

CS 380C:
Advanced Topics in Compilers

Administration

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Meeting times

- Lecture:
 - TTh 9:30-11:00AM, RLM 6.126
- Office hours:
 - Keshav Pingali: Tuesday 11-12 AM, ACES 4.126

Prerequisites

- Compilers and architecture
 - Some background in compilers (front-end stuff)
 - Basic computer architecture
- Software and math maturity
 - Able to implement large programs in C/C++
 - Comfortable with abstractions like graph theory
- Ability to read research papers and understand content

Course material

- Website for course
 - <http://www.cs.utexas.edu/users/pingali/CS380C/2013/index.html>
- All lecture notes, announcements, papers, assignments, etc. will be posted there
- No assigned book for the course
 - but we will put papers and other material on the website as appropriate

Coursework

- 4-5 programming assignments and problem sets
 - Work in pairs
- Term project
 - Substantial implementation project
 - Based on our ideas or yours in the area of compilers
 - Work in pairs
- Paper presentations
 - Towards the end of the semester

What do compilers do?

- Conventional view of compilers

- Program that analyzes and **translates** a high-level language program automatically into low-level machine code that can be executed by the hardware
- May do simple (scalar) optimizations to reduce the number of operations
- Ignore data structures for the most part

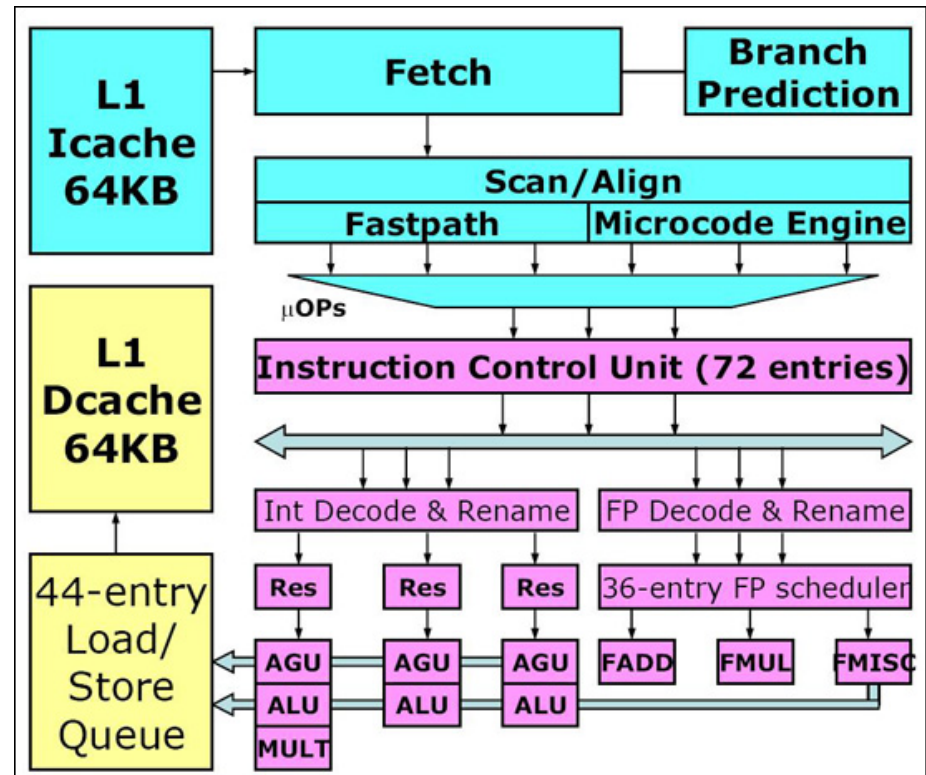
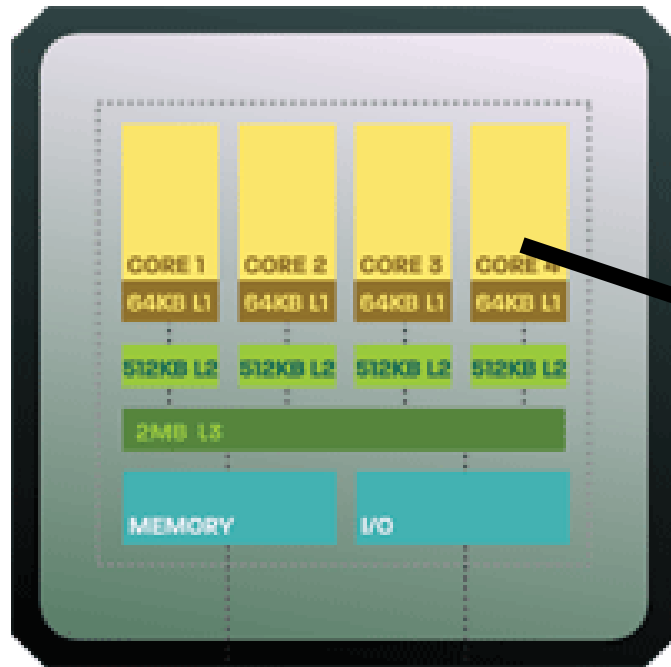
- Modern view of compilers

