Program Optimization

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Goals of Today's Class

- Improving program performance
  - When and what to optimize
  - Better algorithms & data structures vs. tuning the code
- Exploiting an understanding of underlying system
  - Compiler capabilities
  - Hardware architecture
  - Program execution
- Why?
  - To be effective, and efficient, at making programs faster
    - Avoid optimizing the fast parts of the code
    - Help the compiler do its job better
  - To review material from the second half of the course

Improving Program Performance

- Most programs are already "fast enough"
  - No need to optimize performance at all
  - Save your time, and keep the program simple/readable
- Most parts of a program are already "fast enough"
  - Usually only a small part makes the program run slowly
  - Optimize *only* this portion of the program, as needed
- Steps to improve execution (time) efficiency
  - Do timing studies (e.g., gprof)
  - Identify hot spots
  - **Optimize that part of the program**
  - Repeat as needed

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Ways to Optimize Performance

- Better data structures and algorithms
  - Improves the *"asymptotic complexity"*
    - Better scaling of computation/storage as input grows
    - E.g., going from $O(n^2)$ sorting algorithm to $O(n \log n)$
  - Clearly important if large inputs are expected
  - Requires understanding data structures and algorithms
- Better source code the compiler can optimize
  - Improves the *"constant factors"*
    - Faster computation during each iteration of a loop
    - E.g., going from *1000n* to *10n* running time
  - Clearly important if a portion of code is running slowly
  - Requires understanding hardware, compiler, execution

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Helping the Compiler Do Its Job

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Optimizing Compilers

- Provide efficient mapping of program to machine
  - Register allocation
  - Code selection and ordering
  - Eliminating minor inefficiencies
- Don’t (usually) improve asymptotic efficiency
  - Up to the programmer to select best overall algorithm
- Have difficulty overcoming “optimization blockers”
  - Potential function side-effects
  - Potential memory aliasing

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Limitations of Optimizing Compilers

- Fundamental constraint
  - Compiler must not change program behavior
  - Ever, even under rare pathological inputs
- Behavior that may be obvious to the programmer can be obfuscated by languages and coding styles
  - Data ranges more limited than variable types suggest
  - Array elements remain unchanged by function calls
- Most analysis is performed only within functions
  - Whole-program analysis is too expensive in most cases
- Most analysis is based only on static information
  - Compiler has difficulty anticipating run-time inputs

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Avoiding Repeated Computation

- A good compiler recognizes simple optimizations
  - Avoiding redundant computations in simple loops
  - Still, programmer may still want to make it explicit
- Example
  - Repetition of computation: n * i

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

→

```
for (i = 0; i < n; i++) {
  int ni = n * i;
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
}
```

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Worrying About Side Effects

- Compiler cannot always avoid repeated computation
  - May not know if the code has a "side effect"
  - … that makes the transformation change the code's behavior
- Is this transformation okay?

```
int func1(int x) {
  return f(x) + f(x) + f(x) + f(x);
}
```

```
int func1(int x) {
  return 4 * f(x);
}
```

- Not necessarily, if

```
int counter = 0;

int f(int x) {
  return counter++;
}
```

And this function may be defined in another file known only at link time!

Another Example on Side Effects

- Is this optimization okay?

```
for (i = 0; i < strlen(s); i++) {
   /* Do something with s[i] */
}
```

```
length = strlen(s);
for (i = 0; i < length; i++) {
   /* Do something with s[i] */
}
```

- Short answer: it depends
  - Compiler often cannot tell
  - Most compilers do not try to identify side effects
- Programmer knows best
  - And can decide whether the optimization is safe

Memory Aliasing

- Is this optimization okay?

```
void twiddle(int *xp, int *yp) {
   *xp += *yp;
   *xp += *yp;
}
```

```
void twiddle(int *xp, int *yp) {
   *xp += 2 * *yp;
}
```

- Not necessarily, what if xp and yp are equal?
  - First version: result is 4 times *xp
  - Second version: result is 3 times *xp

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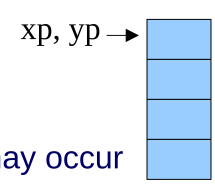
Memory Aliasing

- Memory aliasing
  - Single data location accessed through multiple names
  - E.g., two pointers that point to the same memory location
- Modifying the data using one name
  - Implicitly modifies the values seen through other names



- Blocks optimization by the compiler
  - The compiler cannot tell when aliasing may occur
  - … and so must forgo optimizing the code
- Programmer often *does* know
  - And *can* optimize the code accordingly

