Code Optimization I: Machine Independent Optimizations

Chapter 5 of B&O

Some notes adopted from Bryant and O'Hallaron

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
  - 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 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
  - 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;
```

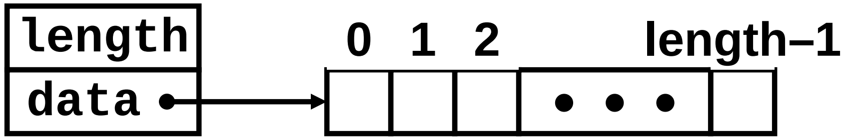
```
int inj = i*n + j;
up =    val[inj - n];
down =  val[inj + n];
left =  val[inj - 1];
right = val[inj + 1];
sum = up + down + left + right;
```

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
```

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

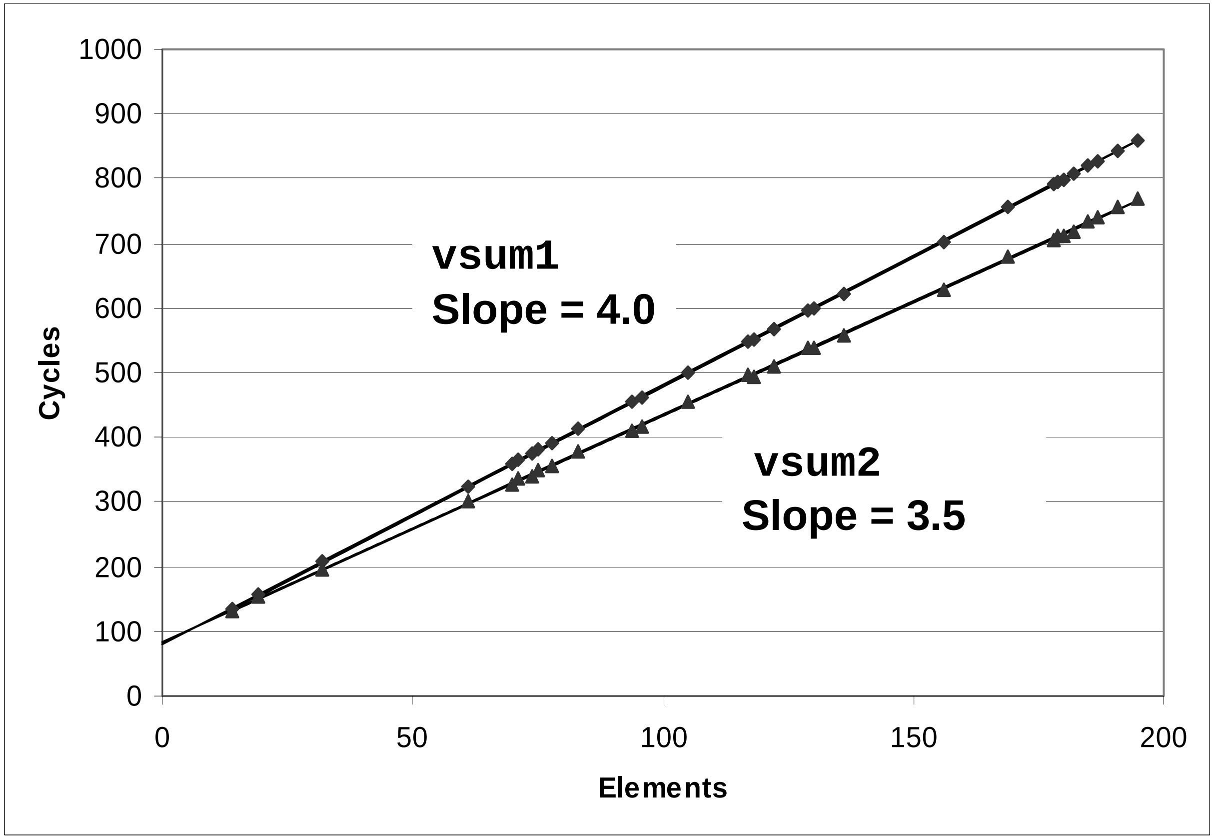
Optimization Example

```
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

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
- 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

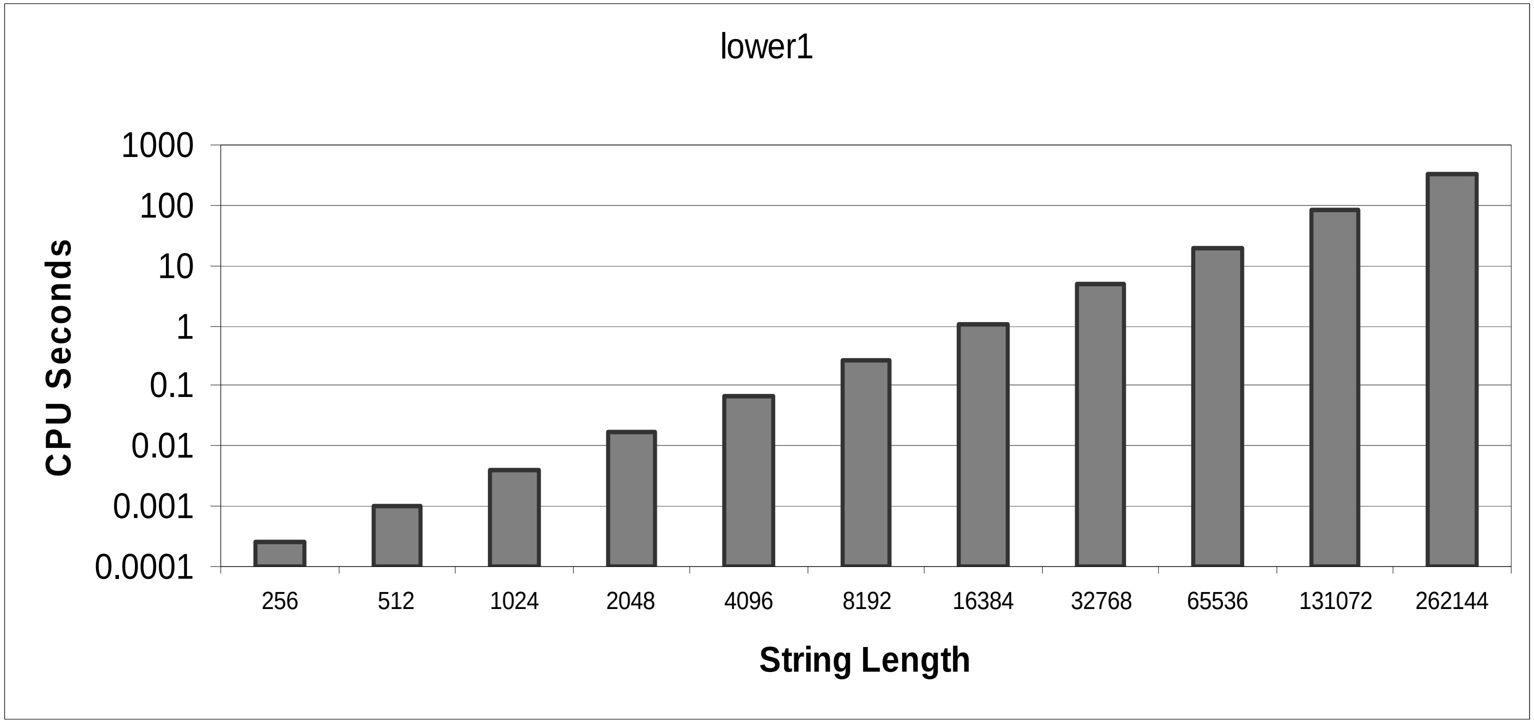
Code Motion Example #2

- 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');
}
```

