CSCI 2021: Program Performance
Micro-Optimizations

Chris Kauffman

Last Updated:
Thu 16 Apr 2020 08:36:05 PM CDT
Logistics

Reading Bryant/O’Hallaron
Ch 5: Optimization

Goals
- The Time to Optimize
- Micro-optimizations
- Review

Lab 12
Functions versus Macros

P4
1. Optimize Matrix Operation
2. Analyze perf of a search data structure

HW 11: Optims
- Micro-optimizations
- Memory Optimization

Upcoming Events

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<td>P4 Due</td>
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Caution: Should I Optimize?

- Optimizing program execution time usually costs human time
- Human time is valuable, don’t waste it
- Determine if there is a NEED to optimize
- **Benchmark** your code - if it is fast enough, move on
- If not fast enough, use a **profiler** to determine where your efforts are best spent
- **Never sacrifice correctness** for speed

First make it **work**, then make it **right**, then make it **fast**.

- Kent Beck

When in doubt, use brute force.

- Ken Thompson
What to Optimize First

In order of impact

1. Algorithms and Data Structure Selection
2. Elimination of unneeded work/hidden costs
3. Memory Utilization
4. Micro-optimizations

“Premature optimization is the root of all evil” - Donald Knuth

Programmers waste enormous amounts of time thinking about, or worrying about, the speed of noncritical parts of their programs, and these attempts at efficiency actually have a strong negative impact when debugging and maintenance are considered. We should forget about small efficiencies, say about 97% of the time: premature optimization is the root of all evil. Yet we should not pass up our opportunities in that critical 3%.

– Donald Knuth
Exercise: Optimize This

- Prema Turopt is tasked by her boss to optimize performance of function `get_min()`
- The current version of the function code looks like the code to the right.
- Prema immediately jumps to the code for `bubble_sort()` and alters the code to enable better processor pipelining.
- This leads to a 2.5% improvement in speed.

Suggest several alternatives that Prema should have explored
Answers: Optimize This

1. Don’t use bubblesort: $O(N^2)$. Use an $O(N \log N)$ sort like Quicksort, Heapsort, Mergesort.

2. Why sort at all? Determine the minimum element with the “get” loop.

3. What is the cost of get_element() and get_size()? Is there a more efficient iterator or array-extraction mechanism?

4. What data structure is used in storage_t? If it is already sorted such as a binary search tree or binary heap, there may be a more efficient way to determine the minimum element.

   ```c
   1 int get_min(storage_t *st){
   2     int *arr =
   3     malloc(sizeof(int)*get_size(st));
   4     for(int i=0; i<get_size(st); i++){
   5         arr[i] = get_element(st,i);
   6     }
   7     bubble_sort(arr, get_size(st));
   8     int ans = arr[0];
   9     free(arr);
  10     return ans;
  11 }
   ```

5. If get_min() is called frequently, cache the min by adding a field to storage_t and modifying other code around it; frequently used strategy such as in Java’s String class for hashCode() to get $O(1)$ lookup.
Exercise: Eliminating Unnecessary Work

void lower1(char *s) {
    for (long i=0; i < strlen(s); i++){
        if (s[i] >= 'A' && s[i] <= 'Z'){
            s[i] -= ('A' - 'a');
        }
    }
}

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

▶ Bryant/O’Hallaron Figure 5.7
▶ Two versions of a lower-casing function
▶ Lowercase by subtracting off constant for uppercase characters: alters ASCII code
▶ Examine them to determine differences
▶ Project speed differences and why one will be faster
Answers: Eliminating Unnecessary Work

- `strlen()` is $O(N)$: searches for \0 character in for() loop
- Don’t loop with it if possible

```c
void lower1(char *s) {
    for (long i=0; i < strlen(s); i++){
        if (s[i] >= 'A' && s[i] <= 'Z'){
            s[i] -= ('A' - 'a');
        }
    }
}

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

long strlen(char *s) {
    long len = 0;
    while(s[len] != '\0'){
        len++;
    }
    return len;
}
```

![Graph comparing CPU time vs. string length for `lower1` and `lower2` functions](image_url)
Exercise: Do Memory References Matter?

void sum_range1(int start,
    int stop,
    int *ans)
{
    *ans = 0;
    for(int i=start; i<stop; i++){
        *ans += i;
    }
}

void sum_range2(int start,
    int stop,
    int *ans)
{
    int sum = 0;
    for(int i=start; i<stop; i++){
        sum += i;
    }
    *ans = sum;
}