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Another Aliasing Example

- Is this optimization okay?

```
int *x, *y;
…
*x = 5;
*y = 10;
printf("x=%d\n", *x);
```

→

```
printf("x=5\n");
```

- Not necessarily
  - If y and x point to the same location in memory…
  - … the correct output is "x = 10\n"

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Summary: Helping the Compiler

- Compiler can perform many optimizations
  - Register allocation
  - Code selection and ordering
  - Eliminating minor inefficiencies
- But often the compiler needs your help
  - Knowing if code is free of side effects
  - Knowing if memory aliasing will not happen
- Modifying the code can lead to better performance
  - Profile the code to identify the "hot spots"
  - Look at the assembly language the compiler produces
  - Rewrite the code to get the compiler to do the right thing

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Exploiting the Hardware

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Underlying Hardware

- Implements a collection of instructions
  - Instruction set varies from one architecture to another
  - Some instructions may be faster than others
- Registers and caches are faster than main memory
  - Number of registers and sizes of caches vary
  - Exploiting both spatial and temporal locality
- Exploits opportunities for parallelism
  - Pipelining: decoding one instruction while running another
    - Benefits from code that runs in a sequence
  - Superscalar: perform multiple operations per clock cycle
    - Benefits from operations that can run independently
  - Speculative execution: performing instructions before knowing they will be reached (e.g., without knowing outcome of a branch)

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Addition Faster Than Multiplication

- Adding instead of multiplying
  - Addition is faster than multiplication
- Recognize sequences of products
  - Replace multiplication with repeated addition

```
for (i = 0; i < n; i++) {
  int ni = n * i;
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
}
```

```
int ni = 0;
for (i = 0; i < n; i++) {
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
  ni += n;
}
```

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Bit Operations Faster Than Arithmetic

- Shift operations to multiple/divide by powers of 2
  - "x >> 3" is faster than "x/8"
  - "x << 3" is faster than "x * 8"

53	0	0	1	1	0	1	0	1
53<<2	1	1	0	1	0	0	0	0

- Bit masking is faster than mod operation
  - "x & 15" is faster than "x % 16"

53	0	0	1	1	0	1	0	1
& 15	0	0	0	0	1	1	1	1
5	0	0	0	0	0	1	0	1

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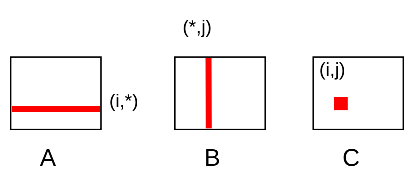
Caching: Matrix Multiplication

- Caches
  - Slower than registers, but faster than main memory
  - Both instruction caches and data caches
- Locality
  - Temporal locality: recently-referenced items are likely to be referenced in near future
  - Spatial locality: Items with nearby addresses tend to be referenced close together in time
- Matrix multiplication
  - Multiply n-by-n matrices A and B, and store in matrix C
  - Performance heavily depends on effective use of caches

Matrix Multiply: Cache Effects

```
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];
  }
}
```

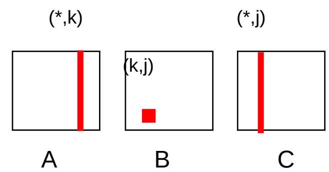
- Reasonable cache effects
  - Good spatial locality for A
  - Poor spatial locality for B
  - Good temporal locality for C



Matrix Multiply: Cache Effects

```
for (j=0; j<n; j++) {
  for (k=0; k<n; k++) {
    for (i=0; i<n; i++)
      c[i][j] += a[i][k] * b[k][j];
  }
}
```

- Rather poor cache effects
  - Bad spatial locality for A
  - Good temporal locality for B
  - Bad spatial locality for C



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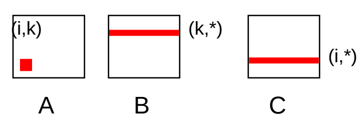
Matrix Multiply: Cache Effects

```
for (k=0; k<n; k++) {
  for (i=0; i<n; i++) {
    for (j=0; j<n; j++)
      c[i][j] += a[i][k] * b[k][j];
  }
}
```

- Good poor cache effects
  - Good temporal locality for A
  - Good spatial locality for B
  - Good spatial locality for C



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Parallelism: Loop Unrolling

- What limits the performance?

```
for (i = 0; i < length; i++)
  sum += data[i];
```