- Program for translation, transformation and verification of high-level language programs
- Reordering (restructuring) the computations is as important if not more important than reducing the amount of computation
- Optimization of data structure computations is critical
- Program analysis techniques can be useful for other applications such as
 - debugging,
 - verifying the correctness of a program against a specification,
 - detecting malware,

Why do we need translators?

- Bridge the “semantic gap”
 - Programmers prefer to write programs at a high level of abstraction
 - Modern architectures are very complex, so to get good performance, we have to worry about a lot of low-level details
 - Compilers let programmers write high-level programs and still get good performance on complex machine architectures
- Application portability
 - When a new ISA or architecture comes out, you only need to reimplement the compiler on that machine
 - Application programs should run without (substantial) modification
 - Saves a huge amount of programming effort

Complexity of modern architectures: AMD Barcelona Quad-core Processor



Discussion

- To get good performance on modern processors, program must exploit
 - coarse-grain (multicore) parallelism
 - memory hierarchy (L1,L2,L3,..)
 - instruction-level parallelism (ILP)
 - registers
 -
- Key questions:
 - How important is it to exploit these hardware features?
 - If you have n cores and you run on only one, you get at most $1/n$ of peak performance, so this is obvious
 - How about other hardware features?
 - If it is important, how hard is it to do this by hand?
- Let us look at memory hierarchies to get a feel for this
 - Typical latencies
 - L1 cache: ~ 1 cycle
 - L2 cache: ~ 10 cycles
 - Memory: ~ 500 -1000 cycles

Software problem

- Caches are useful only if programs have locality of reference
 - temporal locality: program references to given memory address are clustered together in time
 - spatial locality: program references clustered in address space are clustered in time
- Problem:
 - Programs obtained by expressing most algorithms in the straight-forward way do not have much locality of reference
 - Worrying about locality when coding algorithms complicates the software process enormously.

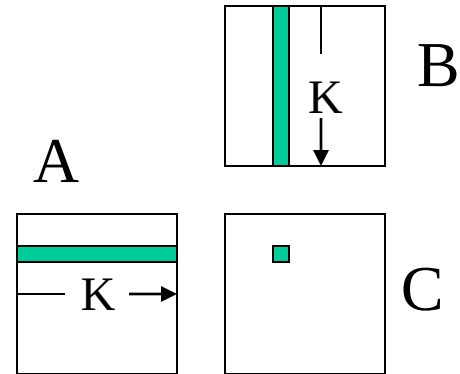
Example: matrix multiplication

```
DO I = 1, N    //assume arrays stored in row-major order
  DO J = 1, N
    DO K = 1, N
      C(I,J) = C(I,J) + A(I,K)*B(K,J)
```

- Great algorithmic data reuse: each array element is touched $O(N)$ times!
- All six loop permutations are computationally equivalent (even modulo round-off error).
- However, execution times of the six versions can be very different if machine has a cache.

