CS 153: Concepts of Compiler Design

November 21 Class Meeting

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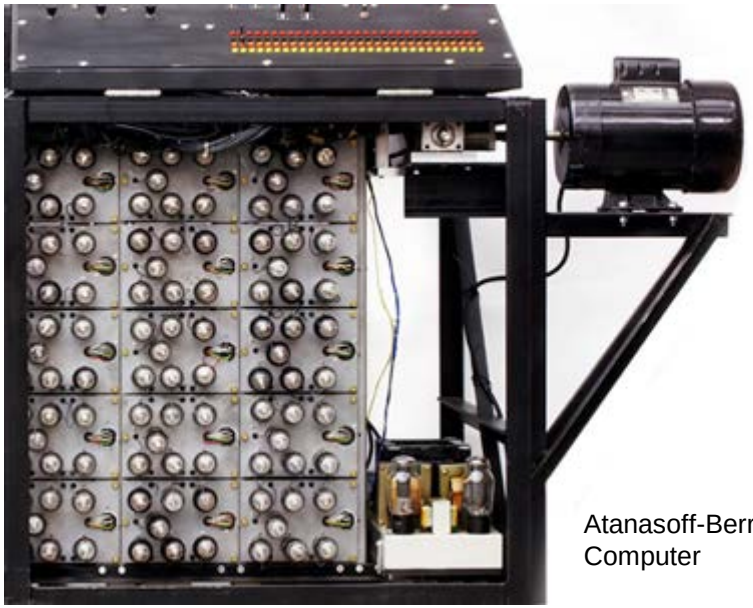
Unofficial Field Trip

- **Computer History Museum in Mt. View**
  - http://www.computerhistory.org/
  - Provide your own transportation to the museum.
- **Saturday, December 9, 11:30 – closing time**
  - Special free admission.
  - Do a self-guided tour of the Revolution exhibit.
  - See a life-size working model of Charles Babbage's Difference Engine in operation, a hand-cranked mechanical computer designed in the early 1800s.
  - Experience a fully restored IBM 1401 mainframe computer from the early 1960s in operation.

Unofficial Field Trip, *cont'd*

- See the extensive Revolution exhibit!
  - Walk through a timeline of the First 2000 Years of Computing History.
  - Historic computer systems, data processing equipment, and other artifacts.
  - Small theater presentations.

Hollerith Census Machine



Atanasoff-Berry Computer

Unofficial Field Trip, *cont'd*

- IBM 1401 computer, fully restored and operational.
  - A small transistor-based mainframe computer.
  - Extremely popular with small businesses in the late 1950s through the mid 1960s
    - Maximum of 16K bytes of memory.
    - 800 card/minute card reader (wire brushes).
    - 600 line/minute line printer (impact).
    - 6 magnetic tape drives, no disk drives.

Unofficial Field Trip, *cont'd*

- Information on the IBM 1401:
  - General info: http://en.wikipedia.org/wiki/IBM_1401
  - My summer seminar: http://www.cs.sjsu.edu/~mak/1401/
  - Restoration: http://ed-thelen.org/1401Project/1401RestorationPage.html

Instruction Selection

- What sequence of target machine instructions should the code generator emit?
- The symbol table and parse tree are the primary sources of information for the code generator.

Instruction Selection, *cont'd*

- Retargetable compilers can generate code for multiple target machines.
  - The symbol table and parse tree are source language independent.
- Use code templates that are customized for each target machine.

Instruction Selection: JVM Examples

- Load and store instructions
  - Emit **`ldc`** *x* or **`iconst_`***n* or **`bipush`** *n*
  - Emit **`iload`** *n* or **`iload_`***n*
  - Emit **`istore`** *n* or **`istore_`***n*
- Pascal **`CASE`** statement
  - Emit **`lookupswitch`** if the test values are sparse.
  - Emit **`tableswitch`** if the test values are densely packed.

Instruction Selection: JVM Examples, *cont'd*

- Pascal assignment **`i := i + 1`**
  (assume **`i`** is local variable #0)

```
iload_0
iconst_1
iadd
istore_0
```

or

```
iinc 0 1
```

Register Allocation

- Unlike the JVM, many real machines can have hardware registers that are faster than main memory.
  - General-purpose registers
  - Floating-point registers
  - Address registers
- A smart code generator emits code that:
  - Loads values into registers as much as possible.
  - Keeps values in registers as long as possible.
    - But no longer than necessary!

Register Allocation, *cont'd*

- The code generator assigns registers on a per-routine basis.
- Procedure or function call:
  - Emit code to save the caller's register contents.
  - The procedure or function gets a "fresh" set of registers.
- Return:
  - Emit code to restore the caller's register contents.
  - Better: Save and restore only the registers that a routine uses.

Register Allocation Challenges

- Limited number of registers.
- May need to spill a register value into memory.
  - Store a register's value into memory in order to free up the register.
  - Later reload the value back from memory into the register.
- Pointer variables
  - Cannot keep a variable's value in a register if there is a pointer to the variable's memory location.

