Low-Power System Design

227-0781-00L

Fall Semester 2019

Jan Beutel

Plan for Today

- Introduction to the course theme
- Broad concepts and technology trends
- Logistics
  - Lecture
  - Reading/Writing Seminar
  - Hands-on Design Project

- Low-power system design opportunities
- Introduction to general terminology
- LP system architectures

Masters Course at D-ITET

- Low-power System Design
  - Engineering course at master level
  - Not another circuit design class (with some low-power aspects)
  - Not purely software/algorithms or applications
  - Not only up-front teaching: discussions, hands-on project participation, time for questions

- Objective
  - Low-power and low-energy design techniques from a systems perspective
  - Aspects both from hard- and software
  - Technology oriented but focusing on the fundamentals
  - Cutting across a number of related areas

- Goals
  - Introduction to the state-of-the-art in research
  - Empowering students to ask relevant questions and develop ideas critically
  - Enable students to work on a research project of publishable quality

What Makes These Perform So Well

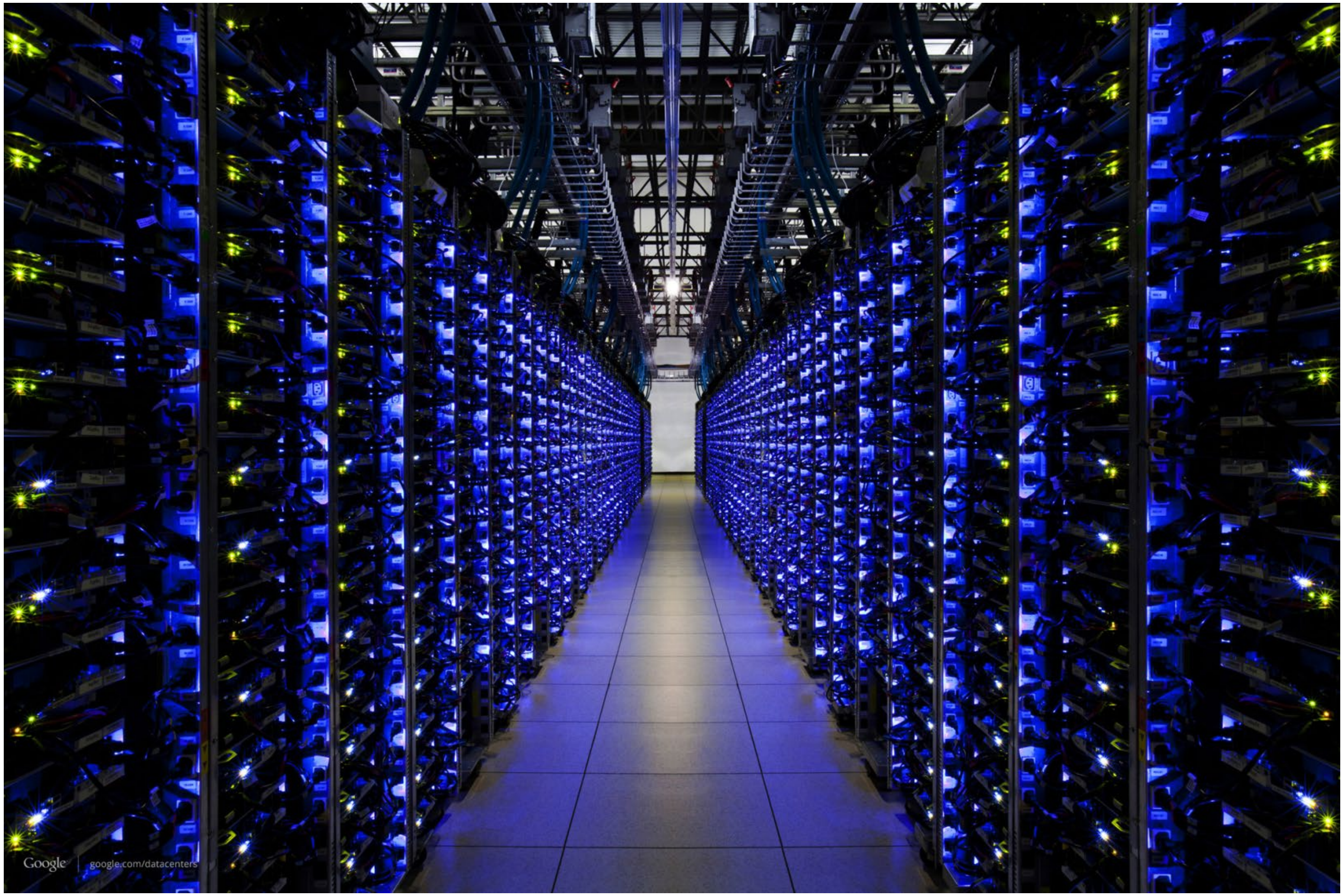
From ifixit.com

ETH zürich

How to Evade Daily Battery Changes

From toysrus

Why Power Is The Limit

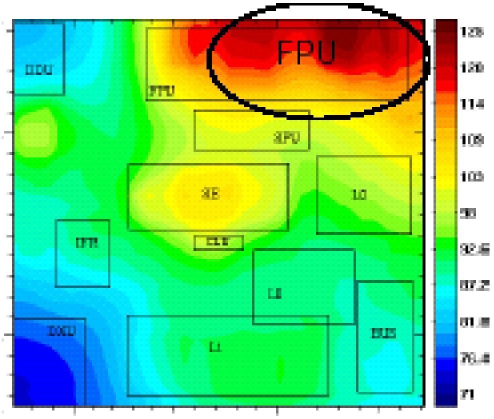


From google.com

What is Power Management?

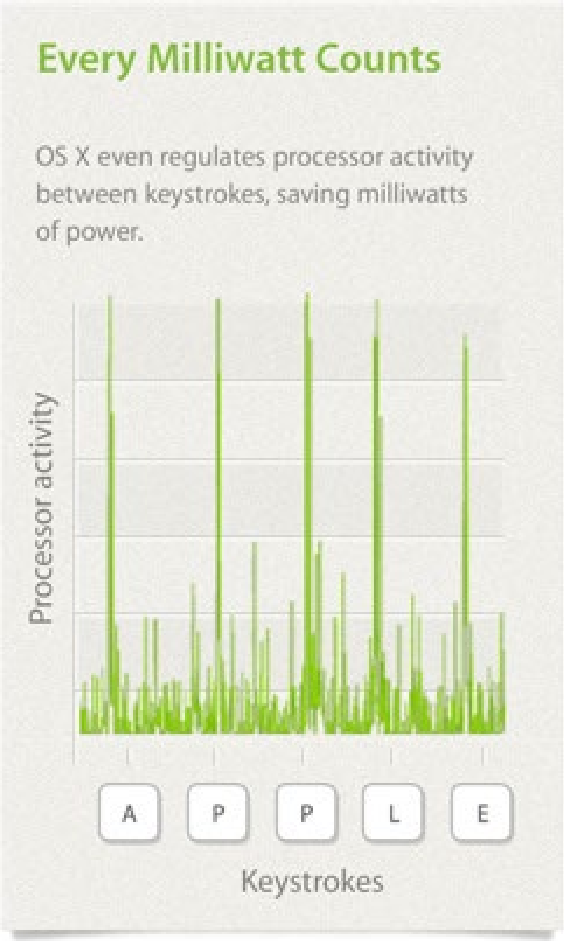
- Provisioning of energy for the required function in a timely manner
  - Availability of energy (volumetric)
  - Locality of energy (temporal, spatial)
  - Detrimental effects, e.g. excess heat production, cost of power and cooling, expensive materials

- Incentives for power management
  - Reduce overall energy consumption
  - Prolong battery life for portable and embedded systems
  - Reduce cooling requirements
  - Reduce noise
  - Reduce operating costs for energy and cooling
  - Cost of dark silicon



Energy-efficient Design Matters

- 2014 Apple MAC mini vs. previous generation
  - 2x CPU performance
  - 1.65x graphics



From apple.com

Recent Research on Energy-Efficiency Covers All Layers of System Design

eSENSE: Energy Efficient Stochastic Sensing Framework for Wireless Sensor Platforms

Haiyang Liu, Abhishek Cha
Dept. of Computer Science and E
Minneapoli
{hliu, chandra, sriv

ata Gathering in Sensor Networks

Energy-Efficient Data Representation and Routing for Wireless Sensor Networks Based on a Distributed Wavelet Compression Algorithm *

nio Ortega and Bhaskar Krishnamachari
tems, University of Southern California
lifornia, USA
ega@sipi.usc.edu, bkrishna@usc.edu

Lucid Dreaming: Reliable Analog Event Detection for Energy-Constrained Applications

Sasha Jevtic† Mathew Kotowsky‡ Robert P. Dick† Peter A. Dinda† Charles Dowding*

sjevtic@eecs.northwestern.edu, {kotowsky, dickrp, pdinda, c-dowding}@northwestern.edu

†EECS Dept. Northwestern University
‡Infrastructure Technology Inst. Northwestern University
*Civil & Environmental Engg. Northwestern University

ptimized Image Communication on
Platforms
al Detection under the
less Sensor Networks*

nmad Rahimi[2]
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ia, Los Angeles
ornia, Los Angeles
, Los Angeles
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rsity
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ehigh.edu

Energy-efficient Coverage for Target Detection in Wireless Sensor Networks

Wei Wang, Vikram Srinivasan, Kee-Chaing Ch
Department of Electrical and Computer I
National University of Singapo
{wang.wei,elevs,eleckc}@nus.edu.sg,wangb

Power Scheduling for Wireless

Energy-efficient routing in wireless sensor networks for delay sensitive applications

