Introduction

Integrated Development Environments (IDEs) and other more lightweight code editors are by far the most used tool of software developers. Yet, improvements of language intelligence, i.e. code completion, debugging as well as static code analysis and enrichment, have traditionally been subject to both the language and the editor used. Language support is thereby brought to IDEs by the means of platform dependent extensions that require repeated efforts for each platform and hence varied a lot in performance, feature-richness and availability. Recent years have seen different works [refs?] towards editor independent code intelligence implementations and unified language independent protocols one of which being put forward by Microsoft - the Language Server Protocol [ref] which is discussed in greater detail in sec. **??**. These approaches reduced the effort of implementing language intelligence from $\mathcal{O}(E \times L)$ to $\mathcal{O}(1 \times L)$ where E stands for the number of *editors* and L for *languages*. As a side effect this also allows for developers to stay in their preferred developing environment instead of needing to resort to e.g. Vim or Emacs emulation or loosing access to other plugins.

Being independent of the editors, the choice of language to implement language servers in lies with the developer. In effect, it is possible for language developers to integrate essential parts of the existing language implementation for a language server. By now the LSP has become the most popular choice for cross-platform language tooling with implementations [langservers and microsoft] for all major and many smaller languages.

Speaking of smaller languages is significant, as both research communities and industry continuously develop and experiment with new languages for which tooling is unsurprisingly scarce. Additionally, previous research [ref], that shows the importance of language tools for the selection of a language, highlights the importance of tooling for new languages to be adopted by a wider community. While previously implementing language tools that integrate with the developer's environment was practically unfeasible for small projects due to the incompatibility between different extension systems, leveraging the LSP reduces the amount of work required considerably.

Problem Definition

Yet, while many of the implementations are freely available as Open Source Software [ref?], the methodology behind these servers is often poorly documented, especially for smaller languages. There are some experience reports [ref: merlin, and others] and a detailed video series on the Rust Analyzer[ref or footnote], project, but implementations remain very opinionated and poorly guided through. The result is that new implementations keep repeating to develop existing solutions.

Moreover, most projects do not formally evaluate the Language Server on even basic requirements. Naïvely, that is, the server should be *performant* enough not to slow down the developer, it should offer *useful* information and capabilities and of course be *correct* as well as *complete.*

To guide future implementations of language servers for primarily small scale languages the research presented in this thesis aims to answer the following research questions at the example of the Nickel Project[1]:

RQ.1 How to develop a language server for a new language with the abovementioned requirements in mind?
RQ.2 How can we assess the implementation both quantitatively based on performance measures and qualitatively based on user satisfaction?
RQ.3 Do the methods used to answer RQ.1 meet the expected requirements under the assessment developed in RQ.2?

Goals

The goal of this research is to describe a reusable approach for representing programs that can be used to query data to answer requests on the Language Server Protocol efficiently. The research is conducted on an implementation of the open source language Nickel[^https://nickel-lang.org] which provides the *Diagnostics*, *Jump to ** and *Hover* features as well as limited *Auto-Completion* and *Symbol resolution.* Although implemented for and with integration of the Nickel runtime, the goal is to keep the internal format largely language independent. Similarly, the Rust based implementation should be described abstractly enough to be implemented in other languages. To support the chosen approach, a user study will show whether the implementation is able to meet the expectations of its users and maintain its performance in real-world scenarios.

Non-Goals

The reference solution portrayed in this work is specific for the Nickel language. Greatest care is given to present the concepts as generically and transferable as possible. However, it is not a goal to explicitly cover a problem space larger than the Nickel language, which is a pure functional language based on lambda calculus featuring recursive record types and optional typing.

Research Methodology

What are the scientific methods

[1] https://nickel-lang.org

Structure of the thesis

Background

This thesis illustrates an approach of implementing a language server for the Nickel language which communicates with its clients, i.e. editors, over the open Language Server Protocol (in the following abbreviated as *LSP*). The current chapter provides the background on the technological details of the project. As the work presented aims to be transferable to other languages using the same methods, this chapter will provide the means to distinguish the nickel specific implementation details.

The primary technology built upon in this thesis is the language server protocol. The first part of this chapter introduces the LSP, its rationale and improvements over classical approaches, technical capabilities and protocol details. The second part is dedicated to Nickel, elaborating on the context and use-cases of the language followed by an inspection of the technical features of Nickel.

