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# TYPELOOM: GRADUAL TYPING WITH THE LSP

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A PREPRINT

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## ABSTRACT

This paper introduces TypeLoom, a tool using a novel approach to add gradual, optional typing into a legacy code bases of dynamically typed languages. TypeLoom leverages the Language Server Protocol (LSP) to provide in-editor type information through inlay hints and utilising code actions to take subsequent input. This approach differs from the ones that exist in so far as it requires no syntactical changes to add type hints (like in Python, TypeScript) and it does not require syntactically correct comments to provide type information (like in @ts-docs and Ruby). TypeLoom utilises a graph based data structure to provide type inference and type checking. This graph-based approach is particularly effective for gradual typing as it allows flexible representation of type relationships and dependencies

**Keywords** Pluggable Types · Gradual Types · Optional Types · LSP · Graph

## 1 Introduction

In computer science, a type system serves as a framework designed to attribute a type to various program components, such as variables, expressions, functions, and modules. The primary goal of a type system is to reduce errors in computer programs by ensuring consistent interfaces and verifying their connections. There are two broad categories of type systems: static and dynamic. Static type systems perform type checking at compile time, dynamically typed languages defer this process until runtime. Proponents of static typing argue that the stronger type checking helps in catching a lot of trivial bugs even before the program is executed, while proponents of dynamic typing argue in favour of the flexibility and rapid iteration the system allows for. These two paradigms are not mutually exclusive, and many programming languages incorporate elements of both static and dynamic typing. The dichotomy between static and dynamic typing continues to shape modern programming discourse, offering developers a spectrum of tools to balance safety, performance, and ease of use based on their specific needs.

Around the 1990s, we observe the emergence of dynamic typing. Languages like Lua, Bash, R, Python, JavaScript, PHP, Perl etc. came around. Dynamic typing became synonymous with scripting languages, allowing developers to discard type annotations and focus on writing programs and shipping them instead of worrying about types. As type systems have enhanced and become more powerful, the programming landscape has shifted once again in favour of static typing. Type systems like the Hindley-Milner type systems make it so that type annotations do not always need to be explicitly stated. Linear Types, Generic Associated Types, and Higher Order Types allow such static system to be more flexible and expressive. Another issue that static types have solved is that of scale. Static type information can serve as a form of self-documentation and help increased maintainability and allow developers to refactor with increased confidence. A new hybrid paradigm that aims to combine the best of the both worlds. Gradual typing takes a pragmatic approach to type systems by allowing developers to add type information for certain variables and expressions which is checked at compile time while allowing some parts of the code base to remain un-typed.

## 2 How do we type gradually?

In this section we will briefly explore the different implementations of gradual type systems. This is by no means an exhaustive list but should be enough to provide a basic understanding of the concepts we will build upon.

### 2.1 Transpilers

Transpiler or a source to source compiler simply is a compiler that takes as its input a programming language and outputs or compiles to another programming language. If we have a language that is dynamically typed and does not support types, one approach to adding types would be to create a super set of the language that supports static types, the transpiler then compiles down to a dynamic language while type checking to ensure type errors are not encountered during program execution. This is the approach the Microsoft took when it introduced TypeScript in 2012. This approach is especially beneficial when the language is common is widely used and interoperability is a must.

### 2.2 Optional Syntax

Another popular approach is introducing optional syntax into the language. Python in 2015 introduced type hints which is additional syntax that allows programmers to add type annotations and then leverage external type checking tools like mypy or pyre. The interpreter or the compiler itself does no type checking. It is important to acknowledge that this approach does break backwards compatibility and requires changes to the compiler to support the new syntax but comes with the advantage of not introducing another language into the mix.

### 2.3 Standardised Comments

An approach similar to the optional syntax approach is to introduce type annotation syntax but making use of comments. This immediately has the benefit of making changes to the language's syntax or making changes to the compiler to accommodate the aforementioned syntax changes. The type annotations in comments are similarly consumed by external type checkers. This approach can be seen with @ts-docs and initial foray of types in Ruby. A major drawback of this approach is that developers expect comments to be ignored by the programming language and it may be awkward for a lot of them to see type errors in comments.

