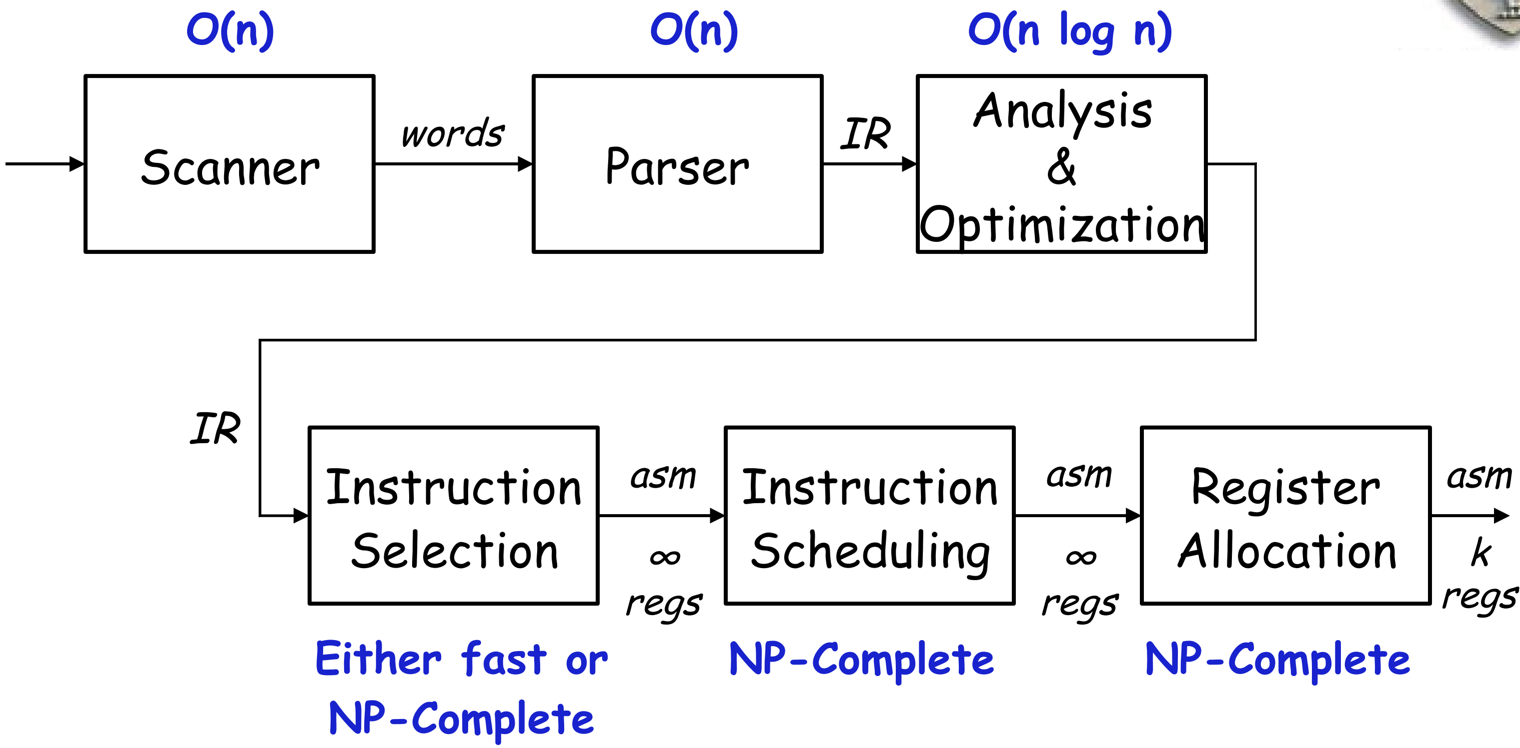
Introduction to Code Generation

Structure of a Compiler



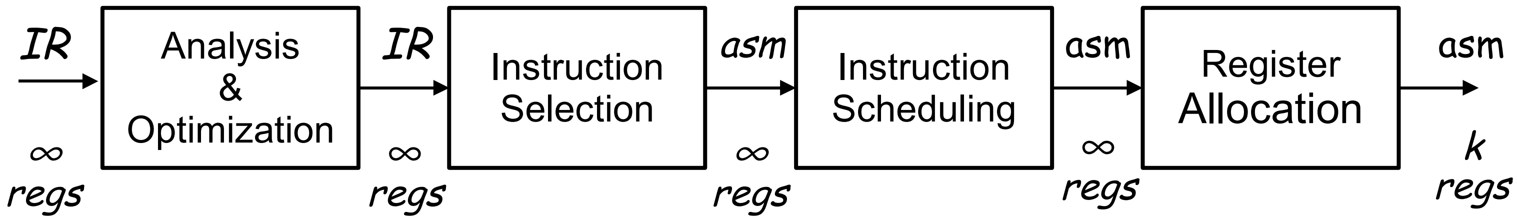
A compiler is a lot of fast stuff followed by some hard problems

→ The hard stuff is mostly in code generation and optimization

→ For superscalars, its allocation & scheduling that count

Structure of a Compiler

For the rest of CT, we assume the following model



- Selection is fairly simple (problem of the 1980s)
- Allocation & scheduling are complex
- Operation placement is not yet critical *(unified register set)*

What about the IR ?

- Low-level, RISC-like IR called ILOC
- Has "enough" registers
- ILOC was designed for this stuff

Branches, compares, & labels
Memory tags
Hierarchy of loads & stores
Provision for multiple ops/cycle

Definitions

Instruction selection

- Mapping *IR* into assembly code
- Assumes a fixed storage mapping & code shape
- Combining operations, using address modes

Instruction scheduling

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

Register allocation

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

These 3 problems are tightly coupled.

The Big Picture

How hard are these problems?

Instruction selection

- Can make locally optimal choices, with automated tool
- Global optimality is (undoubtedly) NP-Complete

