Control Flow

COMS W4115

Prof. Stephen A. Edwards
Fall 2003
Columbia University
Department of Computer Science

Control Flow

“Time is Nature’s way of preventing everything from happening at once.”

Scott identifies seven manifestations of this:

1. Sequencing	foo(); bar();
2. Selection	if (a) foo();
3. Iteration	while (i<10) foo(i);
4. Procedures	foo(10,20);
5. Recursion	foo(int i) **{** foo(i-1); **}**
6. Concurrency	foo() || bar()
7. Nondeterminism	do a **->** foo(); [] b **->** bar();

Ordering Within Expressions

What code does a compiler generate for

```
a = b + c + d;
```

Most likely something like

```
tmp = b + c;
a = tmp + d;
```

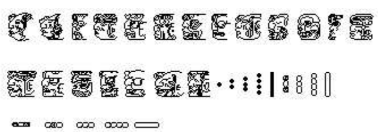
(Assumes left-to-right evaluation of expressions.)

Order of Evaluation

Why would you care?

Expression evaluation can have side-effects.

Floating-point numbers don’t behave like numbers.



Mayan numbers

Side-effects

```
int x = 0;

int foo() { x += 5; return x; }

int a = foo() + x + foo();
```

What’s the final value of a?

Side-effects

```
int x = 0;

int foo() { x += 5; return x; }

int a = foo() + x + foo();
```

GCC sets a=25.

Sun’s C compiler gave a=20.

C says expression evaluation order is implementation-dependent.

Side-effects

Java prescribes left-to-right evaluation.

```
class Foo {
  static int x;
  static int foo() { x += 5; return x; }
  public static void main(String args[]) {
    int a = foo() + x + foo();
    System.out.println(a);
  }
}
```

Always prints 20.

Number Behavior

Basic number axioms:

$a + x$	$=$	a if and only if $x = 0$	Additive identity
$(a + b) + c$	$=$	$a + (b + c)$	Associative
$a(b + c)$	$=$	$ab + ac$	Distributive

Misbehaving Floating-Point Numbers

1e20 + 1e-20 = 1e20

1e-20 $\ll$ 1e20

(1 + 9e-7) + 9e-7 $\neq$ 1 + (9e-7 + 9e-7)

9e-7 $\ll$ 1, so it is discarded, however, 1.8e-6 is large enough

$1.00001(1.000001 - 1) \neq 1.00001 \cdot 1.000001 - 1.00001 \cdot 1$

$1.00001 \cdot 1.000001 = 1.00001100001$ requires too much intermediate precision.

What's Going On?

Floating-point numbers are represented using an exponent/significand format:

$$1\ \underbrace{10000001}_{\text{8-bit exponent}}\ \underbrace{01100000000000000000000}_{\text{23-bit significand}}$$

$$= \quad -1.011_2 \times 2^{129-127} = -1.375 \times 4 = -5.5.$$

What to remember:

$$\underbrace{1363.4568}_{\text{represented}}\underbrace{46353963456293}_{\text{rounded}}$$

What's Going On?

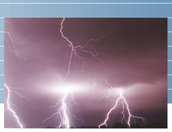
Results are often rounded:

$$\begin{array}{r} 1.00001000000 \\ \times 1.00000100000 \\ \hline 1.000011\ \underbrace{00001}_{\text{rounded}} \end{array}$$

When $b \approx -c$, $b + c$ is small, so $ab + ac \neq a(b + c)$ because precision is lost when ab is calculated.

Moral: Be aware of floating-point number properties when writing complex expressions.

Short-Circuit Evaluation



When you write

```
if (disaster_could_happen)
  avoid_it();
else
  cause_a_disaster();
```

`cause_a_disaster()` is not called when **`disaster_could_happen`** is true.

The *if* statement evaluates its bodies lazily: only when necessary.

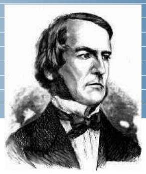
Short-Circuit Evaluation

The section operator **`? :`** does this, too.

```
cost =
 disaster_possible ? avoid_it() : cause_it();
```

`cause_it` is not called if **`disaster_possible`** is true.