Language Server Protocol

Language servers are today's standard of integrating support for programming languages into code editors. Initially developed by Microsoft for the use with their polyglot editor Visual Studio Code[2] before being released to the public in 2016 by Microsoft, RedHat and Codeenvy, the LSP decouples language analysis and provision of IDE-like features from the editor. Developed under open source license on GitHub[3], the protocol allows developers of editors and languages to work independently on the support for new languages. If supported by both server and client, the LSP now supports more than 24 language features[4] including code completion, code navigation facilities, contextual information such as types or documentation, formatting, and more

Motivation

Since its release, the LSP has grown to be supported by a multitude of languages and editors(**lsp-website?**), solving a long-standing problem with traditional IDEs.

[2] https://code.visualstudio.com/

[3] https://github.com/microsoft/language-server-protocol/

[4] https://microsoft.github.io/language-server-protocol/specifications/specification-current/

Before the inception of language servers, it was the editors' individual responsibility to implement specialized features for any language of interest. Under the constraint of limited resources, editors had to position themselves on a spectrum between specializing on integrated support for a certain subset of languages and being generic over the language providing only limited support. As the former approach offers a greater business value, especially for proprietary products most professional IDEs gravitate towards excellent (and exclusive) support for single major languages, i.e. XCode and Visual Studio for the native languages for Apple and Microsoft Products respectively as well as JetBrains' IntelliJ platform and RedHat's Eclipse. Problematically, this results in less choice for developers and possible lock-in into products subjectively less favored but unique in their features for a certain language. The latter approach was taken by most text editors which in turn offered only limited support for any language.

Popularity statistics[5] shows that except Vim and Sublime Text, both exceptional general text editors, the top 10 most popular IDEs were indeed specialized products. The fact that some IDEs are offering support for more languages through (third-party) extensions, due to the missing standards and incompatible implementing languages/APIs, does not suffice to solve the initial problem that developing any sort of language support requires redundant resources.

This is especially difficult for emerging languages, with possibly limited development resources to be put towards the development of language tooling. Consequently, community efforts of languages any size vary in scope, feature completeness and availability.

The Language Server Protocol aims to solve this issue by specifying a JSON-RPC[^Remote Procedure Call] API that editors (clients) can use to communicate with language servers. Language servers are programs that implement a set of IDE features for one language and exposing access to these features through the LSP, allowing to focus development resources to a single project that is above all unrelated to editor-native APIs for analytics processing code representation and GUI integration. Consequently, now only a single implementation of a language server is required, instead of one for each editor and editor maintainers can concentrate on offering the best possible LSP client support to their product independent of the language.

JSON-RPC

JSON-RPC (v2) (**json-rpc?**) is a JSON based lightweight transport independent remote procedure call protocol used by the LSP to communicate between a language server and a client.

The protocol specifies the general format of messages exchanges as well as different kinds of messages. The following snippet lst. 0.1 shows the schema for request messages.

The main distinction in JSON-RPC are *Requests* and *Notifications*. Messages with an `id` field present are considered *requests*. Servers have to respond to requests with a message referencing the same `id` as well as a result, i.e. data or error. If the client does not require a response, it can omit the `id` field sending a

[5] https://web.archive.org/web/20160625140610/https://pypl.github.io/IDE.html

Listing 0.1 JSON-RPC Request

```
// Requests
{
  "jsonrpc": "2.0"
, "method": String
, "params": List | Object
, "id": Number | String | Null
}
```

notification, which servers cannot respond to, with the effect that clients cannot know the effect nor the reception of the message.

Responses as shown in lst. 0.2, have to be sent by servers answering to any request. Any result or error of an operation is explicitly encoded in the response. Errors are represented as objects specifying the error kind using an error `code` and providing a human-readable descriptive `message` as well as optionally any procedure defined `data`.

Listing 0.2 JSON-RPC Response and Error

```
// Responses
{
  "jsonrpc": "2.0"
  "result": any
  "error": Error
, "id": Number | String | Null
}
```

Clients can choose to batch requests and send a list of request or notification objects. The server should respond with a list of results matching each request, yet is free to process requests concurrently.

JSON-RPC only specifies a message protocol, hence the transport method can be freely chosen by the application.

Commands and Notifications

The LSP build on top of the JSON-RPC protocol described in the previous subsection.

File Notification

Diagnostics

Hover

Completion

Go-To-*

Symbols

code lenses

Shortcomings

Configuration programming languages

Nickel (**nickel?**), the language targeted by the language server detailed in this thesis, defines itself as "configuration language" used to automize the generation of static configuration files.

