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
Prefix, Infix, Postfix

- 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):
  
  \[ (*) (+ 5 6) 7 \]

- 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 \( 9 \).

Smalltalk — Keyword Messages

- 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:
  
  DeannaTroi kiss: cheek how: tenderly

  This sends the message \( \text{kiss:how:} \) to the object DeannaTroi with the arguments cheek and tenderly. In Java we would have written:

  \[ \text{DeannaTroi.kisshow(cheek,tenderly)} \]

Operator Precedence

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

  \[ 4 + 5 \ast 3 \]

  means

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

  not

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

- We say that \( \ast \) binds harder than \(+\).
Operator Associativity

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.

^ 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.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Kind</th>
<th>Prec</th>
<th>Assoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>a[k]</td>
<td>Primary</td>
<td>16</td>
<td></td>
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<tr>
<td>f(…)</td>
<td>Primary</td>
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<td>&gt;=</td>
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<tr>
<td>a++, a--</td>
<td>Postfix</td>
<td>15</td>
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<tr>
<td>+=, -=</td>
<td>Unary</td>
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Case Study — C...

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<tbody>
<tr>
<td>+=, -=</td>
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<tr>
<td>^</td>
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<td></td>
<td>Ternary</td>
<td>3</td>
<td>Right</td>
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</tbody>
</table>

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 int, float, etc, but a reference model for 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.

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 (\( b, c, d \) are 32-bit ints)
  \[
  b - c + d
  \]
is reordered as
  \[
  b + d - c
  \]
then an overflow can occur if \( b + d \) doesn’t fit in an int.
Order of Evaluation…

- 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:
    
    $4 > 8 \text{ or } 11 < 3$
    
    is parsed as
    
    $4 > (8 \text{ or } 11) < 3$
    
    Hence, it becomes necessary to insert parenthesis.

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:

  ```pascal
  begin
    x := if b<c then d else e;
    y := begin f(b); g(c) end;
    z := while b<c do g(c) end;
  end;
  2+3
  end
  
  This compound block returns 5.
Unstructured Control-Flow

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, while, 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.

```
procedure P ();
  label 999;
  goto label;
  ...  goto 999;
  ...  ...
  999:   label:   end;
```

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

```plaintext
IF boolean expression THEN
    statement-sequence
ELSIF boolean expression THEN
    statement-sequence
ELSIF boolean expression THEN
    statement-sequence
ELSE
    statement-sequence
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.

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;
        \textit{\textless\textgreater \ smaller meant to fall-through here?!?!}\textit{\textless\textgreater }
    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**:

```fortran
GOTO (15, 20, 30) I
15: \ldots
20: \ldots
30: \ldots
```

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:

  FOR id := first TO last BY step DO
    statement-sequence
  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.

Case Study — Pascal: loops

while boolean expression do
  statement;
repeat
  statement;
  statement;
until boolean expression;

- Note the asymmetry: the while statement body can only contain one statement.

Case Study — Modula-2: loops

- Modula-2 adds an infinite loop:

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

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

  LOOP
  ....
  IF ... THEN EXIT;
  ....
  END

520 —Spring 2008 — 26
Case Study — Algol 60

Algol 60 has one loop construct:
- \textit{for} ::= \texttt{for id := list do stat}
- \textit{list} ::= \texttt{enum \{ \_ enum \}}
- \texttt{enum} ::= \textit{expr} | \texttt{expr step expr until expr} | \texttt{expr while condition}

- \textit{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:
- \text{for } i := 1, 2, 5, 7, 9 \text{ do } ...
- \text{for } i := 1 \text{ step } 2 \text{ until } 10 \text{ do } ...
- \text{for } i := i, i + 2 \text{ while } i < 10 \text{ do } ...

This generality is usually overkill...

Tail Recursion

A function is \textit{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 \textit{reuse} the space of the current stack frame instead of allocating a new one for the recursive call.
Tail Recursion...

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

\text{⇓}

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

You can often transform a non-tail-recursive function into a tail-recursive one.
The idea is to pass a \textit{continuation} of the work that is to be done \textit{after} the call as a parameter to the call.
This is called \textit{continuation-passing style} (CPS).
The next slide shows how the factorial function has been made tail-recursive using the CPS transformation.

Tail Recursion...

\text{(define (fact } n)\
\text{if } (= n 1)\
\quad 1\
\quad (* n (fact (- n 1)))))

\text{(define (fact-cps } n \text{C})\
\text{if } (= n 1)\
\quad \text{C 1)\
\quad (fact-cps (- n 1) (\text{lambda(v) (C (* n v))})))

\text{(fact-cps 5 (lambda(v) (display v)))}

Readings and References

\textbullet \text{ Read Scott, pp. 233–242, 249–257, 260–278, 284–291}