CMSC 330: Organization of Programming Languages

Type Systems
Types: Recall our Intro to OCaml

- Types classify expressions
  - Characterize the set of possible values an expression could evaluate to
  - We use metavariable \( t \) to designate an arbitrary type
    - Examples include `int`, `bool`, `string`, and more.

- Expression \( e \) has type \( t \) if \( e \) will (always) evaluate to a value of type \( t \)
  - \{ ..., −1, 0, 1, ... \} are values of type `int`
  - \( 34+17 \) is an expression of type `int`, since it evaluates to 51, which has type `int`
  - Write \( e : t \) to say \( e \) has type \( t \)
Type Systems

- A type system is a series of rules that ascribe types to expressions
  - The rules prove statements $e : t$

- The process of applying these rules is called type checking
  - Or simply, typing
  - Type checking aka the program’s static semantics

- Different languages have different type systems
OCaml Type System: Conditionals

- **Syntax**
  - if e1 then e2 else e3

- **Type checking**
  - If e1 : bool and e2 : t and e3 : t then
    if e1 then e2 else e3 : t
  - More formally:

\[
\vdash e1 : \text{bool} \quad \vdash e2 : t \quad \vdash e3 : t \\
\vdash \text{if } e1 \text{ then } e2 \text{ else } e3 : t
\]
Type Safety

- **Well-typed**
  - A well-typed program passes the language’s type system

- **Going wrong**
  - The language definition deems the program nonsensical
    - “Colorless green ideas sleep furiously”
    - If the program were to be run, anything could happen
      - char buf[4]; buf[4] = ‘x’; // undefined!

- **Type safe** = “Well-typed programs never go wrong”
  - Robin Milner, 1978
  - In other words: Well-typed $\implies$ well-defined
Type Safe?

- **Java, Haskell, OCaml:** *Yes* (arguably).
  - The languages’ type systems restrict programs to those that are defined
    - Caveats: Foreign function interfaces to type-unsafe C, bugs in the language design, bugs in the implementation, etc.

- **C, C++:** *No.*
  - The languages’ type systems do not prevent undefined behavior
    - Unsafe casts (int to pointer), out-of-bounds array accesses, dangling pointer dereferences, etc.
What’s Bad about Being Undefined?

- Well, undefined behavior is unconstrained
  - Depends on the compiler/interpreter’s treatment
- Undefined behavior in C/C++ is traditionally a source of severe security vulnerabilities
  - These are bugs that have security consequences
- Stack smashing exploits out-of-bounds array accesses to inject code into a running program
  - Write outside the bounds of an array (undefined!)
  - thereby corrupting the return address
  - to point to code the attacker provides
  - to gain control of the attacked machine
Type Safety is Often Conservative

I.e., some well-defined programs are *not* well typed
Well-defined but not Well-typed

- In OCaml, the expression `4+"hi"` is undefined
  - Ocaml’s type system does not typecheck this expression, ensuring it is never executed
    - Good!

- But the following expressions are well-defined, but still rejected
  - `if true then 0 else 4+"hi"`
    - Always evaluates to 0
  - `let f4 x = if x <= abs x then 0 else 4+"hi"`
    - `f4 e` evaluates to 0 for all `(e : int)`
Soundness and Completeness

- Type safety is a *soundness* property
  - That a term type checks implies its execution will be well-defined

- **Static** type systems are rarely *complete*
  - That a term is well-defined *does not* imply that it will type check
    - `if true then 0 else 4+"hi"

- **Dynamic** type systems are often *complete*
  - All expressions are well defined, and all type check
  - `4+"hi"` well-defined: it gives a run-time exception
Static vs. Dynamic Type Systems

- OCaml, Java, Haskell, etc. are statically typed
  - Expressions are given one of various different types at compile time, e.g., `int`, `float`, `bool`, etc.
    - Or else they are rejected

- Ruby, Python, etc. are dynamically typed
  - Can view all expressions as having a single type `Dyn`
    - The language is uni-typed
  - All operations are permitted on values of this type
    - E.g., in Ruby, all objects accept any method call
  - But: Some operations result in a run-time exception
    - Nevertheless, such behavior is well defined
Dynamic Type Checking

- The run-time checks performed by dynamic languages often called dynamic type checking.

