Systems I

Code Optimization I: Machine Independent Optimizations

Topics

- Machine-Independent Optimizations
  - Code motion
  - Reduction in strength
  - Common subexpression sharing
- Tuning
  - Identifying performance bottlenecks

Great 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
- 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 you 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

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

→

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

Compiler-Generated Code Motion

- Most compilers do a good job with array code + simple loop structures

Code Generated by GCC

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

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

```
  imull %ebx,%eax          # i*n
  movl 8(%ebp),%edi        # a
  leal (%edi,%eax,4),%edx # p = a+i*n (scaled by 4)
# Inner Loop
  movl 12(%ebp),%edi       # b
.L40:
  movl (%edi,%ecx,4),%eax # b+j  (scaled by 4)
  movl %eax,(%edx)         # *p = b[j]
  addl $4,%edx             # p++  (scaled by 4)
  incl %ecx                # j++
  cmpl %ebx,%ecx           # loop if j<n
  jl .L40
```

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 II or III, integer multiply only requires 4 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;
}
```

Make Use of Registers

- Reading and writing registers much faster than reading/writing memory

Limitation

- Compiler not always able to determine whether variable can be held in register
- Possibility of *Aliasing*
- See example later

Machine-Independent Opts. (Cont.)

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

```
  leal -1(%edx),%ecx   # i-1
  imull %ebx,%ecx      # (i-1)*n
  leal 1(%edx),%eax    # i+1
  imull %ebx,%eax      # (i+1)*n
  imull %ebx,%edx      # i*n
```

Time Scales

Absolute Time

- Typically use nanoseconds
  - 10^{-9} seconds
- Time scale of computer instructions

Clock Cycles

- Most computers controlled by high frequency clock signal
- Typical Range
  - 100 MHz
    - » 10^8 cycles per second
    - » Clock period = 10ns
  - 2 GHz
    - » 2×10^9 cycles per second
    - » Clock period = 0.5ns

Example of Performance Measurement

Loop unrolling

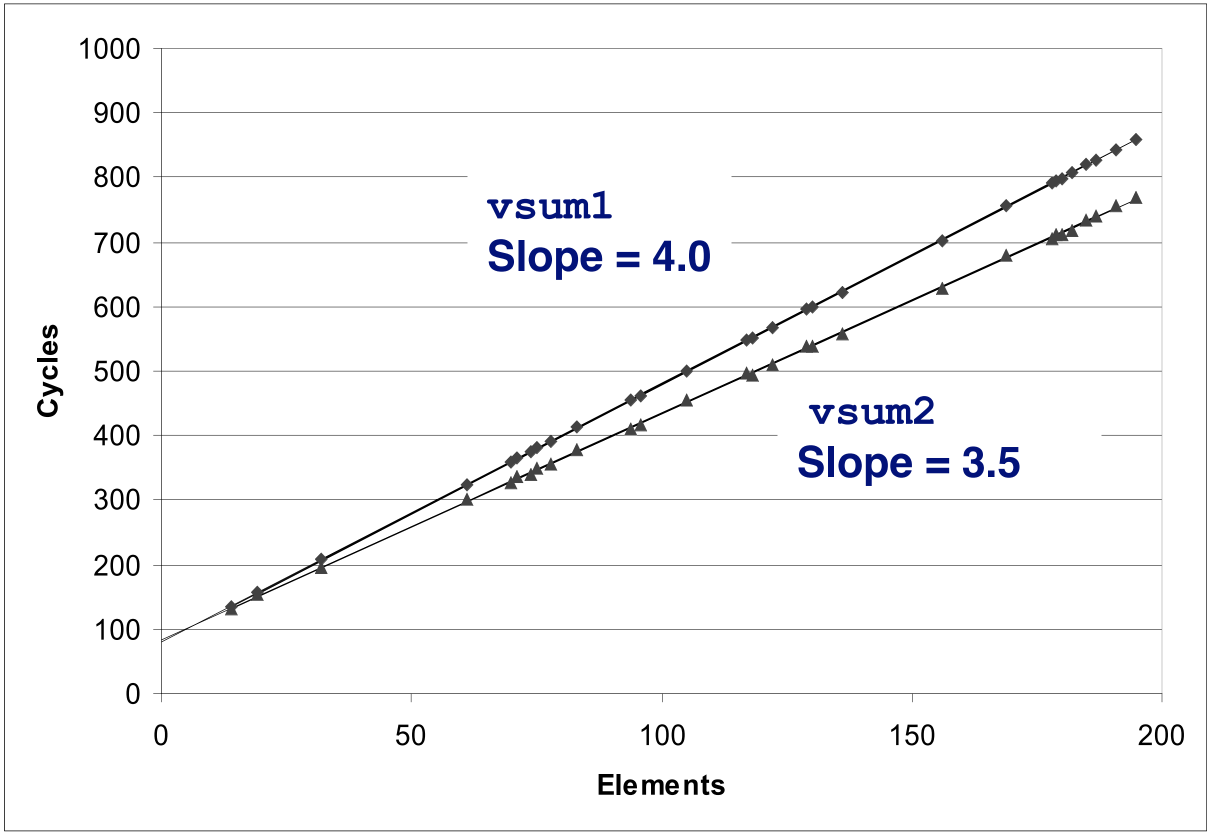
- **Assume even number of elements**

