ECE 571 – Advanced Microprocessor-Based Design Lecture 7

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Announcements

- HW#4 will be posted, some readings

Measuring Power and Energy

Why?

- New, massive, HPC machines use impressive amounts of power
- When you have 100k+ cores, saving a few Joules per core quickly adds up
- To improve power/energy draw, you need some way of measuring it

Energy/Power Measurement is Already Possible

Three common ways of doing this:

- Hand-instrumenting a system by tapping all power inputs to CPU, memory, disk, etc., and using a data logger
- Using a pass-through power meter that you plug your server into. Often these will log over USB
- Estimating power/energy with a software model based on system behavior

Measuring Power and Energy

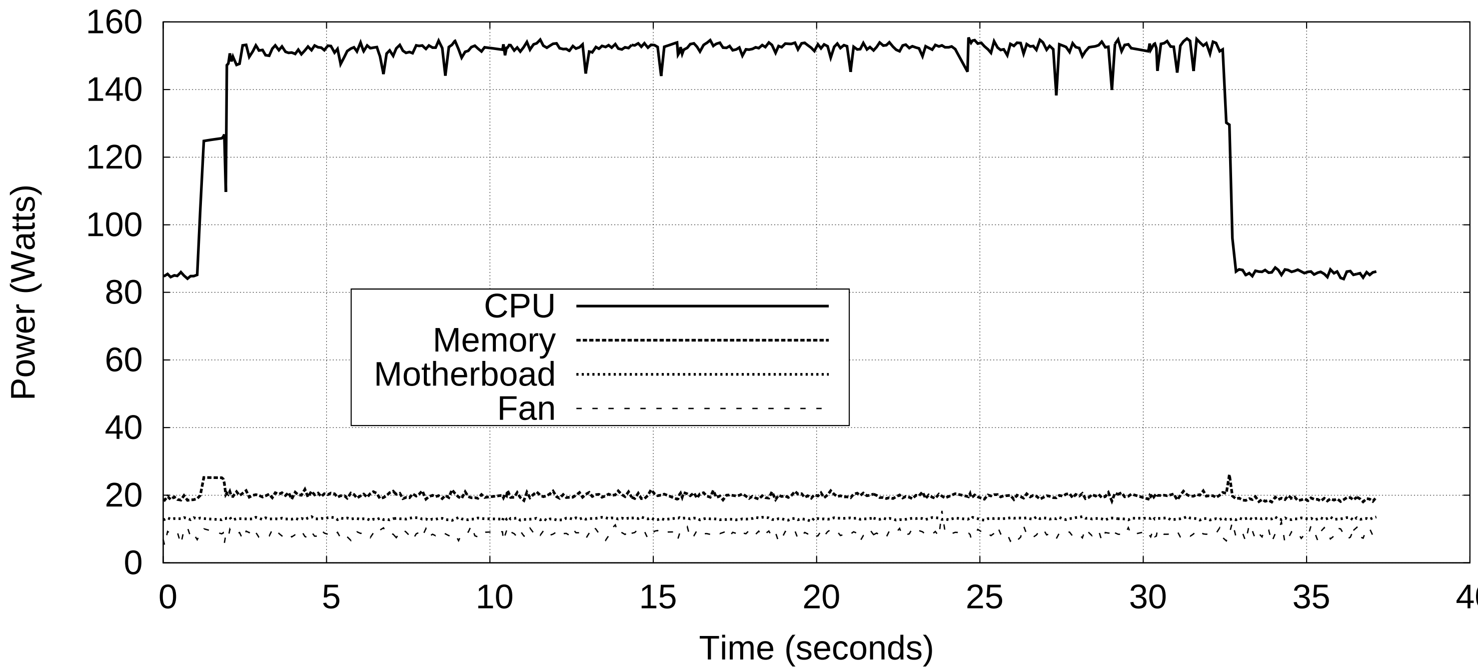
- Sense resistor or Hall Effect sensor gives you the current
- Sense resistor is small resistor. Measure voltage drop. Current V=IR Ohm's Law, so V/R=I
- Voltage drops are often small (why?) so you made need to amplify with instrumentation amplifier
- Then you need to measure with A/D converter
- $P = IV$ and you know the voltage
- How to get Energy from Power?

