CSc 453

Compilers and Systems Software

19 : Code Generation I

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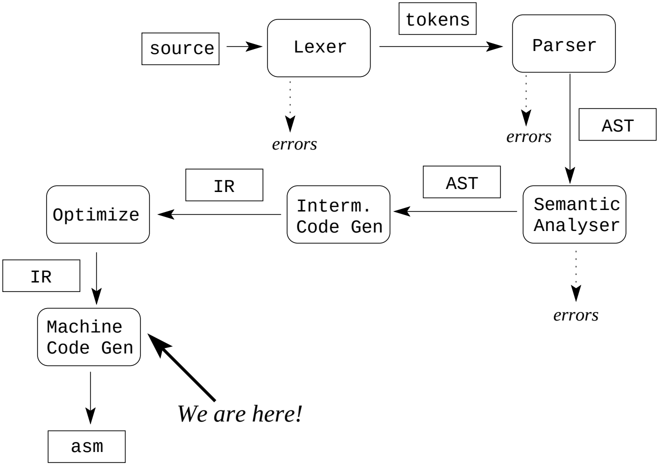
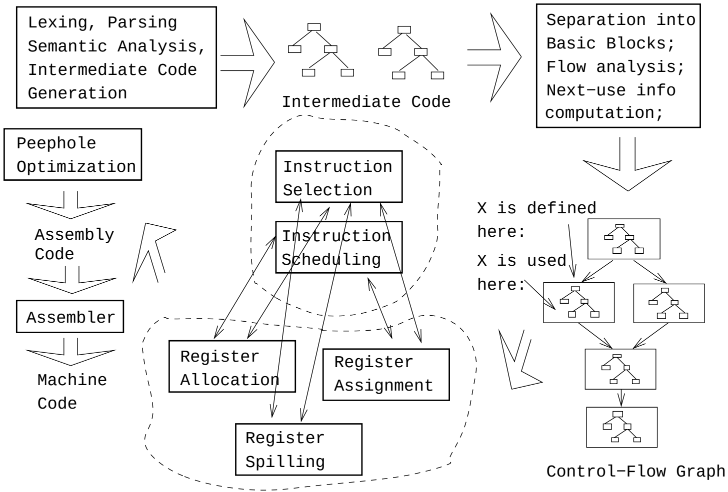
Introduction

Compiler Phases

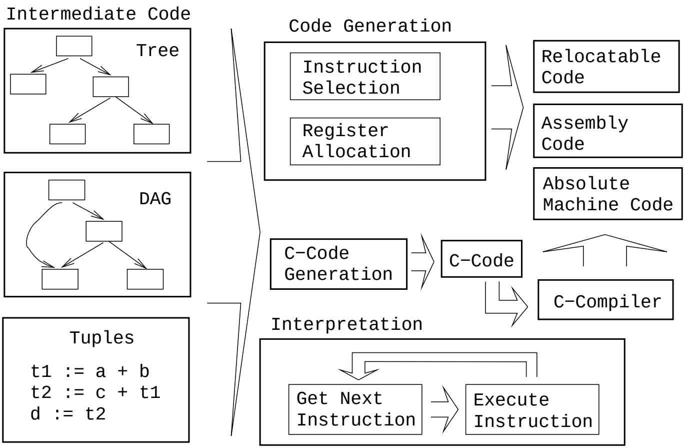



Lexing, Parsing
Semantic Analysis,
Intermediate Code
Generation
Intermediate Code
Separation into
Basic Blocks;
Flow analysis;
Next-use info
computation;
X is defined
here:
X is used
here:
Control-Flow Graph
Peephole
Optimization
Assembly
Code
Assembler
Machine
Code
Instruction
Selection
Instruction
Scheduling
Register
Allocation
Register
Assignment
Register
Spilling

Code Generation Issues

- The purpose of the code generation phase of the compiler is to transform the intermediate code produced by the front end into some other code that can be executed.
- Often the the code generator will produce assembly code or object code which (after assembly and linking) can be directly executed by the hardware.
- Alternatively, the code generator can generate C-code and use the native C-compiler as the "real" back-end.
- Or, the code generator can generate code for a "virtual machine", and use an **interpreter** to execute the code.
- We expect the code generator to produce code that is as efficient as possible.

Code Generation Issues. . .



Code Generation Issues...

- The input to the code generator can be any one of the intermediate representations we've discussed: Trees, Tuples, Graphs,... The work of the code generator consists of several (interdependent) tasks:

  Instruction

  - **selection:** *Which* instructions should be generated?
  - **scheduling:** In *which* order should they be generated?

