Compiler Optimization Research

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Compiler Optimizations

◆ Question
  - Why study compiler optimization?

◆ Reasons compiler optimizations not needed
  - Hardware improving at much faster rate
  - Compiler optimizations are not implemented in commercial compilers, anyway
1) Most Progress is in Hardware

- Progress by computer industry (hardware) is exciting
- Software research is not

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<th>1999</th>
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2) Impact of Economics on Compiler Opts.

- **Assertion**
  - Few new optimizations implemented in commercial compilers

- **Commercial compilers**
  - Expensive to build & maintain

- **Compiler optimizations**
  - Many interesting
  - Most narrowly applicable
  - General purpose compilers
    - Cannot justify expense
  - Custom compilers
    - Too expensive to write
3) Proebsting’s Law

- **Moore’s law**
  - Chip density doubles every 18 months
  - Often reflected in CPU power doubling every 18 months

- **Proebsting’s Law**
  - Compiler technology doubles CPU power every 18 years

- **Corollary**
  - 1 year of code optimization research = 1 month of hardware improvement
  - No further need for compiler optimization research
  - Just wait a few months...

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Todd’s Justification for Proebsting’s Law

- **Assumptions**
  - 4x performance improvement from optimizations
  - Compiler technology represents 36 years of progress

- **Results in**
  - Compiler technology doubles CPU power every 18 years
  - Improvement = 4% a year
Checking Justification for Proebsting’s Law

- **Measure actual benefits from compiler optimization**

- **SPEC 95 benchmarks** [Scott 2001]
  - Numeric Fortran code
    - DEC SPEC results (optimized) vs GNU f77 –O0 (unoptimized)
  - Integer C code
    - DEC SPEC results (optimized) vs DEC cc –O0 (unoptimized)

- **Java benchmarks** [Arnold+ 2000]
  - Jalapeno (optimized) vs Jalapeno (unoptimized)

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**Optimizations for SPECfp Benchmarks**

![Bar chart showing speedup for various SPECfp benchmarks](chart.png)

- **su2cor**: 2
- **hydro2d**: 2
- **tomcatv**: 2
- **fppp**: 4
- **swim**: 6
- **apsi**: 8
- **turb3d**: 10
- **mgrid**: 14
- **applu**: 16
- **Avg**: 8.1

Scott 2001
Optimizations for SPECint Benchmarks

![Graph showing speedup for SPECint benchmarks.](image)

Optimizations for Java Benchmarks

![Graph showing ratio calculation for Java benchmarks.](image)

\[ \text{Ratio} = \frac{\text{compilation + execution time}}{\text{execution time of optimized code}} \]
**Benefits from Compiler Optimization**

- **Average improvements from optimization**
  - 8.1x for numeric codes (DEC SPEC results vs GNU f77 –O0)
  - 3.3x for integer codes (DEC SPEC results vs DEC cc –O0)
  - 2.0x for Java benchmarks (Jalapeno –O vs Jalapeno)

- **SPEC comparisons exaggerate improvements, since compiler optimizations are carefully tuned and targeted**

- **2–4x is a reasonable estimate for applying compiler optimizations to real programs, probably generous**

**Where Do We Go From Here?**

- **Current compiler optimizations**
  - 2–4x improvements from optimization

- **Past work on compiler optimization is relevant**
  - Nobody is going to turn off optimization and discard a factor of 2x improvement

- **What about the next 18 years?**
  1. Can we achieve another 2x improvement?
  2. Is it worth the effort? (Wait 18 months for faster processors)
Compiler Optimization Research

◆ What won't work
  - Take existing C / Fortran benchmarks (e.g., SPEC 95)
  - Apply complex, expensive program analyses / transformations
    - Automatic parallelization for multithreaded processors
      using interprocedural context-sensitive whole-path alias
      analysis of complex pointer-based data structures
  - Targeting existing RISC / x86 microprocessors

◆ Optimizations reaching point of diminishing returns
  - For current languages / applications / architectures
  - Too much work, not enough improvement

◆ So what is left?

Importance of Performance

◆ For general software, many issues dominate
  - Time to market
  - Maintainability
  - Reliability
  - Safety / security

◆ Much more important than another 4% / year speedup
Compiler Optimization Research

✦ So what compiler optimization research is relevant?