D. Ranganathan, P. K. Pothuri, V. Sarangan, and S. Radhakrishnan

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crozell@rice.edu

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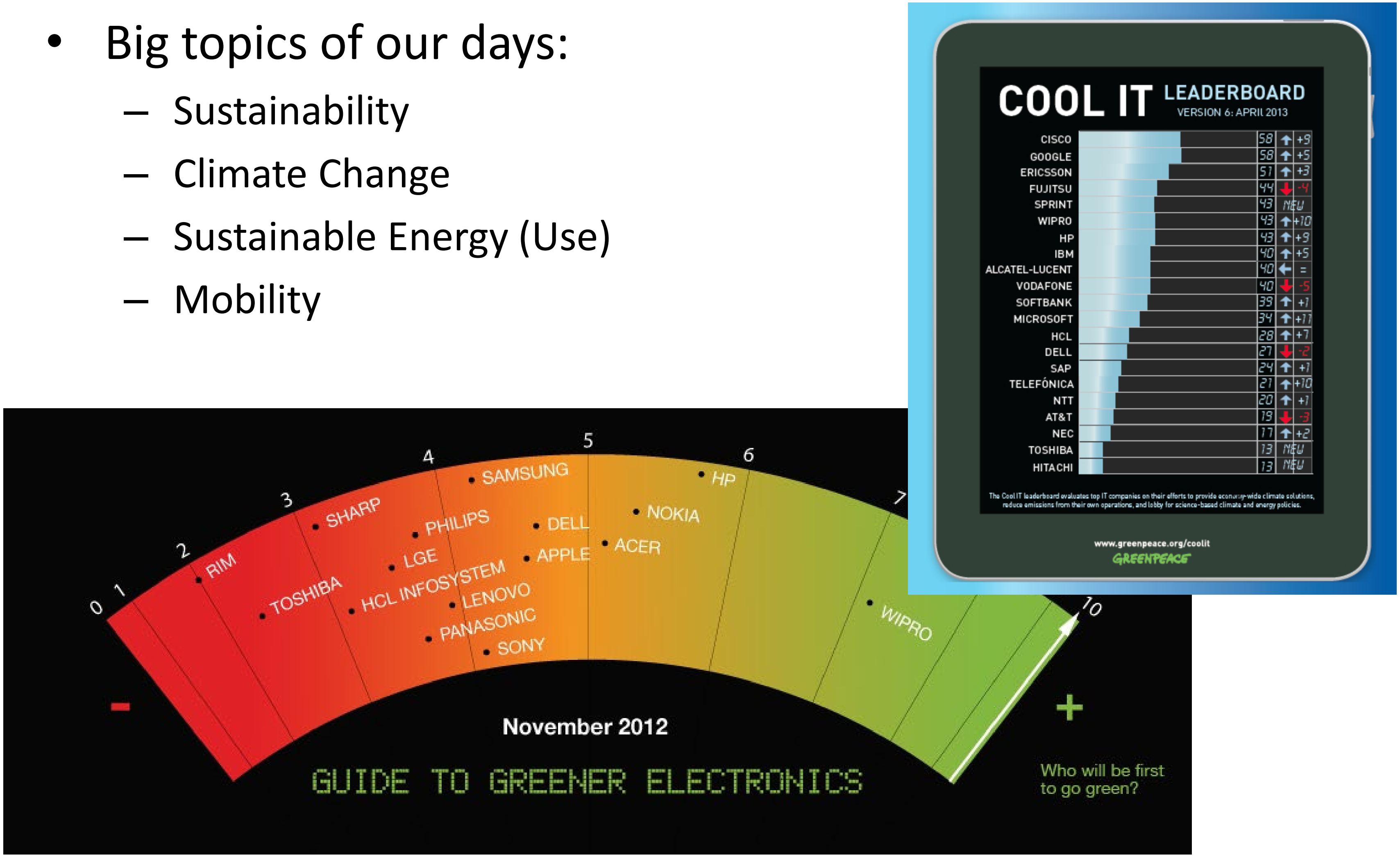
dhj@rice.edu

Slide abridged from P. Dutta, U Michigan

Energy is on the Political Agenda

Implications At The Societal Level

- Big topics of our days:
  - Sustainability
  - Climate Change
  - Sustainable Energy (Use)
  - Mobility



COOL IT LEADERBOARD

VERSION 6: APRIL 2013

CISCO	58	↑	+9
GOOGLE	58	↑	+5
ERICSSON	51	↑	+3
FUJITSU	44	↓	-4
SPRINT	43	NEW	
WIPRO	43	↑	+10
HP	43	↑	+9
IBM	40	↑	+5
ALCATEL-LUCENT	40	←	=
VODAFONE	40	↓	-5
SOFTBANK	39	↑	+1
MICROSOFT	34	↑	+11
HCL	28	↑	+7
DELL	27	↓	-2
SAP	24	↑	+1
TELEFÓNICA	21	↑	+10
NTT	20	↑	+1
AT&T	19	↓	-3
NEC	17	↑	+2
TOSHIBA	13	NEW	
HITACHI	13	NEW	

The Cool IT leaderboard evaluates top IT companies on their efforts to provide economy-wide climate solutions, reduce emissions from their own operations, and lobby for science-based climate and energy policies.

www.greenpeace.org/coolit

GREENPEACE

November 2012

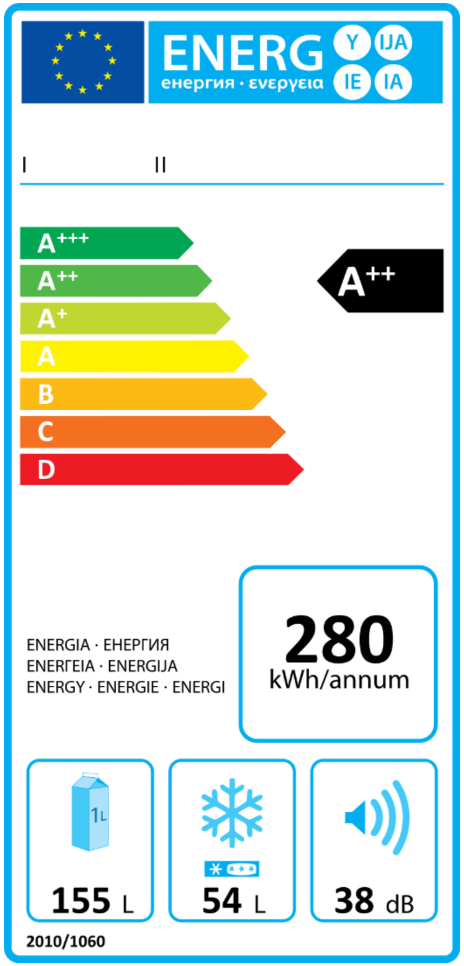
GUIDE TO GREENER ELECTRONICS

Who will be first to go green?

Figures from greenpeace.org

European Union Energy Label

- Energy labels are separated into at least four categories
  - Appliance's details
    - According to each appliance, specific details, of the model and its materials
  - Energy class
    - Color code giving an idea of the appliance's electrical consumption
  - Consumption, efficiency, capacity, etc. according to appliance type
  - Noise emitted by the appliance



From wikipedia

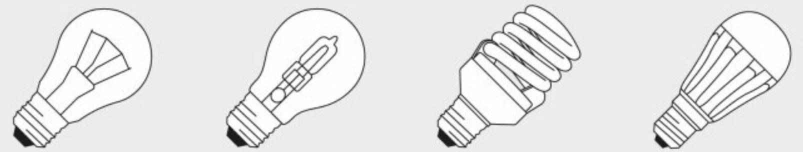
Example: The Incandescent Light Bulb

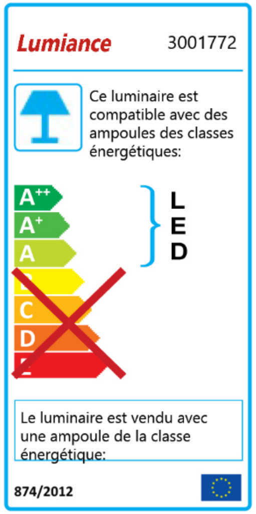
- An incandescent light bulb is an electric light which produces light with a **wire filament heated** to a high temperature by an electric current passing through it, **until it glows**. The hot filament is protected from oxidation with a glass or quartz bulb that is filled with inert gas or evacuated.

From Wikipedia

Example: Light Bulb Evolution

GLS Incandescent lamp	**HAL** Halogen lamp	**CFL** Compact fluorescent lamp	**LED** LED lamp
25 x	12.5 x	2.5 x	1 x
Average lifetime 1000 h	**Average lifetime** 2000 h	**Average lifetime** 10000 h	**Average lifetime** 25000 h





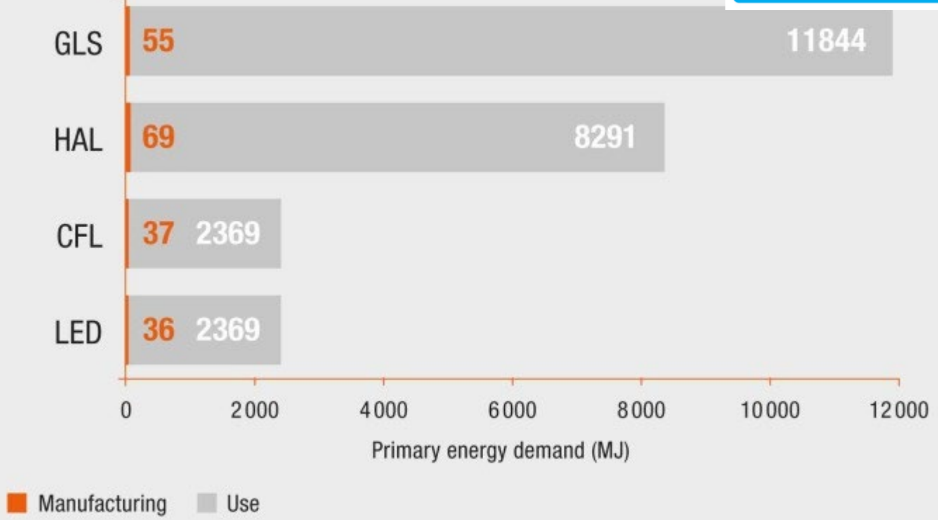
Lumiance 3001772

Ce luminaire est compatible avec des ampoules des classes énergétiques:

Le luminaire est vendu avec une ampoule de la classe énergétique:

874/2012

CUMULATED ENERGY DEMAND GLS, HAL, CFL, LED

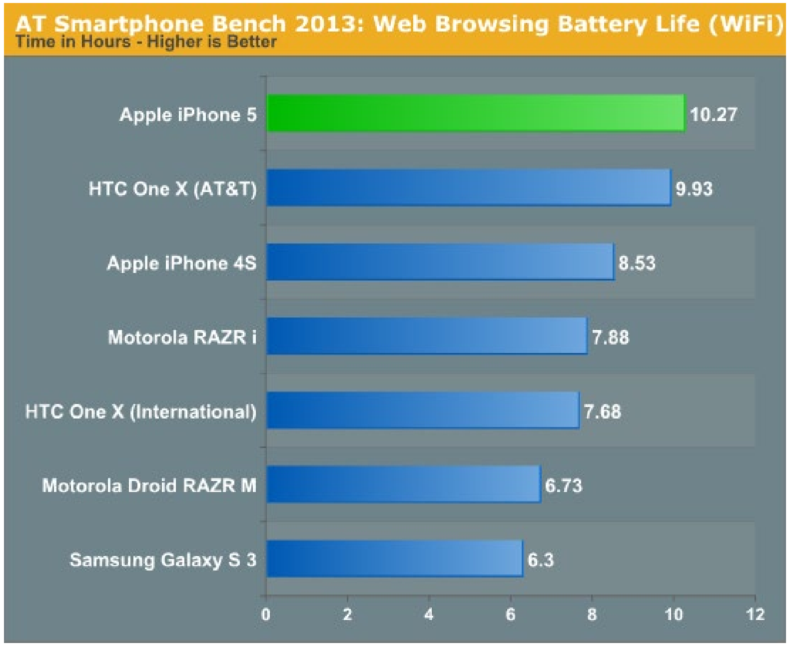


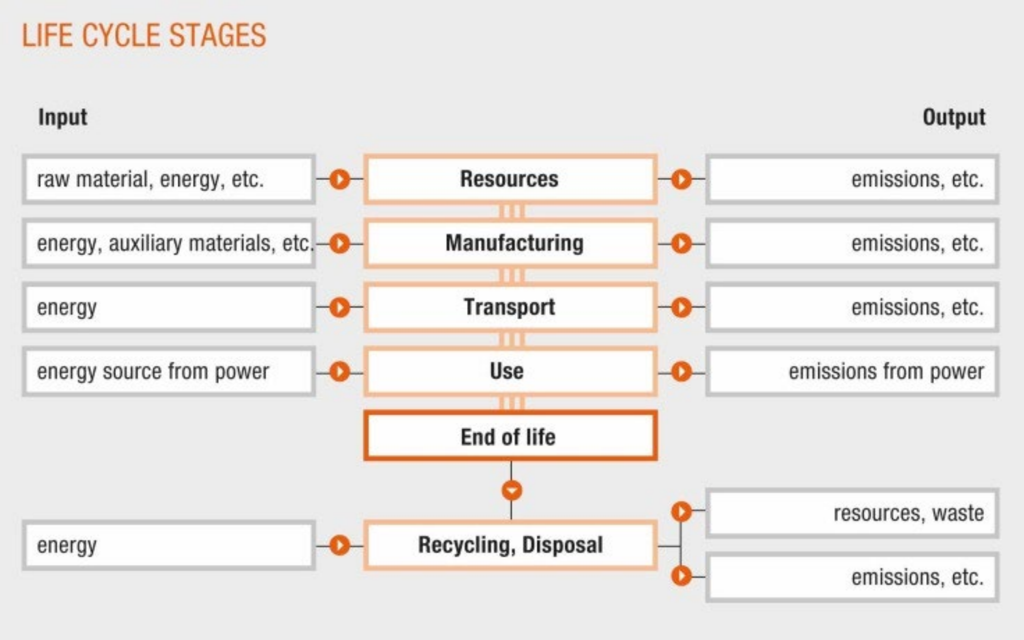
From osram.com

Energy Concerns Beyond System Operation

Popular low-power "sales" arguments is limited to product usage

The real energy footprint is much larger

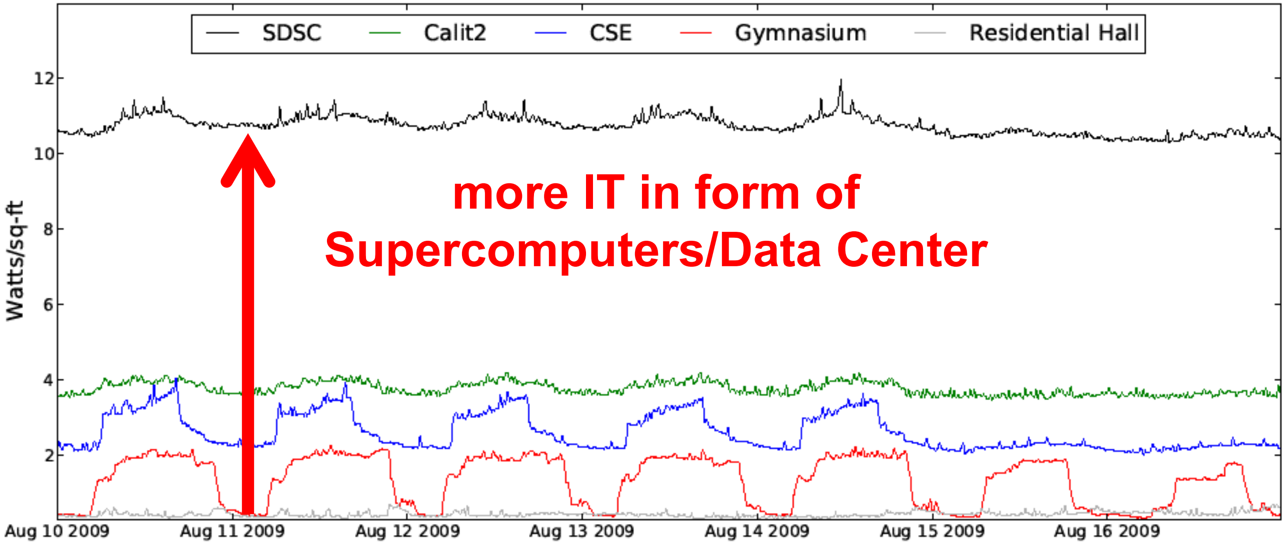




From osram.com

Research Trend: Building- Scale Energy Research (UCSD)

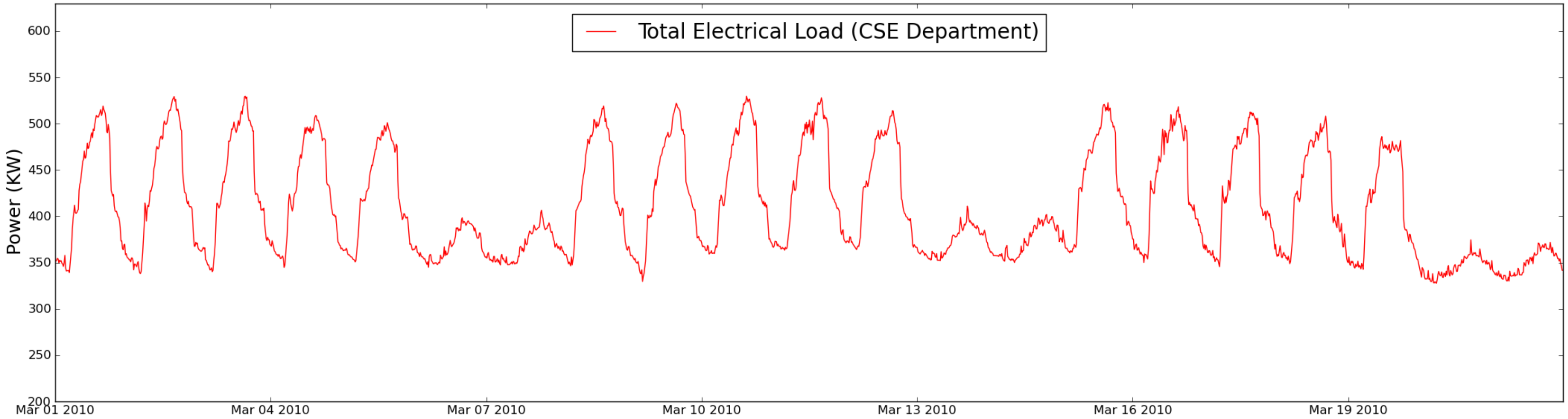
- Electricity in the US
  - Annual production: 4310 TWh, consumption: 3819 TWh in 2013
  - Buildings require: 2,500 TWh, electronics inside: ~290 TWh
- Buildings consume significant amounts of energy
  - >70% of total US electricity consumption
  - >40% of total carbon emissions

