CMSC 330: Organization of Programming Languages

Objects and Functional Programming

OOP vs. FP

- Object-oriented programming (OOP)
  - Computation as interactions between objects
  - Objects encapsulate state, which is usually mutable
    - Accessed / modified via object's public methods

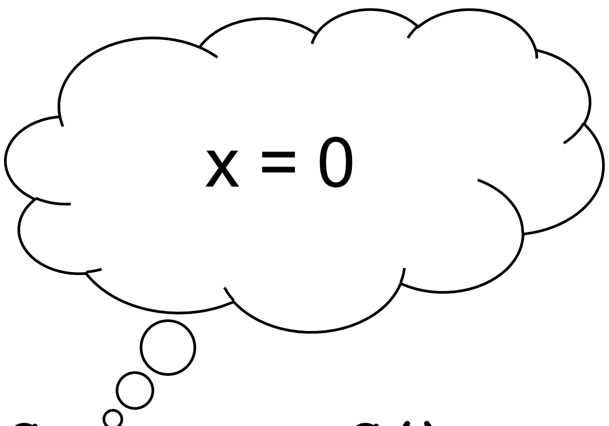
- Functional programming (FP)
  - Computation as evaluation of functions
    - Mutable data used to improve efficiency
  - Higher-order functions implemented as closures
    - Closure = function + environment

Relating Objects to Closures

- An object...
  - Is a collection of fields (data)
  - ...and methods (code)
  - When a method is invoked
    - Method has implicit this parameter that can be used to access fields of object
- A closure...
  - Is a pointer to an environment (data)
  - ...and a function body (code)
  - When a closure is invoked
    - Function has implicit environment that can be used to access variables

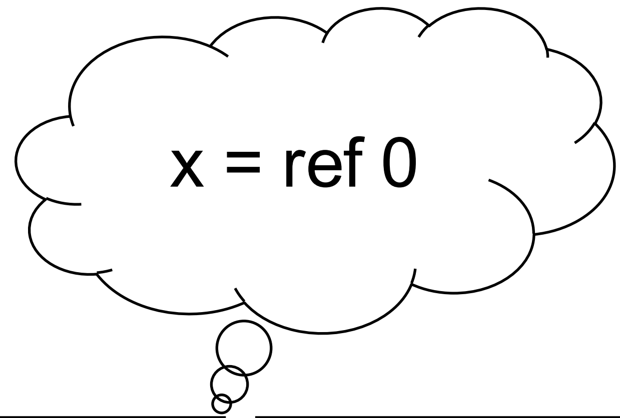
Relating Objects to Closures (cont.)

```
class C {
  int x = 0;
  void set_x(int y) { x = y; }
  int get_x() { return x; }
}
```




```
C c = new C();
c.set_x(3);
int y = c.get_x();
```

```
let make () =
 let x = ref 0 in
   ( (fun y -> x := y),
     (fun () -> !x) )
```




```
fun y -> x := y
```

```
fun () -> !x
```

```
let (set, get) = make ();;
set 3;;
let y = get ();;
```

Encoding Objects with Closures

- We can apply this transformation in general

```
class C { f1 ... fn; m1 ... mn; }
```

  - becomes

```
let make () =
 let f1 = ...
 ...
 and fn = ... in
 ( fun ... , (* body of m1 *)
   ...
   fun ...,   (* body of mn *)
 )
```

Tuple containing closures

  - make ( ) is like the constructor
  - The closure environment contains the fields

Relating Closures to Objects

```
let add1 x = x + 1
```

```
interface IntIntFun {
  Integer eval(Integer x);
}
class Add1 implements IntIntFun {
  Integer eval(Integer x) {
    return x + 1;
  }
}
```

```
add1 2;;
add1 3;;
```

```
new Add1().eval(2);
new Add1().eval(3)
```

Relating Closures to Objects

```
let app_to_1 f = f 1
```

```
interface IntIntFunFun {
  Integer eval(IntIntFun x);
}
class AppToOne
  implements IntIntFunFun {
    Integer eval(IntIntFun f) {
      return f.eval(1);
  }
}
```

```
app_to_1 add1;;
```

```
new AppToOne().eval(new Add1());
```

