Performance Bugs

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Outline

- Two Performance Bugs
  - A bug report
  - A one-line error
- Perspective on Performance Bugs
- Tales
- Lessons

A Subtheme: Software Consulting

Economics 1.01: Buying in Bulk

Unit Cost

- Gasoline is $3.09/gallon

Economy of Scale

- Buy 12, get 1 free (baker's dozen)
- Fast food soft drink: 20 oz: $1.59; 32 oz: $1.69; 44 oz: $1.79

Diseconomy of Scale

- Price of lobster
  - The bigger the lobster, the greater the price per pound
  - 1–1¼: $8.95/lb; 2–3: $12.50/lb
- Bill Engvall's "I'm Stupid" signs: $1 each or 2 for $5
- US income taxes
  - The more you make, the higher the tax rate
- Search area as a function of time

1. A Great Bug Report

We [Wilks & Becker] found that `qsort` is unbearably slow on "organ-pipe" inputs like "0123443210":

```
main(int argc, char **argv)
{   int n=atoi(argv[1]), i, x[100000];
    for (i = 0; i < n; i++)
        x[i] = i;
    for ( ; i < 2*n ; i++)
        x[i] = 2*n-i-1;
    qsort(x, 2*n, sizeof(int), intcmp);
}
```

(Continued …)

1. Wilks and Becker, Cont.

Here are the timings:

```
$ time a.out 2000
real    5.85s
$ time a.out 4000
real    21.65s
$ time a.out 8000
real    85.11s
```

This is clearly quadratic behavior – each time we double the input size, the run time goes up by a factor of four.

A simple experiment establishes that a sort that should be O(*n* log *n*) is in fact quadratic

1. The Big Picture

- **Stages of Debugging**
  - **Original user thought that S had broken**
    - **His program "just stopped running"**
    - **(It would have finished in about a week)**
  - **Maintainers (Wilks & Becker) hunted down the real issue**
    - **Which piece is broken? The sort**
    - **Essential nature of input? "organ-pipe": /**
  - **A bug report**
- **Next Step: Fix the sort**

A Delicate Discussion

Petroski, *To Engineer is Human*, 1985, p. vii

> **"The lessons learned from those disasters can do more to advance engineering knowledge than all the successful machines and structures in the world."**

On the Pedigree of Bugs

- **I have worked as a programmer for over 40 years**
  - **Xerox PARC, SLAC, CMU, IBM, Bell Labs, AT&T, Avaya, …**
- **"The Bug with a Thousand Faces"**
  - **Everyone makes mistakes**
  - **Excellent organizations learn from them**
- **When the fault is mine, I'll take the blame**

2. Some Familiar Code

A Common Schema

```
count = 0;
// … much later, and iterated …
if (++count > 100) {
    // expensive operation
    count = 0;
}
```

Potential Performance Problems?

- What possible minor coding mistakes could be made?
- What impact would they have?

2. Three Potential Performance Problems

Missing Initialization

```
count = 0; …
if (++count > 100) {
    // expensive
    count = 0;
}
```

Impact? *n*/100 →

Initially positive: little change

Initially -∞: 0

Missing Increment

```
count = 0; …
if (++count > 100) {
    // expensive
    count = 0;
}
```

0

Missing Reset

```
count = 0; …
if (++count > 100) {
    // expensive
    count = 0;
}
```

n–100

2. A Big System

E-mail to a Performance Team

I have found what I think is a bug. Search for the variable LocalQCnt and you'll find three references:

```
dup.p nspace.c <global>    85 int LocalQCnt = 0;
dup.p queue.c  <global>    17 extern int LocalQCnt;
dup.p queue.c  nd_lcl_q   173 if ((LocalQCnt++) > 200)
```

It is initialized to zero, incremented in nd_lcl_q, but *never reset*. After the 200th page fault, the test in nd_lcl_q is thereafter *always true*. This means that every time we need a new buffer, we *always flush* the queue.

Performance Impact

$N / 200 \rightarrow N - 200$

Doubles or triples page faults

Increases CPU utilization by about 50%

A Performance Bug

is a minor glitch

(such as an atypical input[1] or one missing source line[2])

that does not alter the correctness of a program

(so it is not revealed by functional testing[1,2])

but does cause the program to consume excessive resources

(such as CPU time[1,2] or page faults[2])

Dimensions of Performance Bugs

- **What Effect Do They Have?**
  - Accretive – death by a thousand paper cuts[2]
  - Catastrophic – sudden and obvious[1]
- **How Are They Discovered?**
  - In the field, after they bite[1]
  - By perusing code[2], before or after they bite
- **What Causes Them?**
  - Unforeseen cases[1]
  - Little coding boo-boos[2]
- **How Are They Conclusively Identified?**
  - Tiny, well-structured experiments[1]
  - Analysis[2]

