ius in, sonet congrue ius at, pro suas meis habeo no.

Acknowledgements

Est suavitate gubergren referrentur an, ex mea dolor eloquentiam, novum ludus suscipit in nec. Ea mea essent prompta constituam, has ut novum prodesset vulputate. Ad noster electram pri, nec sint accusamus dissentias at. Est ad laoreet fierent invidunt, ut per assueverit conclusionemque. An electram efficiendi mea.

Your name

Saturday 1st June, 2024

Contents

1	Introduction	1
2	Background	3
2.1	Evolution of the JavaScript programming language	3
2.1.1	ECMA-262 Proposals	3
2.2	Abstract Syntax Trees	5
2.3	Source Code Querying	6
2.4	Domain-Specific languages	6
2.5	Language Workbenches	7
3	Collecting User Feedback for Syntactic Proposals	8
3.1	The core idea	8
3.1.1	Applying a proposal	9
3.2	Applicable proposals	10
3.2.1	Simple example of a syntactic proposal	10
3.2.2	“Pipeline” Proposal	11
3.2.3	“Do Expression” Proposal	13
3.2.4	“Await to Promise” (imaginary proposal)	14
3.3	Searching user code for applicable parts	15
3.3.1	Structure of JSTQL	15
3.3.2	How a match and transformation is performed	17
3.3.3	Transforming	19
3.3.4	Using JSTQL	20
3.4	Using the JSTQL with syntactic proposals	21
3.4.1	“Pipeline” Proposal	22
3.4.2	“Do Expression” Proposal	23
3.4.3	“Await to promise” imaginary proposal	24
3.5	JSTQL-SH	25

4	Implementation	26
4.1	Architecture of the solution	26
4.2	Parsing JSTQL using Langium	27
4.2.1	Langium	28
4.3	Wildcard extraction and parsing	31
4.4	Using Babel to parse	35
4.5	Outline of transforming user code	37
4.6	Matching	38
4.6.1	Determining if AST nodes match	38
4.6.2	Matching a single Expression/Statement template	39
4.6.3	Matching multiple Statements	42
4.7	Transforming	44
5	Evaluation	48
5.1	Real Life source code	48
6	Related Work	51
6.1	Aspect-Oriented Programming	51
6.2	Other source code query languages	52
6.2.1	CodeQL	52
6.2.2	PMD XPath	53
6.2.3	XSL Transformations	53
6.2.4	Jackpot	54
6.3	JetBrains structural search	54
6.4	Other JavaScript parsers	55
6.5	Model-to-Model Transformations	57
7	Conclusions & Future Work	58
7.1	Conclusions	58
7.2	Future Work	58
	Bibliography	60
A	TypeScript types of wildcard type expressions	65
B	Examples of transformations performed in Evaluation	66

List of Figures

2.1	Example of source code parsed to Babel AST	5
3.1	Writing JSTQL in Visual Studio Code with extension.	20
3.2	Error displayed when declaring a wildcard with no types.	21
3.3	Error displayed with usage of undeclared wildcard.	21
4.1	Tool architecture	27

List of Tables

5.1	Evaluation with Next.js source code	49
5.2	Evaluation with Three.js source code	49
5.3	Evaluation with React source code	50
5.4	Evaluation with Bootstrap source code	50
5.5	Evaluation with Atom source code	50

Listings

3.1	JSTQL definition of a proposal.	17
3.2	Example of “Pipeline” proposal definition in JSTQL.	22
3.3	Definition of Do Proposal in JSTQL.	23
3.4	Definition of “Await to promise” evaluation proposal in JSTQL.	24
4.1	Definition of JSTQL in Langium.	29
4.2	Extracting wildcard from template.	32
4.3	Grammar of type expressions	33
4.4	Simple definition of a Tree structure in TypeScript	35
4.5	Pseudocode of child node matching	41
4.6	Extracting wildcard from match	44
4.7	Traversing <code>transform</code> to AST and inserting user context	45
4.8	Inserting transformed matches into user code	46
A.1	TypeScript types of Type Expression AST	65

Chapter 1

Introduction

The development of the programming language ECMAScript, which is defined by the ECMA-262 language standard, is worked on by Technical Committee 39. The committee has the responsibility to explore proposals suggested for addition to ECMAScript. During this process, proposals go through many iterations in the exploration process of solutions to the problem identified in the proposal. During this process, the community of JavaScript developers can give feedback on proposed solutions. This feedback has to be of some quality, and it is therefore adamant that the user's giving feedback understand the proposal well. This thesis suggests a way of presenting proposals to users by exploiting their familiarity with their own code.

The idea behind using the user's own code, is to lower the barrier to understand a proposal. A user most likely understands the code they themselves have written, therefore there is no need to understand the initial premise of the example. Therefore, this will allow the user to focus solely on the concepts the proposal introduces. This idea applies to syntactic proposals, which are proposals that contains either no, or very limited change to functionality, and no change to semantics.

This thesis discusses a way of defining transformations of code specifically for syntactic proposals. These transformations are used to showcase a syntactic proposal to users by transforming code the user's are already familiar with. The theory is this will help user's understand proposals faster and easier, as they are already familiar with the code the proposal is being presented in. The two proposals discussed in this thesis to evaluate the tool are "Do Expression" [23] and "Pipeline" [20].

The language defined in this thesis is titled JSTQL, and allows for structured template queries to be written, these templates are used to search for code that is applicable to a proposal. A code snippet being applicable to a proposal, means it could have been written using that proposal. These queries come with a definition of a transformation, which will use the matched code snippet in the user's code, and transform it to use the features of the proposal. This newly transformed code can then be presented to the user along with the original unchanged code. This allows a user to see an example of the proposal being applied, and they can then give feedback on the proposal based on that.

Every template uses a notion of wildcards, which are sections of the template that is not defined using JavaScript, but a custom block containing an identifier, and a AST node type expression.

Chapter 2

Background

2.1 Evolution of the JavaScript programming language

Technical Committee 39 (abbreviated as TC39) is a group within ECMA international, whose main goal is to develop the language standard for ECMAScript (JavaScript) and other related standards. These related standards include: ECMA-402 the internationalization API of ECMA-262 ECMA-404 the standard for JSON and ECMA-414 the ECMAScript specification suite standard. The members of the committee are representatives from companies, academic institutions, and various other organizations from all across the world interested in developing the ECMAScript language. The delegates are experts in JavaScript engines, tooling surrounding JavaScript, and other parts of the JavaScript ecosystem.

2.1.1 ECMA-262 Proposals

We explain now what a proposal is, and how proposals are developed in TC39 for the ECMA-262 language standard.

A *proposal* is a suggested change to the ECMA-262 language standard. These additions to the standard have to solve some form of problem with the current version of ECMAScript. Such problems can come in many forms, and can apply to any part of the language. Examples include: a feature that is not present in the language, inconsistent parts of the language, simplification of common patterns, and so on. The proposal development process is defined in the TC39 Process Document.

The **TC39 Process Document** [27] describes each stage a proposal has to go through to be accepted into the ECMA-262 language standard.

The purpose of *stage 0* of the process is to allow for exploration and ideation around which parts of the current version of ECMAScript can be improved, and then define a problem space for the committee to focus on improving.

stage 1 is the stage the committee will start development of a suggested proposal. There are several requirements to enter this stage: a champion, a delegate of the committee responsible for a proposal, has to be identified. A rough outline of the problem must be provided, and a general shape of a solution must be given. There must have been discussion around key algorithms, abstractions and semantics of the proposal. Exploration of potential implementation challenges and cross-cutting concerns must have been done. The final requirement is for all parts of the proposal to be captured in a public repository. Once all these requirements are met, a proposal is accepted into stage 1. During this stage, the committee will work on the design of a solution, and resolve any cross-cutting concerns discovered previously.

At *stage 2* a preferred solution has been identified. Requirements for a proposal to enter this stage are as follows: all high level API's and syntax must be described in the proposal document, illustrative examples created, and an initial specification text must be drafted. During this stage the following areas of the proposal are explored: refining the identified solution, deciding on minor details, and create experimental implementations.

At *stage 2.7* the proposal is principally approved, and has to be tested and validated. To enter this stage, the major sections of the proposal must be complete. The specification text should be finished, and all reviewers of the specification have approved. Once a proposal has entered this stage, testing and validation will be performed. This is done through the prototype implementations created in stage 2.

Once a proposal has been sufficiently tested and verified, it is moved to *stage 3*. During this stage, the proposal is implemented in at least two major JavaScript engines. The proposal should be tested for web compatibility issues, and integration issues in the major JavaScript engines.

At *Stage 4* the proposal is completed and included in the next revision of the ECMA-262.

2.2 Abstract Syntax Trees

An *abstract syntax tree* (AST) is a tree representation of source code. Every node of such a tree represents a construct from the source code. ASTs remove syntactic details while maintaining the *structure* of the program. Each node is set to represent elements of the programming language, such as statements, expressions, declarations to name a few. Every node type represents a grammatical construct in the language the AST was built from.

ASTs are important for manipulating source code; they are used by almost any tool that has to represent source code in some way to perform operations with it [44]. Using ASTs is favored over raw text due to their structured nature, especially when considering tools like compilers, interpreters, or code transformation tools. ASTs are produced by language parsers. For JavaScript, one of the popular libraries used for parsing is *Babel* [4].

Babel is a JavaScript toolchain, its main usage is converting ECMAScript 2015 and newer into older versions of JavaScript. This conversion is done to increase the compatibility of JavaScript in older environments such as older browsers.

Babel has a suite of libraries used to work with JavaScript source code, each library relies on Babel's AST definition [5]. The AST specification Babel uses tries to stay as close to the ECMAScript standard as possible [10], which has made it a recommended parser to use for proposal transpiler implementations [28]. A simple example of how source code parsed into an AST with Babel looks like can be seen in Figure 2.1.

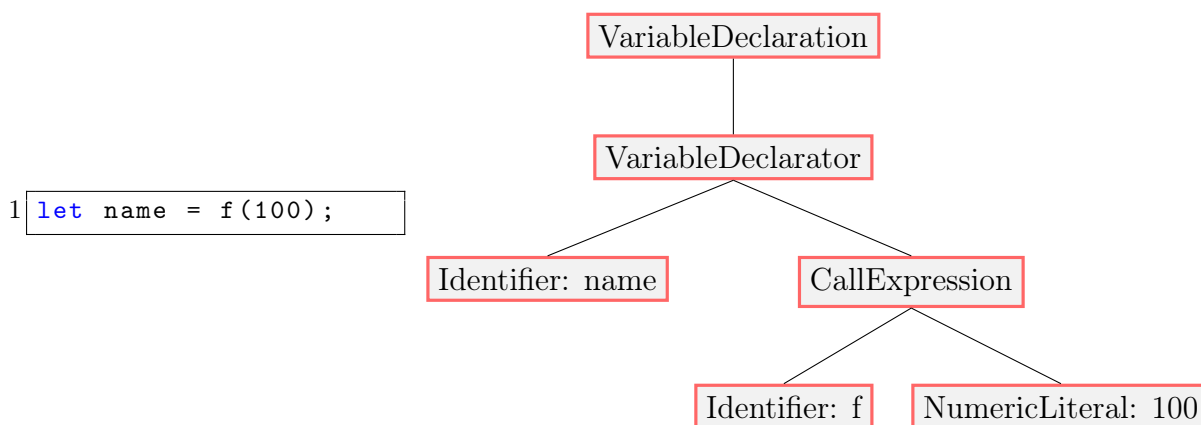


Figure 2.1: Example of source code parsed to Babel AST

To achieve compilation of newer versions into older versions, Babel uses a plugin system that allows a myriad of features to be enabled or disabled. This makes the parser

versatile to fit different ways of working with JavaScript source code. Because of this, Babel allows parsing of JavaScript experimental features. These features are usually proposals that are under development by TC39, and the development of these plugins are a part of the proposal deliberation process. This allows for experimentation as early as stage 1 of the proposal development process. Some examples of proposals that were first supported by Babel's plugin system are "Do Expression" [23] and "Pipeline" [20]. These proposals are both currently in stage 1 and 2, respectively.

2.3 Source Code Querying

Source code querying is the action of searching source code to extract some information or find specific sections of code. Source code querying comes in many forms, the simplest of which is text search. Since source code is primarily text, one can apply text search techniques to perform a query, or a more complex approach using regular expressions (e.g. tools like `grep`). Both these methods do not allow for queries based on the structure of the code, and rely solely on its syntax. AST-based queries allow queries to be written based on both syntax and structure, and are generally more powerful than regular text based queries. Another technique for code querying is based on semantics of code.

The primary use cases for source code querying is code understanding, analysis, code navigation, enforcement of styles, along with others. All these are important tools developers use when writing programs, and they all rely on some form of source code queries. One such tool is Integrated Development Environments (IDEs), as these tools are created to write source code, and therefore rely on querying the source code for many of their features. One such example of code querying being used in an IDE is JetBrains structural search and replace [26], where queries are defined based on code structure to find and replace sections of our program.

2.4 Domain-Specific languages

Domain specific languages are software languages specialized to a specific narrow domain [38]. The difference between DSLs and General Purpose Languages (GPLs) is defined like a spectrum, in which DSL is on one end and GPLs is on the other [39]. DSLs allow domain experts to get involved in the development process, as it is expected that

a domain expert would have the capabilities to read and write DSL code. A DSL allows for very concise and expressive code to be written that is specifically designed for the domain. Using a DSL might result in faster development because of this expressiveness within the domain, this specificity to a domain might also increase correctness. However, there are also some disadvantages to DSL's, the restrictiveness of a DSL might become a hinderance if it is not well designed to represent the domain. DSL's also might have a learning curve, making the knowledge required to use them a hinderance. Developing the DSL might also be a hinderance, as a DSL requires both knowledge of the domain and knowledge of software language engineering.

2.5 Language Workbenches

A language workbench is a tool created to facilitate the development of a computer language, such as a DSL.

Language workbenches support generating tooling for languages, as most modern computer languages are backed by some form of tooling. One such tool is a language parser that is generated from the language definition within the language workbench. Another such tool commonly generated by a language workbench is a language server for integrated development environments, these language servers provide functionality such as syntax highlighting, code navigation, error highlighting, along with others.

A language is defined in a language workbench using a grammar definition. This grammar is a formal specification of the language that describes how each language construct is composed and the structure of the language. This allows the language workbench to determine what is a valid sentence of the language. This grammar is used to create the AST of the language, which is the basis for all the tools generated by the language workbench. Many such language workbenches exist, such as Langium [17], Xtext [34], JetBrains MPS, and Racket.

Chapter 3

Collecting User Feedback for Syntactic Proposals

The goal for this project is to utilize user's familiarity with their own code to gain early and worthwhile feedback on a certain kind of ECMAScript proposals.

3.1 The core idea

When a user of ECMAScript wants to suggest a change to the language, the idea of the change has to be described in a Proposal. A proposal is a general way of describing a change and its requirements, this is done by a language specification, motivation for the idea, and general discussion around the proposed change. A proposal ideally also needs backing from the community of users that use ECMAScript, this means the proposal has to be presented to users some way. This is currently done by many channels, such as polyfills, code examples, and as beta features of the main JavaScript engines, however, this paper wishes to showcase proposals to users by using a different avenue.

Users of ECMAScript have a familiarity with code they themselves have written. This means they have knowledge of how their own code works and why they might have written it a certain way. This project aims to utilize this pre-existing knowledge to showcase new proposals for ECMAScript. This way will allow users to focus on what the proposal actually entails, instead of focusing on the examples written by the proposal authors.

