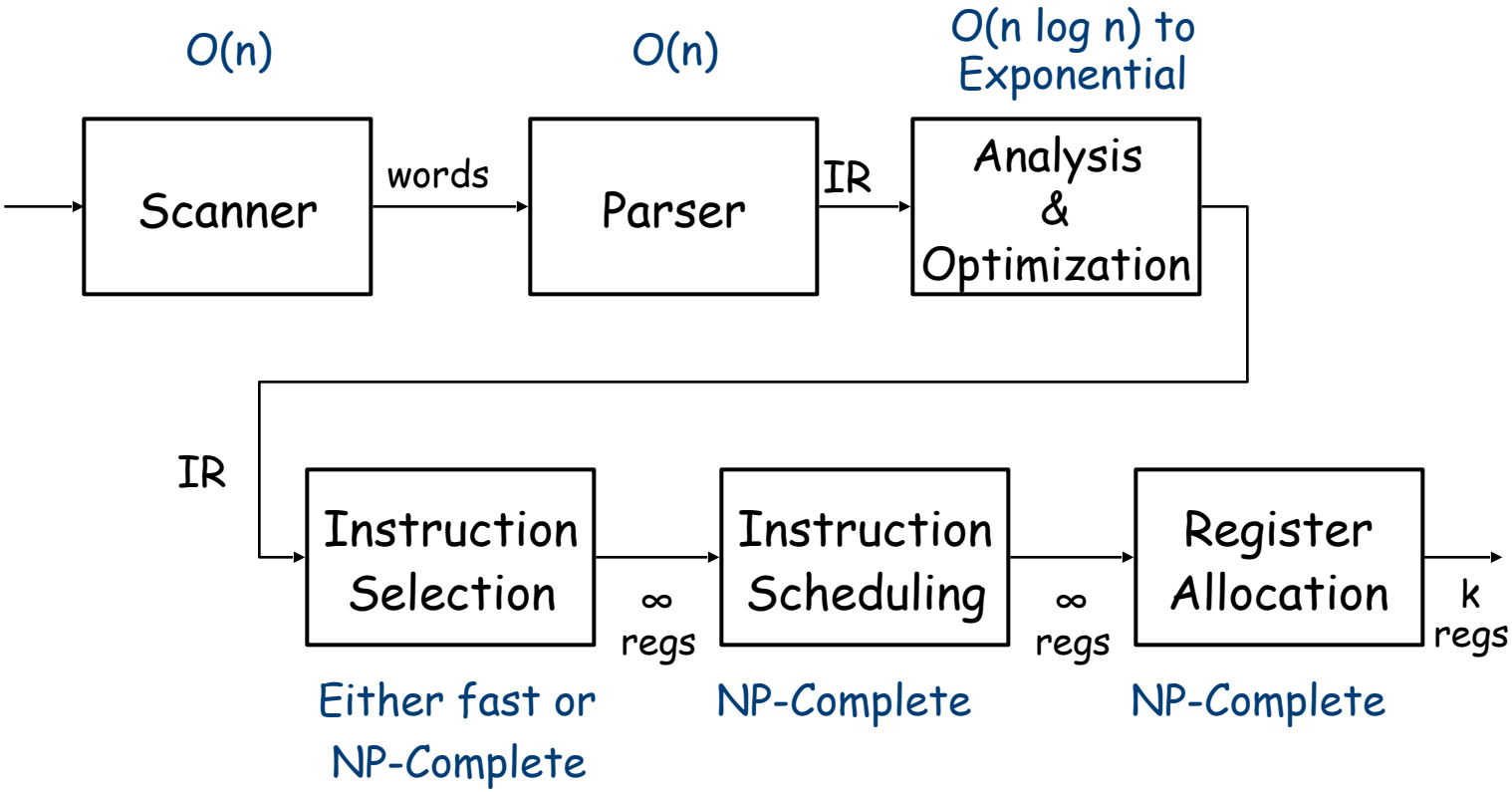
Introduction to Code Generation

Structure of a Compiler

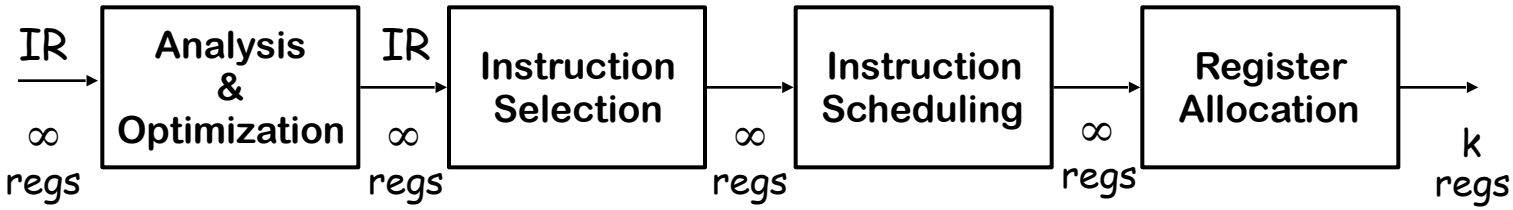


A compiler is a lot of fast stuff followed by some hard problems

- The hard stuff is mostly in code generation and optimization
- For multicores, we need to manage parallelism & sharing
- For unicore performance, allocation & scheduling are critical

Structure of a Compiler

We assume the following model



- Selection can be fairly simple (problem of the 1980s)
- Allocation & scheduling are complex
- Operation placement is not yet critical

  we assumed a unified register set

What about the IR ?