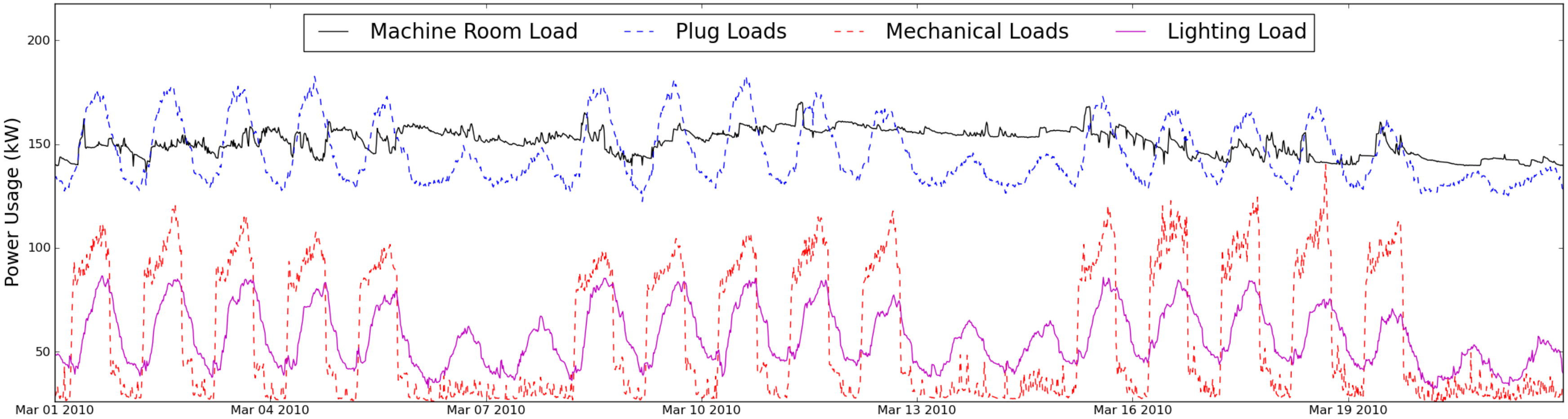


more IT in form of Supercomputers/Data Center

From Yuvraj Agrawal, UCSD

University Building Energy Breakdown





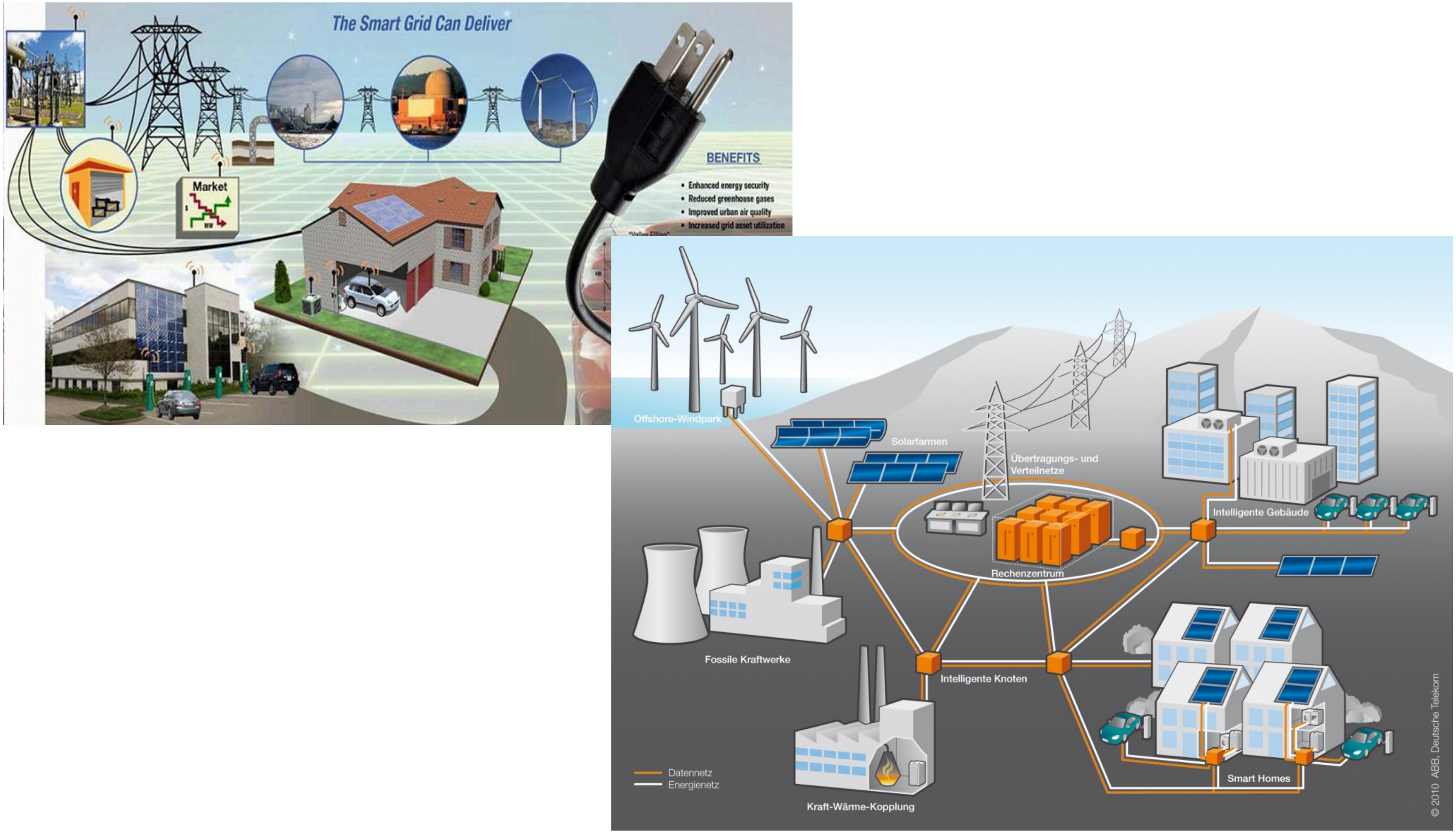
From Yuvraj Agrawal, UCSD

Improving Energy Efficiency in Buildings

1. Reduce energy consumption by IT equipment
   - Servers and PCs left on to maintain network presence
   - Key Idea: “Duty-Cycle” computers aggressively
2. Reduce energy consumption by the HVAC system
   - Energy use is not proportional to number of occupants
   - Key Idea: Use real-time occupancy to drive HVAC

- Issues
  - “Always ON” abstraction of the Internet
  - Once turned OFF, how to turn back on?
  - Use models of user/application and infrastructure
  - Granularity of services/sensors
  - …

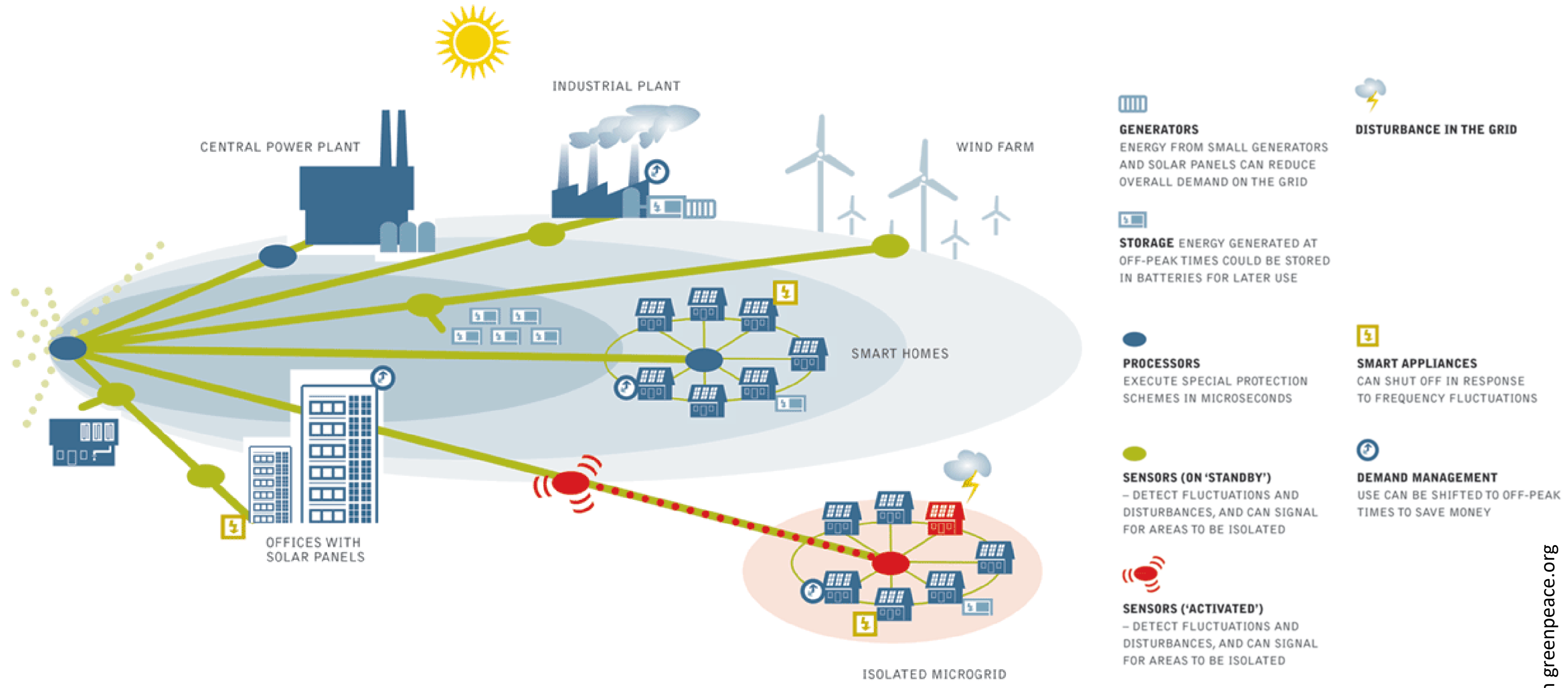
In Practice: A Simple Source And Sink Was Yesterday



© 2010 ABB, Deutsche Telekom

Adding Software And Networking to Large-Scale Energy Systems

- Smart Grid
  - Leveraging information to improve efficiency, reliability, economics and sustainability in production, distribution and use of energy.



GENERATORS ENERGY FROM SMALL GENERATORS AND SOLAR PANELS CAN REDUCE OVERALL DEMAND ON THE GRID

DISTURBANCE IN THE GRID

STORAGE ENERGY GENERATED AT OFF-PEAK TIMES COULD BE STORED IN BATTERIES FOR LATER USE

PROCESSORS EXECUTE SPECIAL PROTECTION SCHEMES IN MICROSECONDS

SMART APPLIANCES CAN SHUT OFF IN RESPONSE TO FREQUENCY FLUCTUATIONS

SENSORS (ON 'STANDBY') – DETECT FLUCTUATIONS AND DISTURBANCES, AND CAN SIGNAL FOR AREAS TO BE ISOLATED

DEMAND MANAGEMENT USE CAN BE SHIFTED TO OFF-PEAK TIMES TO SAVE MONEY

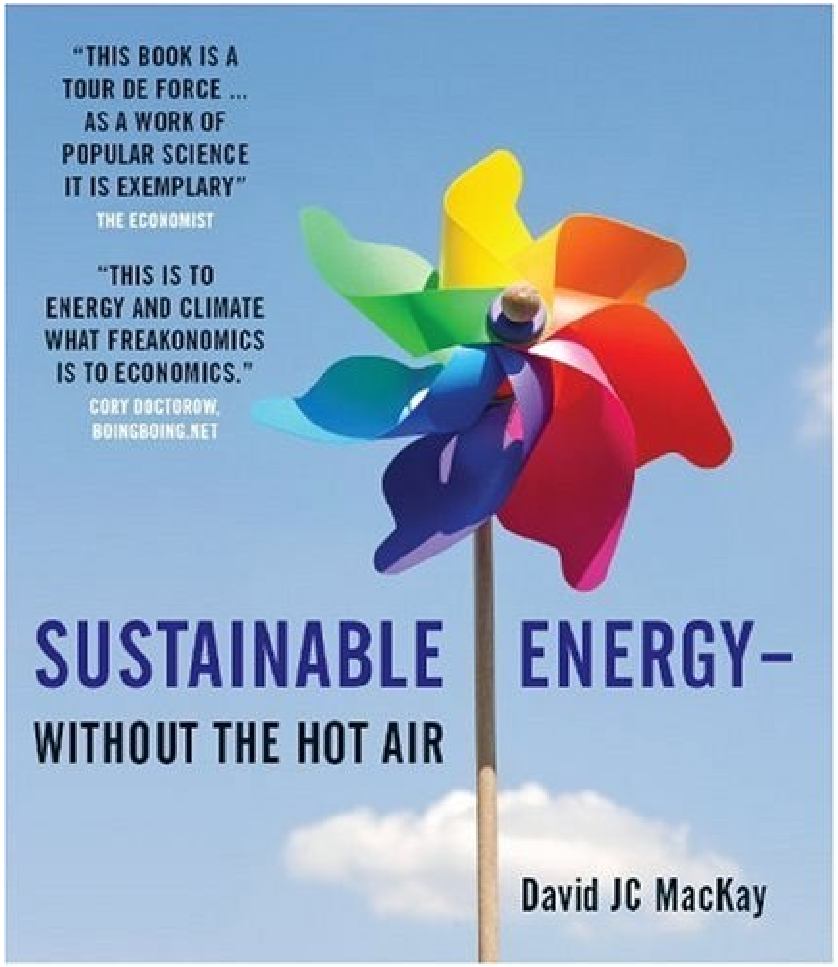
SENSORS ('ACTIVATED') – DETECT FLUCTUATIONS AND DISTURBANCES, AND CAN SIGNAL FOR AREAS TO BE ISOLATED

From greenpeace.org

Some Easy “Bedtime” Reading

- **David JC MacKay**
  Regius Professor of Engineering in the Department of Engineering at the University of Cambridge and chief scientific adviser to the UK Department of Energy and Climate Change
- A physicists view on the present day global energy discussion
- Free book available online
  http://www.withouthotair.com/
- Short video
  David MacKay: A reality check on renewables. **TEDx Warwick**, March 2012.