Further in this chapter, we will be discussing the current version and future version of ECMAScript. What we are referring to in this case is with set of problems a proposal is trying to solve, if that proposal is allowed into ECMAScript as part of the language, there will be a future way of solving said problems. The current way is the current status quo when the proposal is not part of ECMAScript, and the future version is when the proposal is part of ECMAScript and we are utilizing the new features of said proposal.

The program will allow the users to preview proposals way before they are part of the language. This way the committee can get useful feedback from users of the language earlier in the proposal process. Using the users familiarity will ideally allow for a more efficient process developing ECMAScript.

3.1.1 Applying a proposal

The way this project will use the pre-existing knowledge a user has of their own code is to use that code as base for showcasing a proposals features. Using the users own code as base requires the following steps to automatically implement the examples that showcase the proposal inside the context of the users own code.

The idea is to identify where the features and additions of a proposal could have been used. This means identifying parts of the users program that use pre-existing ECMAScript features that the proposal is interacting with and trying to solve. This will then identify all the different places in the users program the proposal can be applied. This step is called *matching* in the following chapters.

Once we have matched all the parts of the program the proposal could be applied to, the users code has to be transformed to use the proposal, this means changing the code to use a possible future version of JavaScript. This step also includes keeping the context and functionality of the users program the same, so variables and other context related concepts have to be transferred over to the transformed code.

The output of the previous step is then a set of code pairs, where one a part of the users original code, and the second is the transformed code. The transformed code is then ideally a perfect replacement for the original user code if the proposal is part of ECMAScript. These pairs are used as examples to present to the user, presented together so the user can see their original code together with the transformed code. This allows for a direct comparison and an easier time for the user to understand the proposal.

The steps outlined in this section require some way of defining matching and transforming of code. This has to be done very precisely and accurately to avoid examples that are wrong. Imprecise definition of the proposal might lead to transformed code not being a direct replacement for the code it was based upon. For this we suggest two different methods, a definition written in a custom DSL JSTQL and a definition written in a self-hosted way only using ECMAScript as a language as definition language.

3.2 Applicable proposals

A *syntactic proposal* is a proposal that contains only changes to the syntax of a language. This means that the proposal contains either no or very limited change to functionality, and no changes to the semantics of the language. This limits the scope of proposals this project is applicable to, but it also focuses solely on some of the most challenging proposals where the users of the language might have the strongest opinions.

3.2.1 Simple example of a syntactic proposal

Consider an imaginary proposal “**numerical literals**”. This proposal describes adding an optional keyword for declaring numerical variables if the expression of the declaration is a numerical literal.

An example of this proposal can be seen below:

```
1 // Original code
2 let x = 100;
3 let b = "Some String";
4 let c = 200;
5
6 // Code after application of proposal
7 int x = 100;
8 let b = "Some String";
9 let c = 200;
```

See above that the change is optional, and is not applied to the declaration of `c`, but it is applied to the declaration of `x`. Since the change is optional to use, and essentially is *syntax sugar*, this proposal does not make any changes to functionality or semantics, and can therefore be categorized as a syntactic proposal.

3.2.2 “Pipeline” Proposal

The “Pipeline” proposal [20] is a syntactic proposal which focuses on solving problems related to nesting of function calls and other expressions that take an expression as an argument.

This proposal aims to solve two problems with performing consecutive operations on a value. In ECMAScript there are two main styles of achieving this functionality currently: nesting calls and chaining calls, each of them come with a differing set of challenges when used.

Nesting calls is mainly an issue related to function calls with one or more arguments. When doing many calls in sequence the result will be a *deeply nested* call expression. Using nested calls can have some specific challenges related to readability. The reading order of nested calls is from right to left rather than the regular reading direction of JavaScript code which is left to right. This means it is difficult to switch the reading direction when working out which call happens in which order. When using functions with multiple arguments in the middle of the nested call, it is not intuitive to see what call its arguments belong to. These issues are the main challenges this proposal is trying to solve. There are currently ways to improve readability with nested calls, as they can be simplified by using temporary variables. While this does introduce its own set of issues, it provides some way of mitigating the readability problem. Another positive side of nested calls is they do not require a specific design to be used, and a library developer does not have to design their library around this specific call style. In the listings below, examples of deeply nested calls with both single and multiple arguments can be seen.

```
1 // Deeply nested call with
  ↪ single arguments
2 f1(f2(f3(f4(v))));
```

```
1 // Deeply nested call with
  ↪ multi argument functions
2 f1(v5, f2(f3(v3, f4(v1, v2)),
  ↪ v4), v6);
```

Chaining calls solves some of these issues: indeed, as it allows for a more natural reading direction left to right when identifying the sequence of call, arguments are naturally grouped together with their respective function call, and it provides a way of untangling deep nesting. However, executing consecutive operations using chaining has its own set of challenges. To use chaining, the API of the code being called has to be designed to allow for chaining. This is not always the case however, making use of chaining when it has not been specifically designed for can be very difficult. There are also concepts in JavaScript not supported when using chaining, such as arithmetic operations, literals,

`await` expressions, `yield` expressions and so on. This is because all of these concepts would break the chain of calls, and one would have to use temporary variables. In the listings below are examples of both chaining with no arguments other than `self`, and examples where additional arguments are passed during the chain.

<pre>1 // Chaining calls 2 f1().f2().f3();</pre>	<pre>1 // Chaining calls with multiple ↪ arguments 2 f1().f2(v1, v2).f3(v2).f4();</pre>
--	---

The “Pipeline” proposal aims to combine the benefits of these two styles without the challenges each method faces. The proposal wants to achieve a similar style to chaining when doing deeply nested calls. The idea is to use syntactic sugar to change the writing order of the calls without influencing the API of the functions. Doing so will allow each call to come in the direction of left to right, while still maintaining the modularity of deeply nested function calls.

The proposal introduces a *pipe operator*, which takes the result of an expression on the left, and pipes it into an expression on the right. The location of where the result is piped to is where the topic token is located. All the specifics of the exact token used as a topic token and exactly what operator will be used as the pipe operator might be subject to change, and is currently under discussion [21].

The code snippets below showcase the machinery of the proposal. They are the examples used to showcase the proposal in the proposal repository [20]

The example below showcases a left to right ordering of function calls that follows the order of execution.

<pre>1 // Status quo 2 const json = await ↪ npmFetch.json(3 npa(pkgs[0]).escapedName, ↪ opts);</pre>	<pre>1 // With pipes 2 const json = pkgs[0] > ↪ npa(%).escapedName > ↪ await npmFetch.json(% , ↪ opts);</pre>
---	---

In the example below, we can see that functions calls with multiple arguments are supported by “Pipeline”.

<pre>1 // Status quo 2 return filter(obj, ↪ negate(cb(predicate)), ↪ context);</pre>	<pre>1 // With pipes 2 return cb(predicate) > ↪ _negate(%) > ↪ _filter(obj, %, context);</pre>
--	--

In the example below, we can see the topic token can be used multiple times to pass the same expression several times on the right side of a “Pipeline” proposal expression.

<pre> 1 // Status quo 2 return xf ↪ xf['@@transducer/result'](obj ↪ xf), acc)); </pre>	<pre> 1 // With pipes 2 return xf 3 > ↪ bind(['@@transducer/step'], ↪ %) 4 > obj[methodName](%, acc) 5 > ↪ xf['@@transducer/result'](%) ; </pre>
--	---

The pipe operator is present in many other languages such as F# [37], Julia [16], Elixir [15] and Unix Shell [12]. The main difference between these languages' pipe operator and the pipe operator suggested in this proposal is the result of the left side expression has to be piped into a function with a single argument, this proposal suggests a topic reference to be used instead, clearly marking where the left side result should be piped to. Proposals suggesting pipe expressions similar to how it is done in F# have been rejected by TC39 multiple times, but were rejected both times due to syntactical concerns and technical challenges [22]

3.2.3 “Do Expression” Proposal

The “Do expression” [23] proposal is a proposal meant to bring a style of *expression oriented programming* [32] to ECMAScript. Expression oriented programming is a concept taken from functional programming which allows for combining expressions in a very free manner, resulting in a highly malleable programming experience.

The motivation of the “Do expression” proposal is to allow for local scoping of a code block that is treated as an expression. Thus, complex code requiring multiple statements will be confined inside its own scope [31, Sect. 8.2] and the resulting value is returned from the block implicitly as an expression, similarly to how unnamed functions or arrow functions are currently used. To achieve this behavior in the current version of ECMAScript, one needs to use immediately invoked; unnamed functions [31, Sect. 15.2] or arrow function [31, Sect. 15.3].

The codeblock of a `do` expression has one major difference from these equivalent functions, as it allows for implicit return of the final statement of the block, and is the resulting value of the entire `do` expression. The local scoping of this feature allows for a cleaner environment in the parent scope of the `do` expression. What is meant by this is for temporary variables and other assignments used once can be enclosed inside a limited scope within the `do` block. Allowing for a cleaner environment inside the parent scope where the `do` block is defined.

The current version of JavaScript enables the use of immediately invoked arrow functions with no arguments to achieve similar behavior to “Do expression”, an example of this can be seen in the Listing below. The main difference between immediately invoked arrow functions and “Do expression” is the final statement/expression will implicitly return its Completion Record [31, Sect. 6.2.4], and we do not need a return statement.

```
1 // Current status quo
2 let x = () => {
3   let tmp = f();
4   return tmp + tmp + 1;
5 }();
```

```
1 // With do expression
2 let x = do {
3   let tmp = f();
4   tmp + tmp + 1;
5 };
```

The example below is very similar to the one above, and uses an unnamed function [31, 15.2] which is invoked immediately to produce similar behavior to the “Do expression” proposal.

```
1 // Current status quo
2 let x = function() {
3   let tmp = f();
4   let a = g() + tmp;
5   return a - 1;
6 }();
```

```
1 // With do expression
2 let x = do {
3   let tmp = f();
4   let a = g() + tmp;
5   a - 1;
6 };
```

3.2.4 “Await to Promise” (imaginary proposal)

We discuss now an imaginary proposal that was used as a running example during the development of this thesis. This proposal is a pure JavaScript transformation example. The transformation this proposal is meant to display is transforming code using `await` [31, Sect. 27.7.5.3] into code which uses a promise [31, Sect. 27.2].

To perform this transformation, we define an equivalent way of expressing an `await` expression as a promise. This means removing `await`, this expression now will return a promise, which has a function `then`, this function is executed when the promise resolves. We pass an arrow function as argument to `then`, and append each following statement in the current scope [31, Sect. 8.2] inside the block of that arrow function. This will result in equivalent behavior to using `await`. An example of a function using `await` can be seen below on the left. The example below on the right is the same function but is using a promise.

<pre> 1 // Code containing await 2 async function a(){ 3 let b = 9000; 4 let s = await asyncF(); 5 let c = s + 100; 6 return c + 1; 7 } </pre>	<pre> 1 // Re-written using promises 2 async function a(){ 3 let b = 9000; 4 return asyncF() 5 .then(async (s) => { 6 let c = s + 100; 7 return c; 8 }) 9 } </pre>
--	---

Transforming using this imaginary proposal will result in a returning the expression present at the first `await` expression, with a deferred function `then` which will execute once the expression is completed. This function takes a callback containing a lambda function with a single argument. This argument shares a name with the initial `VariableDeclaration`. This is needed because we have to transfer all statements that occur after the original `await` expression into the body of the callback function. This callback function also has to be `async`, in case any of the statements placed into it contains `await`. This will result in equivalent behavior to the original code.

3.3 Searching user code for applicable parts

To identify parts of code in the user's code where a proposal is applicable, we need some way to define patterns of code to use as a query. To do this, we have designed and implemented a domain-specific language that allows matching parts of code that is applicable to some proposal, and transforming those parts to use the features of that proposal.

3.3.1 Structure of JSTQL

In this section, we describe the structure of JSTQL (JavaScript Template Query Language).

Proposal definition JSTQL is designed to mimic the examples already provided in proposal descriptions. These examples can be seen in each of the proposals described in Section 3.2. The idea is to allow a similar kind of notation to the examples in order to define the transformations.

The first part of JSTQL is defining the proposal; this is done by creating a named block containing all definitions of templates used for matching alongside their respective transformation.

```
1 proposal Pipeline_Proposal {}
```

Case definition Each proposal will have one or more definitions of a template for code to identify in the users codebase, and its corresponding transformation definition. These are grouped together to have a simple way of identifying the corresponding cases of matching and transformations. This block of the proposal is defined by the keyword **case** and a block that contains its related fields. A proposal definition in JSTQL should contain at least one **case** definition. This allows for matching many different code parts and showcasing more of the proposal than a single concept the proposal has to offer.

```
1     case case_name {  
2  
3     }
```

Template used for matching To define the template used to match, we have another block defined by the keyword **applicable to**. This block will contain the template defined using JavaScript with specific DSL blocks defined inside the template. This template is used to identify applicable parts of the user's code to a proposal.

```
1 applicable to {  
2     "let a = 0;"  
3 }
```

This **applicable to** template will create matches on any **VariableDeclaration** that is initialized to the value 0, and has an **Identifier** with the name **a**.

Defining the transformation To define the transformation that is applied to a specific matched part of the code, the keyword **transform to** is used. This block is similar to the template block, however it uses the specific DSL identifiers defined in **applicable to**, to transfer the context of the matched user code, this allows us to keep parts of the users code important to the original context it was written in.

```
1 transform to{  
2     "()" => {  
3         let b = 100;  
4     }"  
5 }
```

This transformation definition, will change any code matched to its corresponding matching definition into exactly what is defined. This means for any matches produced this code will be inserted in its place.

Full definition of JSTQL Taking all these parts of JSTQL structure, defining a proposal in JSTQL will look as follows.

```
1 proposal PROPOSAL_NAME {
2   case CASE_NAME_1 {
3     applicable to {
4       "let b = 100;"
5     }
6     transform to {
7       "() => {};"
8     }
9   }
10  case CASE_NAME_2 {
11    applicable to {
12      "console.log();"
13    }
14    transform to {
15      "console.dir();"
16    }
17  }
18 }
```

Listing 3.1: JSTQL definition of a proposal.

This complete example of JSTQL has two `case` blocks. Each `case` is applied one at a time to the user's code. The first case will try to find any `VariableDeclaration` statements, where the identifier is `b`, and the right side expression is a `Literal` with value 100. The second case will change any empty `console.log` expression, into a `console.dir` expression.

3.3.2 How a match and transformation is performed

To perform matching and transformation of the user's code, we first have to have some way of identifying applicable user code. These applicable code sections then have to be transformed and inserted it back into the full user code definition.

Identifying applicable code To identify parts of code a proposal is applicable to, we use *templates*, which are defined using JavaScript. These templates are used to identify and match applicable parts of a users code. A matching part for a template is one that produces an exactly equal AST structure, where each node of the AST has the same information contained within it. This means that templates are matched exactly against the users code; this does not really provide some way of querying the code and performing context based transformations, so for that we use *wildcards* within the template.

Wildcards are interspliced into the template inside a block denoted by « ». Each wildcard starts with an identifier, which is a way of referring to that wildcard in the

definition of the transformation template later. This allows for transferring the context of parts matched to a wildcard into the transformed output, like identifiers, parts of statements, or even entire statements, can be transferred from the original user code into the transformation template. A wildcard can also contains a *type expression*. A type expression is a way of defining exactly the types of AST nodes a wildcard will produce a match against. These type expressions use Boolean logic together with the AST node-types from BabelJS [4] to create a very versatile of defining exactly what nodes a wildcard can match against.