- Low-level, **RISC**-like IR such as **ILOC**
- Has "enough" registers
- **ILOC** was designed for this stuff with:
  - Branches, compares, & labels
  - Memory tags
  - Hierarchy of loads & stores
  - Provision for multiple ops/cycle

Analysis & Optimization

- The translation of the front end was obtained by considering the statements one of the time as they were encountered
- This initial IR contains general implementation strategies that will work in any surrounding context
- At run time the code will be executed in a more constrained and predictable context
- The optimizer analyses the IR form of the code to discover facts about the context and use them to rewrite (transform) the code so that it will compute the same answer in a more efficient way

The Back End

The compiler back end traverses the IR form and emits the code for the target machine

- It selects target-machine operations to implement each IR operation (Instruction selection)
- It chooses an order in which the operations will execute efficiently (Instruction scheduling)
- It will decide which values will reside in registers and which in memory (Register allocation)

Definitions

Instruction selection

- Mapping IR into assembly code
- Assumes a fixed storage mapping & code shape
- Combining operations, using address modes (instr. reg+offset or reg to reg mode)

Instruction scheduling

- Reordering operations to hide latencies
- Assumes a fixed program (set of operations)
- Changes demand for registers

These 3 problems are tightly coupled and need static analysis

Register allocation

- Deciding which values will reside in registers
- Changes the storage mapping, may add false sharing
- Concerns about placement of data & memory operations

Code Shape (Chapter 7)

Definition

- The compiler must chose among many alternative ways to implement each construct on a given processor
- Those choices have a strong and direct impact on the quality of the final produced code
- Code shape is the end product of many decisions (big & small)

Impact

- Code shape has a strong impact on the behaviour of the compiled code and on the ability of the optimizer and back end to improve it
- Code shape can encode important facts, or hide them

Code Shape

Example -- the case statement on a character value

- Implement it as cascaded if-then-else statements
  - Cost depends on where your case actually occurs
  - O(256)
- Implement it as a binary search
  - Need a dense set of conditions to search
  - Uniform (log 256) cost
- Implement it as a jump table
  - Lookup address in a table & jump to it
  - We trade data space for speed
  - Uniform (constant) cost

Performance depends on order of cases!

All these are legal (and reasonable) implementations of the switch statement

Which implementation for switch?

The one that is the best for a particular switch statement depends on many factors such as:

-The number of cases and their relative executions frequencies
-The knowledge of the cost structure for branching on the processor

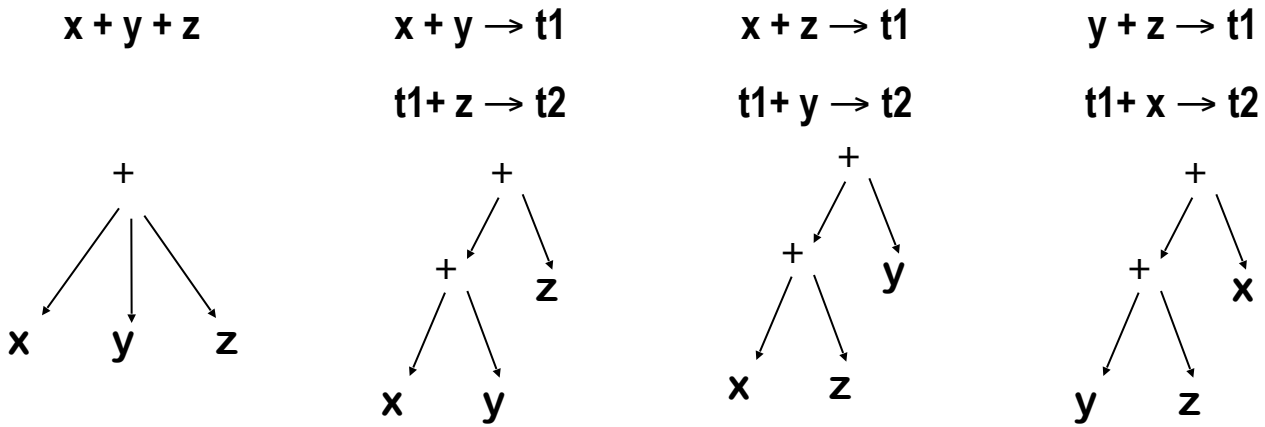
Even when the compiler does not have enough information to choose it must choose an implementation strategy

No amount of massaging or transforming will convert one into another

Code Shape: the ternary operation x+y+z

Several ways to implement x+y+z

Addition is commutative & associative for integers



- What if the compiler knows that x is constant 2 and z is 3?

The compiler should detect 2+3 evaluates and fold it into the code

- What if y+z is evaluated earlier?

The "best" shape for x+y+z depends on contextual knowledge

— There may be several conflicting options

Code Shape

Why worry about code shape? Can't we just trust the optimizer and the back end?

- Optimizer and back end approximate the answers to many hard problems
- The compiler's individual passes must run quickly
- It often pays to encode useful information into the IR
  - Shape of an expression or a control structure
  - A value kept in a register rather than in memory
- Deriving such information may be expensive, when possible
- Recording it explicitly in the IR is often easier and cheaper

How to generate ILOC code

- The three-address form lets the compiler name the result of any operation and preserve it for later reuse

- It uses always new register and leave to the allocator the duty of reduce them

- To generate code for a trivial expression a+b the compiler emits code to ensure that the values of a and b are in registers

- If a is stored in memory at offset $@a$ in the current Activation Record (AR), the code is

$$\begin{array}{lll} loadI & @a & \Rightarrow r_1 \\ loadA0 & r_{arp}, r_1 & \Rightarrow r_a \end{array}$$

Generating Code for Expressions

The idea

- Assume an AST as input and ILOC as output
- Use a postorder treewalk evaluator
  - Visits & evaluates children
  - Emits code for the op itself
  - Returns register with result
- Bury complexity of addressing names in routines that it calls
  - base(), offset() and val()
- Works for simple expressions
- Easily extended to other operators
- Does not handle control flow

the node of the AST

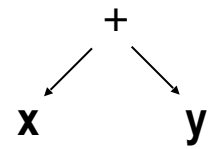
```
expr(node) {
  register result, t1, t2;
  switch (type(node)) {
      case ×,÷,+,– :
          t1← expr(left child(node));
          t2← expr(right child(node));
          result ← NextRegister();
          emit (op(node), t1, t2, result);
          break;
      case IDENTIFIER:
          t1← base(node);
           t2 ← NextRegister();
          emit (loadI, offset(node), none, t2);
          result ← NextRegister();
          emit (loadAO, t1, t2, result);
          break;
      case NUMBER:
          result ← NextRegister();
          emit (loadI, val(node), none, result);
          break;
       }
       return result;
  }
```

Generating Code for Expressions (a naive translation)

```
expr(node) {
  register result, t1, t2;
  switch (type(node)) {
      case ×,÷,+,– :
          t1← expr(left child(node));
          t2← expr(right child(node));
          result ← NextRegister();
          emit (op(node), t1, t2, result);
          break;
      case IDENTIFIER:
          t1← base(node);
           t2 ← NextRegister();
          emit (loadI, offset(node), none, t2);
          result ← NextRegister();
          emit (loadAO, t1, t2, result);
          break;
      case NUMBER:
          result ← NextRegister();
          emit (loadI, val(node), none, result);
          break;
       }
       return result;
 }
```

base(id) loads the right pointer to the AR where id is defined in register r_{arp}