IJK version (large cache)

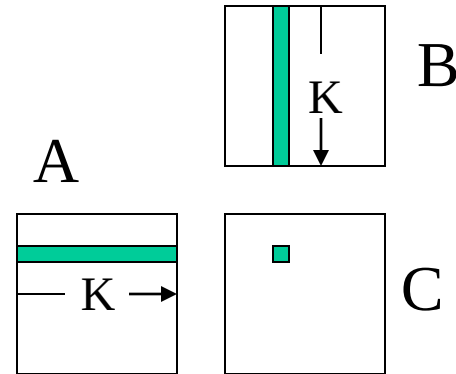
```
DO I = 1, N
  DO J = 1, N
    DO K = 1, N
      C(I,J) = C(I,J) + A(I,K)*B(K,J)
```



- Large cache scenario:
 - Matrices are small enough to fit into cache
 - Only cold misses, no capacity misses
 - Miss ratio:
 - Data size = $3 N^2$
 - Each miss brings in b floating-point numbers
 - Miss ratio = $3 N^2 / b * 4N^3 = 0.75/bN = 0.019$ ($b = 4, N=10$)

IJK version (small cache)

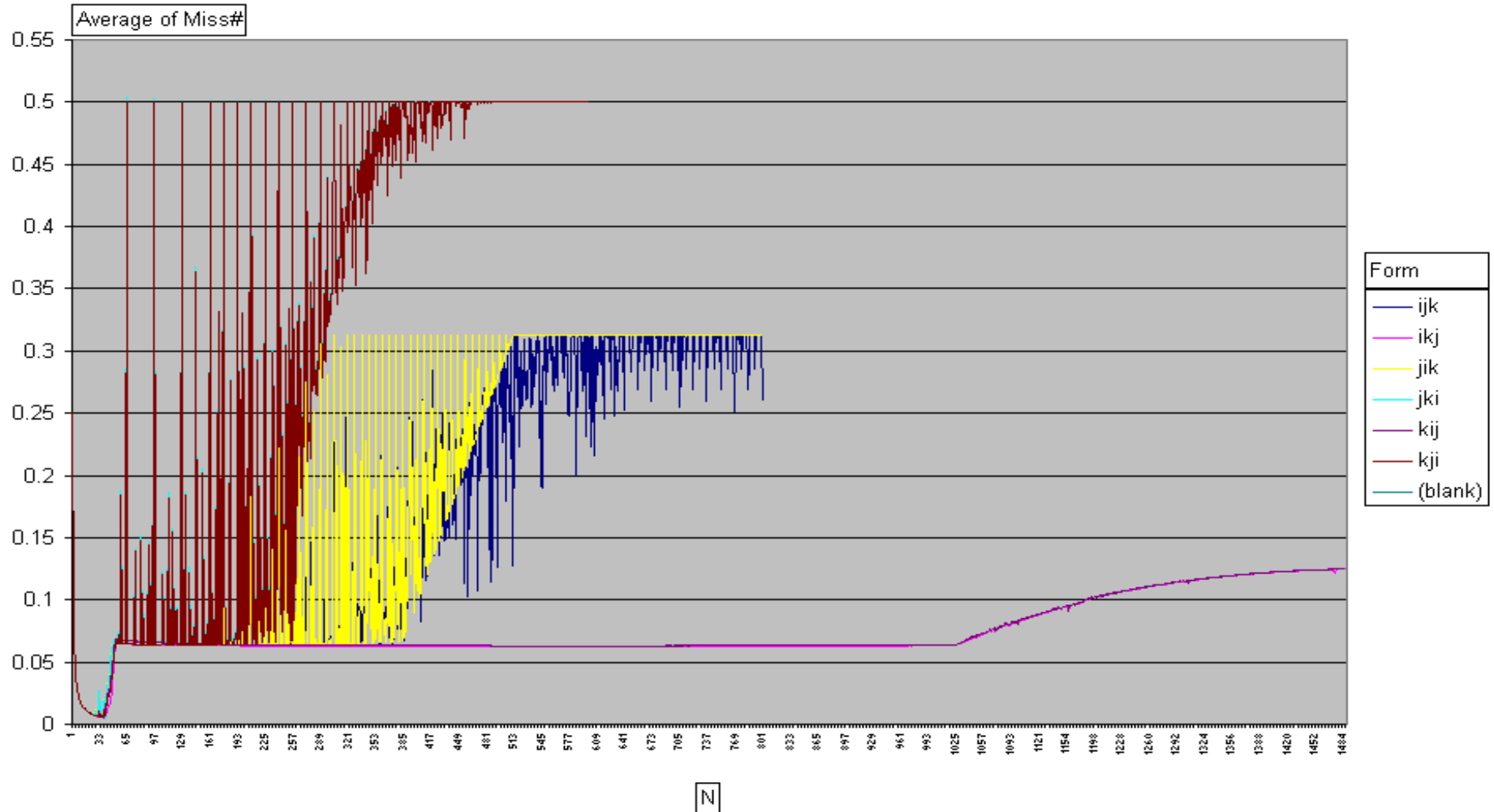
```
DO I = 1, N
  DO J = 1, N
    DO K = 1, N
      C(I,J) = C(I,J) + A(I,K)*B(K,J)
```