Hall Effect Current Sensors

- Output voltage varies based on magnetic field.
- Current in wire causes magnetic field
- Voltage output is linear proportional to current
- Ideally little to no resistance (unlike sense resistor)
- Can measure higher current. 5, 20, 30A
- Need that? 100W CPU at 3.3V is roughly 30A

Existing Related Work

Plasma/dposv results with Virginia Tech's PowerPack



Powerpack

- Measure at Wall socket: WattsUp, ACPI-enabled power adapter, Data Acquisition System

- Measure all power pins to components (intercept ATX power connector?)

- CPU Power – CPU powered by four 12VDC pins.

- Disk power – measure 12 and 5VDC pins on disk power connecter

- Memory Power – DIMMs powered by four 5VDC pins
- Motherboard Power – 3.3V pins. Claim NIC contribution is minimal, checked by varying workload
- System fans

PowerMon 2

- PowerMon 2 is a custom board from RENCI
- Plugs in-line with ATX power supply.
- Reports results over USB
- 8 channels, 1kHz sample rate
- We have hardware; currently not working

Shortcomings of current methods

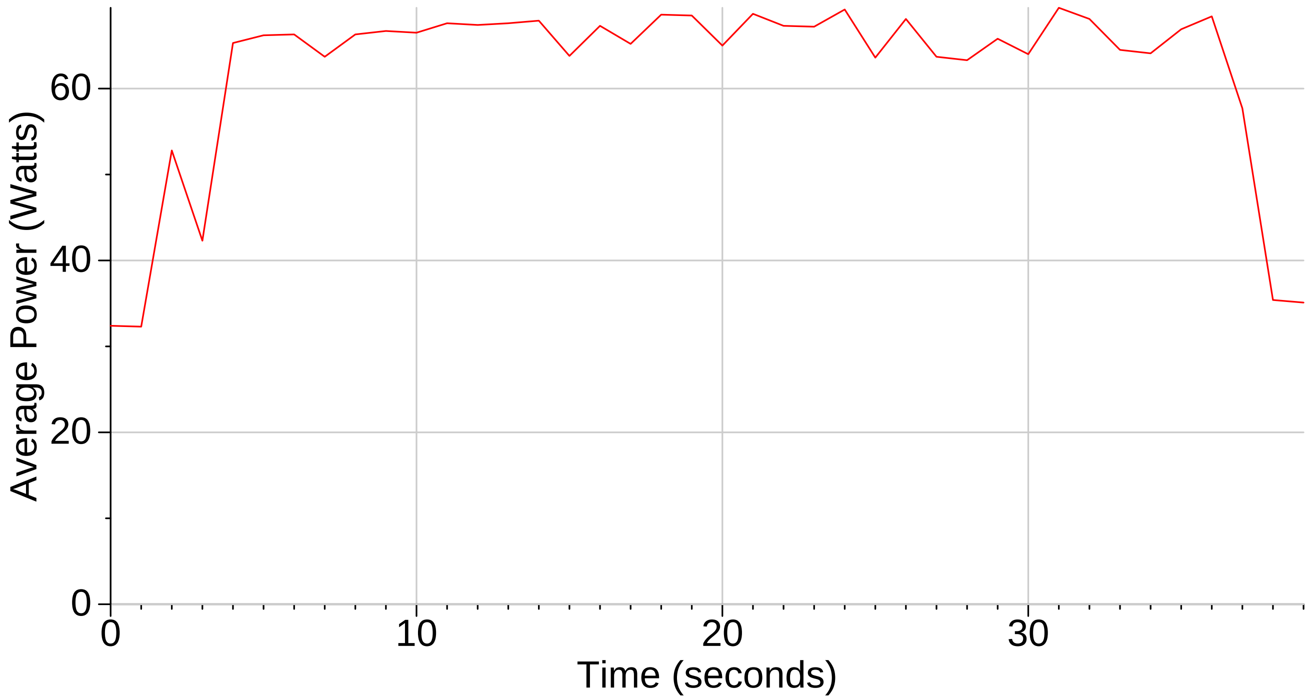
- Each measurement platform has a different interface
- Typically data can only be recorded off-line, to a separate logging machine, and analysis is done after the fact
- Correlating energy/power with other performance metrics can be difficult
- How often can you measure (a lot happens on a CPU at 2GHz)