Example:



Produces for register counter 0 :

espr("x"):

NextRegister(): r1 loadI @x -> r1

NextRegister(): r2 loadAO r_{arp}, r1 -> r2

espr("y"):

NextRegister(): r3 loadI @y -> r3

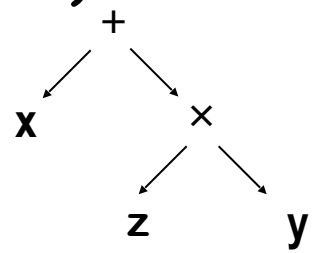
NextRegister(): r4 loadAO r_{arp}, r3 -> r4

NextRegister() : r5

Emit(add, r2,r4,r5) :

add r2, r4 -> r

Generating Code for Expressions (a naive translation)




```
expr(node) {
  register result, t1, t2;
  switch (type(node)) {
      case ×,÷,+,– :
          t1← expr(left child(node));
          t2← expr(right child(node));
          result ← NextRegister();
          emit (op(node), t1, t2, result);
          break;
      case IDENTIFIER:
          t1← base(node);
          t2 ← NextRegister();
          emit (loadI, offset(node), none, t2);
          result ← NextRegister();
          emit (loadAO, t1, t2, result);
          break;
      case NUMBER:
          result ← NextRegister();
          emit (loadI, val(node), none, result);
          break;
      }
      return result;
}
```

Produces for register counter 0 :

```
espr("x"):
NextRegister():r1,  loadI     @x       -> r1
NextRegister():r2   loadAO    rarp, r1 -> r2
espr("z"):
NextRegister():r3   loadI     @z       -> r3
NextRegister():r4   loadAO    rarp, r3 -> r4
espr("y"):
NextRegister():r5   loadI     @y       -> r5
NextRegister():r6   loadAO    rarp, r5 -> r6
NextRegister():r7
Emit(mul, r4,r6,r7) :
                    mult      r4,   r6 -> r7
NextRegister():r8
Emit(add, r2,r7,r8) :
                    add       r2,   r7 -> r8
```

Effects of code shape on the demand of registers

- Code shape decisions encoded into the tree walk code generator have an effect on the demand of registers

- The previous naive code uses 8 registers + r_{arp}

- The register allocator (later in compilation) can reduce the demand for register to 3 + r_{arp}

```
loadI   @x       -> r1
loadAO  rarp, r1 -> r1
loadI   @z       -> r2
loadAO  rarp, r2 -> r2
loadI   @y       -> r3
loadAO  rarp, r3 -> r3
mult    r2,   r3 -> r2
add     r1,   r2 -> r2
```

The best solution: alternate right and left children

evaluating z×y first

$$
\begin{array}{lll}
load & @z & \Rightarrow r_1 \\
loadA0 & r_{arp}, r_1 & \Rightarrow r_2 \\
load & @y & \Rightarrow r_3 \\
loadA0 & r_{arp}, r_3 & \Rightarrow r_4 \\
mult & r_2, r_4 & \Rightarrow r_5 \\
load & @x & \Rightarrow r_6 \\
loadA0 & r_{arp}, r_6 & \Rightarrow r_7 \\
add & r_7, r_5 & \Rightarrow r_8
\end{array}
$$

General rule: evaluate first the child that has more demand for registers

Code shape!

after register allocation

$$
\begin{array}{lll}
load & @z & \Rightarrow r_1 \\
loadA0 & r_{arp}, r_1 & \Rightarrow r_1 \\
load & @y & \Rightarrow r_2 \\
loadA0 & r_{arp}, r_2 & \Rightarrow r_2 \\
mult & r_1, r_2 & \Rightarrow r_1 \\
load & @x & \Rightarrow r_2 \\
loadA0 & r_{arp}, r_2 & \Rightarrow r_2 \\
add & r_2, r_1 & \Rightarrow r_1
\end{array}
$$

Some observations

What if our IDENTIFIER is

- already in a register?
- is in a global data area?
- a parameter value?
  - call by value
  - call by reference

Extending the Simple Treewalk Algorithm

It assumes a single case for id, more cases for IDENTIFIER

- What about values that reside in registers?
  - Modify the IDENTIFIER case
    - Already in a register ⇒ return the register name
    - Not in a register ⇒ load it as before, but record the fact
  - Choose names to avoid creating false dependences
- What about parameter values ?
  - Call-by-value ⇒ it can be handled as it was a local variable as before
  - Call-by-reference ⇒ extra indirection 3 instructions. The value may not be kept in a register across an assignment (see next slide)
- What about function calls in expressions?
  - Generate the calling sequence & load the return value
  - Severely limits compiler's ability to reorder operations

Keeping values in registers

- In a register-to register memory model, the compiler tries to assigns many values as possible to virtual registers
- Then the register allocator will map the set of virtual to physical registers inserting the spills
- However, the compiler can keep values in a register only for unambiguous value:
  a value that can be accessed with just one name is unambiguous

The problem with ambiguous values

- Consider a and b ambiguous and the following code

```
a := m+n;
b := 13;
c:= a+b;
```

If a and b refers to the same location c gets value 26, otherwise c gets value m+n+13;

The compiler cannot keep a in a register during the assignment of b unless it proves that the set of location that the two name refer to are disjoint. This analysis can be expensive!

sharing analysis !

Where do ambiguous values arise?

Ambigous values may arise in several ways :

- values stored in a pointer based variable
- call by reference formal parameter
- many compilers treat array element values as ambiguous because they can not tell if two references A[i,j] e A[n,m] refer to the same location

for safety the compiler has to consider that values as ambiguous

Extending the Simple Treewalk Algorithm

Adding other operators

- Evaluate the operands, then perform the operation
- Complex operations may turn into library calls (exp. and trig fun.)

Mixed-type expressions

- Insert conversion code as needed from conversion table
- Most languages have symmetric & rational conversion tables

Typical Table for Addition

+	Integer	Real	Double	Complex
Integer	Integer	Real	Double	Complex
Real	Real	Real	Double	Complex
Double	Double	Double	Double	Complex
Complex	Complex	Complex	Complex	Complex

If the type cannot be inferred at compile time, the compiler must insert code for run-time checks that test for illegal cases!

Extending the Simple Treewalk Algorithm

What about evaluation order?

