CS 201

Code Optimization, Part 1

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There's more to performance than asymptotic complexity

Constant factors matter too!

- Factor of 10 improvement is possible 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

Don’t (usually) improve asymptotic efficiency

- The programmer must select a good algorithm
- big-O savings are more important than constant factors
  - but constant factors also matter

Compilers have difficulty overcoming “optimization blockers”

- potential memory aliasing
- potential procedure side-effects

Limitations of Optimizing Compilers

Fundamental Constraint:

- Must not cause any change in program behavior under any possible condition
- Even pathological conditions.

Most analysis is performed only within procedures

- whole-program analysis is too expensive

Most analysis is based only on *static* information

- The compiler does't anticipate run-time inputs
- The programmer knows more about constraints on the data than the compiler.

When in doubt, the compiler must be conservative

Compiler-Generated Code Motion

- Most compilers do a good job with array code and 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
.L40:
  movl 12(%ebp),%edi         # b
  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++
  jl .L40                    # loop if j<n
```

Reduction in Strength

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

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

  - The utility of this is machine dependent
  - On Pentium II or III, integer multiply only requires 4 CPU cycles
- Recognize sequence of products

Reduction in Strength

Write C code to show what the compiler generated.

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

```
    movl    16(%ebp), %ebx
    xorl    %esi, %esi
    cmpl    %ebx, %esi
    jge    .L11
    movl    $0, -16(%ebp)
.L9:
    xorl    %ecx, %ecx
    cmpl    %ebx, %ecx
    jge    .L13
    movl    -16(%ebp), %eax
    movl    8(%ebp), %edi
    leal    (%edi,%eax,4), %edx
.L8:
    movl    12(%ebp), %edi
    movl    (%edi,%ecx,4), %eax
    incl    %ecx
    movl    %eax, (%edx)
    addl    $4, %edx
    cmpl    %ebx, %ecx
    jl     .L8
.L13:
    incl    %esi
    addl    %ebx, -16(%ebp)
    cmpl    %ebx, %esi
    jl     .L9
.L11:   # all done
```

Make Use of Registers

- Reading and writing registers is 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

Another limitation in the case of Intel processors

- Almost no registers
- You have to make use of cache

Machine-Independent Opts. (Cont.)

Share Common Subexpressions

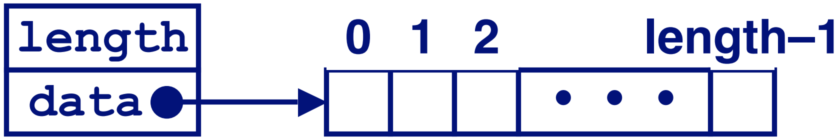
- Reuse portions of expressions
- Compilers often not very sophisticated in exploiting arithmetic properties

```
/* 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;
```

```
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
```

How can we change this code so it doesn’t do 3 multiplications?

Example



Data type: vector, illustrated above

Procedures

`vec_ptr new_vec(int len)`

- Create vector of specified length

`int get_vec_element(vec_ptr v, int index, int *dest)`

- Retrieve vector element, store at *dest
- Return 0 if out of bounds, 1 if successful

`int *get_vec_start(vec_ptr v)`

- Return pointer to start of vector data

- Structured programming
  - Hide the implementation of the array
  - Always do bounds checking

Optimization Example

```
void combine1(vec_ptr v, int *dest)
{
  int i;
  *dest = 0;
  for (i = 0; i < vec_length(v); i++) {
    int val;
    get_vec_element(v, i, &val);
    *dest += val;
  }
}
```

Procedure

- Compute sum of all elements of integer vector
- Store result at destination location
- Vector data structure and operations defined via abstract data type

Pentium II/III Performance: Clock Cycles / Element

- 42.06 (Compiled -g) 31.25 (Compiled -O2)

Understanding the "for" Loop

