ECE 454
Computer Systems Programming
Measuring and profiling

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"*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
  - 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
  - teraFLOPS: 10^{12} FLOPS
  - petaFLOPS: 10^{15} FLOPS
  - Eg: playstation3 capable of 20 GFLOPS
- IPC: instructions per processor-cycle
- CPI: cycles per instruction
  - CPI = 1 / IPC

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)

$$time = IC \times CPI \times ClockPeriod$$

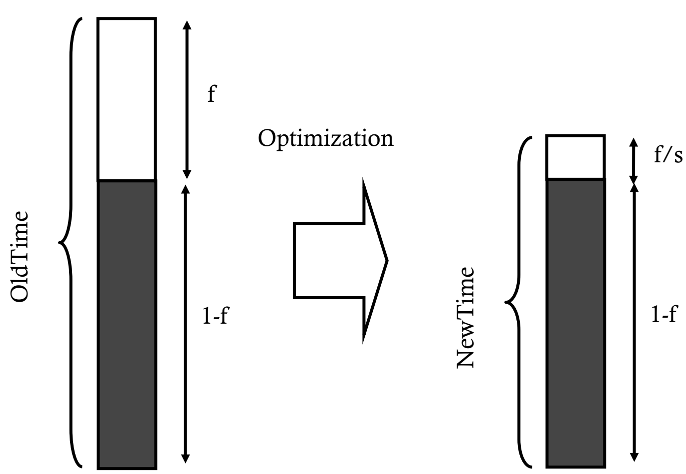
- IC = instruction count (total instructions executed)
- CPI = cycles per instruction
- ClockPeriod = 1 / ClockFrequency = (1 / MHz)

Amdahl's Law: Optimizing part of a program

speedup = OldTime / NewTime

- Eg., 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 (1.0 > f > 0)
  - 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 (1.0 > f > 0)
- let s be the improvement factor

$$\text{NewTime} = \text{OldTime} \times [(1-f) + f/s]$$

$$\text{speedup} = \text{OldTime} / (\text{OldTime} \times [(1-f) + f/s])$$

$$\text{speedup} = 1 / (1 - f + f/s)$$

Example1: 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)

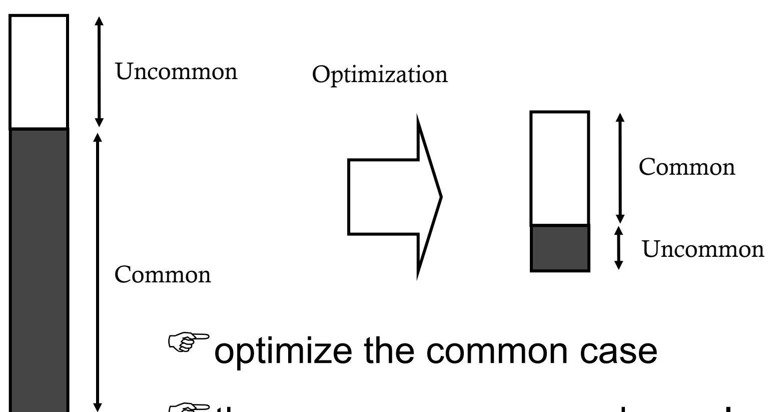
= 1.875

- My program will go 1.875 times faster.

Example2: 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



☞ 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
  - gcov

☞GNU: "Gnu is Not Unix"
--- Founded by Richard Stallman

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 ☞used in HW1

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

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

  - user & sys --- CPU time
  - /usr/bin/time gives you more information

Software Timers: Library: Example

```
#include <sys/times.h>   // C library functions for time
unsigned get_seconds() {
  struct tms t;
  times(&t);  // fills the struct
  return t.tms_utime; // user program time
                      // (as opposed to OS time)
}
…
unsigned start_time, end_time, elapsed_time;
start_time = get_seconds();
do_work();    // function to measure
end_time = get_seconds();
elapsed_time = end_time - start_time;
```

☞can measure within a program

☞used in HW2

Hardware: Cycle Timers

- Programmer can access on-chip cycle counter
  - Eg., via the x86 instruction: rdtsc (read time stamp counter)
    - We use this in hw2:clock.c:line94 to time your solutions
- Example use:
  - `start_cycles = get_tsc();  // executes rdtsc`
  - `do_work();`
  - `end_cycles = get_tsc();`
  - `total_cycles = end_cycles – start_cycles;`
- Can be used to compute #cycles to execute code
  - Watch out for multi-threaded program!

☞can be more accurate than library (if used right)

☞used in HW2

Hardware: Performance Counters

- Special on-chip event counters
  - Can be programmed to count low-level architecture events
  - Eg., cache misses, branch mispredictions, etc.
- Can be difficult to use
  - Require OS support
  - Counters can overflow
  - Must be sampled carefully
- Software packages can make them easier to use
  - Eg: Intel's VTUNE, perf (recent linux)

☞perf used in HW2

Instrumentation

- Compiler/tool inserts new code & data-structures
  - Can count/measure anything visible to software
  - Eg., instrument every load instruction to also record the load address in a trace file.
  - Eg., instrument every function to count how many 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: counting/measuring where time is spent via sampling

Instrumentation: Using gprof

- gprof: how it works
  - Periodically (~ every 10ms) interrupt program
    - Determine what function is currently executing
    - Increment the time counter for that function by interval (e.g., 10ms)
  - Approximates time spent in each function, #calls made
  - Note: interval should be random for rigorous sampling!
- Usage: compile with "-pg" to enable

```
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`

☞ used in HW1

☞ detailed example later in lecture

Instrumentation: Using gcov

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

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

  - Executes in normal fashion
  - Also generates `file.gcda` and `file.gcno` for each `file.o`

```
gcov -b progc
```

  - Generates profile output in `file.c.gcov`

☞used in HW1

Emulation/Instrumentation: valgrind

- Primarily used to find/track memory leaks
  - Eg., if malloc() an item but forget to free it
  - Many other uses for it these days
- valgrind is a fairly sophisticated emulator
  - a virtual machine that just-in-time (JIT) compiles
  - adds instrumentation dynamically (without rerunning gcc)
  - emulates 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