Princeton University

Computer Science 217: Introduction to Programming Systems



Performance Improvement

Background reading:
The Practice of Programming (Kernighan & Pike) Chapter 7

"Programming in the Large" Steps 👧



Design & Implement

- Program & programming style (done)
- · Common data structures and algorithms (done)
- Modularity (done)
- Building techniques & tools (done)

Debug

Debugging techniques & tools (done)

Test

Testing techniques (done)

Maintain

• Performance improvement techniques & tools <-- we are here

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Case study: 25 most common words



Find the 25 most common words in a text file, print their frequencies in decreasing order

No googling
for this trivia
question:

What work of
literature is
this?

Hint:
Project Gutenberg's

3654 and
2225 her
2070 i
2012 a
1937 in
1847 was
1710 she
1594 that
1547 it
1450 not
1427 you
1339 he
1271 his
1260 be
1192 as
1177 had
1098 with
1085 for
1007 but
885 is
847 have
800 at

\$ buzz < novel.txt

A program, "buzz.c"



/* Enter every word from stdin into a SymTable, bound to its # of occurrences */ void readInput (SymTable_T table);

/* Make an array of (word, #occ), from the contents of the SymTable */ struct counts *extractCounts(SymTable_T table);

/* Sort the "counts" array in descending order, and print the first 25 entries */ void analyzeData(struct counts *p);

/* The main program */
int main(void) {
 SymTable_T table = SymTable_new();
 readInput(table);
 analyzeData(extractCounts(table));
 return 0;
}

Reading the input

#1-downloaded book



```
enum {MAX LEN = 1000};
                                               /* Enter every word from stdin into a
                                              SymTable, bound to its # of occurrences */
int readWord(char *buffer, int buflen) {
                                              void readInput (SymTable_T table) {
 int c;
 /* Skip nonalphabetic characters */
                                               char word[MAX LEN+1];
 do {
                                               while (readWord(word, MAX_LEN+1)) {
  c = getchar();
                                                int *p = (int*)SymTable_get(
  if (c==EOF) return 0;
                                                                        table, word);
                                                if (p == NULL) {
 } while (!isalpha(c));
 buffer[0]='\0';
                                                   p = (int*)malloc(sizeof(int));
   * Process alphabetic characters */
 while (isalpha(c)) {
                                                   SymTable_put(table, word, p);
  if (strlen(buffer)<br/><br/>buflen-1) {
    buffer[strlen(buffer)+1]='\0';
    buffer[strlen(buffer)]=tolower(c);
  c=getchar();
 buffer[strlen(buffer)]='\0';
 return 1;
```

Extracting the counts



```
struct word_and_count {
                                                void handleBinding(
 const char *word;
                                                   const char *key.
                                                void *value, void *extra) {
struct counts *c = (struct counts *) extra;
 int count;
                                                assert (c->filled < c->max);
struct counts {
int filled;
                                                c->array[c->filled].word = key;
                                                c->array[c->filled].count = *((int*)value);
 int max;
 struct word_and_count *array;
                                                c->filled += 1;
struct counts *makeCounts(int max) {
                                               /* Make an array of (word, #occ), from
 struct counts *p =
                                                 the contents of the SymTable */
     (struct counts *) malloc (sizeof (*p));
                                               struct\ counts\ *extractCounts(
                                                                  SymTable\_T\ table)\ \{
 assert(p);
                                                  struct counts *p = makeCounts(
 p->filled=0;
                                                            SymTable_getLength(table));
 p->max=max;
 p->array = (struct word and count *)
                                                  SymTable_map(table,
  malloc (max * sizeof (struct word and count));
                                                               handleBinding,
                                                               (void*)p);
 assert (p->array);
 return p;
                                                  return p;
```

Sorting and printing the counts



```
/* Sort the "counts" array in descending
void swap (struct word_and_count *a,
                                               order, and print the first 25 entries *.
           struct word_and_count *b) {
 struct word and count t;
                                               void analyzeData(struct counts *p) {
t=*a; *a=*b; *b=t;
                                                  int i, n;
                                                  assert (p->filled == p->max);
                                                  sortCounts(p);
void sortCounts (struct counts *counts) {
                                                  n = 25  max ? 25 : p > max;
  * insertion sort */
                                                  for (i=0; i<n; i++)
                                                   printf("%10d %s\n",
int \ n = counts \text{-} \\ \text{sfilled};
                                                         p->array[i].count,
 struct word\_and\_count *a = counts->array;
                                                         p->array[i].word);
 for (i=1; i<n; i++) {
      j>0 && a[j-1].count<a[j].count;
   swap(a+j,\;a+j-1);
```

