15-213

Code Optimization
September 27, 2001

Topics

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

Great Reality #4

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**
  - e.g., using an "`int`" in C for what could be an enumerated type

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
.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
```

  – **Utility machine dependent**
  – **Depends on cost of multiply or divide instruction**
  – **On Pentium II or III, integer multiply only requires 4 CPU cycles**

```
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;
```

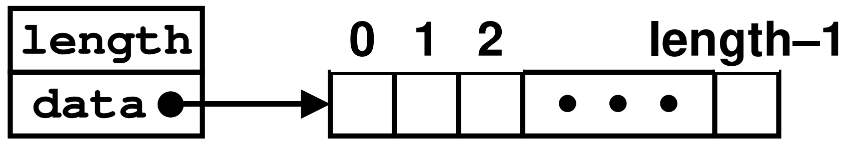
3 multiplications: i*n, (i–1)*n, (i+1)*n

```
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;
```

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
```

Vector ADT



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

- **Similar to array implementations in Pascal, ML, Java**
  - E.g., 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 vector
- Store result at destination location

Time Scales

Absolute Time

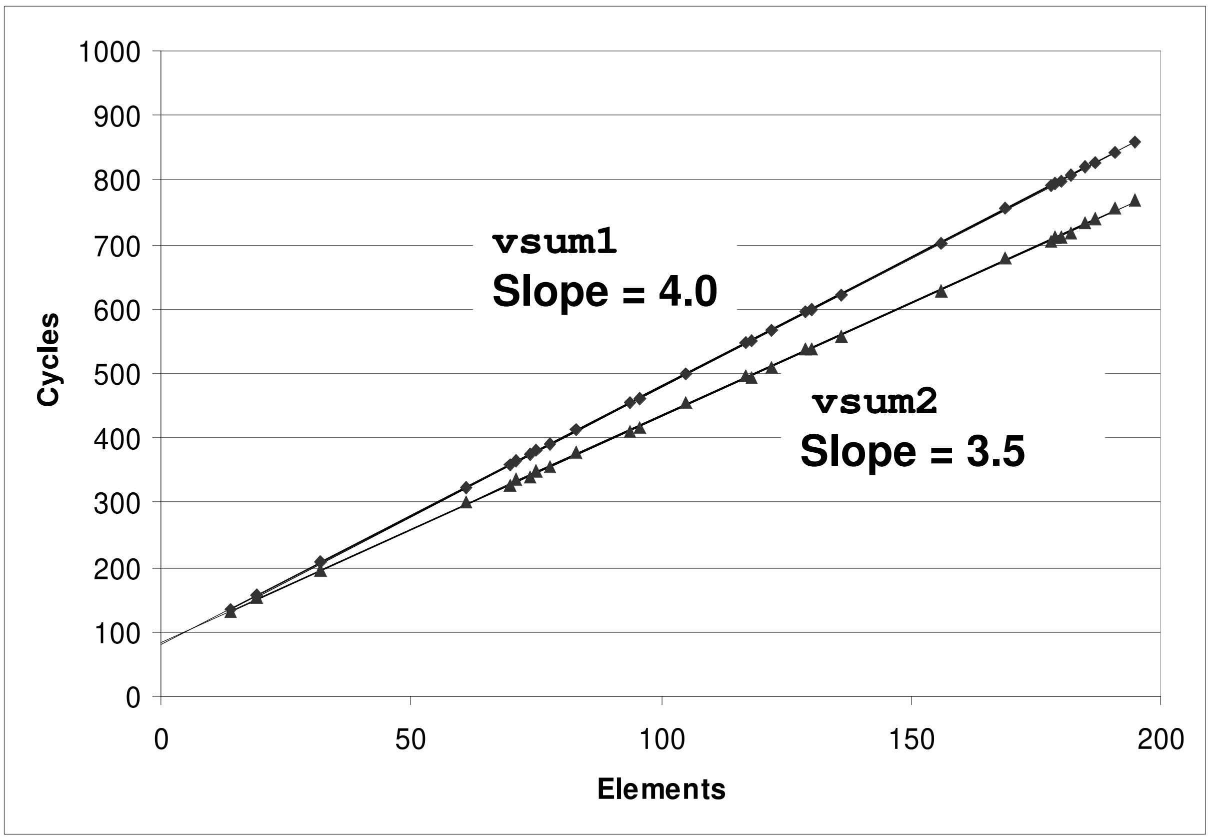
- **Typically use nanoseconds**
  - 10^{-9} seconds
- **Time scale of computer instructions**

