15-213

Code Optimization I
September 24, 2007

Topics

- **Machine-Independent Optimizations**
  - **Basic optimizations**
  - **Optimization blockers**

Harsh Reality

There's more to performance than asymptotic complexity

Constant factors matter too!

- **Easily see 10:1 performance range depending on how code is written**
- **Must optimize at multiple levels:**
  - **algorithm, data representations, procedures, and loops**

Must understand system to optimize performance

- **How programs are compiled and executed**
- **How to measure program performance and identify bottlenecks**
- **How to improve performance without destroying code modularity and generality**

Optimizing Compilers

Provide efficient mapping of program to machine

- register allocation
- code selection and ordering (scheduling)
- dead code elimination
- eliminating minor inefficiencies

Don’t (usually) improve asymptotic efficiency

- up to programmer to select best overall algorithm
- big-O savings are (often) more important than constant factors
  - but constant factors also matter

Have difficulty overcoming “optimization blockers”

- potential memory aliasing
- potential procedure side-effects

Limitations of Optimizing Compilers

Operate under fundamental constraint

- Must not cause any change in program behavior under any possible condition
- Often prevents it from making optimizations when would only affect behavior under pathological conditions.

Behavior that may be obvious to the programmer can be obfuscated by languages and coding styles

- e.g., Data ranges may be more limited than variable types suggest

Most analysis is performed only within procedures

- Whole-program analysis is too expensive in most cases

Most analysis is based only on *static* information

- Compiler has difficulty anticipating run-time inputs

When in doubt, the compiler must be conservative

Machine-Independent Optimizations

Optimizations that you or the compiler should do regardless of processor / compiler

Code Motion

- Reduce frequency with which computation performed
  - If it will always produce same result
  - Especially moving code out of loop

```
void set_row(double *a, double *b,
   long i, long n)
{
    long j;
    for (j = 0; j < n; j++)
         a[n*i+j] = b[j];
}
```

→

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

Compiler-Generated Code Motion

```
void set_row(double *a, double *b,
   long i, long n)
{
    long j;
    for (j = 0; j < n; j++)
         a[n*i+j] = b[j];
}
```

```
    long j;
    long ni = n*i;
    double *rowp = a+ni;
    for (j = 0; j < n; j++)
         *rowp++ = b[j];
```

Where are the FP operations?

```
set_row:
        xorl    %r8d, %r8d            #  j = 0
        cmpq    %rcx, %r8             #  j:n
        jge     .L7                   #  if >= goto done
        movq    %rcx, %rax            #  n
        imulq   %rdx, %rax            #  n*i outside of inner loop
        leaq    (%rdi,%rax,8), %rdx   #  rowp = A + n*i*8
.L5:                                  # loop:
        movq    (%rsi,%r8,8), %rax    #  t = b[j]
        incq    %r8                   #  j++
        movq    %rax, (%rdx)          #  *rowp = t
        addq    $8, %rdx              #  rowp++
        cmpq    %rcx, %r8             #  j:n
        jl      .L5                   #  if < goot loop
.L7:                                  # done:
        rep ; ret                     #  return
```

Reduction in Strength

- Replace costly operation with simpler one
- Shift, add instead of multiply or divide

```
16*x   -->    x << 4
```

  - Utility machine dependent
  - Depends on cost of multiply or divide instruction
  - On Pentium IV, integer multiply requires 10 CPU cycles
- Recognize sequence of products

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

→

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

Share Common Subexpressions

- Reuse portions of expressions
- Compilers often not very sophisticated in exploiting arithmetic properties

```
/* Sum neighbors of i,j */
up =    val[(i-1)*n + j  ];
down =  val[(i+1)*n + j  ];
left =  val[i*n     + j-1];
right = val[i*n     + j+1];
sum = up + down + left + right;
```

```
int inj = i*n + j;
up =    val[inj - n];
down =  val[inj + n];
left =  val[inj - 1];
right = val[inj + 1];
sum = up + down + left + right;
```

3 multiplications: i*n, (i–1)*n, (i+1)*n

1 multiplication: i*n

```
leaq   1(%rsi), %rax  # i+1
leaq   -1(%rsi), %r8  # i-1
imulq  %rcx, %rsi     # i*n
imulq  %rcx, %rax     # (i+1)*n
imulq  %rcx, %r8      # (i-1)*n
addq   %rdx, %rsi     # i*n+j
addq   %rdx, %rax     # (i+1)*n+j
addq   %rdx, %r8      # (i-1)*n+j
```

```
imulq    %rcx, %rsi   # i*n
addq     %rdx, %rsi   # i*n+j
movq     %rsi, %rax   # i*n+j
subq     %rcx, %rax   # i*n+j-n
leaq     (%rsi,%rcx), %rcx # i*n+j+n
```

Optimization Blocker: Procedure Calls

Why couldn't compiler move `strlen` out of inner loop?

