CIS570 Modern Programming Language Implementation

Instructor: **E Christopher Lewis**
Office hours: TDB
605 Levine
eclewis@cis.upenn.edu

Admin. Assistant: **Cheryl Hickey**
cherylh@central.cis.upenn.edu
502 Levine

URL: http://www.cis.upenn.edu/~eclewis/cis570

What is CIS570 About?

Program representation
- Can we do better than ASCII .c files?

Analysis
- How do we mechanically derive meaning and intent?
- How do we reason about programs?

Transformation
- How do we use results of analysis to make the representation "better"?

Domains
- Language implementation (including **Compilation**)
- Computation understanding
    - Software engineering tools (bug detectors, *etc.*)

Structure of CIS570

Lectures
- Participation is essential (no text book)

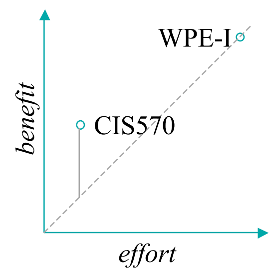
Reading
- 6 or 7 papers
- Read and answer discussion questions before designated class

Discussions
- Some classes will be devoted to discussion
- But there is always room for discussion

Exams
- Final perhaps?

Homework
- Answer discussion questions before class

Bottom line
- Very efficient class



Plan for Today

Motivation
- Why study compilers?

Issues
- Look at some sample optimizations and assorted issues

Administrivia
- Course details

Motivation

What is a compiler?

– A translator that converts a source program into an target program

What is an optimizing compiler?

– A translator that *somehow* improves the program (versus non-opt. comp.)

Why study compilers?

– They are *specifically* important:
  Compilers provide a bridge between applications and architectures
– They are *generally* important:
  Compilers encapsulate techniques for reasoning about programs and their behavior
– They are cool:
  First major computer application

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Traditional View of Compilers

Compiling down

– Translate high-level language to machine code

High-level programming languages

– Increase programmer productivity
– Improve program maintenance
– Improve portability

Low-level architectural details

– Instruction set
– Addressing modes
– Pipelines
– Registers, cache, and the rest of the memory hierarchy
– Instruction-level parallelism

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Isn't Compilation A Solved Problem?

"Optimization for scalar machines is a problem that was solved ten years ago"
-- David Kuck, 1990

Machines keep changing
- New features present new problems (*e.g.,* MMX, EPIC, profiling support, TM)
- Changing costs lead to different concerns (*e.g.,* mem v. ALU ops)

Languages keep changing
- Wacky ideas (*e.g.,* OOP and GC) have gone mainstream

Applications keep changing
- Interactive, real-time, mobile, secure

Values keep changing
- Correctness
- Run-time performance
- Code size
- Compile-time performance
- Power
- Security

Modern View of Compilers

Analysis and translation are useful everywhere
- Analysis and transformations can be performed at run time and link time, not just at "compile time"
- Translation can be used to improve security
- Analysis can be used in software engineering
  - Program understanding
  - Reverse engineering
- Increased interaction between hardware and compilers can improve performance
- Bottom line
  - Analysis and transformation play essential roles in computer systems
  - Computation important ⇒ *understanding* computation important

Types of Optimizations

Definition

- An *optimization* is a transformation that is expected to improve the program in some way; often consists of *analysis* and *transformation* *e.g.,* decreasing the running time or decreasing memory requirements

Machine-independent optimizations

- Eliminate redundant computation
- Move computation to less frequently executed place
- Specialize some general purpose code
- Remove useless code

Types of Optimizations (cont)

Machine-dependent optimizations

- Replace a costly operation with a cheaper one
- Replace a sequence of operations with a cheaper one
- Hide latency
- Improve locality
- Reduce power consumption

Enabling transformations

- Expose opportunities for other optimizations
- Help structure optimizations

Sample Optimizations

Arithmetic simplification

– Constant folding

e.g., `x = 8/2;` → `x = 4;`

– Strength reduction

e.g., `x = y * 4;` → `x = y << 2;`

Constant propagation

– *e.g.,*

```
x = 3;        x = 3;        x = 3;
y = 4+x;  →   y = 4+3;  →   y = 7;
```

Copy propagation

– *e.g.,*

```
x = z;        x = z;
y = 4+x;  →   y = 4+z;
```


Sample Optimizations (cont)

Common subexpression elimination (CSE)

