Caches: PA5 part 2, cache friendly code, digital logic

Yipeng Huang

Rutgers University

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Announcements

PA5: Optimizing programs for caches

Cache-friendly code
  Loop interchange
  Cache blocking
  Cache oblivious algorithms

Memory hierarchy implications for software-hardware abstraction
Looking ahead

Class plan

1. PA5 now out. Due Monday, 4/26.
2. Short quiz 8 now out. Due Monday, 4/19.
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Optimize some code for better cache performance

1. cacheBlocking
2. cacheOblivious
PA5: Optimizing programs for caches

A tour of files in the package

- Baseline implementations: matMul, matTrans.
- Your optimized implementations: cacheBlocking, cacheOblivious.
- What the autograder.py does:
  1. Testing for correctness.
  2. Getting the memory trace.
  3. Comparing your performance against the baseline.
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Cache-friendly code

Algorithms can be written so that they work well with caches:

- Maximize hit rate.
- Minimize miss rate.
- Minimize eviction counts.

Do so by:

- Increasing spatial locality.
- Increasing temporal locality.

A few specific techniques:

- Loop interchange.
- Cache blocking.
- Cache-oblivious algorithm implementation.
Loop interchange

Refer to textbook slides on "Rearranging loops to improve spatial locality"

- Loop interchange increases spatial locality.
- In PA5, fourth part "cacheBlocking" you can explore the impact of this on matrix multiplication.
- In practice, programmers do not have to worry about this optimization.
- Optimized automatically in GCC by compiler flag `-floop-interchange` and `-O3`. 
Cache blocking

Refer to textbook slides on "Using blocking to improve temporal locality"

- Cache blocking increases temporal locality.
- In PA5, fourth part "cacheBlocking" you can explore the impact of this on matrix multiplication.
- In practice, programmers do not have to worry about this optimization.
- Optimized automatically in GCC by compiler flag `-floop-block`. But it is not part of default optimizations such as `-O3` so you have to remember to set it.
Cache oblivious algorithms

The challenge in writing code / compiling programs to take advantage of caches:

- Programmers do not easily have information about target machine.
- Compiling binaries for every envisioned target machine is costly.
Matrix transpose baseline algorithm: iteration

\[ A = \begin{bmatrix}
  a_{0,0} & a_{0,1} & a_{0,2} & a_{0,3} \\
  a_{1,0} & a_{1,1} & a_{1,2} & a_{1,3} \\
  a_{2,0} & a_{2,1} & a_{2,2} & a_{2,3} \\
  a_{3,0} & a_{3,1} & a_{3,2} & a_{3,3}
\end{bmatrix} \]

\[ B = A^T = \begin{bmatrix}
  a_{0,0} & a_{1,0} & a_{2,0} & a_{3,0} \\
  a_{0,1} & a_{1,1} & a_{2,1} & a_{3,1} \\
  a_{0,2} & a_{1,2} & a_{2,2} & a_{3,2} \\
  a_{0,3} & a_{1,3} & a_{2,3} & a_{3,3}
\end{bmatrix} \]

```plaintext
for ( size_t i=0; i<n; i++ ) {
  for ( size_t j=0; j<n; j++ ) {
    B[ j*n + i ] = A[ i*n + j ];
  }
}
```
Matrix transpose via recursion

\[ A = \begin{bmatrix} A_{0,0} & A_{0,1} \\ A_{1,0} & A_{1,1} \end{bmatrix} = \begin{bmatrix} a_{0,0} & a_{0,1} & a_{0,2} & a_{0,3} \\ a_{1,0} & a_{1,1} & a_{1,2} & a_{1,3} \\ a_{2,0} & a_{2,1} & a_{2,2} & a_{2,3} \\ a_{3,0} & a_{3,1} & a_{3,2} & a_{3,3} \end{bmatrix} \]

\[ B = A^\top = \begin{bmatrix} A_{0,0}^\top & A_{0,1}^\top \\ A_{1,0}^\top & A_{1,1}^\top \end{bmatrix} = \begin{bmatrix} a_{0,0} & a_{1,0} & a_{2,0} & a_{3,0} \\ a_{0,1} & a_{1,1} & a_{2,1} & a_{3,1} \\ a_{0,2} & a_{1,2} & a_{2,2} & a_{3,2} \\ a_{0,3} & a_{1,3} & a_{2,3} & a_{3,3} \end{bmatrix} \]

Strategy:

- Divide and conquer large matrix to transpose into smaller transpositions.
- After some recursion, problem will fit well inside cache capacity.
- Once enough locality exists within subroutine, switch to plain iterative approach.

Advantages:

- No need to know about cache capacity and parameters beforehand.
- Works well with deep multilevel cache hierarchies: different amounts of locality for each cache level.

32x32 transpose -> 4 separate 16x16 transpose tasks
16x16 -> 4 separate 8x8
8x8 -> 4 separate 4x4
4x4 -> 4 separate 2x2
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It is not entirely true the architecture can hide details of microarchitecture
Even less true going forward. What to do?

Application level recommendations

▶ Use industrial strength, optimized libraries compiled for target machine.
▶ Lapack, Linpack, Matlab, Python SciPy, NumPy...
▶ https://people.inf.ethz.ch/markusp/teaching/263-2300-ETH-spring11/slides/class08.pdf

Algorithm level recommendations
Deploy cache-oblivious algorithm implementations.

Compiler level recommendations

▶ Enable compiler optimizations—e.g., -O3, -floop-interchange, -floop-block.