CONTROL FLOW

PRINCIPLES OF PROGRAMMING LANGUAGES

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LANGUAGE MECHANISMS FOR CONTROL FLOW

The successful programmer thinks in terms of basic principles of control flow, not in terms of syntax!

The principal categories of control flow mechanisms are:

- Sequencing
- Selection or alternation
- Iteration
- Procedural abstraction (next topic)
- Recursion
- *Concurrency*
- Exception handling and speculation (next topic)
- *Non-determinism*

EXPRESSION EVALUATION

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Imperative languages:

- Computation is a series of changes to the values of variables in memory.
- This is “computation by side effect”.
- The order in which these side effects happen may determine the outcome of the computation.
- There is usually a distinction between an expression and a statement.

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Syntactic differences (Important to know, semantically irrelevant):

`A = 3`	FORTRAN, PL/1, SNOBOL4, C, C++, Java
`A :- 3`	Pascal, Ada, Icon, ML, Modula-3, ALGOL 68
`A <- 3`	Smalltalk, Mesa, APL
`A =. 3`	J
`3 -> A`	BETA
`MOVE 3 TO A`	COBOL
`(SETQ A 3)`	LISP

REFERENCES AND VALUES

Expressions that denote values are referred to as r-values.

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d = a ;
a = b + c;
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- On the right-hand side, it refers to the variable’s value—it is used as an r-value.
- On the left-hand side, it refers to the variable’s location in memory—it is used as an l-value.

a’s value

```
d = a;
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a’s memory location

EXPLICIT DEREFERENCING

Some languages explicitly distinguish between l-values and r-values:

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- ML: `X := !X + 1`

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In some languages, a function can return an l-value (e.g., ML or C++):

```
int a[10];

int &f(int i) {
  return a[i % 10];
}

void main() {
  for (int i = 0; i < 100; ++i)
    f(i) = i;
}
```

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Assignment copies the value.

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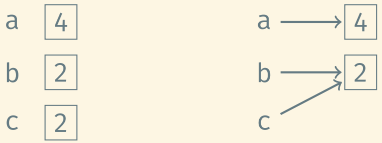
An example: Java

- Value model for built-in types
- Reference model for classes

VALUE MODEL VS REFERENCE MODEL

```
b = 2; c = b; a = b + c;
```

Value model | Reference model



JAVA EXAMPLES

```
int a = 5;
int b = a;
b += 10;
System.out.println("a = " + a);
System.out.println("b = " + b);
```

Output:

```java
int a = 5;
int b = a;
b += 10;
System.out.println("a = " + a);
System.out.println("b = " + b);
```

Output:

```
a = 5
b = 15
```

```
int a = 5;
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b += 10;
System.out.println("a = " + a);
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Output:

```
a = 5
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```
Obj a = new Obj();
Obj b = a;
b.change();
System.out.println(a == b);
```

Output:

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String a = "hi ";
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b += "world";
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Output:

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```
StringBuffer a = new StringBuffer();
StringBuffer b = a;
b.append("This is b's value.");
System.out.println("a = " + a);
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Output:

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a = This is b's value
b = This is b's value
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EVALUATION ORDER WITHIN EXPRESSIONS

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Possible problems:

- Evaluation order is often left to the compiler
  (i.e., undefined in the language specification).
  Thus, such side effects may lead to unexpected results.
- Evaluation order impacts register allocation, instruction scheduling, etc.
  By fixing a particular evaluation ordering, some code improvements may not be possible. This impacts performance.

AN EXAMPLE WITH SIDE EFFECTS IN C

```
for(i = m = M = 1; N - ++i; M = m + (m = M));
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Probably intented

N	m	M
2	1	1
3	1	2
4	2	3
5	3	5
6	5	8

$\mathtt{M} = F_{\mathtt{N}}$ (Nth Fibonacci number)

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$M = F_N$ (Nth Fibonacci number)

Actual

N	m	M
2	1	1
3	1	2
4	2	4
5	4	8
6	8	16

$M = 2^{N-2}$

SHORT-CIRCUIT EVALUATION OF BOOLEAN EXPRESSIONS

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Some languages provide both regular and short-circuit versions of Boolean operators.

Ada:

- `and` vs `and then`
- `or` vs `or else`

COMMON IDIOMS ENABLED BY SHORT-CIRCUIT EVALUATION

Checking for NULL pointers in C:

```
while (p != NULL && p->e != val) {
  p = p->next;
}
```

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Short-circuit and as if-statement in Perl or shell scripts:

```
if (x > max) then max = x;
```

becomes

```
(x > max) && max = x;
```

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  LISP: `(prog2 (setq a 4) (setq b 5) (setq c 6)` $\Longrightarrow 5$

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Many languages provide alternatives:

- One-and-a-half loop
- `return` statement
- Structured exception handling

SELECTION (ALTERNATION)

Standard if-then-else statement:

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```

Switch statement:

```
switch value of
  case pattern1: option1
  case pattern2: option2
  ...
  default:       default action
```

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Compiler can use different methods to generate efficient code:

- Sequential testing
- Binary search
- Hash table
- Jump table

IMPLEMENTATION OF IF STATEMENTS

```
if i == 1:
  option1()
elsif i in [2, 7]:
  option2()
elsif i in [3, 4, 5]:
  option3()
elsif i == 10:
  option4()
else:
  default_action()
```

IMPLEMENTATION OF IF STATEMENTS

Assume `i` is stored in register `R1`.

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```
    if R1 != 1 goto L1
    call option1
    goto L6
L1: if R1 == 2 goto L2
    if R1 != 7 goto L3
L2: call option2
    goto L6
L3: if R1 < 3 goto L4
    if R1 > 5 goto L4
    call option3
    goto L6
L4: if R1 != 10 goto L5
    call option4
    goto L6
L5: call default_action
L6: ...
```

IMPLEMENTATION OF SWITCH STATEMENTS: JUMP TABLE

```
case i:
  1:          option1()
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  3, 4, 5:    option3()
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```
T: &L1
   &L2
   &L3
   &L3
   &L3
   &L5
   &L2
   &L5
   &L5
   &L4
```

```
L1: call option1
    goto L7
L2: call option2
    goto L7
L3: call option3
    goto L7
L4: call option4
    goto L7
L5: call default_action
    goto L7
L6: if R1 < 1 goto L5
    if R1 > 10 goto L5
    R1 := R1 - 1
    R2 := T[R1]
    goto *R2
L7: ...
```

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– Potentially slow
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No single implementation is best in all circumstances.
Compilers often use different strategies based on the specific code.

Enumeration-controlled loops:

- Example: for-loop
- One iteration per element in finite set
- The number of iterations is known in advance.

Logically controlled loops:

- Example: while-loop
- Executed until a Boolean condition changes
- The number of iterations is not known in advance.

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Some languages do not have loop constructs (Scheme, Haskell, ...).
They use tail recursion instead.

Pre-loop test:

```
while (cond) {
  ...
}
```

LOGICALLY CONTROLLED LOOPS

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while (cond) {
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Post-loop test:

```
do {
  ...
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while (cond) {
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```

Post-loop test:

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do {
  ...
} while (cond);
```

Mid-loop test or “one-and-a-half loop”:

```
loop {
  ...
  if (cond1) exit;
  ...
  if (cond2) exit;
  ...
}
```

TRADE-OFFS IN ITERATION CONSTRUCTS (1)

Logically controlled loops:

+ Flexible

```
while (cond) {
  statements;
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L1: R1 := evaluate cond
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    goto L1
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The for-loop in C/C++ is merely syntactic sugar for the init-test-step idiom in implementing enumeration using logically controlled loops!

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for (init; cond; step) {
  statements;
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    step
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L2: ...
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Potentially much more efficient:

```
FOR i = start TO end BY step DO
  statements
END
```

TRADE-OFFS IN ITERATION CONSTRUCTS (2)

Potentially much more efficient:

```
FOR i = start TO end BY step DO
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END
```

If modifying the loop variable inside the loop is allowed:

```
    R1 := start
    R2 := end
    R3 := step
L1: if R1 > R2 goto L2
    statements
    R1 =  R1 + R3
    goto L1
L2: ...
```

TRADE-OFFS IN ITERATION CONSTRUCTS (2)

Potentially much more efficient:

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FOR i = start TO end BY step DO
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END
```

If modifying the loop variable inside the loop is allowed:

```
    R1 := start
    R2 := end
    R3 := step
L1: if R1 > R2 goto L2
    statements
    R1 =  R1 + R3
    goto L1
L2: ...
```

If modifying the loop variable inside the loop is not allowed:

```
    R1 := floor((end - start) /
                step) + 1
L1: if not R1 goto L2
    statements
    decrement R1
    goto L1
L2: ...
```

“Break” statement (“last“ in Perl):

Exit the nearest enclosing for-, do-, while- or switch-statement.

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LABELLED BREAK AND CONTINUE

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A loop may have a `finally` part, which is always executed no matter whether the iteration executes normally or is terminated using a `continue` or `break` statement.

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Generators in Python:

```
def lexy(length):
    yield ''
    if length > 0:
        for ch in ['a', 'b', 'c', 'd']:
            for w in lexy(length - 1):
                yield ch + w

for w in lexy(3):
    print(w)
```

ITERATOR OBJECTS

C++ and Java provide iterator classes that can be used to enumerate the elements of a collection (or programmatically generate a sequence of elements to be traversed).

