ECE 571 – Advanced Microprocessor-Based Design Lecture 2

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Announcements

- I've added some optional readings to the website if you want to review Computer Architecture a bit. You can access the 2007 Edition of Patterson and Hennessy for free via the UMaine Library website.
- HW#1 will be posted
- I will be handing out account username/passwords for the homework.
- Accounts: Log in to the haswell "haswell-ep" machine for homework. Make sure you connect to port 2131.

ece571-1 names are a bit impersonal.

Use `passwd` to change your password.

You can use `chfn` to change your name as it appears in `w` if you want.

Please use the accounts wisely

What do people want ouf of a microprocessor?

- Performance?

Review: What is Performance?

- Getting results as quickly as possible?
- Getting *correct* results as quickly as possible?
- What about Budget?
- What about Development Time?
- What about Hardware Usage?
- What about Power Consumption?
- What about Security?

Motivation for HPC Optimization

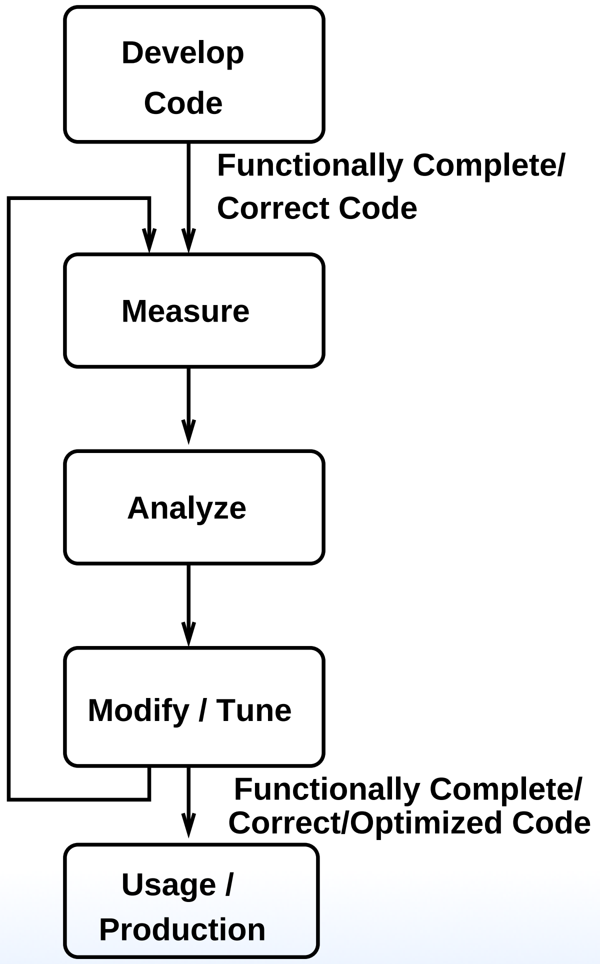
HPC environments are expensive:

- Procurement costs: $\sim\$40$ million
- Operational costs: $\sim\$5$ million/year
- Electricity costs: 1 MW / year $\sim\$1$ million
- Air Conditioning costs: ??

Know Your Limitation

- CPU Constrained
- Memory Constrained (Memory Wall)
- I/O Constrained
- Thermal Constrained
- Energy Constrained

Performance Optimization Cycle


Develop Code
Functionally Complete/ Correct Code
Measure
Analyze
Modify / Tune
Functionally Complete/ Correct/Optimized Code
Usage / Production

