CSc 520

Principles of Programming Languages

28: Control Flow — Introduction

Christian Collberg
collberg@cs.arizona.edu

Department of Computer Science
University of Arizona

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Control Flow

We need some way of ordering computations:

- sequencing
- selection
- iteration
- procedural abstraction — being able to treat a collection of other control constructs as a single unit, a subroutine.
- recursion
- concurrency
- nondeterminacy — being able to explicitly state that the ordering between two statements is unspecified, and, possibly should be selected randomly/fairly.
Control Flow — Paradigms

- **Functional languages** — recursion and selection are important, iteration and sequencing not.
- **Procedural languages** — iteration, sequencing, selection are important, recursion not.
- **Logic languages** — the programmer gives rules that restrict control flow, the interpreter deduces an execution ordering that satisfies these rules.
Operators
Languages use prefix, infix, or postfix notation for operators in expressions.

This means that the operator comes before, among, or after its operands.

Lisp/Scheme uses **Cambridge Polish** notation (a variant of prefix):

\[(\ast \ (\ + \ 5 \ 6 \ ) \ 7)\]

Postscript and Forth use postfix notation.

Smalltalk uses infix notation.
Smalltalk — Binary Messages

A binary message $M$ to receiver $R$ with argument $A$ has the syntax

$$R \ M \ A$$

For example:

$$8 \ + \ 9$$

This sends the message $+$ to the object $8$ with the argument $9$. 
A keyword message $M$ to receiver $R$ with arguments $A_1, A_2, A_3, \ldots$ has the syntax

$$R \ M_1: \ A_1 \ M_2: \ A_2 \ M_3: \ A_3 \ \ldots$$

For example:

```ruby
DeannaTroi kiss: cheek how: tenderly
```

This sends the message `kiss:how:` to the object `DeannaTroi` with the arguments `cheek` and `tenderly`. In Java we would have written:

```java
DeannaTroi.kisshow(cheek, tenderly)
```
Operator Precedence

- The precedence of an operator is a measure of its binding power, i.e. how strongly it attracts its operands.
- Usually \(*\) has higher precedence than \(+\):

\[4 + 5 \times 3\]

means

\[4 + (5 \times 3),\]

not

\[(4 + 5) \times 3.\]

- We say that \(*\) binds harder than \(\pm\).
The *associativity* of an operator describes how operators of equal precedence are grouped.

- $+$ and $-$ are usually *left associative*:

\[
4 - 2 + 3
\]

means

\[
(4 - 2) + 3 = 5,
\]

not

\[
4 - (2 + 3) = -1.
\]

*We say that* $+$ *associates to the left.*

- $^\wedge$ *associates to the right:*

\[
2^3^4 = 2^{(3^4)}.
\]
Case Study — C

- C has so many rules for precedence and associativity that most programmers don’t know them all.
- See the table on the next slide.
## Case Study — C...

<table>
<thead>
<tr>
<th>OPERATOR</th>
<th>KIND</th>
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<th>ASSOC</th>
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<tr>
<td>a[k]</td>
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<td>f(...)</td>
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Variables
Value vs. Reference Model

- **l-value** — an expression that denotes a location, such as the left-hand side in \( x := \ldots, x[i] := \ldots, x.a[i]->v := \ldots \). 

- **r-value** — an expression that denotes a value, such as the right-hand side in \( \ldots := x, \ldots := x[i], \ldots := x.a[i]->v, \ldots := 3+x \). 

  Pascal, C, Ada use a **value model** of variables. In \( \ldots := x \), \( x \) refers to the value stored in \( x \). 

  Clu (and other languages) use a **reference model** for variables. In \( \ldots := x \), \( x \) is a reference to the value stored in \( x \).
In Pascal, after the statements

\[
\begin{align*}
b & := 2; \\
c & := b;
\end{align*}
\]

both \( b \) and \( c \) would hold the value 2. In Clu, \( b \) and \( c \) would both point to the same object, which contains the value 2.