```
void combine1-goto(vec_ptr v, int
*dest)
{
    int i = 0;
    int val;
    *dest = 0;
    if (i >= vec_length(v))
      goto done;
  loop:
    get_vec_element(v, i, &val);
    *dest += val;
    i++;
    if (i < vec_length(v))
      goto loop
  done:
}
```

1 iteration

Inefficiency

- Procedure vec_length is called every iteration
- Even though result is always the same

Exercise

Write a function *combine2* that does the same thing as *combine1,* without calling vec_length on each iteration.

Move `vec_length` Call Out of Loop

Optimization

- Move call to `vec_length` out of inner loop
  - Value does not change from one iteration to next
  - Code motion
- CPE: 20.66 (Compiled -O2)
  - `vec_length` requires only constant time, but significant overhead

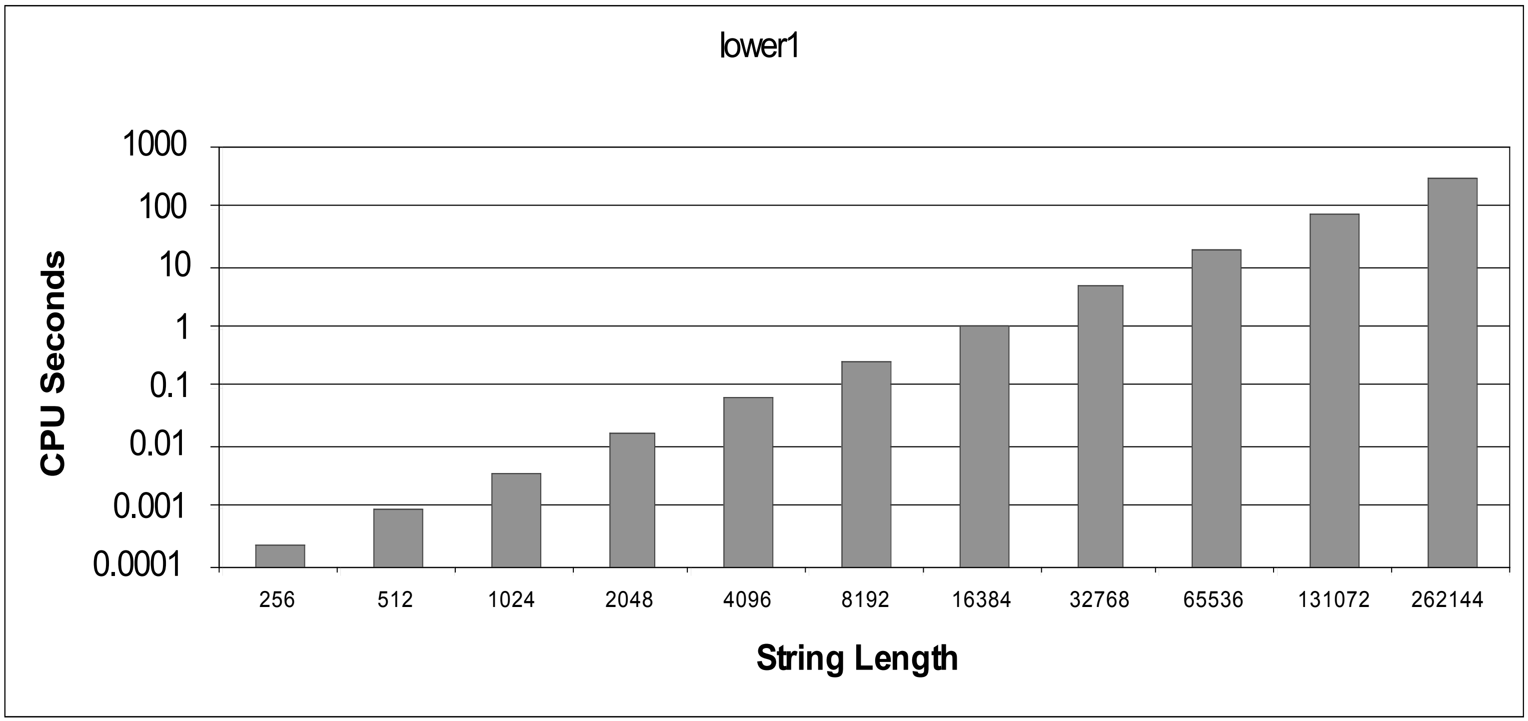
Code Motion Example #2

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 double string length**
- **Quadratic performance**

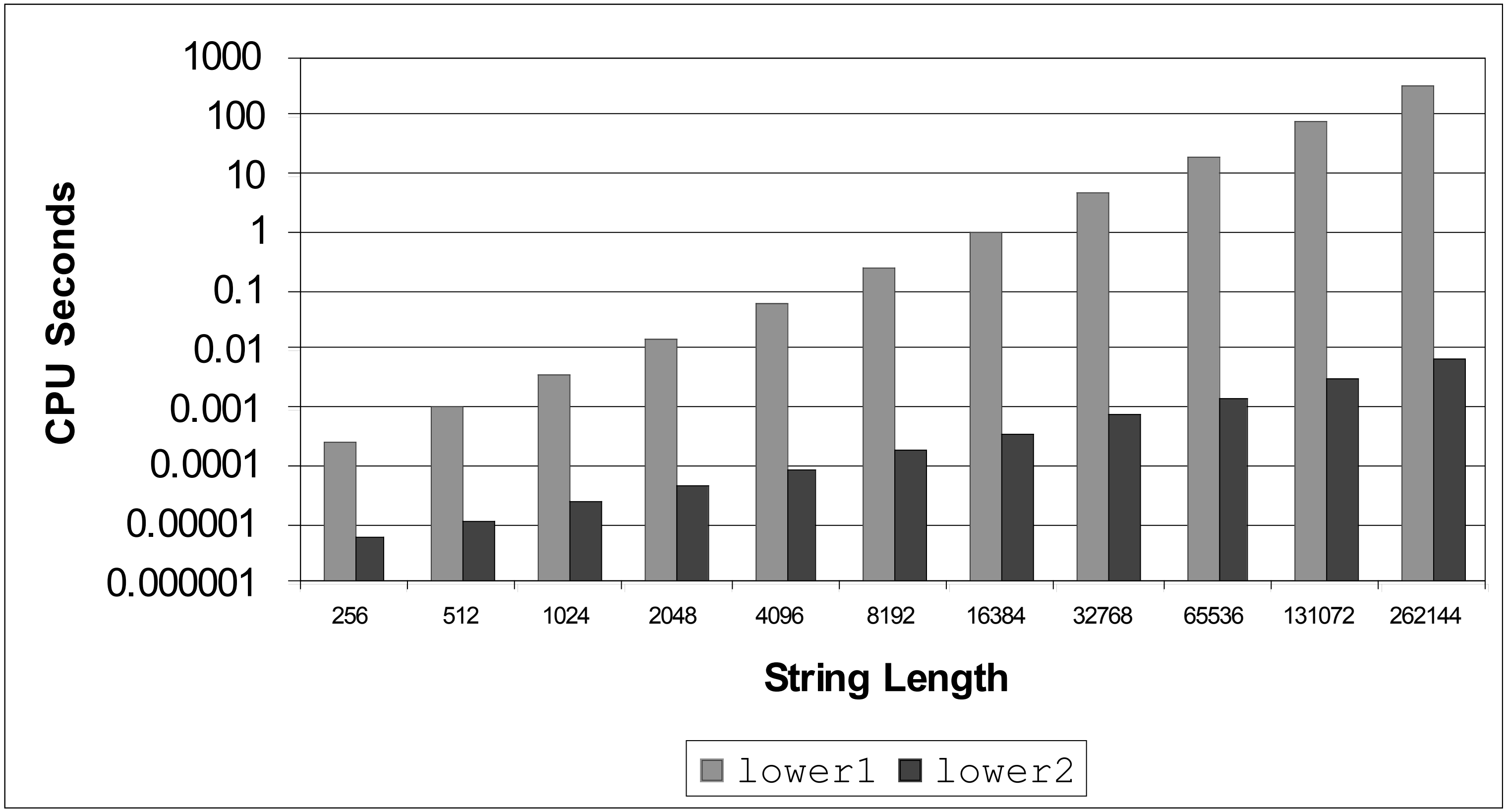


Exercise

- Why is the time proportional to the square of the string length?
- How can you optimize the function to make it linear?
- Write the optimized code.
- Why can't the compiler do that optimization?

Lower Case Conversion Performance

- Time doubles when double string length
- Linear performance



Optimization Blocker: Procedure Calls

Compiler treats procedure call as a black box

- Weak optimizations in and around them

Why?

Reduction in Strength