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 X 10^{9} cycles per second
    - » Clock period = 0.5ns
- **Fish machines: 550 MHz (1.8 ns clock period)**

Cycles Per Element

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



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 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 called every iteration
- Even though result always the same

Move `vec_length` Call Out of Loop

```
void combine2(vec_ptr v, int *dest)
{
  int i;
  int length = vec_length(v);
  *dest = 0;
  for (i = 0; i < length; i++) {
    int val;
    get_vec_element(v, i, &val);
    *dest += val;
  }
}
```

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

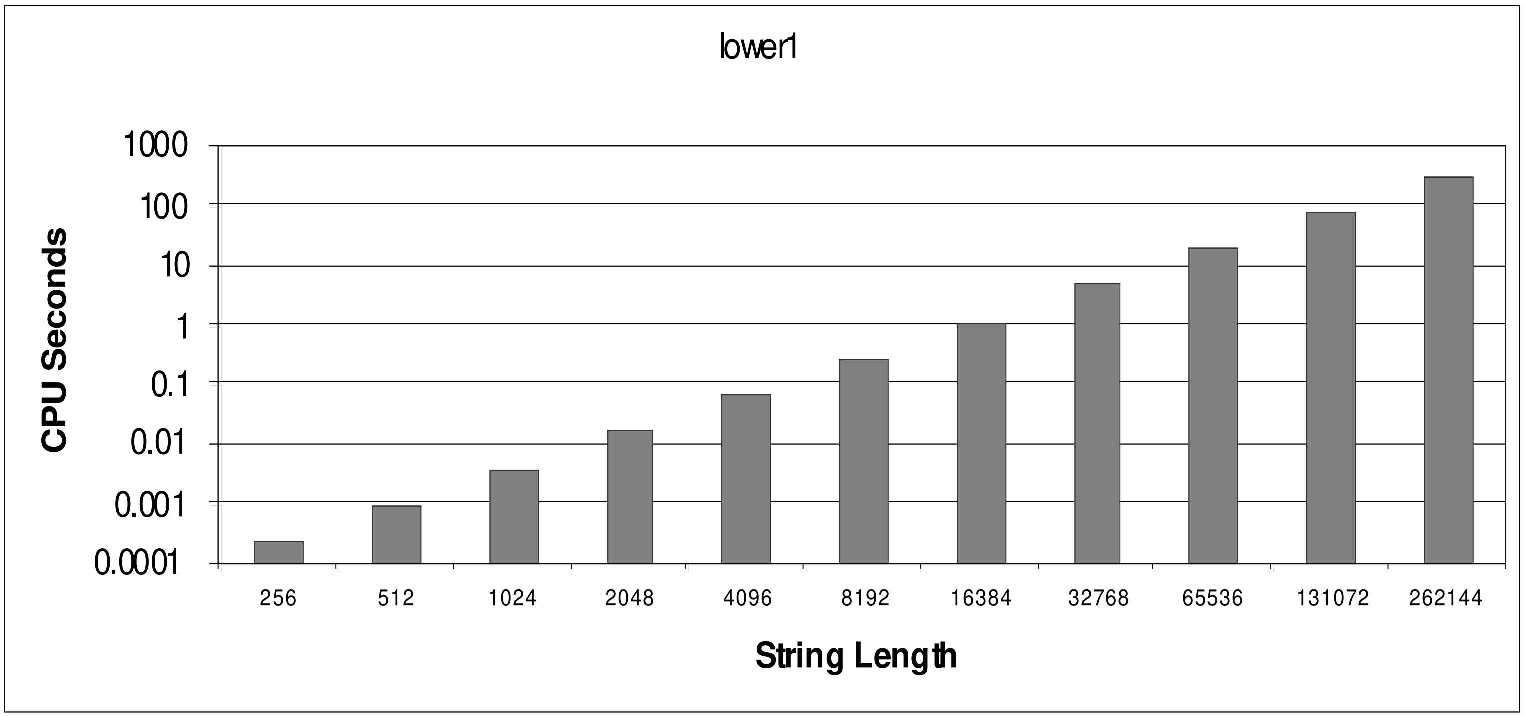
Procedure to Convert String to Lower Case