Data Flow Analysis

- Determine which variables are live.
- A variable ***v*** is live at statement ***p1*** in a program if:
  - There is an execution path from statement ***p1*** to a statement ***p2*** that uses ***v***, and
  - Along this path, the value of ***v*** does not change.
- Only live variables should be kept in registers.

Instruction Scheduling

- Change the order of the instructions that the code generator emits.
- But don't change the program semantics!
- A form of optimization to increase execution speed.

Instruction Scheduling, *cont'd*

- With most machine architectures, different instructions take to execute.
  - Example: Floating-point instructions take longer than the corresponding integer instructions.
  - Example: Loading from memory and storing to memory each takes longer than adding two numbers in registers.

Instruction Scheduling Example

- Assume that **`load`** and **`store`** each takes 3 cycles, **`mult`** takes 2 cycles, and **`add`** takes 1 cycle.
- Simple case: Sequential execution only.

Cycle start	Instruction	Operation
1	`load`	w ➔ *r1*
4	`add`	*r1* + *r1* ➔ *r1*
5	`load`	x ➔ *r2*
8	`mult`	*r1* * *r2* ➔ *r1*
10	`load`	y ➔ *r2*
13	`mult`	*r1* * *r2* ➔ *r1*
15	`load`	z ➔ *r2*
18	`mult`	*r1* * *r2* ➔ *r1*
20	`store`	*r1* ➔ w

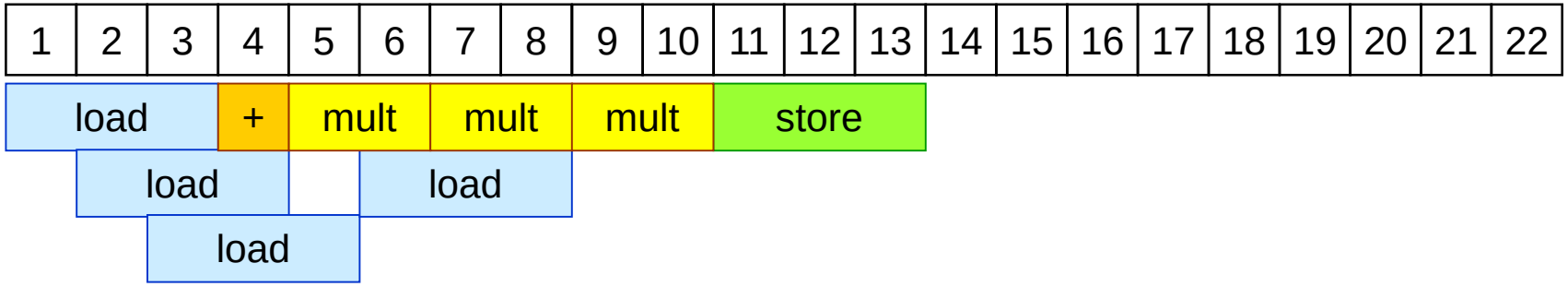
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
load			+	load			mult		load			mult		load			mult		store		

Instruction Scheduling, *cont'd*

- Assume that **`load`** and **`store`** each takes 3 cycles, **`mult`** takes 2 cycles, and **`add`** takes 1 cycle.
- Assume the machine can overlap instruction execution.
  - instruction-level parallelism

Cycle start	Instruction	Operation
1	`load`	w ➔ *r1*
2	`load`	x ➔ *r2*
3	`load`	y ➔ *r3*
4	`add`	*r1* + *r1* ➔ *r1*
5	`mult`	*r1* * *r2* ➔ *r1*
6	`load`	z ➔ *r2*
7	`mult`	*r1* * *r3* ➔ *r1*
9	`mult`	*r1* * *r2* ➔ *r1*
11	`store`	*r1* ➔ w

Requires using another register *r3*.



Introduction to Code Optimization

- Goal: The compiler generates better object code.
- Automatically discover information about the runtime behavior of the source program.
- Use that information to generate better code.

Introduction to Code Optimization, *cont'd*

- Usually done as one or more passes over the parse tree before the code generator emits the object code.
- The front end parser doesn't worry about optimization.
- A code optimizer in the back end can modify the parse tree so that the code generator will emit better code.

“Better” Generated Object Code

- Runs faster
  - What people usually mean when they talk about optimization.
- Uses less memory
  - Embedded chips may have limited amounts of memory.
- Consumes less power
  - A CPU chip may be in a device that needs to conserve power.
  - Some operations can require more power than others.

Code Optimization Challenges: Safety

- The code optimizer must not change the semantics of the source program.
- During execution, the optimized object code must have the same runtime effects as the unoptimized object code.
  - "Same effect": The variables have the same calculated values.
- Bad idea: Compute the wrong values, but faster!

Code Optimization Challenges: Profitability

- Good optimization is difficult to implement correctly.
- It is time-consuming to run an optimizer.
- Optimization can increase compilation time by an order of magnitude or more.
- Is it worth it?

Speed Optimization: Constant Folding

- Suppose we have the constant definition:

```
CONST pi = 3.14;
```

  and we have the real expression `2*pi`

- Instead of emitting instructions to load 2, load 3.14, and multiply ...