Watt's Up Pro Meter

Watt's Up Pro Features

- Can measure 18 different values with 1 second resolution (Watts, Volts, Amps, Watt-hours, etc.)
- Values read over USB
- Joules can be derived from power and time
- Can only measure system-wide

Watt's Up Pro Graph



PLASMA Cholesky Factorization N=10,000 threads=2

Measured on Core2 Laptop

Estimating Power

- Popular thing to do. One example: *Real Time Power Estimation and Thread Scheduling via Performance Counters* by Singh, Bhadauria and McKee.
- Have some sort of hardware measurement setup.
- Then measure lots of easy-to-measure things. Performance counters. Temperature. etc.
- Create a model (machine learning?) that can estimate
- Apparently using as few as 4 counters can give pretty good results

RAPL

- **R**unning **A**verage **P**ower **L**imit
- Part of an infrastructure to allow setting custom per-package hardware enforced power limits
- User Accessible Energy/Power readings are a bonus feature of the interface

How RAPL Works

- RAPL is *not* an analog power meter (usually, Haswell-EP exception)
- RAPL uses a software power model, running on a helper controller on the main chip package
- Energy is estimated using various hardware performance counters, temperature, leakage models and I/O models
- The model is used for CPU throttling and turbo-boost, but the values are also exposed to users via a model-specific register (MSR)

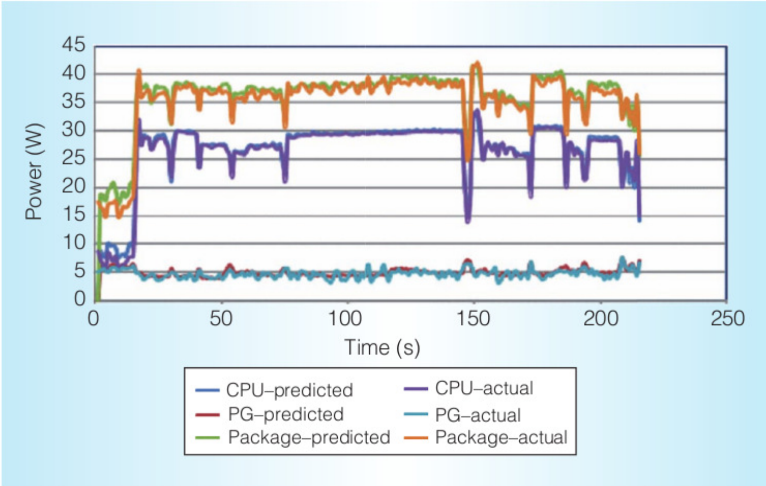
Available RAPL Readings

- PACKAGE_ENERGY: total energy used by entire package
- PP0_ENERGY: energy used by "power plane 0" which includes all cores and caches
- PP1_ENERGY: on original Sandybridge this includes the on-chip Intel GPU
- DRAM_ENERGY: on Sandybridge EP this measures DRAM energy usage. It is unclear whether this is just the interface or if it includes all power used by all the DIMMs too

- SoC energy (skylake and newer?)

