ECE 454 Computer Systems Programming

Measuring and Profiling

Ashvin Goel, Ding Yuan
ECE Dept, University of Toronto

"*It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories instead of theories to suit facts.*"

Sherlock Holmes

Measuring Programs and Computers

Why Measure a Program/Computer?

- To compare two computers/processors
  - Which one is better/faster? Which one should I buy?
- To optimize a program, e.g., improve algorithm
  - Which part of the program should I focus my effort on?
- To compare program implementations
  - Which one is better/faster? Did my optimization work?
- To find a bug
  - Why is it running much more slowly than expected?

Basic Measurements

- IPS: instructions per second
  - MIPS: millions of IPS, BIPS: billions of IPS
- FLOPS: floating point operations per second
  - megaFLOPS: 10^6 FLOPS
  - gigaFLOPS: 10^9 FLOPS, Playstation3 capable of 20 GFLOPS
- IPC: instructions per processor-cycle
  - Another measure of throughput
- CPI: cycles per instruction, CPI = 1 / IPC
  - Measure of the reciprocal of throughput
  - Makes it easier to compare with latency of instructions

How Not to Compare Processors

- Clock frequency (MHz)?
  - IPC for the two processors could be radically different
  - Megahertz myth
    - Started from 1984

Apple II
CPU: MOS Technology 6503@1MHz
LD: 2 cycles (2 microseconds)

IBM PC
CPU: Intel 8088@4.77MHz
LD: 25 cycles (5.24 microseconds)

How Not to Compare Processors

- Clock frequency (MHz)?
  - IPC for the two processors could be radically different
- CPI/IPC?
  - Dependent on instruction sets used
  - Dependent on efficiency of code generated by compiler
- FLOPS?
  - Only if FLOPS are important for the expected applications
  - Also dependent on instruction set used

How to Measure a Processor

- Use wall-clock time (seconds)

```
time = IC x CPI x ClockPeriod
```

- `IC` = instruction count (total instructions executed)
- `CPI` = cycles per instruction
- `ClockPeriod` = seconds/cycle
  = 1 / `ClockFrequency` = (1 / MHz)

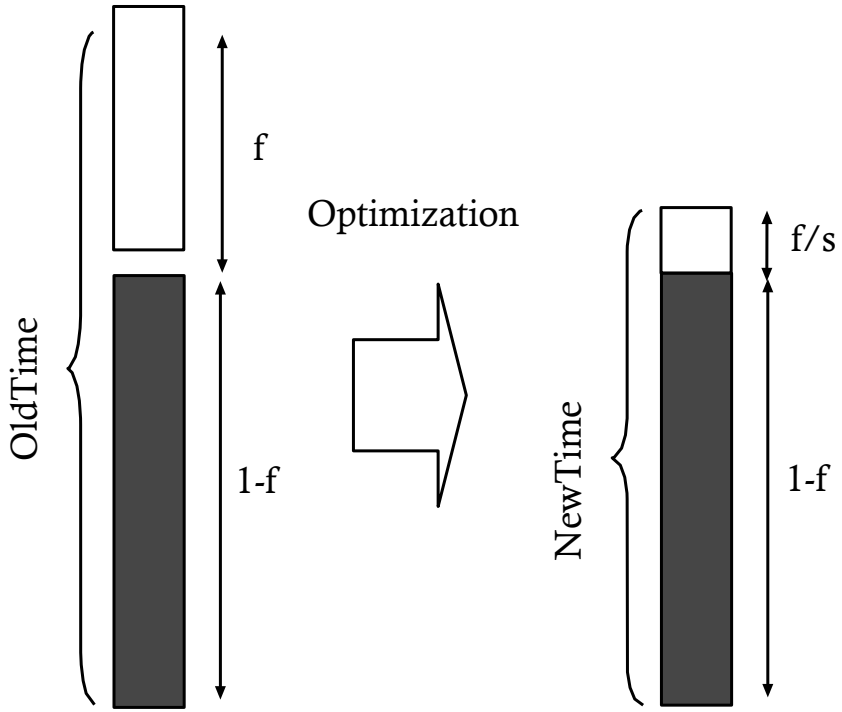
Amdahl's Law: Optimizing Part of a Program

```
speedup = OldTime / NewTime
```