Wildcard type expressions Wildcard expressions are used to match AST node types based on Boolean logic. This Boolean logic is based on comparison of Babel AST node types [5]. We do this because we need an accurate and expressive way of defining specifically what kinds of AST nodes a wildcard can be matched against. This means a type expression can be as simple as `VariableDeclaration`: this will match only against a node of type `VariableDeclaration`. We also special types for `Statement` for matching against a statement, and `Expression` for matching any expression.

The example below will allow any node with type `CallExpression` to match against this wildcard named `expr`.

```
1 << expr: CallExpression >>
```

To make this more expressive, the type expressions use binary and unary operators. The following operators are supported: `&&` for logical conjunction, `||` for logical disjunction, `!` for logical negation. This makes it possible to build complex type expressions, making it very expressive exactly what nodes are allowed to match against a specific wildcard.

In the example below on line 1, we want to limit the wildcard to not match against any nodes with type `VariableDeclaration`, while still allowing any other `Statement`. On line 2 below we want to avoid any loop-specific statements. We express this by allowing any `Statement`, but we negate the expression containing the types of loop specific statements.

```
1 << notVariableDeclaration: Statement && !VariableDeclaration >>
2 << noLoopSpecificStatements: Statement && !(BreakStatement ||
  ↪ ContinueStatement) >>
```

The wildcards support matching subsequent sibling nodes of the code against a single wildcard. We achieve this behavior done by using a Kleene plus at the top level of the expression. A Kleene plus means one or more, so we allow for one or more matches in

order when using this token. This is useful for matching against a series of one or more specific nodes, the matching algorithm will continue to match until the type expression no longer evaluates to true.

In the example below, we allow the wildcard to match multiple nodes with the Kleene plus `+`. This example will continue to match against itself as long as the nodes are a `Statement` and at the same time is not a `ReturnStatement`. This example showcases how a wildcard that matches against many sibling nodes is written.

```
1 << statementsNoReturn : (Statement && !ReturnStatement)+ >>
```

In the example below a wildcard block is defined on the right hand side of an assignment statement. This wildcard will match against any AST node classified as a `CallExpression` or an `Identifier`. This example showcases how wildcards are interspliced with JavaScript templates.

```
1 let variableName = << expr1: ((CallExpression || Identifier) &&  
  ↪ !ReturnStatement)+ >>;
```

3.3.3 Transforming

When matching parts of the users code has been found, we need some way of defining how to transform those parts to showcase a proposal. This is done using the `transform to` template. This template describes the general structure of the newly transformed code.

A transformation template defines how the matches will be transformed after applicable code has been found. The transformation is a general template of the code once the match is replaced in the original AST. However, without transferring over the context from the match, this would be a template search and replace. Thus, to transfer the context from the match, wildcards are defined in this template as well. These wildcards use the same block notation found in the `applicable to` template, however they do not need to contain the types, as those are not needed in the transformation. The only required field of the wildcard is the identifier defined in `applicable to`. This is done to know which wildcard match we are taking the context from, and where to place it in the transformation template.

The example below showcases a transformation that transforms a variable declaration from using `let` to use `const`. We do this by defining the name of the variable as a wildcard, and the expression as a wildcard. These are referenced in the transformation to transfer context from the match into the transformation template.

```

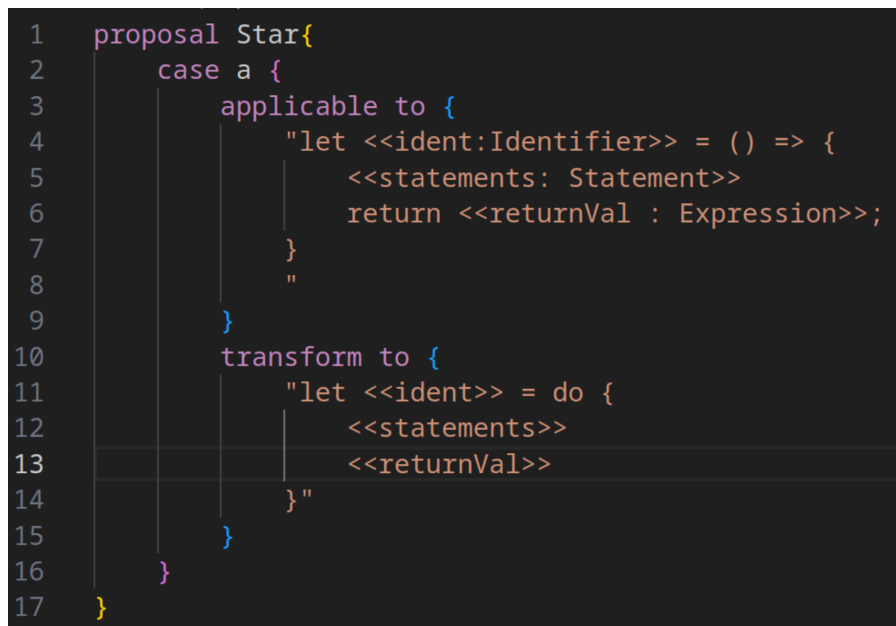
1 // Example applicable to template
2 applicable to {
3   let <<variableName: Identifier>> = <<expr1: Expression>>;
4 }
5
6 // Example of transform to template
7 transform to {
8   const <<variableName>> = <<expr1>>;
9 }

```

3.3.4 Using JSTQL

JSTQL is designed to closely mimic the style of the examples required in the TC39 process [27]. We chose to design it this way to specifically make this tool fit the use-case of the committee. Since the idea behind this project is to gather early user feedback on syntactic proposals, the users of this kind of til is the committee themselves, as they are the ones that want user feedback.

Writing a proposal definition in JSTQL is done with text, most domain-specific languages have some form of tooling to make the process of using the DSL simpler and more intuitive. JSTQL has an extension built for Visual Studio Code, see Figure 3.1. This extension supports auto completion, error checking, and other common IDE features.



```

1  proposal Star{
2    case a {
3      applicable to {
4        "let <<ident:Identifier>> = () => {
5          <<statements: Statement>>
6          return <<returnVal : Expression>>;
7        }
8      }
9    }
10   transform to {
11     "let <<ident>> = do {
12       <<statements>>
13       <<returnVal>>
14     }"
15   }
16 }
17 }

```

Figure 3.1: Writing JSTQL in Visual Studio Code with extension.

The language server included with this extension performs validation of the wildcards. This allows verification of wildcard declarations in `applicable to`, as shown in Figure 3.2. If a wildcard is declared with no types, an error will be reported.

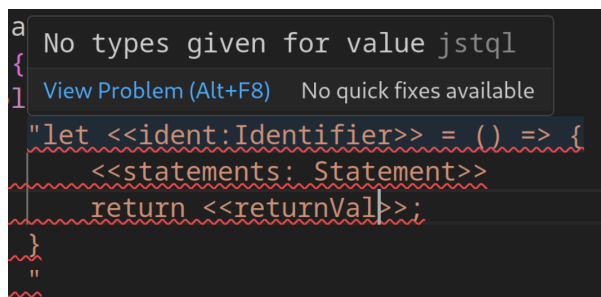


Figure 3.2: Error displayed when declaring a wildcard with no types.

The extension automatically uses wildcard declarations in `applicable to` in order to verify that all wildcards referenced in `transform to` are declared. If an undeclared wildcard is used, an error will be reported and the name of the undeclared wildcard will be displayed, as shown in Figure 3.3.

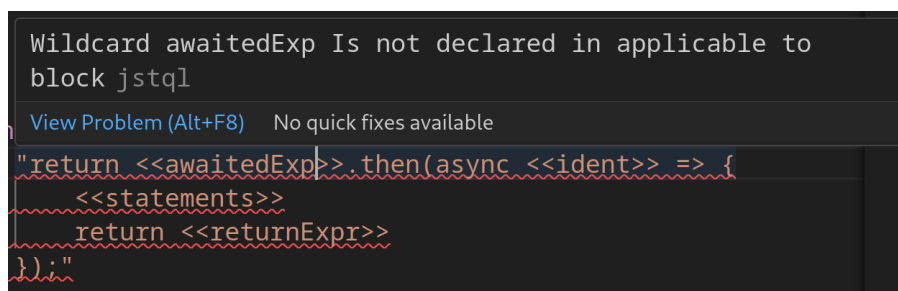


Figure 3.3: Error displayed with usage of undeclared wildcard.

3.4 Using the JSTQL with syntactic proposals

In this section, we present specifications of the proposals described in Section 3.2. We will use these specifications to evaluate the tool created in this thesis. These specifications do not have to cover every single case where the proposal might be applicable, as they only have to be general enough to create some amount of examples that will give a representative number of matches when the transformations are applied to some relatively long user code.

This is because this tool is designed to be used by TC39 to gather feedback from user's on proposals during development. This use case means the specifications should be defined in a way that showcases the proposal. This also means it is important the transformation is correct, as incorrect transformations might lead to bad feedback on a proposal.

3.4.1 “Pipeline” Proposal

This proposal is applicable to call expressions, and is aimed at improving code readability when performing deeply nested function calls.

```

1 proposal Pipeline {
2
3   case SingleArgument {
4     applicable to {
5       "<<someFunctionIdent:Identifier ||
6         ↳ MemberExpression>>(<<someFunctionParam:
7         ↳ Expression>>);"
8     }
9     transform to {
10      "<<someFunctionParam>> |> <<someFunctionIdent>>(%);"
11    }
12  }
13  case TwoArgument{
14    applicable to {
15      "<<someFunctionIdent: Identifier ||
16        ↳ MemberExpression>>(<<someFunctionParam:
17        ↳ Expression>>, <<moreFunctionParam: Expression>>)"
18    }
19    transform to {
20      "<<someFunctionParam>> |> <<someFunctionIdent>>(%,"
21      ↳ <<moreFunctionParam>>)"
22    }
23  }
24 }
```

Listing 3.2: Example of “Pipeline” proposal definition in JSTQL.

In the Listing 3.2, the first `case` definition `SingleArgument` will apply to any `CallExpression` with a single argument. We do not write a `CallExpression` inside a wildcard, as we have defined the structure of a `CallExpression`. The first wildcard `someFunctionIdent` has the types of `Identifier` to match against single identifiers and `MemberExpression` to match against functions who are members of objects, i.e. `console.log`. In the transformation template, we define the structure of a function call using the pipe operator, but the wildcards change order, so the argument passed as argument `someFunctionParam` is placed on the left side of the pipe operator, and the `CallExpression` is on the right, with the topic token as the argument. This case will

produce a match against all function calls with a single argument, and transform them to use the pipe operator. The main difference of the second case **TwoArgument** is that it matches against functions with exactly two arguments, and uses the first argument as the left side of the pipe operator, while the second argument remains in the function call.

3.4.2 “Do Expression” Proposal

The “Do expression” proposal [23] focuses on bringing expression-oriented programming to JavaScript.

```

1 proposal DoExpression{
2   case arrowFunction{
3     applicable to {
4       "(() => {
5         <<statements: (Statement && !ReturnStatement)+>>
6         return <<returnVal : Expression>>;
7       })();"
8     }
9     transform to {
10      "(do {
11        <<statements>>
12        <<returnVal>>
13      })"
14    }
15  }
16
17  case unnamedFunction {
18    applicable to {
19      "(function(){
20        <<statements: (Statement && !ReturnStatement)+>>
21        return <<returnVal : Expression>>;
22      })();"
23    }
24    transform to {
25      "(do {
26        <<statements>>
27        <<returnVal>>
28      })"
29    }
30  }
31 }
32 }

```

Listing 3.3: Definition of Do Proposal in JSTQL.

In Listing 3.3, the specification of “Do expression” proposal in JSTQL can be seen. It has two cases: the first case **arrowFunction** applies to code using an immediately invoked arrow function [31, 15.3] with a return value. The wildcard **statements** matches against one or more statements that are not of type **ReturnStatement**. The reason we limit the wildcard is we cannot match the final statement of the block to this wildcard, as that has to be matched against the return statement in the template. The second wildcard **returnVal** matches against any expressions; the reason for extracting the expression from the **return** statement, is to use it in the implicit return of the **do** block.

In the transformation template, we replace the arrow function with with a `do` expression. This expression has to be defined inside parenthesis, as a free floating `do` expression is not allowed due to ambiguous parsing against a `do while` statement. We insert the statements matched against `statements` wildcard into the block of the `do` expression, and the final statement of the block is the expression matched against the `returnVal` wildcard. This will transform an arrow function into a `do` expression.

The second case `unnamedFunction` follows the same principle as the first case, but is applied to immediately invoked unnamed functions, and produces the exact same output after the transformation as the first case. This is because immediately invoked unnamed functions are equivalent to arrow functions.

3.4.3 ‘Await to promise’ imaginary proposal

```

1 proposal awaitToPromise{
2   case single{
3     applicable to {
4       "let <<ident:Identifier>> = await <<awaitedExpr:
5         ↳ Expression>>;
6         <<statements: (Statement && !ReturnStatement &&
7         ↳ !ContinueStatement && !BreakStatement)+>>
8         return <<returnExpr: Expression>>
9       "
10    }
11    transform to{
12      "return <<awaitedExpr>>.then(async <<ident>> => {
13        <<statements>>
14        return <<returnExpr>>
15      });"
16    }
17  }

```

Listing 3.4: Definition of “Await to promise” evaluation proposal in JSTQL.

The specification of “Await to promise” in JSTQL is created to match asynchronous code inside a function. It is limited to match asynchronous functions containing a single `await` statement, and that `await` statement has to be stored in a `VariableDeclaration`. The second wildcard `statements` is designed to match all statements following the `await` statement up to the return statement. This is done to move the statements into the callback function of `then()` in the transformation. We include `ReturnStatement` because we do not want to consume the return as it would then be removed from the functions scope and into the callback function of `then()`. We also have to avoid matching where there exists loop specific statements such as `ContinueStatement` or `BreakStatement`.

The transformation definition has to use an `async` arrow function as argument for `then`, as there might be more `await` expressions contained within `statements`.

3.5 JSTQL-SH

In this thesis, we also created an alternative way of defining proposals and their respective transformations, this is done using JavaScript as it's own meta language for the definitions, we call this JSTQL-SH. The reason for this is we wanted an alternative to JSTQL, as if this tool is to be used by TC39, we want to present several possible ways to specify a proposal. This has an added benefit of allowing our tool to be independent from the dependencies of JSTQL-SH.

JSTQL-SH is less of an actual language, and more of a program API, it allows for defining proposals purely in JavaScript Object, which is meant to allow a more modular way of using this idea. In JSTQL-SH you define a *prelude*, which is a series of variable declarations in JavaScript. These variable declarations are used to define the type expressions of wildcards, where the identifier of the variable declaration is the identifier of the wildcard, and the expression of the declaration is a string containing the wildcard type expression. The templates are defined in a similar manner to JSTQL, however one does not write wildcard blocks, and instead use the identifier of the wildcard directly. This makes it very clear where wildcards are allowed and might produce a more natural way of defining templates.

In the example below is the first **case** of the “Pipeline” proposal defined using JSTQL-SH JavaScript object. We define the wildcards in the object key **prelude**, where it is defined as valid JavaScript. The variable declarations define the wildcards, and we use the variables defined to reference wildcards in the templates.

```
1 // Equivalent definition in JSTQL-SH
2 {
3   prelude: '
4     let someFunctionIdent = "Identifier || MemberExpression";
5     let someFunctionParam = "Expression";
6   ',
7   applicableTo: "someFunctionIdent(someFunctionParam);",
8   transformTo: "someFunctionParam |> someFunctionIdent(%);"
9 }
```

Chapter 4

Implementation

In this chapter, the implementation of the tool utilizing the JSTQL and JSTQLSH will be presented. It will describe the overall architecture of the tool, the flow of data throughout, and how the different stages of transforming user code are completed.

