CMSC 330: Organization of Programming Languages

Type Systems, Parameter Passing

Topics Covered Thus Far

- Programming languages
  - Ruby
  - OCaml
- Syntax specification
  - Regular expressions
  - Context free grammars
- Implementation
  - Finite automata (scanners)
  - Recursive descent parsers

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

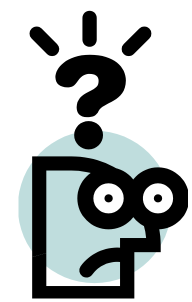
- Syntax
  - Differences usually superficial
    - C / Java if (x == 1) { … } else { … }
    - Ruby if x == 1 … else … end
    - OCaml if (x = 1) then … else …
  - Can cope with differences easily with experience
    - Though may be annoying initially

  - 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
  - Functional
  - Imperative
  - Object oriented
  - Multi-paradigm
- 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

Explicit vs. Implicit Declarations

- Explicit declarations
  - Variables must be declared before used
  - Examples
    - C, C++, Java, OCaml
- Implicit declarations
  - Variables do not need to be declared
  - Examples
    - Ruby

Type System Overview

- Typed vs. untyped
- Static vs. dynamic
- Type safety
  - Weak (not type safe) vs. strong (type safe)

Type vs. Untyped Languages

- Typed language
  - Operations are only valid for specified types
    - 2 * 3 = 6
    - "foo" * "bar" = undefined
  - Helps catch program errors
    - Either at compile or run time
- Untyped language
  - All operations are valid for all values
  - Treat all values as sequences of 0's and 1's
  - Example
    - Assembly languages, FORTH

Static vs. Dynamic Types

- Static types
  - Before program is run
    - Type of all expressions are determined
      - Usually by compiler
    - Disallowed operations cause compile-time error
- Static types may be manifest or inferred
  - Manifest – specified in text (at variable declaration)
    - C, C++, Java, C#
  - Inferred – compiler determines type based on usage
    - ML, OCaml

Static vs. Dynamic Types (cont.)

- Dynamic types
  - While program is running
    - Type of all expressions determined
      - Values maintain tag indicating type
    - Disallowed operations cause run-time exception

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

Type Safety

- Determined by extent programming language allows type errors
- Language should only allow operations on values that are permitted by their type
  - Non-type safe code example
    - printf("%d", 3.12)   // Allows float to be printed as int
- Definitions
  - Type safe language → strong type system
  - Non-type safe language → weak type system

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 (also known as type safe)
  - 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

Weak/Strong vs. Static/Dynamic Types

- How do these properties interact?
  - Weak/strong & static/dynamic are orthogonal
  - Some literature confuse strong & static type
- Strong / static types
  - More work for programmer
  - Catches more errors at compile time
- Weak / dynamic types
  - Less work for programmer
  - More errors occur at run time

Programming Language Features (cont.)

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

Parameter Passing in OCaml

- Quiz: What value is bound to z?

```
let add x y = x + y

let z = add 3 4
```

7

```
let add x y = x + y

let z = add (add 3 1) (add 4 1)
```

9

```
let r = ref 0
let add x y = (!r) + x + y
let set_r () = r := 3; 1

let z = add (set_r ()) 2
```

6

Actuals evaluated before call

Call-by-Value

- In call-by-value (*cbv*), arguments to functions are fully evaluated before the function is invoked
  - Also in OCaml, in let x = e1 in e2, the expression e1 is fully evaluated before e2 is evaluated
- C, C++, and Java also use call-by-value

```
int r = 0;

int add(int x, int y) { return r + x + y; }

int set_r(void) {
  r = 3;
  return 1;
}

add(set_r(), 2);
```

Call-by-Value in Imperative Languages

- In C, C++, and Java, call-by-value has another feature
  - What does this program print? 0

```
void f(int x) {
  x = 3;
}

int main() {
  int x = 0;
  f(x);
  printf("%d\n", x);
}
```

  - Cbv protects function arguments against modifications

Call-by-Value (cont.)