```
void vsum1(int n) {
  int i;
  for(i=0; i<n; i++)
    c[i] = a[i] + b[i];
}
```

```
void vsum2(int n) {
  int i;
  for(i=0; i<n; i+=2) {
    c[i] = a[i] + b[i];
    c[i+1] = a[i+1] + b[i+1];
}
```

Cycles Per Element

- Convenient way to express performance of program that operators on vectors or lists
- Length = n
- T = CPE*n + Overhead



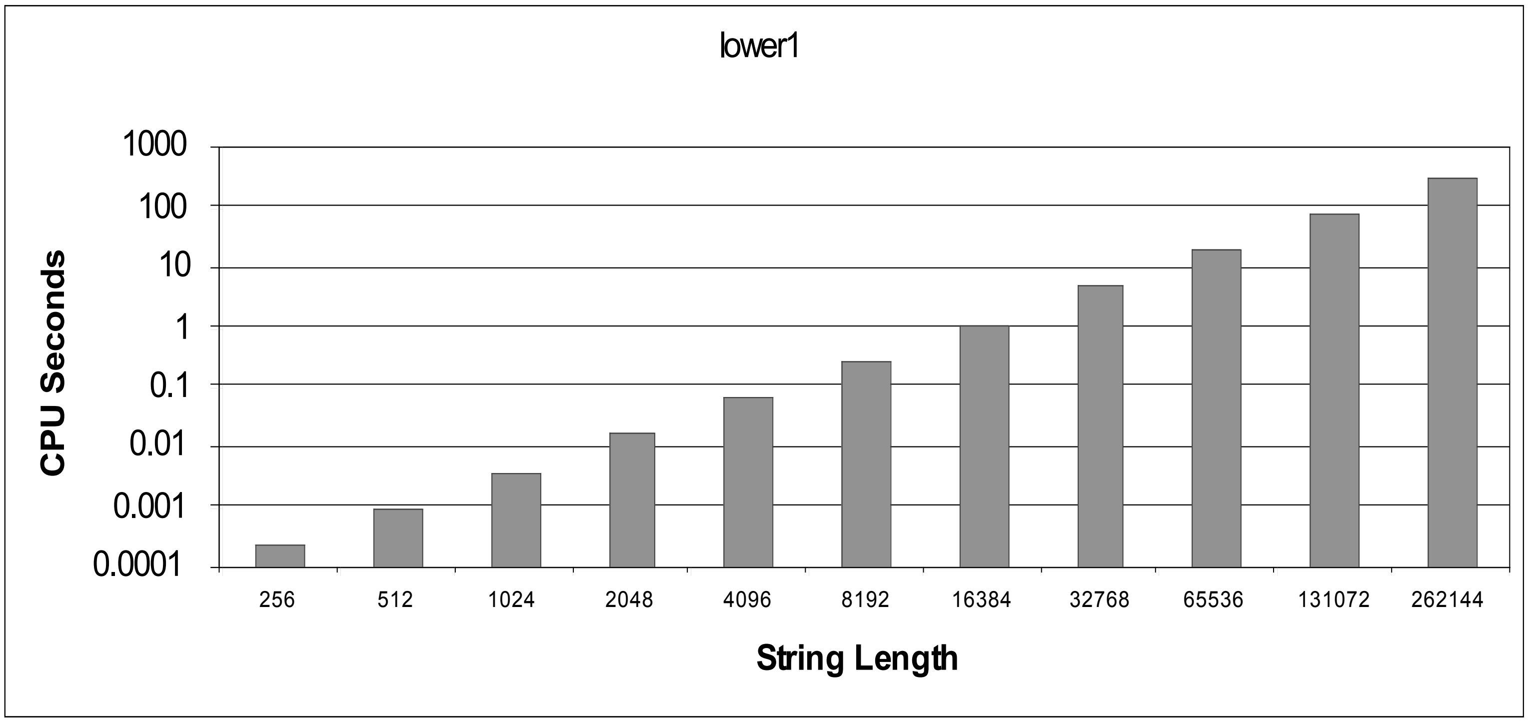
Code Motion Example

Procedure to Convert String to Lower Case

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

Lower Case Conversion Performance

- Time quadruples when string length doubles
- Quadratic performance



Convert Loop To Goto Form