RAPL Measurement Accuracy

- Intel Documentation indicates Energy readings are updated roughly every millisecond (1kHz)
- Rotem at al. show results match actual hardware



Rotem et al. (IEEE Micro, Mar/Apr 2012)

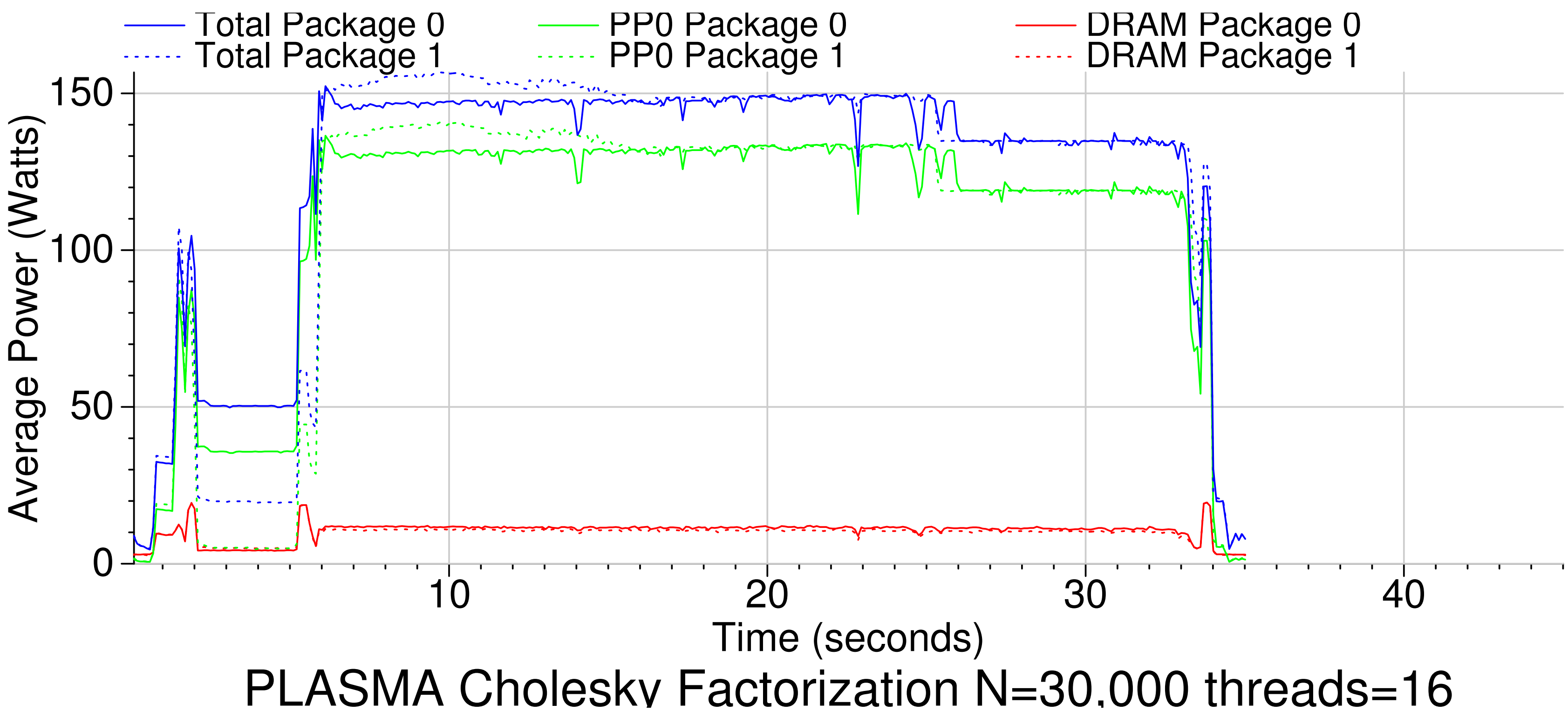
RAPL Accuracy, Continued

- The hardware also reports minimum measurement quanta. This can vary among processor releases. On our Sandybridge EP machine all Energy measurements are in multiples of 15.2nJ
- Power and Energy can vary between identical packages on a system, even when running identical workloads. It is unclear whether this is due to process variation during manufacturing or else a calibration issue.

