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## Control flow mechanisms and their implementation

**Order of execution** matters for statements, and for expressions with side effects. Ordering for statements is **control flow**.

[Expressions have values; statements don't. Statements are evaluated for their side effects. Expressions may have side effects, but don't necessarily (and it's often considered bad style).]

Principal paradigms for control flow:

- sequencing
- selection
- iteration
- subroutines, recursion (and related control abstractions—e.g., iterators)
- nondeterminacy
- concurrency

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## Expression evaluation

**Operators** are built-in functions with, often  
special non-identifier names (+, -, %, ...)  
infix syntax (as opposed to prefix for most functions)  
precedence and associativity  
C has 15 levels -- too many to remember  
Pascal has 3 levels -- too few for good semantics  
Fortran has 8; Ada has 6  
I don't like the rules in **any** of these (Fortran probably closest)  
Ada puts and, or at same level  
Pascal misgroups if a = b or c = d then  
Lesson: when unsure, use parentheses!

evaluation order matters

consider  $f(a+b, c, d(e, h), h)$

- d might have side effects
- reordering might improve register allocation
- some arguments might already be available in registers
- on old machines with old compilers, last-to-first would optimize stack access

Most languages say order of evaluation of arguments is undefined.

Likewise, most leave operand evaluation order undefined  
e.g., in  $f(a, b) + g(c, d)$

arithmetic identities work in math class; not always on a computer  
commutativity of + and \* is usually safe  
associativity is not

$(a + b) + c$	works if $a \approx \text{minint}$ and $b \approx \text{maxint}$ and $c$ is small
$a + (b + c)$	may not (esp. in floating point)

Compilers generally respect parentheses; if in doubt, use them

short-circuiting

```
if (b != 0 && a/b == c) ...  
if (*p && p->foo) ...  
if (f || messy()) ...
```

connection to lazy evaluation of arguments -- e.g., in Haskell

Not all languages evaluate and and or lazily -- beware!

### ***Variables as values v. variables as references***

value-oriented languages

- C, Ada

reference-oriented languages

- most functional languages (Lisp/Scheme, SML/OCaml/Haskell)

- Smalltalk

Java deliberately in-between

- built-in types are values

- user-defined types are objects -- references

C# similar, though user can choose which object variables are values

- ("expanded", in Eiffel terminology) and which are references

Rust is also in-between, but in a different way.

Roughly, the owner variable is a value; other variables are references.

## Assignment

statement (or expression) executed for its side effect(s)

assignment operators ( $+=$ ,  $-=$ , etc)

handy

avoid redundant work (or need for optimization)

perform side effects exactly once

$A[f()] += 1$  is not the same as  $A[f()] = A[f()] + 1$

C  $--$ ,  $++$

prefix v. postfix semantics

postfix more than syntactic sugar

$A[++i] = 3$  is the same as  $A[i += 1] = 3$

$A[i++] = 3$  is much harder to emulate

## Initialization v. assignment

esp. important in OO languages

```
foo b;  
    // calls no-arg constructor foo::foo()  
foo f = b;  
    // calls one-arg "copy constructor" foo::foo(&foo)  
    // This is syntactic sugar for foo f(b)
```

```
foo b, f;  
    // calls no-arg constructor  
f = b;  
    // calls foo::operator=(&foo)
```

also matters in other languages:

globals can be statically initialized

requiring (or defaulting) initialization avoids use of garbage

also avoids some races in parallel programs, but has costs

## Side Effects

often discussed in the context of functions

a side effect is some permanent state change caused by execution of function -- some noticeable effect of call other than return value.

in a more general sense, assignment statements provide the ultimate example of side effects. They change the value of a variable.

### ***Side effects are fundamental to imperative computing***

In (pure) functional, logic, and dataflow languages, there are no such changes. These languages are called ***single-assignment*** languages. They might better be called "simple definition" languages.

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## Sequencing

execute one statement after another  
very straightforward; very imperative

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## Selection

sequential if statements

```
if ... then ... else
```

```
if ... then ... elsif ... else
```

```
(cond
  (C1) (E1)
  (C2) (E2)
  ...
  (Cn) (En)
  (T) (Et)
)
```

```
match e with
| pat1 when cond1 ->
| pat2 when cond2 ->
| ...
| patN when condN ->
| _ ->
```

value of explicit terminators or begin/end (or {}) brackets  
need for elsif (elif)

jump code

When translating

```
if A < B then ... else ... fi
```

one might evaluate the condition to get a Boolean value in a register,  
then branch depending on its value.

