Performance Tuning

CS 217

Principles

- Don't optimize your code
  - Your program might be fast enough already
  - Machines are getting faster and cheaper every year
  - Memory is getting denser and cheaper every year
  - Hand optimization may make the code less readable, less robust, and more difficult to test
- Performance tuning of bottlenecks
  - Identify performance bottlenecks
  - Machine-independent algorithm improvements
  - Hardware-dependent improvements
- Try not to sacrifice correctness, readability and robustness

Amdahl's Law: Only Bottlenecks Matter

- Definition of speedup:

$$Speedup = \frac{Original}{Enhanced} \qquad Enhanced = \frac{Original}{Speedup}$$

- Amdahl's law (1967):

$$OverallSpeedup = \frac{1}{(1-f)+\frac{f}{s}}$$

  - f is the fraction of program enhanced
  - s is the speedup of the enhanced portion

Examples

- Amdahl's law

$$OverallSpeedup = \frac{1}{(1-f)+\frac{f}{s}}$$

- What is the overall speedup if you make 10% of a program 90 times faster?

$$\frac{1}{(1-0.1)+\frac{0.1}{90}} \approx \frac{1}{0.9011} \approx 1.11$$

- What is the overall speedup if you make 90% of a program 10 times faster

$$\frac{1}{(1-0.9)+\frac{0.9}{10}} = \frac{1}{0.19} \approx 5.26$$

Identify Performance Bottlenecks

- Use tools such as gprof to learn where the time goes

```
Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  s/call   s/call  name
 76.21      3.46     3.46  6664590    0.00     0.00  partition
 16.74      4.22     0.76 54358002    0.00     0.00  swap
  3.74      4.39     0.17        1    0.17     0.17  fillArray
  2.86      4.52     0.13        1    0.13     4.35  quicksort
  0.44      4.54     0.02                            printArray
```

- More sophisticated tools
  - Tools that use performance counters to show cache miss/hit etc (e.g. VTune)
  - Tools for multiprocessor systems (for multi-threaded programs)
  - Tools to investigate where I/O operations take place

Strategies to Speedup

- Use a better algorithm
  - Complexity of the algorithm makes a big difference
- Simple code optimizations
  - Extract common expression: f(x*y + x*z) + g(x*y+x*z)
  - Loop unrolling:

```
for (i=0; i<N; i++)
    x[i]=y[i];

for (i=0; i<N; i+=4) {   /* if N is divisible by 4 */
    x[i]   = y[i];
    x[i+1] = y[i+1];
    x[i+2] = y[i+2];
    x[i+3] = y[i+3];
}
```

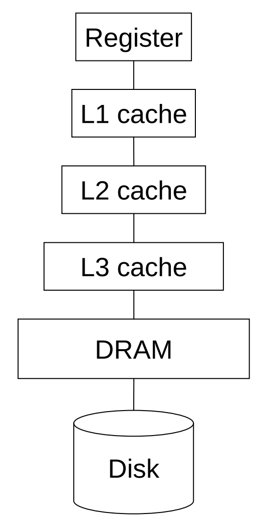
- Enable compiler optimizations
  - Modern compilers perform most of the above optimizations
  - Example: use level 3 optimization in gcc:
    gcc –O3 foo.c

Strategies to Speedup, con'd

- Improve performance with deep memory hierarchy
  - Make the code cache-aware
  - Reduce the number of I/O operations
- Inline procedures
  - Remove the procedure call overhead (compilers can do this)
- Inline assembly
  - Almost never do this unless you deal with hardware directly
  - Or when the high-level language is in the way

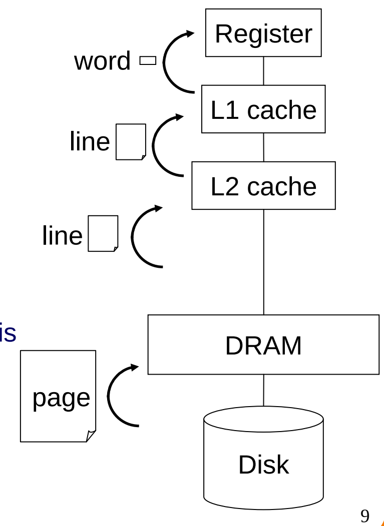
Memory Hierarchy

- Hardware trends
  - CPU clock rate doubles every 18-24 months (50% per year)
  - DRAM and disk Access times improve at a rate about 10% per year
  - Memory hierarchy is getting deeper (L1, L2 and L3 caches)
- Software performance has become more sensitive to cache misses
  - Register: 1 cycle
  - L1 cache hit: 2-4 cycles
  - L2 cache hit: ~10 cycles
  - L3 cache hit: ~50 cycles
  - L3 miss: ~500 cycles
  - Disk I/O: ~30M cycles

