CS107, Lecture 25
Optimization

Reading: B&O 5

😷 masks recommended

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

```
cp -r /afs/ir/class/cs107/lecture-code/lect25 .
```

Lecture Plan

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

```
cp -r /afs/ir/class/cs107/lecture-code/lect25 .
```

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 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

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

```
cp -r /afs/ir/class/cs107/lecture-code/lect25 .
```

Common For Loop Construction

C For loop

```
for (init; test; update) {
        body
}
```

C Equivalent While Loop

```
init
while(test) {
      body
      update
}
```

Assembly pseudocode

```
Init
Check opposite of code condition
Skip loop if test passes
Body
Update
Jump back to test
```

For loops and while loops are treated (essentially) the same when compiled down to assembly.

GCC For Loop Output

GCC Common For Loop Output

```
Initialization
Test
Jump past loop if success
Body
Update
Jump to test
```

Possible Alternative

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

GCC For Loop Output

GCC Common For Loop Output

```
Initialization
Test
Jump past loop if success
Body
Update
Jump to test
```

```
for (int i = 0; i < n; i++)          // n = 100
```

GCC For Loop Output

GCC Common For Loop Output

```
Initialization
Test
Jump past loop if success
Body
Update
Jump to test
```

for (int i = 0; i < n; i++)   // n = 100

```
Initialization
Test
No jump
Body
Update
Jump to test
Test
No jump
Body
Update
Jump to test
...
```

GCC For Loop Output

GCC Common For Loop Output

```
Initialization
Test
Jump past loop if success
Body
Update
Jump to test
```

for (int i = 0; i < n; i++) // n = 100

```
Initialization
Test
No jump
Body
Update
Jump to test
Test
No jump
Body
Update
Jump to test
...
```

GCC For Loop Output

```
for (int i = 0; i < n; i++)          // n = 100

Initialization
Jump to test
Test
Jump to body
Body
Update
Test
Jump to body
Body
Update
Test
Jump to body
...
```

Possible Alternative

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

GCC For Loop Output

```
for (int i = 0; i < n; i++)          // n = 100

Initialization
Jump to test
Test
Jump to body
Body
Update
Test
Jump to body
Body
Update
Test
Jump to body
...
```

Possible Alternative

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

GCC For Loop Output

GCC Common For Loop Output

```
Initialization
Test
Jump past loop if passes
Body
Update
Jump to test
```

Possible Alternative

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

Which instructions are better when n = 0? n = 1000?

for (int i = 0; i < n; i++)

Optimizing Instruction Counts

- Both versions have the same **static instruction count** (# of written instructions).
- But they have different **dynamic instruction counts** (# of executed instructions when program is run).
  - If n = 0, left (GCC common output) is best b/c fewer instructions
  - If n is large, right (alternative) is best b/c fewer instructions
- The compiler may emit a static instruction count that is several times longer than an alternative, but it may be more efficient if loop executes many times.
- Does the compiler *know* that a loop will execute many times? (in general, no)
- So what if our code had loops that always execute a small number of times? How do we know when gcc makes a bad decision?
- (take EE108, EE180, CS316 for more!)

