Programming Language & Compiler

Control Flow

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Control Flow

- Expression evaluation

- Basic paradigms for control flow
  - Sequencing
  - Selection
  - Iteration
  - Procedural abstraction
  - Recursion
  - Concurrency
  - Exception handling and speculation
  - Non-determinacy

Expression Evaluation

- Infix, prefix operators
  - Prefix notation does not incur ambiguity
  - Infix notation leads to ambiguity without parentheses

- Precedence, associativity
  - C has 15 levels – too many to remember
  - Pascal has 3 levels – too few for good semantics
  - Fortran has 8 levels
  - Ada has 6 levels

- Lesson
  - When unsure, use parentheses!

Precedence for Infix Notations

Fortran	Pascal	C	Ada
		++, -- (post-inc., dec.)	
**	not	++, -- (pre-inc., dec.), +, - (unary), &, * (address, contents of), !, ~ (logical, bit-wise not)	abs (absolute value), not, **
*, /	*, /, div, mod, and	* (binary), /, % (modulo division)	*, /, mod, rem
+, - (unary and binary)	+, - (unary and binary), or	+, - (binary)	+, - (unary)
		<<, >> (left and right bit shift)	+, - (binary), & (concatenation)
.eq., .ne., .lt., .le., .gt., .ge. (comparisons)	<, <=, >, >=, =, <>, IN	<, <=, >, >= (inequality tests)	=, /= , <, <=, >, >=
.not.		==, != (equality tests)	
		& (bit-wise and)	
		^ (bit-wise exclusive or)	
		| (bit-wise inclusive or)	
.and.		&& (logical and)	and, or, xor (logical operators)
.or.		|| (logical or)	
.eqv., .neqv. (logical comparisons)		?: (if...then...else)	
		=, +=, -=, *=, /=, %=, >>=, <<=, &=, ^=, |= (assignment)	
		, (sequencing)	

Figure 6.1 Operator precedence levels in Fortran, Pascal, C, and Ada. The operators at the top of the figure group most tightly.

Safe Evaluation

- Ordering of operand evaluation
  - Generally assumed to be safe
    - `a * b + c / d`

      for '*' the order of evaluation can be either a, b or b, a
    - `a + f(b) + c * d`

      What if `f(b)` changes the value of c inside the function body?

- Arithmetic identities
  - Commutativity is assumed to be safe
    - `a + b = b + a`
  - Associativity is known to be dangerous
    - `(a + b) + c ≠ a + (b + c)`

      if `a` ≅ `MAXINT` and `b` ≅ `MININT` and `c<0`

Short-Circuiting

- Evaluating partial boolean expressions, not all
  - Consider `(a < b) && (b < c)`

    If `a >= b` there is no point evaluating whether `b < c` because `(a < b) && (b < c)` is automatically false
  - Other similar situations

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

- Short-circuiting improves the performance

```
if (p != NULL && p->key != val)
   insert(p->next, val);
```

  - What if short-circuiting is not provided as in Pascal?

Value vs. Location

- Assignment statement

```
d = a;
a = b + c;
```

value of a, r-value

location of a, l-value

- Value model
  - Expression can be either l-value or r-value
  - Not all expressions can be an l-value (e.g. 2+3 = a)

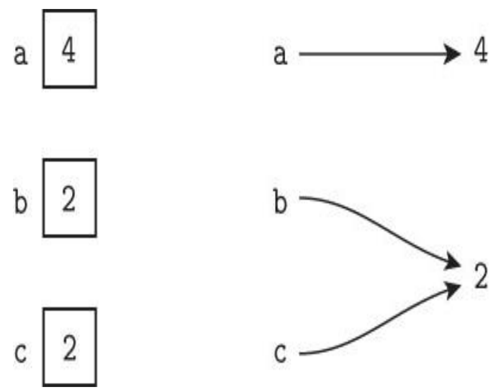
- Reference model
  - Every variable is an l-value
  - When a variable is used for r-value, it must be *dereferenced* to obtain the value. (It is done implicitly and automatically.)

Value Model vs. Reference Model

- Variables as values vs. variables as references
  - Value-oriented languages
    - C, Pascal, Ada
  - Reference-oriented languages
    - Most functional languages (Lisp, Scheme, ML)
    - Clu, Smalltalk
  - Algol-68 kind a halfway in-between
  - Java deliberately in-between
    - Built-in (primitive) types are values

      e.g. byte, char, int, float, boolean, …
    - User-defined types are references to objects

      e.g. all classes



Value model   Reference model

Expression- vs. Statement-Oriented

- Expression-oriented languages:
  - No separate notion of expression and statement
  - Functional languages (Lisp, Scheme, ML), Algol-68

```
a := if  b < c then d else e;
a := begin f(b), g(c) end

g(d);
2 + 3;
```

Statements in other languages can be used as expressions

Expressions are used and the results are thrown away

- Statement-oriented languages:
  - Most imperative languages

- C is kind a halfway in-between
  - Allows expression to appear instead of statement

