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
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

```java
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”

```
53 // 00110101
53<<2 // 11010000
```

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

```
53 // 00110101
& 15 // 00001111
5 // 0000101
```
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

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 cache effects
  • Good temporal locality for A
  • Good spatial locality for B
  • Good spatial locality for C
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:

```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