Compiler Optimization Research

(Based on talk by Prof. Bill Pugh, UMD)

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

	1979	1989	1999	2009
Hardware	8 Mhz 8088 4 Mb DRAM Modem USENET	33 Mhz x386 32 Mb DRAM 10 Mb Ethernet Internet	1 Ghz Pentium3 256 Mb DRAM 100 Mb Ethernet WWW	3 Ghz Core 2 4 Gb DRAM 1 Gb Ethernet P2P BitTorrent
Operating Systems	Unix DOS	Unix Windows 3.1	Unix Windows NT	Linux Windows Vista
Programming Languages	Cobol Fortran LISP	C C++	C++ Java Perl	Java, C#, C Perl, Python, PhP Ruby, Delphi

2) Impact of Economics on Compiler Optimizations

- 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…

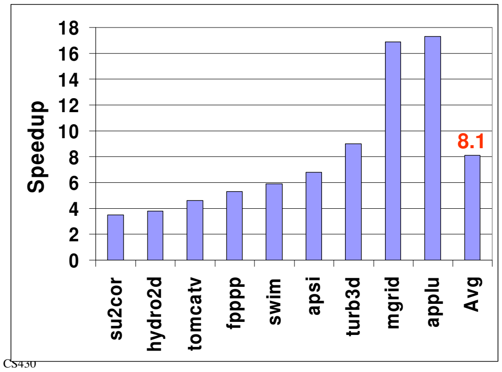
Todd's Justification for Proebsting's Law

- 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

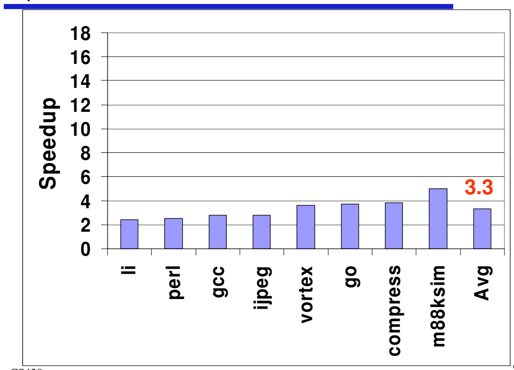
- Measure actual benefits from compiler optimization
- SPEC 95 benchmarks [Scott 2001]
  - → Numeric Fortran code
    DEC SPEC results (optimized) vs GNU f77 –O0 (unoptimized)
  - → Integer C code
    DEC SPEC results (optimized) vs DEC cc –O0 (unoptimized)
- Java benchmarks [Arnold+ 2000]
  - → Jalapeno (optimized) vs Jalapeno (unoptimized)

Optimizations for SPECfp Benchmarks



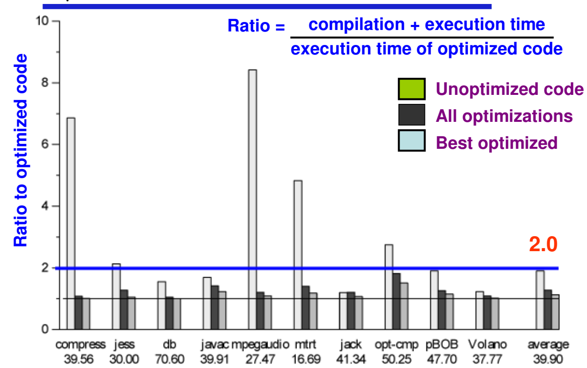
Scott 2001

Optimizations for SPECint Benchmarks



Scott 2001

Optimizations for Java Benchmarks



Arnold+ 2000

Benefits from Compiler Optimization

- Average improvments 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?
  - → Can we achieve another 2x improvement?
  - → 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
  - → Targeting high-performance computing (HPC) applications
  - → Exploiting new architectural features
  - → 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
  - → Multi-core

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, multi-core → automatic parallelization
  - → Speculative threads → dependence analysis
  - → Prefetching → software prefetching
- Otherwise limited benefit from new features

