

Gradual Types as Error Suppression

A Constructive View of Type Warnings

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This paper presents the view of gradual typing adopted by the Luau programming language. Prior work on gradual typing has been based on *type compatibility*, that is a relation on types $T \sim U$ given by contextually closing $T \sim \text{any} \sim U$. Type systems based on type compatibility use \sim rather than type equivalence (or a similar presentation for languages with subtyping). We take a different tack, which is to view type warnings *constructively* as a proof object $\text{Warn}(\Gamma \vdash M : T)$ saying that the type derivation $\Gamma \vdash M : T$ should generate a warning. Viewing type warnings constructively allows us to talk about *error suppression*, for example type errors involving the the any type are suppressed, and so this type system is gradual in the sense that developers can explicitly annotate terms with the any type to switch off type warnings. This system has the usual “well-typed programs don’t go wrong” result for program which do not have explicit type annotations with error suppressing types, except this property can now be stated as the presence of $\text{Warn}(\Gamma \vdash M : T)$ rather than the absence of a run-time error. This system has been deployed as part of the Luau programming language, used by millions of users of Roblox Studio.

CCS Concepts: • **Software and its engineering** → **Semantics**.

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1 INTRODUCTION

1.1 Gradual Typing

The aim of *gradual typing* [8, 9] is to allow a code base to migrate from being untyped to being typed. This is achieved by introducing a type *any* (also called ? or *) which is used as the type of a expression which is not subject to type checking. For example, in Luau, a variable can be declared as having type *any*, which is not subject to type checking:

```
local x : any = "hi"
print(math.abs(x))
```

This program generates a run-time error, but because *x* is declared has having type *any*, no type error is generated. Similarly, any expression can be cast to having type *any*, which is not subject to type checking:

```
print(math.abs("hi" :: any))
```

Again, this program generates a run-time error, but because “hi” is cast to having type *any*, no type error is generated.

Prior work on gradual typing has been based on *type compatibility*, that is a relation on types $T \sim U$ given by contextually closing $T \sim \text{any} \sim U$. Type systems based on type compatibility use \sim rather than type equivalence (or a similar presentation for languages with subtyping).

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For example, the type rules for function application in [8] are:

$$\frac{\Gamma \vdash M : \text{any} \quad \Gamma \vdash N : U}{\Gamma \vdash M(N) : \text{any}} (\text{GAPP1}) \quad \frac{\Gamma \vdash M : (S \rightarrow T) \quad \Gamma \vdash N : U \quad S \sim U}{\Gamma \vdash M(N) : T} (\text{GAPP2})$$

which requires that the argument type is *compatible* with (rather than equal to) to the function source type. For example:

$$\frac{\Gamma \vdash \text{math.abs} : (\text{number} \rightarrow \text{number}) \quad \Gamma \vdash x : \text{any} \quad \text{number} \sim \text{any}}{\Gamma \vdash \text{math.abs}(x) : \text{number}}$$

The problem we discovered in implementing gradual typing on top of type compatibility is that it is a source of subtle bugs, because the type system is very sensitive as to when type equality is used rather than type compatibility. For example comparing two type rules:

$$\frac{\Gamma \vdash M : F \quad \Gamma \vdash N : U \quad F = (S \rightarrow T) \quad S \sim U}{\Gamma \vdash M(N) : T} (\text{GAPP2}') \quad \frac{\Gamma \vdash M : F \quad \Gamma \vdash N : U \quad F \sim (S \rightarrow T) \quad S \sim U}{\Gamma \vdash M(N) : T} (\text{GAPP2}'')$$

These rules only differ in whether they use type compatibility rather than equality, but they have very different semantics. Rule GAPP2' is the same as GAPP2' (and so is sound) but using GAPP2'' we can derive:

$$\frac{\Gamma \vdash \text{math.abs} : (\text{number} \rightarrow \text{number}) \quad \Gamma \vdash x : \text{string} \quad (\text{number} \rightarrow \text{number}) \sim (\text{any} \rightarrow \text{number}) \quad \text{any} \sim \text{string}}{\Gamma \vdash \text{math.abs}(x) : \text{number}}$$

which is unsound. Problems like this come down eventually to the fact that \sim is not transitive, and in the presence of other features such as unification and subtyping gave rise to subtle bugs (for example code that assumed that unification solved for type equality rather than compatibility).

1.2 Error Suppressing Types

There has been a long history of improving type errors reported to users, going back to the 1980s [5, 11]. One source of pain in type error reporting is *cascading* type errors, for example:

```
local x = "hi"
local y = math.abs(x)
local z = string.lower(y)
```

In this case `math.abs(x)` should generate a type error, since the type `string` is inferred for `x`, and the type of `math.abs` is `number → number`. It is not obvious whether a type error should be generated for `string.lower(y)`. If the type `number` is inferred for `y`, then an error should be reported, since the type of `string.lower` is `string → string`. But this will not be the best user experience, since this will give a common experience of multiple cascading type errors, of which only the first error is genuine.

