Intermediate Code & Local Optimizations

Lecture Outline

- What is “Intermediate code” ?
- Why do we need it?
- How to generate it?
- How to use it?
- Local optimization

Code Generation Summary

- We have so far discussed:
  - Runtime organization.
  - Simple stack machine code generation.
  - Improvements to stack machine code generation.
- Our compiler goes directly from the abstract syntax tree (AST) to assembly language...
  - ... and does not perform optimizations.

Most real compilers use intermediate languages.

Why Intermediate Languages?

ISSUE: Reduce code complexity

- Multiple front-ends
  - gcc can handle C, C++, Java, Fortran, Ada, ...
  - each front-end translates source to the same generic language (called GENERIC).
- Multiple back-ends
  - gcc can generate machine code for various target architectures: x86, x86_64, SPARC, ARM, …
- **One Icode to bridge them!**
  - Do most optimization on intermediate representation before emitting machine code.

Why Intermediate Languages?

ISSUE: When to perform optimizations

- On abstract syntax trees
  - Pro: Machine independent
  - Con: Too high level
- On assembly language
  - Pro: Exposes most optimization opportunities
  - Con: Machine dependent
  - Con: Must re-implement optimizations when re-targeting
- On an intermediate language
  - Pro: Exposes optimization opportunities
  - Pro: Machine independent

Kinds of Intermediate Languages

High-level intermediate representations:

- closer to the source language (structs, arrays)
- easy to generate from the input program
- code optimizations may not be straightforward

Low-level intermediate representations:

- closer to target machine: *GCC's* RTL, 3-address code
- easy to generate code from
- generation from input program may require effort

"Mid"-level intermediate representations:

- programming language and target independent
- Java bytecode, Microsoft CIL, LLVM IR, ...

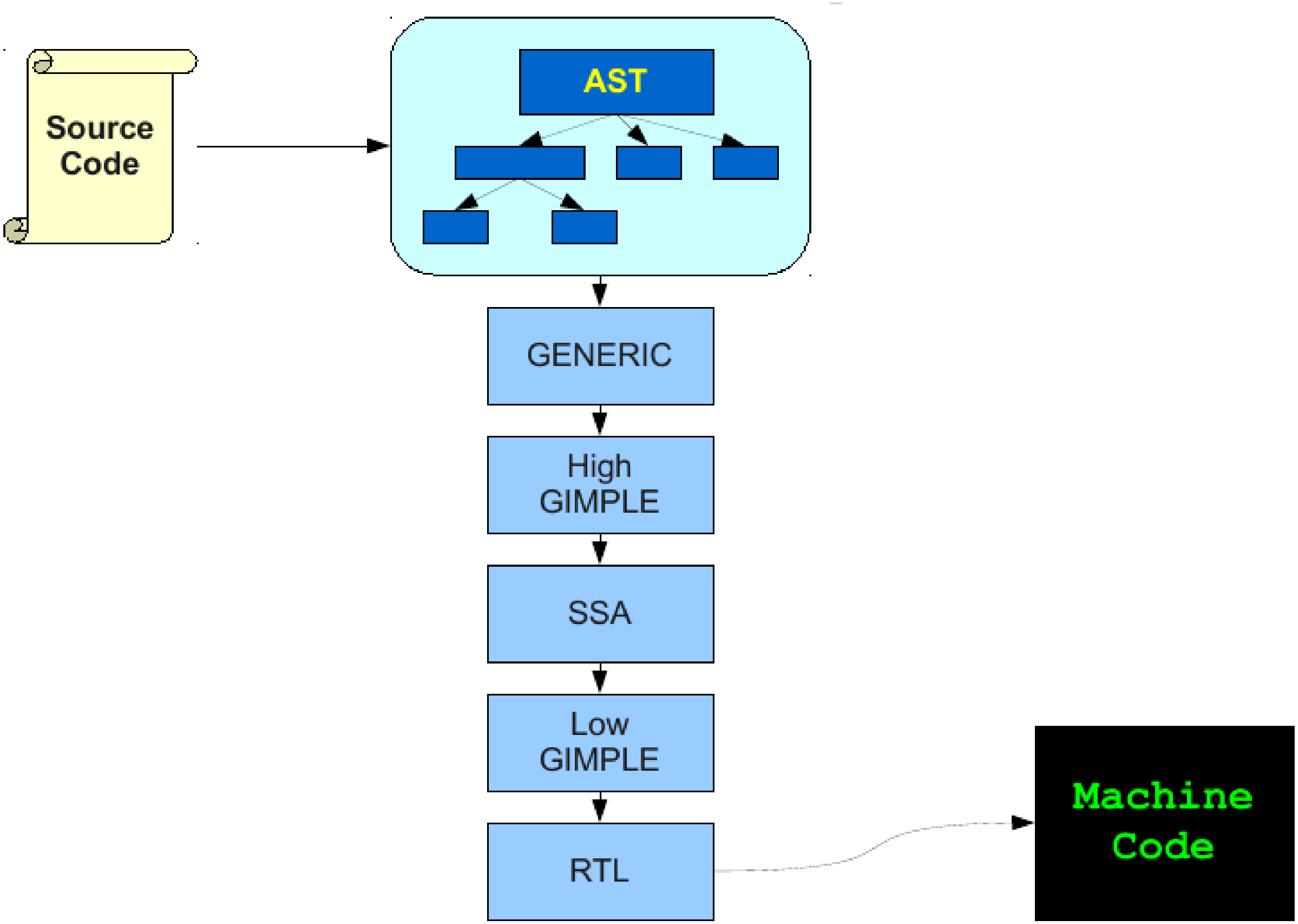
Intermediate Code Languages: Design Issues