Exploiting New Architectural Features

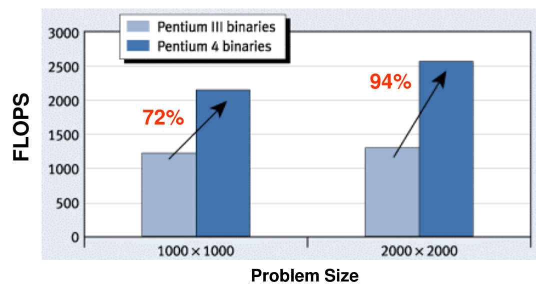
- Compiler research can thus focus on new features
  - → Vector units
  - → Long instruction words
  - → Predicated instructions
  - → Large on-chip caches
  - → Multithreading
  - → Multi-core

  IA64 (Itanium): Vector units, Long instruction words, Predicated instructions, Large on-chip caches

  Core 2: Large on-chip caches, Multithreading, Multi-core
- 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

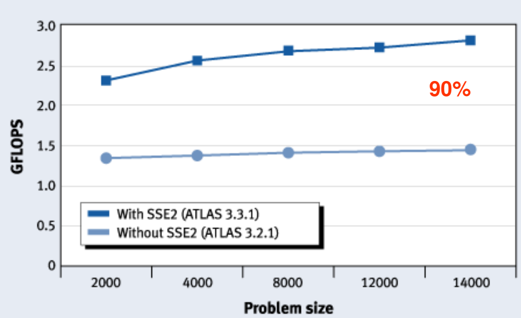
Linpack, 1.8 Ghz Intel Xeon



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

[Mehis+ 2002]

Architectural Features – SSE2 Vector Instructions



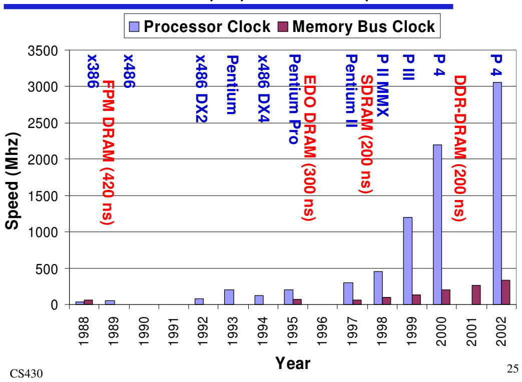
ATLAS, 2.2 Ghz Intel Xeon

[Mehis+ 2002]

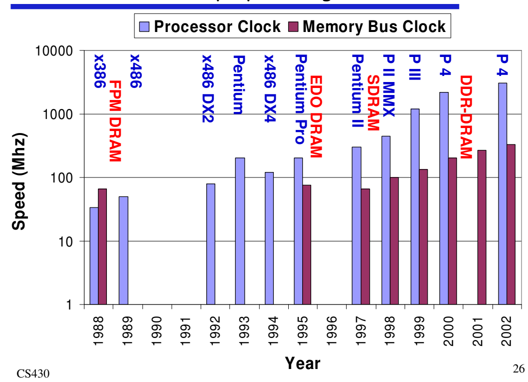
Exploiting New Architectural Features

- 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 vs. Memory Speed (log scale)



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

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

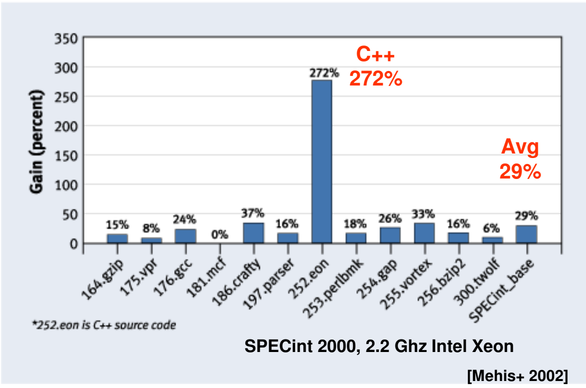
Improving Productivity – High-Level Languages

- 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

Improving Productivity – High-Level Languages

- 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



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