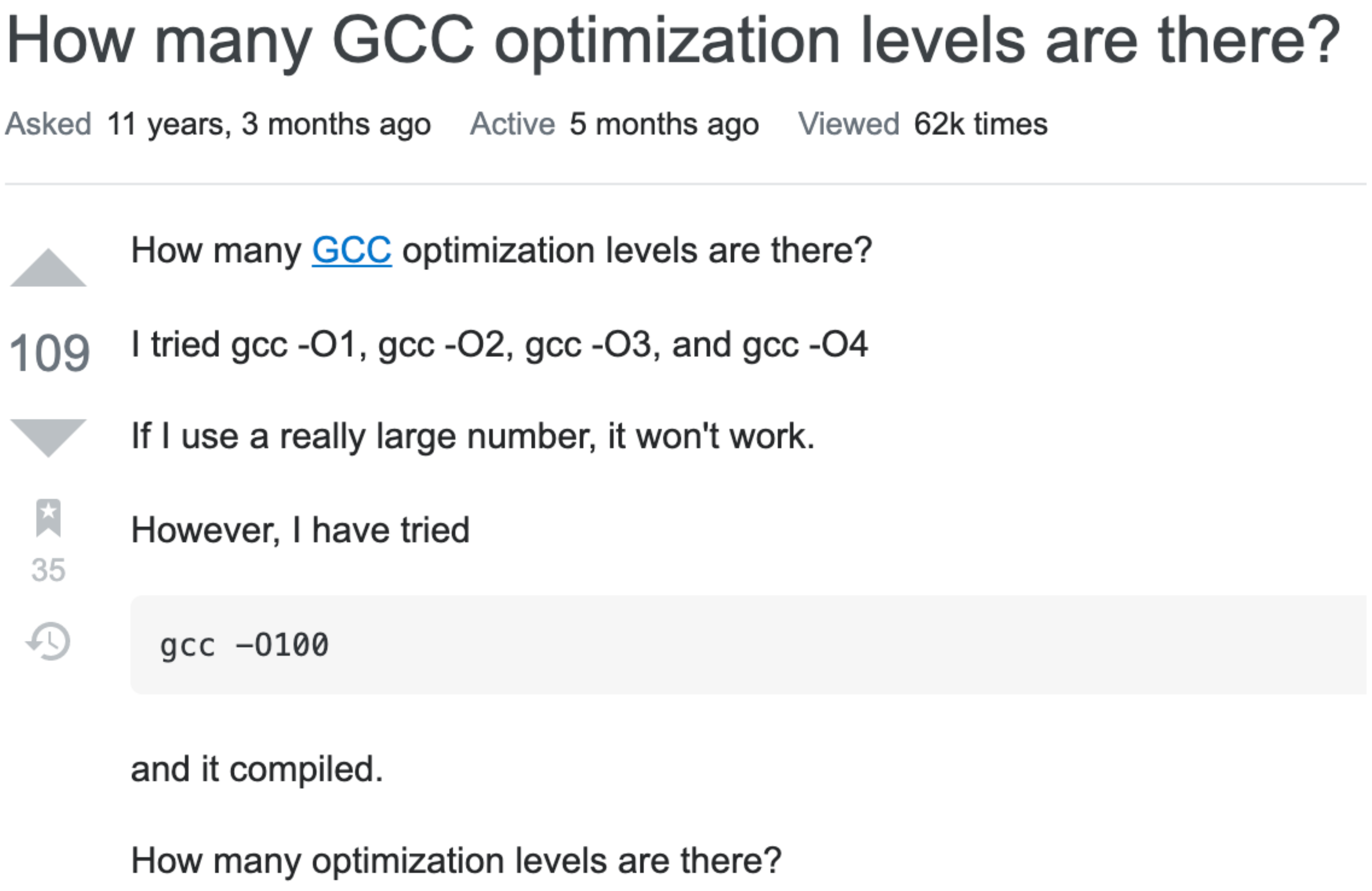
GCC Optimization

- 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 also use –Og, like –O0 but more debugging friendly)

- 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

Compiler optimizations



How many GCC optimization levels are there?

Asked 11 years, 3 months ago Active 5 months ago Viewed 62k times

109

35

How many GCC optimization levels are there?

I tried gcc -O1, gcc -O2, gcc -O3, and gcc -O4

If I use a really large number, it won't work.

However, I have tried

```
gcc -O100
```

and it compiled.

How many optimization levels are there?

Gcc supports numbers up to 3. Anything above is interpreted as 3

https://stackoverflow.com/questions/1778538/how-many-gcc-optimization-levels-are-there

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   1.32M
matrix multiply  50^2: cycles  10.64M
matrix multiply 100^2: cycles  16.55M
```

```
./mult_opt     // -O2 (with optimization)
matrix multiply  25^2: cycles   0.33M (opt)
matrix multiply  50^2: cycles   2.04M (opt)
matrix multiply 100^2: cycles  13.60M (opt)
```

GCC Optimizations

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

GCC Optimizations

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(kidding)

GCC Optimizations

Optimizations may target one or more of:

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

GCC Optimizations

- **Constant Folding**
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Constant Folding

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

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

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 (-O0)

