Program Optimization

Slides adapted from Bryant and O'Hallaron

Today

- **Overview**
- **Generally Useful Optimizations**
  - Code motion/precomputation
  - Strength reduction
  - Sharing of common subexpressions
  - Removing unnecessary procedure calls
- **Optimization Blockers**
  - Procedure calls
  - Memory aliasing

Performance Realities

- **Programmers must optimize at multiple levels**
  - Big-O: algorithm, data representations
  - Systems: optimize memory access, I/O, parallelize execution

- **Steps of manual optimization**
- **1. Identify bottlenecks**
  - Bottleneck is CPU? Disk/SSD? Network? others?
- **2. Measure program performance**
  - If CPU is the bottleneck, profile a program's execution to figure out which code path takes the most time
- **The challenge:**
  - How to improve performance without destroying code modularity and readability
  - Premature optimization.
- **What about automatic optimization?**

Optimizing Compilers

- **Goal is to generate efficient, correct machine code**
  - register allocation
  - code selection and ordering
  - dead code elimination
- **Don't improve asymptotic efficiency**
  - Programmer should select best overall algorithm

Limitations of Optimizing Compilers

- **Constraint: Must not change program behavior in *any* circumstances**
  - → When in doubt, the compiler must be conservative
- **Most analysis is performed only within procedures**
  - Whole-program analysis is too expensive in most cases
  - Newer versions of GCC do inter-procedural analysis within individual files
    - But, not between code in different files
- **Analysis is based only on *static* information**
  - Compiler does not know run-time inputs

Generally Useful Optimizations

- **Code Motion**
  - Reduce frequency with which computation performed
    - If it will always produce same result

```
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 (-O1)

```
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];
}
```

```
set_row:
        testq   %rcx, %rcx              # Test n
        jle     .L1                     # If 0, goto done
        imulq   %rcx, %rdx              # ni = n*i
        leaq    (%rdi,%rdx,8), %rdx     # rowp = A + ni*8
        movl    $0, %eax               # j = 0
.L3:                                    # loop:
        movsd   (%rsi,%rax,8), %xmm0           # t = b[j]
        movsd   %xmm0, (%rdx,%rax,8)           # M[A+ni*8 + j*8] = t
        addq    $1, %rax                       # j++
        cmpq    %rcx, %rax              # j:n
        jne     .L3                     # if !=, goto loop
.L1:                                    # done:
        rep ; ret
```

Reduction in Strength

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

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

  - Recognize sequence of products