Timing a Program



Run a tool to time program execution

• E.g., Unix time command

```
$ time ./buzz < corpus.txt > output.txt
3.58user 0.00system 0:03.59elapsed 99%CPU
```

Output:

- Real (or "elapsed"): Wall-clock time between program invocation and termination
- User: CPU time spent executing the program
- System: CPU time spent within the OS on the program's behalf

In summary: takes 3.58 seconds to process 703,549 characters of input. That's really slow!

(especially if we want to process a whole library of books)

Q

What should you do?



The COS 226 answer:

Use asymptotically efficient algorithms and data structures everywhere.

WRONG!

(and, to be fair, that was a caricature of the COS 226 answer)

What should you do?



Caricature of the COS 226 answer:

Use asymptotically efficient algorithms and data structures everywhere.

Most parts of your program won't run on "big data!" Simplicity, maintainability, correctness, easy algorithms and data structures are most important.

Words of the sages



"Optimization hinders evolution."

- -- Alan Perlis
- "Premature optimization is the root of all evil."
- -- Donald Knuth

"Rules of Optimization:

- Rule 1: Don't do it.
- Rule 2 (for experts only): Don't do it yet."
- -- Michael A. Jackson*

*The MIT professor, not the pop singer.

When to Improve Performance



"The first principle of optimization is



Is the program good enough already? Knowing how a program will be used and the environment it runs in, is there any benefit to making it faster?"

-- Kernighan & Pike

When to Improve Performance



"The first principle of optimization is

The only reason we're even allowed to be here (as good software engineers) is because we did the performance measurement (700k characters in 3.58 seconds) and found it unacceptable.

is there any benefit to making it faster?"

-- Kernighan & Pike

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Goals of this Lecture



Help you learn about:

- Techniques for improving program performance
 - How to make your programs run faster and/or use less memory
- The oprofile execution profiler

Why?

- In a large program, typically a small fragment of the code consumes most of the CPU time and/or memory
- · A good software engineer knows how to identify such fragments,
- · and knows how to improving their performance

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Performance Improvement Pros



Techniques described in this lecture can yield answers to questions such as:

- · How slow is my program?
- · Where is my program slow?
- Why is my program slow?
- · How can I make my program run faster?
- How can I make my program use less memory?

Timing Parts of a Program



Call a function to compute wall-clock time consumed

• E.g., Unix gettimeofday() function (time since Jan 1, 1970)

```
#include <sys/time.h>
struct timeval startTime;
struct timeval endTime;
double wallClockSecondsConsumed;

gettimeofday(&startTime, NULL);
<execute some code here>
gettimeofday(&endTime, NULL);
wallClockSecondsConsumed =
   endTime.tv_sec - startTime.tv_sec +
   1.0E-6 * (endTime.tv_usec - startTime.tv_usec);
```

1.

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Timing Parts of a Program (cont.)



Call a function to compute CPU time consumed

• E.g. clock() function

```
#include <time.h>
clock_t startClock;
clock_t endClock;
double cpuSecondsConsumed;

startClock = clock();
<execute some code here>
endClock = clock();
cpuSecondsConsumed =
   ((double)(endClock - startClock)) / CLOCKS_PER_SEC;
```

Identifying Hot Spots



Gather statistics about your program's execution

- · How much time did execution of a particular function take?
- · How many times was a particular function called?
- How many times was a particular line of code executed?
- · Which lines of code used the most time?
- Etc

How? Use an execution profiler

- Example: gprof (GNU Performance Profiler)
- Reports how many seconds spent in each of your programs' functions, to the nearest millisecond.

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Identifying Hot Spots



Gather statistics

Milliseconds? Really? How much

- My whole program runs in a How mar
- How ma
- couple of milliseconds!
- What century do you think Which line
- we're in? · Etc.

How? Use an execution pro

- Profiler) Example: gprof (GNU Perform)
- Reports how many seconds spen in each of your programs' functions, to the nearest millisecond.