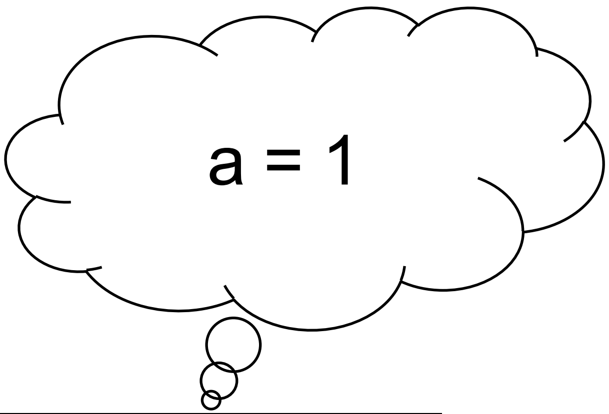
Relating Closures to Objects

```
interface Func<T,U> {
  U eval(T x);
}
class Add1 implements Func<Integer,Integer> {
  public Integer eval(Integer x) {
    return x + 1;
  }
}
class AppToOne
  implements Func<Func<Integer,Integer>,Integer> {
    public Integer eval(Func<Integer,Integer> f) {
      return f.eval(1);
  }
}
```

```
app_to_1 add1;;        new AppToOne().eval(new Add1());
```

Relating Closures to Objects

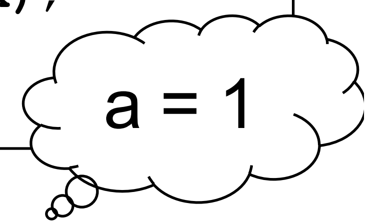
```
let add a b = a + b;;
```




```
fun b -> a + b
```

```
let add1 = add 1;;
add1 4;;
```

```
class Add
  implements Func<Int,Func<Int,Int>> {
    private static class AddClosure
      implements Func<Int,Int> {
        private final Int a;
        AddClosure(Int a) {
          this.a = a;
        }
        Integer eval(Int b) {
          return a + b;
        }
    }
    Func<Int,Int> eval(Int x) {
      return new AddClosure(x);
    }
}
```




```
Func<Int,Int> add1 = new Add().eval(1);
add1.eval(4);
```

Encoding Closures with Objects

- We can apply this transformation in general

```
...(fun x -> (* body of fn *)) ...
let h f ... = ...f y...
```

  - becomes

```
interface F<T,U> { U eval(T x); }
class G implements F<T,U> {
  U eval(T x) { /* body of fn */ }
}
class C {
  Typ1 h(F<Typ2,Typ3> f, ...) {
      ...f.eval(y)...
  }
}
```

  - F is the interface to the callback
  - G represents the particular function

Code as Data

- Closures and objects are related
  - Both of them allow
    - Data to be associated with higher-order code
    - Pass code around the program
- The key insight in all of these examples
  - Treat code as if it were data
    - Allowing code to be passed around the program
    - And invoked where it is needed (as callback)
- Approach depends on programming language
  - Higher-order functions (OCaml, Ruby, Lisp)
  - Function pointers (C, C++)
  - Objects with known methods (Java)

An Integer List Abstraction in Java

```
public class MyList {

  private class ConsNode {
    int head; MyList tail;
    ConsNode (int h, MyList l) { head = h; tail = l; }
  }

  private ConsNode contents;

  public MyList () {
    contents = null;
  }

  public MyList (int h, MyList l) {
    contents = new ConsNode (h, l);
  }

  public MyList cons (int h) {
    return (new MyList (h, this));
  }

  public int hd () {
    return contents.head;
  }

  public MyList tl () {
    return contents.tail;
  }

  public boolean isNull () {
    return (contents == null);
  }

}
```

Recall a Useful Higher-Order Function

```
let rec map f = function
   [] -> []
| (h::t) -> (f h)::(map f t)
```

- Map applies an arbitrary function f
  - To each element of a list
  - And returns the resulting modified list
- Can we encode this in Java?
  - Using object oriented programming

A Map Method for Lists in Java

- Problem – Write a map method in Java
  - Must pass a function into another function
- Solution
  - Can be done using an object with a known method
  - Use interface to specify what method must be present

```
public interface IntFunction {
  int eval(int arg);
}
```

A Map Method for Lists (cont.)