Can use commutativity & associativity to improve code for integers

- For recognising that already computed that value

  a+b = b+a

- For recognising that it can compute subexpressions

  a+b+d and c+a+b

(it does not if it evaluates the expressions in strict left right order!)

It should not reorder floating point expressions!

- The subset of reals represented on a computer does not preserve associativity

  a-b-c the results may depend on the evaluation order!

Handling Assignment (just another operator)

lhs* ← *rhs

Strategy

- Evaluate rhs to a value (an rvalue)
- Evaluate lhs to a location (an lvalue)
  - lvalue is a register ⇒ move rhs
  - lvalue is an address ⇒ store rhs
- If rvalue & lvalue have different types
  - Evaluate rvalue to its "natural" type
  - Convert that value to the type of *lvalue

Unambiguous scalars go into registers

Ambiguous scalars or aggregates go into memory

Handling Assignment

What if the compiler cannot determine the type of the rhs?

- Issue is a property of the language & the specific program
- For type-safety, compiler must insert a run-time check
  - Some languages & implementations ignore safety (bad idea)
- Add a tag field to the data items to hold type information
  - Explicitly check tags at runtime

Code for assignment becomes more complex

```
evaluate rhs
if type(lhs) ≠ rhs.tag
   then
      convert rhs to type(lhs) or
      signal a run-time error
lhs ← rhs
```

Choice between conversion & a runtime exception depends on details of language & type system

Much more complex than static checking, plus costs occur at runtime rather than compile time

Handling Assignment

Compile-time type-checking

- Goal is to eliminate the need for both tags & runtime checks
- Determine, at compile time, the type of each subexpression
- Use runtime check only if compiler cannot determine types

Optimization strategy

- If compiler knows the type, move the check to compile-time
- Unless tags are needed for garbage collection, eliminate them
- If check is needed, try to overlap it with other computation

Can design the language so all checks are static

Handling Assignment when Reference (pointer) Counts is used

Reference counting is an incremental strategy for implicit storage deallocation (alternative to batch collectors called on demand)

- Simple idea
  - Associate a count with each heap allocated object
  - Increment count when pointer is duplicated
  - Decrement count when pointer is destroyed
  - Free when count goes to zero
- Advantages
  - Useful in real-time applications, user interfaces
  - Counts will be in cache

Disadvantages

- Freeing root node of a graph implies a lot of work & disruption
- Cyclic structures pose a problem

Handling Assignment when Reference Counts is used

Implementing reference counts

- Must adjust the count on each pointer assignment
- Extra code on every counted (e.g., pointer) assignment

Code for assignment becomes

```
evaluate rhs
lhs→count--
lhs ← addr(rhs)
rhs→count++
if (lhs→count  = 0)
      free lhs
```

With extra functional units & large caches, the overhead may become either cheap or free …

Summary

Code Generation for Expressions

- Simple treewalk produces reasonable code
  - Execute most demanding subtree first
  - Can implement treewalk explicitly, with an Attributed grammar or ad hoc Syntax directed translation …

- Handle assignment as an operator
  - Insert conversions according to language-specific rules
  - If compile-time checking is impossible, check tags at runtime
  - Talked about how to handle reference counting (an alternative to Garbage Collector

Next computing Array access!

Computing an Array Address of an array A[low:high]

A[i]

- @A + (i – low) x sizeof(A[i])
- In general: base(A) + (i – low) x sizeof(A[i])

Color Code:

Invariant

Varying

Depending on how A is declared, @A may be
- an offset from the ARP,
- an offset from some global label, or
- an arbitrary address.

The first two are compile time constants.

Computing an Array Address A[low:high]

A[i]

where w = sizeof(A[i])

- @A + (i – low) x w
- In general: base(A) + (i – low) x w

Almost always a power of 2, known at compile-time ⇒ use a shift for speed

If the compiler knows low it can fold the subtraction into @A

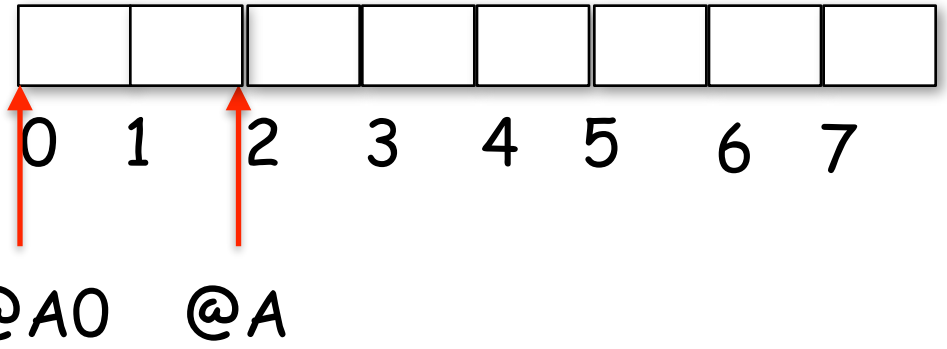
$$A_0 = @A - (low * w)$$

The false zero of A

The False Zero

$$A_0 = @A - (low * w)$$

A[2..7]



computing A[i] with A

$$\begin{array}{lll} loadI & @A & \Rightarrow r_{@A} \\ subI & r_i, 2 & \Rightarrow r_1 \\ lshiftI & r_1, 2 & \Rightarrow r_2 \\ loadA0 & r_{@A}, r_2 & \Rightarrow r_v \end{array}$$

computing A[i] with A0

$$\begin{array}{lll} loadI & @A_0 & \Rightarrow r_{@A_0} \\ lshiftI & r_i, 2 & \Rightarrow r_1 \\ loadA0 & r_{@A_0}, r_1 & \Rightarrow r_v \end{array}$$

How does the compiler handle A[i,j] ?