The 1980s just called, they want their profiler back . . .





For some reason, between 1982 and 2016 while computers got 1000x faster, nobody thought to tweak **gprof** to make it report to the nearest microsecond instead of millisecond.

The 1980s just called, they want their profiler back . . .



So we will use **oprofile**, a 21st-century profiling tool. But **gprof** is still available and convenient: what I show here (with **oprofile**) can be done with **gprof**.

Read the man pages:

\$ man gprof \$ man oprofile

Using oprofile



Step 1: Compile the program with –g and –O2

gcc -g -O2 -c buzz.c; gcc buzz.o symtablelist.o -o buzz1

-g adds "symbol table" to buzz.o (and the eventual executable)

-O2 says "compile with optimizations." If you're worried enough about performance to want to profile, then measure the compiled-for-speed version of the program.

Step 2: Run the program

operf ./buzz1 < corpus.txt >output

· Creates subdirectory oprofile_data containing statistics

Step 3: Create a report

opreport -1 -t 1 > myreport

• Uses oprofile_data and buzz's symbol table to create textual report

Step 4: Examine the report

cat myreport

The oprofile report time spent in

any line whose % is less than 1

% of execution



			this	function		
samples	%	image	app name	symbol name		
20871	75.8807	150c-2.17.so	buzz1	strcmp_sse42		
5732	20.8398	buzz1	buzz1	SymTable_get	Name	of
257	0.9344	buzz1	buzz1	SymTable_put	the fund	etio
256	0.9307	buzz1	buzz1	ortCounts	the fund	LIO.
105	0.3817	buzz1	buzz1	read		
92	0.3345	no-vmlinux	buzz1	/no-vmli		
75	0.2727	libc-2.17.so	buzz1	fgetc	She	11
73	0.2654	libc-2.17.so	buzz1	strlen_sse2_pmi		
	0.0364	buzz1	buzz1	readInput	comm	anc
Name of	0.0327	libc-2.17.so	buzz1	ctype_tolower_l	that rar	ı th
	2001	libc-2.17.so	buzz1	_int_malloc	that run	
he binary		libc-2.17.so	buzz1	ctype_b_loc		_
xecutable	0.0109	libc-2.17.so	buzz1	malloc		
Accutable	0.0073	libc-2.17.so	buzz1	strcpy_sse2_una	ligned	
1	0.0036	buzz1	buzz1	SymTable_map		
1	0.0036	ld-2.17.so	time	bsearch		
1	0.0036	libc-2.17.so	buzz1	malloc_consolidate	е	
1	0.0036	libc-2.17.so	buzz1	strcpy		
1	0.0036	libc-2.17.so	time	write_nocancel		

What do we learn from this?



samples	%	image name	app name	symbol name
20871	75.8807	libc-2.17.so	buzz1	strcmp_sse42
5732	20.8398	buzz1	buzz1	SymTable_get
257	0.934	buzz1	buzz1	SymTable_put
256	0.9307	buzz1	buzz1	sortCounts
105	0.3817	vz1	buzz1	readWord
92	0.3345	n linux	buzz1	/no-vmlinux
75	0.2727	lil 17.so	buzz1	fgetc
73	0.2654	libo	zz1	strlen_sse2_pminub
10	0.0364	by cov		readInput
9	0.0327	796% of execu	ition time	ctype_tolower_loc
8	0.0291	is in stremp() and in	_int_malloc
3	0.0109	SymTable	ant()	ctype_b_loc
3	0.0109	11 Symmatic	_gen()	malloc
2	0.0073	libc-2	_ouzz1	strcpy_sse2_unaligned
1	0.0036	buzz1	buzz1	SymTable_map
1	0.0036	ld-2.17.so	time	bsearch
1	0.0036	libc-2.17.so	buzz1	malloc_consolidate
1	0.0036	libc-2.17.so	buzz1	strcpy
1	0.0036	libc-2.17.so	time	write_nocancel

Who is calling strcmp? Nothing in buzz.c... It's the symtablelist.c implementation of SymTable get . . .

