

CS107, Lecture 15

Optimization

Reading: B&O 5

**CS107 Topic 6: How do the
core malloc/realloc/free
memory-allocation
operations work?**

Learning Goals

- Understand how we can optimize our code to improve efficiency and speed
- Learn about the optimizations GCC can perform

Lecture Plan

- What is optimization?
- GCC Optimization
- Limitations of GCC Optimization
- Caching

Lecture Plan

- **What is optimization?**
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Optimization

- Optimization is the task of making your program faster or more efficient with space or time. You've seen explorations of efficiency with Big-O notation!
- *Targeted, intentional* optimizations to alleviate bottlenecks can result in big gains. But it's important to only work to optimize where necessary.

Optimization

Most of what you need to do with optimization can be summarized by:

- 1) If doing something seldom and only on small inputs, do whatever is simplest to code, understand, and debug
- 2) If doing things thing a lot, or on big inputs, make the primary algorithm's Big-O cost reasonable
- 3) Let gcc do its magic from there**
- 4) Optimize explicitly as a last resort

Lecture Plan

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GCC Optimization

- Today, we'll be comparing two levels of optimization in the gcc compiler:
 - `gcc -O0` // mostly just literal translation of C
 - `gcc -O2` // enable nearly all reasonable optimizations
 - (we use `-Og`, like `-O0` but with less needless use of the stack)
- There are other custom and more aggressive levels of optimization, e.g.:
 - `-O3` //more aggressive than O2, trade size for speed
 - `-Os` //optimize for size
 - `-Ofast` //disregard standards compliance (!!)
- Exhaustive list of gcc optimization-related flags:
 - <https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html>

Example: Matrix Multiplication

Here's a standard matrix multiply, a triply-nested for loop:

```
void mmm(double a[][DIM], double b[][DIM], double c[][DIM], int n) {  
    for (int i = 0; i < n; i++) {  
        for (int j = 0; j < n; j++) {  
            for (int k = 0; k < n; k++) {  
                c[i][j] += a[i][k] * b[k][j];  
            }  
        }  
    }  
}
```

```
./mult // -O0 (no optimization)  
matrix multiply 25^2: cycles 0.43M  
matrix multiply 50^2: cycles 3.02M  
matrix multiply 100^2: cycles 24.82M
```

```
./mult_opt // -O2 (with optimization)  
matrix multiply 25^2: cycles 0.13M (opt)  
matrix multiply 50^2: cycles 0.66M (opt)  
matrix multiply 100^2: cycles 5.55M (opt)
```

GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
- Strength Reduction
- Code Motion
- Tail Recursion
- Loop Unrolling
- Psychic Powers

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(kidding)

GCC Optimizations

Optimizations may target one or more of:

- Static instruction count
- Dynamic instruction count
- Cycle count / execution time

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Constant Folding

Constant Folding pre-calculates constants at compile-time where possible.

```
int seconds = 60 * 60 * 24 * n_days;
```

What is the consequence of this for you as a programmer? What should you do differently or the same knowing that compilers can do this for you?

Constant Folding

```
int fold(int param) {  
    char arr[5];  
    int a = 0x107;  
    int b = a * sizeof(arr);  
    int c = sqrt(2.0);  
    return a * param + (a + 0x15 / c + strlen("Hello") * b - 0x37) / 4;  
}
```


Constant Folding: Before (-00)

```
000000000400626 <fold>:
400626:      55                push   %rbp
400627:      53                push   %rbx
400628:      48 83 ec 08      sub    $0x8,%rsp
40062c:      89 fd            mov    %edi,%ebp
40062e:      f2 0f 10 05 da 00 00  movsd  0xda(%rip),%xmm0
400635:      00
400636:      e8 d5 fe ff ff   callq 400510 <sqrt@plt>
40063b:      f2 0f 2c c8      cvtsd2si %xmm0,%ecx
40063f:      69 ed 07 01 00 00  imul  $0x107,%ebp,%ebp
400645:      b8 15 00 00 00   mov    $0x15,%eax
40064a:      99              cltd
40064b:      f7 f9          idiv  %ecx
40064d:      8d 98 07 01 00 00  lea   0x107(%rax),%ebx
400653:      bf 04 07 40 00   mov    $0x400704,%edi
400658:      e8 93 fe ff ff   callq 4004f0 <strlen@plt>
40065d:      48 69 c0 23 05 00 00  imul  $0x523,%rax,%rax
400664:      48 63 db        movslq %ebx,%rbx
400667:      48 8d 44 18 c9   lea   -0x37(%rax,%rbx,1),%rax
40066c:      48 c1 e8 02      shr   $0x2,%rax
400670:      01 e8          add   %ebp,%eax
400672:      48 83 c4 08      add   $0x8,%rsp
400676:      5b            pop   %rbx
400677:      5d            pop   %rbp
400678:      c3            retq
```