► What is the primary difference between the two routines above?
► What effect if any will this have on runtime?
Answers: Do Memory References Matter?

```c
void sum_range1(int start, int stop, int *ans)
{
    *ans = 0;
    for(int i=start; i<stop; i++){
        *ans += i;
    }
}

sum_range1() makes repeated memory references
```

```c
void sum_range2(int start, int stop, int *ans)
{
    int sum = 0;
    for(int i=start; i<stop; i++){
        sum += i;
    }
    *ans = sum;
}

sum_range2() uses a local variable with only a couple memory references
```

- Must determine if memory references matter for performance
- Guesses?
Memory References Matter, Compiler May Change Them

lila> gcc -Og sum_range.c  # No opt
lila> ./a.out 0 1000000000
sum_range1: 1.9126e+00 secs
sum_range2: 2.6942e-01 secs

▶ Minimal optimizations
▶ Memory reference definitely matters

lila> gcc -O1 sum_range.c  # Opt plz
lila> ./a.out 0 1000000000
sum_range1: 2.8972e-01 secs
sum_range2: 2.7569e-01 secs

▶ Observe code differences between -Og and -O1
▶ Why is performance improved so much?

### Compiled with -Og: minimal opt

sum_range1:
```assembly
    movl $0, (%rdx)  # write to memory
    jmp .LOOTOP
.BODY:
    addl  %edi, (%rdx)  # memory write
    addl  $1, %edi      # in loop
.LOOPTOP:
    cmpl  %esi, %edi
    jl    .BODY
    ret
```

### Compiled with -O1: some opt

sum_range1:
```assembly
    movl $0, (%rdx)  # mem write
    cmpl  %esi, %edi
    jge    .END
    movl  $0, %eax   # 0 to reg
    .LOOP:
    addl  %edi, %eax  # add to reg
    addl  $1, %edi    # no mem ref
    cmpl  %edi, %esi
    jne   .LOOP
    movl  %eax, (%rdx)  # write at end
.END:
    ret
```
Dash-O! Compiler Optimizes for You

▶ gcc like, many compilers, can perform some memory and micro-optimizations for you

▶ Series of -Ox options to enable different techniques

▶ We will use -Og at times to disable many optimizations
  
  ▶ -Og: Optimize debugging. ... optimization level of choice for the standard edit-compile-debug cycle

▶ Individual optimizations can be enabled and disabled

▶ -O or -O1: Optimize. Optimizing compilation takes somewhat more time, and a lot more memory for a large function. With -O, the compiler tries to reduce code size and execution time, without performing any optimizations that take a great deal of compilation time.

▶ -O2: Optimize even more. GCC performs nearly all supported optimizations that do not involve a space-speed tradeoff. As compared to -O, this option increases both compilation time and the performance of the generated code.

▶ -O3: Optimize yet more. -O3 turns on all optimizations specified by -O2 and also...

▶ -Ofast: Disregard strict standards compliance. (!)
Compiler Optimizations

-0 turns on the following optimization flags:

- auto-inc-dec -fbranch-count-reg -fcombine-stack-adjustments
  --fcompare-elim fcprop-registers -fdce -fdefer-pop -fdelayed-branch
  --fdse -ffoward-propagate fguess-branch-probability -fif-conversion2
  --fif-conversion finline-functions-called-once -fipa-pure-const
  --fipa-profile -fipa-reference fmerge-constants -fmove-loop-invariants
  --freorder-blocks -fshrink-wrap fshrink-wrap-separate
  --fsplit-wide-types -fssa-backprop -fssa-phiopt -ftree-bit-ccp
  -ftree-ccp -ftree-ch -ftree-coalesce-vars -ftree-copy-prop -ftree-dce
  -ftree-dominator-opts -ftree-dse -ftree-forwprop -ftree-fre
  --ftree-phiprop -ftree-sink ftree-slsr -ftree-sra -ftree-pta
  --ftree-ter -funit-at-a-time

▶ Some combination of these enables sum_range2() to fly as
fast as sum_range1()

▶ We will look at some “by-hand” versions of these
optimizations but whenever possible, let the compiler do it
Exercise: Quick Review

1. What’s the first thing to consider when optimization seems necessary?
2. What kinds of optimizations would have the biggest impact on performance?
3. What is the smartest way to “implement” micro-optimizations, to get their benefit with minimal effort?
Answers: Quick review

1. What’s the first thing to consider when optimization seems necessary?
   A: Is optimization **really** necessary? Or is there something else that would be more worth the effort (e.g. fixing bugs, adding features, improving documentation, etc.)