Logical Operators



In Java and C, Boolean logical operators "short-circuit" to provide this facility:

```
if (disaster_possible || case_it()) { ... }
```

`cause_it()` only called if **`disaster_possible`** is false.

The **&&** operator does the same thing.

Useful when a later test could cause an error:

```
int a[10];

if (i => 0 && i < 10 && a[i] == 0) { ... }
```

Short-Circuit Operators

Not all languages provide short-circuit operators. Pascal does not.

C and Java have two sets:

Logical operators **`||`** **&&** short-circuit.

Boolean (bitwise) operators **`|`** **&** do not.

Unstructured Control-Flow

Assembly languages usually provide three types of instructions:

Pass control to next instruction:

```
add, sub, mov, cmp
```

Pass control to another instruction:

```
jmp rts
```

Conditionally pass control next or elsewhere:

```
beq bne blt
```

Unstructured Control-Flow

So-called because it's easy to create spaghetti:

```
  beq A
B:
  jmp C
A:
  beq D
C:
  beq B
D:
  bne B
```

Structured Control-Flow

The "object-oriented languages" of the 1960s and 70s.

Structured programming replaces the evil goto with structured (nested) constructs such as

- if-then-else
- for
- while
- do .. while
- break
- continue
- return

Gotos vs. Structured Programming

A typical use of a goto is building a loop. In BASIC:

```
10 print I
20 I = I + 1
30 IF I < 10 GOTO 10
```

A cleaner version in C using structured control flow:

```
do {
  printf("%d\n", i);
  i = i + 1;
} while ( i < 10 )
```

An even better version

```
for (i = 0 ; i < 10 ; i++) printf("%d\n", i);
```

Gotos vs. Structured Programming

Break and continue leave loops prematurely:

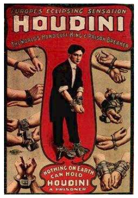
```
for ( i = 0 ; i < 10 ; i++ ) {
  if ( i == 5 ) continue;
  if ( i == 8 ) break;
  printf("%d\n", i);
}

Again: if (!(i < 10)) goto Break;
  if ( i == 5 ) goto Continue;
  if ( i == 8 ) goto Break;
  printf("%d\n", i);
Continue: i++; goto Again;
Break:
```

Escaping from Loops

Java allows you to escape from labeled loops:

```
a: for (int i = 0 ; i < 10 ; i++)
     for ( int j = 0 ; j < 10 ; j++) {
        System.out.println(i + "," + j);
        if (i == 2 && j == 8) continue a;
        if (i == 8 && j == 4) break a;
     }
```



Gotos vs. Structured Programming

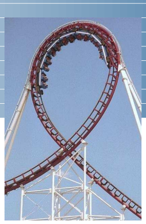
Pascal has no “return” statement for escaping from functions/procedures early, so goto was necessary:

```
procedure consume_line(var line : string);
begin
  if line[i] = '%' then goto 100;
  (* .... *)
100:
end
```

In C and many others, return does this for you:

```
void consume_line(char *line) {
  if (line[0] == '%') return;
}
```

Loops



A modern processor can execute something like 1 billion instructions/second.

How many instructions are there in a typical program? Perhaps a million.

Why do programs take more than 1μs to run, then?

Answer: loops

This insight is critical for optimization: only bother optimizing the loops since everything else is of vanishing importance.

Enumeration-Controlled Loops in FORTRAN

```
      do 10 i = 1, 10, 2
        ...
10:   continue
```

Executes body of the loop with i=1, 3, 5, . . . , 9

Tricky things:

- What happens if the body changes the value of i?
- What happens if gotos jump into or out of the loop?
- What is the value of i upon exit?
- What happens if the upper bound is less than the lower one?

Changing Loop Indices

Most languages prohibit changing the index within a loop.

(Algol 68, Pascal, Ada, FORTRAN 77 and 90, Modula-3)

But C, C++, and Java allow it.

Why would a language bother to restrict this?

Prohibiting Index Modification

Optimizing the behavior of loops is often very worthwhile.

Some processors have explicit looping instructions.

Some compilers transform loop index variables for speed or safety.

Letting the program do whatever it wants usually prevents optimizations.

Empty Bounds

In FORTRAN, the body of this loop is executed once:

```
       do 10 i = 10, 1, 1
         ...
10:    continue
```

“for i = 10 to 1 by 1”

Test is done *after* the body.