### 2.4 So, now what?

Therefore, there is a need for another approach to gradual typing which avoids the following pitfalls that we have seen in the previous approaches.

- Avoid the need for a super set or maintaining a transpiler.
- Avoid the need for new syntax or changes to the existing compiler.
- Avoid making the comments semantic or making them have a definite syntax.

## 3 Exploring a potential solution

I shall be implementing a type system for the Suneido programming language mainly because I have worked with it previously in a professional capacity and have contributed to its open source compiler of which I have a decent understanding.

### 3.1 Gathering Type Information

For a lot of languages even those which are dynamically typed, some amount of information can be easy to extract. For example, in the following line of code. It is quite easy to imagine that the type of `x` must be of type number.

```
x = 123
```

We aren't quite sure if it is a u8, u32, i32, i8 or some other more narrower type. But as it is the case with gradual type systems such narrowing and use of such concrete types is not always possible. Thus, when we are crafting a gradual type system it is important to choose our types carefully. For now let's just consider the type *Number* and we can say that our type system now knows that the variable `x` is of type *Number* and cannot be assigned a value of another type which is not compatible with the the type *Number* in other words, `x` can only be assigned a value which has a sub-type or alias of the type *Number*.

```
x = 123      # Initial type inference
x = -49.690 # this is okay
x = "hello" # this is NOT okay
```

### 3.2 Displaying Type Information

Now with the limited type information we have, we can start displaying it to the user via the Language Server Protocol (LSP). Inlay hints are special markers that appear in the editor, they are typically rendered as virtual text and cannot be edited by the developer. Most modern IDEs like: Neovim, VSCode, and IntelliJ IDEA support Inlay Hints. For our tool the inlay hints look something like the following.

```
File Edit View Search Terminal Help
| basic_inference.su
example = class {
    counter: Number 0;
    GetCount(): Number {
        return this.counter;
    }
    SetCount(c: Number): void {
        this.counter = c;
    }
    New(): Object {
        strig: String = "Hello World!";
        date: Date = Date.Begin();
        obj1: Object<String, String> = Object(key: "value");
        obj2: Object<Number> = #0, 1, 2, 3;
        func: Function<Number> = .SetCount;
        num: Number = 42;
        numb: Number = 3.14;
        bool: Boolean = String("") and Number(-52);
        subn: Number = 99 - 1;
        addn: Number = numb + 14;
    }
}
example();

NORMAL +0 -0 -0  lsp-server/loom/basic_inference.su
welcome Adhyani!
sumeido  utf-8(unix) 38% ln:8/26w:1
```

Figure 1: An example of TypeLoom displaying basic types using Inlay Hints

The types we shall use for our systems resemble the primitive types that Suneido offers mainly:

- Number
- String
- Date
- Objects
- Functions
- Boolean

In my opinion, Objects are the most interesting and powerful types in Suneido. Objects are general purpose containers and can be used as: arrays, lists, records, hashmaps. In fact, Objects are also used to represent instances of classes internally.

### 3.3 Checking Type Information

Implementing a type checker is by no means an easy feat, and as I started to look into type systems the analogy that made the most sense to my head when reading about bi-directional type checking is a graph. A graph where each node represents a variable and is tagged with its type information. An edge between two nodes represent a type constraint in this case a type equality. If two nodes  $x$  and  $y$  are connected, we can be confident that they are equal or at least

compatible in their types. This very simple type checking paradigm also suddenly empower us to do some basic type inference. Say we have two nodes  $x$  and  $y$  which are connected and the type of  $x$  is known to be of type  $Number$  then we can to a degree of confidence say that  $y$  must also have a type that is at the very least compatible with the type  $Number$ . The first step is actually type inference, where the system tries to narrow types if possible, for example, if a node of type  $Unknown$  is connected via an edge to a node that has a more concrete type let's say type  $String$  then we can safely change the type of the  $Unknown$  node to  $String$ . There has already been some research into this field of representing types in a graph. Now we are able to do some simple type checking. Type checking is performed simply by checking if a path exists between two primitive types, if it does a type errors has occurred as a variable cannot have two primitive types at the same time. For example, a variable  $foo$  cannot be  $Number$  and  $String$  at the same time. A variable  $foo$  however, can have the types  $Number$  and  $i32$  at the same time because they are compatible types.

```

File Edit View Search Terminal Help
| [ ] reassign_var.su x |
| example = class():
|   {
|     Reassign()
|     {
|       x: String = "hello"; // << defined here first with type String
|       x = 123; // Reassigned with incompatible type Number
|     }
|   }
|
NORMAL +0 ~0 -0 lsp-server/loom/reassign_var.su
welcome Adhyant!
suneido utf-8(unix) 100% In :9/9a4:1