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

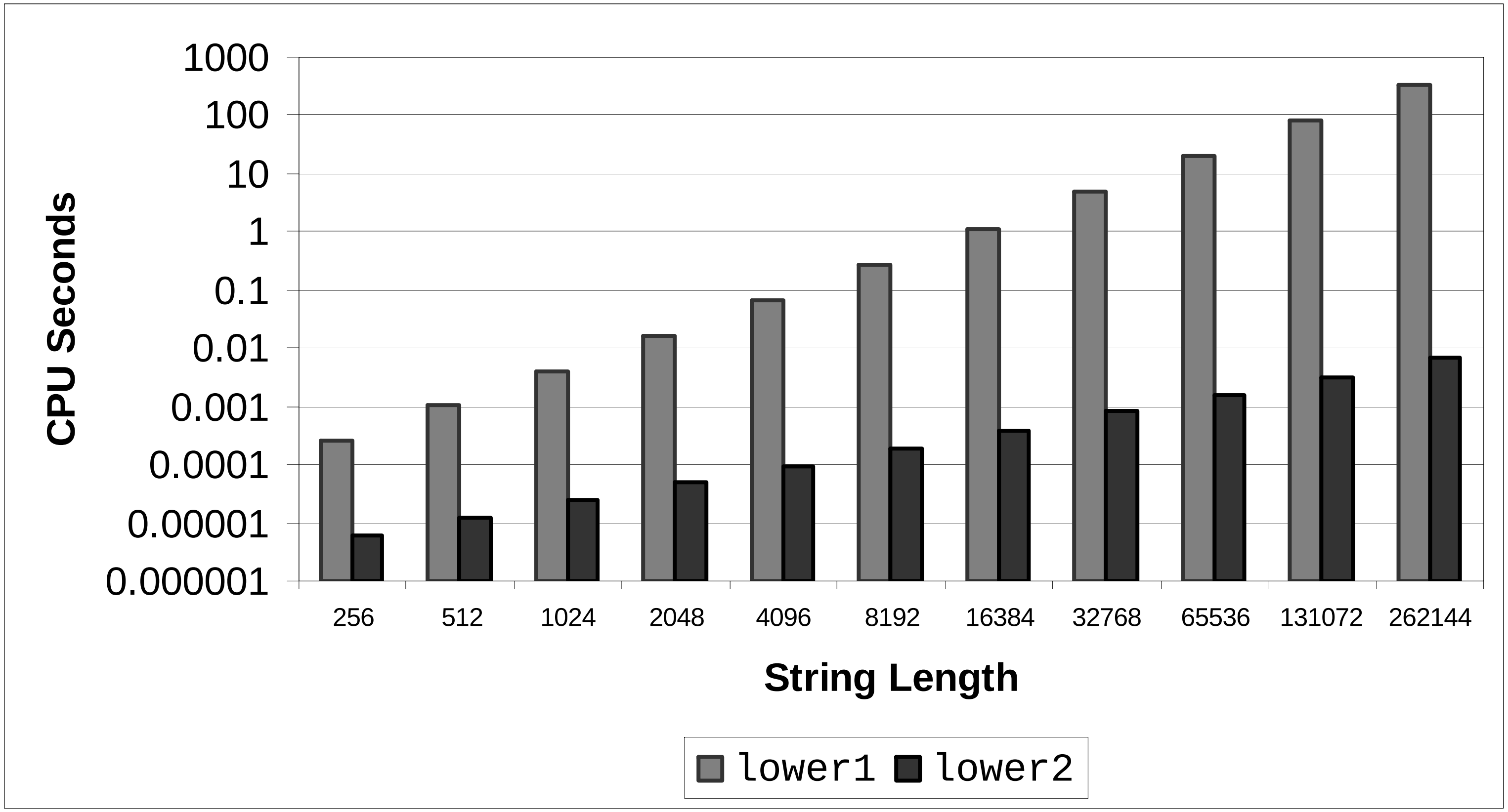
Improving Performance

```
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
    - 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

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 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
  - 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!

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
14,010	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
```

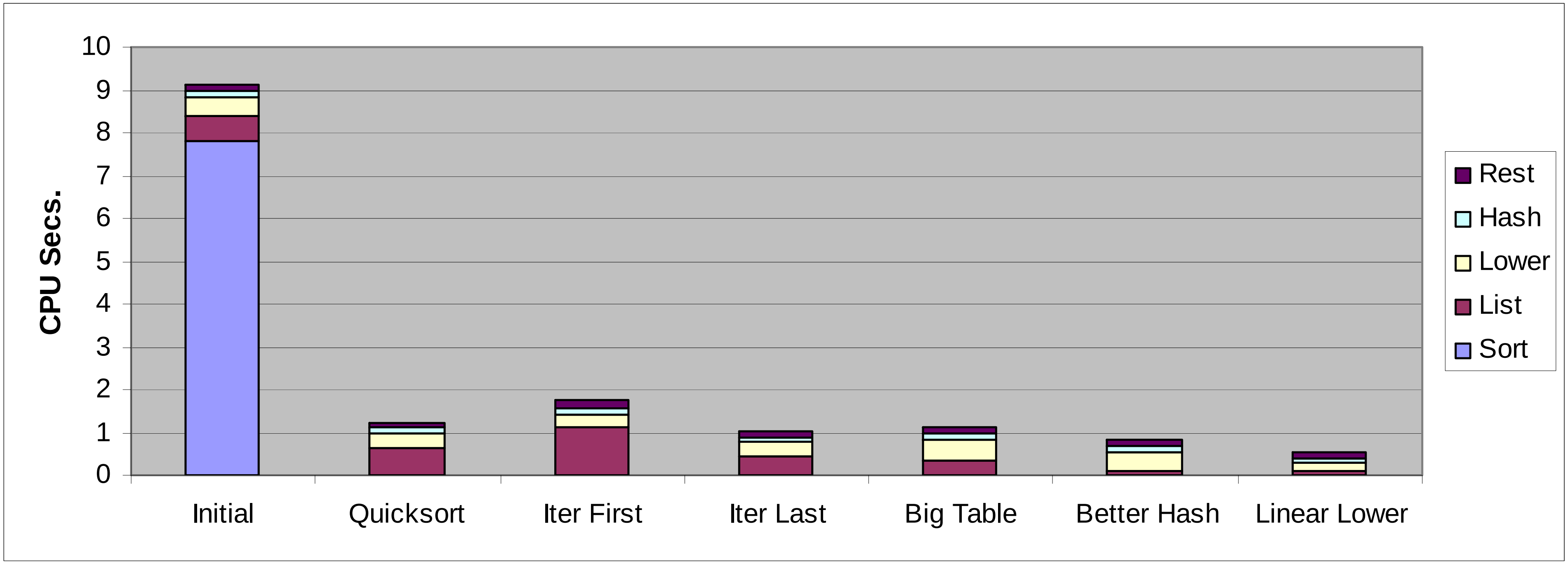
  - Generates profile information based on `gmon.out`