That's often more instructions than needed:

```
r1 := A
r2 := B
r1 := r1 < r2
if !r1 goto L1
  <then clause>
  goto L2
```

```
L1:
  <else clause>
```

```
L2:
```

v.

```
r1 := A
r2 := B
if r1 >= r2 goto L1
  <then clause>
  goto L2
```

```
L1:
  <else clause>
```

```
L2:
```

For expressions with short-circuiting, the difference is more  
compelling (Example 6.49 in the text):

```
if ((A > B) and (C > D)) or (E <> F) then
  then_clause
else
  else_clause
```

w/out short-circuiting (as in, e.g., Pascal):

```
r1 := A          -- load
r2 := B
```

```

    r1 := r1 > r2
    r2 := C
    r3 := D
    r2 := r2 > r3
    r1 := r1 & r2
    r2 := E
    r3 := F
    r2 := r2 <> r3
    r1 := r1 | r2
    if r1 = 0 goto L2
L1: <then clause>      -- label not actually used
    goto L3
L2: <else clause>
L3:

```

with short-circuiting (as in, e.g., C):

```

    r1 := A
    r2 := B
    if r1 <= r2 goto L4
    r1 := C
    r2 := D
    if r1 > r2 goto L1
L4: r1 := E
    r2 := F
    if r1 = r2 goto L2
L1: then_clause
    goto L3
L2: else_clause
L3:

```

Note that this not only avoids performing unnecessary comparisons; it also avoids the **and** and **or** instructions.

guarded commands (example of non-determinacy)

```

if
  cond1 -> stmt1
[] cond2 -> stmt2
  ...
[] condN -> stmtN
fi

```

similar version for loops

case/switch (introduced in Algol-W)

labels normally required to be disjoint

compiler will detect this case in Rust and a few other languages with more general selection constructs

what should happen if there isn't a matching label for value?

Ada: forbid at compile time

C: no-op

Pascal: dynamic semantic error

case implementation

sequential testing

small number of choices, non-dense range

characteristic array (jump table)

dense range

hashing

non-dense range w/out range labels

binary search

large range, range labels

(probably don't need search tree, except perhaps if the key distribution is highly nonuniform and we want better pivots than we get with mean)

Should ranges be allowed in the label list?

they make it easy to state things for which a jump table or hash table is awful: can be done efficiently ( $O(\log n)$ ) with binary search

examples:

3:	1:	1:	1..48:
5:	2:	59:	97..283:
7:	3:	187:	900..1024:
9:	...	...	...
	100:	1000000:	12345..67890:

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Iteration

logically controlled v. enumeration controlled

“while condition is true” v. “for every element of set”

In the latter case, the number of elements (and their identities) are known before we even start the loop (and in general, we don’t want the values we iterate over to depend on anything we do in early iterations).

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Logically-controlled loops

pre-test (while)

post-test (repeat)

mod-test (one-and-a-half loops — loop with exit)

labels for non-closest exit?

implementation options:

L1:

    r1 := <condition>

    if !r1 goto L2

    <loop body>

    goto L1

L2:

That has two branches in every iteration.

    r1 := <condition>

    if !r1 goto L2

L1:

    <loop body>

    r1 := <condition>

    if r1 goto L1

L2:

That evaluates the condition in two different places.

Not a big deal if it doesn’t bloat code size.

If it’s complicated (long code) we can do this instead:

```

    goto L2
L1:
    <loop body>
test:
    r1 := <condition>
    if r1 goto L1

```

That has one extra jump, but only one copy of the test.

C-style for loop

semantically clean, but **not** really a for loop

hard to apply the various optimizations possible for “real” for loops

```

for (int i = first; i <= last; i+= step) {
    ...
}

```

~=

```

{
    int i = first;
    while (i <= last) {
        ...
        i += step;
    }
}

```

-----  
Enumeration-controlled loops

```

for v in my_set /* in my favorite order */ do
    ...
end

```

Arithmetic progressions are a common case:

```

/* Modula-2 syntax */
i : integer;
...
for i := first to last by step do
    ...
end

```

Several natural questions: what should happen if

- the bounds are empty
- the loop body changes the index variable or variables that contribute to the end test
- control jumps in or out
- the index variable is accessed afterward

Modern languages make the index variable local to the loop, calculate step and bounds once, in advance, make the index variable read-only, and forbid jumps in.

Naïve implementation:

```
    i := first
    goto L2
L1: ...
    i += step
L2: if i <= last goto L1
```

Big problem is the direction of the test at the bottom.