4.1 Architecture of the solution

The architecture of the solution described in this thesis is illustrated in Figure 4.1

In this tool, there exists two multiple ways to define a proposal, and each provide the same functionality, they only differ in syntax and writing-method. One can either write the definition in JSTQL, or one can use the program API with JSTQLSH, which is more friendly for programs to interact with.

In the architecture diagram of Figure 4.1, ellipse nodes show data passed into the program sections, and rectangular nodes is a specific section of the program. The architecture is split into seven levels, where each level is a step of the program. The initial step is the proposal definition, the definition can have two different forms, either it is JSTQL code, or it can be a JavaScript object using the self hosted in JSTQLSH. If we use JSTQL, the second step is parsing it using Langium [17], this parses the raw source code into an AST. If JSTQLSH is used, we have to build the prelude, so we have to extract the wildcard definitions from JavaScript source code. At this point the two paths meet at the second step, which is wildcard extraction. At this step, if JSTQL was used, the wildcards are extracted from the template. If JSTQLSH was used extraction is not

needed. In both cases we parse the wildcard type expressions into an AST. The third step is parsing the raw source code with Babel [4]. It is also at this point we parse the users source code into an AST. The fourth step is translating the Babel AST into our own custom tree structure for simpler traversal. Once all data is prepared, the fifth step is matching the user’s AST against the `applicable` to template AST. Once all matches have been found, we transplant the wildcard matches into the `transform` to template, and insert it back into the users code in step six. We have at this point transformed the users code, the final step seven is generating it back into source code.

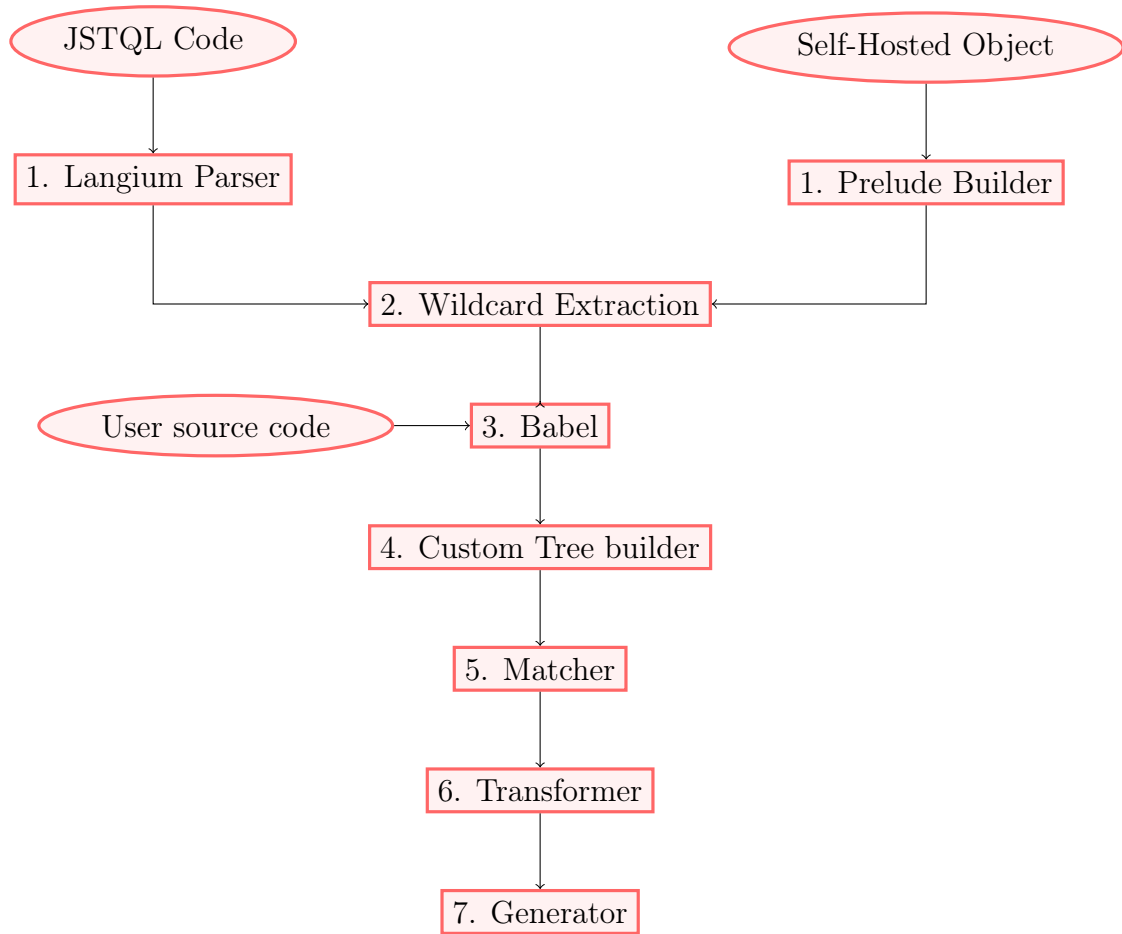


Figure 4.1: Overview of tool architecture

4.2 Parsing JSTQL using Langium

In this section, we describe the implementation of the parser for JSTQL. We outline the tool Langium, used as a parser-generator to create the AST used by the tool later to perform the transformations.

4.2.1 Langium

Langium [17] is a language workbench [35] primarily used to create parsers and Integrated Development Environments for domain specific languages. These kinds of parsers produce Abstract Syntax Trees that are later used to create interpreters or other tooling. In this project, we use Langium to generate an AST definition in the form of TypeScript objects. These objects and their structure are used as definitions for the tool to do matching and transformation of user code.

To generate this parser, Langium requires a definition of a grammar. A grammar is a specification that describes syntax a valid programs. The JSTQL grammar describes the structure of JSTQL, such as `proposals`, `cases`, `applicable to` blocks, and `transform to` blocks. A grammar in Langium starts by describing the `Model`. The model is the top entry of the grammar; this is where the description of all valid top level statements.

Contained within the `Model` rule, is one or more proposals. Each proposal is defined with the rule `Proposals`, and starts with the keyword `proposal`, followed by a name, and a code block. This rule is designed to contain every definition of a transformation related to a specific proposal. To hold every transformation definition, a proposal definition contains one or more cases.

The `Case` rule is created to contain a single transformation. Each case specification starts with the keyword `case`, followed by a name for the current case, then a block for that case's fields. Cases are designed in this way to separate different transformation definitions within a proposal. Each case contains a single definition used to match against user code, and a definition used to transform a match.

The rule `AplicableTo`, is designed to hold a single template used for matching. It starts with the keywords `applicable` and `to`, followed by a block designed to hold the matching template definition. The template is defined as the terminal `STRING`, and is parsed as a raw string for characters by Langium [17].

The rule `TransformTo`, is created to contain a single template used for transforming a match. It starts with the keywords `transform` and `to`, followed by a block that holds the transformation definition. This transformation definition is declared with the terminal `STRING`, and is parser at a string of characters, same as the template in `applicable to`.

To define exactly what characters/tokens are legal in a specific definition, Langium uses terminals defined using regular expressions, these allow for a very specific character-set to be legal in specific keys of the AST generated by the parser generated by Langium.

In the definition of `Proposal` and `Pair` the terminal `ID` is used; this terminal is limited to allow for only words and can only begin with a character of the alphabet or an underscore. In `Section` the terminal `STRING` is used, this terminal is meant to allow any valid JavaScript code and the custom DSL language described in 3.3.2. Both these terminals defined allows Langium to determine exactly what characters are legal in each location.

```

1 grammar Jstql
2
3 entry Model:
4   (proposals+=Proposal)*;
5
6 Proposal:
7   'proposal' name=ID "{"
8     (case+=Case)+
9   "}";
10
11 Case:
12   "case" name=ID "{"
13     aplTo=ApplicableTo
14     traTo=TransformTo
15   "}";
16
17 ApplicableTo:
18   "applicable" "to" "{"
19     apl_to_code=STRING
20   "}";
21 TransformTo:
22   "transform" "to" "{"
23     transform_to_code=STRING
24   "}";
25 hidden terminal WS: /\s+/;
26 terminal ID: /[_a-zA-Z][\w_]*/;
27 terminal STRING: /"[^"]*"|'[^']*'/;

```

Listing 4.1: Definition of JSTQL in Langium.

With JSTQL, we are not implementing a programming language meant to be executed. We are using Langium to generate an AST that will be used as a markup language, similar to YAML, JSON or TOML [29]. The main reason for using Langium in such an unconventional way is Langium provides support for Visual Studio Code integration, and it solves the issue of parsing the definition of each proposal manually. However, with this grammar we cannot actually verify the wildcards placed in `apl_to_code` and `transform_to_code` are correctly written. To do this, we have implemented several validation rules.

Langium Validator

A Langium validator allows for further checks DSL code, a validator allows for the implementation of specific checks on specific parts of the grammar.

JSTQL does not allow empty typed wildcard definitions in `applicable to` blocks, this means we cannot define a wildcard that allows any AST type to match against it. This is not defined within the grammar, as inside the grammar the code is defined as a `STRING` terminal. This means further checks have to be implemented using code. To do this we have a specific `Validator` implemented on the `Case` definition of the grammar. This means every time anything contained within a `Case` is updated, the language server created with Langium will perform the validation step and report any errors.

The validator uses `Case` as its entry point, as it allows for a checking of wildcards in both `applicable to` and `transform to`, allowing for a check for whether a wildcard identifier used in `transform to` exists in the definition of `applicable to`.

```

1 export class JstqlValidator {
2   validateWildcardAplTo(pair: Pair, accept: ValidationAcceptor):
3     void {
4     try {
5       if (validationResultAplTo.errors.length != 0) {
6         accept("error",
7           validationResultAplTo.errors.join("\n"), {
8             node: pair.aplTo,
9             property: "apl_to_code",
10          });
11       }
12       if (validationResultTraTo.length != 0) {
13         accept("error", validationResultTraTo.join("\n"), {
14           node: pair.traTo,
15           property: "transform_to_code",
16         });
17       }
18     } catch (e) {}
19   }
20 }

```

Using Langium as a parser

Langium is designed to automatically generate extensive tool support for the language specified using its grammar. However, in our case we have to parse the JSTQL definition using Langium, and then extract the Abstract syntax tree generated in order to use the information it contains.

To use the parser generated by Langium, we created a custom function `parseDSLtoAST`, which takes a string as an input (the raw JSTQL code), and outputs the pure AST using the format described in the grammar, see Listing 3.3.2. This function is exposed as a custom API for our tool to interface with. This also means our tool is dependent on the implementation of the Langium parser to function with JSTQL. The implementation of JSTQLSH is entirely independent.

When interfacing with the Langium parser to get the Langium generated AST, the exposed API function is imported into the tool, when this API is executed, the output is on the form of the Langium `Model`, which follows the same form as the grammar. This is then transformed into an internal object structure used by the tool, this structure is called `TransformRecipe`, and is then passed in to perform the actual transformation.

4.3 Wildcard extraction and parsing

To refer to internal DSL variables defined in `applicable to` and `transform to` blocks of the transformation, we need to extract this information from the template definitions and pass that on to the matcher.

Why not use Langium for wildcard parsing?

Langium has support for creating a generator to output an artifact, which is some transformation applied to the AST built by the Langium parser. This suits the needs of JSTQL quite well and could be used to extract the wildcards and parse the type expressions. This is the way the developers of Langium want this kind of functionality to be implemented, however, the implementation would still be mostly the same, as the parsing of the wildcards still has to be done “manually” with a custom parser. Therefore, we decided for this project to keep the parsing of the wildcards separate. If we were to use Langium generators to parse the wildcards, it would make JSTQLSH dependent on Langium. This is not preferred as that would mean both ways of defining a proposal are reliant of Langium. The reason for using our own extractor is to allow for an independent way to define transformations using our tool.

Extracting wildcards from JSTQL

To allow the use of Babel [4], the wildcards present in the `applicable to` blocks and `transform to` blocks have to be parsed and replaced with some valid JavaScript. This is done by using a pre-parser that extracts the information from the wildcards and inserts an `Identifier` in their place.

To extract the wildcards from the template, we look at each character in the template. If a start token of a wildcard is discovered, which is denoted by «, everything after that until the closing token, which is denoted by », is then treated as an internal DSL variable and will be stored by the tool. A variable `flag` is used (line 5,10 4.2), when the value of `flag` is false, we know we are currently not inside a wildcard block, this allows us to pass the character through to the variable `cleanedJS` (line 196 4.2). When `flag` is true, we know we are currently inside a wildcard block and we collect every character of the wildcard block into `temp`. Once we hit the end of the wildcard block, when we have consumed the entirety of the wildcard, the contents of the `temp` variable is passed to a tokenizer, then the tokens are parsed by a recursive descent parser (line 10-21 4.2).

Once the wildcard is parsed, and we know it is safely a valid wildcard, we insert the identifier into the JavaScript template where the wildcard would reside. This allows for easier identifications of wildcards when performing matching/transformation as we can identify whether or not an Identifier in the code is the same as the identifier for a wildcard. This however, does introduce the problem of collisions between the wildcard identifiers inserted and identifiers present in the users code. To avoid this, the tool adds `_$$_` at the beginning and end of every identifier inserted in place of a wildcard. This allows for easier identification of if an Identifier is a wildcard, and avoids collisions where a variable in the user code has the same name as a wildcard inserted into the template. This can be seen on line 17-19 of Listing 4.2.

```

1  export function parseInternal(code: string): InternalParseResult {
2      for (let i = 0; i < code.length; i++) {
3          if (code[i] === "<" && code[i + 1] === "<") {
4              // From now in we are inside of the DSL custom block
5              flag = true;
6              i += 1;
7              continue;
8          }
9
10         if (flag && code[i] === ">" && code[i + 1] === ">") {
11             // We encountered a closing tag
12             flag = false;
13             try{
14                 let wildcard = new WildcardParser(
15                     new WildcardTokenizer(temp).tokenize()
16                 ).parse();
17                 wildcard.identifier.name =
18                     "$$_" + wildcard.identifier.name + "$$_";
19                 cleanedJS += wildcard.identifier.name;
20
21
22                 prelude.push(wildcard);
23                 i += 1;
24                 temp = "";
25                 continue;
26             }
27             catch (e){
28                 // We probably encountered a bitshift operator, append
29                 ↪ temp to cleanedJS

```



```

30
31     }
32     if (flag) {
33         temp += code[i];
34     } else {
35         cleanedJS += code[i];
36     }
37 }
38 return { prelude, cleanedJS };
39 }

```

Listing 4.2: Extracting wildcard from template.

Parsing wildcard Once a wildcard has been extracted from definitions inside JSTQL, they have to be parsed into a simple AST to be used when matching against the wildcard. This is accomplished by using a simple tokenizer and a recursive descent parser [33].

Our tokenizer takes the raw stream of input characters extracted from the wildcard block within the template, and determines which part is what token. Due to the very simple nature of the type expressions, no ambiguity is present with the tokens, so determining what token is meant to come at what time is quite trivial. We use a switch case on the current token, if the token is of length one we accept it and move on to the next character. If the next character is an unexpected one it will produce an error. The tokenizer also groups tokens with a *token type*, this allows for a simpler parsing of the tokens later.