```
void lower(char *s)
{
   int i = 0;
   if (i >= strlen(s))
     goto done;
 loop:
   if (s[i] >= 'A' && s[i] <= 'Z')
       s[i] -= ('A' - 'a');
   i++;
   if (i < strlen(s))
     goto loop;
 done:
}
```

- `strlen` executed every iteration
- `strlen` linear in length of string
  - Must scan string until finds `'\0'`
- Overall performance is quadratic

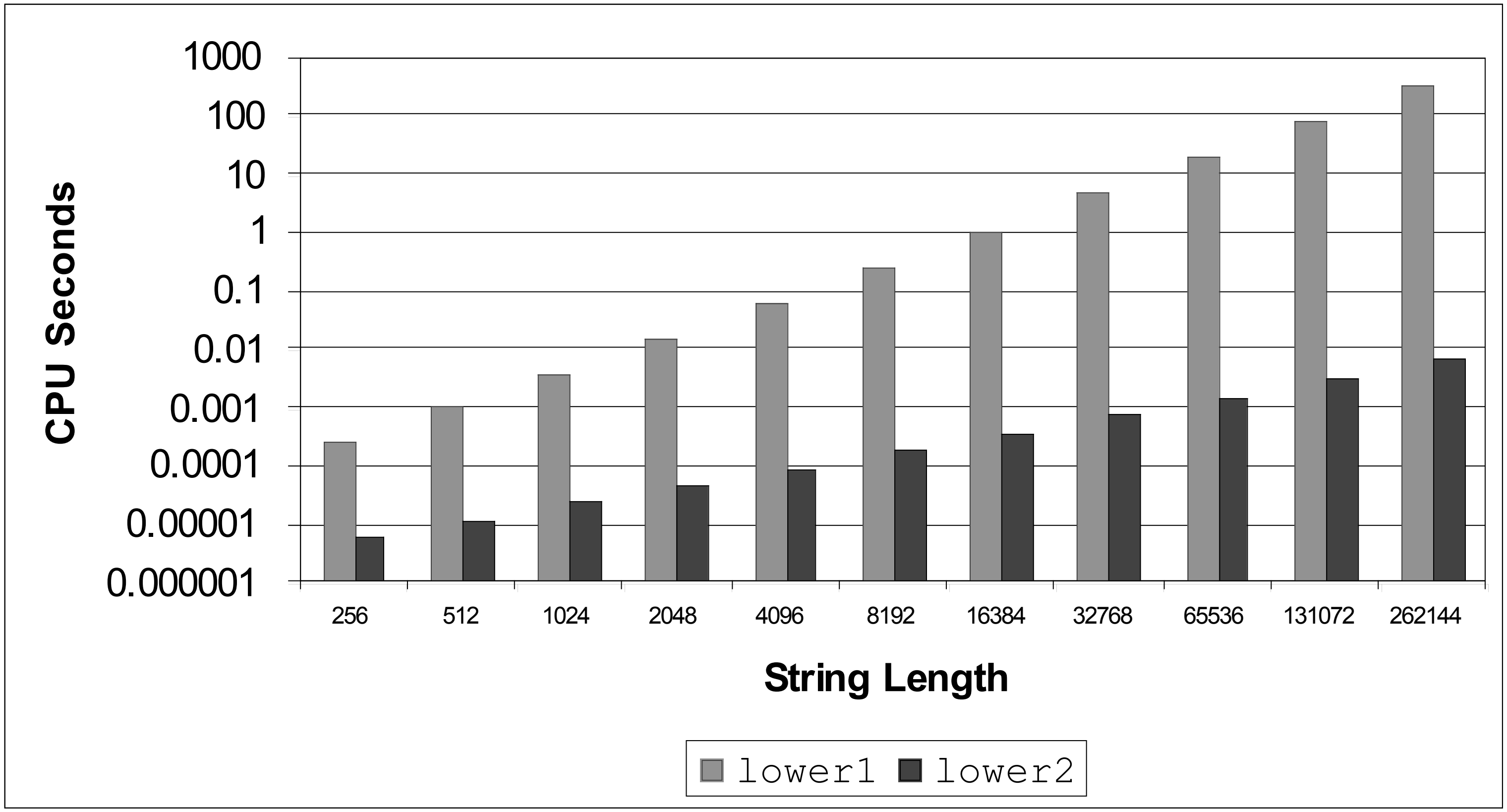
Improving Performance

```
void lower(char *s)
{
  int i;
  int 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
- Form of code motion

Lower Case Conversion Performance

- Time doubles when double string length
- Linear performance



Optimization Blocker: Procedure Calls

Why couldn't the compiler move `strlen` out of the 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`**

Why doesn't compiler look at code for `strlen`?

- **Linker may overload with different version**
  - **Unless declared static**
- **Interprocedural optimization is not used extensively due to cost**

Warning:

- **Compiler treats procedure call as a black box**
- **Weak optimizations in and around them**

Summary

Today

- Improving program performance (machine independent)
- Mostly focusing on instruction count

Next time

- Optimization blocker: procedure calls
- Optimization blocker: memory aliasing
- Tools (profiling) for understanding performance