First, must agree on a storage scheme

Row-major order (most languages)

- Lay out as a sequence of consecutive rows
- Rightmost subscript varies fastest
- A[1,1], A[1,2], A[1,3], A[2,1], A[2,2], A[2,3]

Column-major order (Fortran)

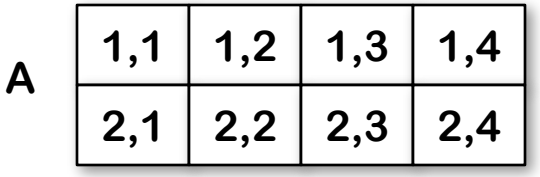
- Lay out as a sequence of columns
- Leftmost subscript varies fastest
- A[1,1], A[2,1], A[1,2], A[2,2], A[1,3], A[2,3]

Indirection vectors (Java)

- Vector of pointers to pointers to … to values
- Takes much more space, trades indirection for arithmetic
- Not amenable to analysis

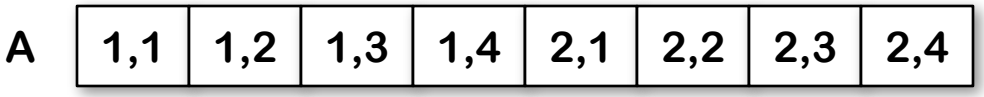
Laying Out Arrays

The Concept

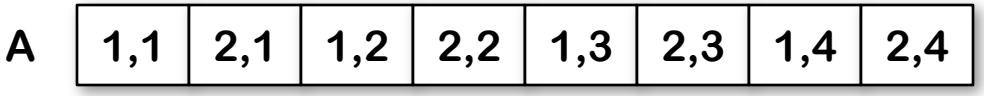


These can have distinct & different cache behavior

Row-major order



Column-major order



Indirection vectors

Computing an Array Address

where w = sizeof(A[1,1])

A[i]

- @A + (i – low) x w
- In general: base(A) + (i – low) x w

low_1 low_2 $hight_2$

$hight_1$

1,1	1,2	1,3	1,4
2,1	2,2	2,3	2,4

What about $A[i_1,i_2]$?

This stuff looks expensive!
Lots of implicit +, -, x ops

Row-major order, two dimensions

$@A + ((i_1 - low_1) \times (high_2 - low_2 + 1) + i_2 - low_2) \times w$

A[2,3] @A+(2-1)x 4+(3-1)

Column-major order, two dimensions

$@A + ((i_2 - low_2) \times (high_1 - low_1 + 1) + i_1 - low_1) \times w$

Indirection vectors, two dimensions

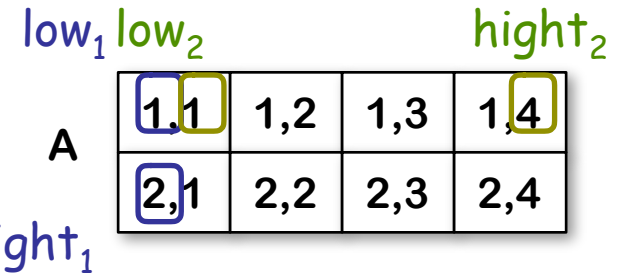
$*(A[i_1])[i_2]$ — where $A[i_1]$ is, itself, a 1-d array reference

e.g., $@A + (i_1 - low) \times w$

Optimizing Address Calculation for A[i,j]

In row-major order

$@A + (i - low_1) \times (high_2 - low_2 + 1) \times w + (j - low_2) \times w$



Which can be factored into

$@A + i \times (high_2 - low_2 + 1) \times w + j \times w$

$- (low_1 \times (high_2 - low_2 + 1) \times w) - (low_2 \times w)$

If low_i, $high_i$, and w are known, the last term is a constant

Define $@A_0$ as

$@A - (low_1 \times (high_2 - low_2 + 1) \times w - low_2 \times w$

If $@A$ is known, $@A_0$ is a known constant.

And len_2 as $(high_2 - low_2 + 1)$

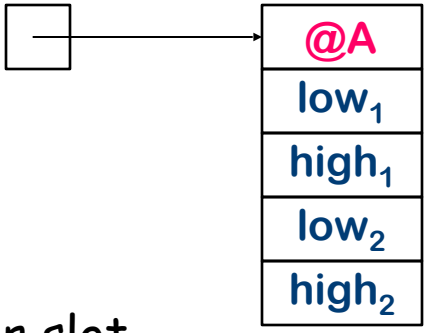
Then, the address expression becomes

$@A_0 + (i \times len_2 + j) \times w$

Compile-time constants

Array References

What about arrays as actual parameters?



Whole arrays, as call-by-reference parameters

- Need dimension information ⇒ build a dope vector
- Store the values in the calling sequence
- Pass the address of the dope vector in the parameter slot
- Generate complete address polynomial at each reference

Some improvement is possible

- Choose the address polynomial based on the false zero
- Pre-compute the fixed terms in prologue sequence

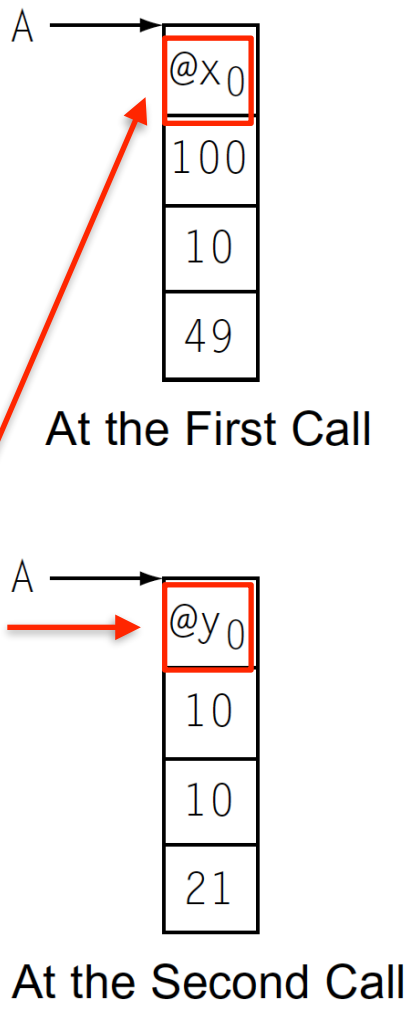
What about call-by-value?

- Most languages pass arrays by reference
- This is a language design issue

The Dope vector

```
program main;
   begin;
     declare x(1:100,1:10,2:50),
             y(1:10,1:10,15:35) float;
     ...
     call fee(x)
     call fee(y);
   end main;

procedure fee(A)
   declare A(*,*,*) float;
   begin;
     declare x float;
       declare i, j, k fixed binary;
       ...
       x = A(i,j,k);
       ...
   end fee;
```



Range checking

A program that refers out-of-the-bound array elements is not well formed.

Some languages like Java requires out-of-the-bound accesses be detected and reported.

In other languages compilers have included mechanisms to detect and report out-of-the-bound accesses.