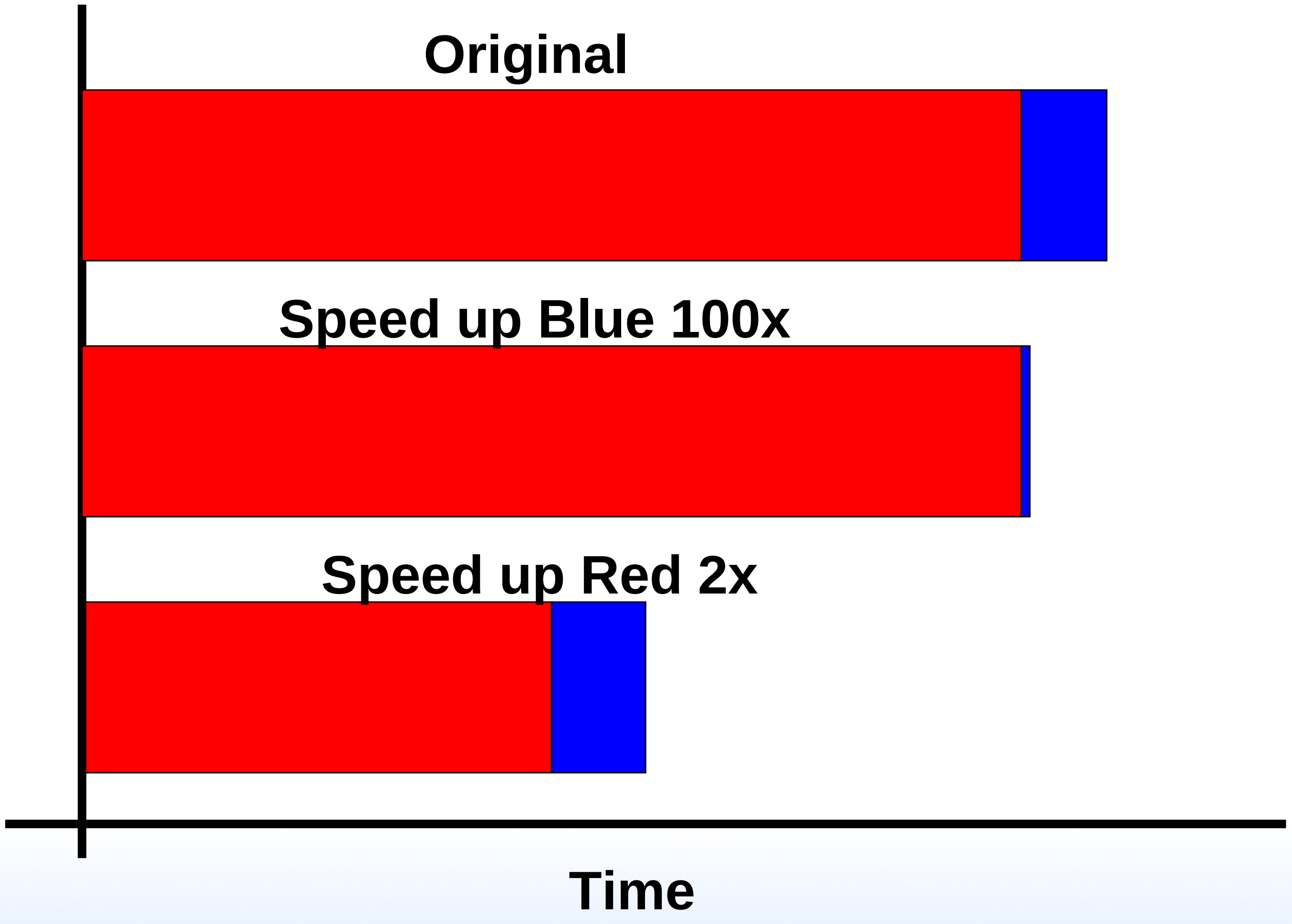
Wisdom from Knuth

“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%. A good programmer will not be lulled into complacency by such reasoning, he will be wise to look carefully at the critical code; but only after that code has been identified” — Donald Knuth

Amdahl's Law



Software Tools for Performance Analysis

Simulators

- Architectural Simulators
- Can generate traces, profiles, or modeled metrics
- Slow, often 1000x or more slower
- Not real hardware, only a model
- Did I mention, slow?
- m5, gem5, simplescalar, etc

Dynamic Binary Instrumentation

- Pin, Valgrind (cachegrind), Qemu
- Still slow (10-100x slower)
- Can model things like cache behavior (can model parameters other than system running on)
- Complicated fine-tuned instrumentation can be created
- Architecture availability – Pin (no longer ARM), Valgrind, Qemu most architectures, hardest to use

Compiler Profiling

- gprof
- gcc -pg
- Adds code to each function to track time spent in each function.
- Run program, gmon.out created. Run "gprof executable" on it.
- Adds overhead, not necessarily fine-tuned, only does time based measurements.
- Pro: available wherever gcc is.