Static configuration languages such as XML(**xml?**), JSON(**json?**), or YAML(**yaml?**) are language specifications defining how to textually represent structural data used to configure parameters of a program[6]. Applications of configuration languages are ubiquitous especially in the vicinity of software development. While XML and JSON are often used by package managers (**composer?**), YAML is a popular choice for complex configurations such as CI/CD pipelines (**gitlab-runner?**) or machine configurations in software defined networks such as Kubernetes and docker compose.

Such static formats are used due to some significant advantages compared to other formats. Most strikingly, the textual representation allows inspection of a configuration without the need of a separate tool but a text editor and be version controlled using VCS software like Git. For software configuration this is well understood as being preferable over databases or other binary formats. Linux service configurations (files in `/etc`) and MacOS `*.plist` files which can be serialized as XML or a JSON-like format, especially exemplify that claim.

Yet, despite these formats being simple to parse and widely supported (**json?**), their static nature rules out any dynamic content such as generated fields, functions and the possibility to factorize and reuse. Moreover, content validation has to be developed separately, which led to the design of complementary schema specification languages like json-schema (**json-schema?**) or XSD (**xsd?**).

These qualities require an evaluated language. In fact, some applications make heavy use of config files written in the native programming language which gives them access to language features and existing analysis tools. Examples include JavaScript frameworks such as webpack (**webpack?**) or Vue (**vue?**) and python package management using `setuptools`(**setuptools?**).

Despite this, not all languages serve as a configuration language, e.g. compiled languages and some domains require language agnostic formats. For particularly complex products, both language independence and advanced features are desirable. Alternatively to generating configurations using high level languages, this demand is addressed by more domain specific languages. Dhall (**dhall?**), Cue (**cue?**) or jsonnet (**jsonnet?**) are such domain specific languages (DSL), that offer varying support for string interpolation, (strict) typing, functions and validation.

[6] some of the named languages may have been designed as a data interchange format which is absolutely compatible with also acting as a configuration language

Infrastructure as Code

A prime example for the application of configuration languages are IaaS[7] products. These solutions arise highly complex solutions with regard to resource provision (computing, storage, load balancing, etc.), network setup and scaling. Although the primary interaction with those systems is imperative, maintaining entire applications' or company's environments manually comes with obvious drawbacks.

Changing and undoing changes to existing networks requires intricate knowledge about its topology which in turn has to be meticulously documented as a significant risk for *config drift*. Beyond that, interacting with a system through its imperative interfaces demands qualified skills of specialized engineers.

The concept of "Infrastructure as Code" (*IaC*) serves the DevOps principle of overcoming the need for dedicated teams for *Dev*elvopent and *Op*erations, by allowing to declaratively specify the dependencies, topology and virtual resources. Today various tools with different scopes make it easy to provision complex networks, in a reproducible way. That is setting up the same environment automatically and independently. Optimally, different environments for testing, staging and production can be derived from a common base and changes to configurations are atomic.

As a notable instance, the Nix(**nix?**) ecosystem even goes as far as enabling declarative system and service configuration using NixOps(**nixops?**).

To get an idea of how this would look like, lst. 0.3 shows the configuration for a deployment of the Git based wiki server Gollum(**gollum?**) behind a nginx reverseproxy on the AWS network. Although targeting AWS, Nix itself is platform-agnostic and NixOps supports different backends through various plugins. Configurations like this are abstractions over many manual steps and the Nix language employed in this example allows for even higher level turing-complete interaction with configurations.

Similarly, tools like Terraform(**terraform?**), or Chef(**chef?**) use their own DSLs and integrate with most major cloud providers. The popularity of these products[8], beyond all, highlights the importance of expressive configuration formats and their industry value.

Finally, descriptive data formats for cloud configurations allow mitigating security risks through static analysis. Yet, as recently as spring 2020 and still more than a year later dossiers of Palo Alto Networks' security department Unit 42 show (**pa2020H1?**) show that a majority of public projects uses insecure configurations. This suggests that techniques(**aws-cloud-formation-security-tests?**) to automatically check templates are not actively employed, and points out the importance of evaluated configuration languages which can implement passive approaches to security analysis.