- Designing a good ICode language is not trivial.
- The set of operators in ICode must be rich enough to allow the implementation of source language operations.
- ICode operations that are closely tied to a particular machine or architecture, make retargeting harder.
- A small set of operations
  - may lead to long instruction sequences for some source language constructs,
  - but on the other hand makes retargeting easier.

Intermediate Languages

- Each compiler uses its own intermediate language.
- Nowadays, usually an intermediate language is a high-level assembly language.
  - Uses register names, but has an unlimited number.
  - Uses control structures like assembly language.
  - Uses opcodes but some are higher level.
    - E.g., push translates to several assembly instructions.
    - Most opcodes correspond directly to assembly opcodes.

Architecture of gcc



Three-Address Intermediate Code

- Each instruction is of the form:

$$x := y \text{ op } z$$

  - y and z can only be temporaries or constants.
  - Just like assembly.
- Common form of intermediate code.
- The expression $x + y * z$ gets translated as:

$$t_1 := y * z$$
$$t_2 := x + t_1$$

  - Temporary names are made up for internal nodes.
  - Each sub-expression has a "home".

Generating Intermediate Code

- Similar to assembly code generation.
- Major difference:
  - Use any number of IL temporaries to hold intermediate results.

Example: `if (x + 2 > 3 * (y - 1) + 42) then z := 0;`

```
    $t_1$ := x + 2
    $t_2$ := y - 1
    $t_3$ := 3 * $t_2$
    $t_4$ := $t_3$ + 42
    if $t_1$ =< $t_4$ goto L
    z := 0
L:
```

Generating Intermediate Code (Cont.)

igen(e, t) : a function that generates code to compute the value of e in temporary t

- Example:

```
igen(e₁ + e₂, t) =
        igen(e₁, t₁)          (t₁ is a fresh register)
        igen(e₂, t₂)          (t₂ is a fresh register)
        t := t₁ + t₂
```

- Unlimited number of temporaries

  ⇒ simple code generation

From ICode to Machine Code

This is almost a macro expansion process.

ICode	**MIPS assembly code**
x := A[i]	load i into *r1* **la** *r2*, *A* **add** *r2*, *r2*, *r1* **lw** *r2*, (*r2*) **sw** *r2*, x
x := y + z	load y into *r1* load z into *r2* **add** *r3*, *r1*, *r2* **sw** *r3*, x
if x >= y goto L	load x into *r1* load y into *r2* **bge** *r1*, *r2*, L

Basic Blocks

- A *basic block* is a maximal sequence of instructions with:
  - no labels (except at the first instruction), and
  - no jumps (except in the last instruction).

- Idea:
  - Cannot jump into a basic block (except at beginning).
  - Cannot jump out of a basic block (except at end).
  - Each instruction in a basic block is executed after all the preceding instructions have been executed.

Basic Block Example

Consider the basic block

```
    L:                              (1)
      t := 2 * x                    (2)
      w := t + x                    (3)
      if w > 0 goto L'              (4)
```

- No way for (3) to be executed without (2) having been executed right before.
  - We can change (3) to `w := 3 * x` ?
  - Can we eliminate (2) as well ?

Identifying Basic Blocks

- Determine the set of *leaders*, i.e., the first instruction of each basic block:
  - The first instruction of a function is a leader.
  - Any instruction that is a target of a branch is a leader.
  - Any instruction immediately following a (conditional or unconditional) branch is a leader.
- For each leader, its basic block consists of itself and all instructions up to, but not including, the next leader (or end of function).