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

- Extracted from 213 lab submissions, Fall, 1998

Lower Case Conversion Performance

- **Time quadruples when double string length**
- **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

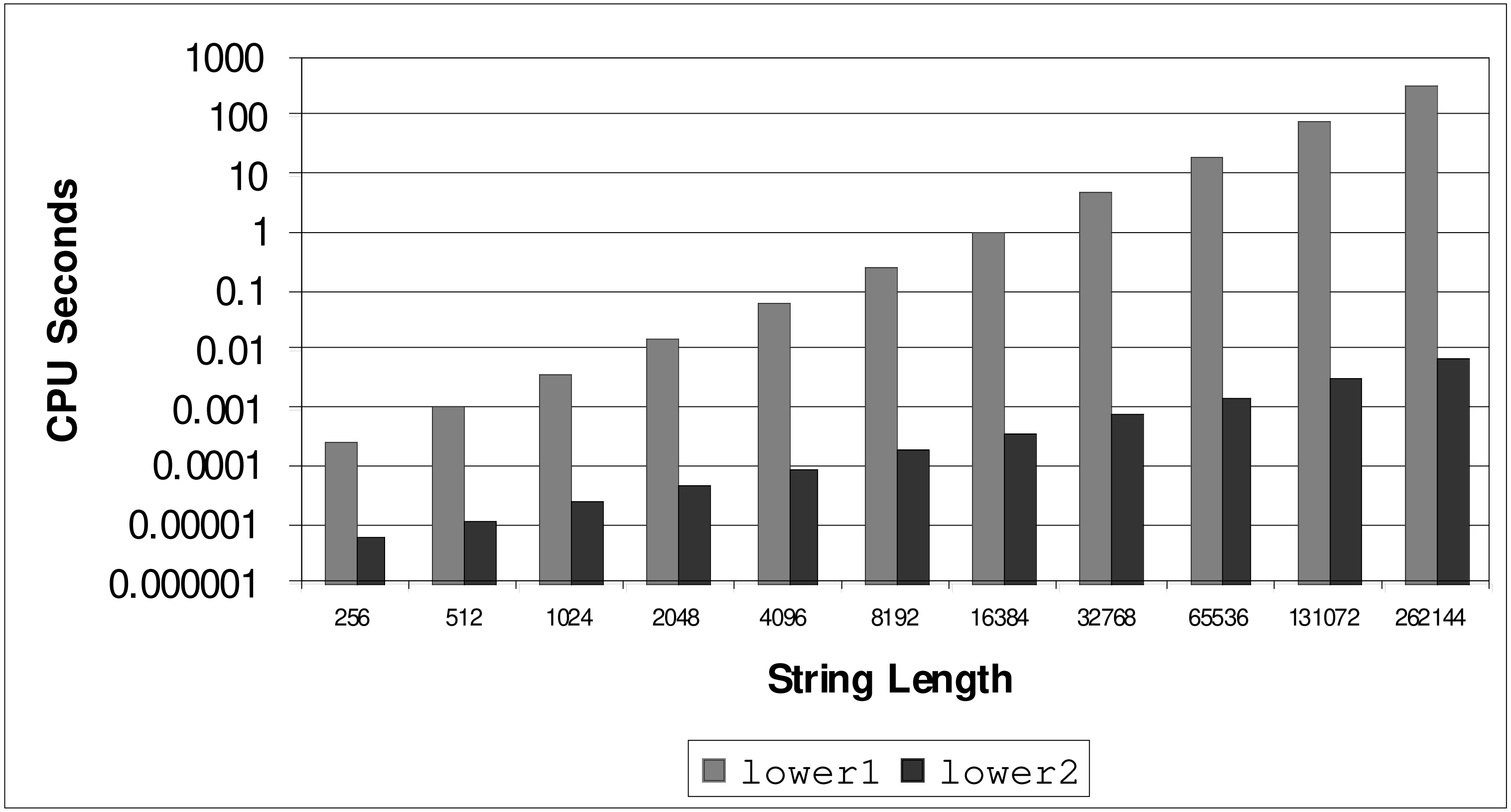
Improving Performance

```
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 `vec_len` *or* `strlen` *out of the inner loop?*

- **Procedure May Have Side Effects**
  - i.e, 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 `vec_len` *or* `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**

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
  - Within loop just do pointer reference
  - Not as clean in terms of data abstraction
- **CPE: 6.00 (Compiled -O2)**
  - Procedure calls are expensive!
  - Bounds checking is expensive

Eliminate Unneeded Memory References