The easy way is to introduce is to introduce a runtime check that verifies that the index value falls in the array range

Expensive!!

the compiler has to prove that a given reference cannot generate an out-of-bounds reference

Information on the bounds in the dope vector

Array Address Calculations

Array address calculations are a major source of overhead

- Scientific applications make extensive use of arrays and array-like structures
  - Computational linear algebra, both dense & sparse
- Non-scientific applications use arrays, too
  - Representations of other data structures
    - → Hash tables, adjacency matrices, tables, structures, …

Array calculations tend iterate over arrays

- Loops execute more often than code outside loops
- Array address calculations inside loops make a huge difference in efficiency of many compiled applications

Reducing array address overhead has been a major focus of optimization since the 1950s.

Example: Array Address Calculations in a Loop

A, B are declared as conformable floating-point arrays

```
DO J = 1, N
    A[I,J] = A[I,J] + B[I,J]
END DO
```

In column-major order

$@A_0 + (j \times len_1 + i) \times w$

len_1: number of rows!

Naïve: Perform the address calculation twice

```
DO J = 1, N
    R1 = @A0 + (J x len1 + I ) x w
    R2 = @B0 + (J x len1 + I ) x w
    MEM(R1) = MEM(R1) + MEM(R2)
END DO
```

Example: Array Address Calculations in a Loop

```
DO J = 1, N
      A[I,J] = A[I,J] + B[I,J]
END DO
```

More sophisticated: Move common calculations out of loop

```
R1 = I x w
c = len1 x w     ! Compile-time constant
R2 = @A0 + R1
R3 = @B0 + R1
DO J = 1, N
      a = J x c
      R4 = R2 + a
      R5 = R3 + a
      MEM(R4) = MEM(R4) + MEM(R5)
END DO
```

Loop-invariant code motion

Example: Array Address Calculations in a Loop

```
DO J = 1, N
      A[I,J] = A[I,J] + B[I,J]
END DO
```

Very sophisticated: Convert multiply to add

```
R1 = I x w
c = len1 x w     ! Compile-time constant
R2 = @A0 + R1 ;
R3 = @B0 + R1;
DO J = 1, N
      R2 = R2 + c
      R3 = R3 + c
      MEM(R2) = MEM(R2) + MEM(R3)
END DO
```

J is now bookkeeping

Operator Strength Reduction (§ 10.4.2 in EaC)

Representing and Manipulating Strings

Character strings differ from scalars, arrays, & structures

- Languages support can be different:
  - In C most manipulations takes the form of calls to library routines
  - Other languages provvide first-class mechanism to specify substrings or concatenate them

- Fundamental unit is a character
  - Typical sizes are one or two bytes
  - Target ISA may (or may not) support character-size operations

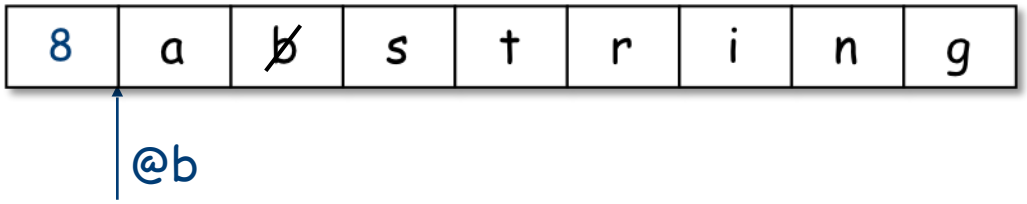
String operation can be costly

- Older CISC architectures provide extensive support for string manipulation
- Modern RISC architectures rely on compiler to code this complex operations using a set a of simpler operations

Representing and Manipulating Strings

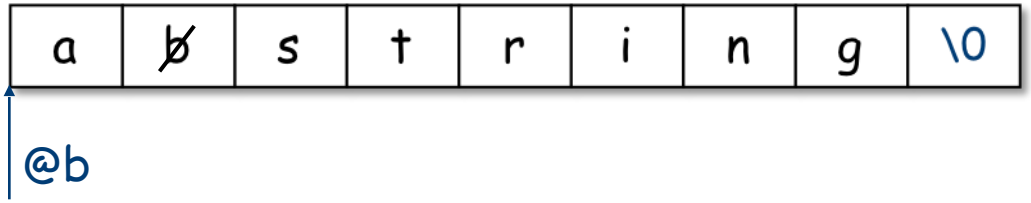
Two common representations of string "a string"

- Explicit length field



Length field may take more space than terminator

- Null termination



- Language design issue

Representing and Manipulating Strings

Each representation as advantages and disadvantages

Operation	Explicit Length	Null Termination
Assignment	Straightforward	Straightforward
Checked Assignment	Checking is easy	Must count length
Length	O(1)	O(n)
Concatenation	Must copy data	Length + copy data

Unfortunately, null termination is almost considered normal

- Hangover from design of C
- Embedded in OS and API designs

Manipulating Strings

Single character assignment

a[1]=b[2]

- With character operations
  - Compute address of rhs, load character
  - Compute address of lhs, store character
- With only word operations (>1 char per word)
  - Compute address of word containing rhs & load it
  - Move character to destination position within word
  - Compute address of word containing lhs & load it
  - Mask out current character & mask in new character
  - Store lhs word back into place

Manipulating Strings

Multiple character assignment

Two strategies

1. Wrap a loop around the single character code, or
2. Work up to a word-aligned case, repeat whole word moves, and handle any partial-word end case

With character operations

With only word operations

Manipulating Strings

Concatenation

- String concatenation is a length computation followed by a pair of whole-string assignments
  - Touches every character
  - There can be length problems!

Manipulating Strings

Length Computation

- Representation determines cost
- Length computation arises in other contexts
  - Whole-string or substring assignment
  - Checked assignment (buffer overflow)
  - Concatenation
  - Evaluating call-by-value actual parameter

Boolean & Relational Values

How should the compiler represent them?

- Answer depends on the target machine

Implementation of booleans, relational expressions & control flow constructs varies widely with the ISA

Two classic approaches

- Numerical (explicit) representation
- Positional (implicit) representation

Best choice depends on both context and ISA

Some cases works better with the first representation other ones with the second!