```
00000000000011b9 <fold>:
    11b9:   55                      push   %rbp
    11ba:   48 89 e5                mov    %rsp,%rbp
    11bd:   41 54                   push   %r12
    11bf:   53                      push   %rbx
    11c0:   48 83 ec 30             sub    $0x30,%rsp
    11c4:   89 7d cc                mov    %edi,-0x34(%rbp)
    11c7:   c7 45 ec 07 01 00 00    movl   $0x107,-0x14(%rbp)
    11ce:   8b 45 ec                mov    -0x14(%rbp),%eax
    11d1:   48 98                   cltq
    11d3:   89 c2                   mov    %eax,%edx
    11d5:   89 d0                   mov    %edx,%eax
    11d7:   c1 e0 02                shl    $0x2,%eax
    11da:   01 d0                   add    %edx,%eax
    11dc:   89 45 e8                mov    %eax,-0x18(%rbp)
    11df:   48 8b 05 2a 0e 00 00    mov    0xe2a(%rip),%rax        # 2010 <_IO_stdin_used+0x10>
    11e6:   66 48 0f 6e c0          movq   %rax,%xmm0
    11eb:   e8 b0 fe ff ff          callq  10a0 <sqrt@plt>
    11f0:   f2 0f 2c c0             cvttsd2si %xmm0,%eax
    11f4:   89 45 e4                mov    %eax,-0x1c(%rbp)
    11f7:   8b 45 ec                mov    -0x14(%rbp),%eax
    11fa:   0f af 45 cc             imul   -0x34(%rbp),%eax
    11fe:   41 89 c4                mov    %eax,%r12d
    1201:   b8 15 00 00 00          mov    $0x15,%eax
    1206:   99                      cltd
    1207:   f7 7d e4                idivl  -0x1c(%rbp)
    120a:   89 c2                   mov    %eax,%edx
    120c:   8b 45 ec                mov    -0x14(%rbp),%eax
    120f:   01 d0                   add    %edx,%eax
    1211:   48 63 d8                movslq %eax,%rbx
    1214:   48 8d 3d ed 0d 00 00    lea    0xded(%rip),%rdi        # 2008 <_IO_stdin_used+0x8>
    121b:   e8 20 fe ff ff          callq  1040 <strlen@plt>
    1220:   8b 55 e8                mov    -0x18(%rbp),%edx
    1223:   48 63 d2                movslq %edx,%rdx
    1226:   48 0f af c2             imul   %rdx,%rax
    122a:   48 01 d8                add    %rbx,%rax
    122d:   48 83 e8 37             sub    $0x37,%rax
    1231:   48 c1 e8 02             shr    $0x2,%rax
    1235:   44 01 e0                add    %r12d,%eax
    1238:   48 83 c4 30             add    $0x30,%rsp
    123c:   5b                      pop    %rbx
    123d:   41 5c                   pop    %r12
    123f:   5d                      pop    %rbp
    1240:   c3                      retq
```

Constant Folding: After (-O2)

```
00000000000011b0 <fold>:
    11b0:   69 c7 07 01 00 00       imul   $0x107,%edi,%eax
    11b6:   05 a5 06 00 00          add    $0x6a5,%eax
    11bb:   c3                      retq
```

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?

GCC Optimizations

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

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.

```
int a = (param2 + 0x107);
int b = param1 * (param2 + 0x107) + a;
return a * (param2 + 0x107) + b * (param2 + 0x107);
// = 2 * a * a + param1 * a * a
```

```
00000000000011b0 <subexp>:  // param1 in %edi, param2 in %esi
    11b0:  lea    0x107(%rsi),%eax       // %eax stores a
    11b6:  imul   %eax,%edi              // param1 * a
    11b9:  lea    (%rdi,%rax,2),%esi     // 2 * a + param1 * a
    11bc:  imul   %esi,%eax              // a * (2 * a + param1 * a)
    11bf:  retq
```

Common Sub-Expression Elimination

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!
- Makes code more readable!

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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 (-O0)

```
00000000000011a9 <dead_code>:
    11a9: 55                      push   %rbp
    11aa: 48 89 e5                mov    %rsp,%rbp
    11ad: 48 83 ec 20             sub    $0x20,%rsp
    11b1: 89 7d ec                mov    %edi,-0x14(%rbp)
    11b4: 89 75 e8                mov    %esi,-0x18(%rbp)
    11b7: 8b 45 ec                mov    -0x14(%rbp),%eax
    11ba: 3b 45 e8                cmp    -0x18(%rbp),%eax
    11bd: 7d 19                   jge    11d8 <dead_code+0x2f>
    11bf: 8b 45 ec                mov    -0x14(%rbp),%eax
    11c2: 3b 45 e8                cmp    -0x18(%rbp),%eax
    11c5: 7e 11                   jle    11d8 <dead_code+0x2f>
    11c7: 48 8d 3d 36 0e 00 00    lea    0xe36(%rip),%rdi        # 2004 <_IO_stdin_used+0x4>
    11ce: b8 00 00 00 00          mov    $0x0,%eax
    11d3: e8 68 fe ff ff          callq  1040 <printf@plt>
    11d8: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
    11df: eb 04                   jmp    11e5 <dead_code+0x3c>
    11e1: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
    11e5: 81 7d fc e7 03 00 00    cmpl   $0x3e7,-0x4(%rbp)
    11ec: 7e f3                   jle    11e1 <dead_code+0x38>
    11ee: 8b 45 ec                mov    -0x14(%rbp),%eax
    11f1: 3b 45 e8                cmp    -0x18(%rbp),%eax
    11f4: 75 06                   jne    11fc <dead_code+0x53>
    11f6: 83 45 ec 01             addl   $0x1,-0x14(%rbp)
    11fa: eb 04                   jmp    1200 <dead_code+0x57>
    11fc: 83 45 ec 01             addl   $0x1,-0x14(%rbp)
    1200: 83 7d ec 00             cmpl   $0x0,-0x14(%rbp)
    1204: 75 07                   jne    120d <dead_code+0x64>
    1206: b8 00 00 00 00          mov    $0x0,%eax
    120b: eb 03                   jmp    1210 <dead_code+0x67>
    120d: 8b 45 ec                mov    -0x14(%rbp),%eax
    1210: c9                      leaveq
    1211: c3                      retq
```

Dead Code: After (-O2)