One heuristic to eliminate cascading errors is to mark the type of any expression which causes a type error to be emitted as *error suppressing*. Error suppressing types are then used to percolate the information that a type error has already been generated, and so avoid cascading type errors.

For example, in Lua, a type error is introduced, and any type T which is a supertype of error is considered to be error suppressing. For instance, the types inferred for the above program are:

```
local x : string = "hi"
local y : number | error = math.abs(x)
local z : string | error = string.lower(y)
```

Since $\text{number} \mid \text{error}$ is an error suppressing type, $\text{string.lower}(y)$ will not report a type error.

Error suppressing types as a technique for minimizing cascading type errors appears to be folklore, for example it is implemented in Typed Racket [10], but does not appear to have been academically published.

1.3 Gradual Typing via Error Suppressing Types

At this point a reader might guess where this paper is going. Gradual types are well established research area which allows programmers to type expressions with type any to suppress type errors. Error suppressing types are well established folklore which allows type inference to type expressions with error suppressing types to suppress cascading type errors.

The connection between these two areas is pretty obvious, but has not been made before. If any is an error suppressing type, then gradual typing is very similar to error suppression, but does not require the non-transitive type compatibility relation.

In Lua, the use of error suppressing types explains why Lua, in common with TypeScript [7], has both an error suppressing type any and a non-error suppressing type unknown . any is the top type, and unknown is the top non-error-suppressing type. We consider any to be equivalent to $\text{unknown} \mid \text{error}$.

1.4 Constructive Type Errors

Error suppressing types is a folklore implementation technique for suppressing cascading type errors. In this paper we present a formalization as a constructive model of type errors. We do this by separating out type derivations from type errors.

For example, one traditional way to present the type rule for function application is:

$$\frac{\begin{array}{l} \Gamma \vdash M : T \\ \Gamma \vdash N : U \\ U <: \text{src}(T) \end{array}}{\Gamma \vdash M(N) : \text{apply}(T, U)}$$

using functions to calculate the domain of a function $\text{src}(T)$, for example following [6, §5.2]:

$$\text{src}(S \rightarrow T) = S \quad \text{src}(S \cap T) = \text{src}(S) \cup \text{src}(T) \quad \dots$$

and to calculate the result type of applying a function $\text{apply}(T, U)$, for example following [6, §5.3]:

$$\text{apply}(S \rightarrow T, U) = \begin{cases} T & \text{if } U <: T \\ \text{any} & \text{otherwise} \end{cases} \quad \text{apply}(S \cap T, U) = \text{apply}(S, U) \cap \text{apply}(T, U) \quad \dots$$

(The details of this function are spelled out in Section 2.)

This formulation is fine if one is only interested in well typed programs, and in not in the behavior of badly typed programs. For example, the classic “well typed programs don’t go wrong” can be stated as:

$$(M \rightarrow^* M') \rightarrow (\text{RunTimeErr}(M')) \rightarrow \neg(\emptyset \vdash M : T)$$

(for an appropriate definition of $\text{RunTimeErr}(M')$). Now, this does not have a constructive model of type warnings, since we are only considering badly typed programs as ones where $\neg(\emptyset \vdash M : T)$.

In this paper, we separate type derivations from their type errors. This is done by explicitly tracking the derivation tree for typing, for example:

$$\frac{D_1 : (\Gamma \vdash M : T) \quad D_2 : (\Gamma \vdash N : U)}{\text{app}(D_1, D_2) : (\Gamma \vdash M(N) : \text{apply}(T, U))}$$

which allows us to define which type derivations generate warnings, for example there are three ways a warning can be generated from a function application $M(N)$, bubbling up a warning from M or N , or by a failure of subtyping:

$$\frac{\text{Warn}(D_1)}{\text{Warn}(\text{app}(D_1, D_2))} \quad \frac{\text{Warn}(D_2)}{\text{Warn}(\text{app}(D_1, D_2))} \quad \frac{U \not\prec: \text{src}(T)}{\text{Warn}(\text{app}(D_1, D_2))}$$

This is based on a constructive framing of failure of subtyping, fleshed out in Section 2:

$$\frac{v \in \llbracket T \rrbracket \quad v \in \llbracket U \rrbracket^{\mathbb{C}}}{T \not\prec: U}$$