- Examples
  - Two classes which both implement Function interface

```
class AddOne implements IntFunction {
  int eval (int arg) {
    return (arg + 1);
  }
}
```

```
class MultTwo implements IntFunction {
  int eval(int arg) {
    return (arg * 2);
  }
}
```

The New List Class

```
class MyList {
  …
  public MyList map (IntFunction f) {
    if (this.isNull()) return this;
    else return (this.tl()).map(f).cons (f.eval (this.hd()));
  }
}
```

Applying Map To Lists

- Then to apply the function, we just do

```
MyList l = ...;
MyList l1 = l.map(new AddOne());
MyList l2 = l.map(new MultTwo());
```

  - We make a new object
    - That has a method that performs the function we want
  - This is sometimes called a callback
    - Because map "calls back" to the object passed into it
  - But it's really just a higher-order function
    - Written more awkwardly

We Can Do This for Fold Also!

- Recall fold

```
let rec fold f a = function
  [] -> a
| (h::t) -> fold f (f a h) t
```

  - Fold accumulates a value (in a) as it traverses a list
  - f is used to determine how to "fold" the head of a list into a
- This can be done in Java using an approach similar to map!

A Fold Method for Lists in Java

- Problem – Write a fold method in Java
  - Must pass a function into another function
- Solution
  - Can be done using an object with a known method
  - Use interface to specify what method must be present

```
public interface IntBinFunction {
  Integer eval(Integer arg1, Integer arg2);
}
```

A Fold Method for Lists (cont.)

- Examples
  - A classes which implements IntBinFunction interface

```
class Sum implements IntBinFunction {
  Integer eval(Integer arg1, Integer arg2) {
    return new Integer(arg1 + arg2);
  }
}
```

- Note: this is not curried
  - How might you make it so?

The New List Class

```
class MyList {
  …
  public MyList map (IntFunction f) {
    if (this.isNull()) return this;
    else return (this.tl()).map(f).cons (f.eval (this.hd()));
  }

  public int fold (IntBinFunction f, int a) {
    if (this.isNull()) return a;
    else return (this.tl()).fold(f, f.eval(a, this.hd()));
  }
}
```

Applying Fold to Lists

- To apply the fold function, we just do this:

```
MyList l = ...;
int s = l.fold (new Sum(), 0);
```

- The result is that s contains the sum of the elements in l

Java 8 eases the syntax

- Java 8 allows you to make objects that act as functions, more easily
  - Instead of this

```
MyList l = ...;
MyList l1 = l.map(new AddOne());
MyList l2 = l.map(new MultTwo());
```

  - Write this

```
MyList l = ...;
MyList l1 = l.map((x) -> x + 1);
MyList l2 = l.map((y) -> y * 2);
```

Names & Binding,
Type Systems

Language Features Covered Thus Far

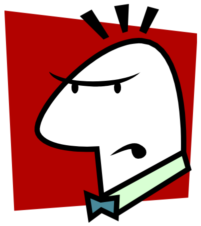
- Ruby
  - Implicit declarations { x = 1 }
  - Dynamic typing { x = 1 ; x = “foo” }
- OCaml
  - Functional programming add 1 (add 2 3)
  - Type inference let x = x+1 (x : int)
  - Higher-order functions let rec x = fun y -> x y
  - Static (lexical) scoping let x = let x = …
  - Parametric polymorphism let x y = y (‘a -> ‘a)
  - Modules module foo struct … end

Programming Languages Revisited

- Characteristics
  - Artificial language for precisely describing algorithms
  - Used to control behavior of machine / computer
  - Defined by its syntax & semantics
- Syntax
  - Combination of meaningful text symbols
    - Examples: if, while, let, =, ==, &&, +
- Semantics
  - Meaning associated with syntactic construct
    - Examples: x = 1 vs. x == 1