2. What kinds of optimizations would have the biggest impact on performance?
   A: From most to least important
   - Algorithms and Data Structure Selection
   - Elimination of unneeded work/hidden costs
   - Memory Utilization
   - Micro-optimizations (today’s lecture)

3. What is the smartest way to “implement” micro-optimizations, to get their benefit with minimal effort?
   A: Use the compiler to mechanically perform code transforms to achieve micro-optimizations. Using -O2 will produce faster-running code because the compiler is transforming generated assembly instructions from C sources.
Consider the following Java code

```java
public classStringUtils{
    public static String repString(String str, int reps) {
        String result = "";
        for(int i=0; i<reps; i++){
            result = result + str;
        }
        return result;
    }
}
```

▸ Give a Big-O estimate for the runtime
▸ Give a Big-O estimate for the memory overhead
Strings are immutable in Java (Python, many others)

Each iteration must
- allocate new memory for a new string sized result.length + str.length
- Copy result to the first part
- Copy str to the second part

Leads to $O(N^2)$ complexity

Much worse memory usage: as much as $O(N^2)$ wasted memory for garbage collector to clean up

```java
public class StringUtils{
    public static String repString(String str, int reps)
    {
        String result = "";
        for(int i=0; i<reps; i++){
            result = result + str;
        }
        return result;
    }

    // Efficient version
    public static String repString2(String str, int reps)
    {
        StringBuilder result = new StringBuilder();
        for(int i=0; i<reps; i++){
            result.append(str);
        }
        return result.toString();
    }
}
```
Exercise: Loop Unrolling

➢ Have seen copying loop iterations manually may lead to speed gains

➢ Why? Which of the following unrolled versions of sum_rangeX() seems fastest?

➢ Why the second loop in sum_rangeB() and sum_rangeC()?

```c
void sum_rangeA(long stop, long *ans){
    long sum=0, i;
    for(i=0; i<stop; i++){
        sum += i+0;
    }
    *ans = sum;
}

void sum_rangeB(long stop, long *ans){
    long sum = 0, i;
    for(i=0; i<stop-3; i+=3){
        sum += (i+0);
        sum += (i+1);
        sum += (i+2);
    }
    for(; i<stop; i++){
        sum += i;
    }
    *ans = sum;
}

void sum_rangeC(long stop, long *ans){
    long sum0=0, sum1=0, sum2=0, i;
    for(i=0; i<stop-3; i+=3){
        sum0 += (i+0);
        sum1 += (i+1);
        sum2 += (i+2);
    }
    for(; i<stop; i++){
        sum0 += i;
    }
    *ans = sum0 + sum1 + sum2;
}
```
Exercise: Loop Unrolling

Expectations

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<tr>
<th>Version</th>
<th>Notes</th>
<th>Performance</th>
</tr>
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<tbody>
<tr>
<td>sum_rangeA()</td>
<td>Not unrolled</td>
<td>Baseline</td>
</tr>
<tr>
<td>sum_rangeB()</td>
<td>Unroll x3, same destinations for sum</td>
<td>Less good</td>
</tr>
<tr>
<td>sum_rangeC()</td>
<td>Unroll x3, different destinations sum add</td>
<td>Expected Best</td>
</tr>
</tbody>
</table>

Actual Performance

apollo> gcc -Og unroll.c
apollo> ./a.out 1000000000
sum_rangeA: 1.0698e+00 secs
sum_rangeB: 6.2750e-01 secs
sum_rangeC: 6.2746e-01 secs

phaedrus> ./a.out 1000000000
sum_rangeA: 2.8913e-01 secs
sum_rangeB: 5.3285e-01 secs
sum_rangeC: 2.6774e-01 secs

Unrolling is Unpredictable

- Performance Gains vary from one compiler+processor to another
- All unrolling requires cleanup loops like those in the B/C versions: add on remaining elements
GCC Options to Unroll

- gcc has options to unroll loops during optimization
- Unrolling has unpredictable performance implications so unrolling is **not enabled** for -O1, -O2, -O3
- Can manually enable it with compiler options like -funroll-loops to check for performance bumps

```
apollo> gcc -Og unroll.c
apollo> ./a.out 1000000000
sum_rangeA: 1.0698e+00 secs
sum_rangeB: 6.2750e-01 secs
sum_rangeC: 6.2746e-01 secs

apollo> gcc -Og -funroll-loops unroll.c
apollo> ./a.out 1000000000
sum_rangeA: 7.0386e-01 secs  # loop unrolled by compiler
sum_rangeB: 6.2802e-01 secs
sum_rangeC: 6.2797e-01 secs

apollo> gcc -Og -funroll-loops -fvariable-expansion-in-unroller unroll.c
apollo> ./a.out 1000000000
sum_rangeA: 5.2711e-01 secs  # unroll + multiple intermediates used
sum_rangeB: 6.2759e-01 secs
sum_rangeC: 6.2750e-01 secs
```