```

Figure 2: An example of TypeLoom detecting a type error where variable is reassigned

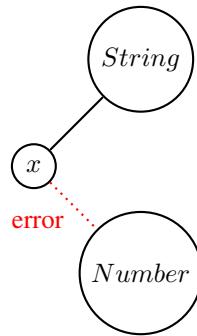


Figure 3: A representation of graph that detects a simple type mismatch

```

File Edit View Search Terminal Help
simple_errors.su
13 example = class{
14     {
15         simpleInferenceErrors(x){
16             {
17                 num: Number = x + 123;
18                 if Number?(x) and x > 100{
19                     {
20                         // CODE;
21                     }
22                 else{
23                     {
24                         num() // ERROR; ■ Mismatched types, type (Number) is not callable
25                     }
26                 }
27             }
28         }
29     }
30 }

```

NORMAL +0 -0 -0 | lsp-server/loom/simple\_errors.su  
welcome Adhyan!

suneido | utf-8[unix] | 75% ln:12/10=4:9 (0:1(L11))

Figure 4: An example of TypeLoom detecting a type error where a type Number is being called as a Function

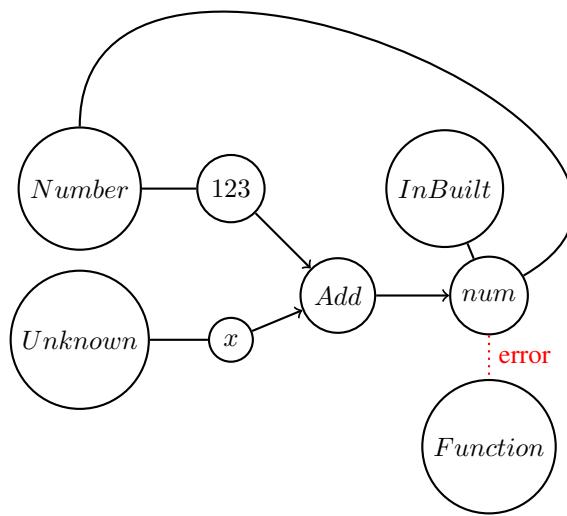


Figure 5: A representation of graph that detects a more complicated type mismatch

In the figure 4 and figure 5 the graph., we can observe a more involved example of catching type errors. This is an excellent example of both inference and checking working. The function *SimpleInferenceErrors* takes an input *x*, we are unaware as to what the type of that argument is so we label it as of type *Unknown* by connecting the node that represents the variable *x* with the node that represents the type *Unknown* itself. On the second line of code we encounter

```
num = x + 123
```

From the above we are able to infer that *x* must be of type *Number*, we know that *123* is of type *Number*. The *+* operator in Suneido only acts on numbers. And we know that the *+* operator returns the type *Number* and so *num* is of type *Number*. As seen in the graph, the nodes are constructed for the aforementioned and connected. Please note that the directional arrows represents input and output of a function, *Add* has two inputs and one output. Later, in the code we see that *num* is being called as a function using the *()* syntax. Our type system connects the node for *num* to the primitive type node for the type *Function*, when we run our type checking algorithm which is a simple depth first search between all the possible primitive types. The type checking algorithm sees that a path between the nodes *Function* and the node *Number* exists, since we know these are incompatible with each other we raise an error.

### 3.4 How do we construct type graphs?

To construct type graph, the TypeLoom system takes in the source code and using the Suneido compiler, compile them down to an s-expression format. After doing so, the loom-compiler generates byte code which when executed produces the graph. Byte-code is used instead of an AST (Abstract Syntax Tree) for the same reason the sqlite engine uses byte code instead of an AST. The byte code that is seen in 6 is simplified, as the actual byte-code output uses UUID (Universally Unique Identifiers) and name mangling as it is possible to have similarly named variables across two methods in a class or in multiple methods across different classes. Suneido has only two scopes: global and local. This also makes the work of the type checker a bit simpler as all variables are within a method are confined to it and braces do not start a new scope.