Comparing Programming Languages

- Syntax
  - Differences usually superficial
    - C / Java if (x == 1) { … } else { … }
    - Ruby if x == 1 … else … end
    - OCaml if (x = 1) then … else …
  - Can cope with differences easily with experience
    - Though may be annoying initially

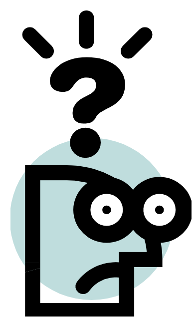


  - You should be able to learn new syntax quickly
    - Just keep language manual / examples handy

Comparing Prog. Languages (cont.)

- Semantics
  - Differences may be major / minor / subtle

	Physical Equality	Structural Equality
Java	a == b	a.equals(b)
C	a == b	*a == *b
Ruby	a.equal?(b)	a == b
OCaml	a == b	a = b



  - Explaining these differences a major goal for 330
  - Will be covering different features in upcoming lectures

Programming Language Features

- Paradigm
  - Imperative
  - Object oriented
  - Functional
  - Logical
- Higher-order functions
  - Closures
- Declarations
  - Explicit
  - Implicit
- Type system
  - Typed vs. untyped
  - Static vs. dynamic
  - Weak vs. strong (type safe)

Programming Language Features (cont.)

- Names & binding
  - Namespaces
  - Static (lexical) scopes
  - Dynamic scopes
- Parameter passing
  - Call by value
  - Call by reference
  - Call by name
    - Eager vs. lazy evaluation
- Polymorphism
  - Ad-hoc
    - Subtype
    - Overloading
  - Parametric
    - Generics
- Parallelism
  - Multithreading
  - Message passing

Names and Binding

- Programs use names to refer to things
  - E.g., in x = x + 1, x refers to a variable

- A binding is an association between a name and what it refers to
  - int x; /* x is bound to a stack location containing an int */
  - int f (int) { ... } /* f is bound to a function */
  - class C { ... } /* C is bound to a class */
  - let x = e1 in e2 (* x is bound to e1 *)

Explicit vs. Implicit Declarations

- Explicit declarations identify allowed names
  - Variables must be declared before used

C, Java, C++, etc.

```
void foo(int y) {
  int x;
  x = y + 1;
  return x + y;
}
```

OCaml

```
let foo y =
  let x = y + 1 in
  x + y;;
```

declaration

use

Explicit vs. Implicit Declarations

- Allowed names also declared implicitly
  - Variables do not need to be declared
    - Implicit declaration when first assigned to

Ruby

```
def foo(y)
  x = y + 1;
  return x + y;
end
```

declared implicitly,
when assigned

Also: Perl, Python

Name Restrictions

- Languages often have various restrictions on names to make scanning and parsing easier
  - Names cannot be the same as keywords in the language
  - OCaml function names must be lowercase
  - OCaml type constructor and module names must be uppercase
  - Names cannot include special characters like ; , : etc
    - Usually names are upper- and lowercase letters, digits, and _ (where the first character can't be a digit)
    - Some languages also allow more symbols like ! or -

Names and Scopes

- Good names are a precious commodity
  - They help document your code
  - They make it easy to remember what names correspond to what entities

- We want to be able to reuse names in different, non-overlapping regions of the code

Names and Scopes (cont.)

- A scope is the region of a program where a binding is active
  - The same name in a different scope can refer to a different binding (refer to a different program object)

- A name is in scope if it's bound to something within the particular scope we’re referring to

Example

```
void w(int i) {
  ...
}

void x(float j) {
  ...
}

void y(float i) {
  ...
}

void z(void) {
   int j;
   char *i;
   ...
}
```

- i is in scope
  - in the body of w, the body of y, and after the declaration of j in z
  - but all those i's are different
- j is in scope
  - in the body of x and z