- **Procedure may have side effects**
  - **Alters global state each time called**
- **Function may not return same value for given arguments**
  - **Depends on other parts of global state**
  - **Procedure `lower` could interact with `strlen`**

Warning:

- **Compiler treats procedure call as a black box**
- **Weak optimizations near them**

Remedies:

- **Use of `inline` functions**
- **Do your own code motion**

```
int lencnt = 0;
size_t strlen(const char *s)
{
    size_t length = 0;
    while (*s != '\0') {
       s++; length++;
    }
    lencnt += length;
    return length;
}
```

Memory Matters

```
/* Sum rows is of n X n matrix a
   and store in vector b  */
void sum_rows1(double *a, double *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
         b[i] = 0;
         for (j = 0; j < n; j++)
             b[i] += a[i*n + j];
    }
}
```

```
# sum_rows1 inner loop
.L53:
        addsd   (%rcx), %xmm0           # FP add
        addq    $8, %rcx
        decq    %rax
        movsd   %xmm0, (%rsi,%r8,8)     # FP store
        jne     .L53
```

- Code updates `b[i]` on every iteration
- Why couldn’t compiler optimize this away?

Memory Aliasing

```
/* Sum rows is of n X n matrix a
   and store in vector b  */
void sum_rows1(double *a, double *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        b[i] = 0;
        for (j = 0; j < n; j++)
            b[i] += a[i*n + j];
    }
}
```

```
double A[9] =
  { 0,   1,   2,
    4,   8,  16},
   32,  64, 128};

double B[3] = A+3;

sum_rows1(A, B, 3);
```

Value of B:

```
init:   [4, 8, 16]
```

```
i = 0: [3, 8, 16]
```

```
i = 1: [3, 22, 16]
```

```
i = 2: [3, 22, 224]
```

- **Code updates `b[i]` on every iteration**
- **Must consider possibility that these updates will affect program behavior**

Removing Aliasing

```
/* Sum rows is of n X n matrix a
   and store in vector b  */
void sum_rows2(double *a, double *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        double val = 0;
        for (j = 0; j < n; j++)
            val += a[i*n + j];
        b[i] = val;
    }
}
```

```
# sum_rows2 inner loop
.L66:
        addsd   (%rcx), %xmm0   # FP Add
        addq    $8, %rcx
        decq    %rax
        jne     .L66
```

- No need to store intermediate results

Unaliased Version

```
/* Sum rows is of n X n matrix a
   and store in vector b  */
void sum_rows2(double *a, double *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
         double val = 0;
         for (j = 0; j < n; j++)
             val += a[i*n + j];
          b[i] = val;
    }
}
```

```
double A[9] =
  { 0,   1,   2,
    4,   8,  16},
   32,  64, 128};

double B[3] = A+3;

sum_rows1(A, B, 3);
```

Value of B:

```
init:   [4,  8, 16]
```

```
i = 0: [3,  8, 16]
```

```
i = 1: [3, 27, 16]
```

```
i = 2: [3, 27, 224]
```

- Aliasing still creates interference

Optimization Blocker: Memory Aliasing

Aliasing

- Two different memory references specify single location
- Easy to have happen in C
  - Since allowed to do address arithmetic
  - Direct access to storage structures
- Get in habit of introducing local variables
  - Accumulating within loops
  - Your way of telling compiler not to check for aliasing

Machine-Independent Opt. Summary

Code Motion

- Compilers are good at this for simple loop/array structures
- Don't do well in the presence of procedure calls and memory aliasing

Reduction in Strength

- Shift, add instead of multiply or divide
  - *Compilers are (generally) good at this*
  - *Exact trade-offs machine-dependent*
- Keep data in registers (local variables) rather than memory
  - *Compilers are not good at this, since concerned with aliasing*
  - *Compilers do know how to allocate registers (no need for* `register` *declaration)*

Share Common Subexpressions

- Compilers have limited algebraic reasoning capabilities