RAPL Validation

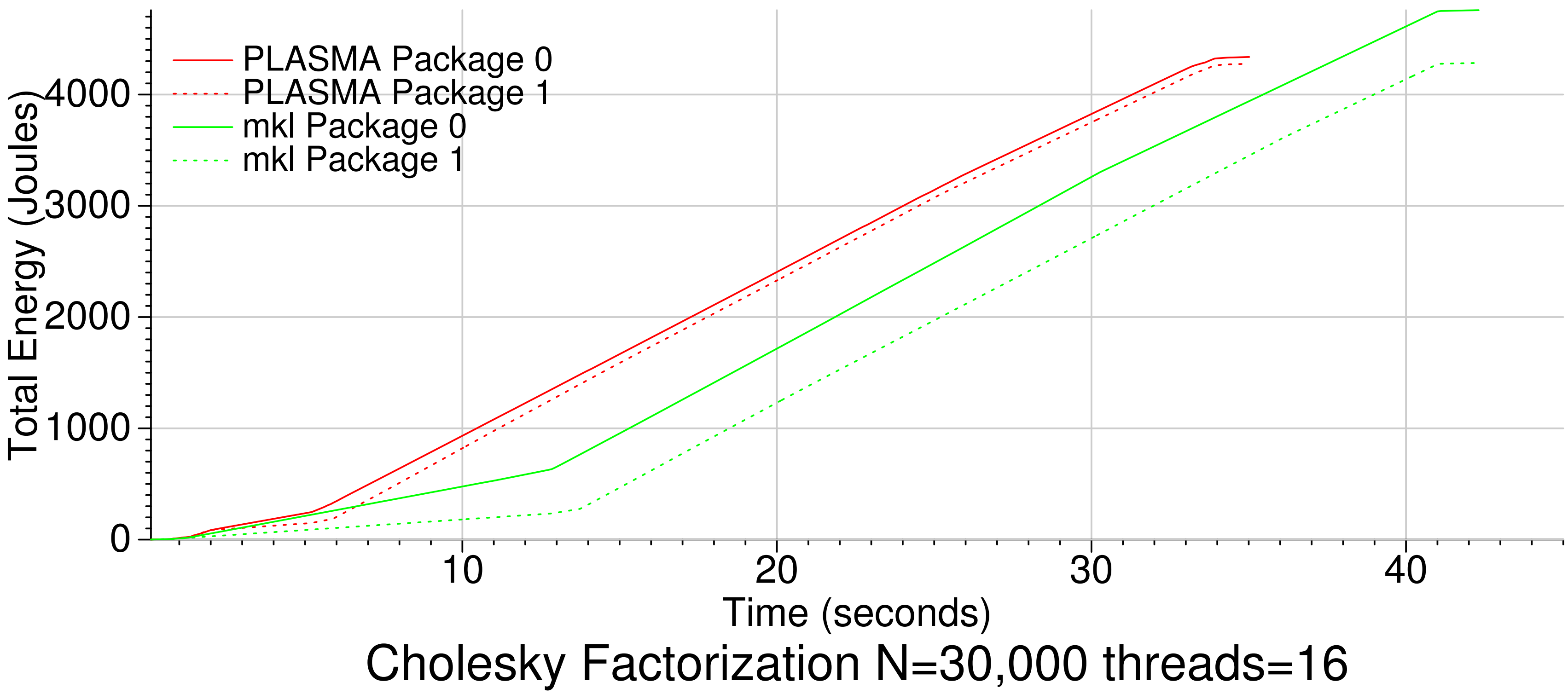
- The Dresden Paper
- My MEMSYS paper (include some plots?)