Constant Folding: After (-O2)

```
00000000004004f0 <fold>:
4004f0: 69 c7 07 01 00 00    imul  $0x107,%edi,%eax
4004f6: 05 a5 06 00 00      add   $0x6a5,%eax
4004fb: c3                  retq
4004fc: 0f 1f 40 00        nopl  0x0(%rax)
```

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Common Sub-Expression Elimination

Common Sub-Expression Elimination prevents the recalculation of the same thing many times by doing it once and saving the result.

```
int a = (param2 + 0x107);  
int b = param1 * (param2 + 0x107) + a;  
return a * (param2 + 0x107) + b * (param2 + 0x107);
```

Common Sub-Expression Elimination

Common Sub-Expression Elimination prevents the recalculation of the same thing many times by doing it once and saving the result.

This optimization is done even at -O0!

```
int a = (param2 + 0x107);  
int b = param1 * (param2 + 0x107) + a;  
return a * (param2 + 0x107) + b * (param2 + 0x107);
```

```
0000000004004f0 <subexp>:  
4004f0: 81 c6 07 01 00 00    add    $0x107,%esi  
4004f6: 0f af fe            imul   %esi,%edi  
4004f9: 8d 04 77            lea   (%rdi,%rsi,2),%eax  
4004fc: 0f af c6            imul   %esi,%eax  
4004ff: c3                  retq
```

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Dead Code

Dead code elimination removes code that doesn't serve a purpose:

```
if (param1 < param2 && param1 > param2) {  
    printf("This test can never be true!\n");  
}
```

```
// Empty for loop  
for (int i = 0; i < 1000; i++);
```

```
// If/else that does the same operation in both cases  
if (param1 == param2) {  
    param1++;  
} else {  
    param1++;  
}
```

```
// If/else that more trickily does the same operation in both cases  
if (param1 == 0) {  
    return 0;  
} else {  
    return param1;  
}
```

Dead Code: Before (-00)

00000000004004d6 <dead_code>:

4004d6:	b8 00 00 00 00	mov	\$0x0,%eax
4004db:	eb 03	jmp	4004e0 <dead_code+0xa>
4004dd:	83 c0 01	add	\$0x1,%eax
4004e0:	3d e7 03 00 00	cmp	\$0x3e7,%eax
4004e5:	7e f6	jle	4004dd <dead_code+0x7>
4004e7:	39 f7	cmp	%esi,%edi
4004e9:	75 05	jne	4004f0 <dead_code+0x1a>
4004eb:	8d 47 01	lea	0x1(%rdi),%eax
4004ee:	eb 03	jmp	4004f3 <dead_code+0x1d>
4004f0:	8d 47 01	lea	0x1(%rdi),%eax
4004f3:	f3 c3	repz retq	

Dead Code: After (-02)

00000000004004f0 <dead_code>:

```
4004f0: 8d 47 01          lea    0x1(%rdi),%eax
4004f3: c3               retq
4004f4: 66 2e 0f 1f 84 00 00  nopw   %cs:0x0(%rax,%rax,1)
4004fb: 00 00 00
4004fe: 66 90           xchg  %ax,%ax
```

GCC Optimizations

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Strength Reduction

Strength reduction changes divide to multiply, multiply to add/shift, and mod to AND to avoid using instructions that cost many cycles (multiply and divide).

```
int a = param2 * 32;
```

```
int b = a * 7;
```

```
int c = b / 3;
```

```
int d = param2 % 2;
```

```
for (int i = 0; i <= param2; i++) {
```

```
    c += param1[i] + 0x107 * i;
```

```
}
```

```
return c + d;
```

GCC Optimizations

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Code Motion

Code motion moves code outside of a loop if possible.

```
for (int i = 0; i < n; i++) {  
    sum += arr[i] + foo * (bar + 3);  
}
```

Common subexpression elimination deals with expressions that appear multiple times in the code. Here, the expression appears once, but is calculated each loop iteration.

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Tail Recursion

Tail recursion is an example of where GCC can identify recursive patterns that can be more efficiently implemented iteratively.

```
long factorial(int n) {  
    if (n <= 1) {  
        return 1;  
    }  
    else return n * factorial(n - 1);  
}
```

You saw this in the last lab!