Empty Bounds

Modern languages place the test *before* the loop.

Does the right thing when the bounds are empty.

Slightly less efficient (one extra test).

Scope of Loop Index

What happens to the loop index when the loop terminates?

Index is undefined: FORTRAN IV, Pascal.

Index is its last value: FORTRAN 77, Algol 60

Index is just a variable: C, C++, Java

Tricky when iterating over subranges. What's next?

```
var c : 'a'..'z';
for c := 'a' to 'z' do begin
  ...
end;  (* what's c? *)
```

Scope of Loop Index

Originally in C++, a locally-defined index variable's scope extended beyond the loop:

```
for (int i = 0 ; i < 10 ; i++) { ... }
a = a + i;   // Was OK: i = 10 here
```

But this is awkward:

```
for (int i = 0 ; i < 10 ; i++) { ... }
...
for (int i = 0 ; i < 10 ; i++) // Error:
                               // i redeclared
```

Scope of Loop Index

C++ and Java now restrict the scope to the loop body:

```
for (int i = 0 ; i < 10 ; i++ ) {
  int a = i; // OK
}
...
int b = i; // Error: i undefined
...
for (int i = 0 ; i < 10 ; i++ ) { // OK
}
```

Rather annoying: broke many old C++ programs.

Better for new code.

Algol's Combination Loop

for → **for** *id* **:=** *for-list* **do** *stmt*

for-list → *enumerator* (**,** *enumerator*)*

enumerator → *expr*
→ *expr* **step** *expr* **until** *expr*
→ *expr* **while** *condition*

Equivalent:

```
for i := 1, 3, 5, 7, 9 do ...
for i := 1 step 2 until 10 do ...
for i := 1, i+2 while i < 10 do ...
```

Language implicitly steps through enumerators (implicit variable).

Algol's Combination Loop

Needlessly general, it turns out.

C's logically controlled loop retains most of the functionality:

```
for ( i = 1 ; i < 10 ; i += 2 ) { ... }
```

is equivalent to

```
i = 1;
while (i < 10) {
  ...
  i += 2;
}
```

Pre- and Post-test Loops

Most loops want their tests first to allow the possibility of zero iterations.

```
struct foo *p = head;  // Sum a linked list
while (p != 0) {
  total += p->value;
  p = p->next;
}
```

But it's sometimes useful to place the test at the end:

```
char line[80];
do {
  scanf("%s", line);
} while (line[0] == '#'); /* skip comments */
```

Mid-test Loops

```
while true do begin
  readln(line);
  if all_blanks(line) then goto 100;
  consume_line(line);
end;
100:
```

```
LOOP
  line := ReadLine;
WHEN AllBlanks(line) EXIT;
  ConsumeLine(line)
END;
```

Mid-test Loops

```
loop
     statements
when condition exit
     statements
when condition exit
     ...
end
```

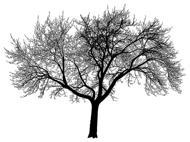
Advantage: a syntactic construct.

Errors caught in parser.

Compare with Tiger's **break**, which must fall within a **while** or **for**. More difficult to check (static semantics).

Multi-way Branching

```
switch (s) {
case 1: one(); break;
case 2: two(); break;
case 3: three(); break;
case 4: four(); break;
}
```



Switch sends control to one of the case labels. Break terminates the statement.

Implementing multi-way branches

```
switch (s) {
case 1: one(); break;
case 2: two(); break;
case 3: three(); break;
case 4: four(); break;
}
```

Obvious way:

```
if (s == 1) { one(); }
else if (s == 2) { two(); }
else if (s == 3) { three(); }
else if (s == 4) { four(); }
```

Reasonable, but we can sometimes do better.