The figure consists of two side-by-side screenshots of a terminal window. Both screenshots show three colored window control buttons (red, yellow, green) at the top.

**Left Screenshot (Suneido code):**

```
// Suneido code
class
{
    Add(x, y)
    {
        a = x + y
        return a
    }
}

// Corresponding s-expression form
class
{
    Add: Function(x,y
                  Binary(Eq a Nary(Add x y))
                  Return(a))
}
```

**Right Screenshot (Bytecode generated):**

```
// Bytecode generated
CREATE_NODE { x, Type::Unknown }
CREATE_NODE { y, Type::Unknown }

CREATE_NODE { Eq, Type::InBuilt }
CREATE_NODE { a, Type::Unknown }
ADD_ARG { Eq, a }
ADD_ARG { Eq, Add }

CREATE_NODE { Add, Type::InBuilt }
ADD_ARG { Add, x }
ADD_ARG { Add, y }

CREATE_NODE { Return, Type::InBuilt }
ADD_ARG { Return, a }
```

Figure 6: An example of source code, s-expression format, and byte code format

```

File Edit View Search Terminal Help
alias.t.su x
// type Number2 >>= Number
example = class{
    SimplePrimitiveTypeAlias(a: Number2){
        {
            a = 1234 // This is fine because the type Number2
            // is assignable to type Number
            a = "thisShouldNotAssign"; // Mismatched Types: type (String) is not assignable to type (Number2)
        }
    }
}

```

NORMAL +0 ~0 -0 | lsp-server/loom/alias.t.su  
"lsp-server/loom/alias.t.su" 111, 233B written

suneido utf-8(unix) 81% ln:9/11e:9 s [6:3]mix-indent-file E:1(L7)

Figure 7: An example of type aliasing in TypeLoom

## 4 Demonstrations

### 4.1 Type Aliases

A common feature across gradually typed systems is type aliases. Type aliases are the first step toward allowing developers and users to define custom types or even build new types from already existing primitives. For example, a user can define a custom type *Message* which is nothing but the type *String*. In TypeLoom, we use the Haskell monad bind operator to define types.

```
type Message >>= String
```

As demonstrated in 7 the parameter *a* to the method *SimplePrimitiveTypeAlias* is defined to be of the type *Number2*, also indicated by the comment on line 1. It should be noted that the comment only exists to provide context to the demonstration and is not actually used by the TypeLoom system. It is okay to assign the value 1234 to the variable *a*, as 1234 is compatible with the type *Number*, but in the next line when the variable is being assigned a value of the type *String* the system throws a type error.

### 4.2 Union Types

A union type simply put allows a variable to have either of the multiple types defined therein. This type is especially useful for gradual types as it allows the developers to represent certain invalid states. For instance, a union type defined as the following:

```
type ID >>= Date | String
```

The type *ID* here is defined such that it maybe of type *Date* or of type *String* but, not both at the same time. This is particularly useful for nullable types. As demonstrated in 8 the user has defined a custom type *Currency* which has only three valid states, either the string literal "USD" or "CAD" or "GBP". Each of the variables *u*, *nu*, and *ou* are declared to be of type *Currency* and we see subsequent errors shown to the user when the values do not match what is expected of the type.

The screenshot shows the TypeLoom IDE interface. The code editor window has a dark background and displays the following Suneido script:

```

File Edit View Search Terminal Help
union_literals.su x
1 // type Currency >= "USD" | "CAD" | "GBP";
2 example = class(
3   {
4     CurrencyTypeAlias()
5     {
6       u: Currency = "USD";           # Does not match literal of type Currency
7       nu = "usd";                  # Does not match literal of type Currency
8       ou = "other";                # Does not match literal of type Currency
9     }
10 }
11 )

```

The terminal window at the bottom shows the command `lsp-server/loom/union\_literals.su` and the message "welcome Adhyan!".