Nickel

[7] Infrastructure as a Service

[8] https://trends.google.com/trends/explore?date=2012-01-01%202022-01-01&q=%2Fg%2F11g6bg27fp,CloudFormation

Gradual typing

Row types

Contracts

Listing 0.3 Example NixOps deployment to AWS

```
{
  network.description = "Gollum server and reverse proxy";
  defaults =
    { config, pkgs, ... }:
    {
      deployment.targetEnv = "ec2";
      deployment.ec2.accessKeyId = "AKIA...";
      deployment.ec2.keyPair = "...";
      deployment.ec2.privateKey = "...";
      deployment.ec2.securityGroups = pkgs.lib.mkDefault [ "default" ];
      deployment.ec2.region = pkgs.lib.mkDefault "eu-west-1";
      deployment.ec2.instanceType = pkgs.lib.mkDefault "t2.large";
    };

  gollum =
    { config, pkgs, ... }:
    {
      services.gollum = {
        enable = true;
        port = 40273;
      };
      networking.firewall.allowedTCPPorts = [ config.services.gollum.port ];
    };

  reverseproxy =
    { config, pkgs, nodes, ... }:
    let
      gollumPort = nodes.gollum.config.services.gollum.port;
    in
    {

      deployment.ec2.instanceType = "t1.medium";

      services.nginx = {
        enable = true;
        virtualHosts."wiki.example.net".locations."/" = {
          proxyPass = "http://gollum:${toString gollumPort}";
        };
      };
      networking.firewall.allowedTCPPorts = [ 80 ];
    };
}
```

Method

This chapter contains a detailed guide through the various steps and components of the Nickel Language Server (NLS). Being written in the same language (Rust(**rust?**)) as the Nickel interpreter allows NLS to integrate existing components for language analysis. Complementary, NLS is tightly coupled to Nickel's syntax definition. Hence, sec. **??** will first detail parts of the AST that are of particular interest for the LSP and require special handling. Based on that sec. **??** will introduce the main datastructure underlying all higher level LSP interactions and how the AST is transformed into this form. Finally, in sec. **??** the implementation of current LSP features is discussed on the basis of the previously reviewed components.

Nickel AST

Nickel's syntax tree is a single sum type, i.e. an enumeration of node types. Each enumeration variant may refer to child nodes, representing a branch or hold terminal values in which case it is considered a leaf of the tree. Additionally, nodes are parsed and represented, wrapped in another structure that encodes the span of the node and all its potential children.

Basic Elements

The primitive values of the Nickel language are closely related to JSON. On the leaf level, Nickel defines `Boolean`, `Number`, `String` and `Null`. In addition to that the language implements native support for `Enum` values. Each of these are terminal leafs in the syntax tree.

Completing JSON compatibility, `List` and `Record` constructs are present as well. Records on a syntax level are HashMaps, uniquely associating an identifier with a sub-node.

These data types constitute a static subset of Nickel which allows writing JSON compatible expressions as shown in lst. 0.4.

Listing 0.4 Example of a static Nickel expression

```
{
  list = [ 1, "string", null],
  "enum value" = `Value
}
```

Building on that Nickel also supports variables and functions which make up the majority of the AST.

Meta Information

One key feature of Nickel is its gradual typing system [ref again?], which implies that values can be explicitly typed. Complementing type information it is possible to annotate values with contracts and additional meta-data such as documentation, default values and merge priority a special syntax as displayed in lst. 0.5.

Listing 0.5 Example of a static Nickel expression

```
let Contract = {
         foo | Num
             | doc "I am foo",
         hello | Str
               | default = "world"
       }
       | doc "Just an example Contract"
in
let value | #Contract = { foo = 9 }
in value == { foo = 9, hello = "world"}

> true
```

Internally, the addition of annotations wraps the annotated term in a `MetaValue` structure, that is creates an artificial tree node that describes its subtree. Concretely, the expression shown in lst. 0.6 translates to the AST in fig. 1. The green `MetaValue` box is a virtual node generated during parsing and not present in the untyped equivalent.

Listing 0.6 Example of a typed expression

```
let x: Num = 5 in x
```

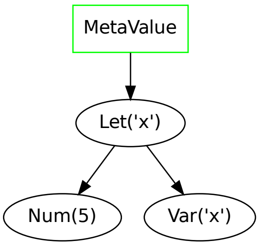

Figure 1: AST of typed expression

Nested Record Access

Nickel supports the referencing of variables which are represented as `Var` nodes that are resolved during runtime. With records bound to a variable, a method to access elements inside that record is required. The access of record members is represented using a special set of AST nodes depending on whether the member name requires an evaluation in which case resolution is deferred to the evaluation pass. While the latter prevents static analysis of any deeper element by the LSP, `StaticAccess` can be used to resolve any intermediate reference.