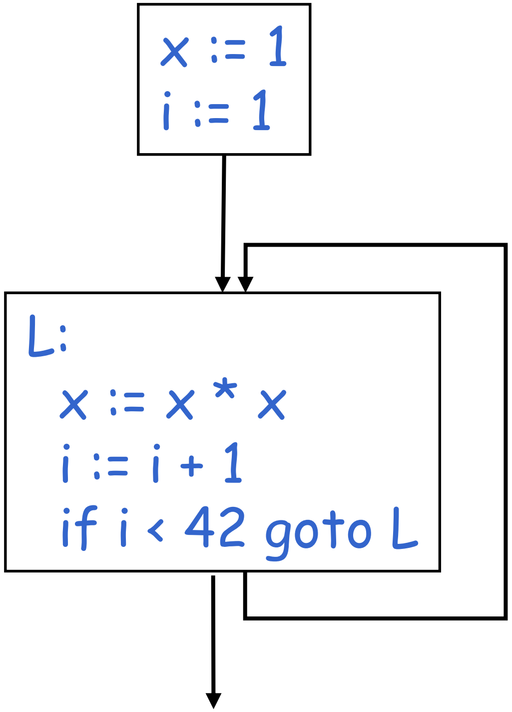
Control-Flow Graphs

A *control-flow graph* is a directed graph with

- Basic blocks as nodes.
- An edge from block A to block B if the execution can flow from the last instruction in A to the first instruction in B.
  - E.g., the last instruction in A is goto L_B .
  - E.g., the execution can fall-through from block A to block B.

Frequently abbreviated as CFGs.

Control-Flow Graphs: Example



```
x := 1
i := 1
```

```
L:
  x := x * x
  i := i + 1
  if i < 42 goto L
```

- The body of a function (or method or procedure) can be represented as a control-flow graph.
- There is one initial node.
- All "return" nodes are terminal.

Constructing the Control Flow Graph

- First identify the basic blocks of the function.
- There is a directed edge between block B_1 to block B_2 if
  - there is a (conditional or unconditional) jump from the last instruction of B_1 to the first instruction of B_2 or
  - B_2 immediately follows B_1 in the textual order of the program, and B_1 does not end in an unconditional jump.

Optimization Overview

- Compiler "optimizations" seek to improve a program's utilization of some resource:
  - Execution time (most often).
  - Code size.
  - Network messages sent.
  - (Battery) power used, etc.

- Optimization should not alter what the program computes:
  - The return value must be the same.
  - Any observable behavior must be the same.

    (This typically also includes termination behavior.)

A Classification of Optimizations

For languages like C, there are three granularities of optimizations:

(1) Local optimizations
- Apply to a basic block in isolation.

(2) Global optimizations
- Apply to a control-flow graph (function body) in isolation.

(3) Inter-procedural optimizations
- Apply across function/procedure boundaries.

Most compilers do (1), many do (2), and very few do (3).

Note: there are also link-time optimizations.

Cost of Optimizations

- In practice, a conscious decision is made **not** to implement the fanciest optimizations.
- Why?
  - Some optimizations are hard to implement.
  - Some optimizations are costly in terms of compilation time.
  - Some optimizations are hard to get completely right.
  - The fancy optimizations are often hard, costly, and difficult to get completely correct.
- Goal: maximum improvement with minimum cost.

Local Optimizations

- The simplest form of optimizations.
- No need to analyze the whole procedure body.
  - Just the basic block in question.

- Example: algebraic simplification.

Algebraic Simplification

- Some statements can be deleted:

x := x + 0

x := x * 1

- Some statements can be simplified:

a := x * 0 ⇒ a := 0

b := y ** 2 ⇒ b := y * y

c := x * 8 ⇒ c := x << 3

d := x * 15 ⇒ t := x << 4; d := t - x

(on some machines << is faster than *; but not on all!)

Constant Folding

- Operations on constants can be computed at compile time.
- In general, if there is a statement

  x := y op z

  - where y and z are constants
  - then y op z can be computed at compile time.

- Example: x := 20 + 22 ⇒ x := 42
- Example: if 42 < 17 goto L can be deleted.

Flow of Control Optimizations

- Eliminating unreachable code:
  - Code that is unreachable in the control-flow graph.
  - Basic blocks that are not the target of any jump or “fall through” from a conditional.
  - Such basic blocks can be eliminated.

- Why/how would such basic blocks occur?

- Removing unreachable code makes the program smaller.
  - And sometimes also faster.
    - Due to memory cache effects (increased spatial locality).

Single Assignment Form

- Some optimizations are simplified if each register occurs only once on the left-hand side of an assignment.
- Basic blocks of intermediate code can be rewritten to be in *single assignment* form.

```
x := z + y                b := z + y
a := x          ⇒         a := b
x := 2 * x                x := 2 * b
```

(b is a fresh temporary.)

- More complicated in general, due to control flow (e.g., loops).
  - *Static single assignment (SSA)* form.

Common Subexpression Elimination

- Assume:
  - A basic block is in single assignment form.
  - A definition `x :=` is the first use of `x` in a block.
- All assignments with same RHS compute the same value.