Java uses a value model for \texttt{int}, \texttt{float}, etc, but a reference model for \texttt{String}. Hence

\[
\begin{align*}
\text{int } i, j; \\
\text{String } s, t; \\
\text{if } (i==j) \ldots \\
\text{if } (s==t) \ldots
\end{align*}
\]

can be confusing for novel programmers.
Expressions
Order of Evaluation

Many languages allow the compiler to reorder operations in an expression, for efficiency.

Java requires strict left-to-right evaluation. Why?

If the expression \((b, c, d \text{ are } 32\text{-bit ints})\)

\[ b - c + d \]

is reordered as

\[ b + d - c \]

then an overflow can occur if \(b + d\) doesn’t fit in an \text{int}. 

[16]
Let $a, b, c$ be 32-bit floats, where $a$ is small, $b, c$ are large, and $b = -c$.

Then the expression

$\ (a + b) + c$

might evaluate to 0 (due to a loss of information), while

$\ a + (b + c)$

would evaluate to $a$. 

Case Study — Pascal

- Pascal does *not* use **short-circuit evaluation**. Hence, this makes for problems:

  ```
  if (x<>0) and (y/x > 5) then
  ```

- Pascal has non-intuitive precedence:

  ```
  4 > 8 or 11 < 3
  ```

  is parsed as

  ```
  4 > (8 or 11) < 3
  ```

  Hence, it becomes necessary to insert parenthesis.
Control-Flow Statements
Statement vs. Expression Orientation

- In Pascal, Ada, Modula-2, if, while, etc. are statements. This means that they are executed for their side-effects only, and return no value.

- In Algol68 if, while, etc. are expressions, they can have both side-effects and return values:

```plaintext
begin
  x := if b<c then d else e;
  y := begin f(b); g(c) end;
  z := while b<c do g(c) end;
  2+3
end
```

This compound block returns 5.
In the early days of FORTRAN, there were no structured control-flow statements (these were introduced in Algol 60).

Instead, programmers built up structured if statements, while statements, etc, using gotos:

```
IF a .LT. B GOTO 10
   ...
GOTO 20
10:  ...
20:
```

This is an if-then-else statement.
Case Study — Pascal: goto

Pascal has no exception handling mechanism. Gotos were the only way of, say, jumping to the end of the program on an unrecoverable error.

Labels have to be integers and have to be declared.

```pascal
procedure P ();
  label 999;
  goto label;
  ...
  goto 999;
  ...
  999:
end;
```
Statements — Selection
Case Study — Pascal: if

if boolean expression then
  statement
else
  if boolean expression then
    statement
  else
    begin
      statement
      statement
      statement
    end

The else is always matched with the closest nested if.
Case Study — Modula-2: if

The **ELSIF** part of an **IF**-statement in Modula-2 is a convenient addition from Pascal:

```
IF boolean expression THEN
  statement-sequence
ELSIF boolean expression THEN
  statement-sequence
ELSIF boolean expression THEN
  statement-sequence
ELSE
  statement-sequence
END
```
Case Study — Pascal: case

```pascal
case ordinal expression of
  list of cases:  statement;
  list of cases:  statement;
  list of cases:  statement;
  otherwise  statement
end;
```

- `otherwise` is optional.
- The `list of cases` looks like this: `1,2,7..9`. I.e. it can contain ranges.
- `case`-statements can be implemented as nested `if`s, jump-tables (most common), or hash-tables, depending on what is most efficient.
Case Study — C: case

In 1990 AT&T’s long distance service fails for nine hours due to a wrong `break` statement in a C program.

```c
switch (e) {
  0 :
  1 :  S_1;
       break;
  2 :  S_2;
  3 :  S_3;
       break;
}
```

C’s design allows several cases to share the same statement (as 0 and 1 do above).
In FORTRAN, you can simulate a case statement using computed gotos:

\[
\text{GOTO (15, 20, 30) } I
\]

