Computer Systems

CS107

Cynthia Lee

Today's Topics

- Code optimization!

Optimization reality check

Don’t let it be your Waterloo.

Optimization Reality Check

- Optimization is really exciting
- …but it's easy to be overzealous or misguided about it.
- "We should forget about small inefficiencies, say about 97% of the time: premature optimization is the root of all evil." – Donald Knuth
- "More computing sins are committed in the name of efficiency (without necessarily achieving it) than for any other single reason–including blind stupidity." – W.A. Wulf
- "Bottlenecks occur in surprising places, so don't try to second guess and put in a speed hack until you have proven that's where the bottleneck is." – Rob Pike

Optimization Reality Check

- Most of what <u>you</u> need to do with optimization can be summarized in 3 easy steps:

- Step 1:
  - If doing something seldom and only on small inputs, do whatever is simplest to code, understand, and debug

- Step 2:
  - If doing things thing a lot, or on big inputs, make the algorithm's Big-O cost reasonable

- Step 3:
  - **Let gcc do its magic from there**

gcc optimization levels

- 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 –OgQ, 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: gcc performance optimization

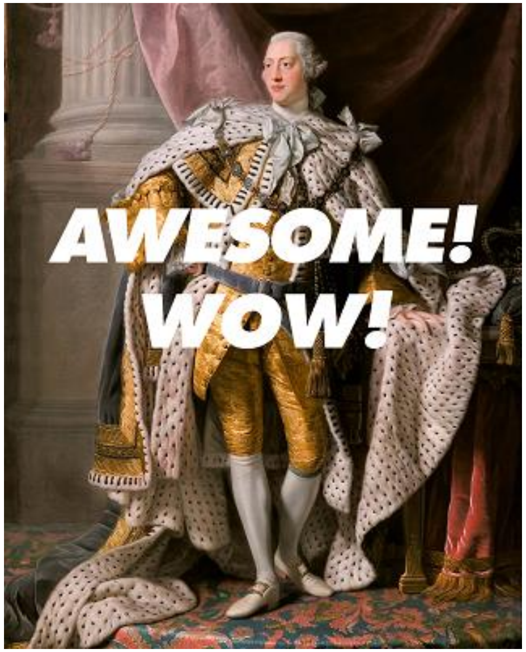
- Just a standard matrix multiply, triply-nested for loop:

```
static 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];
}
```

Measuring performance: Example code

```
› ./mult                                  // -O0 (no optimization)
    matrix multiply  25^2: cycles   0.44M
    matrix multiply  50^2: cycles   3.13M
    matrix multiply 100^2: cycles  24.80M
› ./mult_opt                              // -O2 (with optimization)
    matrix multiply  25^2: cycles   0.11M (opt)
    matrix multiply  50^2: cycles   0.47M (opt)
    matrix multiply 100^2: cycles   3.67M (opt)
```

When I said, "Let gcc do its magic from there," this is what I meant by magic!



Kinds of optimization

Some main categories of optimization that are undertaken by the compiler

Kinds of optimization

- Constant folding
- Common subexpression elimination
- Dead code
- Strength reduction
- Code motion
- Tail recursion
- Loop unrolling

Kinds of optimization

- **Constant folding**
  - Precalculate constants at compile time where possible:
    - `int volume = WIDTH * HEIGHT * DEPTH;`
    - `double radius = sqrt(area) / 3.14;`
- Common subexpression elimination
- Dead code
- Strength reduction
- Code motion
- Tail recursion
- Loop unrolling

- **Discussion question:**
  - **What is a consequence of this for you as a programmer?** What should you do (or do differently) now that you know about compilers doing constant folding for you?

Constant folding

Before:

```
000000000040098d <CF>:
  40098d:       55                      push   %rbp
  40098e:       48 89 e5                mov    %rsp,%rbp
  400991:       41 54                   push   %r12
  400993:       53                      push   %rbx
  400994:       48 83 c4 80             add    $0xffffffffffffff80,%rsp
  400998:       89 bd 7c ff ff ff       mov    %edi,-0x84(%rbp)
  40099e:       c7 45 ec 07 01 00 00    movl   $0x107,-0x14(%rbp)
  4009a5:       8b 45 ec                mov    -0x14(%rbp),%eax
  4009a8:       6b c0 55                imul   $0x55,%eax,%eax
  4009ab:       89 45 e8                mov    %eax,-0x18(%rbp)
  4009ae:       48 b8 00 00 00 00 00    movabs $0x4000000000000000,%rax
  4009b5:       00 00 40
  4009b8:       48 89 85 70 ff ff ff    mov    %rax,-0x90(%rbp)
  4009bf:       f2 0f 10 85 70 ff ff    movsd  -0x90(%rbp),%xmm0
  4009c6:       ff
  4009c7:       e8 b4 fe ff ff          callq  400880 <sqrt@plt>
  4009cc:       f2 0f 2c c0             cvttsd2si %xmm0,%eax
  4009d0:       89 45 e4                mov    %eax,-0x1c(%rbp)
  4009d3:       8b 45 ec                mov    -0x14(%rbp),%eax
  4009d6:       0f af 85 7c ff ff ff    imul   -0x84(%rbp),%eax
  4009dd:       89 c3                   mov    %eax,%ebx
  4009df:       b8 15 00 00 00          mov    $0x15,%eax
  4009e4:       99                      cltd
  4009e5:       f7 7d e4                idivl  -0x1c(%rbp)
  4009e8:       89 c2                   mov    %eax,%edx
  4009ea:       8b 45 ec                mov    -0x14(%rbp),%eax
  4009ed:       01 d0                   add    %edx,%eax
  4009ef:       4c 63 e0                movslq %eax,%r12
  4009f2:       bf b8 1b 40 00          mov    $0x401bb8,%edi
  4009f7:       e8 d4 fd ff ff          callq  4007d0 <strlen@plt>
```

