Control Flow

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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;
```

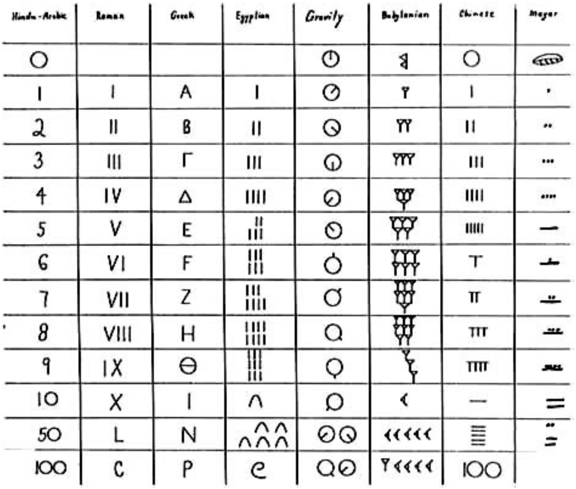
(Assumes left-to-right evaluation of expressions.)

Order of Evaluation

Why would you care?

Expression evaluation can have side-effects.

Floating-point numbers don't behave like numbers.



Side-effects

```
int x = 0;

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

int bar() {
  int a = foo() + x + foo();
  return a;
}
```

What does *bar()* return?

Side-effects

```
int x = 0;

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

int bar() {
  int a = foo() + x + foo();
  return a;
}
```

What does *bar()* return?

GCC returned 25.

Sun's C compiler returned 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:

$$
\begin{array}{ccc}
1 & \underbrace{10000001}_{\text{8-bit exponent}} & \underbrace{01100000000000000000000}_{\text{23-bit significand}}
\end{array}
$$

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

What to remember:

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

What's Going On?

Results are often rounded:

$$\begin{array}{r} 1.000010\,00000 \\ \times 1.000001\,00000 \\ \hline 1.000011\,\underbrace{00001}_{\text{rounded}} \end{array}$$

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();
```

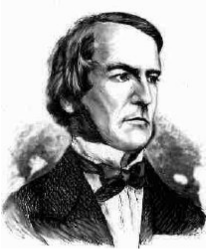
`cause_a_disaster()` is not called when `disaster_could_happen` is true.

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

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

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

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) { ... }
```

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

```
  BEQ A
B:

  JMP C
A:

  BEQ D
C:

  BEQ B
D:

  BNE B
  RTS
```

Structured Control-Flow

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

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

for

while

break

return

continue

do .. while

if .. then .. else

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:

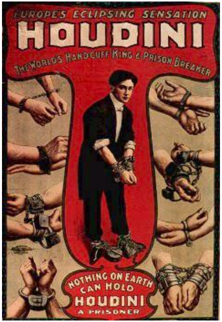
```
for ( i = 0 ; i < 10 ; i++ ) {
  if ( i == 5 ) continue;
  if ( i == 8 ) break;
  printf("%d\n", i);
}
```

```
  i = 0;
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 1ms to run?

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?

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.

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).

Mid-test Loops

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

In Modula-2:

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

Multi-way Branching

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

```
switch (s) {
  case 1: goto One;
  case 2: goto Two;
  case 3: goto Three;
  case 4: goto Four;
}
goto Break;

One:    one(); goto Break;
Two:    two(); goto Break;
Three:  three(); goto Break;
Four:   four(); goto Break;
Break:
```

Switch sends control to one of the case labels. Break terminates the statement. Really just a multi-way *goto*:

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:

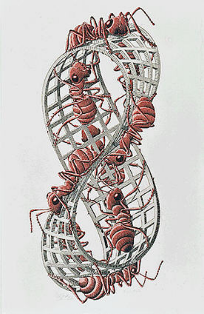
```
switch (s) {
case 1: one(); break;
case 2: two(); break;
case 3: three(); break;
case 4: four(); break;
}
```

A branch table written using a GCC extension:

```
  /* Array of addresses of labels */
  static void *l[] = { &&L1, &&L2, &&L3, &&L4 };

  if (s >= 1 && s <= 4)
     goto *l[s-1];
  goto Break;
L1: one(); goto Break;
L2: two(); goto Break;
L3: three(); goto Break;
L4: four(); goto Break;
Break:
```

Recursion and Iteration

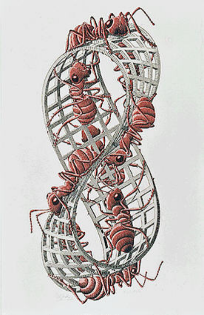


To compute $\sum_{i=0}^{10} f(i)$ in C,

the most obvious technique is iteration:

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

Recursion and Iteration



To compute $\sum_{i=0}^{10} f(i)$ in C,

the most obvious technique is iteration:

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

But this can also be defined recursively

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

sum(0, 0.0);
```

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.

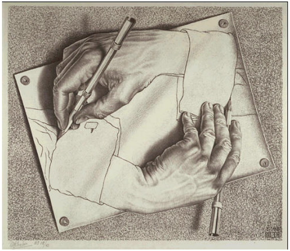
Stack is not necessary: all variables “dead” after the call.

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

Works in O’Caml, too

```
let rec gcd a b =
  if a = b then a
  else if a > b then gcd (a - b) b
  else gcd a (b - a)
```

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;
}
```

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

Less common for imperative languages, but gcc -O was able to handle this 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;
}

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

What does this print?

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) );
```

What does this print?

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.