Boolean & Relational Expressions

First, we need to recognize boolean & relational expressions

Expr	→	Expr ∨ AndTerm	NumExpr	→	NumExpr + Term
	|	AndTerm		|	NumExpr - Term
AndTerm	→	AndTerm ∧ RelExpr		|	Term
	|	RelExpr	Term	→	Term × Value
RelExpr	→	RelExpr < NumExpr		|	Term ÷ Value
	|	RelExpr ≤ NumExpr		|	Value
	|	RelExpr = NumExpr	Value	→	¬ Factor
	|	RelExpr ≠ NumExpr		|	Factor
	|	RelExpr ≥ NumExpr	Factor	|	(Expr)
	|	RelExpr > NumExpr		|	number

Boolean & Relational Values

Next, we need to represent the values

Numerical representation

- Assign numerical values to TRUE and FALSE
- Use hardware AND, OR, and NOT operations
- Use comparison to get a boolean from a relational

If the target machine supports boolean operations that compute the boolean result

cmp_LT rx,ry-> r1 r1=True if rx<=ry, r1=False otherwise

x < y	becomes	cmp_LT	r_x,r_y	$\Rightarrow r_1$
if (x < y) then $stmt_1$ else $stmt_2$	becomes	cmp_LT cbr	r_x,r_y r_1	$\Rightarrow r_1$ $\rightarrow$ _$stmt_1$,_$stmt_2$

Boolean & Relational Values

What if the target machine uses a condition code?

cmp r1,r2 -> cc sets cc with code for LT,LE,EQ,GE,GT,NE

- Must use a conditional branch to interpret result of compare

If the target machine computes a code result of the comparison and we need to store the result of the boolean operation

x < y becomes

cbr_LT cc l2,l3 sets
PC=l2 if CC=LT
PC=l3 otherwise

	cmp	r_x,r_y	⇒	CC_1
	cbr_LT	CC_1	→	L_T,L_F
L_T:	loadI	1	⇒	r_2
	br		→	L_E
L_F:	loadI	0	⇒	r_2
L_E:	*... other statements ...*			

Boolean & Relational Values

The last example actually encoded result in r2

If result is used to control an operation, that may suffice

Example
if (x < y) then a ← c + d else a ← e + f

Straight Condition Codes			
	comp	r_x,r_y	⇒ CC_1
	cbr_LT	CC_1	→ L_1,L_2
L_1:	add	r_c,r_d	⇒ r_a
	br		→ L_{OUT}
L_2:	add	r_e,r_f	⇒ r_a
	br		→ L_{OUT}
L_{OUT}:	nop		

Boolean Comparisons			
	cmp_LT	r_x,r_y	⇒ r_1
	cbr		→ L_1,L_2
L_1:	add	r_c,r_d	⇒ r_a
	br		→ L_{OUT}
L_2:	add	r_e,r_f	⇒ r_a
	br		→ L_{OUT}
L_{OUT}:	nop		

Positional encoding!

Boolean & Relational Values

Other Architectural Variations

Straight Condition Codes				*Boolean Comparisons*			
	comp	r_x,r_y	$\Rightarrow CC_1$		cmp_LT	r_x,r_y	$\Rightarrow r_1$
	cbr_LT	CC_1	$\rightarrow L_1,L_2$		cbr		$\rightarrow L_1,L_2$
L_1:	add	r_c,r_d	$\Rightarrow r_a$	L_1:	add	r_c,r_d	$\Rightarrow r_a$
	br		$\rightarrow L_{OUT}$		br		$\rightarrow L_{OUT}$
L_2:	add	r_e,r_f	$\Rightarrow r_a$	L_2:	add	r_e,r_f	$\Rightarrow r_a$
	br		$\rightarrow L_{OUT}$		br		$\rightarrow L_{OUT}$
L_{OUT}:	nop			L_{OUT}:	nop		

Conditional move & predication both simplify this code

Example
if (x < y) then a ← c + d else a ← e + f

Conditional Move			*Predicated Execution*			
comp	r_x,r_y	$\Rightarrow CC_1$	cmp_LT	r_x,r_y	$\Rightarrow r_1$	
add	r_c,r_d	$\Rightarrow r_1$	(r_1) ? add	r_c,r_d	$\Rightarrow r_a$	
add	r_e,r_f	$\Rightarrow r_2$	($\neg r_1$) ? add	r_e,r_f	$\Rightarrow r_a$	
i2i_LT	CC_1,r_1,r_2	$\Rightarrow r_a$				

i2i_LT cc,r1,r2->r3 copy r1 in r3 if cc matches LT, copy r2 in r3 otherwise

(r1)? add r2,r3 ->r4 the add operation executes if r1 is true

Both versions avoid the branches

Both are shorter than cond'n codes or Boolean-valued compare

Are they equivalent to the initial code? Not always!

Are they better? does code size matter? or execution time?

Boolean & Relational Values

Consider the assignment $x \leftarrow a < b \wedge c < d$

Straight Condition Codes				*Boolean Compare*			
	comp	r_a, r_b	$\Rightarrow CC_1$	cmp_LT	r_a, r_b	$\Rightarrow r_1$
	cbr_LT	CC_1	$\rightarrow L_1, L_2$	cmp_LT	r_c, r_d	$\Rightarrow r_2$
L_1:	comp	r_c, r_d	$\Rightarrow CC_2$	and	r_1, r_2	$\Rightarrow r_x$
	cbr_LT	CC_2	$\rightarrow L_3, L_2$			
L_2:	loadI	0	$\Rightarrow r_x$			
	br		$\rightarrow L_{OUT}$			
L_3:	loadI	1	$\Rightarrow r_x$			
L_{OUT}:	nop					

Here, Boolean compare produces much better code

Boolean & Relational Values

Conditional move help here, too

Straight Condition Codes				*Boolean Compare*			
	comp	r_a,r_b	$\Rightarrow CC_1$	cmp_LT	r_a,r_b	$\Rightarrow r_1$
	cbr_LT	CC_1	$\rightarrow L_1,L_2$	cmp_LT	r_c,r_d	$\Rightarrow r_2$
L_1:	comp	r_c,r_d	$\Rightarrow CC_2$	and	r_1,r_2	$\Rightarrow r_x$
	cbr_LT	CC_2	$\rightarrow L_3,L_2$			
L_2:	loadI	0	$\Rightarrow r_x$			
	br		$\rightarrow L_{OUT}$			
L_3:	loadI	1	$\Rightarrow r_x$			
	br		$\rightarrow L_{OUT}$			
L_{OUT}:	nop					