  https://www.ted.com/talks/david_mackay_a_reality_check_on_renewables



Renewable Energy At Scale

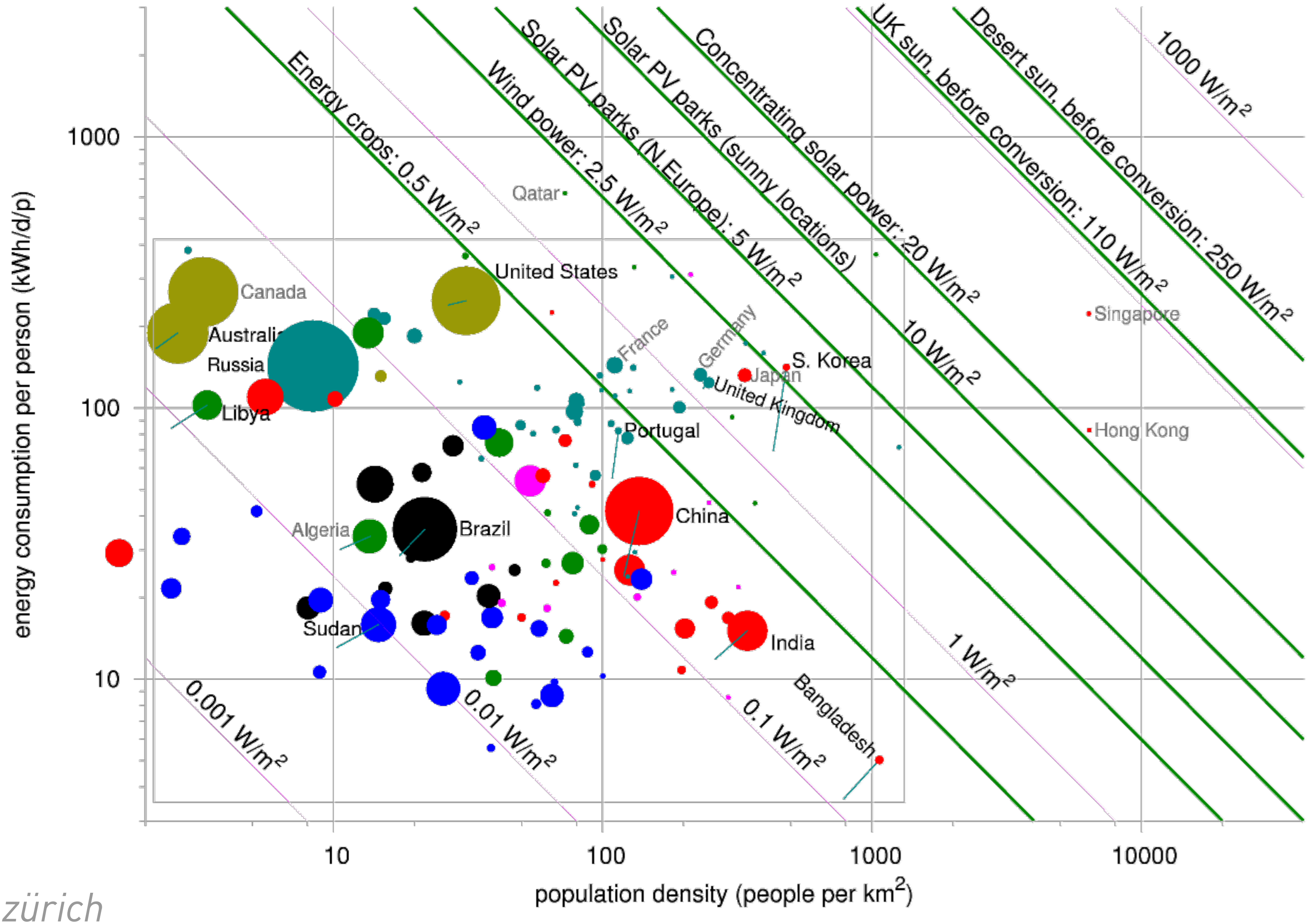
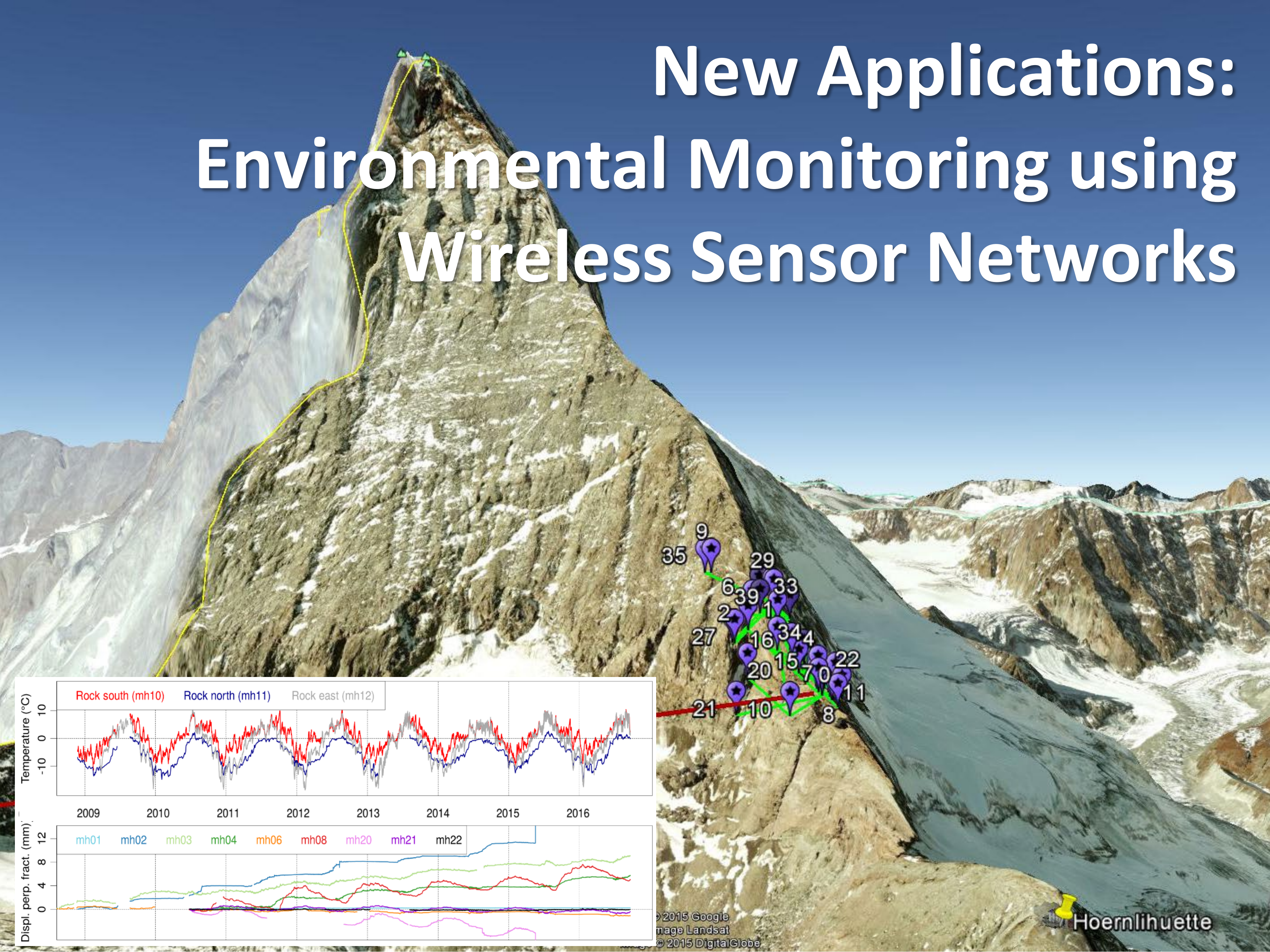


Figure by David J C MacKay www.withouthotair.com

New Applications: Environmental Monitoring using Wireless Sensor Networks



Low-Power System Design

COURSE LOGISTICS

Course Components

- Goals of LPSD
  - Introduction to the state-of-the-art in research
  - Empowering students to ask relevant questions and develop ideas critically
  - Enable students to work on a research project of publishable quality

- Components
  - Up front lecture with slides (please make it interactive, ask questions)
  - Reading and writing seminar
  - Hands-on practical work, design project

Course Resources

- Online course web page
  https://www.tec.ee.ethz.ch/education/lectures/low-power-system-design.html
  - Syllabus
  - Reading material
  - Assignments
  - Links to further resources
  - Updates to material as we progress
- Riot chat room for reading seminar: #lpsd:matrix.ee.ethz.ch
  - Submitting reviews
  - Discussion
  - Sharing of other related papers, interesting stuff
  - Questions/Answers
- In case of questions: janbeutel@ethz.ch

Lecture Schedule

Week	Date	Lecture Wednesday 10-12h	Lab Exercises Wednesday 13-15h
1	18.09.2019	Lecture 1 - Course Introduction, Definitions, Metrics	Reading/Writing Seminar Introduction
2	25.09.2019	Lecture 2 - LP System Architectures	Lab 1
3	02.10.2019	Lecture 3 – LP System Architectures	Lab 2
4	09.10.2019	**No Lecture - Reading Seminar only**	Lab 3
5	16.10.2019	**No Lecture - Reading Seminar only**	Lab 4
6	23.10.2019	Lecture 4 – Networked Embedded Systems	Intro Design Project
7	30.10.2019	Lecture 5 – Networked Embedded Systems	Technical Support for Design Project
8	06.11.2019	Lecture 6 – Networked Embedded Systems	Technical Support for Design Project
9	13.11.2019	Lecture 7 - Networked Embedded Systems	Technical Support for Design Project
10	20.11.2019	Lecture 8 - Modeling, Tools and Methods for Power Analysis	Technical Support for Design Project
11	27.11.2019	Lecture 9 - Modeling, Tools and Methods for Power Analysis	Technical Support for Design Project
12	04.12.2019	Lecture 10 - Renewable Energy	Technical Support for Design Project
13	11.12.2019	Lecture 11 - Renewable Energy	Technical Support for Design Project
14	18.12.2019	Lecture 12 - Project Presentations	Student Presentations of Design Project

Daily Synopsis

- Lecture (~60-75 min)
  - Recap last lecture, introduce structure of topics & objective of today's lecture
  - Daily lecture
  - Feed in a daily
    - Hot research topic/paper of the day
    - Prominent research figure in the area
    - Practical example (success story or failure)
  - Recap objective of the day

- Reading and Writing Seminar (~30 min)
  - Short presentation by group of students
  - Discussion of papers
  - Introduce reading for next week

- Exercises, Lab and Reading Time (2x 45 min)
  - Dual Processor Platform (DPP) on loan for everyone
  - Introduction to DPP platform & FlockLab testbed
  - DPP tutorial support
  - Small design project in groups of 2-3 over whole length of the course

Reading and Writing Seminar

- Reading assignment of 1 paper per week – **until FRIDAY**
  - 2-3 students prepare a written summary (max. 200-300 words)
    - Write-up should contain the (i) essential points of the paper, (ii) it’s main contribution and (iii) your assessment
    - Research of related work: recent papers, different approaches, historical background…
  - Summary is shared with all via discussion forum (matrix chatroom)

- Discussion/questions/comments – **FRIDAY to WEDNESDAY**
  - EVERYBODY comments on review summary and paper
    - Your own opinion
    - Corrections/additions to the reviewers voice
    - Additional questions
  - Joint search for related work, interesting ecosystem etc.