Use better algorithms and data structures



Improve the "buzz" program by using symtablehash.c instead of symtablelist.c

```
gcc -g -O2 -c buzz.c; gcc buzz.o symtablelist.o -o buzz1
gcc -g -02 -c buzz.c; gcc buzz.o symtablehash.o -o buzz2
```

Result: execution time decreases from

3.58 seconds to 0.06 seconds

The use of insertion sort instead of quicksort doesn't actually seem to be a problem! That's what we learned from doing the oprofile. This is engineering, not just hacking.

What if 0.06 seconds isn't fast enough?



```
operf ./buzz2 < corpus.txt >output
opreport -1 -t 1 > myreport
```

samples	%	image name	app name	symbol name
221	39.6057	buzz2	buzz2	sortCounts
66	11.8280	buzz2	buzz2	SymTable_get
66	11.8280	libc-2.17.so	buzz2	strlen_sse2_pminub
50	8.9606	buzz2	buzz2	SymTable_hash
45	8.0645	libc-2.17.so	buzz2	fgetc
37	6.6308	buzz2	buzz2	readWord
20	3.5842	libc-2.17.so	buzz2	strcmp_sse42
20	3.5842	no-vmlinux	buzz2	/no-vmlinux

40% of execution time in sortCounts. Let's make it faster.

Line-by-line view in oprofile



```
operf ./buzz2 <corpus.txt >output2
opannotate -s > annotated-source2
```

```
The file annotated-source2:
              :/*---- Sort the counts --
              :void swap (struct word and count *a
               struct word_and_count *b) {

struct word_and_count t;

t=*a; *a=*b; *b=t;
87 21.42
               :void sortCounts (struct counts *counts) {
                /* insertion sort */
                int i,j;
int n = counts->filled;
                struct word_and_count *a = counts->array;
               for (i=1; i<n; i++)
                 for (j=i; j>0 && a[j-1].count<a[j].count; j--)
 81 19.95
                              source lines
```

Insertion Sort

Quicksort



```
void swap (struct word_and_count *a,
         struct word_and_count *b) {
struct word_and_count t;
t=*a; *a=*b; *b=t;
```

```
void sortCounts (struct counts *counts) {
 /* insertion sort */
 int n = counts - silled;
 struct word_and_count *a = counts->array;
 for (i=1; i< n; i++) {
  for (i=i;
      j>0 && a[j-1].count<a[j].count;
```

swap(a+j, a+j-1);

Use the **qsort** function from the standard library (covered in precept last week)

```
int compare count(
       const void *p, const void *q) {
 ((struct word_and_count *)q)->count
 - ((struct word_and_count *)p)->count;
void sortCounts (struct counts *counts) {
 qsort(counts->array,
       counts->filled.
       sizeof(struct word_and_count),
       compare_count);
```

Use quicksort instead of insertion sort



Result: execution time decreases from

0.06 seconds to 0.04 seconds

We could have predicted this! If 40% of the time was in the sort function, and we practically eliminate all of that, then it'll be 40% faster.

Is that fast enough? Well, yes.

But just for fun, let's run the profiler again.

What if 0.04 seconds isn't fast enough?



samples	%	image name	app name	symbol name
73	27.3408	libc-2.17.so	buzz3	strlen_sse2_pminub
48	17.9775	buzz3	buzz3	readWord
36	13.4831	buzz3	buzz3	SymTable_hash
33	12.3596	libc-2.17.so	buzz3	fgetc
27	10.1124	buzz3	buzz3	SymTable_get
15	5.6180	no-vmlinux	buzz3	/no-vmlinux
11	4.1199	libc-2.17.so	buzz3	strcmp_sse42
4	1.4981	libc-2.17.so	buzz3	_int_malloc
3	1.1236	libc-2.17.so	buzz3	msort_with_t

27% of execution time in strlen(). Who's calling strlen()?

Reading the input



```
enum {MAX_LEN = 1000};
int readWord(char *buffer, int buflen) {
  int c;
    /* Skip nonalphabetic characters */
  do {
    c = getchar();
    if (c==EOF) return 0;
} while (lisalpha(c));
buffer[0]='\0';
    /* Process alphabetic ch
    while (isalpha(c));
    buffer[strlen(buffer)+1]='\0'
    buffer[strlen(buffer)]=tc-cr(c);
}
c=getchar();
}
buffer[strlen(buffer)]='\0';
return 1;
}
```

This is just silly. We could keep track of the length of the buffer in an integer variable, instead of recomputing each time.