Better implementation uses an *iteration count*, supported by “dec. and branch if nonzero” instruction on many machines:

```
    r1 := first
    r2 := step
    r3 := last
    r3 := [(r3-r1+r2)/r2]
    if r3 ≤ 0 goto L2
L1: <loop body>
    r1 += r2
    if r3 > 0 goto L1
L2:
```

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Iterators

supply a for loop with the members of a set  
abstraction/generalization of the “from A to B by C” sorts of  
stuff you see built-in in older languages

pioneered by Clu:

```
for i in <iterator> do ... end
built-in iterators for from_to, from_to_by, etc.
```

wonderful for iterating over arbitrary user-defined sets

very good for abstraction; for loop doesn't have to know whether set is a linked list, hash table, dense array, etc.

may be **true iterators** (as in Clu, C#, Icon, Python, Ruby) or interface-based approximation ("**iterator objects**," as in Euclid, Java, Rust, and C++)

Iterator objects (Euclid, C++, Java, Rust)

Standard interface for abstraction to drive for loops.

Supported in Java with special loop syntax, and in C++ through clever use of standard constructor and operator overload mechanisms.

In Java:

```
List<foo> myList = ...;

for (foo o : myList) {
    // use object o
}
```

requires that the to-be-iterated class (here, List) implements the Iterable interface, which exports a method

```
public Iterator<T> iterator()
```

where Iterator is an interface exporting methods

```
public boolean hasNext()
```

and

```
public T next()
```

The for loop is syntactic sugar for

```
for (Iterator<foo> i = myList.iterator(); i.hasNext();) {
    foo o = i.next();
    // use object o
}
```

C++ version looks like

```
list<foo> my_list;
...
for (list<foo>::const_iterator i = my_list.begin();
     i != my_list.end(); i++) {
    // make use of *i or i->field_name
}
```

Don't have to have an equivalent of the Iterator interface (it's just a convention), because C++ individually type-checks every use of a generic (template).

Note the different conceptual model:

Java has a special for loop syntax that uses methods of a special class

C++ standard library defines iterators as "pointer-like" objects with increment operations to drive ordinary for loops

All the standard library collection/container classes support iterators, in both languages.

True iterators (Clu, Icon, C#, Python)

iterator itself looks like a procedure, except it can include "yield" statements that produce intermediate values. when the iterator returns, the loop terminates

in Python:

```
def uptoby(lo, hi, step):
    while True:
        if (step > 0 and lo > hi) \
            or (step < 0 and lo < hi): return
        yield lo
        lo += step    # ignore overflow

for i in uptoby(1, 20, 2):
    print (i)
```

C# for loop resembles that of Java:

```
foreach (foo o in myList) {  
    // use object o  
}
```

This is syntactic sugar for

```
for (IEnumerator<foo> i =  
    myList.GetEnumerator(); i.MoveNext()) {  
    foo o = i.Current;  
    // use object o  
}
```

Current is an **accessor** -- a special method supporting field-like access:

```
public object Current {  
    get {  
        return ...;  
    }  
    set {  
        ... = value;  
    }  
}
```

In contrast to Java, you don't need to hand-create the hasNext() [MoveNext()] and next() [Current] methods. The compiler does this automatically when your class implements the IEnumerable interface and has an iterator—a method containing “yield return” statements and “returning” an IEnumerator:

```
class List : IEnumerable {  
    ...  
    public IEnumerator GetEnumerator() {  
        node n = head;  
        while (n != null) {  
            yield return n.content;  
            n = n.next;  
        } // NB: no return statement  
    }  
}
```

If you want to be able to have multiple iteration orders, your class can have multiple methods that each return an IEnumerator. Then you can say, e.g.

```
foreach (object o in myTree.InPreOrder) { ...  
foreach (object o in myTree.InPostOrder) { ...
```

detail:

IEnumerator implements MoveNext and Current (also Reset)

IEnumerable implements GetEnumerator, which returns an IEnumerator

Loop body as lambda (Smalltalk, Scheme, ML, Ruby, ~Rust, ...)

OCaml:

```
open Printf;;  
let show n = printf "%d\n" n;;  
  
let upto lo hi =  
  fun f -> let rec helper i =  
    if i > hi then ()  
    else (f i ; helper (i + 1)) in  
  helper lo;;
```

```
upto 1 10 show;;      =>  
1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
- : unit = ()
```

Ruby:

```
sum = 0                => 0  
[ 1, 2, 3 ].each { |i| sum += i } => [1, 2, 3] # array itself  
sum                    => 6
```

Here the (parameterized) brace-enclosed block is passed to the each method as a parameter.

There's also more conventional-looking syntax:

```
sum = 0
for i in [1, 2, 3] do    # 'do' is optional
  sum += i
end
sum
```

The for loop is syntactic sugar for a call to each.