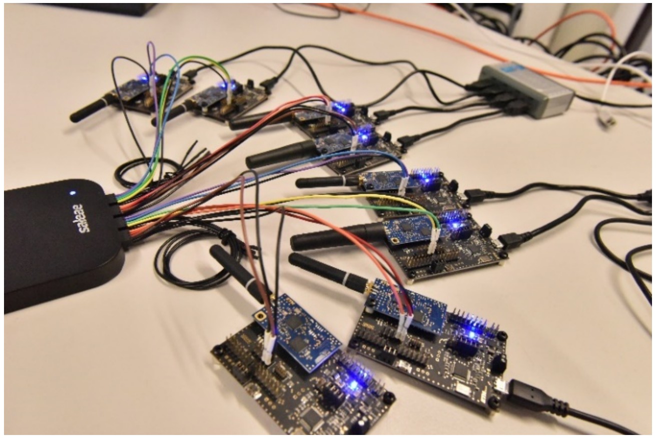
- Joint discussion of papers in class – **WEDNESDAY in class**
  - Short presentation of paper and summary in class to kick off discussion
  - Presentation using max. 3-4 slides (not a full paper presentation)

- Reading/writing and your contributing to the discussions is part of the grade (30%)

- Assignment via signup sheet with
  - 1x summary write-up/paper presentation
  - 4x review/commenting per student

Hands-on Practical Design Project

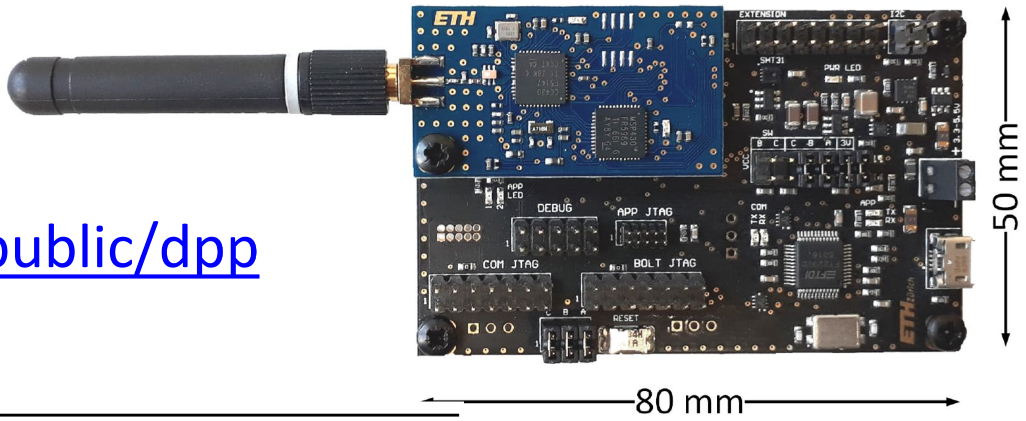
- Design project using Dual Processor Platform (DPP)



- In groups (of 2-3) develop a low-power application
  - Introduction to state-of-the-art tools
  - Effective power consumption effects should be visible
  - Focus on aspects of dynamic range
- Presentation and discussion of results in final lecture
- Tournament: Best team is awarded a prize

Resources for Hands-on

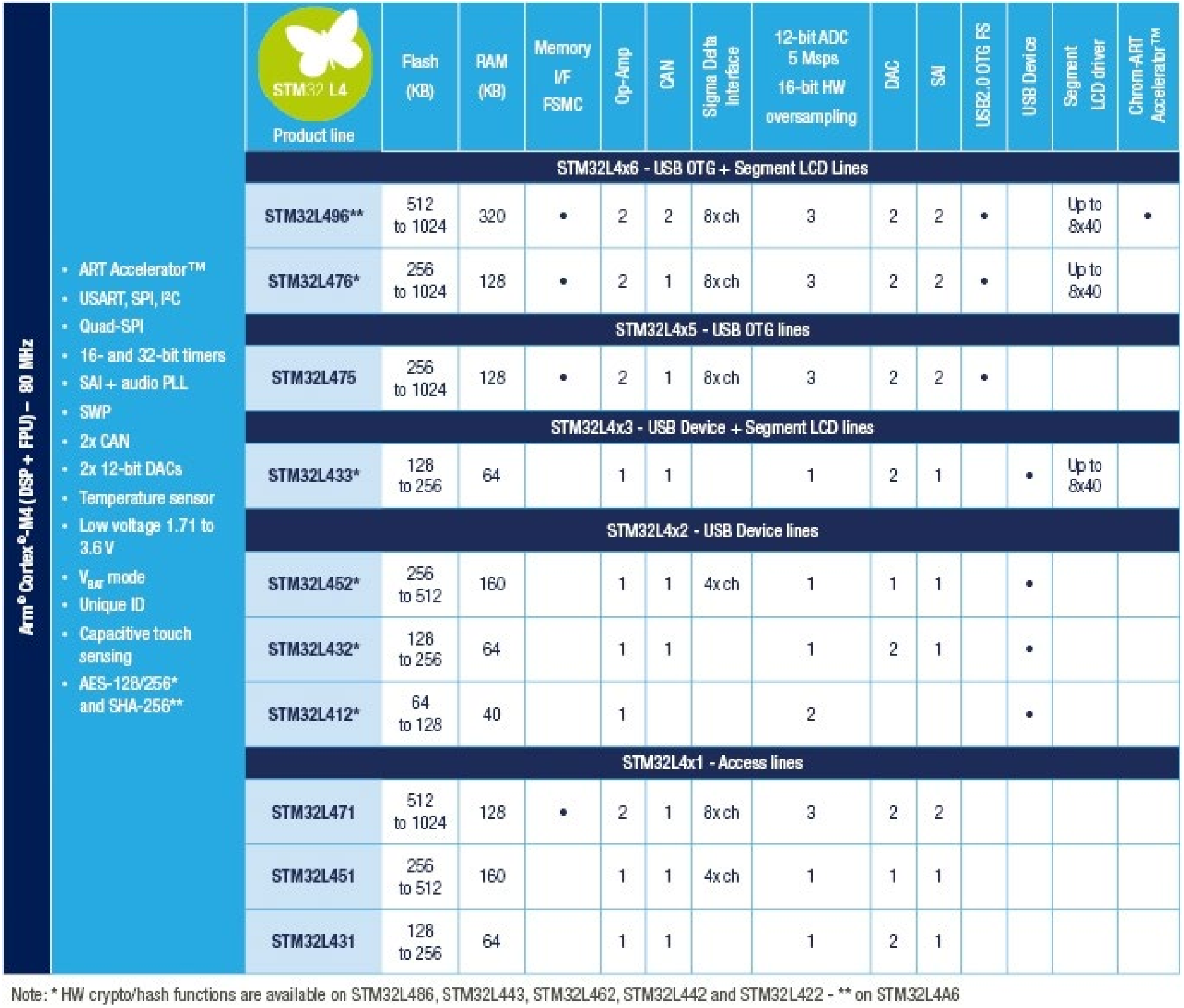
- Dual-Processor Platform
  - State-of-the-Art Sensor network platform
  - ETH-built…



https://gitlab.ethz.ch/tec/public/dpp

DPP2 SX1262 ComBoard
ST STM32L433CC, 256k ROM, 64k SRAM, 80 MHz
RAM2 (16 KiB) has option for retention
0.28 µA (standby with RTC), 7 µs wakeup from stop mode
−148 dB at (SF12, 125 kHz), 389 mW at +22 dB m
LoRa, GFSK

Resources for Hands-on



Arm® Cortex®-M4 (DSP + FPU) – 80 MHz

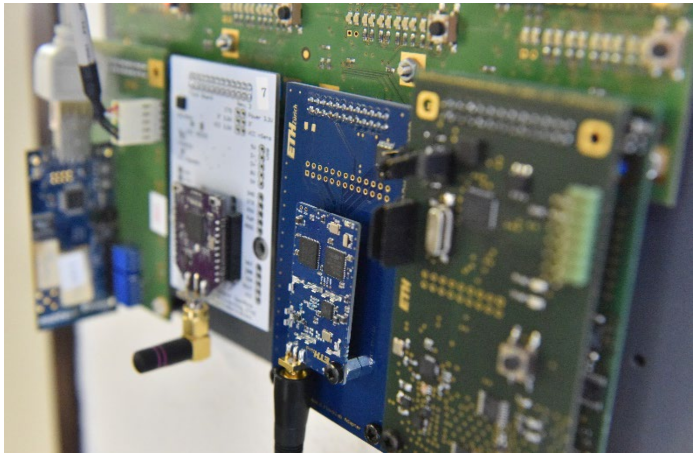
- ART Accelerator™
- USART, SPI, I^{2}C
- Quad-SPI
- 16- and 32-bit timers
- SAI + audio PLL
- SWP
- 2x CAN
- 2x 12-bit DACs
- Temperature sensor
- Low voltage 1.71 to 3.6 V
- V_{BAT} mode
- Unique ID
- Capacitive touch sensing
- AES-128/256* and SHA-256**

STM32 L4 Product line	Flash (KB)	RAM (KB)	Memory I/F FSMC	Op-Amp	CAN	Sigma Delta Interface	12-bit ADC 5 Msps 16-bit HW oversampling	DAC	SAI	USB2.0 OTG FS	USB Device	Segment LCD driver	Chrom-ART Accelerator™
STM32L4x6 - USB OTG + Segment LCD Lines													
STM32L496**	512 to 1024	320	•	2	2	8x ch	3	2	2	•		Up to 8x40	•
STM32L476*	256 to 1024	128	•	2	1	8x ch	3	2	2	•		Up to 8x40	
STM32L4x5 - USB OTG lines													
STM32L475	256 to 1024	128	•	2	1	8x ch	3	2	2	•			
STM32L4x3 - USB Device + Segment LCD lines													
STM32L433*	128 to 256	64		1	1		1	2	1		•	Up to 8x40	
STM32L4x2 - USB Device lines													
STM32L452*	256 to 512	160		1	1	4x ch	1	1	1		•		
STM32L432*	128 to 256	64		1	1		1	2	1		•		
STM32L412*	64 to 128	40		1			2				•		
STM32L4x1 - Access lines													
STM32L471	512 to 1024	128	•	2	1	8x ch	3	2	2				
STM32L451	256 to 512	160		1	1	4x ch	1	1	1				
STM32L431	128 to 256	64		1	1		1	2	1				

Note: * HW crypto/hash functions are available on STM32L486, STM32L443, STM32L462, STM32L442 and STM32L422 - ** on STM32L4A6

Resources for Hands-on

- DPP dev-board on loan for everyone for duration of semester
- FlockLab Testbed
  - Testbed of 30+ nodes
  - Remote programming of nodes
  - Testing of applications in larger networks
  - Power profiling, digital tracing/actuation
- FlockLab is a shared/limited resource
  - Only one user active per time slice
  - Need to accommodate everyone
- Cooja Simulator support
- Support through online forums and TA's
  - Roman Trueb roman.trueb@tik.ee.ethz.ch
  - Matthias Meyer matthias.meyer@tik.ee.ethz.ch
  - Reto Da Forno reto.daforno@tik.ee.ethz.ch



http://www.flocklab.ethz.ch/

Grading

- Official announcement
  - 30% contributions to the reading/writing seminar
  - 70% oral exam
- Hands-on design project
  - A successful design project will count positive towards the oral exam grade
  - Part of the oral exam will review your proposed solution and the concepts underlying the implementation

Some Comments

- Course will mean quite some work for you.