RAPL Power Plot



Measured on SandyBridge EP

RAPL Energy Plot

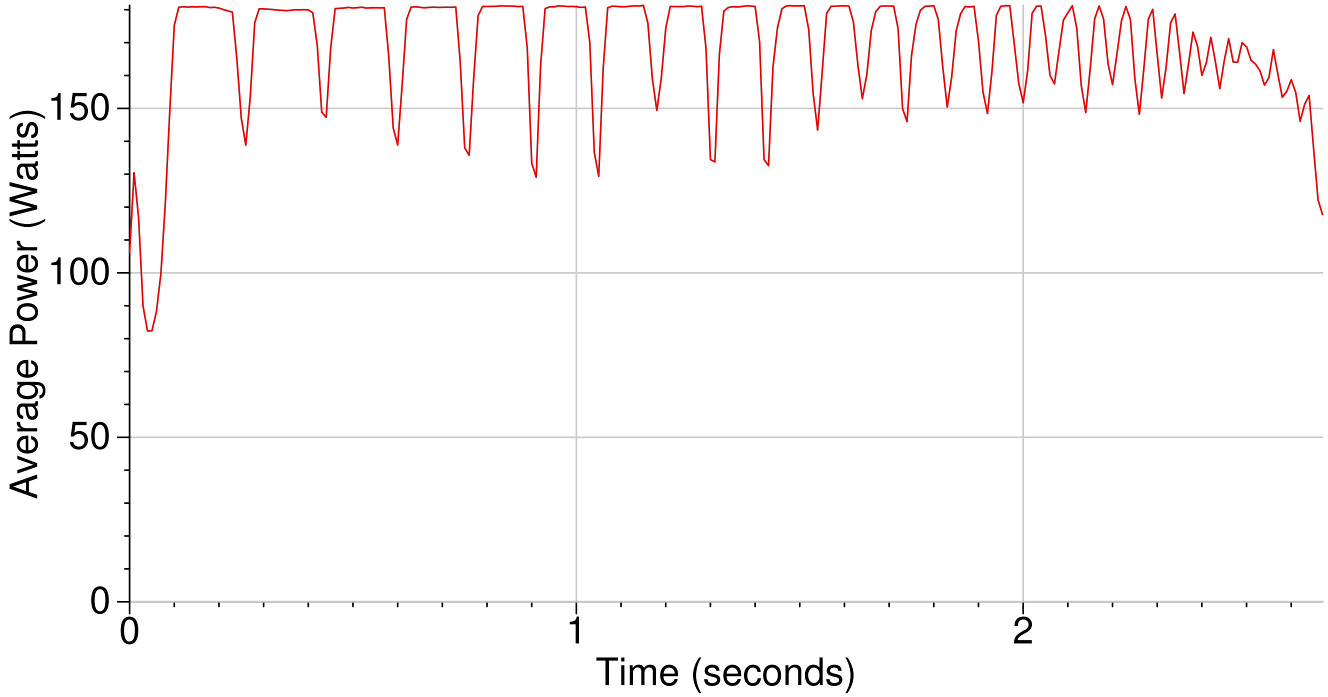


Measured on SandyBridge EP

NVML

- Recent NVIDIA GPUs support reading power via the NVIDIA Management Library (**NVML**)
- On Fermi C2075 GPUs it has milliwatt resolution within $\pm$5W and is updated at roughly 60Hz
- The power reported is that for the entire board, including GPU and memory

NVML Power Graph



MAGMA LU 10,000, Nvidia Fermi C2075

AMD Application Power Management

- Recent AMD Family 15h processors also can report "Current Power In Watts" via the Processor Power in the TDP MSR
- Support for this can be provided similar to RAPL
- Have had bad luck getting accurate readings. Have found various chip errata on fam15h and fam16h hardware

Other ways to measure Power

- IPMI – many server machines have built in (low frequency) measurement of power supply values.
- Thermal? IR camera? Can see how much individual parts of chip use.
  Overheat? Use IR transparent liquid to cool it?