A recursive descent parser mimics the grammar of the language the parser is implemented for, where we define functions for handling each of the non-terminals and ways to determine what non terminal each of the token-types result in. The type expression language is a very simple Boolean expression language, making parsing quite simple.

```

1 Wildcard:
2     Identifier ":" MultipleMatch
3
4 MultipleMatch:
5     GroupExpr "*"
6     | TypeExpr
7
8 TypeExpr:
9     BinaryExpr
10    | UnaryExpr
11    | PrimitiveExpr
12
13 BinaryExpr:
14     TypeExpr { Operator TypeExpr }*
15
16 UnaryExpr:
17     {UnaryOperator}? TypeExpr
18
19 PrimitiveExpr:
20     GroupExpr | Identifier
21

```

```
22 GroupExpr :  
23   "(" TypeExpr ")"
```

Listing 4.3: Grammar of type expressions

The grammar of the type expressions used by the wildcards can be seen in Figure 4.3, the grammar is written in something similar to Extended Backus-Naur form, where we define the terminals and non-terminals in a way that makes the entire grammar parseable by the recursive descent parser.

Our recursive descent parser produces an AST, which is later used to determine when a wildcard can be matched against a specific AST node, the full definition of this AST can be seen in Appendix A.1. We use this AST by traversing it using a [43]visitor pattern and comparing each `Identifier` against the specific AST node we are currently comparing with, and evaluating all subsequent expressions and producing a boolean value, if this value is true, the node is matched against the wildcard, if not then we do not have a match.

Extracting wildcards from JSTQLSH The self-hosted version JSTQLSH also requires some form of pre-parsing to prepare the internal DSL environment. This is relatively minor and only parsing directly with no insertion compared to JSTQL.

To use JavaScript as the meta language, we define a `prelude` on the object used to define the transformation case. This prelude is required to consist of several `Variable declaration` statements, where the variable names are used as the internal DSL variables and right side expressions are strings that contain the type expression used to determine a match for that specific wildcard.

We use Babel to generate the AST of the `prelude` definition, this allows us to get a JavaScript object structure. Since the structure is very strictly defined, we can expect every `stmt` of `stmts` to be a variable declaration, otherwise throw an error for invalid prelude. Then the string value of each of the variable declarations is passed to the same parser used for JSTQL wildcards.

The reason this is preferred is it allows us to avoid having to extract the wildcards and inserting an `Identifier`.

4.4 Using Babel to parse

Allowing the tool to perform transformations of code requires the generation of an Abstract Syntax Tree from the users code, `applicable to` and `transform to`. This means parsing JavaScript into an AST, to do this we use Babel [4].

The most important reason for choosing to use Babel for the purpose of generating the AST's used for transformation is due to the JavaScript community surrounding Babel. As this tool is dealing with proposals before they are part of JavaScript, a parser that supports early proposals for JavaScript is required. Babel works closely with TC39 to support experimental syntax [9] through its plugin system, which allows the parsing of code not yet part of the language.

Custom Tree Structure

Performing matching and transformation on each of the sections inside a `case` definition, they have to be parsed into an AST to allow the tool to match and transform accordingly, for this we use Babel [4]. However, Babels AST structure does not suit traversing multiple trees at the same time, this is a requirement for matching and transforming. Therefore we take the AST and transform it into a simple custom tree structure to allow for simple traversal of the tree.

As can be seen in Figure 4.4 we use a recursive definition of a `TreeNode` where a nodes parent either exists or is null (it is top of tree), and a node can have any number of children elements. This definition allows for simple traversal both up and down the tree. Which means traversing two trees at the same time can be done in the matcher and transformer section of the tool.

```
1 export class TreeNode<T> {
2   public parent: TreeNode<T> | null;
3   public element: T;
4   public children: TreeNode<T>[] = [];
5
6   constructor(parent: TreeNode<T> | null, element: T) {
7     this.parent = parent;
8     this.element = element;
9     if (this.parent) this.parent.children.push(this);
10  }
11 }
```

Listing 4.4: Simple definition of a Tree structure in TypeScript

Placing the AST generated by Babel into this structure means utilizing the library [11]Babel Traverse. Babel Traverse uses the visitor pattern [43] to perform traversal of the AST. While this method does not suit traversing multiple trees at the same time, it allows for very simple traversal of the tree to place it into our simple tree structure.

To place the AST into our tree structure, we use `@babel/traverse` [11] to visit each node of the AST in a *depth first* manner, the idea is we implement a *visitor* for each of the nodes in the AST and when a specific node is encountered, the corresponding visitor of that node is used to visit it. When transferring the AST into our simple tree structure we simply have to use the same visitor for every kind of AST node, and place that node into the tree.

Visiting a node using the `enter()` function means we went from the parent to that child node, and it should be added as a child node of the parent. The node is automatically added to its parent list of children nodes from the constructor of `TreeNode`. Whenever leaving a node the function `exit()` is called, this means we are moving back up into the tree, and we have to update what node was the *last* to generate the correct tree structure.

```

1 traverse(ast, {
2   enter(path: any) {
3     let node: TreeNode<t.Node> = new TreeNode<t.Node>(
4       last,
5       path.node as t.Node
6     );
7
8     if (last == null) {
9       first = node;
10    }
11    last = node;
12  },
13  exit(path: any) {
14    if (last && last?.element?.type != "Program") {
15      last = last.parent;
16    }
17  },
18 });
19 if (first != null) {
20   return first;
21 }

```

One important nuance of the way we place the nodes into the tree, is we still have the same underlying data structure from Babel. Because of this, the nodes can still be used with Babels APIs, and we can still access every field of each node. Transforming it into a tree only creates an easy way to traverse up and down the tree by references. We perform no copying.

4.5 Outline of transforming user code

Below is an outline of every major step performed, and how data is passed through the program.

Algorithm 1 Outline of steps of algorithm

```
1:  $CA, CT, W \leftarrow extractWildcards()$ 
2:  $A, T \leftarrow babel.parse(CA, CT)$  ▷ Parse templates
3:  $C \leftarrow babel.parse()$  ▷ Parse user code
4:  $AT, TT, CT \leftarrow Tree(A, T, C)$  ▷ Build the tree structure from Babel AST
5: if  $AT.length > 1$  then ▷ Decide which matcher to use
6:    $M \leftarrow multiMatcher(CT, AT, W)$ 
7: else
8:    $M \leftarrow singleMatcher(CT, AT, W)$ 
9: end if
10:  $TMap \leftarrow Map()$ 
11: for each  $m$  in  $M$  do ▷ Build transformation templates
12:    $TMap.insert \leftarrow buildTransform(m, TT, W);$ 
13: end for
14: for  $traverse(C)$  do
15:   if  $TMap.has(c)$  then
16:      $C.replaceMany(TMap.get(c));$ 
17:   end if
18: end for
19: return  $babel.generate(C);$ 
```

Each part of Algorithm 1 is a step in the full algorithm for transforming user code based on a proposal specification in our tool. The initial step (line 1) is extraction of wildcards from the template definition. This step also parses the wildcard type expressions into an AST. The second step (lines 2,3) is to parse all templates into an AST with `@babel/parser` [8]. Once we have parsed all code into ASTs, we decide which matching algorithm to use (line 5) based on the `applicable to` template. These algorithms will find all matching sections of the user AST to the template. We then build the transformation templates (lines 11-13), and insert the sections from the use code that was matched with a wildcard. These transformations are stored in a `Map` (line 10). Once all transformations are prepared, we traverse the user AST (line 14), and insert the transformations if the current node traversed is in the `Map` (line 16). The final step, is to generate JavaScript from the transformed AST (line 19).

4.6 Matching

This section discusses how we find matches in the users code, this is the step described in lines 5-10 of Listing 1. Firstly, we will discuss how individual nodes are compared, then how the two traversal algorithms are implemented, and how matches are discovered using these algorithms.

4.6.1 Determining if AST nodes match

The initial problem we have to overcome is a way of comparing AST nodes from the template to AST nodes from the user code. This step also has to take into account comparing against wildcards and pass that information back to the AST matching algorithms.

When comparing two AST nodes in this tool, we use the function `checkCodeNode`, which will give the following values based on what kind of match these two nodes produce.

NoMatch The nodes do not match.

Matched The nodes are a match, and the node of `applicable to` is not a wildcard.

MatchedWithWildcard The node of the user AST produced a match against a wildcard.

MatchedWithPlussedWildcard The node of the user AST produced a match against a wildcard that can match one or more nodes against itself.

When we are comparing two AST nodes, we have to perform an equality check. Due to this being a structural matching search, we can get away with just performing some preliminary checks, such as that names of identifiers, otherwise it is sufficient to just perform an equality check of the types of the nodes we are currently trying to match. If the types are the same, they can be validly matched against each other. This is sufficient because we are currently trying to determine if a single node can be a match, and not the entire template structure is a match. Therefore false positives that are not equivalent are highly unlikely due to the fact the entire structure has to be a false positive match.

There is a special case when comparing two nodes, namely when encountering a wildcard. To know if we have encountered a wildcard, the current AST node of `applicable to` will be either an `Identifier` or a `ExpressionStatement` where the expression is an `Identifier`. The reason it might be an `ExpressionStatement` is due to the wildcard

extraction step, where we replace the wildcard with an identifier of the same name. Due to this replacement, we might place an identifier as a statement, the identifier will then be wrapped inside an `ExpressionStatement` AST node. If the node of `applicable to` is of either of these types, we have to check if the name of the identifier is the same as a wildcard. If it is, we have to compare the type of the user AST node against the type expression of the wildcard.

```

1 if((aplToNode.type === "ExpressionStatement" &&
2   aplToNode.expression.type === "Identifier") ||
3   aplToNode.type === "Identifier"){
4
5   // Check if aplToNode is a wildcard
6 }

```

When comparing an AST node type against a wildcard type expression, we pass the node type into a function `WildcardEvaluator`. This evaluator will traverse through the AST of the wildcard type expression. Every leaf of the tree is equality checked against the type, and the resulting boolean value is returned. Then we evaluate the expression, passing the values through the visitors until we have evaluated the entire expression, and have a result. If the result of the evaluator is `false`, we return `NoMatch`. If the result of the evaluation is `true`, we know we can match the user's AST node against the wildcard. If the wildcard type expression contains a Kleene plus, the comparison returns `MatchedWithPlussedWildcard`, if not, we return `MatchedWithWildcard`.

4.6.2 Matching a single Expression/Statement template

In this section, we will discuss how matching is performed when the `applicable to` template is a single expression/statement. A very complex matching template with many statements might result in a lower chance of finding matches in the users code. Therefore using simple, single root node matching templates provide the highest possibility of discovering a match within the users code. This section will cover line 11 of Listing 1.

Determining if we are currently matching with a template that is only a single expression/statement, we have to verify that the program body of the template has the length of one, if it does we can use the single length traversal algorithm.

There is a special case for if the template is a single expression, as the first node of the AST generated by `@babel/generate` [7] will be of type `ExpressionStatement`, the reason for this is Babel will treat free floating expressions as a statement. This will miss many applicable parts of the users code, because expressions within other statements are

not wrapped in an `ExpressionStatement`. This will give a template that is incompatible with a lot of otherwise applicable expressions. This means the statement has to be removed, and the search has to be done with the expression as the top node of the template. If the node in the body of the template is a statement, no removal has to be done, as a statement can be used directly.

Discovering Matches Recursively The matcher used against single expression/statement templates is based Depth-First Search to traverse the trees. The algorithm can be split into two steps. The initial step is to check if we are currently at the root of the `applicable` to AST, the second is to try to match the current nodes, and start a search on each of their child nodes.

It is important we try to match against the template at all levels of the code AST, this is done by starting a new search one every child node of the code AST if the current node of the template AST is the root node. This ensures we have tried to perform a match at any level of the tree. This also ensures we have no partial matches, as we store it only if it returns a match when being called with the root node of `applicable` to.

```
1 if(aplTo.element === this.aplToRoot){
2   // Start a search from root of aplTo on all child nodes
3   for(let codeChild of code.children){
4     let childMatch = singleMatcher(codeChild, aplTo);
5
6     // If it is a match, we know it is a full match and store it.
7     if(childMatch){
8       this.matches.push(childMatch);
9     }
10  }
11 }
```

We can now determine if we are currently exploring a match. This means the current code AST node is checked against the current node of `applicable` to AST. Based on what kind of result the comparison between these two nodes give, we have perform different steps.

NoMatch: If a comparison between the nodes return a `NoMatch` result, we perform an early return of undefined, as no match was discovered. We can safely discard this search, because we have started a search at all levels of the code AST.

Matched: The current code node matches against the current node of the template, and we have to perform a search on each of the child nodes.

MatchedWithWildcard: When a comparison results in a wildcard match, we pair the current code node and the template wildcard, and do an early return. We can do this because if a wildcard matches, the nodes of the children does not matter and will be placed into the transformation.

MatchedWithPlussedWildcard: this is a special case for a wildcard match. When a match against a wildcard that has the Kleene plus tied to it we also perform an early return. This result means some special traversal has to be done to the current nodes siblings, this is described below.

A comparison result of `Matched` means the two nodes match, but the `applicable` to node is not a wildcard. With this case, we perform a search on each child nodes of `applicable` to AST and the user AST. This is performed in order, meaning the n-th child node of `applicable` to is checked against the n-th child node of the user AST.

When checking the child nodes, we have to check for a special case when the comparison of the child nodes result in `MatchedWithPlussedWildcard`. If this result is encountered, we have to continue matching the same `applicable` to node against each subsequent sibling node of the code node. This is because, a wildcard with a Keene plus can match against multiple sibling nodes. This behavior can be seen in line 17-31 of Listing 4.5.

If all child nodes did not give the result of `NoMatch`, we have successfully matched every node of the `applicable` to AST. This does not yet mean we have a match, as there might be remaining nodes in the child node of the code AST. To check for this, we check whether or not `codeI` is equal to the length of `code.children`. If it is unequal, we have not matched all child nodes of the code AST and have to return `NoMatch`. This can be seen on lines 37-39 of Listing 4.5.

```
1 let codeI = 0;
2 let aplToI = 0;
3
4 while (aplToI < aplTo.children.length && codeI < code.children.length){
5   let [pairedChild, childResult] =
6     ↪ singleMatcher(code.children[codeI], aplTo.children[aplToI]);
7
8   // If a child does not match, the entire match is discarded
9   if(childResult === NoMatch){
10     return [undefined, NoMatch];
11   }
12
13   // Add the match to the current Paired Tree structure
14   pairedChild.parent = currentPair;
15   currentPair.children.push(pairedChild);
16
17   // Special case for Keene plus wildcard match
18   if(childResult === MatchedWithPlussedWildcard){
19     codeI += 1;
```

```

19     while(codeI < code.children.length){
20         let [nextChild, plusChildResult] =
            ↪ singleMatcher(code.children[codeI],
            ↪ aplTo.children[aplToI]);
21
22         if(plusChildResult !== MatchedWithPlussedWildcard){
23             i -= 1;
24             break;
25         }
26
27         pairedChild.element.codeNode.push(...nextChild.element.codeNode);
28
29         codeI += 1;
30     }
31 }
32
33 codeI += 1;
34 aplToI += 1;
35 }
36
37 if(codeI !== code.children.length){
38     return [undefined, NoMatch]
39 }
40
41 return [currentPair, Match];

```

Listing 4.5: Pseudocode of child node matching

4.6.3 Matching multiple Statements

Using multiple statements in the template of `applicable to` means the tree of `applicable to` as multiple root nodes, to perform a match with this kind of template, we use a sliding window [36] with size equal to the amount statements in the template. This window is applied at every *BlockStatement* and *Program* of the code AST, as that is the only placement statements can reside in JavaScript [31, 14].