```
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

- **Don't need to store in destination until end**
- **Local variable `sum` held in register**
- **Avoids 1 memory read, 1 memory write per cycle**
- **CPE: 2.00 (Compiled -O2)**
  – Memory references are expensive!

Detecting Unneeded Memory References

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 clock cycles
  - `addl` must read and write memory
- **Combine4**
  - 4 instructions in 2 clock cyles

Optimization Blocker: Memory Aliasing

Aliasing

- **Two different memory references specify single location**

Example

- `v: [3, 2, 17]`
- `combine3(v, get_vec_start(v)+2)  -->  ?`
- `combine4(v, get_vec_start(v)+2)  -->  ?`

Observations

- **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 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 rather than memory**
  - *compilers are not good at this, since 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
  - Understand capabilities/limitations of particular compiler

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. –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

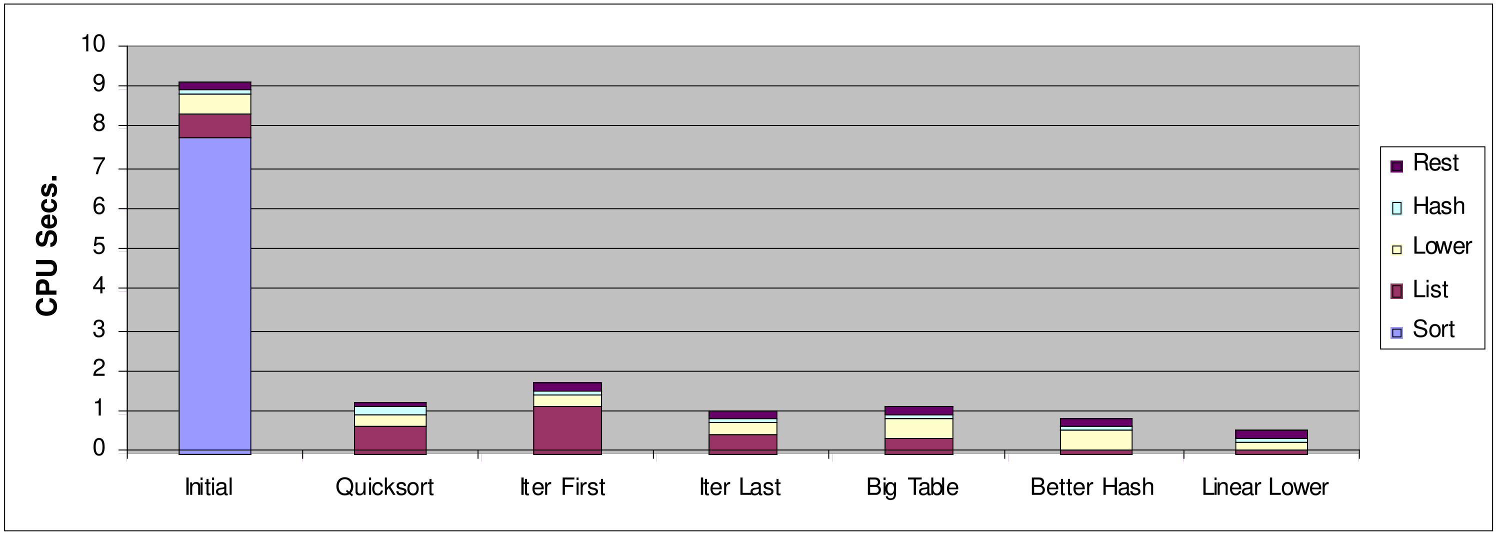