How much faster would the program become?

27% faster: from 0.04 sec to 0.03 sec.

Is it worth it? Perhaps, especially if the program doesn't become harder to read and maintain.

Enabling Speed Optimization



Enable compiler speed optimization

gcc217 -Ox mysort.c -o mysort

- · Compiler spends more time compiling your code so...
- · Your code spends less time executing
- x can be:
 - 0: don't optimize
 - 1: optimize (this is the default)
 - 2: optimize more
 - 3: optimize across .c files
- See "man gcc" for details

Beware: Speed optimization can affect debugging

e.g. Optimization eliminates variable ⇒ GDB cannot print value of variable

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Agenda



Execution (time) efficiency

- · Do timing studies
- · Identify hot spots
- Use a better algorithm or data structure
- · Enable compiler speed optimization
- Tune the code

Memory (space) efficiency

Agenda



Execution (time) efficiency

- Do timing studies
- Identify hot spots
- Use a better algorithm or data structure
- Enable compiler speed optimization
- · Tune the code

Warning! Much of what I'm about to show you will be done automatically by the C compiler: gcc –O3 so you usually shouldn't do it yourself!

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Avoiding Repeated Computation



Avoid repeated computation

Before: $\begin{cases} int g(int x) \\ {return f(x) + f(x) + f(x) + f(x);} \end{cases}$

After:

```
int g(int x)
{    return 4 * f(x);
}
```

Could a good compiler do that for you?

Aside: Side Effects as Blockers



```
int g(int x)
{ return f(x) + f(x) + f(x) + f(x);
}
int g(int x)
{ return 4 * f(x);
}
```

Q: Could a good compiler do that for you?

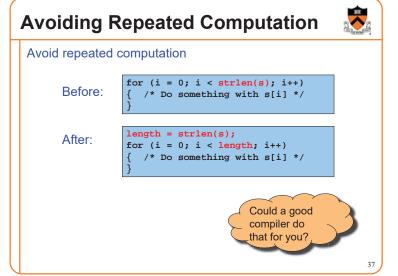
A: Probably not

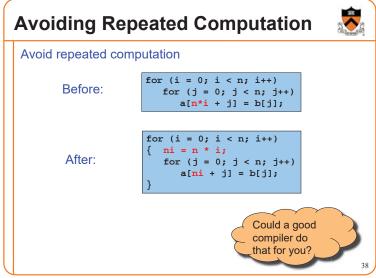
Suppose f() has side effects?

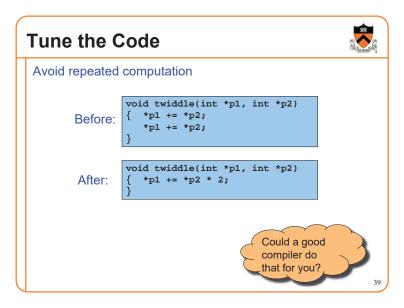
```
int counter = 0;
...
int f(int x)
{ return counter++;
}
```

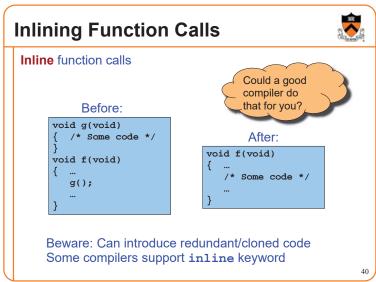
And £() might be defined in another file known only at link time!

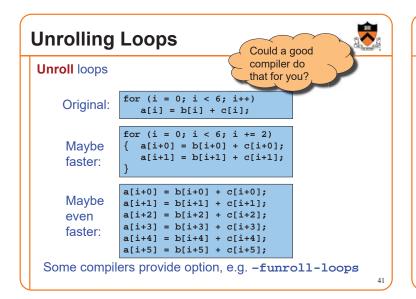
36

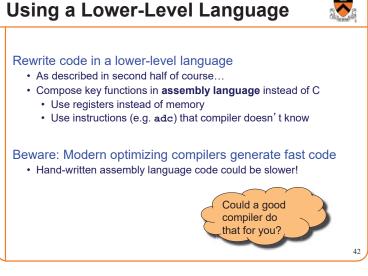












Clarity supersedes performance



Don't improve performance unless you must!!!

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