The initial step of this algorithm is to search through the AST for ast nodes that contain a list of *Statements*. Searching the tree is done by Depth-First search, at every level of the AST, we check the type of the node. Once a node of type *BlockStatement* or *Program* is discovered, we start the trying to match the statements.

```

1 multiStatementMatcher(code, aplTo) {
2     if (
3         code.element.type === "Program" ||
4         code.element.type === "BlockStatement"
5     ) {
6         matchMultiHead(code.children, aplTo.children);
7     }
8
9     for (let code_child of code.children) {
10         multiStatementMatcher(code_child, aplTo);
11     }
12 }

```

`matchMultiHead` uses a sliding window [36]. The sliding window will try to match every statement of the code AST against its corresponding statement in the `applicable` to AST. For every statement, we perform a DFS recursion algorithm is applied, similar to algorithm used in Section 4.6.2, however this search is not applied to all levels, and if it matches it has to match fully and immediately. If a match is not found, the current iteration of the sliding window is discarded and we move on to the next iteration by moving the window one further.

One important case here is we might not know the width of the sliding window, this is due to wildcards using the Keene plus, as they can match one or more nodes against the wildcard. These wildcards might match against `(Statement)+`. Therefore, we use a similar technique to the one described in Section 4.6.2, where we have two pointers and match each statement depending on each pointer.

Output of the matcher

The matches discovered have to be stored such that we can easily find all the nodes that were matched against wildcards and transfer them into the transformation later. To make this simpler, we make use an object `PairedNodes`. This object allows us to easily find exactly what nodes were matched against each other. The matcher will place this object into the same tree structure described in 4.4. This means the result of running the matcher on the user code is a list of `TreeNode<PairedNode>`.

```
1 interface PairedNode{
2     codeNode: t.Node[],
3     aplToNode: t.Node
4 }
```

Since a match might be multiple statements, we use an interface `Match`, that contains separate tree structures of `PairedNodes`. This allows storage of a match with multiple root nodes.

```
1 export interface Match {
2     // Every matching Statement in order with each pair
3     statements: TreeNode<PairedNodes>[];
4 }
```

4.7 Transforming

To perform the transformation and replacement on each of the matches, we take the resulting list of matches, the template from the `transform to` section of the current case of the proposal, and the Babel AST [5] version of original code. All the transformations are then applied to the code and we use `@babel/generate` [7] to generate JavaScript code from the transformed AST.

An important discovery is to ensure we transform the leafs of the AST first, this is because if the transformation was applied from top to bottom, it might remove transformations done using a previous match. This means if we transform from top to bottom on the tree, we might end up with `a(b) |> c(%)` instead of `b |> a(%) |> c(%)` in the case of the “Pipeline” proposal. This is quite easily solved in our case, as the matcher looks for matches from the top of the tree to the bottom of the tree, the matches it discovers are always in that order. Therefore when transforming, all that has to be done is reverse the list of matches, to get the ones closest to the leaves of the tree first.

Building the transformation

Before we can start to insert the `transform to` section into the user’s code AST. We have to insert all nodes matched against a wildcard in `applicable to` into their reference locations.

The first step to achieve this is to extract the wildcards from the match tree. This is done by recursively searching the match tree for an `Identifier` or `ExpressionStatement` containing an `Identifier`. To do this, we have a function `extractWildcardPairs`, which takes a single match, and extracts all wildcards and places them into a `Map<string, t.Node[]>`. Where the key of the map is the identifier used for the wildcard, and the value is the AST nodes the wildcard was matched against in the users code.

```
1 function extractWildcardPairs(match: Match): Map<string, t.Node[]> {
2   let map: Map<string, t.Node[]> = new Map();
3
4   function recursiveSearch(node: TreeNode<PairedNodes>) {
5     let name: null | string = null;
6     if (node.element.aplToNode.type === "Identifier") {
7       name = node.element.aplToNode.name;
8     } else if (
9       // Node is ExpressionStatement with Identifier
10    ) {
11       name = node.element.aplToNode.expression.name;
12    }
13  }
```

```

14     if (name) {
15         // Store in the map
16         map.set(name, node.element.codeNode);
17     }
18     // Recursively search the child nodes
19     for (let child of node.children) {
20         recursiveSearch(child);
21     }
22 }
23 // Start the initial search
24 for (let stmt of match.statements) {
25     recursiveSearch(stmt);
26 }
27 return map;
28 }

```

Listing 4.6: Extracting wildcard from match

Once the full map of all wildcards has been built, we have to insert the wildcards into the Babel AST of the `transform` to template. To do this, we have to traverse the template and insert the matched nodes of the user's code. We use `@babel/traverse` [11] to traverse the AST, as this provides us with a powerful API for modifying the AST. `@babel/traverse` allows us to define visitors, that are executed when traversing specific types of AST nodes. For this, we define a visitor for `Identifier`, and a visitor for `ExpressionStatement`. These visitors will do exactly the same, however for the `ExpressionStatement`, we have to check if the expression is an identifier.

When we visit a node that might be a wildcard, we check if that nodes name is in the map of wildcards built in Listing 4.6. If the name of the identifier is a key in the wildcard, we get the value for that key, and perform a node replacement. Where we replace the identifier with the node from the user's code that was matched against that wildcard. See Listing 4.7

```

1  traverse(transformTo, {
2      Identifier: (path) => {
3          if (wildcardMatches.has(path.node.name)) {
4              let toReplaceWith =
5                  ↪ wildcardMatches.get(path.node.name);
6              if (toReplaceWith) {
7                  path.replaceWithMultiple(toReplaceWith);
8              }
9          },
10     ExpressionStatement: (path) => {
11         if (path.node.expression.type === "Identifier") {
12             let name = path.node.expression.name;
13             if (wildcardMatches.has(name)) {
14                 let toReplaceWith = wildcardMatches.get(name);
15                 if (toReplaceWith) {
16                     path.replaceWithMultiple(toReplaceWith);
17                 }
18             }
19         }
20     },
21 });

```

Listing 4.7: Traversing transform to AST and inserting user context

Due to some wildcards allowing matching of multiple sibling nodes, we have to use `replaceWithMultiple` when performing the replacement. This can be seen on line 6 and 16 of Listing 4.7.

Inserting the template into the AST

We have now created the `transform` to template with the user's context. This has to be inserted into the full AST definition of the users code. To do this we have to locate exactly where in the user AST this match originated. We can perform an equality check on the top noe of the user node stored in the match. To do this efficiently, we perform this check by using this top node as the key to a `Map`, so if a node in the user AST exists in that map, we know it was matched.

```

1 transformedTransformTo.set(
2   match.statements[0].element.codeNode[0],
3   [
4     transformMatchFaster(wildcardMatches, traToWithWildcards),
5     match,
6   ]
7 );

```

To traverse the user AST, we use `@babel/traverse` [11]. In this case we cannot use a specific visitor, and therefore we use a generic visitor that applies to every node of the AST. If the current node we are visiting is a key to the map of transformations, we know we have to insert the transformed code. This is done similarly to before where we use `replaceWithMultiple`.

Some matches have multiple root nodes. This is likely when matching was done with multiple statements as top nodes. This means we have to remove n-1 following sibling nodes. Removal of these sibling nodes can be seen on lines 12-15 of Listing 4.8.

```

1 traverse(codeAST, {
2   enter(path) {
3     if (transformedTransformTo.has(path.node)) {
4       let [traToWithWildcards, match] =
5         transformedTransformTo.get(path.node) as [
6           t.File,
7           Match
8         ];
9       path.replaceWithMultiple(
10        traToWithWildcards.program.body);
11
12       let siblings = path.getAllNextSiblings();
13
14       // For multi line applicable to
15       for (let i = 0; i < match.statements.length - 1; i++) {
16         siblings[i].remove();
17       }
18     }
19   }
20 });

```

```

19      // When we have matched top statements with +, we
20      ↪ might have to remove more siblings
21      for (let matchStmt of match.statements) {
22          for (let codeStmt of matchStmt.element
23              .codeNode) {
24              let siblingnodes = siblings.map((a) => a.node);
25              if (siblingnodes.includes(codeStmt)) {
26                  let index = siblingnodes.indexOf(codeStmt);
27                  siblings[index].remove();
28              }
29          }
30      },
31  });
32

```

Listing 4.8: Inserting transformed matches into user code

There is a special case when a wildcard with a Keene plus, allowing the match of multiple siblings, means we might have more siblings to remove. In this case, it is not so simple to know exactly how many we have to remove. Therefore, we have to iterate over all statements of the match, and check if that statement is still a sibling of the current one being replace. This behavior can be seen on lines 20-29 of Listing 4.8.

After one full traversal of the user AST. All matches found have been replaced with their respective transformation. All that remains is generating JavaScript from the transformed AST.

Generating source code from transformed AST

To generate JavaScript from the transformed AST created by this tool, we use a JavaScript library titled [7]babel/generator. This library is specifically designed for use with Babel to generate JavaScript from a Babel AST. The transformed AST definition of the users code is transformed, while being careful to apply all Babel plugins the current proposal might require.

Chapter 5

Evaluation

In this chapter we will present the results of running each of the proposals discussed in this thesis on large scale JavaScript projects.

5.1 Real Life source code

To evaluate this tool on real life JavaScript code, we have collected some JavaScript projects from Github containing many or large JavaScript files. Every JavaScript file within the project is transformed with our tool, and we will evaluate it based upon the amount of matches discovered, as well as manual checking that the transformation resulted in correct output code.

Each case study was evaluated by running this tool on every .js file in the repository, then collecting the number of matches found in total and how many files were successfully searched. Evaluating if the transformation was correct is done by manually sampling output files, and verifying that it passes through Babel Generate [7] without error.

“Pipeline” [20] is applicable to most files, as the concept it touches (function calls) is widely used when writing JavaScript code. Our tool found matches in almost all files that Babel [8] managed to parse, and the transformed files are correct.

The “Do Expression” proposal [23] is not as applicable as the "Pipeline" proposal, as it does not re-define a concept that is used quite as frequently as call expressions. This means the amount of transformed code this specification in JSTQL will be able to

perform is expected and proven to be lower. This is due to the “Do Expression” proposal introducing an entirely new way to write expression-oriented code in JavaScript. If the code has not used the current way of writing in an expression-oriented style in JavaScript, JSTQL is limited in the amount of transformations it can perform. Nevertheless, matches are discovered and transformed correctly.

The imaginary “Await to promise” proposal also has an expected number of matches, but this evaluation proposal is not meant to be real life representative, and was only created to evaluate the expressiveness of our tool.

Next.js [18] is one of the largest projects on the web. It is used with React [24] to enable feature such as server-side rendering and static site generation.

Proposal	Matches found	Files with matches	Files processed
“Pipeline”	242079	1912	3340
“Do Expression”	229	37	3340
Await to Promise	143	75	3340

Table 5.1: Evaluation with Next.js source code

Three.js [30] is a library for 3D rendering in JavaScript. It is written purely in JavaScript and uses GPU for 3D calculations. It being a popular JavaScript library, and being written in mostly pure JavaScript makes it a good case study for our tool. It currently sits at over 1 million downloads weekly.

Proposal	Matches found	Files with matches	Files searched
Pipeline	84803	1117	1384
“Do Expression”	248	36	1384
Await to Promise	13	7	1384

Table 5.2: Evaluation with Three.js source code

React [24] is a graphical user interface library for JavaScript, it facilitates the creation of user interfaces for both web and native platforms. React is based upon splitting a user interface into components for simple development. It is currently one of the most popular libraries for creating web apps and has over 223000 stars on Github.

Proposal	Matches found	Files with matches	Files searched
“Pipeline”	16353	1266	2051
“Do Expression”	0	0	2051
Await to Promise	30	13	2051

Table 5.3: Evaluation with React source code

Bootstrap [13] is a front-end framework used for creating responsive and mobile-first websites, it comes with a variety of built-in components, as well as a built in styling. This styling is also customizable using CSS. This library is a good evaluation point for this thesis as it is written in pure JavaScript and is used by millions of developers.

Proposal	Matches found	Files with matches	Files searched
"“Pipeline”	13794	109	115
“Do Expression”	0	0	115
Await to Promise	0	0	115

Table 5.4: Evaluation with Bootstrap source code

Atom [3] is a text editor made in JavaScript using the Electron framework. It was created to give a very minimal and modular text editor. It was bought by Microsoft, and later discontinued in favor for Visual Studio Code.

Proposal	Matches found	Files with matches	Files searched
“Pipeline”	40606	361	401
“Do Expression”	3	3	401
Await to Promise	12	7	401

Table 5.5: Evaluation with Atom source code

See Appendix B for some examples of the transformations discussed in this section.

Chapter 6

Related Work

In this chapter, we present work related to other query languages for source code, aspect-oriented programming, some code querying methods, and other JavaScript parsers. This all relates to the work described in this thesis.

6.1 Aspect-Oriented Programming

AoP, is a programming paradigm that gives increased modularity by allowing for a high degree of separation of concerns, specifically focusing on cross-cutting concerns.

Cross-cutting concerns are aspects of a software program or system that have an effect at multiple levels, cutting across the main functional requirements. Such aspects are often related to security, logging, or error handling, but could be any concern that are shared across an application.

In AOP, one creates an *aspect*, which is a module that contains some cross-cutting concern the developer wants to achieve, this can be logging, error handling or other concerns not related to the original classes it should applied to. An aspect contains advices, which is the specific code executed when certain conditions of the program are met, an example of these are *before advice*, which is executed before a method executes, *after advice*, which is executed after a method regardless of the methods outcome, and *around advice*, which surrounds a method execution. Contained within the aspect is also a *pointcut*, which is the set of criteria determining when the aspect is meant to be executed. This can be at specific methods, or when specific constructors are called etc.

Aspect oriented programming is similar to this project in that to define where *pointcuts* are placed, we have to define some structure and the AOP library has to search the code execution for events triggering the pointcut and run the advice defined within the aspect of that given pointcut. Essentially performing a rewrite of the code during execution to add functionality to multiple places in the executing code.

6.2 Other source code query languages

To allow for simple analysis and refactoring of code, there exists many query languages designed to query source code. These languages use several methods to allow for querying code based on specific paradigms such as logical queries, declarative queries, or SQL-like queries. All provide similar functionality of being able to query code. In this section we will look some of these languages for querying source code, and how they relate to JSTQL developed in this thesis.

6.2.1 CodeQL

CodeQL [14] is an object-oriented query language, it was previously known as .QL. . CodeQL is used to analyze code semantically to discover vulnerabilities [40]. CodeQL has taking inspiration from several areas of computer science to create their query language [40], such a inspiration from SQL, Datalog, Eindhoven QUantifier Notation, and Classes are Predicates.

An example of how queries are written in CodeQL can be defined below [14]. This query will find all methods that declare a method `equals` and not a method `hashCode`. This query is performed using an erroneous class `c`, and we define what properties that class should have.

```
1 from Class c
2 where c.declaresMethod("equals") and
3       not(c.declaresMethod("hashCode")) and
4       c.fromSource()
5 select c.getPackage(), c
```

The syntax of writing queries in CodeQL is not similar to JSTQL, as it is SQL-like, and not declarative patterns, which makes the writing experience of the two languages very different. Writing CodeQL queries are similar to querying a database, while queries written in JSTQL are similar to defining an example of the structure you wish to search for.

