Energy-Aware Computing Systems

Energiebewusste Rechensysteme

VIII. System Software

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Agenda

Preface

Terminology

Accounting and Management
- Abstracting Energy Demand
- Operational Concerns

Energy-Aware Operating Systems
- Currentcy and ECOSystem
- Cinder Operating System
- Linux Energy-Aware Scheduling (EAS)

Summary

Preface: Higher-Level Energy Management

- **motivation** and **origin**
  - lack of feedback on **design decisions** regarding energy demand
  - gap between vision of energy control and reality
    → Milly Watt Project
- use case: *Hiker's Buddy* [3]
  - energy-constraint operations (e.g., GPS)
  - functional design ↔ power state model

Carla Schlatter Ellis
The Case for Higher-Level Power Management
Proceedings of the Seventh Workshop on Hot Topics in Operating Systems (HotOS'99), 1999.

Preface: Higher-Level Energy Management

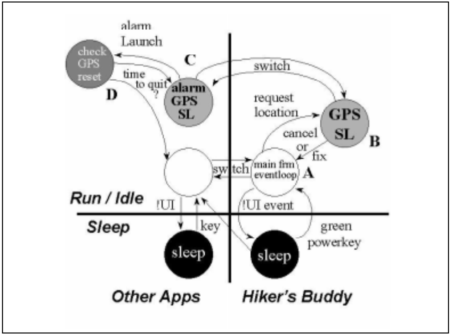


Figure 1. Power State Model

Carla Schlatter Ellis
The Case for Higher-Level Power Management
Proceedings of the Seventh Workshop on Hot Topics in Operating Systems (HotOS'99), 1999.

Preface: Higher-Level Energy Management

- **lower-level** building blocks
  - **energy-management features** at the hardware level (i.e., non-blocking energy management methods)
  - **firmware interfaces** for system controls (i.e., blocking energy management methods)

- **higher-level** abstractions
  - energy **accounting** with energy **models** and **measurements**
  - **resource** management
  - **policies and rights** management → conflict of interests

Abstract Concept: System Software

- **system software**
  - **operating system**
    - program or a set of programs that support (other) programs or applications to **facilitate the programming or operation** of a computer system
    - **monitor** and **control** the execution of programs
    - **operate** the computer system in a specific manner for a particular application
    - implement an **abstract machine**
  - interlocking with **low-level user-space programs** (i.e. system deamons)
- **resource management**
  - {de,}allocation of resources by the system software
  - accounting and enforcement

Abstracting Energy Demand: Resource Peculiarities

- **software resources** as to be used by programs

reusable	
code	critical section/region
data	variable, placeholder

consumable	
signal	notice
message	packet, stream

- **hardware resources** as to be managed by an operating system

reusable	
processor	CPU, FPU, GPU; MMU
memory	RAM, scratch pad, flash
peripheral	input, output, storage

consumable	
signal	IRQ, NMI, trap

- **energy** as a basic **operating-system resource** required to provide hardware and software resources
  - software resources → hardware resources → energy demand
  - energy accounting and management (i.e. resource allocation vs. residual resources)

Abstracting Energy Demand: Accounting

- energy **accounting** at operating system level
  - map resource demand by processes to energy demand
  - exclusive use vs. shared use of resources → attribution of proportions

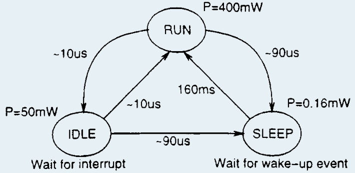
- capturing and tracking energy demand during run-time
  - apply **models**
    - tracking of state and time → device states
    - discrete, logic events → performance counter events
    - ...
  - apply **measurements**

- appropriate metrics for individual capturing methods
  - basic metrics and composite metrics
  - use-case specific granularity (i.e. µW vs. MW)

Abstracting Energy Demand: Accounting

- consideration of power states
- transition delays

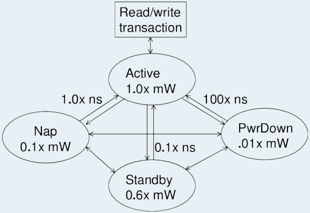
CPU



[2]

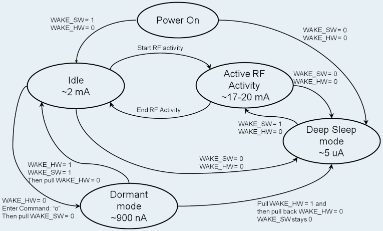
- in isolation...
- ...and in cooperation.