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

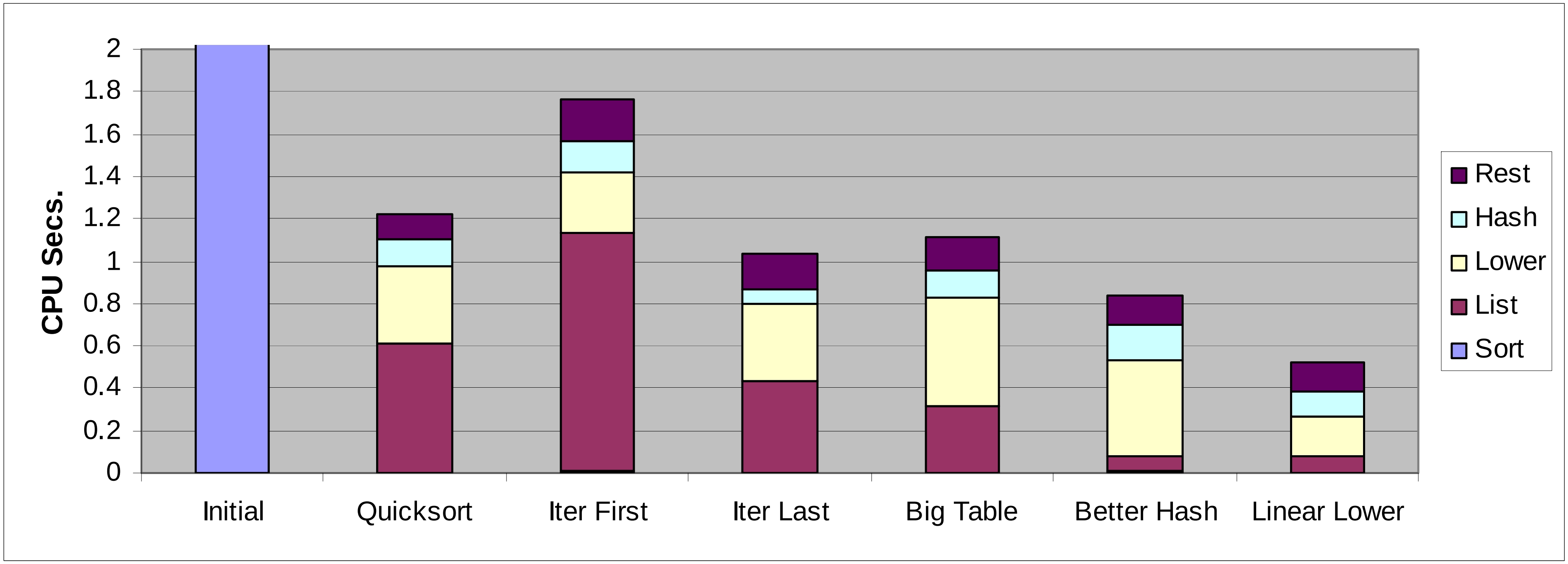
- Call Statistics
  - Number of calls and cumulative time for each function
- Performance Limiter
  - Using inefficient sorting algorithm
  - Single call uses 87% of CPU time

Code Optimizations



– First step: Use more efficient sorting function
– Library function `qsort`

Further Optimizations



- Iter first: Use iterative function to insert elements into 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