$x \leftarrow a < b \wedge c < d$

Conditional Move		
comp	r_a,r_b	$\Rightarrow CC_1$
i2i_LT	CC_1,r_T,r_F	$\Rightarrow r_1$
comp	r_c,r_d	$\Rightarrow CC_2$
i2i_LT	CC_2,r_T,r_F	$\Rightarrow r_2$
and	r_1,r_2	$\Rightarrow r_x$

i2i_LT cc,r1,r2->r3 copy r1 in r3 if cc matches LT, copy r2 in r3 otherwise

Conditional move is worse than Boolean compare

The bottom line:

⇒ Context & hardware determine the appropriate choice

Control Flow

If-then-else

- Follow model for evaluating relationals & booleans with branches

Branching versus predication

- Frequency of execution
  - Uneven distribution ⇒ do what it takes to speed common case
- Amount of code in each case
  - Unequal amounts means predication may waste issue slots
- Control flow inside the construct
  - Any branching activity within the construct complicates the predicates and makes branches attractive

Short-circuit Evaluation

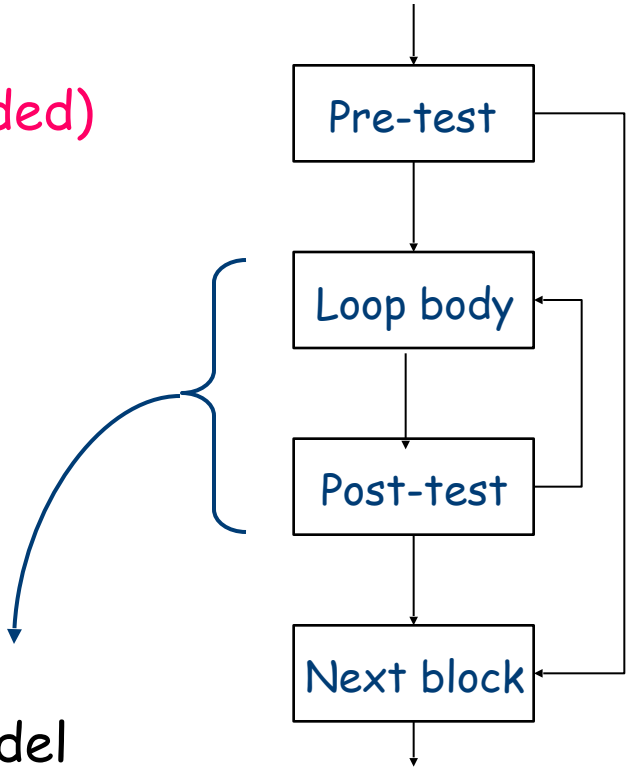
Optimize boolean expression evaluation (lazy evaluation)

- Once value is determined, skip rest of the evaluation
  `if (x or y and z) then …`
  - If x is true, need not evaluate y or z
    - → Branch directly to the "then" clause
  - On a PDP-11 or a VAX, short circuiting saved time
- Modern architectures may favor evaluating full expression
  - Rising branch latencies make the short-circuit path expensive
  - Conditional move and predication may make full path cheaper
- Past: compilers analyzed code to insert short circuits
- Future: compilers analyze code to prove legality of full path evaluation where language specifies short circuits

Control Flow

Loops

- Evaluate condition before loop (if needed)
- Evaluate condition after loop
- Branch back to the top (if needed)



while, for, do, & until all fit this basic model

Implementing Loops

for (i = 1; i< 100; 1) { loop body }
next statement

```
        loadI     1        ⇒ r1
        loadI     1        ⇒ r2
        loadI     100      ⇒ r3
        cmp_GE    r1,r3    ⇒ r4
        cbr       r4       → L2,L1
L1:     loop body
        add       r1,r2    ⇒ r1
        cmp_LT    r1,r3    ⇒ r5
        cbr       r5       → L1,L2
L2:     next statement
```

Initialization

Pre-test

Post-test

Case (switch) Statements

1. Evaluate the controlling expression
2. Branch to the selected case
3. Execute the code for that case
4. Branch to the statement after the case

Parts 1, 3, & 4 are well understood,

part 2 is the key:

need an efficient method to locate the designated code

many compilers provvide several different search schemas each one can be better in some cases.

Case Statements

1. Evaluate the controlling expression
2. Branch to the selected case
3. Execute the code for that case
4. Branch to the statement after the case (use break)

Parts 1, 3, & 4 are well understood, part 2 is the key

Strategies

- Linear search (nested if-then-else constructs)
- Build a table of case expressions & binary search it
- Directly compute address (requires dense case set)

Linear Search

```
switch (e1) {
   case 0:  block0;
            break;
   case 1:  block1;
            break;
   case 3:  block3;
            break;
   default: blockd;
            break;
}
```

Switch Statement

```
t1 ← e1
if (t1 = 0)
   then block0
   else if (t1 = 1)
      then block1
      else if (t1 = 2)
         then block2
         else if (t1 = 3)
            then block3
            else blockd
```

Implementing as a Linear Search

Binary Search

```
switch (e1)  {
   case 0:   block0
             break;
   case 15:  block15
             break;
   case 23:  block23
             break;
   ...
   case 99:  block99
             break;
   default:  blockd
             break;
}
```

Switch Statement

Value	Label
0	LB_0
15	LB_{15}
23	LB_{23}
37	LB_{37}
41	LB_{41}
50	LB_{50}
68	LB_{68}
72	LB_{72}
83	LB_{83}
99	LB_{99}

Search Table

```
t1 ← e1
down ← 0   // lower bound
up ← 10    // upper bound + 1
while (down + 1 < up)  {
   middle ← (up + down) ÷ 2
   if (Value [middle] ≤ t1)
      then down ← middle
      else up ← middle
}
if (Value [down] = t1
   then jump to Label[down]
   else jump to LBd
```

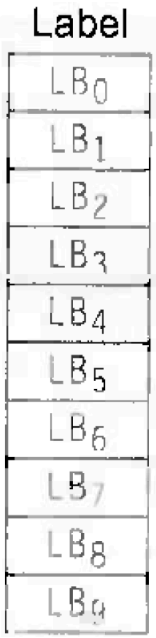
Code for Binary Search

Direct Address Computation

- requires dense case set

```
switch (e1) {
  case 0:  block0
           break;
  case 1:  block1
           break;
  case 2:  block2
           break;
  ...
  case 9:  block9
           break;
  default: blockd
           break;
}
```

Switch Statement



Jump Table

```
t1 ← e1
if (0 > t1 or t1 > 9)
   then jump to LBd
   else
      t2 ←@Table + t1 x 4
      t3 ← memory(t2)
      jump to t3
```

Code for Address Computation