- Limited apparent parallelism
  - One main operation per iteration (plus book-keeping)
  - Not enough work to keep multiple functional units busy
  - Disruption of instruction pipeline from frequent branches
- Solution: unroll the loop
  - Perform multiple operations on each iteration

Parallelism: After Loop Unrolling

- Original code

```
for (i = 0; i < length; i++)
  sum += data[i];
```

- After loop unrolling (by three)

```
/* Combine three elements at a time */
limit = length – 2;
for (i = 0; i < limit; i+=3)
  sum += data[i] + data[i+1] + data[i+2];

/* Finish any remaining elements */
for ( ; i < length; i++)
  sum += data[i];
```

Program Execution

Avoiding Function Calls

- Function calls are expensive
  - Caller saves registers and pushes arguments on stack
  - Callee saves registers and pushes local variables on stack
  - Call and return disrupt the sequence flow of the code
- Function inlining:

```
void g(void) {
    /* Some code */
}

void f(void) {
    …
    g();
    …
}
```

Some compilers support "inline" keyword directive.

```
void f(void) {
    …
    /* Some code */
    …
}
```

Writing Your Own Malloc and Free

- Dynamic memory management
  - Malloc to allocate blocks of memory
  - Free to free blocks of memory
- Existing malloc and free implementations
  - Designed to handle a wide range of request sizes
  - Good most of the time, but rarely the best for all workloads
- Designing your own dynamic memory management
  - Forego using traditional malloc/free, and write your own
  - E.g., if you know all blocks will be the same size
  - E.g., if you know blocks will usually be freed in the order allocated
  - E.g., <insert your known special property here>

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Conclusion

- Work smarter, not harder
  - No need to optimize a program that is "fast enough"
  - Optimize only when, and where, necessary
- Speeding up a program
  - Better data structures and algorithms: better asymptotic behavior
  - Optimized code: smaller constants
- Techniques for speeding up a program
  - Coax the compiler
  - Exploit capabilities of the hardware
  - Capitalize on knowledge of program execution

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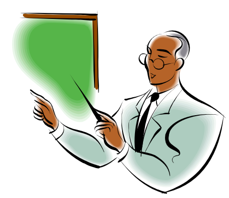
Course Wrap Up

The Rest of the Semester



- Deans Date: Tuesday May 12
  - Final assignment due at 9pm
  - Cannot be accepted after 11:59pm
- Final Exam: Friday May 15
  - 1:30-4:20pm in Friend Center 101
  - Exams from previous semesters are online at
    - http://www.cs.princeton.edu/courses/archive/spring09/cos217/exam2prep/
  - Covers entire course, with emphasis on second half of the term
  - Open book, open notes, open slides, etc. (just no computers!)
    - No need to print/bring the IA-32 manuals
- Office hours during reading/exam period
  - Daily, times TBA on course mailing list
- Review sessions
  - May 13-14, time TBA on course mailing list

Goals of COS 217

- Understand boundary between code and computer
  - Machine architecture
  - Operating systems
  - Compilers

- Learn C and the Unix development tools
  - C is widely used for programming low-level systems
  - Unix has a rich development environment
  - Unix is open and well-specified, good for study & research
- Improve your programming skills
  - More experience in programming
  - Challenging and interesting programming assignments
  - Emphasis on modularity and debugging

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Relationship to Other Courses

- Machine architecture
  - Logic design (306) and computer architecture (471)
  - COS 217: assembly language and basic architecture
- Operating systems
  - Operating systems (318)
  - COS 217: virtual memory, system calls, and signals
- Compilers
  - Compiling techniques (320)
  - COS 217: compilation process, symbol tables, assembly and machine language
- Software systems
  - Numerous courses, independent work, etc.
  - COS 217: programming skills, UNIX tools, and ADTs

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Lessons About Computer Science

- Modularity
  - Well-defined interfaces between components
  - Allows changing the implementation of one component without changing another
  - The key to managing complexity in large systems
- Resource sharing
  - Time sharing of the CPU by multiple processes
  - Sharing of the physical memory by multiple processes
- Indirection
  - Representing address space with virtual memory
  - Manipulating data via pointers (or addresses)

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Lessons Continued

- Hierarchy
  - Memory: registers, cache, main memory, disk, tape, …
  - Balancing the trade-off between fast/small and slow/big
- Bits can mean anything
  - Code, addresses, characters, pixels, money, grades, …
  - Arithmetic can be done through logic operations
  - The meaning of the bits depends entirely on how they are accessed, used, and manipulated

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Have a Great Summer!!!

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