- Small cache scenario:
 - Matrices are large compared to cache/row-major storage
 - Cold and capacity misses
 - Miss ratio:
 - C: N^2/b misses (good temporal locality)
 - A: N^3/b misses (good spatial locality)
 - B: N^3 misses (poor temporal and spatial locality)
 - Miss ratio $\rightarrow 0.25(b+1)/b = 0.3125$ (for $b = 4$)

MMM Experiments

- Simulated L1 Cache Miss Ratio for Intel Pentium III
 - MMM with $N = 1 \dots 1300$
 - 16KB 32B/Block 4-way 8-byte elements



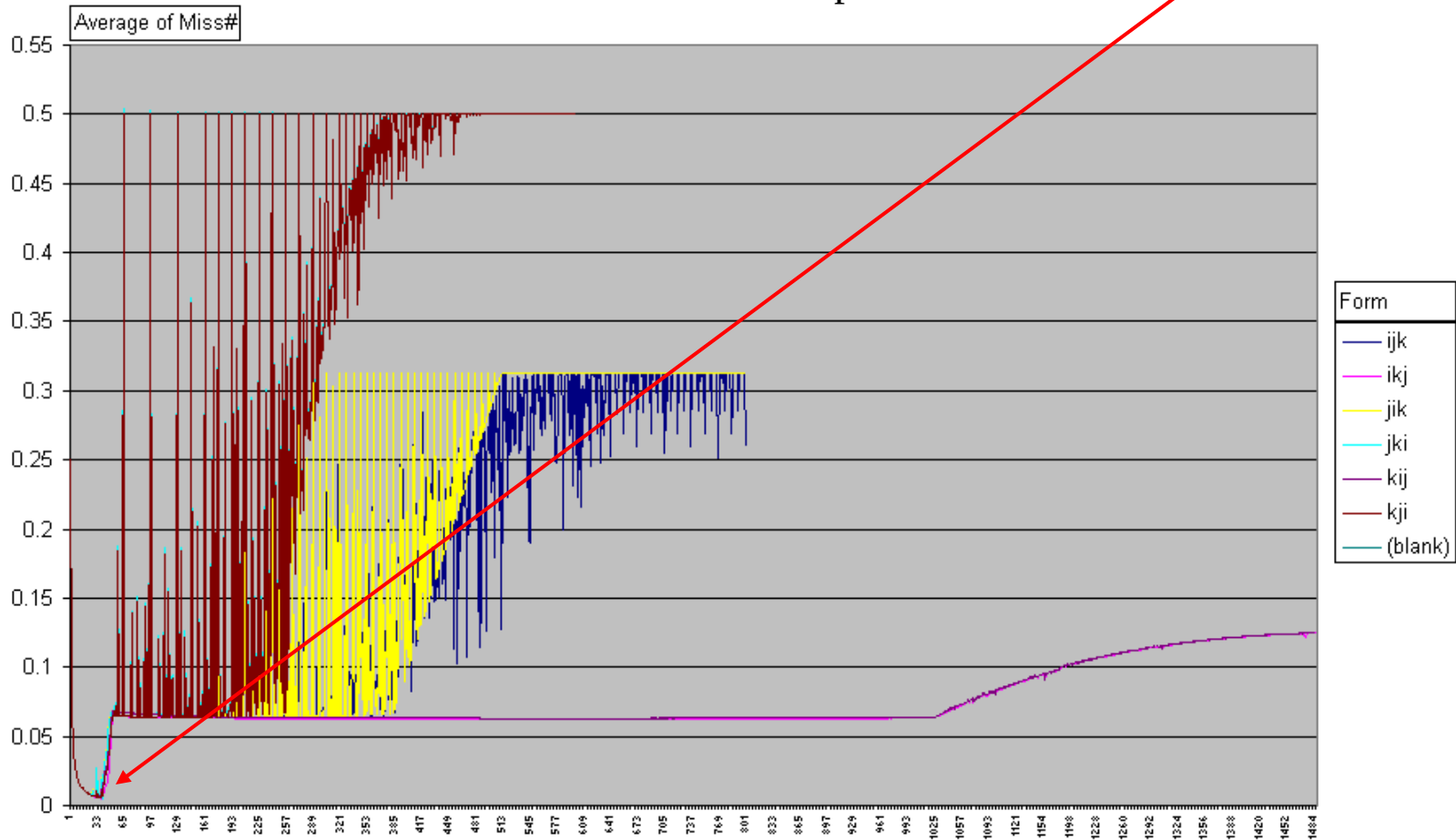
Quantifying performance differences

```
DO I = 1, N //assume arrays stored in row-major order
  DO J = 1, N
    DO K = 1, N
      C(I,J) = C(I,J) + A(I,K)*B(K,J)
```