  Register

  - **allocation:** *Which* variables should be kept in registers?
  - **assignment:** In *which* registers should they be stored?
  - **spilling:** *Which* registers should be spilled *when*?

Architectures

Machine Architectures—Instruction Sets

3-Register: $\boxed{\texttt{add R1, R2, R3}}$
`[R1 := R2 + R3]` (MIPS,VAX,$\cdots$).

Register-Address: $\boxed{\texttt{add R, Addr}}$
`[R := R + Addr]` (VAX,x86,MC68k)

2-Register: $\boxed{\texttt{add R1, R2}}$
`[R1 := R1 + R2]` (VAX,x86,MC68k)

2-Address: $\boxed{\texttt{add Addr1, Addr2}}$
`[Addr1 := Addr1 + Addr2]` (VAX)

3-Address: $\boxed{\texttt{add Addr1, Addr2, Addr3}}$
`[Addr1 := Addr2 + Addr3]` (VAX)

Machine Architectures—Register Classes

General
: One set of register that can hold any type of data (VAX, Alpha).

Integer+Float
: Separate integer and floating point register sets (Sparc, MIPS).

Integer+Float+Address
: Separate integer, floating point, and address register sets (MC68k).

Machine Architectures—Addressing Modes

Immediate: $\boxed{\#X}$ The value of the constant `X`. (All architectures.)

Register Direct: $\boxed{\texttt{R}}$ The contents of register `R`. (All.)

Register Indirect: $\boxed{\texttt{(R)}}$ The contents of the memory address in register `R`. (All.)

Register Indirect with increment: $\boxed{\texttt{(R+)}}$ The contents of the memory address in register `R`. `R` is incremented by the **size** of the instruction (i.e. if `MOVE.W (R+),Addr` moves two bytes, then R would be incremented by 2). (VAX, MC68k.)

Register Ind. with Displacement: $\boxed{\texttt{d(R)}}$ The contents of the memory address `R+d`, where `R` is a register and `d` a (small) constant. (All architectures.)

Machine Architectures—Instruction Cost

- The Cost of an instruction is the number of machine cycles it takes to execute it.
- On RISCs, most instructions take 1 cycle to execute. Loads, stores, branches, multiplies, and divides may take longer.
- On CISCs, the number of cycles required to execute an instruction $\boxed{\texttt{Instr Op}_1\texttt{, Op}_2}$ is $\texttt{cost(Instr)+cost(Op}_1\texttt{)+cost(Op}_2\texttt{)}$. $\texttt{cost(Op}_i\texttt{)}$ is the number of cycles required to compute the addressing mode $\texttt{Op}_i$.

A Simple Example

Example — Source

- A straight-forward code generator considers one tuple at a time, without looking at other tuples. The code generator is simple, but the generated code is sub-optimal.

The Source Program:

```
int A[5], i, x;
main(){
   for(i=1;i<=5;i++)
      x=x*A[i]+A[i];
}
```

Example — Intermediate Code

```
int A[5], i, x;
main(){for(i=1;i<=5;i++) x=x*A[i]+A[i];}
```

The Tuple Code

(1) i := 1	(9) T5 := i
(2) T0 := i	(10) T6 := A[T5]
(3) IF T0<6 GOTO (5)	(11) T7 := T4+T6
(4) GOTO (17)	(12) x := T7
(5) T1 := i	(13) T8 := i
(6) T2 := A[T1]	(14) T9 := T8+1
(7) T3 := x	(15) i := T9
(8) T4 := T2*T3	(16) GOTO (2)