Gathering Performance Info – Aggregate Counts

- Aggregate counts (total instructions, total cycles, etc)
- Actual measurements: `perf`, `time`

- DBI measurements: `valgrind`, `qemu`

- Simulators: `gem5`, `simplescalar`

Gathering Performance Info – Profiling

- Insert calls on entry to function (or basic block) to track how much time spent in each
- Do you need source code?
- Manually add?
- DBI: `valgrind`
- compiler: `gprof`

Gathering Performance Info – Sampled Counts

- Sampled counts – periodically interrupt program, note the instruction pointer
- Can use info to statistically determine which part of code where most time (or other metric) is spent
- hardware: `perf`
- DBI: `valgrind`

Gathering Performance Info – Tracing

- Tracing – gather a record of every event (instruction?) that is executed. Can then replay this trace through various tools for analysis.
- Downside: huge trace files (gigabytes+)

Performance Data Analysis

Manual Analysis

- Visualization, Interactive Exploration, Statistical Analysis
- Examples: TAU, Vampir

Automatic Analysis

- Try to cope with huge amounts of data by automatic analysis
- Examples: Paradyn, KOJAK, Scalasca, Perf-expert

Evaluating Performance of Modern Systems

Benchmarks

- When measuring performance, need a reference workload to compare
- Ideally reproducible, portable, easy to compile, relevant
- Benchmarks can be gamed

Selected Commonly Seen Benchmarks

- SPEC
  - CPU 2000, CPU 2006, CPU 2017 – Commercial, Single-threaded (floating point and integer)
  - OMP – Commercial, Parallel
  - jbb – Java
- HPC Challenge – Free. HPL (Linpack). High-performance / Linear Algebra
- HPCG (conjugate gradient) new replacement for HPL
- PARSEC – Free, Multithreaded / CMP

- MiBench – Free, Embedded (2000)
- BioBench, BioParallel – Free, Bio/Data-Mining
- lmbench – Free, Operating System
- iobench – Disk I/O
- Stream – Memory

Measuring Performance

Using `time`

- For example

```
$ time xhpl
...
real    0m9.484s
user    0m29.150s
sys     0m7.440s
```

Real Time = Wall clock

User Time = Time used by program alone

Sys Time = Time used by OS

- When could Real be greater than User?

Other users/jobs on system.

When could User be greater than Real?

Multiple threads.

- Run multiple times and notice time changes

What if Time isn't Enough?

What are Hardware Performance Counters?

- Registers on CPU that measure low-level system performance
- Available on most modern CPUs; increasingly found on GPUs, network devices, etc.
- Low overhead to read

Hardware Implementation of Counters

- Not much documentation available
- Jim Callister/Intel: “Confessions of a Performance Monitor Hardware Designer” 2005, Workshop on Hardware Performance Monitor Design
  - Transistors free, wires not. Also design time, validation, documentation, time to market. PMU has tentacles “everywhere” bringing data back to center.
  - Architect too much, lower performance, events don’t

map well to hardware. Architect too little.. software design harder.

– Which events are important? Are cache misses important if don't hurt performance? (no stalls)
– Mapping events to signal difficult. On critical path. Not enough wires. Combining signals hard if distance between wires.
– Use logging. May miss events in "shadow" of another event being logged. Use random behavior?

Learning About the Counters

- Number of counters varies from machine to machine
- Available events different for every vendor and every generation
- Available documentation not very complete (Intel Vol3b, AMD BKDG, ARM ARM/TRM)

Low-level interface

- on x86: MSRs
- ARM: CP15 system control register

Overflow

- overflows after hitting a threshold (often when wrapping, most counters are between 32 and 44 bits wide)
- One use is to keep track of counters that may wrap multiple times between reads
- If want to overflow earlier, init to a high value. So 0xc0000000 to overflow at 1 billion

Accuracy, Determinism vs Overcount

- Determinism – same count every time you run
- Overcount – an event counts more than the expected amount

SW Sources of Non-Determinism

- Accessing changing values, such as time
- Pointer-value dependencies

Linux interface

- Abstract away.
- perf_event_open(). See the manpage.
- Very complicated system call.
- Most people use perf or PAPI rather than calling it directly.

