Updates

- Feb 29. Added reflexivity for is_subtype. Clarified lca_class and castable behavior when given the same class/type.
- Feb 27. Typo fix (replaced lub with lca).
- Feb 25. Forbid class from being its own ancestor in the inheritance hierarchy.
- Feb 22. Renamed lookup_class to defined_class, and changed functionality to return a boolean.
- Feb 22. Clarified that no class named bot may be defined.
- Feb 16. Fixed main.ml to print yes or no depending on whether typechecking succeeds.

Introduction

In this project, you will add a static type checking system to a language called Rube, which is a simple object-oriented programming language with a syntax similar to Ruby. Depending on the semester in which you took CMSC 330, you may or may not have seen this language before. However, even if you have not seen it, the language will be easy to learn. Also, this is the language that we’ll ultimately build a compiler for, so time spent understanding this language design will pay off later in the course.

Rube Syntax

The formal syntax for Rube programs is shown in Figure 1. Note that this grammar is for a purely dynamically typed variant of Rube; we will extend the grammar in the first part of the project to include static types.

A Rube program $P$ consists of a sequence of class definitions followed by a single expression. To execute a program, we evaluate the expression given the set of class definitions. Every class has some superclass; there is a built-in class Object containing no methods, and the superclass of Object is itself. In Rube, methods are inherited from superclasses and may be overridden; there is no overloading in Rube. In Rube, as in Ruby, everything is an object, including integers $n$, the null value nil, and strings "str". Local variables are identifiers $id$, which are made up of upper and lower case letters or symbols (including +, -, *, /, _, and ?). The special identifier self refers to the current object. An identifier with an @ in front of it refers to a field. Rube also includes the conditional form if, which evaluates to the true branch if the guard evaluates to anything except nil, and the false branch otherwise. Rube includes sequencing of expressions, assignments to local variables and fields, and method invocation with the usual syntax.

Project Structure

The project skeleton code is divided up into the following files:
$P ::= C\ast E \quad \text{Rube program}$

$C ::= \text{class } id < id \begin{array}{c} M \ast \end{array} \text{begin } M \ast \text{end} \quad \text{Class definition}$

$M ::= \text{def } id \begin{array}{c} \ldots, id \end{array} E \ast \text{end} \quad \text{Method definition}$

$E ::= n \quad \text{Integers}$

$\mid \text{nil} \quad \text{Nil}$

$\mid "str" \quad \text{String}$

$\mid \text{self} \quad \text{Self}$

$\mid id \quad \text{Local variable}$

$\mid @id \quad \text{Field}$

$\mid \text{if } E \text{ then } E \text{ else } E \ast \text{end} \quad \text{Conditional}$

$\mid E; E \quad \text{Sequencing}$

$\mid id = E \quad \text{Local variable write}$

$\mid @id = E \quad \text{Field write}$

$\mid \text{new } id \quad \text{Object creation}$

$\mid E.\text{id}(E, \ldots, E) \quad \text{Method invocation}$

Figure 1: Rube syntax (without types)

You will only change rube.ml, lexer.mll, and parser.mly; you should not edit any of the other files. The file main.ml includes code to run the parser and then dispatch to the type checker. Right now, the “type checker” implementation just unparses the input file to standard output, e.g., after running make you can run:

```bash
$ ./rube r1.ru
"Hello, world!\n".print()
yes
```

to parse r1.ru and print the parsed result to standard out. You’ll change this code so that the parsed input is no longer printed to standard output. The yes is extra text printed to show that this program type checks. In fact, the current implementation will also print yes, until you implement your type checker.

### Part 1: Adding Type Annotations to Rube

Next, we are going to add type annotations to Rube. Figure 2 shows the necessary changes to the source language. In the revised language, classes begin with field definitions, which include types, followed by method definitions, which include type annotations on arguments and the method return (this type is to the left of the method name). We also introduce a new expression $(E : T)$ that performs a dynamic type cast to check at run time that $E$ has type $T$.

Types themselves are given by the grammar for $T$, which includes class names as types and the special “smallest” or “bottom” type $\bot$, the type of $\text{nil}$. We need a special type because $\text{nil}$ can masquerade as an instance of any class. (In mathematical notation this last type is written $\bot$, but that’s hard to type on most keyboards.)
Finally, types include method types of the form \((T_1 \times \cdots \times T_n) \rightarrow T\), which is a method such that its \(i\)th argument has type \(T_i\) and that returns type \(T\). Method types are not allowed to appear in the surface syntax, so you don’t need to parse them; however, they are handy to have during type checking.

Abstract syntax trees Figure 3 shows the OCaml abstract syntax tree data types for programs with type annotations. It bears a suspicious similarity to the formal grammar. Important: Don’t modify these constructors or types. Otherwise our grading scripts won’t work.