Using RAPL

- On Linux, at least 3 ways to get these values
- Read msr directly, either with instruction or /dev/msr. Need root as you can do bad things with msrs. "safemsr"
- perf_event
- hwmon/powercap (/sys/class/powercap/)

Listing Events

```
$ perf list
...
  power/energy-cores/                                 [Kernel P
  power/energy-gpu/                                   [Kernel P
  power/energy-pkg/                                   [Kernel P
  power/energy-ram/                                   [Kernel P
...
```

Measuring

```
$ perf stat -a -e power/energy-cores/,power/energy-ram/,instru

 Performance counter stats for 'system wide':

            63.79 Joules power/energy-cores/
             2.34 Joules power/energy-ram/
      21038123875        instructions              #    1.06
      19782762541        cycles

      3.407427702 seconds time elapsed
```

Measuring

- The key is -a which enables system-wide mode (needs root too if not configured as such)
- Why do you need system-wide?
- What does that do to the other metrics?

Power and Energy Concerns

Table 1: OpenBLAS HPL N=10000 (Matrix Multiply)

Machine	Processor	Cores	Freq	Idle Power	Load Power	Time Time	Total Energy
Raspberry Pi 2	Cortex-A7	4	900MHz	1.8W	3.4W	454s	1543J
Dragonboard	Cortex-A53	4	1.2GHz	2.4W	4.7W	241s	1133J
Raspberry Pi 3	Cortex-A53	4	1.2GHz	1.8W	4.3W	178s	765J
Jetson-TX1	Cortex-A57	4	1.9GHz	2.1W	13.4W	47s	629J
Macbook Air	Broadwell	2	1.6GHz	10.0W	29.1W	14s	407J

1. Which machine has the lowest under-load power draw?
   Pi 2

2. Which machine consumes the least amount of energy?
   Broadwell Macbook Air

3. Which machine computes the result fastest?
   Broadwell Macbook Air

4. Consider a use case with an embedded board taking a picture once every 60 seconds and then performing a matrix-multiply similar to the one in the benchmark (perhaps for image-recognition purposes). Could all of the boards listed meet this deadline?
   No, only the Jetson and Macbook Air can meet the

deadline

5. Assume a workload where a device takes a picture once a minute then does a large matrix multiply (as seen in Table 1). The device is idle when not multiplying, but under full load when it is.

(a) Over a mine, what is the total energy usage of the Jetson TX-1?

Each Minute = (13s Idle * 2.1W) + (47s Load *13.4W) = 657J

(b) Over a minute, what is the total energy usage of the Macbook Air?

Each Minute $=$ (46s * 10W) $+$ (14*29.1) $=$ 867J

Pandaboard Power Stats

- Wattsuppro: 2.7W idle, seen up to 5W when busy
- `http://ssvb.github.com/2012/04/10/cpuburn-arm-cortex-a9.html`
- With Neon and CPU burn:

Idle system	550 mA	2.75W
cpuburn-neon	1130 mA	5.65W
cpuburn-1.4a (burnCortexA9.s)	1180 mA	5.90W
ssvb-cpuburn-a9.S	1640 mA	8.2W

Easy ways to reduce Power Usage

DVFS

- Voltage planes – on CMP might share voltage planes so have to scale multiple processors at a time
- DC to DC converter, programmable.
- Phase-Locked Loops. Orders of ms to change. Multiplier of some crystal frequency.
- Senger et al ISCAS 2006 lists some alternatives. Two phase locked loops? High frequency loop and have programmable divider?
- Often takes time, on order of milliseconds, to switch

frequency. Switching voltage can be done with less hassle.

When can we scale CPU down?

- System idle
- System memory or I/O bound
- Poor multi-threaded code (spinning in spin locks)
- Thermal emergency
- User preference (want fans to run less)