- Typical cache parameters:
 - L2 cache hit: 10 cycles, cache miss 70 cycles
- Time to execute IKJ version:
$$2N^3 + 70*0.13*4N^3 + 10*0.87*4N^3 = 73.2 N^3$$
- Time to execute JKI version:
$$2N^3 + 70*0.5*4N^3 + 10*0.5*4N^3 = 162 N^3$$
- Speed-up = 2.2
- Key transformation: loop permutation

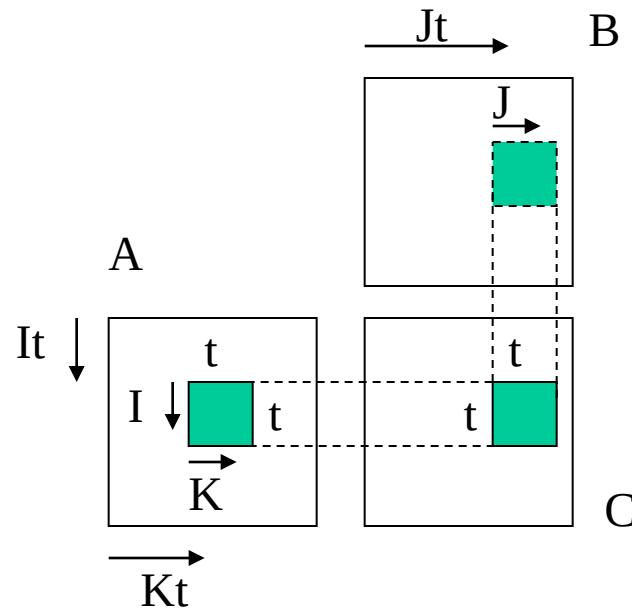
Even better.....

- Break MMM into a bunch of smaller MMMs so that large cache model is true for each small MMM
 - large cache model is valid for entire computation
 - miss ratio will be $0.75/bt$ for entire computation where t is



Loop tiling/blocking

```
DO It = 1,N, t
  DO Jt = 1,N,t
    DO Kt = 1,N,t
      DO I = It,It+t-1
        DO J = Jt,Jt+t-1
          DO K = Kt,Kt+t-1
            C(I,J) = C(I,J)+A(I,K)*B(K,J)
```



- Break big MMM into sequence of smaller MMMs where each smaller MMM multiplies sub-matrices of size txt.
- Parameter t (tile size) must be chosen carefully
 - as large as possible
 - working set of small matrix multiplication must fit in cache