```
for (i = 0; i < n; i++) {
  int ni = n*i;
  for (j = 0; j < n; j++)
    a[ni + 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
- GCC will do this with –O1

```
/* 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;
```

```
long 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 #1: Procedure Calls

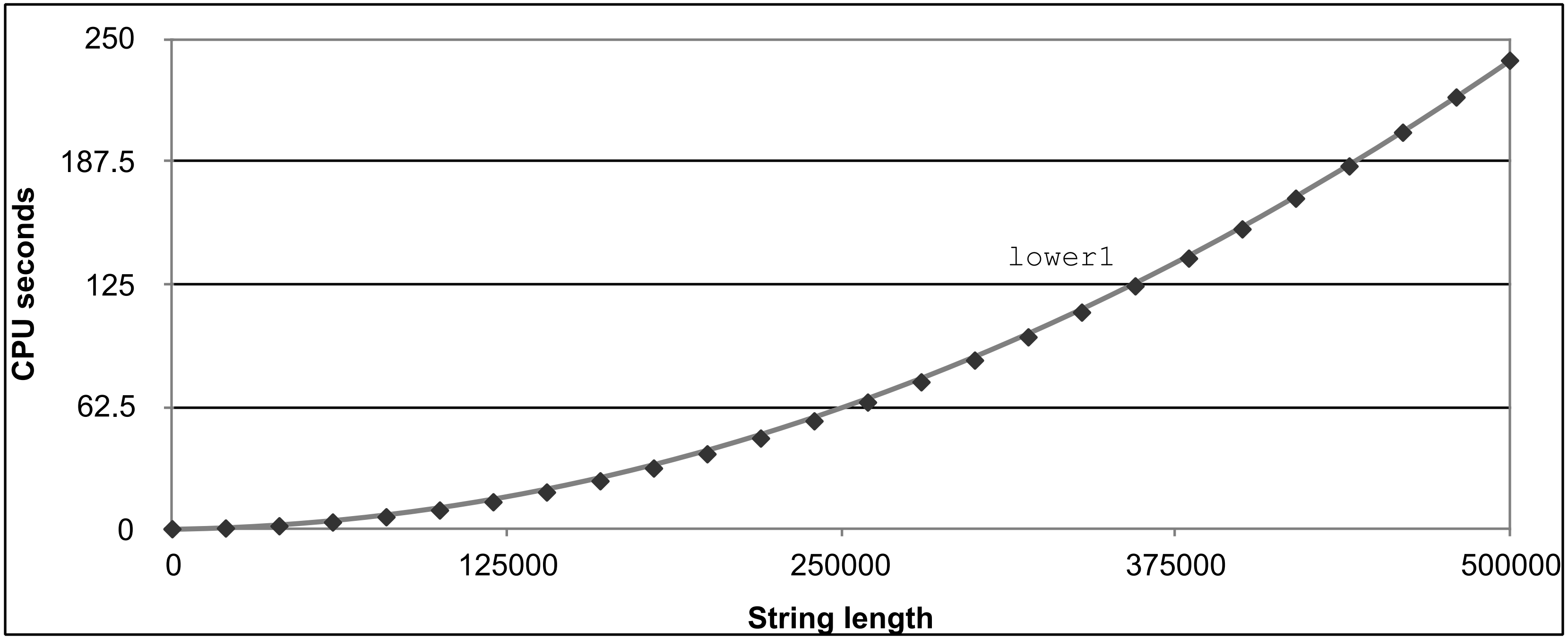
- Procedure to Convert String to Lower Case

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

Question: What’s the big-O runtime of lower, O(n)?

Lower Case Conversion Performance

- Quadratic performance!



Calling strlen in loop

- Strlen takes O(n) to finish
- Strlen is called n times

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

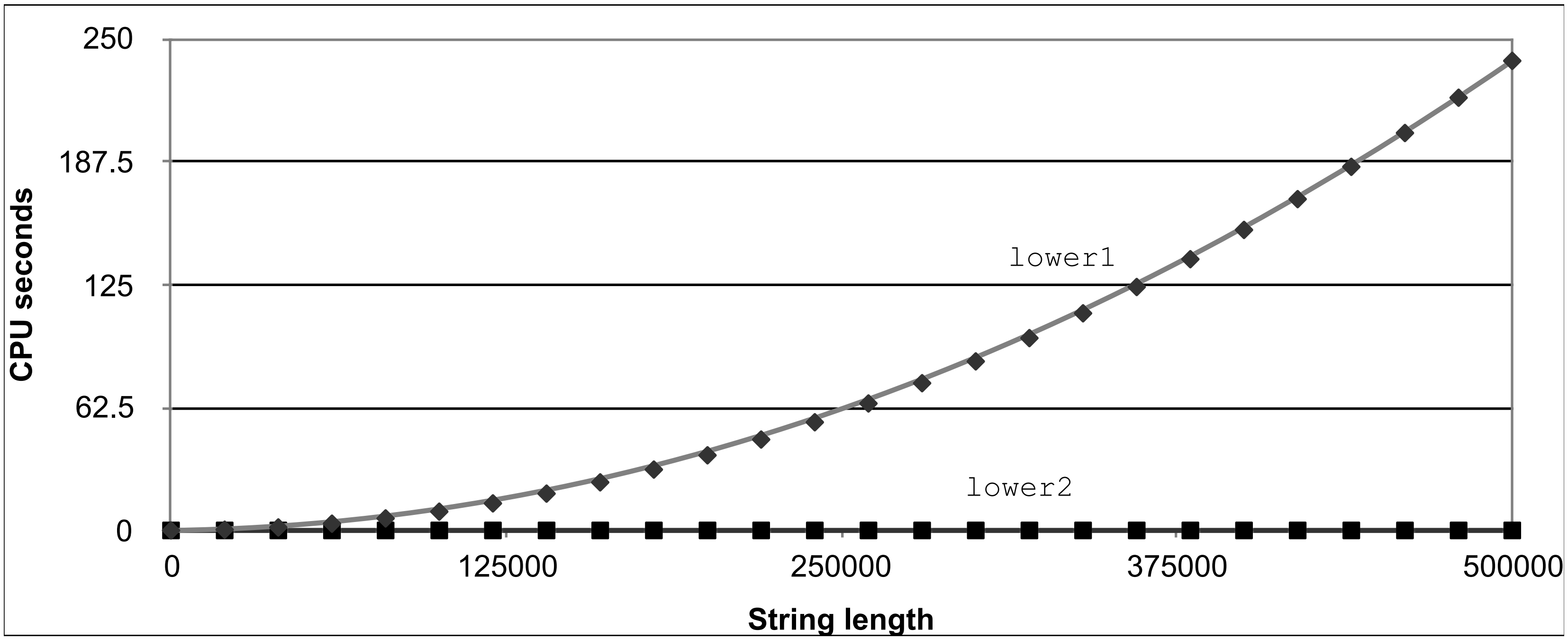
Improving Performance

```
void lower2(char *s)
{
  size_t i;
  size_t len = strlen(s);
  for (i = 0; i < len; i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

- Move call to `strlen` outside of loop
- Since result does not change from one iteration to another

Lower Case Conversion Performance

- Time doubles when double string length
- Linear performance of lower2



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:**
  - Do your own code motion

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
.L4:
        movsd   (%rsi,%rax,8), %xmm0      # FP load
        addsd   (%rdi), %xmm0             # FP add
        movsd   %xmm0, (%rsi,%rax,8)      # FP store
        addq    $8, %rdi
        cmpq    %rcx, %rdi
        jne     .L4
```

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

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

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

```
# sum_rows2 inner loop
.L10:
        addsd   (%rdi), %xmm0      # FP load + add
        addq    $8, %rdi
        cmpq    %rax, %rdi
        jne     .L10
```

- No need to store intermediate results

Optimization Blocker: Memory Aliasing

- **Aliasing**
  - Two different memory references specify single location
  - Easy to 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

Getting High Performance

- **Use compiler optimization flags**
- **Watch out for:**
  - hidden algorithmic inefficiencies
  - Watch out for optimization blockers: procedure calls & memory aliasing
- **Profile the program's performance**