Call Statistics

- Number of calls and cumulative time for each function

Performance Limiter

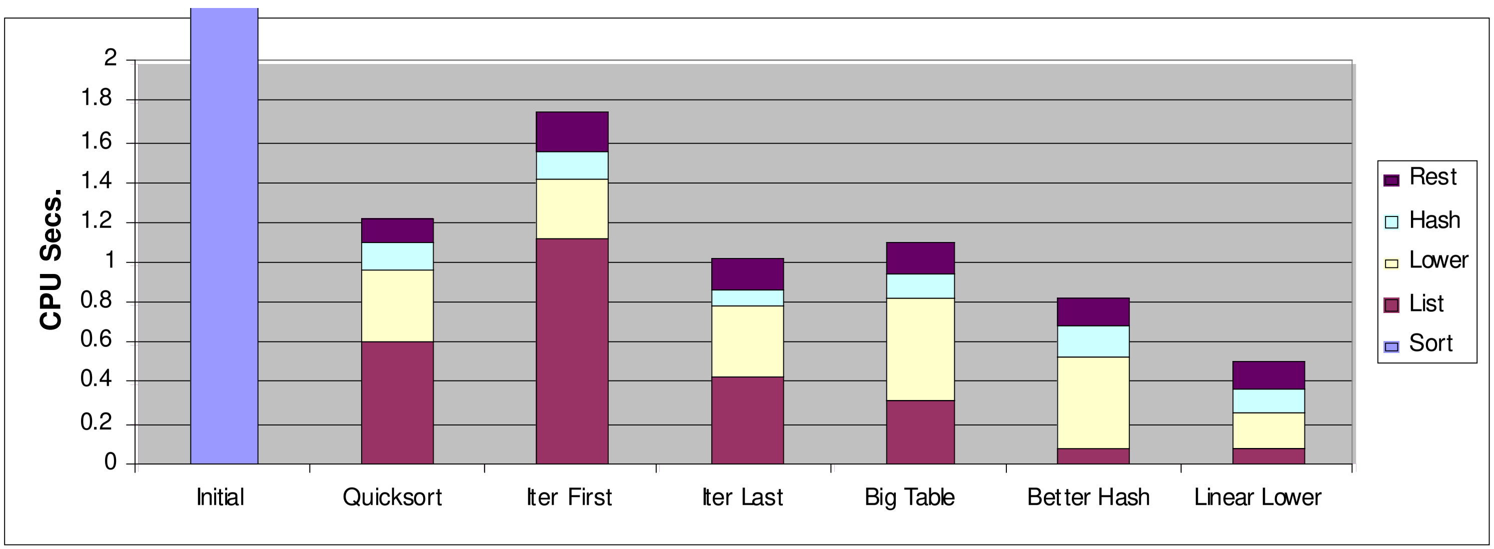
- Using inefficient sorting algorithm
- Single call uses 87% of CPU time

Code Optimizations



- **First step: Use more efficient sorting function**
- **Library function `qsort`**

Further Optimizations



- **Iter first: Use iterative function to insert elements in linked list**
  - Causes code to slow down
- **Iter last: Iterative function, places new entry at end of list**
  - Tend to place most common words at front of list
- **Big table: Increase number of hash buckets**
- **Better hash: Use more sophisticated hash function**
- **Linear lower: Move `strlen` out of loop**

Profiling Observations

Benefits

- **Helps identify performance bottlenecks**
- **Especially useful when have complex system with many components**

Limitations

- **Only shows performance for data tested**
- **E.g., linear lower did not show big gain, since words are short**
  - Quadratic inefficiency could remain lurking in code
- **Timing mechanism fairly crude**
  - Only works for programs that run for > 3 seconds