Instruction scheduling

- Single basic block $\Rightarrow$ heuristics work quickly
- General problem, with control flow $\Rightarrow$ NP-Complete

Register allocation

- Single basic block, no spilling, & 1 register size $\Rightarrow$ linear time
- Whole procedure is NP-Complete

The Big Picture

Conventional wisdom says that we lose little by solving these problems independently

Instruction selection

- Use some form of pattern matching
- Assume enough registers or target "important" values

Optimal for > 85% of blocks

Instruction scheduling

- Within a block, list scheduling is "close" to optimal
- Across blocks, build framework to apply list scheduling

Register allocation

- Start from virtual registers & map "enough" into *k*
- With targeting, focus on good priority heuristic

Code Shape

Definition

- All those nebulous properties of the code that impact performance & code "quality"
- Includes code, approach for different constructs, cost, storage requirements & mapping, & choice of operations
- Code shape is the end product of many decisions *(big & small)*

Impact

- Code shape influences algorithm choice & results
- Code shape can encode important facts, or hide them

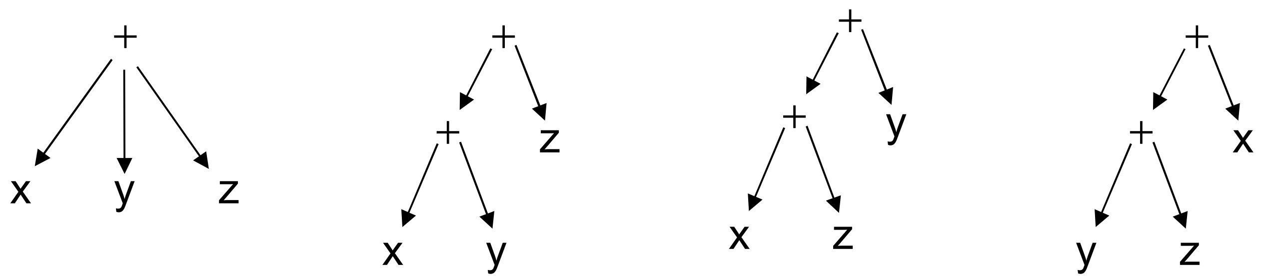
Rule of thumb: expose as much derived information as possible