Example – Unoptimized MIPS Code

```
        (1) i := 1
    li      $2,0x1              # $2 := 1
    sw      $2,i                # i := $2

L2:     (2) T0 := i
    lw      $2,i                # $2 := i
        (3) IF i < 6 GOTO (5)
    slt     $3,$2,6             # $3 := i < 6
    bne     $3,$0,L5            # IF $3≠0 GOTO L5
        (4) GOTO (17)
    j       L3                  # GOTO L3
```

```
L5:       (5) T1 := i
   lw     $2,i                    # $2 := CONT(i)
          (6) T2 := A[T1]
   move   $3,$2                   # $3 := $2
   sll    $2,$3,2                 # $2 := $3 * 4
   la     $3,A                    # $3 := ADDR(A)
   addu   $2,$2,$3                # $2 := $2 + $3
   lw     $2,0($2)                # $2 := CONT(A[i])
          (7) T3 := x
   lw     $3,x                    # $3 := CONT(x);
          (8) T4 := T2 * T3
   mult   $3,$2                   # $lo := $3 * $2
   mflo   $4                      # $4 := $lo
```

```
        (9) T5 := i
lw      $2,i                # $2 := CONT(i)
        (10) T6 := A[T5]
move    $3,$2               # $3 := $2
sll     $2,$3,2             # $2 := $3 * 4
la      $3,A                # $3 := ADDR(A)
addu    $2,$2,$3            # $2 := $2 + $3
lw      $3,0($2)            # $2 := CONT(A[i])

        (11) T7 := T4 + T6
addu    $2,$4,$3            # $2 := $4 + $3
        (12) x := T7
sw      $2,x                # x := $2
```

```
        (13) T8 := i
    lw      $3,i                    # $3 := CONT(i)
        (14) T9 := T8 + 1
    addu    $2,$3,1                 # $2 := $3 + 1
    move    $3,$2                   # $3 := $2
        (15) i := T9
    sw      $3,i                    # i := $3

        (16) GOTO (2)
    j       L2                      # GOTO L2
L3:
```

Common Sub-expression Elimination

Example — After CSE

- The generated code becomes a lot faster if we perform Common Sub-Expression Elimination (CSE) and keep the index variable `i` in a register ($6) over the entire loop:

```
        (1) i := 1
    li      $6,0x1              # $6 := 1

L2:     (2) T0 := i
        (3) IF i < 6 GOTO (5)
    slt     $3,$6,6             # $3 := i < 6
    bne     $3,$0,L5            # IF $3≠0 GOTO L5
        (4) GOTO (17)
    j       L3                  # GOTO L3
```

- `A[T1]` is computed once, and the result is kept in register $5 until it's needed the next time.

```
L5:       (5) T1 := i
          (6) T2 := A[T1]
   move   $3,$6                # $3 := $6
   sll    $2,$3,2              # $2 := $3 * 4
   la     $3,A                 # $3 := ADDR(A)
   addu   $2,$2,$3             # $2 := $2 + $3
   lw     $5,0($2)             # $5 := CONT(A[i])
          (7) T3 := x
   lw     $3,x                 # $3 := CONT(x);
          (8) T4 := T2 * T3
   mult   $3,$5                # $lo := $3 * $5
   mflo   $4                   # $4 := $lo
```

- After the loop we need to store \$6 back into `i`.

```
        (9) T5 := i
        (10) T6 := A[T5]
        (11) T7 := T4 + T6
   addu $2,$4,$5               # $2 := $4 + $5
        (12) x := T7
   sw   $2,x                   # x := $2
        (13) T8 := i
        (14) T9 := T8 + 1
        (15) i := T9
   addu $6,$6,1                # $6 := $6 + 1
        (16) GOTO (2)
   j    L2                     # GOTO L2
L3:sw   $6,i                   # i := $6
```

More Optimization

Example — More Register Allocation

- Since `x` and `ADDR(A)` seem to be used a lot in the loop, we keep them in registers ($7 and $8, respectively) as well.
- We also reverse the comparison, which allows us to remove one jump.
- The `move` instruction is unnecessary, so we remove it also.

```
        (1) i := 1
li      $6,0x1              # $6 := 1

lw      $7,x                # $7 := CONT(x);
la      $8,A                # $8 := ADDR(A)
```

```
L2:       (2) T0 := i
          (3) IF i < 6 GOTO (5)
          (4) GOTO (17)
   sge    $3,$6,6                # $3 := i >= 6
   bne    $3,$0,L3               # IF $3≠0 GOTO L3
L5:       (5) T1 := i
          (6) T2 := A[T1]
   sll    $2,$6,2                # $2 := $3 * 4
   addu   $2,$2,$8               # $2 := $2 + $8
   lw     $5,0($2)               # $5 := CONT(A[i])
          (7) T3 := x
          (8) T4 := T2 * T3
   mult   $7,$5                  # $lo := $7 * $5
   mflo   $4                     # $4 := $lo
```

```
        (9) T5 := i
        (10) T6 := A[T5]
        (11) T7 := T4 + T6
        (12) x := T7
    addu  $7,$4,$5             # $7 := $4 + $5

        (13) T8 := i
        (14) T9 := T8 + 1
        (15) i := T9
    addu  $6,$6,1              # $6 := $6 + 1
        (16) GOTO (2)
    j     L2                   # GOTO L2
L3: sw    $6,i                 # i := $6
    sw    $7,x                 # x := $7
```

Example — Summary

- The unoptimized code (produced by `gcc -S -g`) was 28 instructions long. Our optimized code is 16 instructions. Improvement: 42%.
- More importantly, in the original code there were 26 instructions **inside the loop**, and 2 outside. Since the loop runs 5 times, **we will execute** $3 + 5 * 25 = 128$ instructions.
- In the optimized case, we have 11 instructions in the loop and 5 outside. We will execute only $5 + 5 * 11 = 60$ instructions. Improvement: 53%.