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C++:

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for (cont::iterator i = cont.begin(); i != cont.end(); ++i) {
  // Use i
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for (cont::iterator i = cont.begin(); i != cont.end(); ++i) {
  // Use i
}
```

Java 1.4 is similar in its use of the `Enumeration` interface:

```
Enumeration e = cont.elements();
while (e.hasMoreElements()) {
  MyObj o = (MyObj) e.nextElement();
  // Use o
}
```

TYING ITERATOR OBJECTS TO FOR-LOOPS

Many modern languages provide convenient syntax for iterating over sequences generated using iterators. Behind the scenes, this is translated into code that explicitly uses iterator objects.

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Modern Java (post Java 5):

```
for (MyObj obj : cont) {
  // Use obj
}
```

Modern C++ (post C++11):

```
for (auto &obj : cont) {
  // Use obj
}
```

In languages without iterators/generators (e.g., C), we can simulate iterators using function calls:

```
for (it = begin(coll); it != end(coll); it = next(it)) {
  /* Do something with *it */
}
```

Functions being first-class objects allows passing a function to be applied to every element to an "iterator" that traverses the collection.

Haskell:

```
doubles  = map    (* 2) [1 ..]
pairs    = zip          [1 ..] doubles
doubles2 = filter even  [1 ..]
```

RECURSION

Every iterative procedure can be turned into a recursive one:

```
while (condition) { S1; S2; ... }
```

becomes

```
procedure P() {
  if (condition) {
    S1; S2; ...; P();
  }
}
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The type of recursive procedure above can be translated back into a loop by the compiler (tail recursion).

Applicative-order evaluation

Arguments are evaluated before a subroutine call

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Normal-order evalutaion is potentially inefficient. Why? How can we avoid this?

Lazy evaluation

- Evaluate expressions when their values are needed.
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Haskell:

```haskell
naturals :: [Int]
naturals = next 1
  where next i = i : rest
          where rest = next (i+1)

take 10 naturals -- [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]
```

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take 10 naturals -- [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]
```

Strict evaluation may be more efficient. Haskell provides means for us to force the strict evaluation of arguments (bang patterns).

By default, Scheme uses strict applicative-order evaluation.

This code runs forever:

```
(define naturals
  (letrec ((next (lambda (n)
                   (cons n (next (+ n 1))))))
    (next 1)))
```

A lazy version of the same code:

```
(define naturals
  (letrec ((next (lambda (n)
                   (cons n (delay (next (+ n 1)))))))
    (next 1)))

(define head car)

(define (tail stream) (force (cdr stream)))

(head naturals)                ; 1
(head (tail naturals))         ; 2
(head (tail (tail naturals))) ; 3
```

IMPLEMENTATION OF DELAY AND FORCE (1)

`delay` is a special form or macro that wraps the expression in a function:

```
(define-syntax delay
  (syntax-rules ()
    ((delay exp)  (lambda () exp))))
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```

What's the problem with this implementation of `delay`?

It evaluates `exp` every time. This is inefficient (essentially normal-order evaluation).

A better implementation of `delay`:

```
(define-syntax delay
  (syntax-rules ()
    ((delay exp) (memoize (lambda () exp)))))

(define (memoize f)
   (let ((first? #t)
         (val #f))
     (lambda ()
       (if first?
         (begin (set! first? #f)
                (set! val (f))))
       val)))
```

A better implementation of `delay`:

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     (lambda ()
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       val)))
```

This is pretty much what Haskell does.

NORMAL ORDER EVALUATION: C/C++ MACROS (1)

Example:

```
#define DIVIDES(n, a) (!((n) % (a)))
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```
#define DIVIDES(n, a) (!((n) % (a)))
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Problems:

- Cannot be used recursively.
- Textual expansion may not mean what's intended: Evaluate `DIVIDES(x, y+2)` using the above definition and using

```
#define DIVIDES(n, a) (!(n % a))
```

NORMAL ORDER EVALUATION: C/C++ MACROS (2)

- Side effects: Evaluate `MAX(x++, y++)` using

```
#define MAX(a, b) ((a) > (b) ? (a) : (b))
```

NORMAL ORDER EVALUATION: C/C++ MACROS (2)

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- Name clashes with variables: Evaluate `SWAP(x, t)` using

```
#define SWAP(a, b) { int t = a; a = b; b = t; }
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  #define MAX(a, b) ((a) > (b) ? (a) : (b))
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- Name clashes with variables: Evaluate `SWAP(x, t)` using

  ```
  #define SWAP(a, b) { int t = a; a = b; b = t; }
  ```

In C++, inline functions are usually a better alternative.

- Think in terms of control abstractions rather than syntax!
- Expression evaluation order is left to the compiler; avoid side effects.
- Understand what a variable use means (l-value/r-value; value/reference).
- Short-circuiting helps efficiency and allows some elegant idioms.
- Avoid `goto`.
- `switch` is often more efficient than multi-way `if`.
- `for`-loops can be more efficient than `while`-loops (not in C, Java, Python, ...).
- Iterators/generators provide an abstraction for enumerating the elements of a sequence useful for iteration constructs.
- Recursion is more general/powerful than iteration.
- Applicative-order evaluation is fast, normal-order evaluation is flexible, lazy evaluation offers a trade-off.