✦ Some suggestions
  1. Targeting high-performance computing (HPC) applications
  2. Exploiting new architectural features
  3. Improving programmer productivity

✦ But only if performance improvement is significant
  - I.e., closer to 4% / month (processor) than 4% / year (compiler)

Overview

✦ Motivation
✦ High-performance computing (HPC)
✦ Exploiting new architectural features
✦ Improving programmer productivity
1) Targeting HPC Applications

- High performance computing applications
  - Computational science
  - Simulation using numerical models (molecules to galaxies)
  - Precision depends on computation power
- Unlike general applications, performance is important
- Compiler optimization research is worthwhile
- Caveat
  - Techniques may not be economical for general compiler
  - May produce programming tool instead of compiler

2) Exploiting New Architectural Features

- Moore’s law
  - Chip density doubles every 18 months
- Chip density improves performance
  - Smaller gate size = faster switching speed
  - Smaller chip = less wire delay
- But performance does not automatically double
  - 2x chip density ≠ 2x clock speed increase
  - 2x clock speed increase ≠ 2x performance improvement
Exploiting New Architectural Features

- **Source of additional improvement**
  - Extra transistors = more processor features

- **Uses for extra transistors**
  - Larger on-chip caches
  - Vector operations
  - Long instruction words (VLIW)
  - Out-of-order execution
  - Branch prediction
  - Value prediction
  - Predicated instructions
  - Multithreading
  - Speculative threads
  - Prefetching

Exploiting New Architectural Features

- **Many features require compiler optimizations**
  - On-chip caches → locality optimizations
  - Vector operations → automatic vectorization
  - Long instruction words (VLIW) → instruction scheduling
  - Out-of-order execution → instruction scheduling
  - Predicated instructions → control dependence analysis
  - Multithreading → automatic parallelization
  - Speculative threads → dependence analysis
  - Prefetching → software prefetching

- **Otherwise limited benefit from new features**
Exploiting New Architectural Features

- Compiler research can thus focus on new features
  - Large on-chip caches
  - Vector units
  - Long instruction words
  - Multithreading
  - Predicated instructions

- Improvements can be much larger than 4% / year

- Key
  - Pick architectural features responsible for largest gains
  - Balance improvement against compiler implementation effort
  - Avoid falling back into 4% improvement / year range

Architectural Features – Pentium 3 vs 4 Binaries

Linpack, 1.8 Ghz Intel Xeon

Other improvements – 3% SPECint 2000, 8% SPECfp 2000

[Meheis+ 2002]
Exploiting New Architectural Features

- **Locality**
  - Processors faster than memory, network
  - In cache ⇒ avoid memory latency
  - On processor ⇒ avoid network latency

- **Growing processor – memory gap**
  - Performance impact of locality increasing
  - Prime candidate for compiler optimizations
Processor vs. Memory Speed (Latency)

Processor Clock
Memory Bus Clock

Year

Speed (Mhz)

Processor vs. Memory Speed (log scale)

Processor Clock
Memory Bus Clock

Year

Speed (Mhz)
3) Improving Programmer Productivity

- **Improving programmer productivity is probably most important problem facing computer science today**
  - How can compiler optimization research help?

- **Areas**
  - Discourage manual optimizations
  - Encourage high-level languages
  - Reduce cost of
    - High-level language constructs
    - Error-checking / security
  - Provide / exploit user feedback

- **Goal is higher productivity**

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**Improving Productivity – Reduce Manual_OPTS.**

- **People tweak their code for performance**
  - “Register” variable declarations
  - Write compact, dense code
  - Unroll loops by hand

- **Problem**
  - Code hard to understand and maintain
  - More difficult to optimize
  - May even introduce errors

- **Compiler optimizations help**
  - Handle simple cases, remove temptation

- **Result → less hand-optimized code, easier to maintain**
Improving Productivity – High-Level Languages

- **People use low-level languages for performance**
  - Use assembly code instead of C
  - Use C instead of C++
  - Use C++ instead of Java
  - Use MPI instead of HPF

- **Problem**
  - Low-level programming generally less productive
  - May even introduce errors
    - `malloc` / `free` vs. garbage collection
    - Arbitrary pointer arithmetic vs. multidimensional arrays
    - Arbitrary type casting vs. safe types
    - Message deadlock in message-passing programs

- **Compiler optimizations help**
  - Reduce penalty for high-level language constructs
    - Type safety
    - Objects
    - Inheritance
    - Abstract data types
    - Parametric polymorphism
    - Exceptions
    - Tagged unions
    - Garbage collection
    - Higher-order functions
    - Parameterized typedefs
  - Many of these features are already in Java compilers

- **Result → cleaner, high-level code**
High-Level Languages – Intel cc vs GNU gcc

![Graph showing performance gains for High-Level Languages](image)

**SPECint 2000, 2.2 Ghz Intel Xeon**

[Source: Mehis+ 2002]

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**Summary**

- **Compiler optimization research** can be relevant
  - But not by doing the same thing for the next 18 years

- **Some relevant research areas**
  - High performance computing applications
  - Exploiting new processor architectural features
  - Improving programmer productivity

- **Caveats**
  - Only care about performance if improvement >> 4% / year
  - If narrowly applicable, may produce programming tool instead of compiler