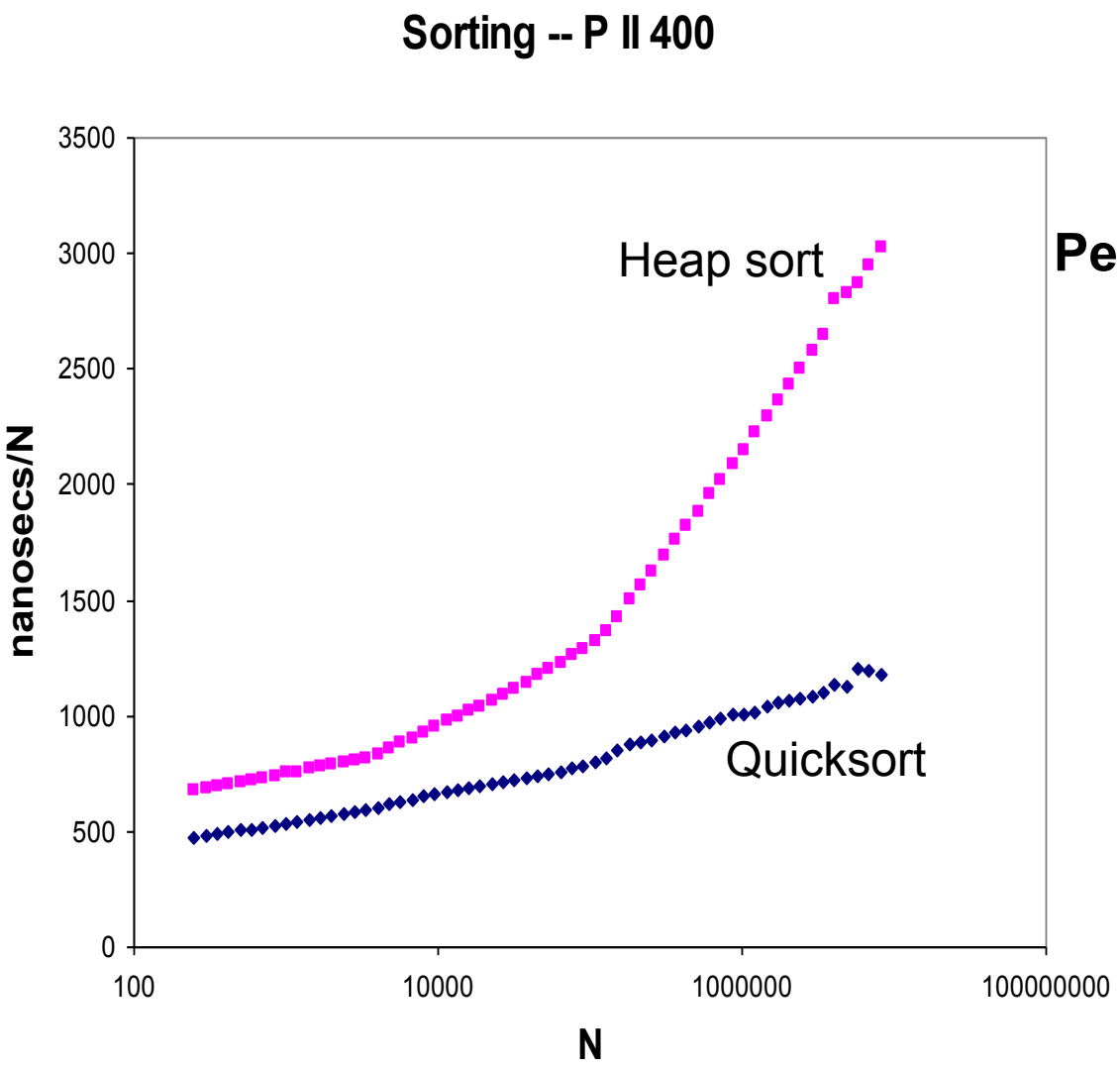
A Survey of Problems

- **Sorting Problems**
  - **Q: But I don't care about sorting!**
  - **A: But you know about it, and it illustrates deep truths**
    - **And I can speak from (sometimes bitter) personal experience**
- **System Issues**
  - **Caching, I/O speed, memory allocation**
- **Some Big Systems**
- **Personal Performance Bugs**

Engineering a New Sort Function

- **Survey Existing Code**
  - A dozen system sorts all traced to three original programs
  - Each was easily driven to quadratic time
    - E.g., an array of random 0s and 1s
    - Each had many similar performance bugs
- **3. Our New Code**
  - Consistently N lg N in all of our tests
  - One user's response: It is *way* too slow
    - It takes N lg N time on my input
    - Its predecessor took just N time for my (all equal) inputs
  - A performance "curio" – implicitly specified by the previous implementation
- **4. How to implement sort – Quicksort or Heapsort?**

4. CPU Times for Sorting



Performance Bugs Lurking?