GCC Optimizations

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- **Loop Unrolling**

Loop Unrolling

Loop Unrolling: Do n loop iterations' worth of work per actual loop iteration, so we save ourselves from doing the loop overhead (test and jump) every time, and instead incur overhead only every n -th time.

```
for (int i = 0; i <= n - 4; i += 4) {  
    sum += arr[i];  
    sum += arr[i + 1];  
    sum += arr[i + 2];  
    sum += arr[i + 3];  
} // after the loop handle any leftovers
```

Lecture Plan

- What is optimization?
- GCC Optimization
- **Limitations of GCC Optimization**
- Caching

Limitations of GCC Optimization

GCC can't optimize everything! You ultimately may know more than GCC does.

```
int char_sum(char *s) {  
    int sum = 0;  
    for (size_t i = 0; i < strlen(s); i++) {  
        sum += s[i];  
    }  
    return sum;  
}
```

What is the bottleneck? **strlen called for every character**
What can GCC do? **code motion – pull strlen out of loop**

Limitations of GCC Optimization

GCC can't optimize everything! You ultimately may know more than GCC does.

```
void lower1(char *s) {
    for (size_t i = 0; i < strlen(s); i++) {
        if (s[i] >= 'A' && s[i] <= 'Z') {
            s[i] -= ('A' - 'a');
        }
    }
}
```

What is the bottleneck?
What can GCC do?

strlen called for every character

nothing! s is changing, so GCC doesn't know if length is constant across iterations. But we know its length doesn't change.

Demo: limitations.c

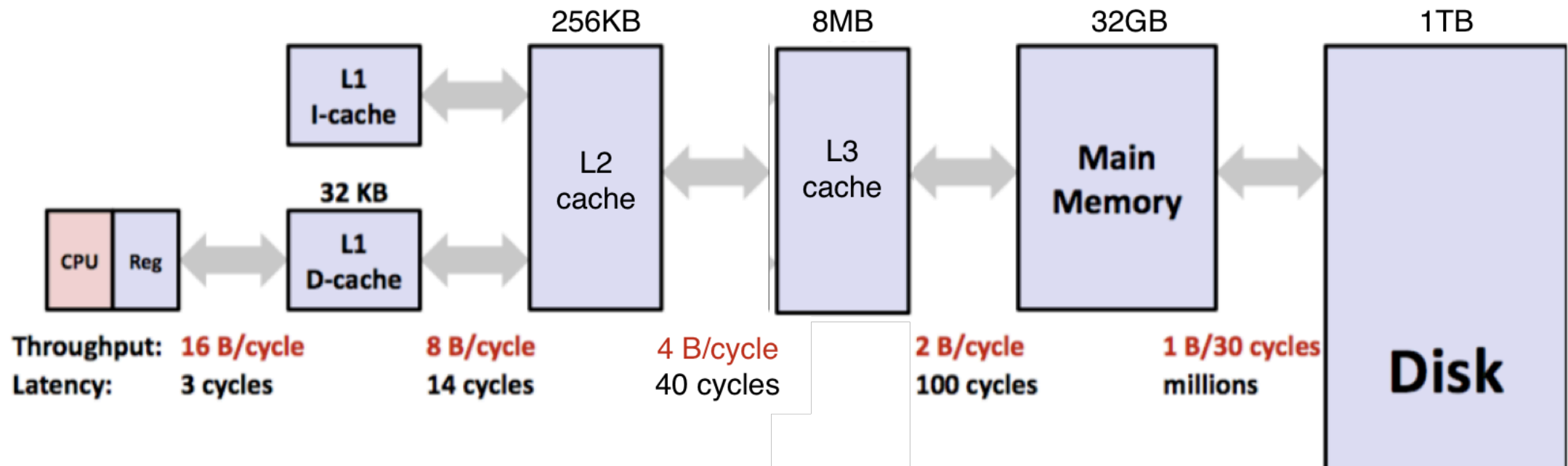


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- **Caching**

Caching

- Processor speed is not the only bottleneck in program performance – memory access is perhaps even more of a bottleneck!
- Memory exists in levels and goes from *really fast* (registers) to *really slow* (disk).
- As data is more frequently used, it ends up in faster and faster memory.



Caching

All caching depends on locality.

Temporal locality

- Repeat access to the same data tends to be co-located in TIME
- Intuitively: things I have used recently, I am likely to use again soon

Spatial locality

- Related data tends to be co-located in SPACE
- Intuitively: data that is near a used item is more likely to also be accessed

Caching

All caching depends on locality.

Realistic scenario:

- 97% cache hit rate
- Cache hit costs 1 cycle
- Cache miss costs 100 cycles
- How much of your memory access time is spent on 3% of accesses that are cache misses?

Demo: cache.c



Optimizing Your Code

- Explore various optimizations you can make to your code to reduce instruction count and runtime.
 - More efficient Big-O for your algorithms
 - Explore other ways to reduce instruction count
 - Look for hotspots using callgrind
 - Optimize using `-O2`
 - And more...

Recap

- What is optimization?
- GCC Optimization
- Limitations of GCC Optimization
- Caching

Next time: wrap up

Question Break

Post any questions you have to today's lecture thread on the discussion forum!

Compiler Optimizations

Why not always just compile with -O2?

- Difficult to debug optimized executables – only optimize when complete
- Optimizations may not *always* improve your program. The compiler does its best, but may not work, or slow things down, etc. Experiment to see what works best!

Why should we bother saving repeated calculations in variables if the compiler has common subexpression elimination?

- The compiler may not always be able to optimize every instance. Plus, it can help reduce redundancy!