Programming Paradigms

Control Flow (Part 1)

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Control Flow

Control flow: Ordering of instructions

- Fundamental to most models of computation
- Common language mechanisms
  - Sequencing, selection, iteration, recursion, concurrency, exceptions
- Each PL defines its rules
  - Think in terms of concepts, not specific syntax

Quiz: Argument Evaluation

What does the following Java code print?

```
class WarmUp {
    static void foo(int x, int y) {
        System.out.println(y + ", " + x);
    }

    public static void main(String[] args) {
        int i = 20;
        foo(i++, --i);
    }
}
```

Quiz: Argument Evaluation

What does the following Java code print?

```
class WarmUp {
    static void foo(int x, int y) {
        System.out.println(y + ", " + x);
    }

    public static void main(String[] args) {
        int i = 20;
        foo(i++, --i);
    }
}
```

Result: 20, 20

Quiz: Argument Evaluation

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```
class WarmUp {
    static void foo(int x, int y) {
        System.out.println(y + ", " + x);
    }

    public static void main(String[] args) {
        int i = 20;
        foo(i++, --i);
    }
}
```

Post-increment: Returns `i` and then increments it

Result: 20, 20

Quiz: Argument Evaluation

What does the following Java code print?

```
class WarmUp {
    static void foo(int x, int y) {
        System.out.println(y + ", " + x);
    }

    public static void main(String[] args) {
        int i = 20;
        foo(i++, --i);
    }
}
```

Pre-decrement: Decrements `i` and then returns it

Result: 20, 20

Quiz: Argument Evaluation

What does the following Java code print?

```
class WarmUp {
    static void foo(int x, int y) {
        System.out.println(y + ", " + x);
    }

    public static void main(String[] args) {
        int i = 20;
        foo(i++, --i);
    }
}
```

Evaluation order: Left-to-right

Result: 20, 20

Overview

- Expression Evaluation
- Structured and Unstructured Control Flow
- Selection
- Iteration
- Recursion

Expressions

Operator vs. operand

- Operator: Built-in function with a simple syntax
- Operand: Arguments of operator
- Examples:

```
i++

foo() + 23

(a * b) / c
```

Expressions: Notation

Three popular notations

- Prefix
  - `op a b` or `op(a, b)` or `(op a b)`
- Infix
  - `a op b`
- Postfix
  - `a b op`

Expressions: Notation

Three popular notations

- Prefix
  - `op a b` or `op(a, b)` or `(op a b)`
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Example: Lisp

`(* (+ 1 3) 2)`

Expressions: Notation

Three popular notations

- Prefix
  - `op a b` or `op(a, b)` or `(op a b)`
- Infix
  - `a op b` —— **Example: Java**

    `(1 + 3) * 2`
- Postfix
  - `a b op`

Expressions: Notation

Three popular notations

- Prefix
  - `op a b` or `op(a, b)` or `(op a b)`
- Infix
  - `a op b`
- Postfix —— **Example: C**
  - `a b op`

  `a++`

Multiplicity

Number of arguments expected by an operator

- Unary
  - `a++` or `!cond`
- Binary
  - `a + b` or `x instanceof MyClass`
- Ternary
  - `cond ? a : b`
- (More are possible, but uncommon in practice)

Order of Evaluating Expressions

Given a complex expression, in what order to evaluate it?

Examples:

- Multiple arithmetic operations in Python:

  `2 + 3 * 4`

- Mix of boolean and other expressions in Java:

  `!x && a == false`

- Dereference and increment a pointer in C:

  `*p++`

Precedence and Associativity

Choice among evaluation orders:

Specified by precedence and associativity rules of the PL

- Precedence: Specify which operators group "more tighly" than others
- Associativity: For operators of equal precedence, specify whether to group to the left or right

Precedence Levels in C

<table>
<tr><th>Operator</th><th>Meaning</th></tr>
<tr><td>++, --</td><td>Post-increment, post-decrement</td></tr>
<tr><td>++, --
*</td><td>Pre-increment, pre-decrement
Pointer dereference</td></tr>
<tr><td><, ></td><td>Inequality test</td></tr>
<tr><td>==, !=</td><td>Equality test</td></tr>
<tr><td>&&</td><td>Logical and</td></tr>
<tr><td>||</td><td>Logical or</td></tr>
<tr><td>=, +=</td><td>Assignment</td></tr>
</table>

Higher means higher precedence

This list is incomplete.

Precedence Levels in C

Operator	Meaning
++, --	Post-increment, post-decrement
++, --	Pre-increment, pre-decrement
*	Pointer dereference
<, >	Inequality test
==, !=	Equality test
&&	Logical and
||	Logical or
=, +=	Assignment

Same precedence level

This list is incomplete.

Examples

- **Dereference and increment a pointer:**
  - `*p++`
- **Mix of logical operators:**
  - `a && b || c`
- **Mix of inequality and equality tests:**
  - `x < y == foo`

Examples

- **Dereference and increment a pointer:**
  - `*p++` means `*(p++)`
- **Mix of logical operators:**
  - `a && b || c` means `(a && b) || c`
- **Mix of inequality and equality tests:**
  - `x < y == foo` means `(x < y) == foo`

Examples

- **Dereference and increment a pointer:**
  - `*p++` means `*(p++)`
- **Mix of logical operators:**
  - `a && b || c` means `(a && b) || c`
- **Mix of inequality and equality tests:**
  - `x < y == foo` means `(x < y) == foo`

General rule:

When in doubt, use parentheses

Associativity Rules

- Decide about same-level operators
- Arithmetic operators:

  Mostly left-to-right a.k.a. left-associative

  - `12 - 3 - 2` yields `7` in most languages
  - Exception: Exponentiation is mostly right-associative
    - `2 ** 3 ** 2` yields `512` in most languages
    - But: `2 ^^ 3 ^^ 2` yields `64` in Excel
- Assignments: Mostly right-associative
  - `a = b = a + c` assigns `a + c` into `b` and then `a`

Quiz: Precedence and Associativity

1) What are the values of `foo` and `bar`

(a) when **assignments are left-associative**?

(b) when **assignments are right-associative**?

```
int foo = 5, bar = 2;
foo = bar = foo + bar;
```

2) What is the value of `z`

(a) when `&&` has **higher prededence** than `||`?

(b) when `||` has **higher prededence** than `&&`?

```
bool x = false, y = false, z = true;
bool z = x || y && y || z;
```

Quiz: Precedence and Associativity

1) What are the values of `foo` and `bar`

(a) when **assignments are left-associative**? — foo=2, bar=4

(b) when **assignments are right-associative**? — foo=7, bar=7

```
int foo = 5, bar = 2;
foo = bar = foo + bar;
```

2) What is the value of `z`

(a) when `&&` has **higher prededence** than `||`? — true

(b) when `||` has **higher prededence** than `&&`? — false

```
bool x = false, y = false, z = true;
bool z = x || y && y || z;
```

Ordering within Expressions

- **Discussed so far:**
  Order of performing operations
- **But: In what order are the operands evaluated?**
- **Example:**
  `a - f(b) - c * d`

Ordering within Expressions

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  `a - f(b) - c * d`

  Has precedence over subtraction

Ordering within Expressions

- **Discussed so far:**
  Order of performing operations
- **But: In what order are the operands evaluated?**
- **Example:**

```
a - f(b) - c * d
```

Subtraction is left-associative:
This is computed first

Ordering within Expressions

- **Discussed so far:**
  Order of performing operations
- **But: In what order are the operands evaluated?**
- **Example:**

```
a - f(b) - c * d
```

But: Which of these two operands is evaluated first?

Why Does It Matter?

- **Reason 1: Side effects**
  - Evaluating `f(b)` may modify `c` or `d`
- **Reason 2: Compiler optimizations**
  - Influences register allocation and instruction scheduling

Example:

```
a - f(b) - c * d
```

Ordering: Language-specific

Different PLs: Different ordering within expressions

- Java and C#: Left-to-right
- C and many other languages: Undefined
  - Compiler can choose best order
  - Earlier example again:

```
int i = 20;
foo(i++, --i);
```

Ordering: Language-specific

Different PLs: Different ordering within expressions

- Java and C#: Left-to-right
- C and many other languages: Undefined
  - Compiler can choose best order
  - Earlier example again:

```
int i = 20;
foo(i++, --i);
```

May pass 20, 20 (left-to-right) or 19, 19 (right-to-left) to `foo`

Short-circuit Evaluation

- **Saving time** when evaluating **boolean expressions**
- **Example:**

```
if (very_unlikely && very_expensive())
{
    ...
}
```

Short-circuit Evaluation

- **Saving time** when evaluating **boolean expressions**
- **Example:**

```
if (very_unlikely && very_expensive())
{
    ...
}
```

If first operand is false, no need to evaluate the second

Short-circuit Evaluation

- **Saving time** when evaluating **boolean expressions**
- **Example:**

```
if (very_unlikely && very_expensive())
{
     ...
}
```

But: Side effects of second operand may or may not happen

Short-circuit Evaluation (2)

- **Most PLs implement short-circuit evaluation**
  - Boolean and: Ignore second operand if first is false
  - Boolean or: Ignore second operand if first is true
- **One (relatively) popular exception: Pascal**

Short-circuit Evaluation (3)

- Beware that side effects in some boolean expressions may not happen
- Use it to your advantage:

```
// C code
p = my_list;
while (p && p->key != val) {
    ...
    p = p ->next;
}
```

Overview

- Expression Evaluation
- Structured and Unstructured Control Flow ←
- Selection
- Iteration
- Recursion

Control Flow with `gotos`

- **Most assembly languages: Control flow via conditional and unconditional jumps**
- **Early PLs: `goto` statements**
  - Jump to a statement label
  - Target label can be anywhere in the code

Example

```
// C code
int a = 10;
my_label: do {
    if(a == 12) {
        a = a + 1;
        goto my_label;
    }
    printf("%d\n", a);
    a++;
} while(a < 15);
```

Example

```
// C code
int a = 10;
my_label: do {
    if(a == 12) {
        a = a + 1;
        goto my_label;
    }
    printf("%d\n", a);
    a++;
} while(a < 15);
```

Output:

10

11

13

14

Quiz: Goto Hell

```
// C code
int result = 0;
int bound = 3;
here : for (int i = 0; i < bound; ++i)
{
there:
    result += i;
    goto elsewhere;
}
goto here;
elsewhere : if (result < 2)
{
    goto there;
}
printf("%d\n", result);
```

What does this code print?

Quiz: Goto Hell

```
// C code
int result = 0;
int bound = 3;
here : for (int i = 0; i < bound; ++i)
{
there:
    result += i;
    goto elsewhere;
}
goto here;
elsewhere : if (result < 2)
{
    goto there;
}
printf("%d\n", result);
```

What does this code print?

Nothing! It never terminates.

Beyond `gotos`

- *Go To Statement Considered Harmful* article by Edsger Dijkstra (CACM, 1968)
- Instead: Structured control flow
- Express algorithms with
  - Sequencing
  - Selection
  - Iteration

Avoiding `goto`s

Use case of `goto`	Structured control flow alternative
Jump to end of subroutine	`return` statement
Escape from middle of loop	`break` and `continue` statements
Propagate to surrounding context	Exceptions

Continuations

- **Generalization of `gotos`**
- **Powerful language feature:**
  Allows programmer to define new control flow constructs
  - Exceptions
  - Iterators
  - Coroutines
  - etc.

Continuations

- **Generalization of `gotos`**
- **Powerful language feature:**
  Allows programmer to define new control flow constructs
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  - Iterators
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  - etc.

Note:

- Not recommended for everyday programming
- But useful to think about other control flow constructs

Continuations (2)

- **High-level definition: Context in which to continue execution**
- **Low-level definition: Three parts**
  - Code address (where to continue)
  - Referencing environment (for resolving names)
  - Another continuation (to use when code returns)

Example