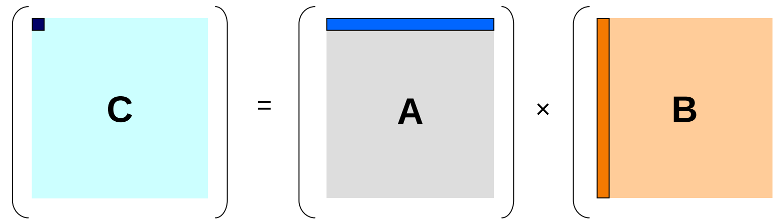


Memory Hierarchy

- Typical numbers:
  - Size
    - L1 cache: 8K
    - L2 cache: 256K
  - Granularity of movement
    - “Cache line size:” 128 bytes
    - “Memory page size:” 4K or 8K
- Some properties:
  - “Inclusion property”
  - Upon a “miss,” a whole line (or page) is brought up from the lower level
  - “Eviction” from higher level to make space
  - Caches managed by hardware
  - Memory managed by OS (software)



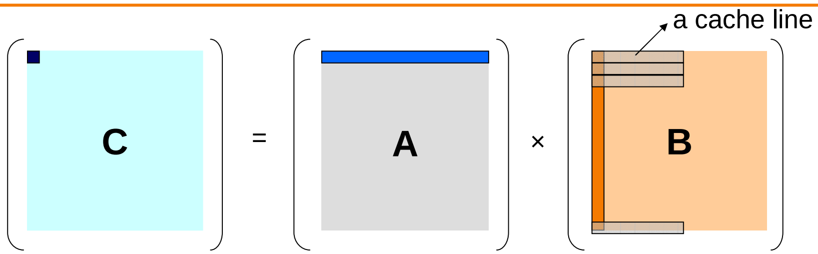
Example: Matrix Multiply




```
int i, j, k;
for (i=0; i<N; i++)
   for (j=0; j<N; j++)
      for (k=0; k<N; k++)
         C[i][j] += A[i][k] * B[k][j];
```

- Matrix B stored in “row major order”
- How many cache misses?
- Execution time on tux (N=1000, -O3 with gcc): 18.5sec

Example: Matrix Multiply




```
int i, j, k;
for (i=0; i<N; i++)
   for (j=0; j<N; j++)
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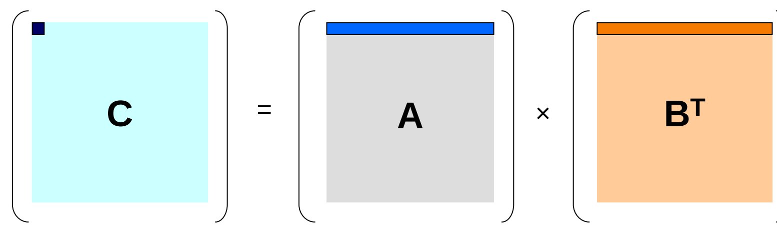
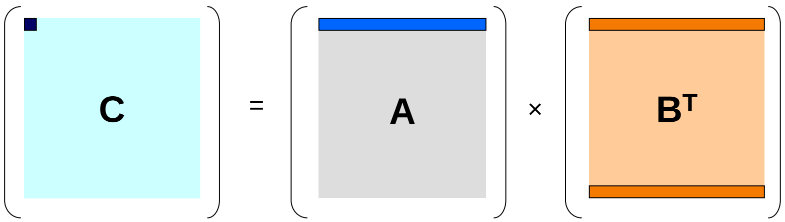
Transpose Matrix B First