After:

```
0000000000400d80 <CF>:
  400d80:       69 c7 07 01 00 00       imul   $0x107,%edi,%eax
  400d86:       05 61 6d 00 00          add    $0x6d61,%eax
  400d8b:       c3                      retq
```

** Notice it also got rid of the stack frame handling overhead

Kinds of optimization

- Constant folding
- **Common subexpression elimination**
  - Prevent recalculation of the same thing many times by doing it once and saving result

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

- Dead code
- Strength reduction
- Code motion
- Tail recursion
- Loop unrolling

CSE

After:

```
0000000000400d90 <CSE>:
  400d90:       81 c6 07 01 00 00       add    $0x107,%esi
  400d96:       0f af fe                imul   %esi,%edi
  400d99:       8d 04 77                lea    (%rdi,%rsi,2),%eax
  400d9c:       0f af c6                imul   %esi,%eax
  400d9f:       c3                      retq
```

Before:

```
0000000000400a1c <CSE>:
  400a1c:       55                      push   %rbp
  400a1d:       48 89 e5                mov    %rsp,%rbp
  400a20:       89 7d ec                mov    %edi,-0x14(%rbp)
  400a23:       89 75 e8                mov    %esi,-0x18(%rbp)
  400a26:       8b 45 e8                mov    -0x18(%rbp),%eax
  400a29:       05 07 01 00 00          add    $0x107,%eax
  400a2e:       89 45 fc                mov    %eax,-0x4(%rbp)
  400a31:       8b 45 e8                mov    -0x18(%rbp),%eax
  400a34:       05 07 01 00 00          add    $0x107,%eax
  400a39:       0f af 45 ec             imul   -0x14(%rbp),%eax
  400a3d:       89 c2                   mov    %eax,%edx
  400a3f:       8b 45 fc                mov    -0x4(%rbp),%eax
  400a42:       01 d0                   add    %edx,%eax
  400a44:       89 45 f8                mov    %eax,-0x8(%rbp)
  400a47:       8b 45 f8                mov    -0x8(%rbp),%eax
  400a4a:       8b 55 fc                mov    -0x4(%rbp),%edx
  400a4d:       01 c2                   add    %eax,%edx
  400a4f:       8b 45 e8                mov    -0x18(%rbp),%eax
  400a52:       05 07 01 00 00          add    $0x107,%eax
  400a57:       0f af c2                imul   %edx,%eax
  400a5a:       5d                      pop    %rbp
  400a5b:       c3                      retq
```

Kinds of optimization

- Constant folding
- Common subexpression elimination
- **Dead code**
  - Remove code that doesn't serve a purpose:

```
while (false) {
    j = func(j);
    printf("This loop can't happen!\n");
    i++;
    if (i == 1000000) break;
}
```

- Strength reduction
- Code motion
- Tail recursion
- Loop unrolling

DC

After:

```
0000000000400da0 <DC>:
  400da0:       8d 47 01                lea    0x1(%rdi),%eax
  400da3:       c3                      retq
  400da4:       66 66 66 2e 0f 1f 84    data32 data32
```

Before:

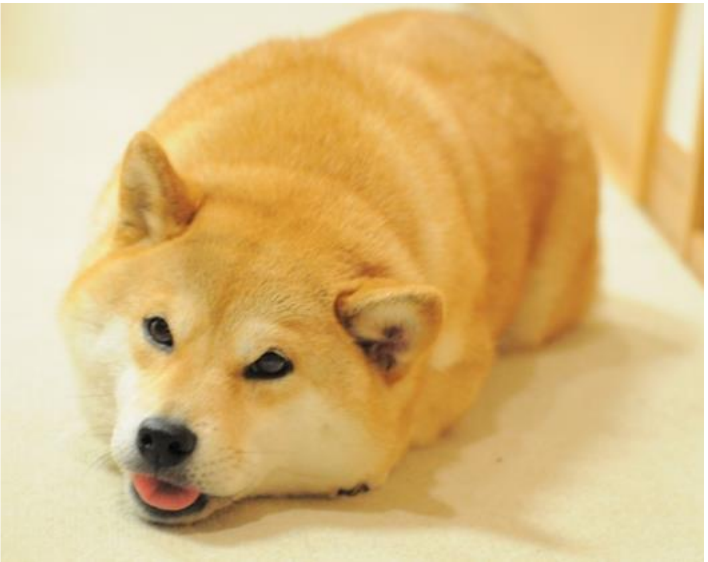
```
0000000000400a5c <DC>:
  400a5c:       55                      push   %rbp
  400a5d:       48 89 e5                mov    %rsp,%rbp
  400a60:       48 83 ec 20             sub    $0x20,%rsp
  400a64:       89 7d ec                mov    %edi,-0x14(%rbp)
  400a67:       89 75 e8                mov    %esi,-0x18(%rbp)
  400a6a:       8b 45 ec                mov    -0x14(%rbp),%eax
  400a6d:       3b 45 e8                cmp    -0x18(%rbp),%eax
  400a70:       7d 17                   jge    400a89 <DC+0x2d>
  400a72:       8b 45 ec                mov    -0x14(%rbp),%eax
  400a75:       3b 45 e8                cmp    -0x18(%rbp),%eax
  400a78:       7e 0f                   jle    400a89 <DC+0x2d>
  400a7a:       bf c0 1b 40 00          mov    $0x401bc0,%edi
  400a7f:       b8 00 00 00 00          mov    $0x0,%eax
  400a84:       e8 57 fd ff ff          callq  4007e0 <printf@plt>
  400a89:       c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
  400a90:       eb 04                   jmp    400a96 <DC+0x3a>
  400a92:       83 45 fc 01             addl   $0x1,-0x4(%rbp)
  400a96:       81 7d fc e7 03 00 00    cmpl   $0x3e7,-0x4(%rbp)
  400a9d:       7e f3                   jle    400a92 <DC+0x36>
  400a9f:       8b 45 ec                mov    -0x14(%rbp),%eax
  400aa2:       3b 45 e8                cmp    -0x18(%rbp),%eax
  400aa5:       75 06                   jne    400aad <DC+0x51>
  400aa7:       83 45 ec 01             addl   $0x1,-0x14(%rbp)
  400aab:       eb 04                   jmp    400ab1 <DC+0x55>
  400aad:       83 45 ec 01             addl   $0x1,-0x14(%rbp)
  400ab1:       83 7d ec 00             cmpl   $0x0,-0x14(%rbp)
  400ab5:       75 07                   jne    400abe <DC+0x62>
  400ab7:       b8 00 00 00 00          mov    $0x0,%eax
  400abc:       eb 03                   jmp    400ac1 <DC+0x65>
  400abe:       8b 45 ec                mov    -0x14(%rbp),%eax
  400ac1:       c9                      leaveq
```

Kinds of optimization

- Constant folding
- Common subexpression elimination
- Dead code
- **Strength reduction**
  - Change divide to multiply, multiply to add or shift, and mod to and
  - Avoids using instructions that cost many cycles (multiply and divide)

```
int doge_years = human_years * 7;
```

- Code motion
- Tail recursion
- Loop unrolling



Kinds of optimization

- Constant folding
- Common subexpression elimination
- Dead code
- Strength reduction
- **Code motion**
  - Move code out of a loop if possible

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

- Tail recursion
- Loop unrolling

Kinds of optimization

- Constant folding
- Common subexpression elimination
- Dead code
- Strength reduction
- Code motion
- **Tail recursion**
  - Compiler notices some simple recursion patterns that could be more efficiently implemented using iteration (i.e. a loop) to avoid function call and return overhead

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

- Loop unrolling

Kinds of optimization

- Constant folding
- Common subexpression elimination
- Dead code
- Strength reduction
- Code motion
- Tail recursion
- **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
```

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For loop construction

```
# for-loop literal translation
Initialization
Test
Branch past loop if fails
Body
Increment
jmp to Test
```

```
# loop unrolling
Initialization
jmp to Test
Body
Increment
Body
Increment
Body
Increment
Test
Branch to Body if succeeds
```

```
# for-loop gcc actually emits
Initialization
jmp to Test
Body
Increment
Test
Branch to Body if succeeds
```

Measuring performance

Lab preview

Two techniques for measuring performance—learn more in lab

- Wall clock time
  - `gettimeofday() // #include <sys/time.h>`

- Cycle counting
  - RTC: real-time clock counts elapsed cycles of the CPU
  - Available on some hardware
  - Will reveal some cases where an instruction takes more than one cycle (and a few interesting cases where more than one instruction was able to execute per clock cycle)
    - Recall that multiply instruction is more expensive (takes more cycles) than add
  - See `/afs/ir/class/cs107/samples/lect15/fcyc.h`