The first four constructors should be self-explanatory. The expression \(E\text{Local } s\) represents (reading) the local variable \(s\). Notice in our abstract syntax tree, we use strings for the names of local variables. The expression \(E\text{Field } s\) represents reading a field \(s\). Here \(s\) is also a string, but it will happen to be the case that because of the way the parser works, it will always begin with an @.

The expression \(E\text{If}(e_1,e_2,e_3)\) corresponds to \(\text{if } e_1 \text{ then } e_2 \text{ else } e_3 \text{ end}\). The expression \(E\text{Seq}(e_1,e_2)\) corresponds to \(e_1 ; e_2\). The expression \(E\text{Write}(s,e)\) corresponds to \(s = e\), where \(s\) is a local variable, and the expression \(E\text{WriteField}(s,e)\) corresponds to \(s = e\) when \(s\) is a field. \(E\text{Invoke}(e,s,e_l)\) corresponds to calling method \(s\) of object \(e\) with the arguments given in \(e_l\). (The arguments are in the same order in the list as in the program text, and may be empty.) Finally, \(E\text{Cast}(e,t)\) represents a type cast.

A method \(\text{meth}\) is a record containing the method name, return type, arguments (with types), local variable definitions, and method body. A class \(\text{cls}\) is a record containing the class name, superclass, fields,
and methods. Finally, a program prog is a record containing the list of classes and the top-level expression.

**What to Do** For this part of the project, you must extend the Rube lexer and parser to support the grammar extensions just described: fields with types; method type annotations; locals with types; and type casts. As mentioned earlier, your parser should not permit method types (with arrows) to appear in the surface syntax. Right now the parser does produce ASTs of the form just described, but it puts type bot wherever a type is needed, and uses empty lists for the locals and fields.

**Part 2: Typing Utilities**

To implement type checking for Rube with type annotations, we’ll need the following utility functions. You should write these functions in rube.ml. Important: We will test your code by calling these functions directly, so it’s important you put them in the right file.

In the following functions, you should assume the existence of three built-in classes: Object, Integer, and String, where Object is the root of the inheritance hierarchy, and Integer and String extend Object. Figure 4 gives type signatures for built-in methods of these classes; you should assume these built-in methods exist. (Note that there is no class corresponding to bot.)

1. Write a function defined_class p c : prog -> string -> bool that returns true if and only if class c is defined in program p. This function should return true if asked whether Object, Integer, and String are defined.

2. Write a function lca_class p c1 c2 : string -> string -> string that, given classes c1 and c2, returns the lowest common ancestor of classes c1 and c2 in the inheritance hierarchy. For example, lca_class "String" "Integer" would return "Object"; if A is a subclass of B, then lca_class "A" "B" would return "B"; and lca_class "A" "A" would return "A".

3. Write a function castable p t1 t2 : prog -> typ -> typ -> boolean that returns true if and only if a cast from type t1 to type t2 could potentially succeed at runtime, meaning that either t1 is an ancestor of t2 in the inheritance hierarchy (downcast), t2 is an ancestor of t1 (upcast), or t1 = t2. For example, castable p (TClass "Object") (TClass "String") would return true, but castable p (TClass "String") (TClass "Integer") would return false.

4. Write a function no_builtin_redef : prog -> boolean that returns true if the program does not try to define classes Object, String, Integer, or bot.

5. Write a function lookup_meth p c m : prog -> string -> string -> typ that returns the type (a TMeth instance) of method m in class c or, if that method is not defined, it should return the type from c’s superclass (and so on, recursively up the class hierarchy). This function should raise
Part 3: Subtyping

Since our language includes subclassing, we will need to define a subtyping relationship as part of type checking. Figure 5 shows the subtyping rules for this language. In words, the rules are as follows:

- **Bot** states that the bottom type `bot` is a subtype of any other type.
- **Obj** states that any type is a subtype of `Object`.
- **Meth** says that for one method type to be a subtype of another, the arguments and return types must have the correct subtyping relationships. Refer to the class notes for an explanation.
- **Class** says that `id_1` is a subtype of `id_2` if `id_1` is a subclass of `id_2` in the program text.
- **Trans** says that subtyping of classes is transitive, and **Refl** says that subtyping is reflexive.

Write a function `is_subtype p t1 t2 : prog -> typ -> typ -> bool` that returns true if and only if `t1` is a subtype of `t2` according to this definition.

Next, notice that the `is_subtype` function you wrote assumes that subclasses are actually subtypes (rule **Class**); but a programmer could violate this assumption. For example, a programmer could create a class that overrides a method from a parent class and changes the type of that method in an unsafe way:

```
class A < Object begin def int m() 42 end end
class B < A begin def string m() "oops!" end end
```

Thus, the next step is to write a function `check_class p c : prog -> string -> boolean` that checks whether the type annotations in `c` make that class a valid subtype of its superclass, according to the following rules:

- For every method `m` defined in `c`, the type of `m` in `c` must be a subtype of `m` in its superclass. (Use `lookup_meth` to help you here, so that you handle the case that the superclass inherits its type for `m`, and to handle the built-in methods of `Object`, `String`, and `Integer`.)
- For every field `f` defined in `c`, there is no definition of `f` in any superclass (including transitively). In other words, shadowing fields in subclasses is not allowed in this language.
- Except for `Object`, class `c` may not be an ancestor of itself in the inheritance hierarchy.