apollo> gcc -O3 unroll.c
apollo> ./a.out 1000000000
sum_rangeA: 9.4124e-01 secs
sum_rangeB: 4.1833e-01 secs
sum_rangeC: 4.1832e-01 secs

apollo> gcc -O3 -funroll-loops unroll.c
apollo> ./a.out 1000000000
sum_rangeA: 5.2711e-01 secs  # unroll + multiple intermediates used
sum_rangeB: 6.2759e-01 secs
sum_rangeC: 6.2750e-01 secs
```
Do Conditionals Matter?

Consider two examples of adding even numbers in a range

```c
1 // CONDITION version
2 long sum_evensA(long start, long stop){
3     long sum=0;
4     for(int i=start; i<stop; i++){
5         if((i & 0x01) == 0){
6             sum += i;
7         }
8     }
9     return sum;
10 }
11 // STRAIGHT-LINE version
12 long sum_evensB(long start, long stop){
13     long sum=0;
14     for(int i=start; i<stop; i++){
15         int odd = i & 0x01;
16         int even_mask = odd - 1;
17         // 0x00000000 for odd
18         // 0xFFFFFFFF for even
19         sum += even_mask & i;
20     }
21     return sum;
22 }
```

Timings for these two are shown below at two levels of optimization.

```
lila> gcc -Og condloop.c
lila> a.out 0 400000000
sum_evensA: 1.1969e+00 secs
sum_evensB: 2.8953e-01 secs
# 4x speedup
lila> gcc -O3 condloop.c
lila> a.out 0 400000000
sum_evensA: 2.3662e-01 secs
sum_evensB: 9.6242e-02 secs
# 2x speedup
```

Message is simple: eliminate conditionals whenever possible to improve performance
Exercise: Row Sums with Function v Macro

- How is a macro different from a function call?
- Which of the below codes will run faster and why?

```c
int mget(matrix_t mat, int i, int j)
{
    return mat.data[i*mat.cols + j];
}

int vset(vector_t vec, int i, int x)
{
    return vec.data[i] = x;
}

void row_sumsA(matrix_t mat, vector_t sums)
{
    for(int i=0; i<mat.rows; i++){
        int sum = 0;
        for(int j=0; j<mat.cols; j++){
            sum += mget(mat,i,j);
        }
        vset(sums, i, sum);
    }
}

#define MGET(mat,i,j) ((mat).data[((i)*((mat).cols)) + (j)])

#define VSET(vec,i,x) ((vec).data[(i)] = (x))

void row_sumsB(matrix_t mat, vector_t sums)
{
    for(int i=0; i<mat.rows; i++){
        int sum = 0;
        for(int j=0; j<mat.cols; j++){
            sum += MGET(mat,i,j);
        }
        VSET(sums, i, sum);
    }
}
```
Answers: Row Sums with Function v Macro

- `row_sumsA()` uses standard function calls to retrieve elements
- `row_sumsB()` uses macros to do the element retrieval
- A macro is a textural expansion done by the **preprocessor**: insert the literal text associated with the macro
- See macro results with `gcc -E rowsums.c` which stops after preprocessor step (early)
- Function calls cost some operations but not many
- Function calls **prevent optimization across boundaries**
- Cannot pipeline effectively when jumping around, using registers for arguments, restoring registers, etc
- Macros can alleviate this but they are a **pain** to write and notoriously buggy
- Better to let the compiler do this for us
Inlining Functions/Procedures

- **Function Inlining** inserts the body of a function where it would have been called.
- Turned on fully partially at -O2 and fully at -O3.
- Enables other optimizations blocked by function boundaries.
- Can only be done if source code (C file) for function is available.
- Like loop unrolling, function inlining has trade-offs:
  - Enables pipelining
  - More predictable control
  - More register pressure
  - Increased code size

Example:

```bash
> FILES="rowsums.c matvec_util.c"
> gcc -Og $FILES
> ./a.out 8000 8000
row_sumsA: 1.3109e-01 secs
row_sumsB: 4.0536e-02 secs

> gcc -Og -finline-small-functions $FILES
> ./a.out 8000 8000
row_sumsA: 7.4349e-02 secs
row_sumsB: 4.2682e-02 secs