```
00000000000011b0 <dead_code>:
    11b0:   8d 47 01                lea    0x1(%rdi),%eax
    11b3:   c3                      retq
```

GCC Optimizations

- Constant Folding
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- Dead Code
- **Strength Reduction**
- Code Motion
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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

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
- Strength Reduction
- **<u>Code Motion</u>**
- Tail Recursion
- Loop Unrolling

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.

Practice: GCC Optimization

```
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? What (if anything) can GCC do?

Input your answer on PollEv:
pollev.com/cs107 or text CS107 to 22333 once to join.

What is the bottleneck? What can GCC do?

strlen called every loop iteration - common subexpression elimination to eliminate redundancy

strlen called every loop iteration - code motion to pull out of loop

strlen called every loop iteration - GCC can't optimize

i incremented every loop iteration - code motion to pull out of loop

i incremented every loop iteration - GCC can't optimize

Practice: GCC Optimization

```
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? What (if anything) can GCC do?

strlen is called every loop iteration – <u>code motion</u> can pull it out of the loop

GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
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- **Tail Recursion**
- Loop Unrolling

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);
}
```

Tail recursion example: Lab6 bonus

Recall the factorial problem from assembly lectures:

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

What happens with **`factorial(-1)`**?

https://web.stanford.edu/class/cs107/lab6/extra.html

- Infinite recursion → Literal stack overflow!
- Compiled with `-Og`!

Factorial: -Og vs –O2

```
401146 <+0>:  cmp    $0x1,%edi
401149 <+3>:  jbe    0x40115b <factorial+21>
40114b <+5>:  push   %rbx
40114c <+6>:  mov    %edi,%ebx
40114e <+8>:  lea    -0x1(%rdi),%edi
401151 <+11>:callq   0x401146 <factorial>
401156 <+16>:imul    %ebx,%eax
401159 <+19>:pop     %rbx
40115a <+20>:retq
40115b <+21>:mov     $0x1,%eax
401160 <+26>:retq
```

-O2:

- What happened?
- Did the compiler “fix” the infinite recursion?

```
4011e0 <+0>:  mov    $0x1,%eax
4011e5 <+5>:  cmp    $0x1,%edi
4011e8 <+8>:  jbe    0x4011fd <factorial+29>
4011ea <+10>:nopw    0x0(%rax,%rax,1)
4011f0 <+16>:mov     %edi,%edx
4011f2 <+18>:sub     $0x1,%edi
4011f5 <+21>:imul    %edx,%eax
4011f8 <+24>:cmp     $0x1,%edi
4011fb <+27>:jne     0x4011f0 <factorial+16>
4011fd <+29>:retq
```

GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
- Strength Reduction
- Code Motion
- Tail Recursion
- **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**

```
cp -r /afs/ir/class/cs107/lecture-code/lect25 .
```

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? **strlen called for every character**

What can GCC do? **nothing! s is changing, so GCC doesn’t know if length is constant across iterations. But *we* know its length doesn’t change.**

Callgrind

- Callgrind is another tool in the Valgrind suite of tools
- Callgrind is a **profiler** that measures instruction counts – another way to measure efficiency
- Can measure the number of instructions executed in a given run of our program, and where they came from
- Useful for optimizing – we can see where large #s of instruction executions come from

Demo: `limitations.c` and callgrind

Why not always optimize?

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!

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

Lecture 25 takeaway: Compilers can apply various optimizations to make our code more efficient, without us having to rewrite code. However, there are limitations to these optimizations, and sometimes we must optimize ourselves, using tools like Callgrind.

Next time: wrap up