- Example: explicit branch targets in ILOC simplify analysis
- Example: hierarchy of memory operations in ILOC *(in EaC)*

Code Shape

My favorite example

$x + y + z$	$x + y \rightarrow t1$ $t1 + z \rightarrow t2$	$x + z \rightarrow t1$ $t1 + y \rightarrow t2$	$y + z \rightarrow t1$ $t1 + z \rightarrow t2$



- What if x is 2 and z is 3?
- What if y+z is evaluated earlier?

Addition is commutative & associative for integers

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

→ There may be several conflicting options

Code Shape

Another example -- the case statement

- Implement it as cascaded if-then-else statements
  - → Cost depends on where your case actually occurs
  - → O(number of cases)
- Implement it as a binary search
  - → Need a dense set of conditions to search
  - → Uniform (log n) cost
- Implement it as a jump table
  - → Lookup address in a table & jump to it
  - → Uniform (constant) cost

Compiler must choose best implementation strategy

No amount of massaging or transforming will convert one into another

Generating Code for Expressions

The key code quality issue is holding values in registers

- When can a value be safely allocated to a register?
  - → When only 1 name can reference its value
  - → Pointers, parameters, aggregates & arrays all cause trouble
- When should a value be allocated to a register?
  - → When it is both *safe* & *profitable*

Encoding this knowledge into the *IR*

- Use code shape to make it known to every later phase
- Assign a virtual register to anything that can go into one
- Load or store the others at each reference
- ILOC has textual "memory tags" on loads, stores, & calls
- ILOC has a hierarchy of loads & stores (*see the digression*)

Relies on a strong register allocator

Generating Code for Expressions

```
expr(node) {
   int 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← offset(node);
              result ← NextRegister();
              emit (loadAO, t1, t2, result);
              break;
         case NUMBER:
              result ← NextRegister();
              emit (loadI, val(node), none, result);
              break;
          }
          return result;
  }
```

The concept

- Use a simple treewalk evaluator
- Bury complexity in routines it calls
  - *base*(), *offset*(), & *val*()
- Implements expected behavior
  - Visits & evaluates children
  - Emits code for the op itself
  - Returns register with result
- Works for simple expressions
- Easily extended to other operators
- Does not handle control flow

Generating Code for Expressions

```
expr(node) {
  int 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← offset(node);
          result ← NextRegister();
          emit (loadAO, t1, t2, result);
          break;
      case NUMBER:
          result ← NextRegister();
          emit (loadI, val(node), none, result);
          break;
   }
   return result;
}
```

Example:

```
      +
    ↙   ↘
   x     y
```

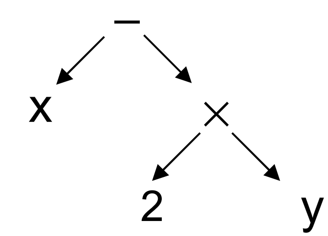
Produces:

```
expr(x)
  loadI @x          → r1
  loadA0 r0,r1      → r2

expr(y)
  loadI @y          → r3
  loadA0 r0,r3      → r4

NextRegister() : R5
emit(add,r2,r4,r5)
  add r2,r4         → r5
```

Generating Code for Expressions

```
expr(node) {
  int 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← offset(node);
            result ← NextRegister();
            emit (loadAO, t1, t2, result);
            break;
        case NUMBER:
            result ← NextRegister();
            emit (loadI, val(node), none, result);
            break;
         }
         return result;
 }
```

Example:



Generates:

loadI	@x	→ r1
loadAO	r0, r1	→ r2
loadI	2	→ r3
loadI	@y	→ r4
loadAO	r0,r4	→ r5
mult	r3, r5	→ r6
sub	r2, r6	→ r7

Extending the Simple Treewalk Algorithm

More complex cases for IDENTIFIER

- What about values 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?
  - → Many linkages pass the first several values in registers
  - → Call-by-value ⇒ just a local variable with "funny" offset
  - → Call-by-reference ⇒ needs an extra indirection
- What about function calls in expressions?
  - → Generate the calling sequence & load the return value
  - → Severely limits compiler's ability to reorder operations

Extending the Simple Treewalk Algorithm

Adding other operators

- Evaluate the operands, then perform the operation
- Complex operations may turn into library calls
- Handle assignment as an operator

Mixed-type expressions

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

Typical Addition Table

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

Extending the Simple Treewalk Algorithm

What about evaluation order?

- Can use commutativity & associativity to improve code
- This problem is truly hard

What about order of evaluating operands?

- 1^{st} operand must be preserved while 2^{nd} is evaluated
- Takes an extra register for 2^{nd} operand
- Should evaluate more demanding operand expression first

(Ershov in the 1950's, Sethi in the 1970's)

Taken to its logical conclusion, this creates Sethi-Ullman scheme

Generating Code in the Parser

Need to generate an initial IR form

- Chapter 4 talks about ASTs & ILOC
- Might generate an AST, use it for some high-level, near-source work (type checking, optimization), then traverse it and emit a lower-level IR similar to ILOC

The big picture

- Recursive algorithm really works bottom-up
  - → Actions on non-leaves occur after children are done
- Can encode same basic structure into *ad-hoc* SDT scheme
  - → Identifiers load themselves & stack virtual register name
  - → Operators emit appropriate code & stack resulting VR name
  - → Assignment requires evaluation to an *lvalue* or an *rvalue*
    - ♦ Some modal behavior is unavoidable

Ad-hoc SDT versus a Recursive Treewalk

```
expr(node) {
  int 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← offset(node);
          result ← NextRegister();
          emit (loadAO, t1, t2, result);
          break;
      case NUMBER:
          result ← NextRegister();
          emit (loadI, val(node), none, result);
          break;
       }
       return result;
}
```

```
Goal :      Expr  { $$ = $1; } ;
Expr:       Expr PLUS Term
            { t = NextRegister();
              emit(add,$1,$3,t); $$ = t; }
       |    Expr MINUS Term  {…}
       |    Term { $$ = $1; } ;
Term:       Term TIMES Factor
            { t = NextRegister();
              emit(mult,$1,$3,t); $$ = t; };
       |    Term DIVIDES Factor {…}
       |    Factor { $$ = $1; };
Factor:     NUMBER
            { t = NextRegister();
              emit(loadI,val($1),none, t );
              $$ = t; }
       |    ID
             { t1 = base($1);
               t2 = offset($1);
               t = NextRegister();
              emit(loadAO,t1,t2,t);
              $$ =  t; }
```

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*

Let hardware sort out the addresses !

Unambiguous scalars go into registers

Ambiguous scalars or aggregates go into memory

Handling Assignment

What if the compiler cannot determine the rhs's type ?

- This is a property of the language & the specific program
- If type-safety is desired, compiler must insert a run-time check
- Add a *tag* field to the data items to hold type information

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
```

This is much more complex than if it knew the types

Handling Assignment

Compile-time type-checking

- Goal is to eliminate both the check & the tag
- Determine, at compile time, the type of each subexpression
- Use compile-time types to determine if a run-time check is needed

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 (with reference counting)

The problem with reference counting

- Must adjust the count on each pointer assignment
- Overhead is significant, relative to assignment

Code for assignment becomes