- Actual parameter is copied to stack location of formal parameter

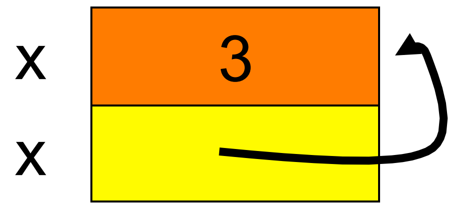
```
void f(int x) {
  x = 3;
}
int main() {
  int x = 0;
  f(x);
  printf("%d\n", x);
}
```

x	0
x	3

Call-by-Reference

- Alternative idea
  - Implicitly pass a pointer or reference to actual parameter
  - If the function writes to it the actual parameter is modified

```
void f(int x) {
  x = 3;
}
int main() {
  int x = 0;
  f(x);
  printf("%d\n", x);
}
```



Call-by-Reference (cont.)

- Advantages
  - Allows multiple return values
  - Avoid copying entire argument to called function
    - More efficient when passing large (multi-word) arguments
    - Can do this without explicit pointer manipulation
- Disadvantages
  - More work to pass non-variable arguments
    - Examples: constant, function result
  - May be hard to tell if function modifies arguments
  - Introduces aliasing

Aliasing

- We say that two names are aliased if they refer to the same object in memory
  - C examples (this is what makes optimizing C hard)

```
int x;
int *p, *q; /*Note that C uses pointers to
               simulate call by reference */
p = &x;  /* *p and x are aliased */
q = p;   /* *q, *p, and x are aliased */
```

```
struct list { int x; struct list *next; }
struct list *p, *q;
...
q = p;   /* *q and *p are aliased */
         /* so are p->x and q->x */
         /* and p->next->x and q->next->x... */
```

Call-by-Reference (cont.)

- Call-by-reference is still around (e.g., C++)

```
int x = 0;                       // C++
void f(int& y) { y = 1; }  // y = reference var
f(x); printf("%d\n", x);   // prints 1
f(2);                            // error
```

- Seems to be less popular in newer languages
  - Older languages still use it
    - Examples: Fortran, Ada, C with pointers
  - Possible efficiency gains not worth the confusion
  - The “hardware” is basically call-by-value
    - Although call by reference is not hard to implement and there may be some support for it

Call-by-Value Discussion

- Cbv is standard for languages with side effects
  - When we have side effects, we need to know the order in which things are evaluated
    - Otherwise programs have unpredictable behavior
  - Call-by-value specifies the order at function calls
  - Call-by-reference can sometimes give different results
- Differences blurred for languages like Java
  - Language is call by value
  - But most parameters are object references anyway
    - Still have aliasing, parameter modifications at object level

Call-by-Name

- Call-by-name (cbn)
  - First described in description of Algol (1960)
  - Generalization of Lambda expressions (to be discussed later)
  - Idea: In a function:

    Let add x y = x+y

    add (a*b) (c*d)

    Example:

    add (a*b) (c*d) =

    (a*b) + (c*d) ← executed function

    Then each use of x and y in the function definition is just a literal substitution of the actual arguments, (a*b) and (c*d), respectively
  - Implementation: Highly complex, inefficient, and provides little improvement over other mechanisms

Call-by-Name (cont.)

- In call-by-name (*cbn*), arguments to functions are evaluated at the last possible moment, just before they're needed

```
let add x y = x + y

let z = add (add 3 1)  (add 4 1)
```

OCaml; cbv; arguments evaluated here

Haskell; cbn; arguments evaluated here

```
add x y = x + y

z = add (add 3 1) (add 4 1)
```

Call-by-Name (cont.)

- What would be an example where this difference matters?

```
let cond p x y = if p then x else y
let rec loop n = loop n
let z = cond true 42 (loop 0)
```

OCaml; cbv; infinite recursion at call

```
cond p x y = if p then x else y
loop n = loop n
z = cond True 42 (loop 0)
```

Haskell; cbn; never evaluated because parameter is never used

Call by Name Examples

- P(x) {x = x + x;}

  What is: Y = 2;
  P(Y); ← becomes Y = Y+Y = 4
  write(Y)

- F(m) {m = m + 1; return m;}

  What is: int A[10];
  m = 1;
  P(A[F(m)])

becomes P(A[F(m)]) → A[F(m)] = A[F(m)]+A[F(m)]
→ A[m++] = A[m++]+A[m++]
→ A[2] = A[3]+A[4]

Call by Name Anomalies

- Write a function to exchange values of X and Y
- Usual way - swap(x,y) { t=x; x=y; y=t; }
  - Cannot do it with call by name!
- Reason
  - Cannot handle both of following
    - swap(A[m], m)
    - swap(m, A[m])
  - One of these must fail
    - swap(A[m], m) → t = A[m] ; A[m] = m; m = t;
    - swap(m, A[m]) → t = m ; m = A[m]; A[m] = t;   // fails!