Notably, Nickel represents static access chains in inverse order as unary operations which in turn puts the terminal `Var` node as a leaf in the tree. Figure 2 shows the representation of the static access perfomed in lst. 0.7 with the rest of the tree omitted.

Listing 0.7 Nickel static access

```
let x = {
  y = {
    z = 1;
  }
} in x.y.z
```

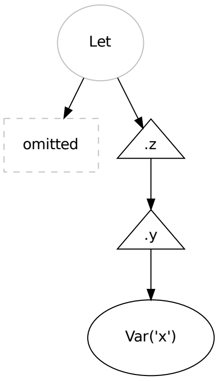

Figure 2: AST of typed expression

Record Shorthand

Nickel supports a shorthand syntax to efficiently define nested records similarly to how nested record fields are accessed. As a comparison the example in lst. 0.8 uses the shorthand syntax which resolves to the semantically equivalent record defined in lst. 0.9

Yet, on a syntax level different Nickel generates a different representation.

Listing 0.8 Nickel record using shorthand

```
{
  deeply.nested.record.field = true;
}
```

Listing 0.9 Nickel record defined explicitly

```
{
  deeply = {
    nested = {
      record = {
        field = true
      }
    }
  }
}
```

Linearization

Being a domain specific language, the scope of analyzed Nickel files is expected to be small compared to other general purpose languages. Hence, NLS takes an eager approach to code analysis, resolving all information at once which is then stored in a linear data structure with efficient access to elements. This data structure is referred to as *linearization*. The term arises from the fact that the linearization is a transformation of the syntax tree into a linear structure which is presented in more detail in sec. **??**. The implementation distinguishes two separate states of the linearization. During its construction, the linearization will be in a *building* state, and is eventually post-processed yielding a *completed* state. The semantics of these states are defined in sec. **??**, while the post-processing is described separately in sec. **??**. Finally, sec. **??** explains how the linearization is accessed.

States

At its core the linearization in either state is represented by an array of `LinearizationItem`s which are derived from AST nodes during the linearization process as well as state dependent auxiliary structures.

Closely related to nodes, `LinearizationItem`s maintain the position of their AST counterpart, as well as its type. Unlike in the AST, *metadata* is directly associated with the element. Further deviating from the AST representation, the *type* of the node and its *kind* are tracked separately. The latter is used to distinguish between declarations of variables, records, record fields and variable usages as well as a wildcard kind for any other kind of structure, such as terminals control flow elements.

The aforementioned separation of linearization states got special attention. As the linearization process is integrated with the libraries underlying the Nickel interpreter, it had to be designed to cause minimal overhead during normal execution. Hence, the concrete implementation employs type-states(**typestate?**) to separate both states on a type level and defines generic interfaces that allow for context dependent implementations.

At its base the `Linearization` type is a transparent smart pointer(**deref-chapter?**; **smart-pointer-chapter?**) to the particular `LinearizationState` which holds state specific data. On top of that NLS defines a `Building` and `Completed` state.

The `Building` state represents an accumulated created incrementally during the linearization process. In particular that is a list of `LinearizationItems` of unresolved type ordered as they appear in a depth-first iteration of the AST. Note that new elements are exclusively appended such that their `id` field during this phase is equal to the elements position at all time. Additionally, the `Building` state maintains the scope structure for every item in a separate mapping.

Once fully built a `Building` instance is post-processed yielding a `Completed` linearization. While being defined similar to its origin, the structure is optimized for positional access, affecting the order of the `LinearizationItems` and requiring an auxiliary mapping for efficient access to items by their `id`. Moreover, types of items in the `Completed` linearization will be resolved.

Type definitions of the `Linearization` as well as its type-states `Building` and `Completed` are listed in lsts. 0.10, 0.11, 0.12. Note that only the former is defined as part of the Nickel libraries, the latter are specific implementations for NLS.