- **Experiments in one range do not extrapolate linearly to other ranges**
- **Caching has a huge influence**

5. Knuth's Disk Sort

- **A New Disk Sort Utility**
  - Passes all correctness tests
  - Takes twice as long as he predicted
- **Next Steps**
  - Check and recheck the math
  - Simple experiments to measure the disk speed
    - Result: due to an OS bug, the disks had been running at half their advertised speed for over a year
    - Cause: "optimize" the seek to arrive just before the record rotates under the head, and miss by a little
- **Result of the Bug Fix**
  - His sort ran twice as fast, just as predicted
  - Many other programs were faster, too

6. Another `qsort` Bug

A Bug Report

Our new sort code caused our system to crash. The maximum number of items to sort is 512. But that sort is recursive, and when sorting 512 entries, it ran out of process stack space. So we removed it.

We might want to put the sorting back. Do you know of another sort algorithm that can sort up to 512 32-bit integers very fast but without using recursion?

An Embarrassing Clarification

They were using *my* sort function

Two Separable Issues

Is the sort really guilty?

Do I know another algorithm?

6. My Response

Good news – I have 30 lines of code with worst-case time that is faster than your current sort.

But first, let's make sure that recursion is the culprit. I've attached a little recursive program that allocates about the same amount of stack memory as your sort. Here is its output on my system:

```
$ gcc recdepth.c; a.out
Passed n=10
Passed n=100
Passed n=1000
Passed n=10000
Passed n=100000
Segmentation Fault(coredump)
```

It runs at $n=10^5$, and dies at one million. A binary search could locate the exact failure point.

I suggest that you do a similar experiment. Put code like this at the place where you removed the sort, and you can find out how deep your recursion can go.

6. A Recursion Depth Tester

```
/* Sum 1+2+…+n recursively
   Use extra memory to simulate stack
     size (and fool smart compilers)
 */
int recsum(int n)
{ int i, sum, x[MEMSIZE];
  if (n == 0) return 0;
  for (i = 0; i < MEMSIZE; i++
      x[i] = n;
  sum = 0;
  for (i = 0; i < MEMSIZE; i++)
      sum += x[i];
  return sum + recsum(n-1);
}
```

n

Use memory

Dink around

The Power of Profiling
(And non-Performance Bugs)

- **Kernighan on Awk**
  - Statement-count profile
    - Almost all counts were four decimal digits or fewer
    - Six lines of initialization code had a count near a million
  - Fix: only re-initialize as many as you used last time
  - Not a performance bug: young software tends to have time spikes
- **An OS Performance Group**
  - Time profiling shows half the time in one tiny loop
  - Rewriting the hot spot in microcode gives ×10 speedup
    - No change in system throughput, though
  - They had optimized the idle loop
  - Not a performance bug: a well-deserved spike

7. Profiling A Big System

A Prototype Page Profiler

- "Frequent flyers" among 10^7 page faults

count	page addr	instr addr
764210	08fbb6f0	086fe958
206058	0e6fc064	088cb2c9
204235	085b1822	08081372
203168	084decc4	0809e388
181556	0e6fd114	088c5541
179481	0e232028	086ff492

Observations

- About 7½% of the faults come from that one instruction
  - Second place is only about 2%
- Time to check that instruction

7. The Expensive Piece

The Code

```
/* Do not deliver the following lines ENABLED: these
 * are ONLY used for automated unit testing.
 */
#if DY_H842_AFQ_TEST IS_ENABLED
        H842_test_phase = 0;
#endif
```

The MR

- Disable DY_H842_AFQ_TEST. As the comment indicates, it is only for automated unit testing and should not be enabled. Additionally, it causes code to be executed unnecessarily. Another side effect is that it touches test flags that are stored in shadowed memory causing numerous, unnecessary page faults.
- This change reduces the number of page faults and the amount of data transmitted by about 7.5%

Perspective on Performance Bugs

- Causes
  - Big Systems
    - Two tiny programming goofs, each just one line of code[2,7]
    - One problem with stack space[5]
  - Sorting
    - Different nature of input
      - Becker and Wilks' s "pipe organ"[1]
      - Duff' s duplicates[3]
    - User expectations
      - Implicit contracts – Duff: "you can' t make it slower"[3]
    - Underlying system behavior: Caching[4], disk speed[5]
- Cures
  - Awareness, general performance testing[4,5,7], definitive experiments[1,5,6]
- Remainder of the Talk
  - More stories, with an emphasis on causes and cures

8. Memory Allocation

Classic – Memory Leaks

- The program runs out of memory way too early

My Slow Program

- The code is surprisingly and painfully slow
- Profiling shows that the lion's share of the time goes to allocation
- After days of abstraction and experiments, distill the problem to its essence