Two Cool Things to Do with CBN

- CBN is also called lazy evaluation
  - CBV is also known as eager evaluation

- Build control structures with functions

```
let cond p x y = if p then x else y
```

- Build "infinite" data structures

```
integers n = n::(integers (n+1))
take 10 (integers 0)  (* infinite loop in cbv *)
```

Simulating CBN with CBV

- Thunk
  - A function with no arguments
- Algorithm
  1. Replace arguments $a_1 \ldots a_k$ by thunks $t_1 \ldots t_k$
     - When called, t_i evaluates and returns a_i
  2. Within body of the function
     - Replace formal argument with thunk invocations

```
let add1 x = x + 1 in add1 (2+3)
```

↓

```
let add1 x = x() + 1 in add1 (fun () -> (2+3))
```

Simulating CBN with CBV (cont.)

```
let cond p x y = if p then x else y
let rec loop n = loop n
let z = cond true 42 (loop 0)
```

- becomes...

Get 1st arg

Return 2nd arg

Never invoked

```
let cond p x y = if (p ()) then (x ()) else (y ())
let rec loop n = loop n  (* didn't transform... *)
let z = cond (fun () -> true)
             (fun () -> 42)
             (fun () -> loop 0)
```

Parameters are now thunks

Three-Way Comparison

- Consider the following program under the three calling conventions
  - For each, determine i's value and which a[i] (if any) is modified

```
int i = 1;

void p(int f, int g) {
  g++;
  f = 5 * i;
}

int main() {
  int a[] = {0, 1, 2};
  p(a[i], i);
  printf("%d %d %d %d\n",
    i, a[0], a[1], a[2]);
}
```

Example: Call-by-Value

```
int i = 1;

void p(int f, int g) {
  g++;
  f = 5 * i;
}

int main() {
  int a[] = {0, 1, 2};
  p(a[i], i);
  printf("%d %d %d %d\n",
    i, a[0], a[1], a[2]);
}
```

i	a[0]	a[1]	a[2]	f	g
1	0	1	2		
				1	1
				5	2

Example: Call-by-Reference

```
int i = 1;

void p(int f, int g) {
  g++;
  f = 5 * i;
}

int main() {
  int a[] = {0, 1, 2};
  p(a[i], i);
  printf("%d %d %d %d\n",
    i, a[0], a[1], a[2]);
}
```

i/g	a[0]	a[1]/f	a[2]
1	0	1	2
2		10	
2		10	

Example: Call-by-Name

```
int i = 1;

void p(int f, int g) {
  g++;
  f = 5 * i;
}

int main() {
  int a[] = {0, 1, 2};
  p(a[i], i);
  printf("%d %d %d %d\n",
    i, a[0], a[1], a[2]);
}
```

```
i++;
a[i] = 5*i;
```

i	a[0]	a[1]	a[2]
1	0	1	2
2			10
2			10

The expression a[i] isn't evaluated until needed, in this case after i has changed.

Other Calling Mechanisms

- Call-by-result
  - Actual argument passed by reference, but not initialized
  - Written to in function body (and since passed by reference, affects actual argument)
- Call-by-value-result
  - Actual argument copied in on call (like cbv)
  - Mutated within function, but does not affect actual yet
  - At end of function body, copied back out to actual
- These calling mechanisms didn't really catch on
  - They can be confusing in cases
  - Recent languages don’t use them

CBV versus CBN

- CBN is flexible- strictly more programs terminate
  - E.g., where we might have an infinite loop with cbv, we might avoid it with cbn by waiting to evaluate
- Order of evaluation is really hard to see in CBN
  - Call-by-name doesn't mix well with side effects (assignments, print statements, etc.)
- Call-by-name is more expensive since
  - Functions have to be passed around
  - If you use a parameter twice in a function body, its thunk (the unevaluated argument) will be called twice
    - Haskell actually uses *call-by-need* (each formal parameter is evaluated only once, where it's first used in a function)