Instruction Selection

Instruction Selection

- Instruction selection is usually pretty simple on RISC architectures – there is often just one possible sequence of instructions to perform a particular kind of computation.
- CISC's like the VAX, on the other hand, leave the compiler with more choices: `ADD2 1, R1` `ADD3 R1, 1, R1` `INC R1` all add 1 to register `R1`.

$V * 2$ – Unoptimized Sparc Code

```
set     V, %o0            # %o0 := ADDR(V);
ld      [%o0], %o0        # %o0 := CONT(V);
set     2, %o1            # %o1 := 2;
call    .mul, 2           # %o0 := %o0 * %o1;
nop                       # Empty delay slot
```

$V * 2$ – Better Instr. Selection

- The Sparc has a library function `.mul` and a hardware multiply instruction `smul`:

```
set    V, %o0
ld     [%o0], %o0
smul   %o0, 1, %o0               # %o0 := %o0 * %o1;
```

$V * 2$ – Even Better Instr. Selection

- The Sparc also has hardware shift instructions (`sll, srl`). To multiply by 2^i we shift i steps to the left.

```
set    V, %o0
ld     [%o0], %o0
sll    %o0, 1, %o0               # %o0 := %o0 * 2;
```

Instruction Scheduling

- Instruction scheduling is important for architectures with several functional units, pipelines, delay slots. I.e. most modern architectures.
- The Sparc (and other RISCs) have **branch delay slots**. These are instructions (textually immediately following the branch) that are "executed for free" during the branch.

$V * 2$ – Unoptimized Sparc Code

```
ld      [%o0], %o0          # %o0 := CONT(V);
set     2, %o1              # %o1 := 2;
call    .mul, 2             # %o0 := %o0 * %o1;
nop                         # Empty delay slot
```

Instruction Scheduling

$V * 2$ – Unoptimized Sparc Code

```
ld      [%o0], %o0              # %o0 := CONT(V);
set     2, %o1                  # %o1 := 2;
call    .mul, 2                 # %o0 := %o0 * %o1;
nop                             # Empty delay slot
```

$V * 2$ – Better Instr. Scheduling

```
ld      [%o0], %o0              # %o0 := CONT(V);
call    .mul, 2
set     2, %o1                  # Filled delay slot
```

Instruction Scheduling...

- The Sparc's integer and floating point units can execute in parallel. Integer and floating point instructions should therefore be reordered so that operations are interleaved.

```
int a, b, c; double x, y, z;
{     a = b - c;
      c = a + b;
      b = a + c;
      y = x * x;
      z = x + y;
      x = y / z;
}
```

```
int a, b, c; double x, y, z;
{     a = b - c; c = a + b; b = a + c;
      y = x * x; z = x + y; x = y / z;}
```

cc -O2		cc -O3	
set	b,%o3	fmuld	%f30,%f30,%f28
sub	%o0,%o1,%o1	set	c,%o1
set	a,%o0	ld	[%o1],%o2
add	%o4,%o5,%o4	faddd	%f30,%f28,%f30
add	%o0,%o2,%o0	set	b,%o0
set	x, %o0	ld	[%o0],%o4
fmuld	%f0,%f2,%f0	set	z,%g1
sethi	%hi(z),%o2	sub	%o4,%o2,%o2
faddd	%f6,%f8,%f6	fdivd	%f28,%f30,%f2
fdivd	%f12,%f14,%f12	add	%o4,%o2,%o4
		add	%o2,%o4,%o5

Register Allocation/Assignment/Spilling

Registers — Why do we need them?

1. We only need 4–7 bits to access a register, but 32–64 bits to access a memory word.
2. Hence, a one-word instruction can reference 3 registers but a two-word instruction is necessary to reference a memory word.
3. Registers have short access time.

Register — When do we use them?