8. A Definitive Experiment

The Code

```
void main(int argc, char *argv[])
{   int n = atoi(argv[1]);
    while (n-- > 0)
        malloc(16);
}
```

The Data

```
$ time a.out 50000
1.8u
$ time a.out 100000
8.5u
$ time a.out 200000
38.3u
$
```

Doubling input quadruples time, so it is quadratic

8. Why Is It Quadratic?

- **My First Assumption**
  - I ran to gloat with my friend over a sloppy design
- **Doug McIlroy's Response**
  - "That's my code!"
  - His reasoning 15 years earlier
    - Machine has 64K words of memory
    - Code runs in time $c_1N + c_2N^2$
    - The second term is always negligible
    - Tune so that c_1 (always the dominant term) is small
  - What happens 15 years later?
    - Moore's law implies growth of a factor of 1000
- **Soul Searching**
  - How will the code you write today fare in 15 years?

Bridges and Software

- Ressler on "Great Structures"
  - Teaching Company, 2011
  - Bear Mountain Bridge
    - Main span 1632 feet
    - World's longest suspension bridge, 1924–1926
- "Do-Overs": much easier for software than bridges
- But What If?
  - One scaled a bridge design by a factor of 1000?
  - Leaving in one "test rivet" caused that rivet to weigh 7½% as much as the rest of the structure put together?
  - Leaving out one strand of wire caused the main cable weight to increase by a factor of 200?
  - Humility about the fragility of software

9. A Notification System

Essence: Mix and match phone, voice mail, text, e-mail, IM, …

How long to send e-mail to *N* recipients?

N	Seconds
1000	11.4
2000	39.6
4000	167.1

Quadratic once again

29 hours for *N*=100,000

Why?

- **Sending the same piece of e-mail twice is wasteful**
- **Therefore keep a list of recipients, and search it for each**

How to find such bugs?

- **Tiny performance tests along critical dimensions**
- **Force accretive bugs to become catastrophic**

Personal Performance Bugs

10. Change the `max` function to a macro

- Sometimes a speedup of 2
- In a recursive function, a slowdown of 10,000
  - Details in *Programming Pearls*, 1999, Sec. 9.2

11. Hash table size

- 8191: List size is 1.92
- 8192: List size is 3510

A disaster waiting to happen!

12. A clever caching scheme

N \ P	1	100	2000	10000	
10000	100.0	98.6	91.3	89.5	10.5% better!
9000	100.0	106.7	91.5	193.2	mixed
7000	100.0	104.0	211.5	2463.4	25 times worse!

Review of Performance Bugs

1. Changing the nature of inputs to be sorted
2. Forgetting one reset to zero
3. A new sort runs in optimal time and is too slow
4. Different speeds in different memory hierarchies
5. Knuth's double-time disk sort
6. Excessive stack space kills the system
7. A unit test feature was enabled in production
8. Memory management grows by a factor of 1000
9. An e-mail system caches its recipient list
10. Change a function to a macro
11. 8191 → 8192
12. Clever new cache

Some Causes of Performance Bugs

Changes to the Code

- Tiny coding goofs: missing reset[2], uncommented line[7]
- Small changes with unforeseen big impact[5,10,11,12]

New Inputs

- Unexpected size: McIlroy's malloc[8], sort with caching[4]
- Different nature of input
  - Becker and Wilks's "pipe organ"[1], cache access patterns[4]

User Expectations

- Inadequate performance specifications
- Implicit contracts: Duff's "you can't make it slower"[3]

Underlying System Behavior

- Caching[4]; memory allocation[8]; disk speed[5]; sort performance[1]

Premature Optimization[1,3,5,9]

Attacking Performance Bugs

Awareness

Specification

Design

Coding

Testing

Performance Models

Profiling

Ongoing Monitoring

Identifying the Culprit

Certifying the Problem

Repairing

Performance Testing

- Test Both Components and Overall System
- Monitoring and Profiling Tools
  - Count anything and everything
    - Microseconds, kilobytes, pages, critical events, …
  - Automate tests, analyses and meta-analyses
- Experiments
  - Exploratory – *Where* does the time go?
    - Page profiles, e-mail system
  - Confirmatory – Does it *really* go there?
    - Memory allocation, sorting time and space, e-mail
  - Maintenance – Did I introduce any new bugs?

Concrete Proposals

- **Catalog Recent Performance Bugs**
  - **Search for patterns**
  - **Perform root cause analyses**
    - **Mechanically scan for missing resets**
    - **Were other tests were enabled? Would this help?**

```
#if UNIT_TEST && DY_H842_AFQ_TEST IS_ENABLED
```

- **Add a time measurement to every single functional test**
- **Test performance along critical dimensions**
- **Routinely gather profiles and perform meta-analyses**
- **Insert run-time checks into delicate structures**