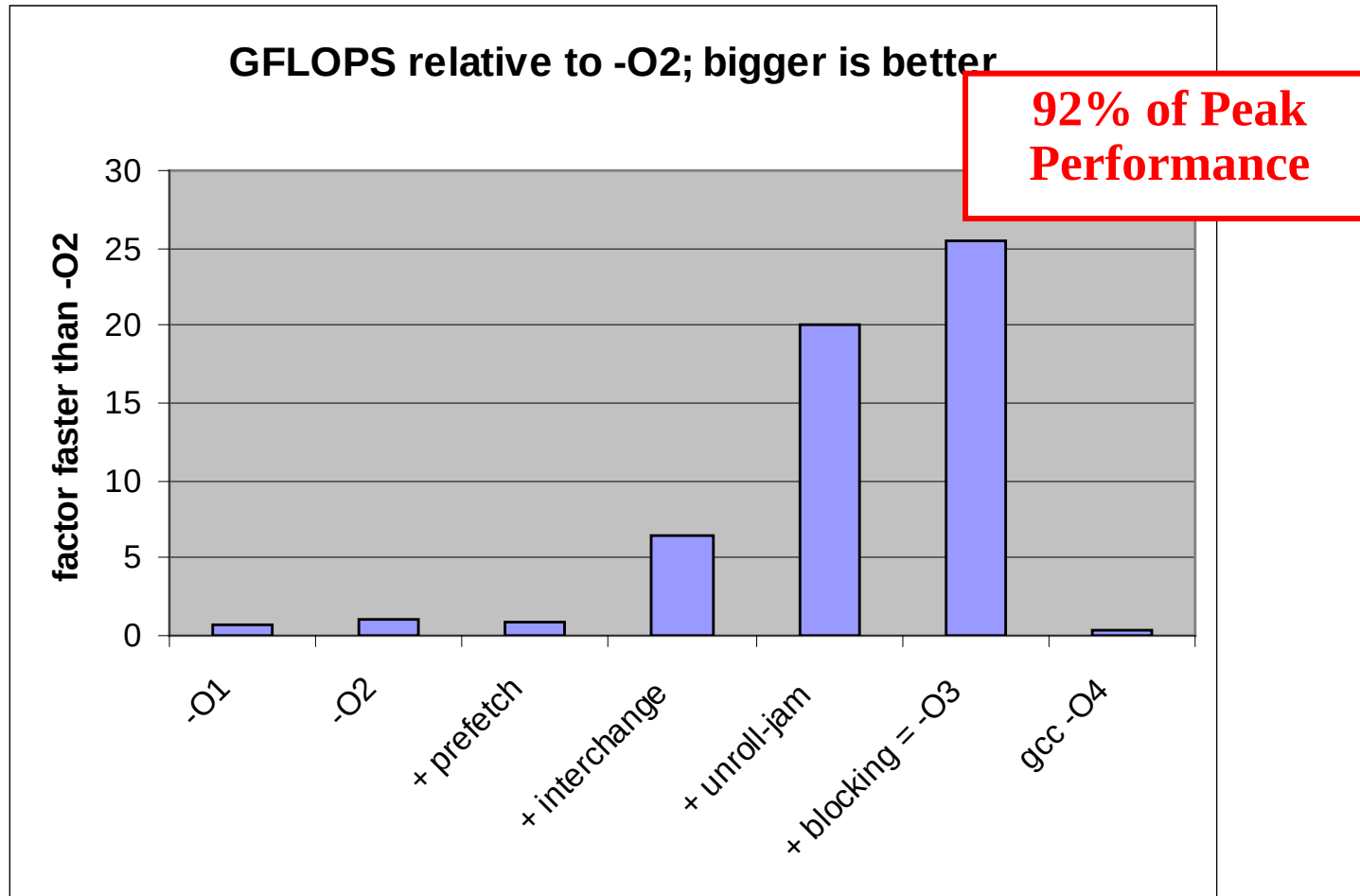
Speed-up from tiling/blocking

- Miss ratio for block computation
= miss ratio for large cache model
= $0.75/bt$
= 0.001 ($b = 4, t = 200$)
- Time to execute tiled version =
 $2N^3 + 70*0.001*4N^3 + 10*0.999*4N^3 = 42.3N^3$
- Speed-up over JKI version = 4

Observations

- Locality optimized code is more complex than high-level algorithm.
- Locality optimization changed the order in which operations were done, not the number of operations
- “Fine-grain” view of data structures (arrays) is critical
- Loop orders and tile size must be chosen carefully
 - cache size is key parameter
 - associativity matters
- Actual code is even more complex: must optimize for processor resources
 - registers: register tiling
 - pipeline: loop unrolling
 - Optimized MMM code can be ~1000's of lines of C code
- Wouldn't it be nice to have all this be done automatically by a compiler?
 - Actually, it is done automatically nowadays...