Now, there are two important results about this presentation of constructive type errors. The first is *infallible typing*, that every program can be type checked in every context:

$$\forall \Gamma, M. \exists T. (\Gamma \vdash M : T)$$

(We write $\text{typeof}(\Gamma, M)$ for this derivation tree.) The second is that we can state “well typed programs don’t go wrong” constructively:

$$(M \rightarrow^* M') \rightarrow (\text{RunTimeErr}(M')) \rightarrow \text{Warn}(\text{typeof}(\emptyset, M))$$

Since this is phased constructively, Curry Howard means we can think of this statement in two ways:

- as a proof that “well typed programs don’t go wrong”
- as a time-travel debugger, that for any execution $(M \rightarrow^* M')$ where M' has a run-time error, it can be run back in time to find a root cause type error for M' .

Constructive type errors can be easily adapted to error suppressing types, for example we only report a failure of subtyping when both the type of the function and the type of argument are not error suppressing:

$$\frac{\text{error} \not\prec: T \quad \text{error} \not\prec: U \quad U \not\prec: \text{src}(T)}{\text{Warn}(\text{app}(D_1, D_2))}$$

Now, in general this breaks type soundness, because if every type is any then all type errors are suppressed. But we can show that in the case of a program in which no types are error suppressing, “well typed programs don’t go wrong”.

1.5 Contributions

In summary, this paper combines two well-explored areas:

- gradual types, and
- error suppressing types.

The new contributions of this paper are:

$v ::= \text{error} \mid s \mid (a \mapsto r)$
 $a ::= () \mid (v)$
 $r ::= \text{diverge} \mid \text{check} \mid (v)$

Fig. 1. Semantic values

$\llbracket s \rrbracket = \langle\langle s \rangle\rangle$
 $\llbracket \text{error} \rrbracket = \{\text{error}\}$
 $\llbracket S \rightarrow T \rrbracket = \{a \mapsto (w) \mid w \in \llbracket T \rrbracket\} \cup$
 $\{(v) \mapsto r \mid v \in \llbracket T \rrbracket^C\} \cup$
 $\{a \mapsto \text{diverge}\} \cup$
 $\{() \mapsto \text{check}\}$
 $\llbracket S \cap T \rrbracket = \llbracket S \rrbracket \cap \llbracket T \rrbracket$
 $\llbracket S \cup T \rrbracket = \llbracket S \rrbracket \cup \llbracket T \rrbracket$

Fig. 2. Semantics of types as sets of values

$\llbracket s \rrbracket^C = \langle\langle s \rangle\rangle^C$
 $\llbracket \text{error} \rrbracket^C = \{s\} \cup$
 $\{a \mapsto r\}$
 $\llbracket S \rightarrow T \rrbracket^C = \{s\} \cup$
 $\{() \mapsto (w) \mid w \in \llbracket T \rrbracket^C\} \cup$
 $\{(v) \mapsto (w) \mid v \in \llbracket T \rrbracket \mid w \in \llbracket T \rrbracket^C\} \cup$
 $\{(v) \mapsto \text{check} \mid v \in \llbracket T \rrbracket\}$
 $\llbracket S \cap T \rrbracket^C = \llbracket S \rrbracket^C \cup \llbracket T \rrbracket^C$
 $\llbracket S \cup T \rrbracket^C = \llbracket S \rrbracket^C \cap \llbracket T \rrbracket^C$

Fig. 3. Complemented semantics of types as sets of values

- combining gradual types and error suppressing types,
- formalizing error suppressing types as constructive type errors,
- presenting a new *pragmatic* model of semantic subtyping, and
- showing type soundness for programs which do not contain error suppressing types.

The results are mechanized in Agda [1]. The concepts in this paper are released as part of Roblox Studio, used by millions of creators.

2 PRAGMATIC SEMANTIC SUBTYPING

2.1 What is pragmatic semantic subtyping

In Luau, we use a variant of semantic subtyping [2, 4, 6]. The important properties of semantic subtyping are:

- there is a set \mathcal{D} of semantic values,
- each type T has a semantics $\llbracket T \rrbracket \subseteq \mathcal{D}$,
- any and never types are interpreted as \mathcal{D} and \emptyset ,

- union and intersection types are interpreted as set union and intersection, and
- subtyping $T <: U$ is interpreted as $\llbracket T \rrbracket \subseteq \llbracket U \rrbracket$.