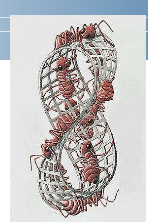
Implementing multi-way branches

If the cases are *dense*, a branch table is more efficient:

```
switch (s) {
case 1: one(); break;
case 2: two(); break;
case 3: three(); break;
case 4: four(); break;
}
```

```
labels l[] = { L1, L2, L3, L4 }; /* Array of labels */
if (s>=1 && s<=4) goto l[s-1];   /* not legal C */
L1: one(); goto Break;
L2: two(); goto Break;
L3: three(); goto Break;
L4: four(); goto Break;
Break:
```

Recursion and Iteration



Consider computing

$$\sum_{i=0}^{10} f(i)$$

In C, the most obvious evaluation is iterative:

```
double total = 0;
for ( i = 0 ; i <= 10 ; i++ )
  total += f(i);
```

Recursion and Iteration

$$\sum_{i=0}^{10} f(i)$$

But this can also be defined recursively

```
double sum(int i)
{
  double fi = f(i);
  if (i <= 10) return fi + sum(i+1);
  else return fi;
}

sum(0);
```

Recursion and Iteration

Grammars make a similar choice:

Iteration:

```
clist : item ( "," item )* ;
```

Recursion:

```
clist : item tail ;

tail : "," item tail
     | /* nothing */
     ;
```

Tail-Recursion and Iteration

```
int gcd(int a, int b) {
  if ( a==b ) return a;
  else if ( a > b ) return gcd(a-b,b);
  else return gcd(a,b-a);
}
```

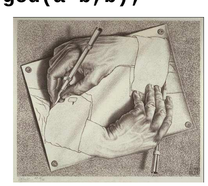
Notice: no computation follows any recursive calls.

Stack is not necessary: all variables “dead” after the call.

Local variable space can be reused. Trivial since the collection of variables is the same.

Tail-Recursion and Iteration

```
int gcd(int a, int b) {
  if ( a==b ) return a;
  else if ( a > b ) return gcd(a-b,b);
  else return gcd(a,b-a);
}
```



Can be rewritten into:

```
int gcd(int a, int b) {
start:
  if ( a==b ) return a;
  else if ( a > b ) a = a-b; goto start;
  else b = b-a; goto start;
}
```

Tail-Recursion and Iteration

Good compilers, especially those for functional languages, identify and optimize tail recursive functions.

Less common for imperative languages.

But gcc -O was able to rewrite the gcd example.

Applicative- and Normal-Order Evaluation

```
int p(int i) { printf("%d ", i); return i; }

void q(int a, int b, int c)
{
  int total = a;
  printf("%d ", b);
  total += c;
}
```

What is printed by

```
q( p(1), 2, p(3) );
```

Applicative- and Normal-Order Evaluation

```
int p(int i) { printf("%d ", i); return i; }
void q(int a, int b, int c)
{
  int total = a;
  printf("%d ", b);
  total += c;
}
q( p(1), 2, p(3) );
```

Applicative: arguments evaluated before function is called.

Result: 1 3 2

Normal: arguments evaluated when used.

Result: 1 2 3

Applicative- vs. and Normal-Order

Most languages use applicative order.

Macro-like languages often use normal order.

```
#define p(x) (printf("%d ",x), x)
#define q(a,b,c) total = (a), \
   printf("%d ", (b)), \
   total += (c)

q( p(1), 2, p(3) );
```

Prints 1 2 3.

Some functional languages also use normal order evaluation to avoid doing work. “Lazy Evaluation”

Argument Order Evaluation

C does not define argument evaluation order:

```
int p(int i) { printf("%d ", i); return i; }
int q(int a, int b, int c) {}

q( p(1), p(2), p(3) );
```

Might print 1 2 3, 3 2 1, or something else.

This is an example of *nondeterminism*.

Nondeterminism

Nondeterminism is not the same as random:

Compiler usually chooses an order when generating code.

Optimization, exact expressions, or run-time values may affect behavior.

Bottom line: don’t know what code will do, but often know set of possibilities.

```
int p(int i) { printf("%d ", i); return i; }
int q(int a, int b, int c) {}
q( p(1), p(2), p(3) );
```

Will *not* print 5 6 7. It will print one of

1 2 3, 1 3 2, 2 1 3, 2 3 1, 3 1 2, 3 2 1

Nondeterminism

Nondeterminism lurks in most languages in one form or another.

Especially prevelant in concurrent languages.

Sometimes it’s convenient, though:

```
if a >= b -> max := a
[] b >= a -> max := b
fi
```

Nondeterministic (irrelevant) choice when a=b.

Often want to avoid it, however.