```
void combine3(vec_ptr v, int *dest)
{
  int i;
  int length = vec_length(v);
  int *data = get_vec_start(v);
  *dest = 0;
  for (i = 0; i < length; i++) {
    *dest += data[i];
}
```

Optimization

- Avoid procedure call to retrieve each vector element
  - Get pointer to start of array before loop
  - Not as clean in terms of data abstraction
    - Makes assumption about what a vector looks like internally
- CPE: 6.00 (Compiled -O2)
  - Procedure calls are expensive!
  - Bounds checking is expensive

Eliminate Unneeded Memory Refs

```
void combine4(vec_ptr v, int *dest)
{
  int i;
  int length = vec_length(v);
  int *data = get_vec_start(v);
  int sum = 0;
  for (i = 0; i < length; i++)
    sum += data[i];
  *dest = sum;
}
```

Optimization

- How many memory references does this avoid per element?
- How does it avoid them?
- CPE: 2.00 (Compiled -O2)
  - Memory references are expensive!

Detecting Unneeded Memory Refs.

Combine3

```
.L18:
        movl (%ecx,%edx,4),%eax
        addl %eax,(%edi)
        incl %edx
        cmpl %esi,%edx
        jl .L18
```

Combine4

```
.L24:
        addl (%eax,%edx,4),%ecx

        incl %edx
        cmpl %esi,%edx
        jl .L24
```

Performance

- Combine3
  - 5 instructions in 6 (or more) clock cycles
  - `addl` must read memory and write to cache
    - » With 200 mhz CPU, a cache miss can entail up to 30 cycles
- Combine4
  - 4 instructions in 2 clock cycles

Optimization Blocker: Memory Aliasing

Aliasing

- Two different memory references specify single location

Example

- `v: [3, 2, 17]`
- `combine3(v, get_vec_start(v)+2)`
- `What's the problem?`

Observations

- Easy for this to happen in C, with address arithmetic
- Get in habit of introducing local variables
  - Accumulating within loops
  - Your way of telling compiler it can optimize to its heart's content

Machine-Independent Opt. Summary

Code Motion

- *Compilers are good at this for simple loop/array structures*
  - *Local variables, no possible side effects*
- *Don't do well in 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 are machine-dependent***

Keep data in registers rather than memory

- ***compilers are not good at this, concerned with aliasing***

Share Common Subexpressions

- *compilers have limited algebraic reasoning capabilities*

Important Tools

Measurement

- Accurately compute time taken by code
  - Most modern machines have built in cycle counters
  - Using them to get reliable measurements is tricky
- Profile procedure calling frequencies
  - Unix tool gprof

Observation

- Generating assembly code
  - Lets you see what optimizations compiler can make

Code Profiling Example

Task

- Count word frequencies in text document
- Produce sorted list of words from most frequent to least

Steps

- Convert strings to lowercase
- Apply hash function
- Read words and insert into hash table
  - Mostly list operations
  - Maintain counter for each unique word
- Sort results

Data Set

- Collected works of Shakespeare
- 946,596 total words, 26,596 unique
- Initial implementation: 9.2 seconds

Shakespeare's most frequent words

29,801	the
27,529	and
21,029	I
20,957	to
18,514	of
15,370	a
14010	you
12,936	my
11,722	in
11,519	that

Code Profiling

Augment Executable Program with Timing Functions

- Computes (approximate) amount of time spent in each function
- Time computation method
  - Periodically (~ every 10ms) interrupt program
  - Determine what function is currently executing
  - Increment its timer by interval (e.g., 10ms)
- Also maintains counter for each function indicating number of times called

Using

```
gcc -O2 -pg prog.c -o prog
```

```
./prog
```

- Executes in normal fashion, but also generates file `gmon.out`

```
gprof prog
```

- Generates profile information based on `gmon.out`

Profiling Results

% time	cumulative seconds	self seconds	calls	self ms/call	total ms/call	name
86.60	8.21	8.21	1	8210.00	8210.00	sort_words
5.80	8.76	0.55	946596	0.00	0.00	lower1
4.75	9.21	0.45	946596	0.00	0.00	find_ele_rec
1.27	9.33	0.12	946596	0.00	0.00	h_add

Call Statistics

- Number of calls and total time for each function

sort_words, called just once, uses 87% of CPU time

Where do you think we should focus our optimization efforts?

What Profiling is Good For

Amdahl's Law

- The performance enhancement possible with a given improvement limited by the amount that the improved feature is used

Suppose a module requires a fraction α of the total time, and we improve its performance by a factor of k

- $T_{new} = (1 - \alpha)T_{old} + (\alpha T_{old})/k$
  $= T_{old}[(1 - \alpha) + \alpha/k]$

  $\text{Speedup} = [(1 - \alpha) + \alpha/k]^{-1}$
- As $\alpha \rightarrow 0$, Speedup $\rightarrow 1$, regardless of k
- As $\alpha \rightarrow 1$, Speedup $\rightarrow$ k

Profiling Observations

Benefits

- Helps identify performance bottlenecks
- Especially useful with a complex system with many components

Limitations

- Only shows performance for data tested
  - Quadratic inefficiency could remain lurking in code
- Timing mechanism fairly crude
  - Only works for programs that run for > 3 seconds

Is it really a good idea to move code around to save some CPU cycles?

How often is it worthwhile to sacrifice maintainability for a linear performance improvement?

- Almost never.
- If you're writing specialized library code, for example.

Why is it good to understand these concepts?

- Using local variables and avoiding possible side effects is a good habit in general
  - If the compiler can do good optimizations, it's a sign that the code is well-structrured
  - Optimizable code is not necessarily un-maintainable
- Every once in a while you run into a bottleneck or a performance anomaly that you need to understand.