6.2.2 PMD XPath

PMD XPath is a language for Java source code querying, it supports querying of all Java constructs [45]. The reason it has this wide support is due to it constructing the entire codebase's AST in XML format, and then performing the query on the XML. These queries are performed using XPath rules, that define the matching on the XML. This makes the query language very versatile for static code analysis, and is used in the PMD static code analysis tool.

```
1 public class KeepingItSerious{
2     Delegator bill; // FieldDeclaration
3
4     public void method(){
5         short bill; // LocalVariableDeclaration
6     }
7 }
```

There are two queries with PMD XPath defined in the example below [19]. If we execute these on the code above, the first will match against the field declaration **Delegator bill** and **short bill**, while the second will only return **short bill**. The reason the second limits the search, is we define the type of the declaration.

```
1 //VariableId[@Name = "bill"]
2 //VariableId[@Name = "bill" and ../../Type[@TypeImage = "short"]]
```

Comparing this tool to JSTQL, we can see it is good at querying code based on structure, which our tool also excels at. The main difference is the manor of which each tool does this, JSTQL uses JavaScript templates to perform the query, making writing queries simple for users as they are based in JavaScript. PMD XPath uses XPath to perform define structural queries that is quite verbose, and requires extended knowledge of the AST that is currently being queried.

6.2.3 XSL Transformations

XSLT [1] is a language created to perform transformations of XML documents, transforming an XML document into a different format, this can be into other XML documents, HTML or even plain text.

XSLT is part of Extensible Stylesheets Language family of programs. The XSL language is expressed in the form of a stylesheet [1, 1.1], whose syntax is defined in XML. This language uses a template based approach to define matches on specific patterns in

the source to find sections to transform. These transformations are defined by a transformation declaration that describes how the output of the match should look.

This language defines matching and transformation very similarly to JSTQL, and uses the same technique, where the transformation declaration describes how the output should look, and not exactly how the transformation is performed.

6.2.4 Jackpot

Jackpot [42] is a query language created for the Apache Netbeans platform [41], it has since been mostly renamed to Java Declarative Hints Language, we will continue to refer to it as Jackpot in this section. The language uses declarative patterns to define source code queries, these queries are used in conjunction with multiple rewrite definitions. This is used in the Apache Netbeans suite of tools to allow for declarative refactoring of code.

This is quite similar to the form of JSTQL, as both language define som query by using similar structure, in Jackpot you define a *pattern*, then every match of that pattern can be re-written to a *fix-pattern*, each fix-pattern can have a condition attached to it. This is quite similar to the *applicable to* and *transform to* sections of JSTQL. Jackpot also supports something similar to the wildcards in JSTQL, as you can define variables in the *pattern* definition and transfer them over to the *fix-pattern* definition. This is closely related to the definition of wildcards in JSTQL, though without type restrictions and notation for matching more than one AST node.

The example of a query and transformation below, will query the code for variable declarations with initial value of 1, and then change them into a declaration with initial value of 0.

```
1 "change declarations of 1 to declarations of 0":  
2   int $1 = 1;  
3 =>  int $1 = 0
```

6.3 JetBrains structural search

JetBrains integrated development environments have a feature that allows for structural search and replace [26]. This feature is intended for large code bases where a developer wants to perform a search and replace based on syntax and semantics, not just a regular

text based search and replace. A search is applied to specific files of the codebase or the entire codebase. It does not recursively check the entire static structure of the code, but this can be specified in the user interface of structural search and replace.

When doing structural search in JetBrains IntelliJ IDEA, templates are used to describe the query used in the search. These templates use variables described with `$variable$`, these allow for transferring context to the structural replace.

This tool is an interactive experience, where each match is showcased in the find tool, and the developer can decide which matches to apply the replace template to. This allows for error avoidance and a stricter search that is verified by humans. If the developer wants, they do not have to verify each match and just replace everything.

When comparing this tool to JSTQL and its corresponding program, there are some similarities. They are both template based, which means a search uses a template to define query, both templates contain variables/wildcards to match against a free section, and the replacing structure is also a template based upon those same variables. A way of matching the variables/wildcards of structural search and replace also exists, one can define the amount of X node to match against, similar to the `+` operator used in JSTQL. A core difference between JSTQL and structural search and replace is the variable type system. When performing a match and transformation in JSTQL the types are used extensively to limit the match against the wildcards, while this limitation is not possible in structural search and replace.

6.4 Other JavaScript parsers

This section will explore other JavaScript parsers that could have been used in this project. We will give a brief introduction of each of them, and discuss why they were not chosen.

Speedy Web Compiler

Speedy Web Compiler [25] is a library created for parsing JavaScript and other dialects like JSX, TypeScript faster. It is written in Rust and advertises faster speeds than Babel and is used by large organizations creating applications and tooling for the web platform.

Similar to Babel [4], Speedy Web Compiler is an extensible parser that allows for changing the specification of the parsed program. Its extensions are written in Rust. While it does not have as mature of a plugin system as Babel, its focus on speed makes it widely used for large scale web projects.

Speedy Web Compiler supports features out of the box such as compilation, used for TypeScript and other languages that are compiled down to JavaScript. Bundling, which takes multiple JavaScript/TypeScript files and bundles them into a single output file, while handling naming collisions. Minification, to make the bundle size of a project smaller, transforming for use with WebAssembly, and custom plugins to change the specification of the languages parsed by SWC.

Compared to Babel used in this paper, SWC focuses on speed, as its main selling point is a faster way of developing web projects. This parser was considered to be used for this project, however it had some shortcomings which made us decide it was not a good fit. SWC is written in Rust, which considering this project is targeted at TC39 we wanted it to be in JavaScript or one of JavaScript's dialects. SWC does have such an extensive library of early stage proposal plugins as Babel, this by itself is the deal breaker for use in this project, as we rely on support of proposals as early as stage one.

Acorn

Acorn [2] is parser written in JavaScript to parse JavaScript and it's related languages. Acorn focuses on plugin support to support extending and redefinition of how it's internal parser works. Acorn focuses on being a small and fast JavaScript parser, has it's own tree traversal library Acorn Walk. Babel is originally a fork of Acorn, while Babel has since had a full rewrite, Babel is still heavily based on Acorn and Acorn-jsx [6].

Acorn suffers from a similar problem to SWC when it was considered for use in this project. It does not have the same wide community as Babel, and does not have the same recommendation from TC39 as Babel does [28]. Even though it supports plugins and the plugin system is powerful, there does not exist the same amount of pre-made plugins for early stage proposals as Babel has.

6.5 Model-to-Model Transformations

Model-to-Model transformations are a part of model-driven engineering (MDE). These transformations involve transforming one model into another. a model is an abstraction of representation and behavior within a system.

The process of performing a model-to-model transformation is to convert one model into another, while preserving or adapting its underlying semantics and structure [46]. This is usually done by traversing its structure, and extracting data and transforming its format to fit the model it should be transformed into. This allows a model described within one domain to be transformed into another automatically.

This is quite similar to what our tool described in this thesis is doing. We are transforming the AST of the user code from one AST definition not using a proposal, so one form of representation, into another using a proposal not part of the original AST.

Chapter 7

Conclusions & Future Work

7.1 Conclusions

In this thesis, we have developed a way to define transformations of JavaScript based on a proposal definition. The idea this thesis started to explore is to create a way to gather early feedback on syntactic proposals for ECMAScript. The tool created allows for matching and transformation of user code based on a proposal definition. This is the initial step of gathering user feedback by using a user's familiarity with their own code. While more work still remains, this thesis has proved the idea of transforming user code to use new proposals to be feasible.

7.2 Future Work

Provide access and gather feedback This project is build upon creating a tool for users of EcmaScript to see new proposals within their own codebase. The idea behind this is to use the users familiarity to showcase new syntactic proposals, and get valuable feedback to the committee developing the ECMA-262 standard. This means making the definitions of a proposal in JSTQL and this tool available to end-users to execute using their own code. This can come in multiple forms, we suggest some ideas, such as a playground on the web, an extension for Visual Studio Code, or to be used in github pull requests.

Supporting other languages The idea of showcasing changes to a programming language by transforming user code is not only limited to EcmaScript, and could be applied to many other programming languages using a similar development method to EcmaScript. The developers of a language could write definitions of new changes for their respective language, and use a similar tool to the one discussed in this thesis to showcase possible new changes.

Parameterized specifications The current form of JSTQL supports writing each template as its own respective case, but multiple templates might be very similar and could be written using generics that are shared between case definitions. Introducing this might give a simpler way of writing more complex definitions of a proposal transformation by re-using generic type parameters for the wildcards used in the transformations.

Fully self-hosting JSTQLSH The current version of JSTQLSH relies on this tools parser to generate the AST for the type expressions used for matching by wildcards. This might make this tool more difficult to adopt for the committee. Therefore adding functionality for writing these type expressions purely in JavaScript and allowing for the use of JavaScript as its own meta language is an interesting avenue to explore.

Support for custom proposal syntax Currently this tool relies heavily on that a proposal is supported by Babel [4]. This makes the tool quite limited in what proposals could be defined and transformed due to relying on Babel for parsing the templates and generating the output code. Introducing some way of defining new syntax for a proposal in the proposal definition, and allowing for parsing JavaScript containing that specific new syntax would limit the reliance on Babel, and allow for defining proposals earlier in the development process. This can possibly be done by implementing a custom parser inside this tool that allows defining custom syntax for specific new proposals.

Support of a wider syntax for wildcards The current syntax for wildcards allow limiting on node types only. An interesting avenue of exploration is to specify wildcards with code snippets in them. This would allow for an even deeper template structure to define matches, and would also give the transformation a more specified expected structure to insert.

Bibliography

- [1] XSL Transformations (XSLT) Version 2.0 (Second Edition), March 2021.
URL: <https://www.w3.org/TR/xslt20>. [Online; accessed 30. May 2024].
- [2] acorn, May 2024.
URL: <https://github.com/acornjs/acorn>. [Online; accessed 21. May 2024].
- [3] atom, May 2024.
URL: <https://github.com/atom/atom>. [Online; accessed 23. May 2024].
- [4] Babel · Babel, May 2024.
URL: <https://babeljs.io>. [Online; accessed 10. May 2024].
- [5] babel/packages/babel-parser/ast/spec.md at main · babel/babel, May 2024.
URL: <https://github.com/babel/babel/blob/main/packages/babel-parser/ast/spec.md>.
[Online; accessed 28. May 2024].
- [6] @babel/parser · Babel, May 2024.
URL: <https://babeljs.io/docs/babel-parser#credits>. [Online; accessed 30. May 2024].
- [7] @babel/generator · Babel, May 2024.
URL: <https://babeljs.io/docs/babel-generator>. [Online; accessed 12. May 2024].
- [8] @babel/parser · Babel, May 2024.
URL: <https://babeljs.io/docs/babel-Parser>. [Online; accessed 14. May 2024].
- [9] proposals, May 2024.
URL: <https://github.com/babel/proposals>. [Online; accessed 27. May 2024].
- [10] What is Babel? · Babel, May 2024.
URL: <https://babeljs.io/docs/#spec-compliant>. [Online; accessed 29. May 2024].
- [11] @babel/traverse · Babel, May 2024.
URL: <https://babeljs.io/docs/babel-traverse>. [Online; accessed 12. May 2024].

- [12] Bash Reference Manual, June 2024.
URL: <https://www.gnu.org/software/bash/manual/bash.html#Pipelines>. [Online; accessed 1. Jun. 2024].
- [13] bootstrap, May 2024.
URL: <https://github.com/twbs/bootstrap>. [Online; accessed 23. May 2024].
- [14] CodeQL, May 2024.
URL: <https://codeql.github.com>. [Online; accessed 29. May 2024].
- [15] Enumerables and Streams — Elixir v1.16.3, May 2024.
URL: <https://hexdocs.pm/elixir/1.16.3/enumerable-and-streams.html#the-pipe-operator>. [Online; accessed 1. Jun. 2024].
- [16] Functions · The Julia Language, May 2024.
URL: <https://docs.julialang.org/en/v1/manual/functions/#Function-composition-and-piping>. [Online; accessed 24. May 2024].
- [17] Langium, April 2024.
URL: <https://langium.org>. [Online; accessed 10. May 2024].
- [18] next.js, May 2024.
URL: <https://github.com/vercel/next.js>. [Online; accessed 23. May 2024].
- [19] Writing XPath rules | PMD Source Code Analyzer, April 2024.
URL: https://docs.pmd-code.org/latest/pmd_userdocs_extending_writing_xpath_rules.html. [Online; accessed 30. May 2024].
- [20] proposal-pipeline-operator, May 2024.
URL: <https://github.com/tc39/proposal-pipeline-operator>. [Online; accessed 21. May 2024].
- [21] Bikeshedding the Hack topic token · Issue #91 · tc39/proposal-pipeline-operator, May 2024.
URL: <https://github.com/tc39/proposal-pipeline-operator/issues/91>. [Online; accessed 24. May 2024].
- [22] proposal-pipeline-operator/HISTORY.md at main · tc39/proposal-pipeline-operator, May 2024.
URL: <https://github.com/tc39/proposal-pipeline-operator/blob/main/HISTORY.md>. [Online; accessed 31. May 2024].

- [23] proposal-do-expressions, May 2024.
URL: <https://github.com/tc39/proposal-do-expressions>. [Online; accessed 2. May 2024].
- [24] react, May 2024.
URL: <https://github.com/facebook/react>. [Online; accessed 23. May 2024].
- [25] Rust-based platform for the Web – SWC, May 2024.
URL: <https://swc.rs>. [Online; accessed 21. May 2024].
- [26] Structural search and replace | IntelliJ IDEA, April 2024.
URL: <https://www.jetbrains.com/help/idea/structural-search-and-replace.html>. [Online; accessed 22. May 2024].
- [27] The TC39 Process, April 2024.
URL: <https://tc39.es/process-document>. [Online; accessed 24. May 2024].
- [28] how-we-work/implement.md at main · tc39/how-we-work, May 2024.
URL: <https://github.com/tc39/how-we-work/blob/main/implement.md#transpiler-implementations>. [Online; accessed 29. May 2024].
- [29] TOML: Tom’s Obvious Minimal Language, May 2024.
URL: <https://toml.io/en>. [Online; accessed 27. May 2024].
- [30] three.js, May 2024.
URL: <https://github.com/mrdoob/three.js>. [Online; accessed 23. May 2024].
- [31] ECMAScript® 2025 Language Specification, May 2024.
URL: <https://tc39.es/ecma262>. [Online; accessed 28. May 2024].
- [32] Boyko B. Bantchev. Putting more meaning in expressions. *SIGPLAN Not.*, 33(9): 77–83, September 1998. ISSN 0362-1340. doi: 10.1145/290229.290237.
URL: <https://dl.acm.org/doi/10.1145/290229.290237>.
- [33] Matthew S. Davis. An object oriented approach to constructing recursive descent parsers. *SIGPLAN Not.*, 35(2):29–35, feb 2000. ISSN 0362-1340. doi: 10.1145/345105.345113.
URL: <https://doi.org/10.1145/345105.345113>.
- [34] Sven Efftinge and Miro Spoenemann. Xtext - Language Engineering Made Easy!, February 2024.
URL: <https://eclipse.dev/Xtext>. [Online; accessed 29. May 2024].