Listing 0.10 Definition of Linearization structure

```rust
pub trait LinearizationState {}

pub struct Linearization<S: LinearizationState> {
    pub state: S,
}
```

Listing 0.11 Type Definition of Building state

```rust
pub struct Building {
    pub linearization: Vec<LinearizationItem<Unresolved>>,
    pub scope: HashMap<Vec<ScopeId>, Vec<ID>>,
}
impl LinearizationState for Building {}
```

Listing 0.12 Type Definition of Completed state

```rust
pub struct Completed {
    pub linearization: Vec<LinearizationItem<Resolved>>,
    scope: HashMap<Vec<ScopeId>, Vec<ID>>,
    id_to_index: HashMap<ID, usize>,
}
impl LinearizationState for Completed {}
```

Transfer from AST

Retyping

Post-Processing

Resolving Elements

Resolving by position

As part of the post-processing step discussed in sec. ??, the `LinearizationItems` in the `Completed` linearization are reorderd by their occurence of the corresponding AST node in the source file. To find items in this list three preconditions have to hold:

1. Each element has a corresponding span in the source
2. Items of different files appear ordered by `FileId`
3. Spans may overlap never intersect.

$$\text{Item}^2_{\text{start}} \geq \text{Item}^1_{\text{start}} \land \text{Item}^2_{\text{end}} \leq \text{Item}^1_{\text{end}}$$

4. Items referring to the spans starting at the same position have to occur in the same order before and after the post-processing. Concretely, this ensures that the tree-induced hierarchy is maintained, more precise elements follow broader ones

This first two properties are an implication of the preceding processes. All elements are derived from AST nodes, which are parsed from files retaining their position. Nodes that are generated by the runtime before being passed to the language server are either ignored or annotated with synthetic positions that are known to be in the bounds of the file and meet the second requirement. For all other nodes the second requirement is automatically fulfilled by the grammar of the Nickel language. The last requirement is achieved by using a stable sort during the post-processing.

The algorithm used is listed in lst. 0.13. Given a concrete position, that is a `FileId` and `ByteIndex` in that file, a binary search is used to find the *last* element that *starts* at the given position. According to the aforementioned preconditions an element found there is equivalent to being the most concrete element starting at this position. In the more frequent case that no element starting at the provided position is found, the search instead yields an index which can be used as a starting point to iterate the linearization *backwards* to find an item with the shortest span containing the queried position. Due to the third requirement, this reverse iteration can be aborted once an item's span ends before the query. If the search has to be aborted, the query does not have a corresponding `LinearizationItem`.

Resolving by ID

During the building process item IDs are equal to their index in the underlying List which allows for efficient access by ID. To allow similarly efficient access to nodes with using IDs a `Completed` linearization maintains a mapping of IDs to their corresponding index in the reordered array. A queried ID is first looked up in this mapping which yields an index from which the actual item is read.

Listing 0.13 Resolution of item at given position

```
impl Completed {
  pub fn item_at(
    &self,
    locator: &(FileId, ByteIndex),
  ) -> Option<&LinearizationItem<Resolved>> {
    let (file_id, start) = locator;
    let linearization = &self.linearization;
    let item = match linearization
      .binary_search_by_key(
        locator,
        |item| (item.pos.src_id, item.pos.start))
      {
        // Found item(s) starting at `locator`
        // search for most precise element
        Ok(index) => linearization[index..]
          .iter()
          .take_while(|item| (item.pos.src_id, item.pos.start) == locator)
          .last(),
        // No perfect match found
        // iterate back finding the first wrapping linearization item
        Err(index) => {
          linearization[..index].iter().rfind(|item| {
            // Return the first (innermost) matching item
            file_id == &item.pos.src_id
            && start > &item.pos.start
            && start < &item.pos.end
          })
        }
    };
    item
  }
}
```

Resolving by scope

During the construction from the AST, the syntactic scope of each element is eventually known. This allows to map scopes to a list of elements defined in this scope. Definitions from higher scopes are not repeated, instead they are calculated on request. As scopes are lists of scope fragments, for any given scope the set of referable nodes is determined by unifying IDs of all prefixes of the given scope, then resolving the IDs to elements. The Rust implementation is given in lst. 0.14 below.

LSP Server

Diagnostics and Caching

Listing 0.14 Resolution of all items in scope

```
impl Completed {
  pub fn get_in_scope(
    &self,
    LinearizationItem { scope, .. }: &LinearizationItem<Resolved>,
  ) -> Vec<&LinearizationItem<Resolved>> {
    let EMPTY = Vec::with_capacity(0);
    // all prefix lengths
    (0..scope.len())
      // concatenate all scopes
      .flat_map(|end| self.scope.get(&scope[..=end])
        .unwrap_or(&EMPTY))
      // resolve items
      .map(|id| self.get_item(*id))
      // ignore unresolved items
      .flatten()
      .collect()
  }
}
```

Capabilities

Hover

Completion

Jump to Definition

Show references