> gcc -O3 $FILES
> ./a.out 8000 8000
row_sumsA: 2.1974e-02 secs
row_sumsB: 2.0820e-02 secs
```

- Inlining typically most effective for small functions (getters/setters).
Profilers: gprof and Friends

- **Profiler**: a tool that monitors code execution to enable performance optimizations
- **gprof** is stock on Linux systems, interfaces with gcc
- Compile with profiling options: gcc -pg
- Run code to produce data file
- Examine with gprof
- **Note**: gcc version 6 and 7 contain a bug requiring use of -no-pie option, not a problem on apollo

```bash
# Compile
# -pg: instrument code for profiling
# -no-pie: bug fix for new-ish gcc's
> gcc -pg -no-pie -g -Og -o unroll unroll.c

> ls
unroll  unroll.c

> ./unroll 1000000000
sum_rangeA: 2.9401e-01 secs
sum_rangeB: 5.3164e-01 secs
sum_rangeC: 2.6574e-01 secs

# gmon.out now created with timing info
> ls
gmon.out  unroll  unroll.c

> file gmon.out
gmon.out: GNU prof performance data

> gprof -b unroll
... output on next slide ...
```
gprof output for unroll

> gprof -b unroll

Flat profile:
Each sample counts as 0.01 seconds.

<table>
<thead>
<tr>
<th>% cumulative</th>
<th>self seconds</th>
<th>self calls</th>
<th>ms/call</th>
<th>total ms/call</th>
<th>name</th>
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</thead>
<tbody>
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<td>time seconds</td>
<td>seconds</td>
<td>calls</td>
<td></td>
<td></td>
<td>ms/call</td>
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<td>282.11 sum_rangeA</td>
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<td>24.26</td>
<td>1.09</td>
<td>0.26</td>
<td>1</td>
<td>261.95</td>
<td>261.95 sum_rangeC</td>
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Call graph

<table>
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<th>index</th>
<th>% time</th>
<th>self seconds</th>
<th>children called name</th>
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<tbody>
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<td>0.00</td>
<td>1.09 main [1]</td>
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<td>0.00 1/1 sum_rangeB [2]</td>
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<td>0.00 1/1 sum_rangeC [4]</td>
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<td>[2]</td>
<td>50.0</td>
<td>0.54</td>
<td>0.00 1 main [1]</td>
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<td>[3]</td>
<td>25.9</td>
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<td>0.00 1 main [1]</td>
</tr>
<tr>
<td>[4]</td>
<td>24.1</td>
<td>0.26</td>
<td>0.00 1 main [1]</td>
</tr>
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26
> ./dictionary < craft-67.txt
... Total time = 0.829561 seconds
> gprof -b dictionary

<table>
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<tr>
<th>% cumulative</th>
<th>time</th>
<th>seconds</th>
<th>self</th>
<th>seconds</th>
<th>calls</th>
<th>ms/call</th>
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gprof Example Cont’d: Dictionary Application

> ./dictionary < craft-67.txt  ## After upgrading sort_words() to qsort()
... Total time = 0.624172 seconds
> gprof -b dictionary

% cumulative  self  total
  time  seconds  seconds  calls  ms/call  ms/call  name
     60.08    0.12    0.12  463016  0.00    0.00  find_ele_rec
     15.02    0.15    0.03  2862749 0.00    0.00    Strlen
     10.01    0.17    0.02  463016  0.00    0.00      lower1
      5.01    0.18    0.01  463017  0.00    0.00     get_token
      5.01    0.19    0.01  463016  0.00    0.00       h_mod
      5.01    0.20    0.01  20451  0.00    0.00    save_string
     0.00    0.20    0.00  463017  0.00    0.00     get_word
     0.00    0.20    0.00  463016  0.00    0.00  insert_string
     0.00    0.20    0.00  20451  0.00    0.00     new_ele
     0.00    0.20    0.00     8  0.00    0.00    match_length
     0.00    0.20    0.00     7  0.00    0.00    add_int_option
     0.00    0.20    0.00     1  0.00    0.00    add_string_option
     0.00    0.20    0.00     1  0.00    0.00     find_option
     0.00    0.20    0.00     1  0.00    0.00    init_token
     0.00    0.20    0.00     1  0.00    0.00    new_table
     0.00    0.20    0.00     1  0.00    0.00    parse_options
     0.00    0.20    0.00     1  0.00    0.00    show_options
     0.00    0.20    0.00     1  0.00    0.00    sort_words ** was 0.18 **
     0.00    0.20    0.00     1  0.00   200.28    word_freq