- The type of an expression checked when needed:
  - Values keep a tag, set when the value is created, indicating its type (e.g., what class it has).

- Disallowed operations cause run-time exception:
  - Type errors may be latent in code for a long time.
Quiz 1

- When is the type of a variable determined in a dynamically typed language?
  - A. When the program is compiled
  - B. At run-time, when that variable is first assigned to
  - C. At run-time, when the variable is last assigned to
  - D. At run-time, when the variable is used
Quiz 1

When is the type of a variable determined in a dynamically typed language?

- A. When the program is compiled
- B. At run-time, when that variable is first assigned to
- C. At run-time, when the variable is last assigned to
- D. At run-time, when the variable is used
Quiz 2

When is the type of a variable determined in a 
*statically typed* language?

- A. When the program is compiled
- B. At run-time, when that variable is first assigned to
- C. At run-time, when the variable is last assigned to
- D. At run-time, when the variable is used
Quiz 2

- When is the type of a variable determined in a statically typed language?
  
  - A. When the program is compiled
  - B. At run-time, when that variable is first assigned to
  - C. At run-time, when the variable is last assigned to
  - D. At run-time, when the variable is used
Devil’s Bargain?

- Dynamic typing is sound and complete
  - That seems good …
- But it trades compile-time errors for (well-defined) run-time exceptions!
- Can’t we build a better static type system?
  - I.e., that that aims to eliminate all language-level run-time errors and is also complete?
- Yes, we can build more precise static type systems, but never a perfect one
  - To do so would be undecidable!
Fancy Types

- Lots of ideas over the last few decades aimed at improving the precision of type systems
  - So they can rule out more run-time errors
- **Generic** types (**parametric polymorphism**)  
  - for containers and generic operations on them
- **Subtyping**  
  - for interchanging objects with related shapes
- **Dependent types** can include *data in types*  
  - Instead of `int list`, we could have `int n list` for a list of `n` elements. Hence `hd` has type `int n list` where `n>0`. 
Type Systems with Fancy Types

- OCaml’s type system has types for
  - generics (polymorphism), objects, curried functions, …
  - all unsupported by C

- Haskell’s type system has types for
  - Type classes (qualified types), effect-isolating monads, higher-rank polymorphism, …
  - All unsupported by OCaml

- More precision ensures more run-time errors prevented, with less contorted programs: Good!
  - But now the programmer must understand (and sometimes do) more ..
Quiz 3

Which of the following is well-defined in OCaml, but is not well-typed?

- A. let f g = (g 1, g "hello") in f (fun x -> x)
- B. List.map (fun x -> x + x) [1; "hello"]
- C. let x = 0 in 5 / x
- D. let x = Array.make 1 1 in x.(2)
Quiz 3

Which of the following is well-defined in OCaml, but is not well-typed?

- A. let \( f \ g = (g \ 1, \ g \ "hello") \) in \( f \ (\text{fun} \ x -> x) \)
- B. List.map (fun \( x -> x + x \)) [1; “hello”]
- C. let \( x = 0 \) in \( 5 / x \)
- D. let \( x = \text{Array.make} \ 1 \ 1 \) in \( x.(2) \)

Functions as arguments cannot be used polymorphically.

Ill-typed and ill-defined

Well-typed and well-defined
Perfect Type System? Impossible

- No type system can do all of following
  - (1) always terminate, (2) be sound, (3) be complete
  - While trying to eliminate all run-time exceptions, e.g.,
    - Using an int as a function
    - Accessing an array out of bounds
    - Dividing by zero, ...