Ordering of Bindings

- Languages make various choices for when declarations of things are in scope

Order of Bindings – OCaml

- let x = e1 in e2 – x is bound to e1 in scope of e2
- let rec x = e1 in e2 – x is bound in e1 and in e2

```
let x = 3 in
  let y = x + 3 in...    (* x is in scope here *)
```

```
let x = 3 + x in ...     (* error, x not in scope *)
```

```
let rec length = function
    [] -> 0
  | (h::t) -> 1 + (length t)   (* ok, length in scope *)
in ...
```

Order of Bindings – C

- All declarations are in scope from the declaration onward

```
int i;
int j = i;   /* ok, i is in scope */
i = 3;       /* also ok */
```

```
void f(...) { ... }

int i;
int j = j + 3;    /* error */
f(...);           /* ok, f declared */
```

```
void f(...);

void f(...) { .. f(…); . }
```

Order of Bindings – Java

- Declarations are in scope from the declaration onward, except for methods and fields, which are in scope throughout the class
  - Methods are mutually recursive, by default

```
class C {
   void f(){
      ...g()...    // OK
   }

   void g(){
      ...
   }
}
```

Shadowing Names

- Shadowing is rebinding a name in an inner scope to have a different meaning
  - May or may not be allowed by the language

C

```
int i;

void f(float i) {

  {
    char *i = NULL;
    ...
  }

}
```

OCaml

```
let g = 3;;
let g x = x + 3;;
```

Java

```
void h(int i) {
  {
    float i; // not allowed
    ...
  }
}
```

Scoping, Shadowing, and Declarations

- Explicit declarations typically made at the outset of a scope
  - { int x; …. /* x valid here */ … } /* x out of scope */
  - Explicit declaration clarifies shadowing
- Implicit declarations occur within a scope
  - Not always immediately clear which scope you are in
  - May inadvertently use a name in an outer scope
    - No shadowing

Shadowing and Implicit/Explicit Decls

OCaml

```
let x = ref 5;;
let f = fun y -> let x = ref (y + 5) in !x;;
let f' = fun y -> x := y + 5; !x;;
let gs = List.map f [1;2;3];;
!x;; (* returns 5 *)
let gs' = List.map f' [1;2;3];;
!x;; (* returns 8 *)
```

declaration shadows outer x

refers to outer x

Ruby

```
x = 5
arr = [1,2,3]
gs = arr.collect { |y| x = y + 5; x }
x ## returns 8 (surprise!)
```

Namespaces

- Languages have a "top-level" or outermost scope
  - Many things go in this scope; hard to control collisions
- Common solution is to add a hierarchy
  - OCaml: Modules
    - List.hd, String.length, etc.
    - open to add names into current scope
    - Can also nest modules inside of other modules
  - Java: Packages
    - java.lang.String, java.awt.Point, etc.
    - import to add names into current scope
  - C++: Namespaces
    - namespace f { class g { ... } }, f::g b, etc.
    - using namespace to add names to current scope

Static Scoping (revisited)

- In static scoping, a name refers to its closest binding, going from inner to outer scope in the program text
  - Languages like C, C++, Java, Ruby, and OCaml are statically scoped

```
int i;

{
  int j;

  {
    float i;

    j = (int) i;
  }
}
```

Free and Bound Variables

- The bound variables of a scope are those names that are declared in it
- If a variable is not bound in a scope, it is free
  - The bindings of variables which are free in a scope are inherited from declarations of those variables in outer scopes in static scoping

j is bound in scope 1

j is free in scope 2

```
{ /* 1 */
  int j;

  { /* 2 */
    float i;

    j = (int) i;
  }
}
```