perf tool

A a tutorial on perf can be found here:
https://perf.wiki.kernel.org/index.php/Tutorial

perf list

```
Lists available events
List of pre-defined events (to be used in -e):
  cpu-cycles OR cycles                                [Hardware event]
  instructions                                        [Hardware event]
  cache-references                                    [Hardware event]
  cache-misses                                        [Hardware event]
  branch-instructions OR branches                     [Hardware event]
  branch-misses                                       [Hardware event]
  bus-cycles                                          [Hardware event]

  cpu-clock                                           [Software event]
  task-clock                                          [Software event]
  page-faults OR faults                               [Software event]
  minor-faults                                        [Software event]
  major-faults                                        [Software event]
  context-switches OR cs                              [Software event]
```

perf stat – Aggregate results

```
vince@arm:~/class/ece571$ perf stat ./matrix_multiply
Matrix multiply sum: s=27665734022509.746094

 Performance counter stats for './matrix_multiply':

      11585.144036 task-clock                #    0.999 CPUs utilized
                19 context-switches          #    0.000 M/sec
                 0 CPU-migrations            #    0.000 M/sec
             1,633 page-faults               #    0.000 M/sec
    10,343,746,076 cycles                    #    0.893 GHz
         5,031,717 stalled-cycles-frontend   #    0.05% frontend cycles idle
     9,521,135,479 stalled-cycles-backend    #   92.05% backend  cycles idle
     1,176,286,814 instructions              #    0.11  insns per cycle
                                             #    8.09  stalled cycles per insn
       137,835,961 branches                  #   11.898 M/sec
           831,736 branch-misses             #    0.60% of all branches

      11.591796875 seconds time elapsed
```

perf stat – Specifying Events

```
vince@arm:~/class/ece571$ perf stat -e instructions,cycles ./matrix_multip
Matrix multiply sum: s=27665734022509.746094

 Performance counter stats for './matrix_multiply':

     1,174,788,622 instructions              #    0.14  insns per cycle
     8,346,588,065 cycles                    #    0.000 GHz

      12.394775391 seconds time elapsed
```

perf stat – Specifying Masks

:u is user, :k kernel

ARM Cortex A9 cannot specify this distinction (results shown here are x86)

```
vince@arm:~/class/ece571$ perf stat -e instructions,instructions:u ./matri
Matrix multiply sum: s=27665734022509.746094

 Performance counter stats for './matrix_multiply':

       950,526,051 instructions              #    0.00  insns per cycle
       945,661,967 instructions:u            #    0.00  insns per cycle

       1.052072277 seconds time elapsed
```

libpfm4 – Finding All Event Names

```
./showevtinfo
Supported PMU models:
        [51, perf, "perf_events generic PMU"]
        [65, arm_ac8, "ARM Cortex A8"]
        [66, arm_ac9, "ARM Cortex A9"]
        [75, arm_ac15, "ARM Cortex A15"]
Detected PMU models:
        [51, perf, "perf_events generic PMU", 80 events, 1 max encoding, 0 counters, OS g
        [66, arm_ac9, "ARM Cortex A9", 57 events, 1 max encoding, 2 counters, core PMU]
Total events: 254 available, 137 supported
...
#-----------------------------
IDX      : 138412068
PMU name : arm_ac9 (ARM Cortex A9)
Name     : NEON_EXECUTED_INST
Equiv    : None
Flags    : None
Desc     : NEON instructions going through register renaming stage (approximate)
Code     : 0x74
#-----------------------------
....
```

libpfm4 – Finding Raw Event Values

```
./check_events NEON_EXECUTED_INST
Supported PMU models:
[51, perf, "perf_events generic PMU"]
[65, arm_ac8, "ARM Cortex A8"]
[66, arm_ac9, "ARM Cortex A9"]
[75, arm_ac15, "ARM Cortex A15"]
Detected PMU models:
[51, perf, "perf_events generic PMU"]
[66, arm_ac9, "ARM Cortex A9"]
Total events: 254 available, 137 supported
Requested Event: NEON_EXECUTED_INST
Actual    Event: arm_ac9::NEON_EXECUTED_INST
PMU            : ARM Cortex A9
IDX            : 138412068
Codes          : 0x74
```

perf – Using Raw Event Values

```
vince@arm:~/class/ece571$ perf stat -e r74 ./matrix_multiply
Matrix multiply sum: s=27665734022509.746094

 Performance counter stats for './matrix_multiply':

                 1 r74

      11.303955078 seconds time elapsed
```

perf stat – multiplexing

```
perf stat -e instructions,instructions,branches,cycles,cycles ./matrix_multiply
Matrix multiply sum: s=27665734022509.746094

 Performance counter stats for './matrix_multiply':

     1,178,121,057 instructions   #    0.12  insns per cycle [40.23%]
     1,180,460,368 instructions   #    0.12  insns per cycle [60.25%]
       138,550,072 branches                                  [80.09%]
     9,999,614,616 cycles         #    0.000 GHz             [79.85%]
     9,926,949,659 cycles         #    0.000 GHz             [20.17%]

      11.214630127 seconds time elapsed
```