Memory



[4]

Network



Microchip Technology, Inc.

Operational Concerns: Energy Management

1. accounting ✓
2. **allocating** energy (e.g. epoch-based)
   - implicit → process analysis (i.e. based on periodicity)
   - explicit → provisioning based on requests
   - avoid overbooking that would conflict with global goal, prevent:
     - thermal breakdown (i.e. by exceed maximum power)
     - too short operating time (i.e. imbalance of power supply and demand)
3. **administering** residual energy (for next epoch)
   - use residual energy as feedback information
     - amount of residual energy depends on accuracy of energy models and measurements, respectively
   - redistribution and reallocation strategies
     - exhaustion control
     - over-provisioning controls

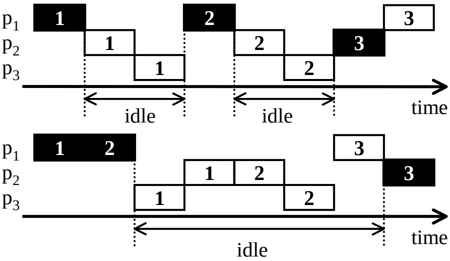
...but OS integration comes with pitfalls...

Operational Concerns: Energy Management

- basic functional requirements
  - accounting ✓
  - allocating ✓
  - administering ✓
- integration causes **conflicts of interest**: process scheduling
  - upon exhaustion of allocated resources
  - reordering of events
  - ...
- pitfalls as to **entering sovereign territory** of the process scheduler
  - priority inversion
  - data dependencies
  - ...

Operational Concerns: Energy Management

- Requester-Aware Power Reduction [5]
  - **track requests** and how they are generated (i.e. by which processes)
  - interaction between **processes** and **power management** facilities at operating system level
  - reordering of requests to reduce overhead and energy demand



black box: **active**
device access (e.g. I/O)

white box: **idle**
no device access (e.g. computation)

challenges:

- violation of priority-based scheduling decisions
- interdependencies between individual processes

Overview

- Currentcy [9] and ECOSystem [8]

  Heng Zeng et al.
  ECOSystem: managing energy as a first class operating system resource
  Proceedings of the 2002 Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS '02), 2002.

- Cinder Operating System [6]

  A. Roy et al.
  Energy Management in Mobile Devices with the Cinder Operating System
  Proceedings of the 2011 ACM European Conference on Computer Systems (EuroSys'11), 2003.

- Linux Energy-Aware Scheduling (EAS)

Currentcy and ECOSystem

- Currentcy: A Unifying Abstraction for Expressing Energy Management Policies
  - **Current** → *amount of energy that an application can spend*
  - Curren**cy** → *cf. money as unified abstraction for buying commodities*
  - abstract energy model (1 unit of currentcy is valued at 0.01 mJ)
- **currentcy** is used for...

  ...**energy accounting** and **allocation** across components and processes
  ...**capturing interactions** among energy users in the system

Heng Zeng et al.
Currentcy: A Unifying Abstraction for Expressing Energy Management Policies
Proceedings of the 2003 USENIX Annual Technical Conference (ATC'03), 2003.

Currentcy and ECOSystem

- ECOSystem:
  managing energy as a first-class operating system resource
  - Energy-Centric Operating System
  - motivation: change primary goal of the OS to **energy-efficiency** rather than (speed-based) **performance**
  - primary goal: **user-defined battery life** → determines **amount of currentcy** that can be spent in **each epoch**
  - adaptation of **resource containers** [1]

📄 Heng Zeng et al.
ECOSystem: managing energy as a first class operating system resource
Proceedings of the 2002 Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS '02), 2002.

