Performance Improvement Revisited

Goals of this Lecture

• Help you learn how to:
  • Improve program performance by exploiting knowledge of underlying system
    • Compiler capabilities
    • Hardware architecture
    • Program execution

• And thereby:
  • Help you to write efficient programs
  • 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

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
Helping the Compiler Do Its Job

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
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

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: \( n \times i \)

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

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

• Is this transformation okay?

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

• Not necessarily, if

```c
int counter = 0;
int f(int x) {
    return counter++;
}
```

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

• 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

Another Example on Side Effects

• Is this optimization okay for compiler to do?

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

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

  ```c
  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

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
Another Aliasing Example

• Is this optimization okay?

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

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

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
Exploiting the Hardware

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)
Addition Faster Than Multiplication

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

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

Bit Operations Faster Than Arithmetic

- Use shifts to multiply/divide by powers of 2
  - “x >> 3” is faster than “x/8”
  - “x << 3” is faster than “x * 8”

```c
53 << 2
```

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

```c
53 & 15
```
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

```c
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

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

```c
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];
    }
}
```

Matrix Multiply: Cache Effects

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

```c
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];
    }
}
```
Parallelism: Loop Unrolling

- What limits the performance?

```c
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

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

- After loop unrolling (by three)

```c
/* 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:

```c
void g(void) {
    /* Some code */
}
void f(void) {
    ... 
g();
    ... 
}
```

Some compilers support “inline” keyword directive.
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() and 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>

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
Course Wrap Up

The Rest of the Semester

• Final Assignment Due: Sunday Jan 10
• Deans Date: Tuesday Jan 12
  • Cannot submit final assignment after 11:59PM
• Final Exam: Friday, Jan 22
  • 7:30 PM in room McCosh 10
  • Exams from previous semesters are online at
    • http://www.cs.princeton.edu/courses/archive/fall09/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
  • During exam period, time TBA on course mailing list
Goals of COS 217

• Understand Modularity and Abstraction
  • Separation of interface from implementation
  • Process/Processor, Virtual/Physical memory, etc.

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

• Learn C and the Unix development tools

• Improve your programming and debugging skills

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
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)

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
Have a Great Holiday

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“I forgot to make a back-up copy of my brain, so everything I learned last semester was lost.”