Control Flow

Language Mechanisms

- Sequencing: intuition of linear order between back-to-back statements
- Selection: to represent conditions and choices; if/case/switches
- Iteration: repeat some piece of code
- Procedural abstraction: logical aggregation of work (and probably data)
- Recursion: expression or entity defined in (simpler) terms of itself, directly or indirectly; computational model requires a stack on which to save information

Language Mechanisms

- Concurrency: parts of a program to be executed at the same time, either partially or in full
- Exception handing and speculation: program fragment executed with the knowledge and possibility that something could go wrong; mechanisms to handle the wrong part; state back-tracking; different forms of speculation

Symbol Table

- We will implement it as as array of symbols
- Each symbol will have:
  - Identifier name
  - Identifier type
  - Identifier width
  - Value
- Will assume that we have a function: maketemp (table);
- Our simple compiler will only support int

Instruction Table

- A list / table / array of instructions
- Each instruction will have some number of fields (for us):
  - operator
  - operand 1
  - operand 2
  - operand 3
- If using 3 operands, it’s called 3-address form (standard terminology)
- Will assume we have a function: gencode (op, a1, a2, a3)

Program Execution in our Interpreter

- We distinguish between instructions being generated at compile time and instructions that will be executed (at run-time)
- At compile-time, we need to know how many instructions we have created and/or what is the entry or position of the last instruction generated
- At run-time, execution flows mostly linearly:
    - Execution position defined by the Program Counter (PC)
    - Start with ”first” instruction: PC ← 0
    - Statement Sequencing is achieved by executing instructions in the table code, one after another, and incrementing the Program Counter (PC): PC ← PC + 1
    - Control-flow constructs (for, while, repeat, do-while, if-then, if-then-else, switch, try, etc): all manipulate the PC by changing it in non-linear fashion

Instruction Semantics

Operator	a1	a2	a3	Description
OP_ADD	reg0	reg1	reg2	reg0 ← reg1 + reg2
OP_MUL	reg0	reg1	reg2	reg0 ← reg1 + reg2
OP_UMIN	reg0	N/A	reg2	reg0 ← - reg2
OP_LT	reg0	reg1	reg2	reg0 ← reg1 < reg2
OP_JMP	N/A	N/A	instr	pc ← instr
OP_JNZ	cond	N/A	instr	If (cond = True) pc ← instr
OP_JZ	cond	N/A	instr	If (cond = False) pc ← instr
OP_PUSHA	arg			
OP_CALL	new_instr	Ret	Old_instr	sp ← sp + something; pc ← new_instr
OP_LOAD	reg		addr	reg ← M[addr]
OP_STORE	addr		reg	M[addr] ← reg

Sequencing

- Essentially, list of statements:
  - S1; S2; S3; …; Sn
- Effect: S1 executes first, followed by S2, S3, and so on
- Compilers will exploit lack of dependencies (information flow) between pairs of statements (e.g. Si and Sj) to reorder them in a legal fashion → similar to out-of-order (OoO) execution
- Imperative languages would provide dedicated delimiters: {/}, begin/end
- List of statements surrounded by delimiters = block or compounded statement

Short-Circuit Evaluation

Consider:

- if (a < b && b < c) { …}
- for (i = 0; i < N && A[i] != NULL; i++)
- for (i = 0; A[i] != NULL && i < N; i++)

Idea: avoid unnecessary work

Problem: some of the leftover work could desired side effects

Example: while (a = my_function(x,a) && x++) { … }

Language dependent

Some languages (I didn't know this) might have dedicated operators for short-circuit

Ada provides:

- `and` vs `and` followed by `then`
- `or` vs `or` followed by `else`

Examples:

- if (d = 0.0 or else n/d < threshold) then ..
- if (p /= null and then p.parent = someval) …