- Reading takes some time. Use Wednesday afternoons.

- Will shift around timing as needed.

- Also we can discuss your topics/questions as needed.

- Hands-on design project was very successful in past years
  - Depends on your own laptop infrastructure
  - Need to share resources on FlockLab testbed
  - Requires you to plan ahead (not just a last minute effort)

Timeout

- What do you want to learn about low-power system design?
- Your expectations?
- Your backgrounds?

LOW-POWER SYSTEM DESIGN OPPORTUNITIES

What’s Inside & Makes It Tick So Well?

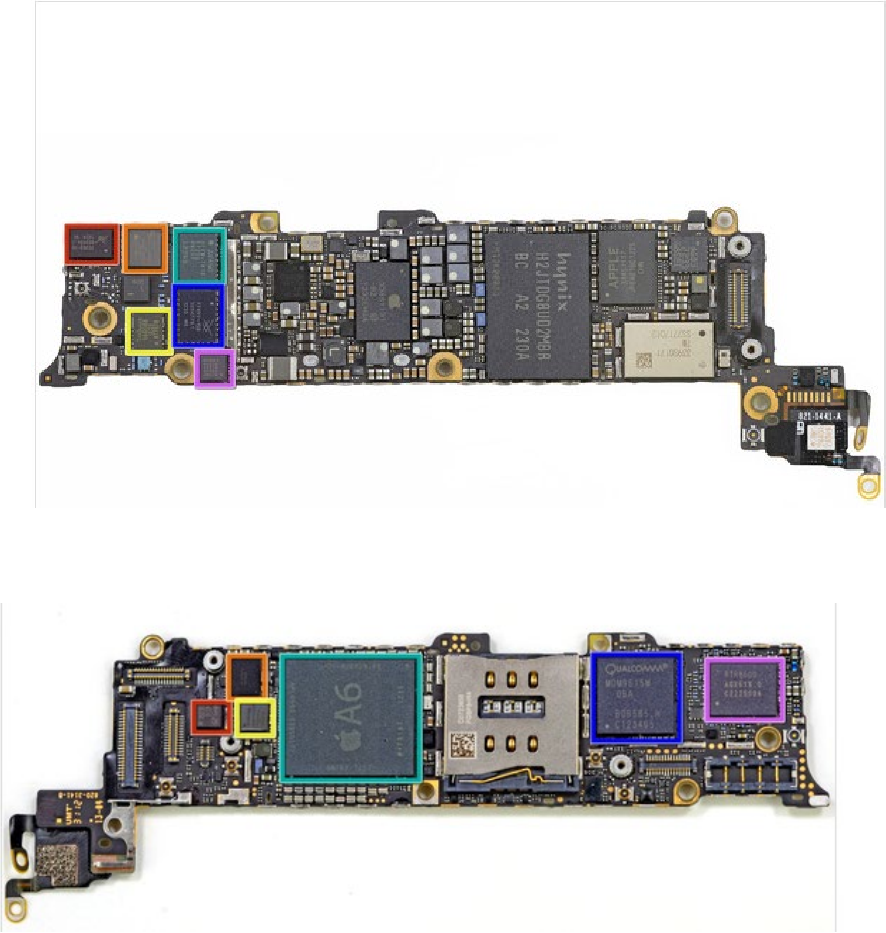
From ifixit.com

Inside an iPhone5

From ifixit.com

What’s Inside an iPhone5?

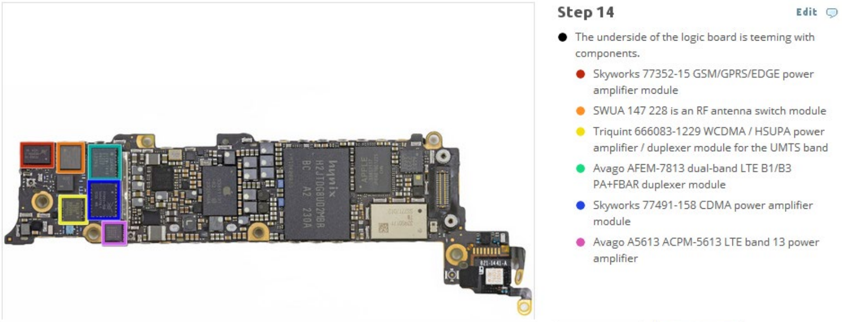
- How many
  - CPU’s + Storage?
  - Wireless radios?
  - Wireless amplifiers/peripherals?
  - Sensors?
  - Peripherals?
  - Power management?



From ifixit.com

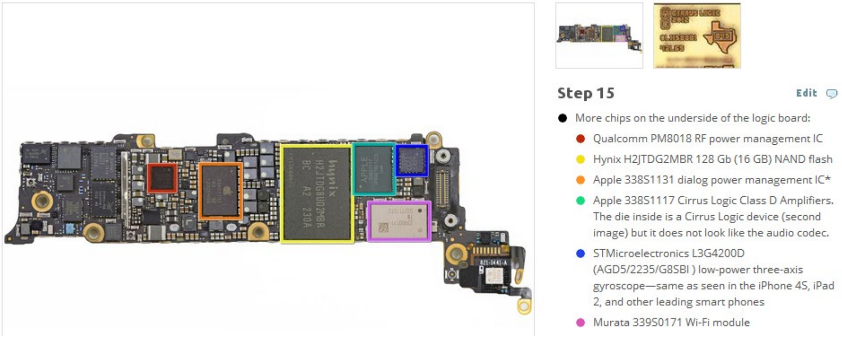
What’s Inside an iPhone5?

- CPU’s + Storage
    - Apple A6 339S0177 Application Processor. (2x ARM, 3x GPU)
    - Elpida 1 GB LPDDR2 DRAM
    - Hynix H2JT0G8UD2MBG NAND Flash. 16 GB
    - Qualcomm MDM9615 4G LTE processor + Samsung 1Gb DRAM memory
- Wireless radios
    - CDMA (800, 1900, 2100 MHz)
    - UMTS/HSPA+/DC-HSDPA (850, 900, 1900, 2100 MHz)
    - GSM/EDGE (850, 900, 1800, 1900 MHz)
    - LTE (+ GPS)
    - 802.11a/b/g/n Wi-Fi (2.4GHz, 5GHz) + Bluetooth 4.0
- Wireless amplifiers/peripherals
    - Skyworks 77352-15 GSM/GPRS/EDGEPower Amplifier Module
    - Skyworks 77491-15B Power Amplifier Module
    - Avago AFEM 7813 Power Amplifier Module
    - Avago ACPM-5613 LTE band 13 Power Amplifier
    - Skyworks 70631 LNA
    - Triquint 666083-1229 WCDMA / HSUPA power amplifier / duplexer module
    - Murata module D06 with Peregrine DP12T RF Switch
    - Murata module SWUA147
    - RF Micro RF1101 Hi-Power SPDT Switch
    - RF Micro RF1102 Antenna Tuning Module
    - Qualcomm MDM9615 LTE Processor
    - PM8018 RF Power Management
    - Murata 339S0171 WiFi module
    - Qualcomm RTR8600
- Sensors
    - STMicroelectronics L3G4200D 3 Axis gyro.
    - STMicroelectronics LIS331DLH (2233/DSH/GFGHA) three axes accelerometer
    - OmniVision Camera 1.2Mp
    - Sony Camera 8 Mp
- Peripherals
    - Apple 338S1077 Audio CODEC
    - Apple 338S1117 Cirrus Audio Chip
    - Texas Instruments 27C24S1 / 343S0628 touch screen controller
    - BCM5976 trackpad controller
- Power management
    - Apple 338S1131 Power Management IC
    - PM8018 Qualcomm RF Power Management IC



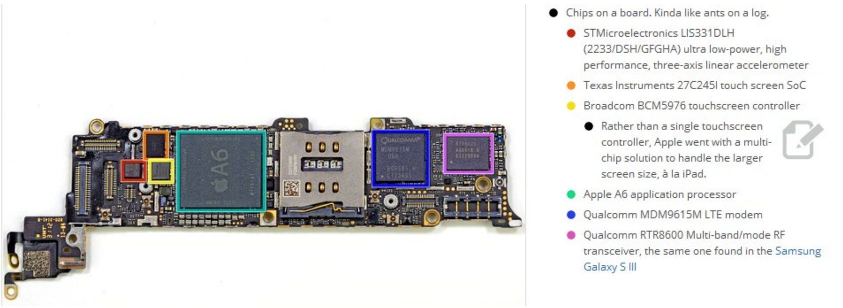
Step 14 Edit

- The underside of the logic board is teeming with components.
    - ● Skyworks 77352-15 GSM/GPRS/EDGE power amplifier module
    - ● SWUA 147 228 is an RF antenna switch module
    - ● Triquint 666083-1229 WCDMA / HSUPA power amplifier / duplexer module for the UMTS band
    - ● Avago AFEM-7813 dual-band LTE B1/B3 PA+FBAR duplexer module
    - ● Skyworks 77491-158 CDMA power amplifier module
    - ● Avago A5613 ACPM-5613 LTE band 13 power amplifier



Step 15 Edit

- More chips on the underside of the logic board:
    - ● Qualcomm PM8018 RF power management IC
    - ● Hynix H2JTDG2MBR 128 Gb (16 GB) NAND flash
    - ● Apple 338S1131 dialog power management IC*
    - ● Apple 338S1117 Cirrus Logic Class D Amplifiers. The die inside is a Cirrus Logic device (second image) but it does not look like the audio codec.
    - ● STMicroelectronics L3G4200D (AGD5/2235/G8SBI) low-power three-axis gyroscope—same as seen in the iPhone 4S, iPad 2, and other leading smart phones
    - ● Murata 339S0171 Wi-Fi module

