CS 380C:
Advanced Topics in Compilers

Administration

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Meeting times

- Lecture:
  - TTh 12:30-2:00PM, GDC 2.210
- Office hours:
  - Keshav Pingali: Tuesday 3-4 PM, POB 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/2016/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

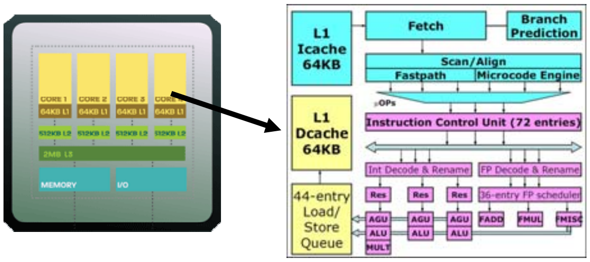
What do compilers do?

- 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.

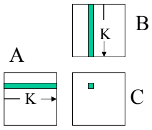
Example: matrix multiplication

```
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)

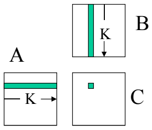
```
DO I = 1, N
  DO J = 1, N
    DO K = 1, N
      C(I,J) = C(I,J) + A(I,K)*B(K,J)
```



- 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)

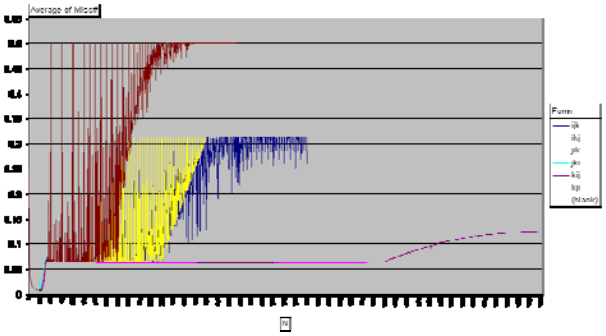
```
DO I = 1, N
  DO J = 1, N
    DO K = 1, N
      C(I,J) = C(I,J) + A(I,K)*B(K,J)
```



- 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 → 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…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)
```

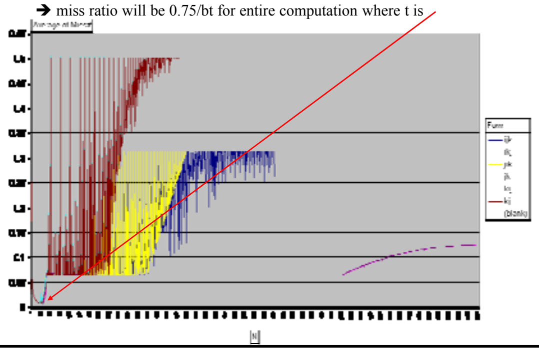
- Typical cache parameters:
  - L2 cache hit: 10 cycles, cache miss 70 cycles
- Time to execute IKJ version:
  $2N^3 + 70*0.13*4N^3 + 10*0.87*4N^3 = 73.2 N^3$
- Time to execute JKI version:
  $2N^3 + 70*0.5*4N^3 + 10*0.5*4N^3 = 162 N^3$
- Speed-up = 2.2
- Key transformation: loop permutation

Even better…..

- Break MMM into a bunch of smaller MMMs so that large cache model is true for each small MMM

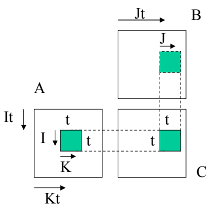
  ➔ large cache model is valid for entire computation

  ➔ 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

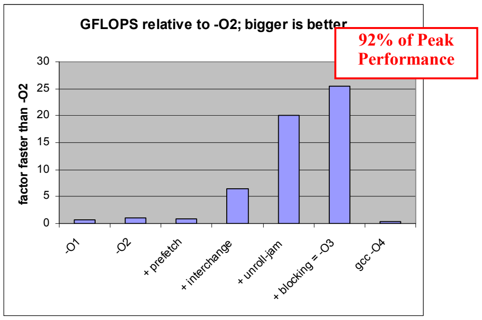
  = 0.001 (b = 4, t = 200)
- Time to execute tiled version =

  $2N^3 + 70*0.001*4N^3 + 10*0.999*4N^3 = 42.3N^3$
- 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)



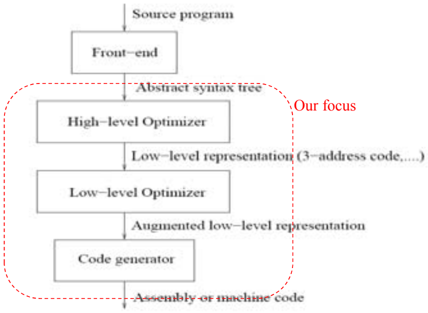
92% of Peak Performance

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: energy
  - takes much more energy to move data than to perform an arithmetic operation
  - exploiting locality is critical for power/energy 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/2016/index.html
- Some lectures will be given by guest lecturers from my group and from industry