- Example:

```
x := y * z              x := y * z
…             ⇒         …
w := y * z              w := x
```

(Due to the block being in single assignment form, the values of `x`, `y` and `z` do not change in the … code.)

Copy Propagation

- If w := x appears in a block, all subsequent uses of w can be replaced with uses of x.

- Example:

```
b := z + y               b := z + y
a := b          ⇒        a := b
x := 2 * a               x := 2 * b
```

- This does not make the program smaller or faster but might enable other optimizations:
  - Constant folding.
  - Dead code elimination.

Constant Propagation and Constant Folding

- Example:

```
a := 5                    a := 5
x := 2 * a        ⇒       x := 10
y := x + 6                y := 16
t := x * y                t := 160
```

Dead Code Elimination

If

w := RHS appears in a basic block, and

w does not appear anywhere else in the program

Then

the statement w := RHS is dead and can be eliminated.

- <u>Dead</u> = does not contribute to the program's result.

Example: (a is not used anywhere else)

```
x := z + y          x := z + y          x := z + y
a := x        ⇒     a := x        ⇒     b := 2 * x
b := 2 * a          b := 2 * x
```

Applying Local Optimizations

- Each local optimization does very little by itself.

- However, typically optimizations interact.
  - Performing one optimization enables another.

- Optimizing compilers repeatedly perform optimizations until no improvement is possible.
  - The optimizer can also be stopped at any time to limit the compilation time.

An Example

Initial code:

```
a := x ** 2
b := 3
c := x
d := c * c
e := b * 2
f := a + d
g := e * f
```

Assume that only f and g are used in the rest of program.

An Example

Algebraic simplification:

```
a := x ** 2
b := 3
c := x
d := c * c
e := b * 2
f := a + d
g := e * f
```

An Example

Algebraic simplification:

```
a := x * x
b := 3
c := x
d := c * c
e := b « 1
f := a + d
g := e * f
```

An Example

Copy and constant propagation:

```
a := x * x
b := 3
c := x
d := c * c
e := b << 1
f := a + d
g := e * f
```

An Example

Copy and constant propagation:

```
a := x * x
b := 3
c := x
d := x * x
e := 3 << 1
f := a + d
g := e * f
```

An Example

Constant folding:

```
a := x * x
b := 3
c := x
d := x * x
e := 3 << 1
f := a + d
g := e * f
```

An Example

Constant folding:

```
a := x * x
b := 3
c := x
d := x * x
e := 6
f := a + d
g := e * f
```

An Example

Common subexpression elimination:

```
a := x * x
b := 3
c := x
d := x * x
e := 6
f := a + d
g := e * f
```

An Example

Common subexpression elimination:

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + d
g := e * f
```

An Example

Copy and constant propagation:

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + d
g := e * f
```

An Example

Copy and constant propagation:

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + a
g := 6 * f
```

An Example

Dead code elimination:

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + a
g := 6 * f
```

An Example

Dead code elimination:

```
a := x * x




f := a + a
g := 6 * f
```

This is the final form.

Peephole Optimizations on Assembly Code

- The optimizations presented before work on intermediate code.
  - They are target independent.
  - But they can be applied on assembly language also.

Peephole optimization is an effective technique for improving assembly code.
  - The "peephole" is a short sequence of (usually contiguous) instructions.
  - The optimizer replaces the sequence with another equivalent (but faster) one.

Implementing Peephole Optimizations

- Write peephole optimizations as replacement rules:

  $i_1, \ldots, i_n \to j_1, \ldots, j_m$

  where the RHS is the improved version of the LHS.
- Example:

  move \$a \$b, move \$b \$a → move \$a \$b
  - Works if move \$b \$a is not the target of a jump.
- Another example:

  addiu \$a \$a i, addiu \$a \$a j → addiu \$a \$a i+j

Peephole Optimizations

- Redundant instruction elimination, e.g.:

```
      . . .
    goto L
L:
      . . .
```

⇒

```
      . . .
L:
      . . .
```

- Flow of control optimizations, e.g.:

```
     . . .
     goto L1
     . . .
L1: goto L2
     . . .
```

⇒

```
     . . .
     goto L2
     . . .
L1: goto L2
     . . .
```

Peephole Optimizations (Cont.)

- Many (but not all) of the basic block optimizations can be cast as peephole optimizations.
  - Example: addiu \$a \$b 0 → move \$a \$b
  - Example: move \$a \$a →
  - These two together eliminate addiu \$a \$a 0.
- Just like for local optimizations, peephole optimizations need to be applied repeatedly to achieve maximum effect.

Concluding Remarks

- Multiple front-ends, multiple back-ends via intermediate codes.
- Intermediate code is the right representation for many optimizations.
- Many simple optimizations can still be applied on assembly language.
- Next time: global optimizations.