1. Instructions take operands in regs.
2. Intermediate results are stored in regs.
3. Procedure arguments are passed in regs.
4. Loads and Stores are expensive $\Rightarrow$ keep variables in regs for as long as possible.
5. Common sub-expressions are stored in regs.

Register Allocation/Assignment

Register Allocation:

- First we have to decide which variables should reside in registers at which point in the program.
- Variables that are used frequently should be favored.

Register Assignment:

- Secondly, we have to decide which physical registers should hold each of these variables.
- Some architectures have several different **register classes**, groups of registers that can only hold one type of data:
  - MIPS & Sparc have floating point and integer registers;
  - MC68k has address, integer, and floating point, etc.

Register Assignment

- Sparc passes it's first 6 arguments in registers `%o0,%o1,%o2,%o3,%o4,%o5`.
- If a value is used twice, first in a computation and then in a procedure call, we should allocate the value to the appropriate procedure argument register.

```
a = b + 15;     /* ⇐ b is used here /*
P(b);           /* ⇐ and here.   */
      ⇓ ⇓ ⇓
ld    [%fp-8],%o0        # %o0 := CONT(b);
add   %o0,15,%o1         # %o1 := %o0 + 15
st    %o1,[%fp-4]        # a := %o1;
call  P,1                # P(%o0)
```

Register Spilling

- We may have 8 | 16 | 32 regs available.
- When we run out of registers (during code generation) we need to pick a register to **spill**. I.e. in order to free the register for its new use, it's current value first has to be stored in memory.
- Which register should be spilt? Least recently used, Least frequently used, Most distant use, . . . (take your pick).

Register Spilling — Example

- Assume a machine with registers `R1--R3`.
- `R1` holds variable `a`; `R2` holds `b`, `R3` holds `c`, and `R4` holds `d`. Generate code for:

```
x = a + b;              # ⇐ Which reg for x?
y = x + c;
```

- Which register should be spilt to free a register to hold `x`?

Register Allocation Example

```
FOR i := 1 TO n DO
    B[5,i] := b * b * b;
    FOR j := 1 TO n DO
        FOR k := 1 TO n DO
            A[i,j] := A[i,k] * A[k,j];
```

2 Registers Available: `k` and `ADDR(A)` in registers. (Prefer variables in inner loops).

4 Registers Available: `k`, `ADDR(A)`, `j`, and `i` in registers. (Prefer index variables).

5 Registers Available: `k`, `ADDR(A)`, `j`, `i`, and `b` in registers. (Prefer most frequently used variables).

Register Spilling Example

```
FOR i := 1 TO 100000 DO
   A[5,i] := b;
   FOR j := 1 TO 100000 DO
      A[j,i] := <Complicated Expression>;
```

1st Attempt (4 Regs available):

Allocation/Assignment: `i` in R_1, `j` in R_2, `ADDR(A)` in R_3, `ADDR(A[5,_])` in R_4.

Spilling: Spill R_4 in the inner loop to get enough registers to evaluate the complicated expression.

Register Spilling Example...

```
FOR i := 1 TO 100000 DO
   A[5,i] := b;
   FOR j := 1 TO 100000 DO
      A[j,i] := <Complicated Expression>;
```

2nd Attempt (4 Regs available):

Allocation/Assignment: `i` in R_1, `j` in R_2, `ADDR(A)` in R_3.

Spilling: No spills. But `ADDR(A[5,i])` must be loaded every time in the outer loop.

Summary

Readings and References

- Read Louden:

  Basic code generation 407–416
  Data structures 416–428
  Control structures 428–436
  Procedure calls 436–443

- Read the Dragon book:

  Introduction 513–521
  Basic Blocks 528–530
  Flow Graphs 532–534

Summary

- Instruction selection picks which instruction to use, instruction scheduling picks the ordering of instructions.
- Register allocation picks which variables to keep in registers, register assignment picks the actual register in which a particular variable should be stored.
- We prefer to keep index variables and variables used in inner loops in registers.
- When we run out of registers, we have to pick a register to *spill*, i.e. to store back into memory. We avoid inserting spill code in inner loops.

Summary. . .

- Code generation checklist:
  1. Is the code correct?
  2. Are values kept in registers for as long as possible?
  3. Is the cheapest register always chosen for spilling?
  4. Are values in inner loops allocated to registers?
- A basic block is a *straight-line* piece of code, with no jumps in or out except at the beginning and end.
- *Local* code generation considers one basic block at a time, *global* one procedure, and *inter-procedural* one program.