Figure 8: An example of union types in TypeLoom

### 4.3 Structural Types

Structural types are types whose compatibility or equality is determined by the definition of how the type is constructed. Structural types as the name suggests are useful in defining the type of particular objects like structs. In Suneido, objects are general purpose containers and so structural types are excellent at modelling such behaviour.

In figure 9 we see two types that are of interest to us,

```

type User >>= Object(name: String , age: Number)
type Admin >>= User & Object(role: String)

```

The ampersand sign is used to define intersectional types. Intersectional types define a new type that must have a value that can be assigned both of two other given types. Intersection types are only supported on Objects as of now. In the type definition we can see a new type being defined which is type *User* which has two fields *name* of type *String* and *age* of type *Number*. Another type *Admin* is defined with the same two fields in the type *User* and an additional field *role* which is of type *String*. In the demonstration, two variables *user* and *user2* are inferred to be of type *Admin* and *User* respectively based on what the methods *NewUser()* and *NewUser2()* are annotated to return by the user. When we try to pass the variable *user2* whose type is *User* to a method *GetUserAuth* which expects type *Admin* we get an error as the type *User* cannot be passed in place of the type *Admin*, but it is safe to pass the type *Admin* where a type *User* is expected. It can be said that the type *Admin* is inherited from the type *User* or in more technical terms, *Admin* is subtype of *User*.

```

File Edit View Search Terminal Help
| [structural.t.su] x
1 // type User >= Object(name: String, age: Number)
2 // type Admin >= User & Object(role: String)
3 // type GetUserAuth >= Fn(Admin) -> Bool
4 example = class:
5   {
6     defUserAuth(user: Admin):
7       {
8         return true
9       }
10    NewUser():
11      {
12        return Object(name: "Jane", age: 28, role: "admin")
13      }
14    NewUser2():
15      {
16        return Object(name: "John", age: 28)
17      }
18  }
19
20 eg = example()
21
22 user = eg.NewUser()
23 user2 = eg.NewUser2()
24
25 eg.GetUserAuth(user)
26 eg.GetUserAuth(user2)  ■ Type Mismatch: type Admin is not assignable to type User

```

NORMAL +0 -0 -0 | lsp-server/loom/structural.t.su  
lsp-server/loom/structural.t.su" 26L, 463B Written

Figure 9: An example of structural types in TypeLoom

```

File Edit View Search Terminal Help
| [runtime_guards.su] x
1 // type SimpleRuntimeGuard >= Fn(String) -> Void
2 example = class:
3   {
4     // the parameter x is a String but in the function it is:
5     // okay to treat it as a Number even though the two types:
6     // are incompatible:
7     SimpleRuntimeGuard(x: String):
8       {
9         if Number?(x):
10           {
11             num = x + 123 // This is fine because the type system knows:
12             // that x is a number after the runtime check
13             []
14           }
15         }
16       }

```

NORMAL +0 -0 -0 | lsp-server/loom/runtime\_guards.su  
welcome Adhyani!

Figure 10: An example of type guards based inference and checking in TypeLoom

#### 4.4 Type Guards based inference

Many languages that have dynamic typing, also support some level of type reflection i.e. the ability to examine the type of a variable at runtime. This is useful in asserting a variable is of a certain type. Suneido also supports this, and TypeLoom leverages this feature to gain additional information about what type a variable is. In 10 we see that even though the argument  $x$  is defined to be of type *String*, when it is used in an addition operation, which we have demonstrated before to only work for the *Number* type, our type system throws no such errors. This is because the if statement, checks if  $x$  is of type *Number*, and only proceeds if that is true. The code within the if-statement can be thought of as unreachable code as  $x$  will never be of type *Number* and always be of type *String* if TypeLoom does its job correctly.

### 5 Drawbacks

1. The system of using Code Actions to take in type information wasn't implemented due to time constraints.
2. The parser and lexer and that parse the types and add them to the graph are incomplete so types for the purposes of demonstration were hard coded into their graphical representation.
3. It is unclear if the approach of using a graph would scale on an enormous project.
4. We have not mathematically proved that this type system is correct.
5. I have observed the type system to be undecidable, as for certain combinations of type guards, it is unable to infer and check types.

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