- E.g., my program used to take 10 minutes
  - Now it only takes 5 minutes after optimization
  - speedup = 10min/5min = 2.0 i.e., 2x faster

- If only optimizing part of a program (on following slide):
  - Let `f` be the fraction of execution time that the optimization applies to (`0 < f < 1`)
  - Let `s` be the improvement factor (speedup of the optimization)

Amdhal's Law Visualized



- the best you can do is eliminate f; 1-f remains

Amdahl's Law: Equations

- Let `f` be the fraction of execution time that the optimization applies to (`0 < f < 1`)
- Let s be the improvement factor (speedup of the optimization)

```
NewTime = OldTime x [(1-f) + f/s]

speedup = OldTime / NewTime

speedup = 1 / (1 – f + f/s)
```

Example 1: Amdahl's Law

- If an optimization makes loops go 3 times faster, and my program spends 70% of its time in loops, how much faster will my program go?

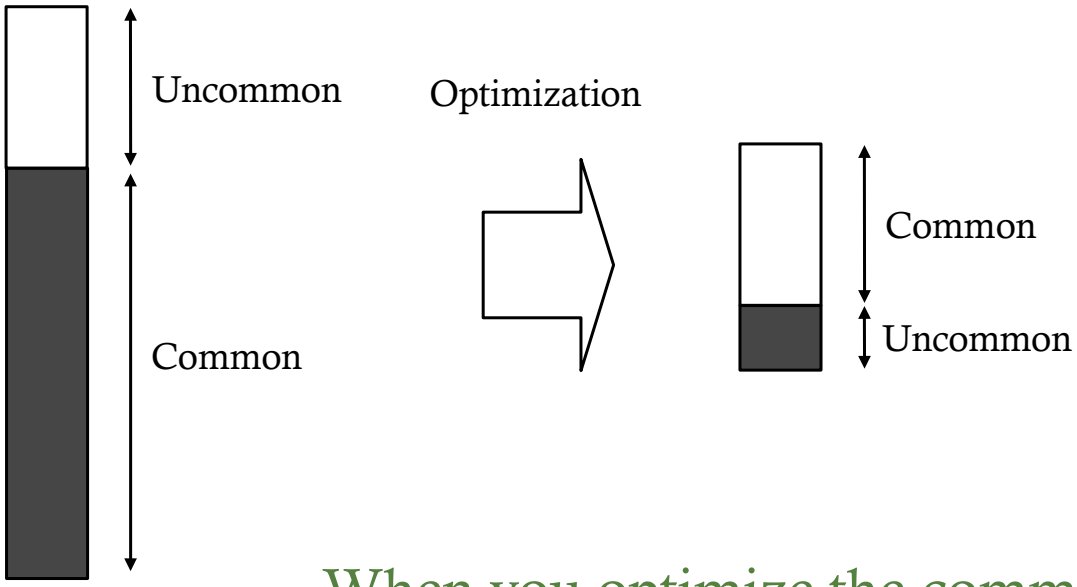
```
speedup = 1 / (1 – f + f/s)

= 1 / (1 – 0.7 + 0.7/3.0)

= 1/(0.533333)

= 1.875
```

- My program will go 1.875 times faster

Example 2: Amdahl's Law

- If an optimization makes loops go 4 times faster, and applying the optimization to my program makes it go twice as fast, what fraction of my program is loops?

Implications of Amdahl's Law



When you optimize the common case, the common case may change!