Side Effects

- Side effect is a permanent state change by a function
  - Often discussed in the context of functions
  - 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 the whole von Neumann model of computing
  - In (pure) functional, logic, and dataflow languages, there are no such changes (single-assignment languages)
  - But side effect can be nice for some functions   e.g. rand()

Sequencing

- Sequencing
  - Specifies a linear ordering on statements
    - One statement follows another
  - Very imperative, Von-Neuman

Selection

- Selection
  - Same meaning as series of `if-then-else` statements

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

  - Examples

<Modula-2 >

```
IF a = b THEN ...
ELSIF a = c THEN ...
ELSIF a = d THEN ...
ELSE ...
END
```

<Lisp>

```
(cond

        ((= A B) (Expr1))
        ((= A C) (Expr2))
        ((= A D) (Expr3))
        (T       (Exprt))
)
```

Selection Implementation

- Conditional branch instruction
  - For simple selections
- Jump code
  - For general selections and logically-controlled loops

- Implementation with short-circuiting
  - No need to compute the whole boolean value into a register, then test it for conditional jump
  - Indicate the addresses to which control should branch, if a partial expression is true or false (short-circuiting)

Jump Code for Short-Circuiting

- Jump is especially useful in the presence of short-circuiting

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

Code for No Short-Circuiting

- Code generated w/o short-circuiting (Pascal)

```
((A > B) and (C > D)) or (E <> F)
```

```
        r1 := A
        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:
```

Code for Short-Circuiting

- Code generated w/ short-circuiting (C)

```
((A > B) and (C > D)) or (E <> F)
```

```
        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:
```

Selection – case/switch

- Sequence of *if-then-else* (nested *if-then-else*) can be rewritten as *case/switch*

<Modula-2>

```
CASE ... OF
   1:    clause_A
|  2, 4: clause_B
|  3, 6: clause_C
   ELSE  clause_D
END
```

Jump Tables for case/switch

- (Linear) jump tables
  - Instead of sequential test, compute *address* to jump to

```
T:   &L1                              -- case 1
     &L2                              -- case 2
     &L3                              -- case 3
     &L2                              -- case 4
     &L4                              -- case 5
     &L3                              -- case 6
L5:  r1 := ...                        -- calculate tested expr
     if r1 < 0 or r1 > 6 goto L4   -- ELSE case
     r2 := T[r1-1]
     goto *r2
L6:
```

Alternative Implementations

- Linear jump table is fast for case/switch
  - Also space efficient, if overall set of cases are dense and does not contain a large ranges
  - May consume extraordinary space for large value ranges

- Alternatives
  - Sequential testing (nested ifs), $O(n)$
    - Good for small number of cases
  - Hashing, $O(1)$
    - Attractive for large label values
    - But space inefficient for large value ranges
  - Binary search , $O(\log n)$
    - Accommodate ranges easily

Iteration

- Logically-controlled loops
  - Controlled by a boolean expression

```
while condition_expr
do
    ...
enddo
```

- Enumeration-controlled loops
  - `i`: index of the loop, loop variable
  - Controlled by *index*'s *initial value*, *its bound*, and *step size*
  - Semantic complications
    - Loop enter/exit in other ways
    - Scope of control variable
    - Changes to bounds within loop
    - Changes to loop variable within loop
    - Value after the loop

```
do i = 1, 10, 2
    ...
enddo
```

Recursion

- Recursion is equally powerful to iteration
  - Mechanical transformation back and forth
  - Often more intuitive (sometimes less)
  - *Naïve* implementation is less efficient
    - If a recursive call is actually implemented with a subroutine call, it will allocate space for its function frame (local variables, bookkeeping information)
    - Compiler optimizations is required to generate excellent code for recursion (e.g., tail recursion)

Tail Recursion

- If no computation follows a recursive call, we call it *tail recursion*
- Tail recursion is desirable for optimization
  - Optimizing compiler can optimize it easily
  - The information to store for the previous function is only the return address, since nothing to compute after return
  - Otherwise, we may need to keep local variables for the remaining computation after recursive calls

Tail Recursion Elimination

```
int gcd (int a, int b) { /* assume a, b > 0 */
   if (a == b) return a;
   else if (a > b) return gcd (a - b,b);
   else return gcd (a, b – a);
}
```

Return multiple times at the end

```
int gcd (int a, int b) { /* assume a, b > 0 */
start:
   if (a == b) return a;
   else if (a > b) { a = a - b; goto start; }
   else { b = b – a; goto start; }
}
```

Return once at the end

Summary

- Expression
  - Evaluation order – commutativity, associativity
- Control flow
  - Sequencing
  - Selection
    - Short-circuiting, jump table, …
  - Iteration (loop)
    - Logically-controlled, enumeration-controlled
  - Recursion
    - Optimization for tail-recursion