CS380C Compilers

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Today's Plan

- Motivation
  - Why study compilers?
- Let's get started
  - Look at some sample optimizations and assorted issues
- A few administrative matters
  - Course details

Motivation

- Q: Why study compilers?

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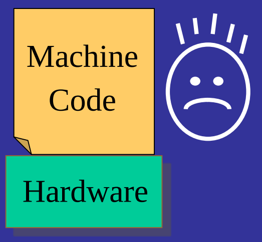
Life B.C.

- Before compilers



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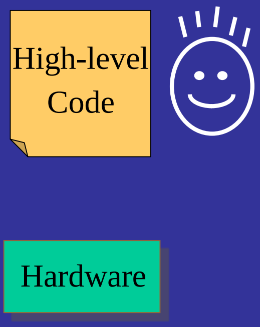
Liberation

Along came Backus



Compilers liberate the programmer from the machine

Traditional View of Compilers

- 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
  - Registers, cache, and the rest of the memory hierarchy
  - Pipelines, instruction-level parallelism

Optimization

- Translation is not enough
  - Backus recognized the importance of obtaining good performance
- Can perform tedious optimizations that programmers won't do

Consider Matrix Multiplication

- Obvious code

```
for i = 1 to n
  for j = 1 to n
    for k = 1 to n
      c[i,j] = c[i, j] + a[i, k]* b[k,j]
```

- Tiled code– can be significantly faster

```
for it = 1 to n by t
  for jt = 1 to n by
    for kt = 1 to n by t
      for i = it to it+t-1
        for j = jt to jt+t-1
          for k = kt to kt+t-1
            c[i,j] = c[i, j] + a[i, k]* b[k,j]
```

Why don't we want programmers to write this code?

Translation + Optimization

- Enable language design to flourish
  - Functional languages
  - Object oriented languages
  - . . .

Compilers liberate language designers

  - Logic languages

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, IA64, trace caches)
  - Changing costs lead to different concerns (*e.g.*, loads)
- Languages keep changing
  - Wacky ideas (*e.g.*, OOP and GC) have gone mainstream
- Applications keep changing
  - Interactive, real-time, mobile

Isn't Compilation A Solved Problem? (cont)

- Values keep changing
- We used to just care about run-time performance
- Now?
  - Compile-time performance
  - Code size
  - Correctness
  - Energy consumption
  - Security
  - Fault tolerance

Value-Added Compilation

- The more we rely on software, the more we demand more of it
- Compilers can help– treat code as data
  - Analyze the code
- Correctness
- Security

Correctness and Security

- 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 verify that a given compiler transformation is correct?

Value-Added Compilation

- The more we rely on software, the more we demand more of it
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- Correctness
- Security
- Reliability
- Program understanding
- Program evolution
- Software testing
- Reverse engineering
- Program obfuscation
- Code compaction
- Energy efficiency

Computation important ⇒ understanding computation important

Freedom Cuts Both Ways

- Just as compilers liberate the language designer, they also liberate the computer architect
- Can we change the ISA from one generation to the next?
  - Yes, if we trust our compilers
- Enables richer design space
  - VLIW
  - IA64
  - TRIPS
  - Multicore
  - Heterogeneous multi-core
  - Reconfigurable architectures

Benefits to the Architect (cont)

- Two benefits of the compiler
  - Can simplify the hardware by shifting burden to the compiler
    - VLIW, IA64, TRIPS, software controlled caches, Cell
  - Can let the compiler inform the hardware
    - Bias bits
    - Prefetch instructions

Virtualization is a Virtue

- High-level languages provide virtualization
  - Why is virtualization good?
- We can virtualize at many levels
  - Transmeta: dynamically compile x86 to VLIW
  - GPUs rely on dynamic compilation
  - JVMs and JITs

The Point

- Compilers are a fundamental building block of modern systems
- We need to understand their power and limitations
  - Computer architects
  - Language designers
  - Software engineers
  - OS/Runtime system researchers
  - Security researchers
  - Formal methods researchers (model checking, automated theorem proving)

Plan For Today

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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

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Sample Optimizations

- Arithmetic simplification
  - Constant folding
    e.g., **`x = 8/2;`**

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Sample Optimizations (cont)

- Constant propagation
  - *e.g.,*
```
x = 3;
y = 4+x;
```


Sample Optimizations (cont)

- Common subexpression elimination (CSE)
  - *e.g.,*
```
x = a + b;
y = a + b;
```

Sample Optimizations (cont)

- 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
   ...
```

Sample Optimizations (cont)

- 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
```


Sample Optimizations (cont)

- 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;
```

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?

Scope of Analysis/Optimizations

- Peephole
  - Consider a small window of instructions
  - Usually machine-specific
- Local
  - Consider blocks of straight line code (no control flow)
  - Simple to analyze

Scope of Analysis/Optimizations (cont)

- Global (intraprocedural)
  - Consider entire procedures
  - Must consider branches, loops, merging of control flow
  - Use data-flow analysis
  - Make simplifying assumptions at procedure calls
- Whole program (interprocedural)
  - Consider multiple procedures
  - Analysis even more complex (calls, returns)
  - Hard with separate compilation

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Time of Optimization

- Compile time
- Link time
- Configuration time
- Runtime

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Optimization Dimensions: A Rich Space

- Abstraction level
  - Machine-dependent, machine-independent
- Goal
  - Performance, correctness, etc
  - Enabling transformation
- Scope
  - Peephole, local, global, interprocedural
- Timing
  - Compile time, link time, configuration time,run time

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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!)*

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Optimizations Don't Always Help

- Common Sub-expression 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

- 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?

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 sub-expression 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...

Two Approaches– Which is Better?

- Build a compiler from scratch
- Extend an existing compiler

Administrative Matters

- Turn to your syllabus

Next Time

- Reading
  - Syllabus
- Lecture
  - Undergraduate compilers in a day!