```
# Ruby code
def foo(i, c)
    printf("start %d; ", i)
    if i < 3
        foo(i+1, c)
    else c.call(i)
    end
    printf "end %d; ", i
end


v = callcc{ |d| foo(1, d) }
printf "got %d\n", v
```

Example

```
# Ruby code
def foo(i, c)
    printf("start %d; ", i)
    if i < 3
        foo(i+1, c)
    else c.call(i)
    end
    printf "end %d; ", i
end
```

Creates a continuation, i.e., execution will continue here

```
v = callcc{ |d| foo(1, d) }
printf "got %d\n", v
```

Example

```
# Ruby code
def foo(i, c)
    printf("start %d; ", i)
    if i < 3
        foo(i+1, c)
    else c.call(i)
    end
    printf "end %d; ", i
end
```

`d` is a reference to the continuation

```
v = callcc{ |d| foo(1, d) }
printf "got %d\n", v
```

Example

```
# Ruby code
def foo(i, c)
    printf("start %d; ", i)
    if i < 3
        foo(i+1, c)
    else c.call(i)
    end
    printf "end %d; ", i
end


v = callcc{ |d| foo(1, d) }
printf "got %d\n", v
```

`foo` gets called and calls itself two more times

Example

```
# Ruby code
def foo(i, c)
    printf("start %d; ", i)
    if i < 3
        foo(i+1, c)
    else c.call(i)
    end
    printf "end %d; ", i
end

v = callcc{ |d| foo(1, d) }
printf "got %d\n", v
```

Jumps into context captured by `c` and makes `callcc` appear to return `i`

Example

```
# Ruby code
def foo(i, c)
    printf("start %d; ", i)
    if i < 3
        foo(i+1, c)
    else c.call(i)
    end
    printf "end %d; ", i
end
```

Code prints:

start 1; start 2; start 3; got 3

```
v = callcc{ |d| foo(1, d) }
printf "got %d\n", v
```

Another Example

```
def here
    return callcc { |a| return a }
end

def bar(i)
    printf "start %d; ", i
    b = if i < 3 then bar(i+1) else here end
    printf "end %d; ", i
    return b
end

n = 3
c = bar(1)
n = n - 1
puts  # print newline
if n > 0 then c.call(c) end
puts "done"
```

Another Example

```
def here
    return callcc { |a| return a }
end

def bar(i)
    printf "start %d; ", i
    b = if i < 3 then bar(i+1) else here end
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    return b
end

n = 3
c = bar(1)
n = n - 1
puts  # print newline
if n > 0 then c.call(c) end
puts "done"
```

bar gets called and calls itself two more times

Another Example

```
def here
    return callcc { |a| return a }
end

def bar(i)
    printf "start %d; ", i
    b = if i < 3 then bar(i+1) else here end
    printf "end %d; ", i
    return b
end

n = 3
c = bar(1)
n = n - 1
puts  # print newline
if n > 0 then c.call(c) end
puts "done"
```

Creates a continuation, which gets stored in c

Another Example

```
def here
    return callcc { |a| return a }
end

def bar(i)
    printf "start %d; ", i
    b = if i < 3 then bar(i+1) else here end
    printf "end %d; ", i
    return b
end

n = 3
c = bar(1)
n = n - 1
puts  # print newline
if n > 0 then c.call(c) end
puts "done"
```

`n` is 2, therefore execution jumps to the continuation

Another Example

```
def here
    return callcc { |a| return a }
end

def bar(i)
    printf "start %d; ", i
    b = if i < 3 then bar(i+1) else here end
    printf "end %d; ", i
    return b
end

n = 3
c = bar(1)
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puts  # print newline
if n > 0 then c.call(c) end
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```

We are here again!