- Doing so would be undecidable
  - by reduction to the halting problem
  - Eg., `while (...) {...} arr[-1] = 1;` error tantamount to proving that the while loop terminates
Type Checking and Type Inference

- Type inference is a part of (static) type checking
  - Reduces the programmer’s effort
- Static types are explicit (aka manifest) or inferred
  - Manifest – specified in text (at variable declaration)
    - C, C++, Java, C#
  - Inferred – compiler determines type based on usage
    - OCaml, C# and Go (limited)
- Fancier type systems may require explicit types
  - Haskell considers adding a type signature your function to be good style, even when not required
Static vs. Dynamic Type Checking

Having carefully stated facts about static checking, can now consider arguments about which is better:

static checking or dynamic checking
Claim 1: Dynamic is more convenient

- Dynamic typing lets you build a heterogeneous list or return a “number or a string” without workarounds

Ruby: \[a = [1,1.5]\]

OCaml:

```ocaml
type t =  
  Int of int  
| Float of float

let a = [Int 1; Float 1.5];;
```
Claim 1: Static is more convenient

- Can assume data has the expected type without cluttering code with dynamic checks or having errors far from the logical mistake

Ruby:

```ruby
def cube(x)
    if x.is_a?(Numeric)
        x * x * x
    else
        "Bad argument"
    end
end
```

OCaml:

```ocaml
let cube x = x * x * x
(* we know x is int *)
```
Claim 2: Static prevents useful programs

Any sound static type system forbids programs that do nothing wrong

**Ruby:**

```ruby
if e1 then
    "lady"
else
    [7,"hi"]
end
```

**OCaml:**

```ocaml
if e1 then "lady" else (7,"hi")
(* does not type-check *)
```
Claim 2: But always workarounds

- Rather than suffer time, space, and late-errors costs of tagging everything, statically typed languages let programmers “tag as needed” (e.g., with types)

Ruby: Tags everything implicitly (uni-typed)
OCaml: Tag explicitly, as needed (code up unifying type)

type tort = Int of int
        | String of string
        | Cons of tort * tort
        | Fun of (tort -> tort)
        | ...

if e1 then
  String "lady"
else
  Cons (Int 7, String "hi")
Claim 3: Static catches bugs earlier

- Static typing catches many simple bugs as soon as “compiled”.
  - Since such bugs are always caught, no need to test for them.
  - In fact, can code less carefully and “lean on” type-checker

Ruby:

```ruby
def pow (x,y)
  if y == 0 then
    1
  else
    x * pow (y - 1)
  end
end
# can’t detect until run
```

OCaml:

```ocaml
let pow x y =
  if y = 0  then 1
  else x * pow (y-1)

(* does not type-check *)
```
Claim 3: Static catches only easy bugs

- But static often catches only “easy” bugs, so you still have to test your functions, which should find the “easy” bugs too

Ruby:

```ruby
def pow (x,y)
  if y == 0 then
    1
  else
    x + pow (x,(y-1))
  end
end
```

OCaml:

```ocaml
let pow x y =
  if y = 0  then 1
  else x + pow x (y-1)

(* oops *)
```
Claim 4: Static typing is faster

- Language implementation:
  - Does not need to store tags (space, time)
  - Does not need to check tags (time)
  - Can rely on values being a particular type, so it can perform more optimizations

- Your code:
  - Does not need to check arguments and results beyond what is evidently required
Claim 4: Dynamic typing is not too much slower

- Language implementation:
  - Can use remove some unnecessary tags and tests despite the lack of types
    - While difficult (impossible) in general, it is often possible for the performance-critical parts of a program

- Your code:
  - Do not need to “code around” type-system limitations with extra tags, functions etc.
Claim 5: Code reuse easier with dynamic

Without a restrictive type system, more code can just be reused with data of different types

- If you use cons cells for everything, libraries that work on cons cells are useful

- Collections libraries are amazingly useful but often have very complicated static types
  - Polymorphism/generics/etc. are hard to understand, but are aiming to provide what dynamic typing gives naturally

- Etc.
Claim 5: Code reuse easier with static

The type system serves as “checked documentation,” making the “contract” with others’ code easier to understand and use correctly.
Static vs. Dynamic: Age-old Debate

- Static vs. dynamic typing is too coarse a question
  - Better question: *What should we enforce statically?*
    - E.g., OCaml checks array bounds, division-by-zero, at run-time
  - Legitimate trade-offs

- Idea: Flexible languages allowing *best-of-both-worlds?*
  - Use static types in some parts of the program, but dynamic checking in other parts?
    - Called *gradual typing:* an idea still under active research
  - Would programmers use such flexibility well? Who decides?