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
  - Ex: { …, `-1`, `0`, `1`, … } is the set corresponding to `int`
    - `34+17` is an expression of type `int`, since it evaluates to `51`, which has type `int`

- Expression ***e*** has type ***t*** if ***e*** will (always) evaluate to a value of type ***t***
  - Write ***e : t*** as shorthand 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:*

$$\frac{\vdash e1 : \texttt{bool} \qquad \vdash e2 : t \qquad \vdash e3 : t}{\vdash \texttt{if } e1 \texttt{ then } e2 \texttt{ else } e3 : t}$$

Type Safety

- A well-typed program is accepted by the language's type system
- A program going wrong is one that the language's semantics gives no definition (undefined)
  - "Colorless green ideas sleep furiously"
  - If the program were to be run, anything could happen
  - char buf[4]; buf[4] = 'x'; // undefined!
- A type-safe language is one in which for every program, well-typed $\Longrightarrow$ well-defined
  - Or, *Well-typed programs never go wrong*, in the words of Robin Milner in 1978

Not *always* well defined ⟹ Not well typed

- Consider the following OCaml function *f*

```
let f x y =
  let z = if x<0 then "0" else x in
  z/y
```

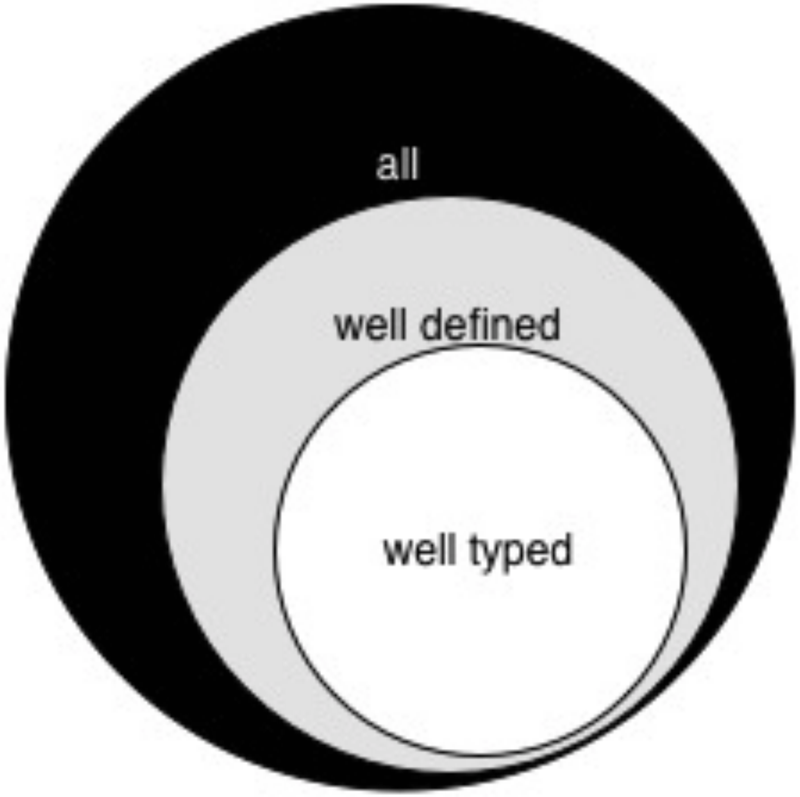
- *f*'s execution is defined in some cases
  - `f 1 1` ⟶ `1`
  - `f 1 0` ⟶ `Division_by_zero` exception
- But not all
  - `f 1 [2]` ↛ since [2] can't be a divisor
  - `f "hi" 0` ↛ since "hi" cannot compare with 0
  - `f -1 2` ↛ since "0" cannot be a dividend
- So: *f* cannot be well typed
  - (type system doesn't prevent all bad arg types)

Possibility: Well-defined, *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`)

Type Safety is Often Conservative



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

Dynamic Type Checking

- The run-time checks performed by dynamic languages often called dynamic type checking
  - These languages may be said to have a dynamic type system
- The “type” of an expression checked as needed
  - Values keep 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

Value, or exception, always

- Reconsider our earlier OCaml function, in Ruby

```
def f(x,y)
  if x<0 then z="0" else z=x end
  z/y
end
```

- Its execution is defined in *all* cases, by throwing an exception
  - `f(1,[2])` ⟶ `TypeError` exception (array not an int)
  - `f("hi",0)` ⟶ `TypeError` exception (can't compare string and int)
  - `f(-1,2)` ⟶ `TypeError` exception (no method '/' for string)
- In OCaml, each of the above executions was undefined

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 the variable is used
- C. At run-time, when that variable is first assigned to
- D. At run-time, when the variable is last assigned to

Quiz 1

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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 the variable is used
- C. At run-time, when that variable is first assigned to
- D. At run-time, when the variable is last assigned to

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 the variable is used
- C. At run-time, when that variable is first assigned to
- D. At run-time, when the variable is last assigned to

Static vs. Dynamic Type Systems

- OCaml, Java, Haskell, etc. are statically typed
- Ruby, Python, etc. are dynamically typed
- But we can *view* dynamically typed languages as statically typed in a particular sense:
  - Can view all expressions as having a static 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
    - Those not supported by the value's dynamic "type" (tag)
    - Nevertheless, such behavior is well defined

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 (statically) type check
  - **`4+"hi"`** well-defined: it gives a run-time exception

Type Safe?

- Java, Haskell, Ocaml, Ruby, Python: **Yes** (arguably).
  - The languages' (static) 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?

- Why is being undefined worse than throwing an exception?
  - Because it's impossible to reason about!
- 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 an attacker provides, to gain control of the program

Devil's Bargain with Dynamic Types?

- OK, dynamically typed languages are type-safe
- … but only by trading compile-time errors for (well-defined) run-time exceptions!
  - I'd prefer to know that no exceptions will be possible
- 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?

Functions as arguments cannot be used polymorphically

- 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)

Ill-typed and ill-defined

well-typed and well-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

Poll: Which Do You Prefer?

- (a) static type systems (e.g., Java, Ocaml)
- (b) dynamic type systems (e.g., Ruby, Python)

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:

```
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:

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

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:

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

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:

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

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:

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

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

Redux: Which Do You Prefer?

- (a) static type systems (e.g., Java, Ocaml)
- (b) dynamic type systems (e.g., Ruby, Python)

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?