Semantically equivalent to nested ifs, additional logic and control flow

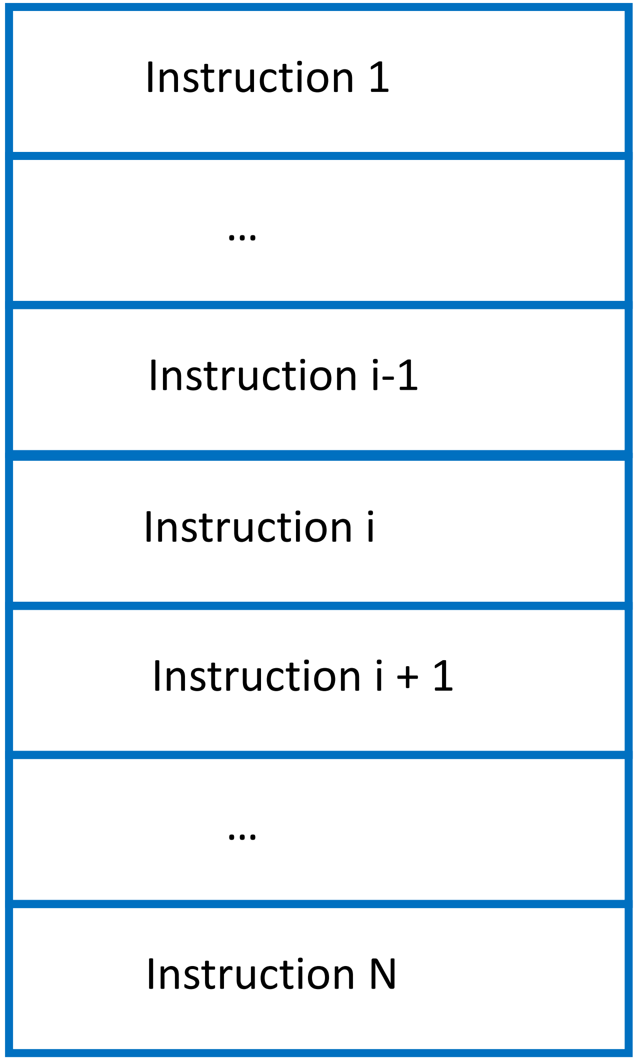
Control-Flow Productions

```
assign ← id ":=" expr ;
block ← BEGIN stmt_list END ;
stmt ← assign
   | if
   | repeat
   | write
   | read
   ;
stmt_list ← stmt_list ';' stmt
   | stmt
   ;
```

```
body ← stmt
   | block
   ;
if ← IF '(' expr ')'
       THEN body
       elsebranch ;
elsebranch ← ELSE body
   | ε
   ;
repeat ← REPEAT body
          UNTIL expr ;
```

Structured and Unstructured Flow

- In memory, all instructions are stored in contiguous fashion
- *Structured* refers refers to using control-flow structures (if-then, for, while, do, repeat, case/switch, exceptions, break/exit) → *top-down design*
- Many control-flow constructs were introduced from Algol 60
- *Unstructured* relies on labels and unconditional jumps (as in assembly)
- Label: Identifier serving as placeholder for some instruction position
- Jump: some instruction in the PL that forces continuing execution at the target of the jump
- Some languages no dot support unstructured control-flow
- Unstructured flow considered bad (makes code hard to read, maintain, etc)



Repeat Codegen

```
repeat ← REPEAT { $$ = next_instr; }
          body
          UNTIL
          expr {
            $$ = gencode (JZ, expr, N/A, $2);
          }
```

Target of
jump instruction
is “backward”, so need to
store temporarily the
instruction
destination that will
be generated “later”

While Codegen

```
while ← WHILE
        { $$ = next_instr; }
        cond
        { $$ = gencode(JZ, $3, N/A, TBDA); }
        body
        {
          gencode(JMP, N/A, N/A, $2);
          itable[$4].a3 = next_instr;
        }
  ;
```

- Target of jump instruction is “forward”, so need to store temporarily the instruction entry that will be completed later.
- Unconditional jump to re-evaluate condition

If last_instr is used instead, you will get an infinite loop

IF Codegen

```
if ← IF '(' expr ')' THEN
        { $$ = gencode(JZ, expr, N/A, TBDA); }
        body
        { $$ = gencode (JMP, N/A, N/A, TBDA);
          itable[$6].a3 = next_instr;
        }
        elsebranch
        { itable[$8].a3 = next_instr; }
   ;
elsebranch ← ELSE body
  | ε
  ;
```

Skip the true-branch if cond is false

Skip the false-branch if cond is True

Targets of both jump instructions are "forward", so need to store temporarily the instruction entry that will be completed later