Note same event not same results, approximate because an estimate. Percentage shown is percentage event was active during run.

perf stat – all cores

```
vince@arm:~/class/ece571$ sudo perf stat -a ./matrix_multiply
Matrix multiply sum: s=27665734022509.746094

 Performance counter stats for './matrix_multiply':

      24089.660644 task-clock                #    2.001 CPUs utilized           [100.00%]
               105 context-switches          #    0.000 M/sec                   [100.00%]
             1,641 page-faults               #    0.000 M/sec
     9,218,451,619 cycles                    #    0.383 GHz                     [100.00%]
         9,707,195 stalled-cycles-frontend   #    0.11% frontend cycles idle    [100.00%]
     8,393,095,067 stalled-cycles-backend    #   91.05% backend  cycles idle    [100.00%]
     1,193,164,945 instructions              #    0.13  insns per cycle
                                             #    7.03  stalled cycles per insn [100.00%]
       139,913,572 branches                  #    5.808 M/sec                   [100.00%]
         1,221,237 branch-misses             #    0.87% of all branches

      12.040527344 seconds time elapsed
```

Run on *all* cores of system even if your process not running there. -a option. Need root permissions. (Why? Security)

perf record – sampling

```
vince@arm:~/class/ece571$ time ./matrix_multiply
Matrix multiply sum: s=27665734022509.746094

real0m10.747s
user0m10.688s
sys0m0.055s
vince@arm:~/class/ece571$ time perf record ./matrix_multiply
Matrix multiply sum: s=27665734022509.746094
[ perf record: Woken up 2 times to write data ]
[ perf record: Captured and wrote 0.454 MB perf.data (~19853 samples) ]

real0m12.009s
user0m11.797s
sys0m0.203s
```

`perf record` creates `perf.data`, use `-o` to specify output

perf report – summary of recorded data

```
  99.62%  matrix_multiply  matrix_multiply              [.] naive_matrix_multiply
   0.38%  matrix_multiply  [kernel.kallsyms].head.text  [k] 0xc0046a54
   0.00%  matrix_multiply  ld-2.13.so                   [.] _dl_relocate_object
   0.00%  matrix_multiply  [kernel.kallsyms]            [k] __do_softirq
```

Our benchmark is simple (only one function) so the profiled results are not that exciting.

The `[k]` indicates that profile happened while the kernel was running.

Similar ways to get Similar Results

- Valgrind/Callgrind
  valgrind - -tool=callgrind BENCHMARK
  then run *callgrind_annotate*
  Note Valgrind is probably around 50 times slower

- Use gprof
  Compile your code with -pg
  Run *gprof BENCHMARK*

perf annotate – show hotspots in assembly

```
    0.00 :             845a:       vldr    d7, [pc, #124]  ; 84d8 <naive_matrix_m
   30.97 :             845e:       adds    r1, r4, r3
    1.43 :             8460:       add.w   r3, r3, #4096   ; 0x1000
    1.17 :             8464:       adds    r2, #8
    1.36 :             8466:       cmp.w   r3, #2097152    ; 0x200000
    2.97 :             846a:       vldr    d5, [r2]
    2.62 :             846e:       vldr    d6, [r1]
    2.78 :             8472:       mov     r9, r2
    2.42 :             8474:       vmla.f64        d7, d5, d6
   53.81 :             8478:       bne.n   845e <naive_matrix_multiply+0x72>
    0.01 :             847a:       adds    r5, #1
```

The annotated results show a branch and an add instruction accounting for 83% of profiles. Likely this is due to skid and the key instruction is the previous `vmla.f64` floating point multiply instruction. The processor just isn't able to stop at the exact instruction when the interrupt comes in.

Skid

- Beware of “skid” in sampled results
- This is what happens when a complex processor cannot stop immediately, so the reported instruction might be off by a few instructions.
- Some processors do not have this problem, other Intel processors have special events that can compensate for this.