Energy-Aware Computing Systems

Energiebewusste Rechensysteme

III. Energy Demand Analysis

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Preface

Terminology

System Activities and Analysis
   Principle of Causality, System Activities
   Measurement-Based Analysis

Energy Demand Analysis
   Dimensions, Resolution, and Accuracy
   Physical Methods
   Logical Methods

Summary
System Model (Leonardo da Vinci, 1493)
429 years before the first flying prototype

Physical System (Pescara, 1922)
first flying prototype

- analysis: measure physical system to refine model and improve system
- measure to answer: fitting, progressing, and comparison
- by the way, the first prototype did not really fly very long...
energy demand analysis

- originates from the Ancient Greek:
  *analysis*, "a breaking up"; from
  *ana-"up, throughout" and
  *lysis" a loosening".

- is the process of breaking a complex topic or substance into smaller parts in order to gain a deeper understanding of it

- resolution of anything complex into simple elements
energy demand analysis

- dissecting a computing system and its components with regards to energy demand
- quantifying energy demand by applying \textit{physical} and \textit{logical} analysis methods
- disclosure of cause and effect
Principle of Causality

- A causal chain of events related to some other event $e_i$: $i$ is effect of $e_i$
- $A$, $B$ and $C$ are system activities
- Cause and effect relationship of system activities
- Activities ("cause") influence the system state $\rightarrow$ impact on the energy demand of sequel activities ("effect")
Analyzing System Activities

- system level activity → effects are subject to analysis
  - component-based energy demand analysis
  - correlation with software-level activities (i.e., process execution)

- quantify energy demand on the background of different aspects
  - level of activity (i.e., timers)
  - impact on the system (i.e., cache trashing)
    - first-level analysis (in isolation)

- determine overall relevance of system activity
  - identify (and rule out) cause-and-effect relationships
    - second-level analysis (with side activities)

- measurement-based analyses to investigate consequences with regards to the energy demand is the focus of today’s lecture
measurement-based analysis of a physical system

Figure 2: Block Diagram of System Modeling Procedure

Wang '93 [2]
measurement-based analysis of a physical system

point of origin: **physical system** (e.g., a prototype)

apply measurements to analyze system properties and impact of external stimuli (i.e., input)
measurement-based analysis of a physical system

- Point of Origin
- Goals
  - Input
  - Physical System
    - measure
  - Model
    - initial measurements, physical principles, etc.
    - simulate
  - Analyze and compare
    - time or frequency domain
    - analyze: actual vs. target
  - identify non-linearities
    - improve measurement technique

Figure 2: Block Diagram of System Modeling Procedure

Wang '93 [2]

- goals: improve physical **system**, build **model**, improve **measurement**, identify **input dependencies**
- pre-post comparison, analyze: **actual vs. target**
measurement-based analysis of a physical system

Point of Origin

Goals

Analysis

Figure 2: Block Diagram of System Modeling Procedure

Wang '93 [2]

analysis: iterative approach to build either refined systems, improved models, or both (depending on goal)

improve first-order goals, consider second-order constraints
energy demand analysis at system level

what system properties to measure?
- energy demand → requires knowledge of power over time
- power demand → requires data of circuitry (electric current, voltage)
...
- time demand → timing and time requirements
- thermal impact and the duality thereof
  ...minimum/maximum/average of the above system properties

how to measure?
- physical measurements
- logical measurements
  ← interlude: measuring errors, wrong statistics, avoiding false conclusion

consider: measuring resolution and accuracy
- resolution: ability to differentiate between two similar measured values
- accuracy: deviation of measured values from the physically ground truth
measuring energy demand: commonly based on measurements which quantify the power demand, integrate power demand over time

average power \cdot time interval (i.e., execution time) \Rightarrow energy demand

different physical measurement methods (direct/indirect)
  - shunt based measurement methods
  - Hall effect measurement methods
  - current mirror based measurement methods
  - ...

measuring the energy demand is a first step towards energy awareness and towards improving energy efficiency
shunt based measurement; indirection: current measurement
analyze electric current in a circuit with constant DC voltage
idea: build low resistance path with a resistor (shunt), measure voltage drop(s) across shunt
determine electric current by applying Ohm’s law
known: resistance \((R)\); sense: DC voltage \((V)\)
calculate: current \(I\) (…and electrical power \(P\))
Measuring Energy with a Resistor (Shunt)

- system setup and preparations
  - verify baseline setup: functioning without alteration (i.e., without shunt)
  - identify hardware component that is subject to analysis
  - integrate measuring setup (i.e., assemble shunt resistor)
  - determine proper functioning without measuring device (i.e., without voltmeter)

- measuring procedure
  - activate and instruct hardware to execute workload → trigger signals
  - analyze setup under varying external conditions
  - reveal non-linearities of measured values

- determining power and energy demand
  - time series
  - calculate current, (average) power, and energy demand
  - apply statistics on measurement data
Measuring Energy with a Resistor (Shunt)

- Voltage drop ($V_{shunt}$) across the resistor ($R_{shunt}$) is proportional to the electric current ($I$).
- Sampling $V_{shunt}$ is subject to special focus.