- [35] Sebastian Erdweg, Tijs Van Der Storm, Markus Völter, Laurence Tratt, Remi Bosman, William R Cook, Albert Gerritsen, Angelo Hulshout, Steven Kelly, Alex Loh, et al. Evaluating and comparing language workbenches: Existing results and benchmarks for the future. *Computer Languages, Systems & Structures*, 44:24–47, 2015.
- [36] Martin Hirzel, Scott Schneider, and Kanat Tangwongsan. Sliding-Window Aggregation Algorithms: Tutorial. In *DEBS '17: Proceedings of the 11th ACM International Conference on Distributed and Event-based Systems*, pages 11–14. Association for Computing Machinery, New York, NY, USA, June 2017. ISBN 978-1-45035065-5. doi: 10.1145/3093742.3095107.
URL: <https://dl.acm.org/doi/abs/10.1145/3093742.3095107>.
- [37] KathleenDollard. Symbol and Operator Reference - F#, May 2024.
URL: <https://learn.microsoft.com/en-us/dotnet/fsharp/language-reference/symbol-and-operator-reference/#type-symbols-and-operators>. [Online; accessed 24. May 2024].
- [38] Anneke G. Kleppe. *Software Language Engineering: Creating Domain-Specific Languages Using Metamodels*. Addison-Wesley Professional, Boston, MA, USA, January 2008. ISBN 978-0-32155345-4.
- [39] Marjan Mernik, Jan Heering, and Anthony M. Sloane. When and how to develop domain-specific languages. *ACM Comput. Surv.*, 37(4):316–344, dec 2005. ISSN 0360-0300. doi: 10.1145/1118890.1118892.
URL: <https://doi.org/10.1145/1118890.1118892>.
- [40] Oege de Moor, Mathieu Verbaere, Elnar Hajiyeu, Pavel Avgustinov, Torbjorn Ekman, Neil Ongkingco, Damien Sereni, and Julian Tibble. Keynote address: .ql for source code analysis. In *Seventh IEEE International Working Conference on Source Code Analysis and Manipulation (SCAM 2007)*, pages 3–16, 2007. doi: 10.1109/SCAM.2007.31.
- [41] Apache NetBeans. Welcome to Apache NetBeans, February 2024.
URL: <https://netbeans.apache.org/front/main/index.html>. [Online; accessed 21. May 2024].
- [42] Apache NetBeans. Java Declarative Hints Language, March 2024.
URL: <https://netbeans.apache.org/front/main/jackpot/HintsFileFormat/#variables>. [Online; accessed 21. May 2024].

- [43] J. Palsberg and C.B. Jay. The essence of the visitor pattern. In *Proceedings. The Twenty-Second Annual International Computer Software and Applications Conference (Compsac '98) (Cat. No.98CB 36241)*, pages 9–15, 1998. doi: 10.1109/CMPSAC.1998.716629.
- [44] Weisong Sun, Chunrong Fang, Yun Miao, Yudu You, Mengzhe Yuan, Yuchen Chen, Quanjun Zhang, An Guo, Xiang Chen, Yang Liu, and Zhenyu Chen. Abstract syntax tree for programming language understanding and representation: How far are we?, 2023.
- [45] Raoul-Gabriel Urma and Alan Mycroft. Programming language evolution via source code query languages. In *Proceedings of the ACM 4th Annual Workshop on Evaluation and Usability of Programming Languages and Tools, PLATEAU '12*, page 35–38, New York, NY, USA, 2012. Association for Computing Machinery. ISBN 9781450316316. doi: 10.1145/2414721.2414728.
URL: <https://doi.org/10.1145/2414721.2414728>.
- [46] Andrzej Wąsowski and Thorsten Berger. *Model and Program Transformation*, pages 233–292. Springer International Publishing, Cham, 2023. ISBN 978-3-031-23669-3. doi: 10.1007/978-3-031-23669-3_7.
URL: https://doi.org/10.1007/978-3-031-23669-3_7.

Appendix A

TypeScript types of wildcard type expressions

```
1 export interface Identifier extends WildcardNode {
2   nodeType: "Identifier";
3   name: string;
4 }
5
6 export interface Wildcard {
7   nodeType: "Wildcard";
8   identifier: Identifier;
9   expr: TypeExpr;
10  star: boolean;
11 }
12
13 export interface WildcardNode {
14   nodeType: "BinaryExpr" | "UnaryExpr" | "GroupExpr" | "Identifier";
15 }
16
17 export type TypeExpr = BinaryExpr | UnaryExpr | PrimitiveExpr;
18
19 export type BinaryOperator = "||" | "&&";
20
21 export type UnaryOperator = "!";
22
23 export interface BinaryExpr extends WildcardNode {
24   nodeType: "BinaryExpr";
25   left: UnaryExpr | BinaryExpr | PrimitiveExpr;
26   op: BinaryOperator;
27   right: UnaryExpr | BinaryExpr | PrimitiveExpr;
28 }
29 export interface UnaryExpr extends WildcardNode {
30   nodeType: "UnaryExpr";
31   op: UnaryOperator;
32   expr: PrimitiveExpr;
33 }
34
35 export type PrimitiveExpr = GroupExpr | Identifier;
36
37 export interface GroupExpr extends WildcardNode {
38   nodeType: "GroupExpr";
39   expr: TypeExpr;
40 }
```

Listing A.1: TypeScript types of Type Expression AST

Appendix B

Examples of transformations performed in Evaluation

```
1 async function getCurrentRules() {
2   return
3     ↪ fetch('https://api.github.com/repos/vercel/next.js/branches/canary/protection
4     ↪ {
5       headers: {
6         Accept: 'application/vnd.github+json',
7         Authorization: 'Bearer ${authToken}',
8         'X-GitHub-API-Version': '2022-11-28'
9       }
10    }.then(async res => {
11      if (!res.ok) {
12        throw new Error('Failed to check for rule ${res.status} ${await
13          ↪ res.text()}');
14      }
15      const data = await res.json();
16      return {
17        // Massive JS object
18      };
19    });
20 }
```

"Await to Promise" transformation, from `next.js/test/integration/typescript-hmr/index.test.`

```
1 for (const file of typeFiles) {
2   const content = await fs.readFile(join(styledJsxPath, file), 'utf8')
3   await fs.writeFile(join(typesDir, file), content)
4 }
```

```
1 for (const file of typeFiles) {
2   const content = await (styledJsxPath |> join(%, file) |>
3     ↪ fs.readFile(%, 'utf8'));
4   await (typesDir |> join(%, file) |> fs.writeFile(%, content));
5 }
```

"Pipeline" transformation, taken from `next.js/packages/next/taskfile.js`

```
1 tracks.push( parseKeyframeTrack( jsonTracks[ i ] ).scale( frameTime )
    ↪ );
```

```
1 frameTime
2 |> (jsonTracks[i] |> parseKeyframeTrack(%)).scale(%)
3 |> tracks.push(%);
```

Transformation taken from `three.js/src/animation/AnimationClip.js`

```
1 const logger = createLogger({
2   storagePath: join(__dirname, '.progress-estimator'),
3 });
```

```
1 const logger = {
2   storagePath: __dirname |> join(%, '.progress-estimator')
3 } |> createLogger(%);
```

“Pipeline” transformation, taken from `react/scripts/devtools/utils.js`

```
1 if (isElement(content)) {
2   this._putElementInTemplate(getElement(content), templateElement)
3   return
4 }
```

```
1 if (content |> isElement(%)) {
2   content |> getElement(%) |> this._putElementInTemplate(%,
    ↪   templateElement);
3   return;
4 }
```

“Pipeline” transformation, taken from `bootstrap/js/src/util/template-factory.js`

```
1 if (repo && repo.onDidDestroy) {
2   repo.onDidDestroy(() =>
3     this.repositoryPromisesByPath.delete(pathForDirectory)
4   );
5 }
```

```
1 if (repo && repo.onDidDestroy) {
2   (() => pathForDirectory |>
    ↪   this.repositoryPromisesByPath.delete(%)) |>
    ↪   repo.onDidDestroy(%);
3 }
```

“Pipeline” transformation, taken from `atom/src/project.js`

```

1 Lensflare.Geometry = do {
2   const geometry = new BufferGeometry();
3   const float32Array = new Float32Array([
4     -1, -1, 0, 0, 0, 1, -1, 0, 1, 0, 1, 1, 0, 1, 1, -1, 1, 0, 0, 1,
5   ]);
6   const interleavedBuffer = new InterleavedBuffer(float32Array, 5);
7   geometry.setIndex([0, 1, 2, 0, 2, 3]);
8   geometry.setAttribute(
9     "position",
10    new InterleavedBufferAttribute(interleavedBuffer, 3, 0, false)
11  );
12  geometry.setAttribute(
13    "uv",
14    new InterleavedBufferAttribute(interleavedBuffer, 2, 3, false)
15  );
16  geometry;
17 };

```

```

1 Lensflare.Geometry = do {
2   const geometry = new BufferGeometry();
3   const float32Array = new Float32Array([
4     -1, -1, 0, 0, 0, 1, -1, 0, 1, 0, 1, 1, 0, 1, 1, -1, 1, 0, 0, 1,
5   ]);
6   const interleavedBuffer = new InterleavedBuffer(float32Array, 5);
7   geometry.setIndex([0, 1, 2, 0, 2, 3]);
8   geometry.setAttribute(
9     "position",
10    new InterleavedBufferAttribute(interleavedBuffer, 3, 0, false)
11  );
12  geometry.setAttribute(
13    "uv",
14    new InterleavedBufferAttribute(interleavedBuffer, 2, 3, false)
15  );
16  geometry;
17 };

```

“Do expression” transformation, taken from `three.js/examples/jsm/objects/Lensflare.js`

```

1 addHelper: (function () {
2     var geometry = new THREE.SphereGeometry(2, 4, 2);
3     var material = new THREE.MeshBasicMaterial({
4         color: 0xff0000,
5         visible: false,
6     });
7
8     return function (object, helper) {
9         if (helper === undefined) {
10             if (object.isCamera) {
11                 helper = new THREE.CameraHelper(object);
12             } else if (object.isPointLight) {
13                 helper = new THREE.PointLightHelper(object, 1);
14             } else if (object.isDirectionalLight) {
15                 helper = new THREE.DirectionalLightHelper(object,
16                     ↪ 1);
17             } else if (object.isSpotLight) {
18                 helper = new THREE.SpotLightHelper(object);
19             } else if (object.isHemisphereLight) {
20                 helper = new THREE.HemisphereLightHelper(object,
21                     ↪ 1);
22             } else if (object.isSkinnedMesh) {
23                 helper = new
24                     ↪ THREE.SkeletonHelper(object.skeleton.bones[0]);
25             } else if (
26                 object.isBone === true &&
27                 object.parent &&
28                 object.parent.isBone !== true
29             ) {
30                 helper = new THREE.SkeletonHelper(object);
31             } else {
32                 // no helper for this object type
33                 return;
34             }
35
36             const picker = new THREE.Mesh(geometry, material);
37             picker.name = "picker";
38             picker.userData.object = object;
39             helper.add(picker);
40
41             this.sceneHelpers.add(helper);
42             this.helpers[object.id] = helper;
43             this.signals.helperAdded.dispatch(helper);
44         }
45     }();
46 }

```

```

1 addHelper: do {
2     var geometry = new THREE.SphereGeometry(2, 4, 2);
3     var material = new THREE.MeshBasicMaterial({
4         color: 0xff0000,
5         visible: false
6     });
7     function (object, helper) {
8         if (helper === undefined) {
9             if (object.isCamera) {
10                 helper = new THREE.CameraHelper(object);
11             } else if (object.isPointLight) {
12                 helper = new THREE.PointLightHelper(object, 1);
13             } else if (object.isDirectionalLight) {
14                 helper = new THREE.DirectionalLightHelper(object, 1);
15             } else if (object.isSpotLight) {
16                 helper = new THREE.SpotLightHelper(object);
17             } else if (object.isHemisphereLight) {
18                 helper = new THREE.HemisphereLightHelper(object, 1);
19             } else if (object.isSkinnedMesh) {
20                 helper = new THREE.SkeletonHelper(object.skeleton.bones[0]);
21             } else if (object.isBone === true && object.parent &&
22                 ↪ object.parent.isBone !== true) {
23                 helper = new THREE.SkeletonHelper(object);
24             } else {
25                 // no helper for this object type
26                 return;
27             }
28             const picker = new THREE.Mesh(geometry, material);
29             picker.name = 'picker';
30             picker.userData.object = object;

```

```

1  const panLeft = (function () {
2      const v = new Vector3();
3
4      return function panLeft(distance, objectMatrix) {
5          v.setFromMatrixColumn(objectMatrix, 0); // get X column of
6              ↪ objectMatrix
7          v.multiplyScalar(-distance);
8
9          panOffset.add(v);
10     };
11 })();
12
13 const panUp = (function () {
14     const v = new Vector3();
15
16     return function panUp(distance, objectMatrix) {
17         if (scope.screenSpacePanning === true) {
18             v.setFromMatrixColumn(objectMatrix, 1);
19         } else {
20             v.setFromMatrixColumn(objectMatrix, 0);
21             v.crossVectors(scope.object.up, v);
22         }
23
24         v.multiplyScalar(distance);
25
26         panOffset.add(v);
27     };
28 })();

```

```

1  const panLeft = do {
2      const v = new Vector3();
3      function panLeft(distance, objectMatrix) {
4          v.setFromMatrixColumn(objectMatrix, 0); // get X column of
5              ↪ objectMatrix
6          v.multiplyScalar(-distance);
7          panOffset.add(v);
8      }
9  };
10 const panUp = do {
11     const v = new Vector3();
12     function panUp(distance, objectMatrix) {
13         if (scope.screenSpacePanning === true) {
14             v.setFromMatrixColumn(objectMatrix, 1);
15         } else {
16             v.setFromMatrixColumn(objectMatrix, 0);
17             v.crossVectors(scope.object.up, v);
18         }
19         v.multiplyScalar(distance);
20         panOffset.add(v);
21     }
22 };

```

“Do expression” transformation, taken from `three.js/examples/jsm/objects/Lensflare.js`

```

1 async loadAsync(url, onProgress) {
2   const scope = this;
3   const path =
4     this.path === "" ? LoaderUtils.extractUrlBase(url) : this.path;
5   this.resourcePath = this.resourcePath || path;
6   const loader = new FileLoader(this.manager);
7   loader.setPath(this.path);
8   loader.setRequestHeader(this.requestHeader);
9   loader.setWithCredentials(this.withCredentials);
10  return loader.loadAsync(url, onProgress).then(async (text) => {
11    const json = JSON.parse(text);
12    const metadata = json.metadata;
13    if (
14      metadata === undefined ||
15      metadata.type === undefined ||
16      metadata.type.toLowerCase() === "geometry"
17    ) {
18      throw new Error("THREE.ObjectLoader: Can't load " + url);
19    }
20    return await scope.parseAsync(json);
21  });
22 }

```

```

1 async loadAsync(url, onProgress) {
2   const scope = this;
3
4   const path = this.path === "" ? LoaderUtils.extractUrlBase(url) :
5     ↪ this.path;
6   this.resourcePath = this.resourcePath || path;
7
8   const loader = new FileLoader(this.manager);
9   loader.setPath(this.path);
10  loader.setRequestHeader(this.requestHeader);
11  loader.setWithCredentials(this.withCredentials);
12
13  const text = await loader.loadAsync(url, onProgress);
14
15  const json = JSON.parse(text);
16
17  const metadata = json.metadata;
18
19  if (
20    metadata === undefined ||
21    metadata.type === undefined ||
22    metadata.type.toLowerCase() === "geometry"
23  ) {
24    throw new Error("THREE.ObjectLoader: Can't load " + url);
25  }
26
27  return await scope.parseAsync(json);
28 }

```

“Await to promise” transformation, taken from `three.js/src/loaders/ObjectLoader.js`