Tools for Measuring and Understanding Software

Tools for Measuring/Understanding

- Software timers
  - C library and OS-level timers
- Hardware timers and performance counters
  - Built into the processor chip
- Instrumentation
  - Decorates your program with code that counts & measures
  - gprof – profiling tool, outputs where time is spent in program
  - gcov – coverage tool, outputs how many times each line executed
  - Used together to find commonly executed code where time should be spent on optimization

Software Timers: Command Line

- Example: /usr/bin/time
- Measures the time spent in user code and OS code
- Measures entire program (can't measure a specific function)
- Not super-accurate, but good enough for many uses

$ time ls

```
real    0m13.860s
user    0m10.669s
sys     0m0.720s
```

```
real    0m3.515s
user    0m10.837s
sys     0m0.672s
```

Used in Lab 1

- real – Wall clock time
- user & sys --- CPU time in user mode, kernel mode

Software Timers: Library: Example

- Used to measure time within parts of a program

```
#include <sys/times.h>      // C library functions for time

unsigned get_time() {
    struct tms t;
     times(&t);  // fills the struct
     // user CPU time (as opposed to OS CPU time)
     return t.tms_utime;
}

unsigned start_time, end_time, elapsed_time;
start_time = get_time();
do_work(); // function to measure
end_time = get_time();
elapsed_time = end_time - start_time;
```

Used in Lab 2

Hardware: Cycle Timers

- Programmer can access on-chip cycle counter
- E.g., via the x86 instruction: rdtsc (read time stamp counter)
- We use this in Lab 2 in clock.c to time your solutions, e.g.

```
start_cycles = get_tsc(); // executes rdtsc
do_work();
end_cycles = get_tsc();
total_cycles = end_cycles – start_cycles;
```

Used in Lab 2

- Can be used to compute #cycles required to execute code
  - Can be more accurate than library (when used correctly)
- Watch out for multi-threaded programs!

Hardware: Performance Counters

- Special on-chip event counters
  - Can be programmed to count low-level architectural events
  - Eg., cache misses, branch mispredictions, etc.
- Previously, difficult to use
  - Full OS support was missing
  - Counters can overflow
  - Must be sampled carefully
- Today, software packages can make them easier to use
  - E.g.: Intel's VTUNE, Linux perf
- We use perf in Lab 2

Instrumentation

- Compiler/tool inserts new code & data-structures
  - Can count/measure anything visible to software
  - E.g., instrument every load instruction to record load address
  - E.g., instrument every function to count #times it is called
- Observer effect
  - Can't measure system without disturbing it
  - Instrumentation code can slow down execution
- Example instrumentors (open/freeware):
  - Intel's PIN: general purpose tool for x86
  - Valgrind: tool for finding bugs and memory leaks
  - gprof: counts & measures where time is spent via sampling

Instrumentation: Using gprof

- gprof
  - Uses sampling to approximate time spent in each function and #of calls to each function
  - Periodically interrupts program, e.g., roughly every 10ms
  - Determines what function is currently executing
  - Increments the time counter for that function by interval (10ms)
- Usage: compile with `-pg` Used in Lab 1

```
gcc –O2 –pg prog.c –o prog
```

`./prog`

Executes normally, but also generates file gmon.out

`gprof prog`

Uses gmon.out to show profiling information

Instrumentation: Using gcov

- Gives a profile of execution within a function
  - E.g., how many times each line of C code was executed
  - Helps decide which loops are most important
  - Helps decide which part of if/else is most important
- Usage: compile with `-g -fprofile-arcs -ftest-coverage`

```
gcc -g -fprofile-arcs -ftest-coverage file.c –o file.o
```

```
./prog
```

Executes normally, but also generates files file.gcda and file.gcno for each file.o

```
gcov -b prog
```

Generates profile output in file.c.gcov

Used in Lab 1

Emulation/Instrumentation: valgrind

- Primarily used to find/track memory leaks
  - Eg., if you malloc() an item but forget to free it
  - Many other uses for it today
- valgrind adds instrumentation to the binary dynamically
  - So gcc doesn't need to be rerun
  - Execution time is 4-5x slower than native execution
  - Usage: (available on ug machines)
    - valgrind myprogram

```
== LEAK SUMMARY:
== definitely lost: 0 bytes in 0 blocks
== indirectly lost: 0 bytes in 0 blocks
== possibly lost: 0 bytes in 0 blocks
== still reachable: 330,372 bytes in 11,148 blocks
```

Demo: Using gprof

Demo: Using gcov