Performance of MMM code produced by
Intel's Itanium compiler (-O3)

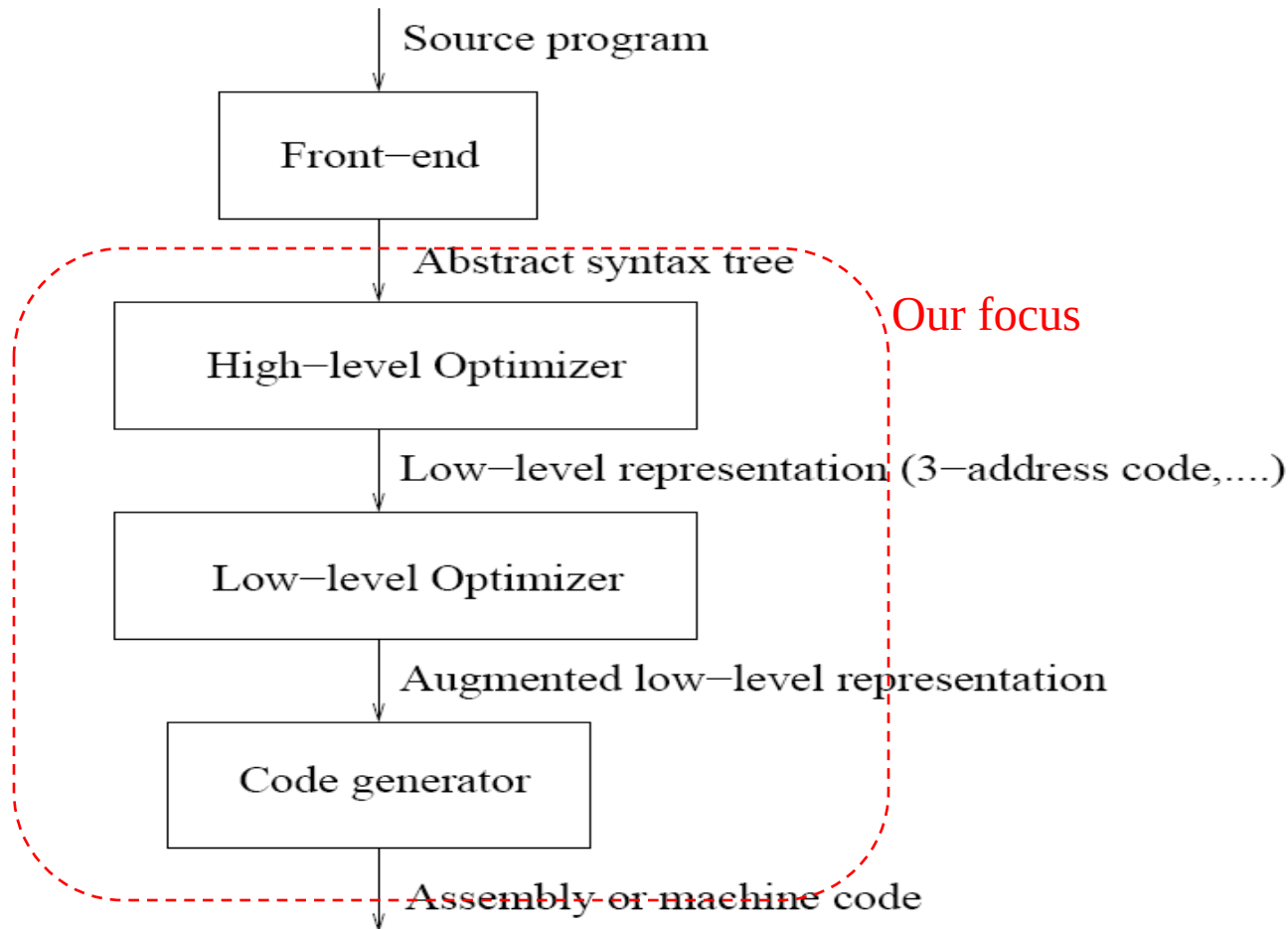


Goto BLAS obtains close to 99% of peak, so compiler is pretty good!