Structured and Unstructured Flow

- In Basic, the target of the GOTO could also be a line number
- *break*: stops execution of single loop construct in C/C++
- *continue*: skips the remaining instructions in a loop and proceeds with evaluating the condition of the next iteration
- Multi-level returns (MLR): some construct that allows to exit from several function calls
- Unwinding:
  - repair stack, remove corrupted/failed functions, deallocate stack frames
  - A lot of book-keeping: state in registers, fetching access links
- Think how to implement the <u>break</u> and <u>continue</u> constructs in our compiler

```
function f1 () {
  …
  call f2 ();
  …
  label HERE;
…
}

function f2 ()
{ … call f3 (); …}

function f3 () {
  …
  if (error) goto HERE;
  …
}
```

Structured and Unstructured Flow

- Exception handling:
  - dangerous code + repair code
  - Internally, not very different from a switch or for
  - Several implicit jumps, depending on what happens, where, and when → control transfer
- Similarities between MLR and structured exceptions:
  - Control transfer from inner to outer context
  - Unwinding stack (functions that failed)
- Distinction between (MLR) and structured exceptions:
  - Completion of task: success for MLR, failure for exceptions

```
try {
  // dangerous code
} catch (ExceptionType e1) {
  // do something
} catch (ExceptionType e2) {
  // some other error
}
[ finaly {
  // optional
  // code to always executed
  }
]
```

Expression Evaluation

- An expression is either a simple object (literal or variable) or some function of these
- For the latter, we use the terms *operators* and *operands*
- Languages provide ”simple”, pre-built math functions via operators
- Operators are applied to operands
- FYI: ”simple” is relative; compare C vs. Python
- Some languages could have more than a single name for an operator, and rely on syntactic sugar to simplify writing; examples:
  - Ada: a + b is short for “+”(a,b)
  - C++: a+b is short for a.operator+(b) or operator+(a,b)
  - Other (some language): 0 <= i,j < N could be short for 0 <= i < N and 0 <= j < N

Expression Evaluation

- Language defines the operator notation: infix, prefix, postfix
  - prefix: **op** a b, or **op**(a,b) or (**op** a b)
  - infix: a **op** b
  - postfix: a b **op**
- Most imperative languages use infix notation for binary operators and prefix notation for unary ones
- Lisp uses prefix notation for all functions, in Cambridge Polish notation:
  - (* (+ 1 3) 2) == (1 + 3)*2
  - (append a b c my_list)
- ML-family languages avoid parentheses, except for disambiguation:
  - max (2 + 3) 4;

Precedence and Associativity

- In what order should operators be evaluated?
- Example with Fortran: a + b * c ** d ** e / f
- Choices:
  i. ((((a + b) * c) ** d) ** e) / f or
  ii. a + (((b * c) **) ** (e/f))
  iii. a + ((b * (c ** (d ** e))) / f)
- Fortran opts for the last one, exponentiation being right associative, and having higher precedence than multiplicative operators
- Recall:
  - Precedence: in which order should operators of different categories be evaluated, e.g. {+,-} and {*,/}
  - Associativity: in what order should operations in the same category be evaluated, i.e. left-to-right or right-to-left?

Precedence and Associativity

- I like this statement from the book:

  ”The precedence structure of C (…, of its descendants, C++, Java, C#) is substantially richer than that of most other languages …”

- And this other statement:

  “It is probably fair to say that most C programmers do not remember all of their language’s precedence levels.”

- When in doubt: consult the language reference or add parentheses
- Now, compare with Pascal:

  ```
  if (A < B and C < D) then (* good luck *)
  ```

Precedence and Associativity

- Rules for basic arithmetic operators are mostly standard and uniform across languages, i.e. associate left-to-right
- Example 1: 9 – 3 – 2 == 4, not 8
- Example 2 (Fortran): 4 ** 3 ** 2 == 4 ** 9 and not 256 ** 2
- Example 3 (Ada): exponentiation does not associate, so explicit parenthesis are necessary: (4 ** 3) ** 2 or 4 ** (3 ** 2)
- Example 4 (C): multiple assignments as ”a = b = a + c”, obviously is right associative

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)	