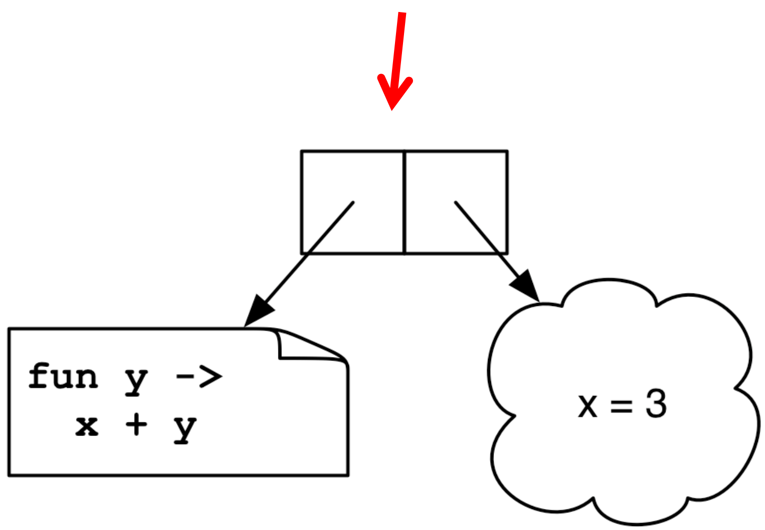
i is bound in scope 2

Static Scoping and Nested Functions

- Closures needed when
  - Nested function declarations
  - Static scoping
  - Returning a function from function call (upwards funargs)

```
let add x = (fun y -> x + y)
```

`(add 3) 4` → `<closure> 4` → `3 + 4` → `7`

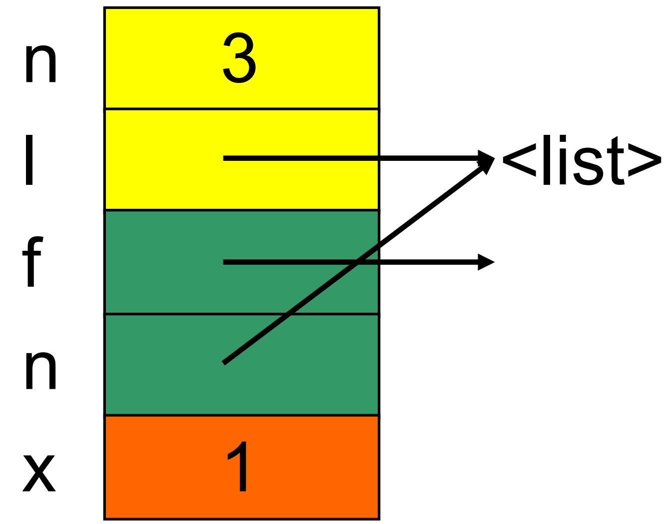


Dynamic Scoping

- In a language with dynamic scoping, a name refers to its closest binding at runtime

```
let map (f, n) = match n with
  [] -> []
| (h::t) -> (f h)::(map (f, t))
let addN (n, l) =
  let add x = n + x in
  map (add, l)

addN (3, [1; 2; 3])
```



- Value of n in add
  - Dynamic scope: reads it off the stack (n = <list>)
  - Static scope: lexical binding (n = param n to addN)

Static vs. Dynamic Scoping

Static scoping

- Local understanding of function behavior
- Know at compile-time what each name refers to
- A little more work to implement (keep a link to the lexical nesting scope in stack frame)

Dynamic scoping

- Can be hard to understand behavior of functions
- Requires finding name bindings at runtime
- Easier to implement (keep a global table of stacks of variable/value bindings)

Types

- Typed vs. untyped languages
- Type safety
- Static vs. dynamic type checking
- Weak vs. strong typing
  - Not great terms; mentioned for historical reasons