Discussion

- Exploiting parallelism, memory hierarchies etc. is very important
- If program uses only one core out of n cores in processors, you get at most $1/n$ of peak performance
- Memory hierarchy optimizations are very important
 - can improve performance by factor of 10 or more
- Key points:
 - need to focus on data structure manipulation
 - reorganization of computations and data structure layout are key
 - few opportunities usually to reduce the number of computations

Organization of modern compiler



Front-end

- Goal: convert linear representation of program to hierarchical representation
 - Input: text file
 - Output: abstract syntax tree + symbol table
- Key modules:
 - Lexical analyzer: converts sequence of characters in text file into sequence of tokens
 - Parser: converts sequence of tokens into abstract syntax tree + symbol table
 - Semantic checker: (eg) perform type checking

High-level optimizer

- Goal: perform high-level analysis and optimization of program
- Input: AST + symbol table from front-end
- Output: Low-level program representation such as 3-address code
- Tasks:
 - Procedure/method inlining
 - Array/pointer dependence analysis
 - Loop transformations: unrolling, permutation, tiling, jamming,....

Low-level optimizer

- Goal: perform scalar optimizations on low-level representation of program
- Input: low-level representation of program such as 3-address code
- Output: optimized low-level representation + additional information such as def-use chains
- Tasks:
 - Dataflow analysis: live variables, reaching definitions, ...
 - Scalar optimizations: constant propagation, partial redundancy elimination, strength reduction,

Code generator

- Goal: produce assembly/machine code from optimized low-level representation of program
- Input: optimized low-level representation of program from low-level optimizer
- Output: assembly/machine code for real or virtual machine
- Tasks:
 - Register allocation
 - Instruction selection

Discussion (I)

- Traditionally, all phases of compilation were completed before program was executed
- New twist: virtual machines
 - Offline compiler:
 - Generates code for virtual machine like JVM
 - Just-in-time compiler:
 - Generates code for real machine from VM code while program is executing
- Advantages:
 - Portability
 - JIT compiler can perform optimizations for particular input

Discussion (II)

- On current processors, accessing memory to fetch operands for a computation takes much longer than performing the computation
 - ➔ performance of most programs is limited by memory latency rather than by speed of computation (memory wall problem)
 - ➔ reducing memory traffic (locality) is more important than optimizing scalar computations
- Another problem: power
 - takes much more power to move data than to perform an arithmetic operation
 - exploiting locality is critical for power management as well

Course content (scalar stuff)

- **Introduction**
 - compiler structure, architecture and compilation, sources of improvement
- **Control flow analysis**
 - basic blocks & loops, dominators, postdominators, control dependence
- **Data flow analysis**
 - lattice theory, iterative frameworks, reaching definitions, liveness
- **Static-single assignment**
 - static-single assignment, constant propagation.
- **Global optimizations**
 - loop invariant code motion, common subexpression elimination, strength reduction.
- **Register allocation**
 - coloring, allocation, live range splitting.
- **Instruction scheduling**
 - pipelined and VLIW architectures, list scheduling.

Course content (data structure stuff)

- **Array dependence analysis**
 - integer linear programming, dependence abstractions.
- **Loop transformations**
 - linear loop transformations, loop fusion/fission, enhancing parallelism and locality
- **Self-optimizing programs**
 - empirical search, ATLAS, FFTW
- **Analysis of pointer-based programs**
 - points-to and shape analysis
- **Parallelizing graph programs**
 - amorphous data parallelism, exploiting amorphous data-parallelism
- **Program verification**
 - Floyd-Hoare style proofs, model checking, theorem provers

Lecture schedule

- See
 - <http://www.cs.utexas.edu/users/pingali/CS380C/2013/index.html>
- Some lectures will be given by guest lecturers from my group and from industry