Put `is_subtype` and `check_class` in `rube.ml`. 
### Part 4: Type Checking

Finally, you must write a function `tc_prog p : prog -> boolean` that returns true if and only if `p` type checks. Put this function in `rube.ml`. Figure 6 gives the static type checking rules that you will translate into OCaml. Here `A` is a *type environment*, which as discussed in class is an associative list mapping local variables to their types. Most of the rules have the form `P; A ⊢ E : T`, meaning that in program `P` with environment `A`, expression `E` has type `T`. We’ll explain the other kinds of rules as we encounter them. We’ve labeled the rules so we can refer to them in the discussion:

- The rules `Int`, `Nil`, and `Str` all say that an integer, nil, or string have the obvious types.
- The *local variables* of a method include the parameters of the current method, locals defined at the top of the method, and `self`, which refers to the object whose method is being invoked. The rules `SELF` and `ID` say that `self` or the identifier `id` has whatever type is assigned to it in the environment `A`. If `self` or `id` is not bound in the environment, then this rule doesn’t apply—and hence your type checker would signal an error.
- The rule `FIELD-R` says that when a field is accessed, it has whatever type we get by looking it up in the program according to the `lookup_field` function you already wrote, finding the current class by looking up the type of `self`. Notice that unlike in Ruby, it is an error to refer to fields that have not been pre-defined. Also notice that like Ruby, only fields of `self` are accessible, and it is impossible to access a field of another object.

![Type Checking Rules Table](image-url)

Figure 6: Static Type Rules
The rule **If** says that to type a conditional, the three sub-expressions must all be well-typed, and the type of the whole if is the least-common ancestor of the types of the then and else branches.

The rule **SEQ** says that the type of \(E_1; E_2\) is the type of \(E_2\). Notice that this rule requires \(E_1\) to be well typed, but it doesn’t matter what that type is.

The rule **Id-W** says that a write to a local variable is well-typed if the type of the right-hand side of the assignment is a subtype of the variable type. Notice that unlike Ruby, it is an error to write to a variable that hasn’t been defined as either a parameter or local. Notice also that it is an error to write to the local variable self (which is implicitly syntactically distinct from the non-terminal \(id\)), and your implementation should signal an error in this case.

Similarly, the rule **FIELD-W** says that a field write is well-typed if the type of the right-hand side is a subtype of the field type. Again, unlike Ruby, fields must be defined with types prior to writing to them.

The rule **NEW** says that a new expression is well-typed if the class being constructed exists in the program according to the defined_class function you wrote earlier.

The rule **CAST** says that an expression can be type cast if it is well typed and its type is castable to the type of the cast (using the castable function you wrote earlier). The resulting type of the cast is the cast-to type.

The rule **INVoke** says that for a method invocation to be well-typed, the receiver object expression and all arguments must be well-typed. Also, the types of the arguments must be subtypes of the method type we find by looking up id_m in whatever class corresponds to the receiver object, using the lookup_method function you wrote earlier.

Notice that we don’t need to do anything else here, e.g., we don’t need to look inside the method body. That’s because we’ll separately check that the method actually has the type the lookup_method function says it has. Neat!

The rule **METHOD** says that for a method definition to be well-typed inside of class \(id\), it must be that if we typecheck the method body with locals assigned their types as given, parameters assigned their types as given, and self given type \(id\), the body of the method has a type \(T'\) that is a subtype of the declared method return type. Note the order here says that locals may shadow parameters, which may shadow self; however, we will not test whether you implement this shadowing.

The rule **CLASS** says that for a class definition to be well-typed, all its method definitions must be well-typed, and the class’s type annotations must be consistent with its superclasses, according to the check_class function you wrote above. There must also be no definitions of Object, Integer, String, or bot.

Finally, rule **PROGRAM** says that for a program to be well-typed, all of its classes must be well-typed, and its top-level expression must be well-typed under the empty environment. Notice this means the top-level expression cannot even refer to self!

When you’re writing **tc_prog**, you’ll probably want to write several other functions, including

```ml
val tc_expr : prog -> environment -> expr -> typ
```

that type checks an expression. It’s up to you to choose the type for environment, but something simple like \((\text{string} * \text{typ})\) list should work just fine. (Functions like List.assoc will be handy in working with this type.)

Your type checking functions can raise any exception to signal that a program is ill-typed. We’ve supplied the exception **Type_error** as a convenient exception to throw, but you’re not required to use it. In main.ml, there’s code that calls your tc_prog function and either prints yes or no, depending on whether tc_prog type checked the input or found a type error (i.e., raised an exception), respectively.
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