Taken from the book "Programming Language Pragmatics" by Michael L. Scoot

Assignments

- Pure functional languages:
  - rely solely on expressions
  - computation = expression evaluation
  - complex computations employ recursion to generate values, expressions and contexts
- Imperative programming:
  - Attempts to model memory state
  - Sequences of changes/updates on/to memory
  - Assignment = abstraction for memory write
  - Assignments = {value, references/address} → value stored to address

Assignments

- Side effect: influence of a program construct on subsequent computations
- Best example, the assignment in imperative languages, two parts:
  - right-hand side evaluation
  - more importantly, writing the result of the rhs expression to the address of the variable on the lhs
- Some PL distinguish between expressions and statements:
  - expressions ***may*** have side effects, e.g. a = ++c * 2
  - statements used to provide side effects
- Purely functional languages: no side effects, value of expression depends only on the referencing environment

References and Values

- Consider the following assignments in C:
  - d = a;
  - a = b + c;
- RHS: value
- LHS: location / address, where to store something
- Variables are named containers for values
- Distinction between l-values (address) and r-values (proper values, which could be addresses)
- Bunch of subtle rules:
  - not all expressions can be l-values → why?
  - Compare two (potential) assignments: 2 + 3 = a and a = 2 + 3, when will these be valid (if ever)
  - Not all l-values are simple names, consider:
    - (f(a)+3)->b[c] = 2;

References and Values

- Value model vs reference model
- Value model: values flow from rhs to lhs
- Reference model:
  - All variables are l-values
  - Variables automatically dereferenced when they appear in r-value contexts (equivalent to doing *variable in C)
  - Becomes important to distinguish 2 cases:
    a. variables that refer to the same object
    b. variables that refer to different objects, but with the same value

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

Pascal and Clu example

C example: int a; int * ptra;

Java == and equals

References and Values

Reference Model

a := b + c; // Apparently as in Clu

a, b and c are essentially addresses

Actions for the above:

1. Get the value stored in the address of b
2. Get the value stored in the address of c
3. Compute new value
4. Store the value in the address of a

Value Model

Consider: a = b + c; // in C

Variables in rhs have values associated to them, so fetching their value is automatic

Actions for the above:

1. Get the address associated to b
2. Dereference the address of b and get the value stored there
3. Repeat the above for c
4. Compute new value
5. Store value at the address of a (lhs)

Read page 232, example 6.16: Boxing

Assignment Operators

- Assignment operators modify memory:
  - +=
  - *=
  - op=
- Advantage:
  - address calculation performed just once
  - simplifies code (we write a lot of something = something + somethingelse)
- C provides an assignment operator for each of its binary arithmetic and bit-wise operators, for a total of 10
  - also prefix and postfix [in|de]crements: var++, ++var, var-- and –var
- Prefix form: syntactic sugar for += and -=

Assignment Operators

- Postfix form: NOT syntactic sugar, i.e. has different semantics. Consider:

```
*p++ = *q++;
```

- The above copies values from q to p, then advances both pointers

Initialization

- Not all (imperative) languages provide mechanisms for declaration + initialization (a la c ➔ int c = (2 * something);)
- Useful to initialize variables:
  - static variables local to subroutines need an initial value (usually 0)
  - Initialized static variables can use global memory
  - Avoid computational errors
- Most languages will have mechanisms to initialize variables for pre-built datatypes
- Special mechanisms for “aggregate” types, i.e. arrays, structures
- Initialization saves time only for statically allocated variables, not for stack variables nor for heap variables

Definite Assignment

- Uses the (static) control flow of the program
- Conservative analysis
- Considers every possible execution path in the program
- Languages like java use this
- Example:

```
int i;
int j = 3;
…
if (j > 0) {
   i = 2;
}
…
if (j < 0) {
 // do something with i
}
```

Ordering in Expressions

- Precedence and associativity define order in which binary infix operators are evaluated
  - Do not necessarily specify orders in which operands are evaluated
- Example 1: a – g(b) – c * d
- Equivalent to : (a – g(b)) - (c * d)
- But: which one is evaluated first: (a – g(b)) or (c * d)
- Example 2: f(a, g(b), h(c))
- In which order are the arguments evaluated?

- This is important because of:
  - side effects
  - Code speed
- Usually this is “implementation dependent”
- Java and C# evaluate arguments from left to right