– *e.g.,*

```
x = a + b;     t = a + b;
y = a + b; →   x = t;
               y = t;
```

Dead (unused) assignment elimination

– *e.g.,*

```
x = 3;
... x not used...
x = 4;
```

this assignment is dead

Dead (unreachable) code elimination

– *e.g.,*

```
if (false == true) {
    printf("debugging...");
}
```

this statement is dead

Sample Optimizations (cont)

Loop-invariant code motion

– *e.g.,*

```
for i = 1 to 10 do
    x = 3;
    ...
```

➡

```
x = 3;
for i = 1 to 10 do
    ...
```

Induction variable elimination

– *e.g.,*

```
for i = 1 to 10 do
    a[i] = a[i] + 1;
```

➡

```
for p = &a[1] to &a[10] do
    *p = *p + 1
```

Loop unrolling

– *e.g.,*

```
for i = 1 to 10 do
    a[i] = a[i] + 1;
```

➡

```
for i = 1 to 10 by 2 do
    a[i] = a[i] + 1;
    a[i+1] = a[i+1] + 1;
```

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Is an Optimization Worthwhile?

Criteria for evaluating optimizations

– Safety: does it preserve behavior?
– Profitability: does it actually improve the code?
– Opportunity: is it widely applicable?
– Cost (compilation time): can it be practically performed?
– Cost (complexity): can it be practically implemented?

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Scope of Analysis/Optimizations

Peephole
- Consider a small window of instructions
- Usually machine specific
- Know nothing about context

Global (intraprocedural)
- Consider entire procedures
- Must consider branches, loops, merging of control flow
- Use data-flow analysis
- Make certain assumptions at procedure calls

Local
- Consider blocks of straight line code (no control flow)
- Simple to analyze
- Know nothing about context

Whole program (interprocedural)
- Consider multiple procedures
- Analysis even more complex (calls, returns)
- Hard with separate compilation

Limits of Compiler Optimizations

Fully Optimizing Compiler (FOC)
- $FOC(P) = P_{opt}$
- P_{opt} is the *smallest* program with same I/O behavior as P

Observe
- If program Q produces no output and never halts, FOC(Q) = L: goto L

Aha!
- We've solved the halting problem?!

Moral
- Cannot build FOC
- Can always build a better optimizing compiler (*full employment theorem* for compiler writers!)

Optimizations Don’t Always Help

Common Subexpression Elimination

```
x = a + b          t = a + b
y = a + b    ⇒     x = t
                   y = t
```

2 adds
4 variables

1 add
5 variables

Optimizations Don’t Always Help (cont)

Fusion and Contraction

```
for i = 1 to n
   T[i] = A[i] + B[i]
for i = 1 to n
   C[i] = D[i] + T[i]
```

⇒

```
for i = 1 to n
   t = A[i] + B[i]
   C[i] = D[i] + t
```

`t` fits in a register, so no loads or stores in this loop.

Huge win on most machines.

Degrades performance on machines with hardware managed stream buffers.

Optimizations Don't Always Help (cont)

Backpatching

`o.foo();` In Java, the address of **`foo()`** is often not known until runtime (due to dynamic class loading), so the method call requires a table lookup.

After the first execution of this statement, backpatching replaces the table lookup with a direct call to the proper function.

Q: How could this optimization ever hurt?

A: The Pentium 4 has a *trace cache*, when any instruction is modified, the entire trace cache has to be flushed.

Phase Ordering Problem

In what order should optimizations be performed?

Simple dependences

- One optimization creates opportunity for another
  e.g., copy propagation and dead code elimination

Cyclic dependences

- *e.g.,* constant folding and constant propagation

Adverse interactions

- *e.g.,* common subexpression elimination and register allocation
  e.g., register allocation and instruction scheduling

Engineering Issues

Building a compiler is an engineering activity

Balance multiple goals
- Benefit for *typical* programs
- Complexity of implementation
- Compilation speed

Overall Goal
- Identify a small set of general analyses and optimization
- Easier said than done: just one more...

Beyond Optimization

Security and Correctness
- Can we check whether pointers and addresses are valid?
- Can we detect when untrusted code accesses a sensitive part of a system?
- Can we detect whether locks are used properly?
- Can we use compilers to certify that code is "correct"?
- Can we use compilers to obfuscate code?

Next Time

Reading

– "Binary Translation" by Sites *et al.*

Lecture

– Undergraduate compilers in a day!