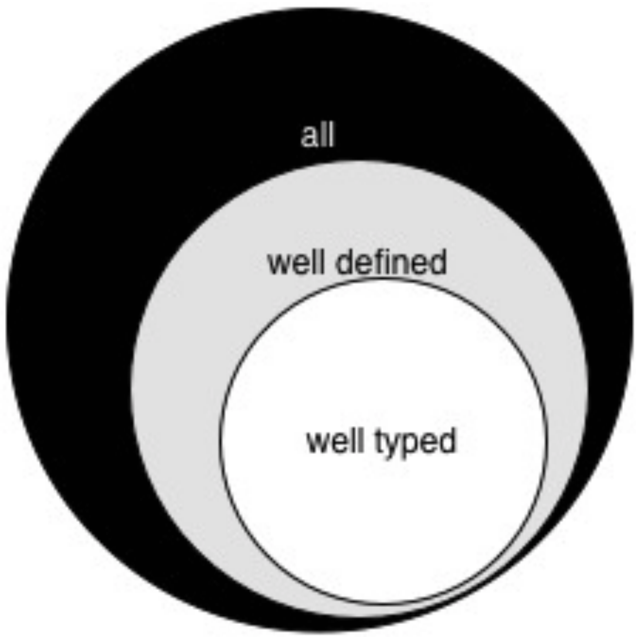
Typed vs. Untyped Languages

- Typed language
  - Operations are only valid for values of specific types
    - 2 * 3 = 6
    - "foo" * "bar" = undefined
- Untyped language
  - All operations are valid for all values
  - Treat all values as sequences of 0's and 1's
  - Very few languages are untyped
    - Assembly languages, FORTH (maybe)

Type Safety

- Well-typed
  - A well-typed program passes the language's type system
    - The "type system" depends on the language
    - Definition is nuanced for dynamically typed languages
- Going wrong
  - The language definition deems the program nonsensical
    - "Colorless green ideals 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

Type Safety is Conservative



http://www.pl-enthusiast.net/2014/08/05/type-safety/

Static Type Checking

- Before program is run
  - Type of all expressions are determined
  - Disallowed operations cause compile-time error
    - Cannot run the program

- 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),

Static Checking, and Type Safe?

- 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.

- Java, C#, OCaml: **Yes** (arguably).
  - The languages' type system aim to 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.

Dynamic Type Checking

- During program execution
  - Type of expression determined when needed
    - Values maintain tag indicating type
  - Disallowed operations cause run-time exception
    - Type errors may be latent in code for a long time

- Dynamic types are not manifest (obviously)
  - Examples
    - Ruby, Python, Javascript, Lisp

Dynamic Checking, and Type Safe?

- Ruby, Python: **Yes** (arguably).
  - All syntactically correct programs are well defined
    - The meaning of a program can be “throws an exception”
      - E.g., when accessing an array out of bounds, or when trying to call a nonexistent method
  - In effect, languages have a null type system
    - All syntactically valid programs are well typed
  - Another POV: these languages are uni-typed
    - All objects have the same type (sometimes called *Dynamic*) and support all operations
      - For some objects, some operations will throw an exception, while for others they will return a result
    - Requires “type tags” to implement

Static vs. Dynamic Type Checking

- Static type checking
  - More work for programmer (at first)
    - Catches more errors at compile time
  - Precludes some correct programs
    - May require a contorted rewrite
  - More efficient code (fewer run-time checks)
- Dynamic type checking
  - Less work for programmer (at first)
    - Delays some errors to run time
  - Allows more programs
    - Including ones that will fail
  - Less efficient code (more run-time checks)

Type Systems are Not The Same

- 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), generalized abstract data types, higher-rank polymorphism, …
  - All unsupported by Ocaml
- Added expessiveness ensures more errors prevented before execution
  - Less contorted programs
  - Easier to reason about program correctness

Weak vs. Strong Typing

- Weak typing
  - Allows one type to be treated as another or provides (many) implicit casts
  - Example (int treated as bool)
    - C

```
int i = 1 ;
if (i)                    // checks for 0
    printf("%d", i);
```

    - Ruby

```
i = 1
if i                      // checks for nil
    puts i
end;
```

  - Example languages
    - C, C++, Ruby, Perl, Javascript

Weak vs. Strong Typing (cont.)

- Strong typing
  - Prevents one type from being treated as another, implicitly
  - Example (int not treated as bool)
    - Java

```
int i = 1 ;
if (i)                    // error, not bool
   System.out.println(i);
```

    - OCaml

```
let i = 1 in
   if i then              // error, not bool
      print_int i
```

  - Example languages
    - Java (rare exceptions), OCaml

Terms: Strong vs. Weak Typing

- These terms are not illuminating, or even agreed upon
  - “strong typing” is often confused with “type safety” or “static typing”
  - Supporting implicit casts, or not, is not particularly interesting as a language feature
    - And is confused with features like subtyping

- Other terms we’ve discussed are more well understood