```
int i, j, k;
for (i=0; i<N; i++)
   for (j=0; j<N; j++)
      for (k=0; k<N; k++)
         C[i][j] += A[i][k] * BT[j][k];
```

- Matrix B stored in “column-major” order
- What about the cache miss situation now?
- Execution time on tux (N=1000, -O3 with gcc): 13sec

Transpose Matrix B First




```
int i, j, k;
for (i=0; i<N; i++)
   for (j=0; j<N; j++)
      for (k=0; k<N; k++)
         C[i][j] += A[i][k] * BT[j][k];
```

- Matrix B stored in “column-major” order
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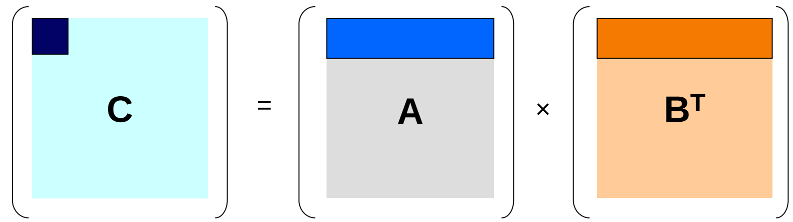
- Execution time on tux (N=1000, -O3 with gcc): 13sec

A Blocked Matrix Multiply




```
int i, j, ii, jj, k, block;
block = 10;
for (ii=0; ii<N; ii+=block)
   for (jj=0; jj<N; jj+=block)
     for (i=ii; i<ii+block; i++)
        for (j=jj; j<jj+block; j++)
           for (k=0; k<N; k++)
              C[i][j] += A[i][k] * BT[j][k];
```

- Execution time on tux (N=1000, -O3 with gcc): 4.4sec

Inline Procedure

- To specify an inline procedure

```
static inline int plus5(int x)
{
   return x + 5;
}
```

- Is this better than using macro?

  #define plus5(x) (x+5)

Why Inline Assembly?

- For most system modules (>99%), programming in C delivers adequate performance
- It is more convenient to write system programs in C
  - Robust programming techniques apply to C better
  - Modular programming is easier
  - Testing is easier
- When do you have to use assembly?
  - You need to use certain instructions that the compiler don’t generate (MMX, SSE, SSE2, and IA32 special instructions)
  - You need to access some hardware, which is not possible in a high-level language
- A compromise is to write most programs in C and as little as possible in assembly: inline assembly

Inline Assembly

- Basic format for gcc compiler

```
asm [volatile] ( "asm-instructions" );
__asm__ [volatile] ( "asm-instructions" );
```

  - “asm-instructions” will be inlined into where this statement is in the C program
  - The key word “volatile” is optional: telling the gcc compiler not to optimize away the instructions
  - Need to use “\n\t” to separate instructions. Otherwise, the strings will be concatenated without space in between.
- Example
  - `asm volatile( "cli" );`
  - ```
    __asm__( “pushl %eax\n\t”
             “incl %eax” );
    ```
- But, to integrate assembly with C programs, we need a contract on register and memory operands

Extended Inline Assembly

- Extended format

```
asm [volatile]
  ( “asm-instructions”: out-regs: in-regs: used-
  regs);
```

  - Both “asm” and “volatile” can be enclosed by “__”
  - “volatile” is telling gcc compiler not to optimize away
  - “asm-instructions” are assembly instructions
  - “out-regs” provide output registers (optional)
  - “in-regs” provide input registers (optional)
  - “used-regs” list registers used in the assembly program (optional)

Summary

- Don’t optimize your code, unless it is really necessary
- Use a better algorithm is choice #1
- Then, tune the bottleneck first (Amdahl’s law)
  - Identify the bottlenecks by using tools
  - Make program cache aware
  - Reduce I/O operations
  - Inline procedures
  - Inline assembly (to access hardware including special instructions)
- Additional reading besides the textbook
  - Jon Bentley’s *Writing Efficient Programs* (Prentice-Hall, 1982), Programming Pearls and More Programming Pearls (Addision Wesley, 1986 and 1988)
  - John Hennessy and David Patterson’s Computer Organization and Design: The Hardware/Software Interface (Morgan Kaufman, 1997)

The Final Exam

- Time: Friday, 1/21, 8:30am – 10:30am
- Location: CS 104
- Cumulative
- Open book and open notes
```