In addition, the off-the-shelf presentation of semantic subtyping is *set theoretic* [2, §2.5]:

$$\llbracket T_1 \rrbracket \subseteq \llbracket T_2 \rrbracket \text{ if and only if } \mathcal{E}[\llbracket T_1 \rrbracket] \subseteq \mathcal{E}[\llbracket T_2 \rrbracket]$$

where the most important case for $\mathcal{E}[\llbracket T \rrbracket]$ is function types:

$$\mathcal{E}[\llbracket S \rightarrow T \rrbracket] = \mathcal{P}(\mathcal{D}^2 \setminus (\llbracket S \rrbracket \times (\mathcal{D} \setminus \llbracket T \rrbracket)))$$

The set theoretical requirement has some consequences:

- All functions types ($\text{never} \rightarrow T$) are identified, since:

$$\begin{aligned} \mathcal{E}[\llbracket \text{never} \rightarrow T_1 \rrbracket] &= \mathcal{P}(\mathcal{D}^2 \setminus (\llbracket \text{never} \rrbracket \times (\mathcal{D} \setminus \llbracket T_1 \rrbracket))) \\ &= \mathcal{P}(\mathcal{D}^2 \setminus (\emptyset \times (\mathcal{D} \setminus \llbracket T_1 \rrbracket))) \\ &= \mathcal{P}(\mathcal{D}^2) \\ &= \mathcal{P}(\mathcal{D}^2 \setminus (\emptyset \times (\mathcal{D} \setminus \llbracket T_2 \rrbracket))) \\ &= \mathcal{P}(\mathcal{D}^2 \setminus (\llbracket \text{never} \rrbracket \times (\mathcal{D} \setminus \llbracket T_2 \rrbracket))) \\ &= \mathcal{E}[\llbracket \text{never} \rightarrow T_2 \rrbracket] \end{aligned}$$

in particular, this means we cannot define a semantics-preserving function $\text{apply}(T, U)$ such that:

$$\text{apply}(S \rightarrow T, U) = T \text{ when } U <: S$$

because there is a nasty case where S is uninhabited. In this presentation, the apply function used in the rule for function application:

$$\frac{D_1 : (\Gamma \vdash M : T) \quad D_2 : (\Gamma \vdash N : U)}{\text{app}(D_1, D_2) : (\Gamma \vdash M(N) : \text{apply}(T, U))}$$

so we have to accept that in a set-theoretic model, the type rule for function application has corner cases for uninhabited types.

- Union does not distributed through function types. Semantic subtyping gives a natural model of overloaded functions as intersections of arrows, for example the Roblox API for matrices include an overloaded function which supports multiplication of both 1D and 2D matrices:

```
mul : (Matrix1D , Matrix1D) -> Matrix1D
    & (Matrix1D , Matrix2D) -> Matrix1D
    & (Matrix2D , Matrix1D) -> Matrix1D
    & (Matrix2D , Matrix2D) -> Matrix2D
```

Overloaded functions are a key part of the Roblox API, and we might expect that all function types can be presented as overloaded functions. We can do this if we can present unions of overloaded functions as overloaded functions. Now, union distributes through intersection, so all that is required is to distribute union through arrow:

$$\llbracket (S_1 \rightarrow T_1) \cup (S_2 \rightarrow T_2) \rrbracket = \llbracket (S_1 \cap S_2) \rightarrow (T_1 \cup T_2) \rrbracket$$

For example:

$$\llbracket (\text{number?} \rightarrow \text{number}) \cup (\text{string?} \rightarrow \text{string}) \rrbracket = \llbracket \text{nil} \rightarrow (\text{number} \cup \text{string}) \rrbracket$$

Unfortunately, set-theoretic models do not allow union to distributed through intersection, for example:

$$\begin{aligned} \{(1, \text{nil}), ("hi", \text{nil})\} &\in \mathcal{E}[\text{nil} \rightarrow (\text{number} \cup \text{string})] \\ \{(1, \text{nil}), ("hi", \text{nil})\} &\notin \mathcal{E}[\text{number?} \rightarrow \text{number}] \\ \{(1, \text{nil}), ("hi", \text{nil})\} &\notin \mathcal{E}[\text{string?} \rightarrow \text{string}] \end{aligned}$$

This is why type normalization for function types in set-theoretic models uses a conjunctive normal form of unions of intersections of functions e.g. [6, §4.1.2].

In addition, Luau does not support negation of all types, but only negation of *test types* [3], which simplifies the model, by not requiring arbitrary type negation. In particular, since the model does not support negation of function types, the normal form for function types is just overload functions, not combinations of positive and negative function types.

In summary there is a trade-off in semantic subtyping:

- *set-theoretic* models, which are closer to the set-theoretic model of functions, and
- *pragmatic* models, which drop the set-theoretic requirement, and in return a) do not have corner cases on the type of function application when the argument has uninhabited type, and b) have overloaded functions (that is intersections of arrows) as the normal for function types.

Luau chooses to adopt a pragmatic semantic subtyping model.

3 FURTHER WORK

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