Mathematical formula:

$$V_{shunt} \propto I$$
Measuring Energy with a Resistor (Shunt)

Physical

missed voltage peaks \(\Rightarrow\) unrecognized power demand

higher sampling rate \(\Rightarrow\) refined power demand
Feasibility and Limits

- **physical energy demand measurement methods**
  - isolated: little overhead 😊, several systems 😞
  - alteration and/or extension of original baseline setup
    - difficult access to power rails in designs using ball grid arrays (e.g., package-on-package, PoP)
    - internal wires inaccessible, for example, when measuring the energy demand of peripherals of a system on chip (SoC)
  - extra efforts, experience in electrical engineering necessary

- **logic energy demand measurement methods**
  - integrated: overhead-prone 😞, single system 😊
  - energy models, event-based analyses, maintaining of the hardware setup
    - qualitative statements are sufficient for simple analyses
    - correlation of occurrence and frequency of logic (software) events with power or energy demand of hardware components
  - energy models are, despite their limits, often the first choice
Measuring Energy Demand

- build logical energy model on empirical knowledge as obtained by measurements or calculations based on measurements
  - requires physical measurements beforehand to establish the model
- static/dynamic components of logical energy demand measurements
  - cost model for specific events in the system
    - execution of a (specific) instruction (within a given system state)
    - transmission of a network packet
    - ...
  - presence of event(s), time and frequency of occurrence
- measurement accuracy depends on quality of energy model
  - consideration of non-deterministic effects (e.g., thermal aspects, impact of unconsidered system activities, state of caches)
  - logical energy models must adapt to the hardware platform and to its specific usage scenario (i.e., system complexity)
Measuring Energy with Performance Counters

- measuring energy demand: identify occurrence of events using hardware performance monitoring counters (PMCs)
- each PMC is configured to measure the occurrence of a particular event (e.g., retired instructions, data cache misses, TLB misses etc.)
- intended use of PMCs: performance analysis
  - Intel Corporation
- energy modeling using performance counters
  - event \(\Rightarrow\) demand of a certain amount of energy
  - register relevant events and their frequency/total number of occurrences
  - Frank Belossa
    The Benefits of Event–Driven Energy Accounting in Power-Sensitive Systems
Bellosa '00 [1]

- workload: integer operations; microinstructions ⇒ energy demand
- calibration: multimeter (integrated power monitor, 1 Watt resolution)
Measuring Energy with Performance Counters

FIG. 3. Correlation of L2 Cache references and energy consumption

Bellosa ‘00 [1]

- Workload: varying integer and memory operations
- Second level cache ⇒ energy demand
Measuring Energy with Performance Counters

- Intel Running Average Power Limit (RAPL)

- between the worlds: logical and physical measurements
  - originally, RAPL was using a software power model → logical measurements with hardware performance counters and I/O models
  - recent Intel CPUs (i.e., Haswell and onwards) → physical measurements

- hybrid approach towards energy-aware systems
  - adjusting performance levels (i.e., dynamic voltage and frequency scaling) ⇒ impacting power demand
  - adjusting power levels (i.e., power capping) ⇒ impacting performance
Considerations and Caveats

- physical and logical methods to measure the energy demand
  - analysis method strictly depends on system and use case
  - alternatives that augment and complement each other (i.e., verification)

- isolation and partitioning
  - separate measuring device from device under test (physical)
  - determine and quantify the influence of the measurement (logical and physical)

- overhead and side-effects
  - increased resource demand, system slowdown or speedup
  - interrelation to otherwise unrelated system components
Interlude: Measuring Done Right

- performing measurements is good, but...

- common measurement problems
  - measuring the **wrong thing**
  - drawing inappropriate conclusions
  - using bad statistics
  - ignoring **system interaction**
  - ignoring timing granularity

- ...and further considerations
  - comparing apples to oranges
  - comparing end-to-end measurements with the sum of parts
  - using the **wrong metrics**
  - mistakes

- Margo Seltzer and Aaron Brown

**Measuring Computer Systems: How to Measure Performance**

complex systems require thorough understanding of individual system aspects to allow focussed energy demand analyses.

physical and logical energy demand measurements have individual benefits and are often complementary.

available analysis methods must be suitable for individual use.

reading list for Lecture 4:

- Andreas Weissel and Frank Bellosa
  Process Cruise Control: Event-Driven Clock Scaling for Dynamic Power Management