```
evaluate rhs
lhs→count ← lhs→count - 1
lhs ← addr(rhs)
rhs→count ← rhs→count + 1
```

Plus a check for zero at the end

This adds *1 +, 1 -, 2 loads, & 2 stores*

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

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

These have distinct & different cache behavior

The Concept

A

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

Row-major order

A

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

Column-major order

A

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

Indirection vectors

A

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

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

Computing an Array Address

A[i]

- @A + (i - low) x sizeof(A[1])
- In general: base(A) + (i - low) x sizeof(A[1])

Computing an Array Address

A[i]

- @A + (i - low) x sizeof(A[1])
- In general: base(A) + (i - low) x sizeof(A[1])

int A[1:10] ⇒ low is 1
Make low 0 for faster access (saves a –)

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

Computing an Array Address

A[i]

- @A + (i – low) x sizeof(A[1])
- In general: base(A) + (i – low) x sizeof(A[1])

What about $A[i_1,i_2]$?

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

Row-major order, two dimensions

$@A + ((i_1 - low_1) \times (high_2 - low_2 + 1) + i_2 - low_2) \times sizeof(A[1])$

Column-major order, two dimensions

$@A + ((i_2 - low_2) \times (high_1 - low_1 + 1) + i_1 - low_1) \times sizeof(A[1])$

Indirection vectors, two dimensions

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

Optimizing Address Calculation for A[i,j]

In row-major order

where $w = \text{sizeof}(A[1,1])$

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

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

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

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

Then, the address expression becomes

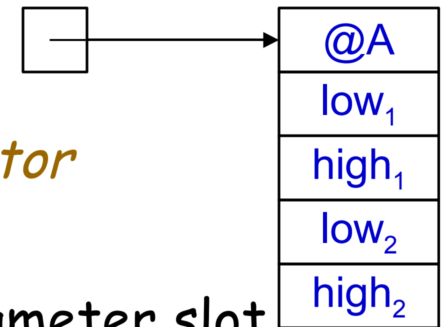
$$@A_0 + (i \times len_2 + j\ ) \times w$$

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

- Save len_i and low_i rather than low_i and $high_i$
- Pre-compute the fixed terms in prologue sequence

What about call-by-value?

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

Array References

What about A[12] as an actual parameter?

If corresponding parameter is a scalar, it's easy

- Pass the address or value, as needed
- Must know about both formal & actual parameter
- Language definition must force this interpretation

What is corresponding parameter is an array?

- Must know about both formal & actual parameter
- Meaning must be well-defined and understood
- Cross-procedural checking of conformability

⇒ Again, we're treading on language design issues

Array References

What about variable-sized arrays?

Local arrays dimensioned by actual parameters

- Same set of problems as parameter arrays
- Requires dope vectors (or equivalent)
  - → dope vector at fixed offset in activation record

  ⇒ Different access costs for textually similar references

This presents a lot of opportunity for a good optimizer

- Common subexpressions in the address polynomial
- Contents of dope vector are fixed during each activation
- Should be able to recover much of the lost ground

⇒ Handle them like parameter arrays

Example: Array Address Calculations in a Loop

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

- Naïve: Perform the address calculation twice

DO J = 1, N

  $R1 = @A_0 + (J \times len_1 + I) \times floatsize$

  $R2 = @B_0 + (J \times len_1 + I) \times floatsize$

  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
```

- Sophisticated: Move common calculations out of loop

```
R1 = I x floatsize
c = len₁ x floatsize    ! 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
```

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 (Operator Strength Reduction)

R1 = I x floatsize

c = len_1 x floatsize ! Compile-time constant

R2 = $@A_0$ + R1 ; R3 = $@B_0$ + R1

```
DO J = 1, N
    R2 = R2 + c
    R3 = R3 + c
    MEM(R2) = MEM(R2) + MEM(R3)
END DO
```

See, for example, Cooper, Simpson, & Vick, “Operator Strength Reduction”, ACM TOPLAS, Sept 2001