Here's a more object-oriented alternative:

```
sum = 0
1.upto 3 {|i| sum += i}
sum
```

or instead of using braces:

```
sum = 0
i.upto 3 do |i| sum += i end
sum
```

You can write your own iterators using 'yield'.

```
class Array
  def find
    for i in 0...size
      value = self[i]
      return value if yield(value)
    end
    return nil
  end
end
...
[1, 3, 5, 7, 9].find {|v| v*v > 30 }    => 7
```

Think of yield as invoking the block that was juxtaposed ("associated") with the call to the iterator.

(FWIW, the array class already has a `find` method in Ruby, but we can redefine it, and it probably looks like this anyway.)

Blocks can also be turned into first-class closures, with unlimited extent:

```
def nTimes(aThing)
  # Ruby, like most scripting languages, is dynamically typed
  return proc { |n| aThing * n }
end
```

In recent Ruby, `->` is a synonym for `proc`

```
p1 = nTimes(3)
p2 = nTimes("foo")
p1.call(4)           => 12
p2.call(4)           => "foofoofoofoo"
```

This lets us build higher-level functions. Here's reduction for arrays:

```
class Array
  def reduce(n)
    each { |value| n = yield n, value } # that's self.each
    # yield invokes (just once) the block associated
    # with the call to reduce. Note the lack of parens:
    # "yield (n, value)" would pass a single tuple.
    n # return value
  end
  def sum
    reduce(0) { |a, v| a + v }
  end
  def product
    reduce(1) { |a, v| a * v }
  end
end

[2, 4, 6].sum           => 12
[2, 4, 6].product       => 48
```

All in all Ruby is pretty cool. Check it out.

(I do wish it let you associate more than one block with a call.)

## Implementation of true iterators (section 9.5.3-CS)

coroutines or threads  
overkill

single-stack  
used in Clu  
works, but would confuse a standard debugger, and not compatible  
with some conventions for argument passing

implicit iterator object  
kinda cool; used in C# and Python  
same mechanism supports async in C# and JavaScript

block as lambda expression (Ruby, functional languages)

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## Recursion

equally powerful to iteration, and as efficient when you can use tail recursion.  
mechanical transformations back and forth  
often more intuitive (sometimes less)  
**naive** implementation less efficient  
no special syntax required  
fundamental to functional languages like Scheme

tail recursion

```
(* OCaml: *)  
let rec gcd b c =  
  if b = c then b  
  else if b < c then gcd b (c - b)  
  else gcd (b - c) c;;
```

implemented as

```
gcd (b c)
```

```

start:
  if b = c
    return b
  if b < c
    c := c - b
    goto start
  if b > c
    b := b - c
    goto start

```

changes to create tail recursion (e.g. pass along an accumulator)

```

(* OCaml: *)
let rec summation f low high =
  if low == high then f low
  else f low + summation f (low+1) high;;

```

becomes

```

let rec summation2 f low high st =
  if low == high then st + f low
  else summation2 f (low+1) high (st + f low);;

```

and then

```

let summation3 f low high =
  let rec helper low st =
    let new_st = st + f low in
    if low == high then new_st
    else helper (low+1) new_st in
  helper low 0;;

```

More generally (absent an associative operator), pass along a *continuation*.

This is perfectly natural to someone used to programming in a functional language. Note that the summation example depends for correctness on the associativity of addition. To sum the elements in the *same* order we could have counted down from high instead of up from low, but that makes a more drastic change to the structure of the recursive calls.

There is no perfectly general algorithm to discover tail-recursive versions of functions, but compilers for functional languages recognize all sorts of common cases.

Sisal and pH have “iterative” syntax for tail recursion:

```
function sum (f : function (n : integer returns integer),
             low : integer, high : integer returns integer)
for initial
  st := f (low);
while low <= high
  low := old low + 1
  st := old st + f (low)
returns value of st
end for
end function
```

The Sisal compiler was *really* good at finding tail recursive forms.

### Concurrency

specifies that statements are to occur (at least logically) concurrently  
concurrency is fundamental to probably half the research in computer  
science today  
subject of chapter 13

### Nondeterminacy

choice “doesn’t matter”  
periodically popular, promoted by Dijkstra for use with selection  
(*guarded command* syntax)  
can apply to execution order as well  
useful for certain kinds of concurrency, inc. event-driven code

### process server

```
do
  receive read request ->
  reply with data
[]
  receive write request ->
  update data and reply
od
```

also nice for certain axiomatic proof schemes

raises issues of “randomness”, “fairness”, “liveness”, etc.