15:  
20:  
30:  

If \( I=1 \), we’ll jump to 15; if \( I=2 \), we’ll jump to 20; if it’s 3, we’ll jump to 30, otherwise we’ll do nothing.
Statements — Iteration
Case Study — Pascal: for

for index := start to stop do
    statement;
for index := start downto stop do
    statement;

- The index must be declared outside the loop.
- Only ordinal datatypes are allowed.
- You can only increment the index variable with $\pm 1$!
Case Study — Modula-2: FOR

Modula-2 generalizes Pascal’s for-loop, so that it’s possible to iterate by an arbitrary amount:

(* The BY-part is optional.
  step must be a constant.*)

FOR i := from TO to [BY step] DO
  statement-sequence
END

step still has to be constant, though!
Case Study — Modula-3: FOR

- Modula-3, finally, provides a FOR-loop in its full generality:

  ```plaintext
  FOR id := first TO last BY step DO
    S
  END
  ```

- `id` is a read-only variable with the same type as `first` and `last`.
- `first`, `last` and `step` are executed once.
- `step` can be a run-time expression, not just a constant. (At least, I think so — Scott says otherwise, and the manual is silent. Anyone care to check what the compiler thinks?)
Case Study — Modula-3: FOR

FOR id := first TO last BY step DO
  S
END

- If step is negative, the loop iterates downwards.
- It is non-trivial to implement a fully general FOR-loop. See the next slide for how Modula-3’s FOR-statement is translated.
- The index variable id is automatically defined by the loop.
- In Pascal/Modula-2, the programmer had to define it herself outside the loop. This lead to the question what value will id have after the end of the loop? Either the compiler got it wrong, or the programmer got it wrong.
FOR id := first TO last BY step DO S END

VAR i := ORD(first); done := ORD(last); delta := step;
BEGIN
  IF delta >= 0 THEN
    WHILE i <= done DO
      WITH id=VAL(i,T) DO S END; INC(i,delta);
    END
  ELSE
    WHILE (i >= done DO
      WITH id=VAL(i,T) DO S END; INC(i,delta);
    END
  END END END
Case Study — Pascal: loops

```pascal
while boolean expression do
  statement;

repeat
  statement;
  statement;
  statement;
until boolean expression;
```

Note the asymmetry: the `while` statement body can only contain one statement.
Modula-2 adds an infinite loop:

```modula2
LOOP
    statement-seq (* EXIT can occur here. *)
END
```

This makes it convenient to exit a loop in the middle:

```modula2
LOOP
    ....
    IF ... THEN EXIT;
    ....
END
```
Case Study — Algol 60

Algol 60 has one loop construct:

for ::= for id := list do stat

list ::= enum { , enum }

enum ::= expr

    expr step expr until expr

    expr while condition

id takes on values specified by a sequence of enumerators.

Each expression is re-evaluated at the top of the loop.
Each of the following is equivalent:

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

This generality is usually overkill...
Recursion
A function is tail-recursive if there is no more work to be done after the recursive call.

Tail-recursive functions are important because they can be easily be made iterative —no stack space needs to be allocated dynamically.

For tail-recursive functions the compiler can reuse the space of the current stack frame instead of allocating a new one for the recursive call.
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);
}

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; }
}
尾递归...

- 你可以经常将非尾递归函数转换为尾递归函数。
- 想法是将工作后续任务的继续传递给调用的参数。
- 这称为继续传递样式 (CPS)。
- 下一页显示了如何使用 CPS 转换使阶乘函数变成尾递归的。
Tail Recursion...

(define (fact n)
  (if (= n 1)
      1
      (* n (fact (- n 1)))))

(define (fact-cps n C)
  (if (= n 1)
      (C 1)
      (fact-cps (- n 1) (lambda(v) (C (* n v))))))

(fact-cps 5 (lambda(v) (display v))))
Read Scott, pp. 249–287, 294–303, 303–310