Another Example

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n = 3
c = bar(1)
n = n - 1
puts  # print newline
if n > 0 then c.call(c) end
puts "done"
```

← **We are here again!**

Another Example

```
def here
    return callcc { |a| return a }
end

def bar(i)
    printf "start %d; ", i
    b = if i < 3 then bar(i+1) else here end
    printf "end %d; ", i
    return b
end

n = 3
c = bar(1)
n = n - 1
puts  # print newline
if n > 0 then c.call(c) end
puts "done"
```

n is 1, therefore execution jumps to the continuation

Another Example

```
def here
    return callcc { |a| return a }
end

def bar(i)
    printf "start %d; ", i
    b = if i < 3 then bar(i+1) else here end
    printf "end %d; ", i
    return b
end

n = 3
c = bar(1)
n = n - 1
puts  # print newline
if n > 0 then c.call(c) end
puts "done"
```

n is 0. We are finally done

Another Example

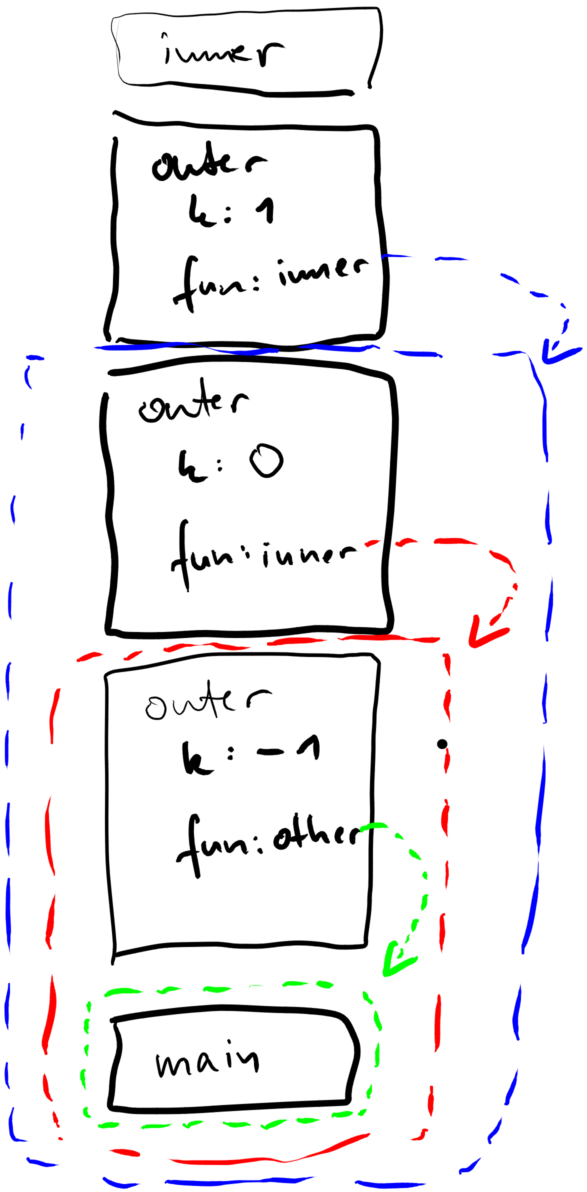
```
def here
    return callcc { |a| return a }
end

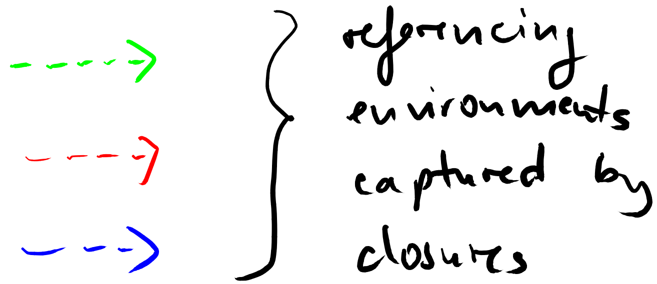
def bar(i)
    printf "start %d; ", i
    b = if i < 3 then bar(i+1) else here end
    printf "end %d; ", i
    return b
end

n = 3
c = bar(1)
n = n - 1
puts  # print newline
if n > 0 then c.call(c) end
puts "done"
```

Code prints:

start 1; start 2; start 3; end 3; end 2; end 1;
end 3; end 2; end 1;
end 3; end 2; end 1;
done


inner
outer
k: 1
fun: inner
outer
k: 0
fun: inner
outer
k: -1
fun: other
main


referencing environments captured by closures

prints 0