Currentcy and ECOSystem

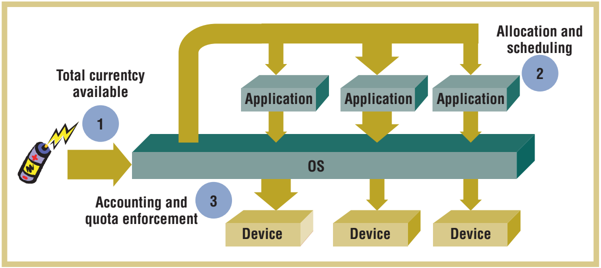
1. query **smart battery** (→ state of charge) prepare for fair allocation of currentcy among processes
2. **allocate** and schedule

→ **block** processes on currentcy depletion

→ processes may decide not to spend their currentcy share during an epoch

3. **accounting**

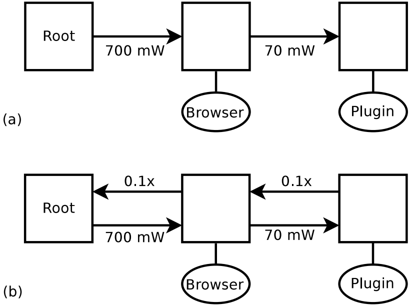
- accumulation of unspent currency is bounded (max. 10x of currentcy per epoch)


Total currentcy available
1
Allocation and scheduling
2
Application
Application
Application
OS
Accounting and quota enforcement
3
Device
Device
Device

[7]

Cinder Operating System

- Energy Management in Mobile Devices with the Cinder Operating System
  - **exokernel-based** operating system built on top HiStar OS
  - concept of reserves and taps
  - **reserve** (energy) → available energy resources
  - **taps** (power) → connection between (hierarchic) reserves



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Energy Management in Mobile Devices with the Cinder Operating System
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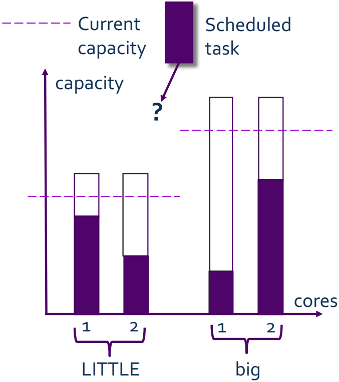
Linux Energy-Aware Scheduling

- Linux Energy-Aware Scheduling (EAS)
  - motivation: exploit heterogeneity for **peak performance** but **low average power** → software counterpart to ARM big.LITTLE architecture
  - energy-aware scheduling for heterogeneous multi-core systems
  - per-CPU energy model necessary

- EAS goals
  - process-dependent core pinning → reliable per-process predictions
  - adaptations of process scheduler
    - adapt to heterogeneous cores
    - energy-awareness → models + estimation
    - integration with DVFS subsystem



elinux.org

- Linux upstream: work in progress

Considerations and Caveats

- **system software**
  - abstraction of energy demand at operating-system level
  - identify interrelationships from higher-level perspectives
- managing energy as a **basic system resource**
  - accounting, allocation, and administering
  - capture and track power states → processes and devices
  - reduce energy demand by reordering
- **energy-aware operating systems**
  - holistic, system-wide resource management
  - use lower-level building blocks (i.e. energy management functions)
  - challenging integration for legacy operating systems

Paper Discussion

- paper discussion
  - Rolf Neugebauer and Derek McAuley
    Energy is just another resource: Energy accounting and energy pricing in the Nemesis OS
    Proceedings of the 8th Workshop on Hot Topics in Operating Systems (HotOS'01), 2001.

Subject Matter

- **system software** is the pivotal element for the **operation of energy-aware computing systems**
- „***energy is just another resource***", its management is a challenging endeavour
- **high-level perspectives** are essential for holistic, system-wide energy management techniques

- reading list for Lecture 9:
  - R. Pereira et al.
    Energy efficiency across programming languages: how do energy, time, and memory relate?
    Proceedings of the 10th ACM SIGPLAN International Conference on Software Language Engineering (SLE'17), 2017.

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In: *IEEE Transactions on Very Large Scale Integration (VLSI) Systems* 8 (2000), June, Nr. 3, S. 299–316

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Interaction of Power-aware Memory Systems and Processor Voltage Scaling.
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Experiences in managing energy with ecosystem.
In: *IEEE Pervasive Computing* (2005), Nr. 1, S. 62–68

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In: *Proceedings of the 2003 USENIX Annual Technical Conference (ATC'03)*, 2003, S. 43–56