- Simply emit a single instruction to load the value 6.28

Speed Optimization: Constant Propagation

- Suppose parse tree analysis determines that a variable v always has the value c for a given set of statements.
- When generating code for those statements, instead of emitting an instruction to load the value of v from memory ...
- Emit an instruction to load the constant c.

Speed Optimization: Strength Reduction

- Replace an operation by a faster equivalent operation.

Speed Optimization: Strength Reduction, *cont'd*

- Example: Suppose the integer expression `5*i` appears in a tight loop.
  - Given: Multiplication is more expensive than addition.
  - One solution: Generate code for `i+i+i+i+i` instead.
  - Another solution: Treat the expression as if it were written `(4*i)+i` and do the multiplication as a shift left of 2 bits.
    - Generate the code to shift the value of `i` and then add the original value of `i`.

Speed Optimization: Dead Code Elimination

- Suppose we have the **WHILE** statement:

```
WHILE i <> i DO
    BEGIN
        ...
    END
```

If there are no statement labels, none of the statements in the compound statement can ever be executed.

- Don't emit any code for this **WHILE** statement.

Speed Optimization: Loop Unrolling

- Loop overhead: initialize, test, and increment.
- Example:

```
FOR i := 1 TO n DO BEGIN
    FOR j := 1 TO 3 DO BEGIN
        s[i,j] := a[i,j] + b[i,j]
    END
END
```

- Unroll the inner loop by generating code for:

```
FOR i := 1 TO n DO BEGIN
    s[i,1] := a[i,1] + b[i,1];
    s[i,2] := a[i,2] + b[i,2];
    s[i,3] := a[i,3] + b[i,3];
END
```

Common Subexpression Elimination

- Example:

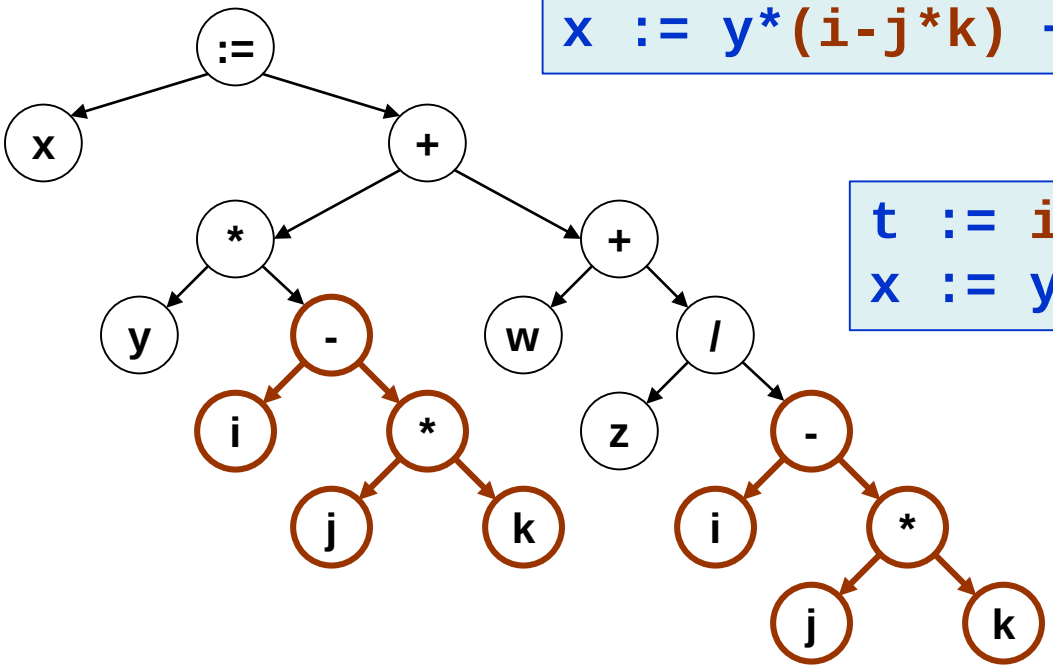
```
x := y*(i-j*k) + (w + z/(i-j*k))
```

- Generate code as if the statement were instead:

```
t := i-j*k;
x := y*t + (w + z/t);
```

- This may not be so easy for the back end to do!

Common Subexpression Elimination, *cont'd*




```
x := y*(i-j*k) + (w + z/(i-j*k))
```

```
t := i-j*k;
x := y*t + (w + z/t)
```

- How do you recognize the common subexpression in the parse tree?

Debugging Compiler

- AKA development compiler
- Used during program development
- Fast compiles = fast turnaround
- Doesn't change the order of the generated code.
- Easy for debuggers (such as Eclipse) to set breakpoints, single-step, and monitor changes to the values of variables.

Optimizing Compiler

- AKA production compiler
- Used after a program has been "thoroughly" debugged.
- Can optimize for speed, memory usage, or power consumption.
- Different levels of optimization.

Compiling Object-Oriented Languages

- Extra challenges!
- Dynamically allocated objects
  - Allocate objects in the heap.
- Method overloading
- Inheritance
- Virtual methods