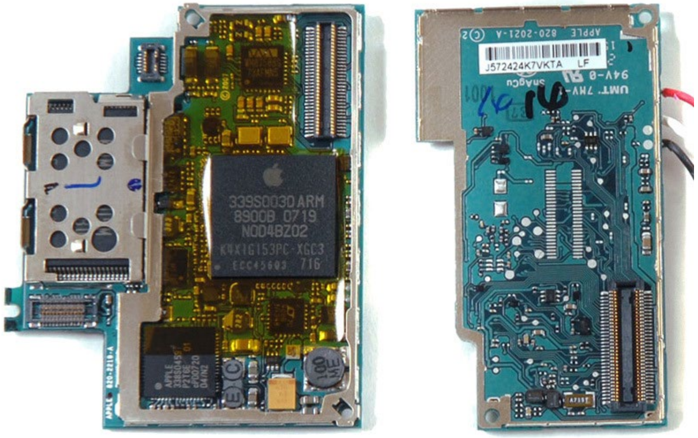


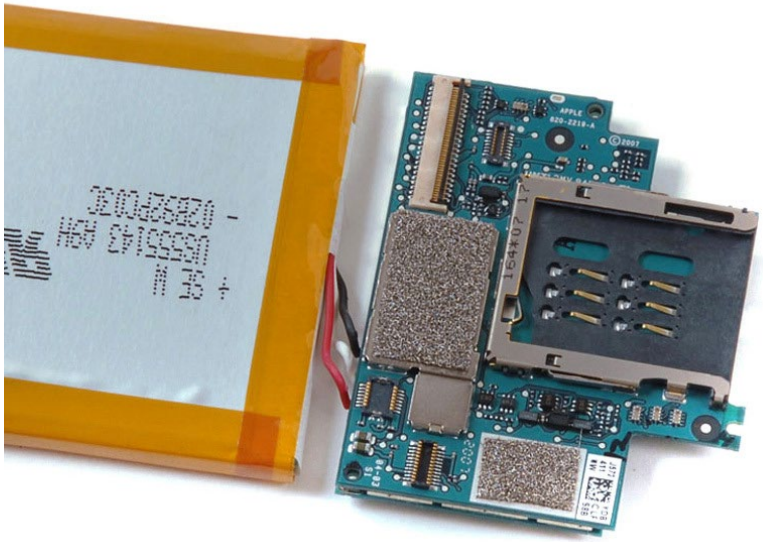
- Chips on a board. Kinda like ants on a log.
    - ● STMicroelectronics LIS331DLH (2233/DSH/GFGHA) ultra low-power, high performance, three-axis linear accelerometer
    - ● Texas Instruments 27C245I touch screen SoC
    - ● Broadcom BCM5976 touchscreen controller
        - Rather than a single touchscreen controller, Apple went with a multi-chip solution to handle the larger screen size, à la iPad.
    - ● Apple A6 application processor
    - ● Qualcomm MDM9615M LTE modem
    - ● Qualcomm RTR8600 Multi-band/mode RF transceiver, the same one found in the Samsung Galaxy S III

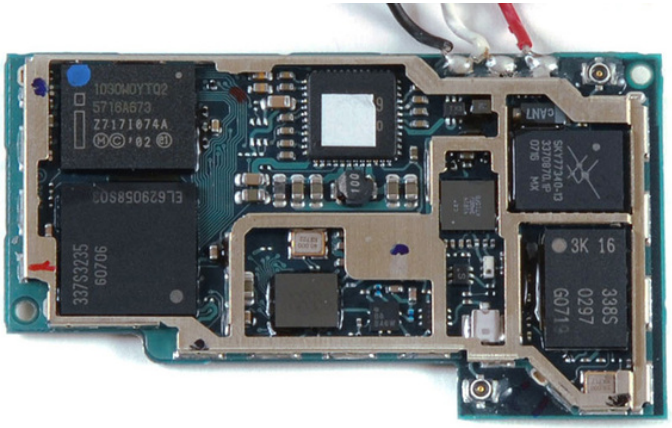
From ifixit.com

In Comparison – 1st Generation iPhone

- Dual board stack
  - 620 MHz ARM + 512 MB DRAM stacked chip
  - WLAN + Bluetooth
  - SIM card holder
- Solder on battery pack
  - 3.7V@1400mAh Li-Ion Polymer

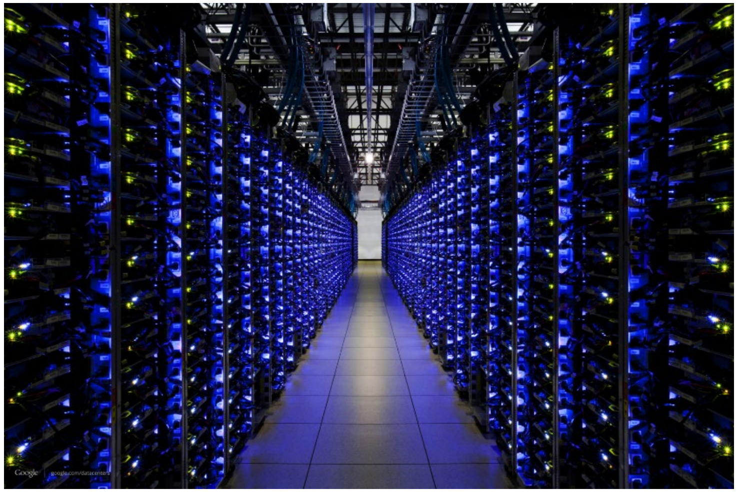






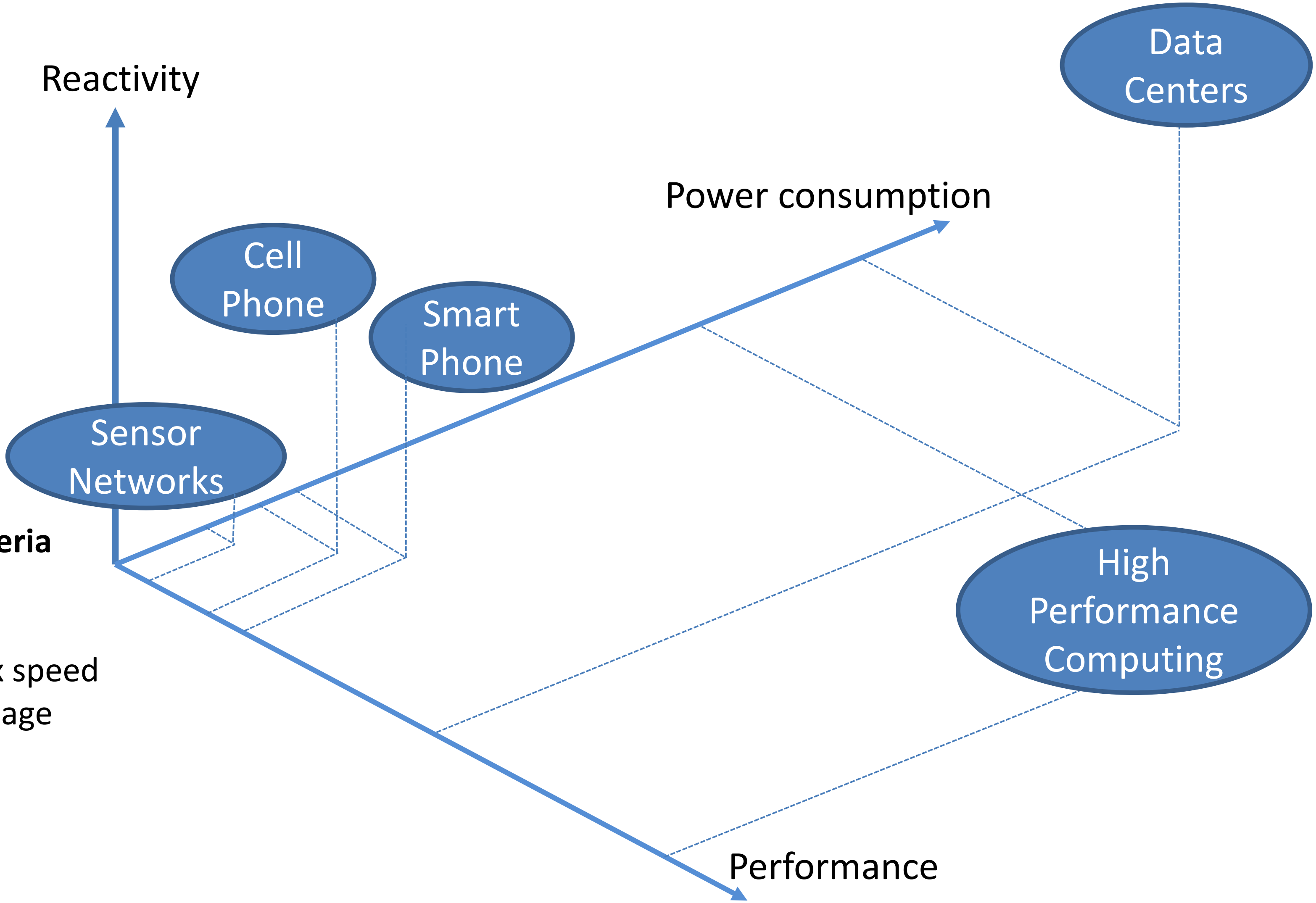
From ifixit.com

Where Does the Energy Go?



From ifixit.com

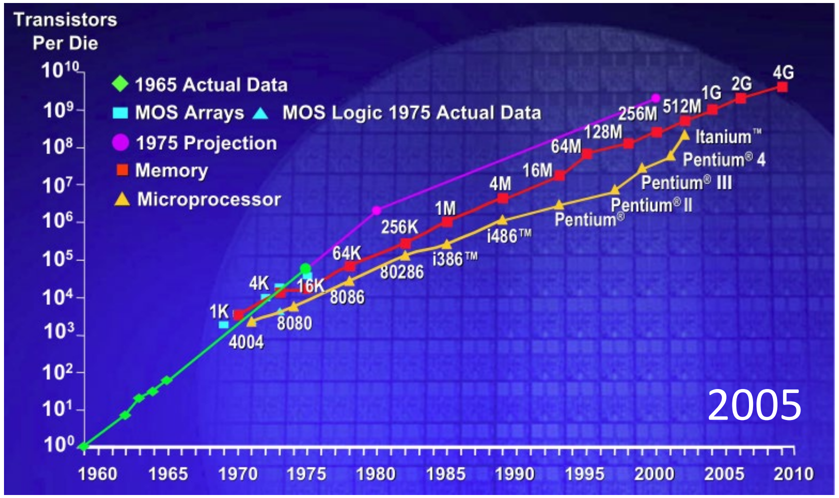
System Design Options



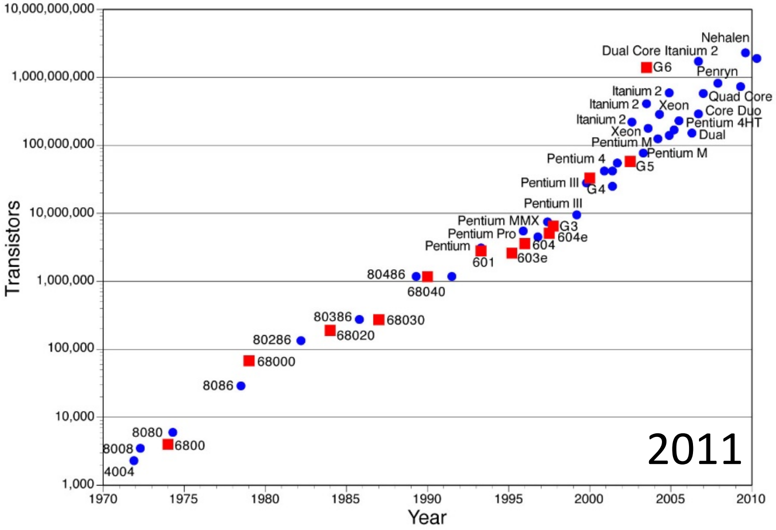
Conflicting Criteria
- Battery life
- Cost
- Avg. vs. max speed
- Resource usage
- Latency
- Reliability
- Size
- …

Broad Technology Trends

Moore's Law: # transistors on cost-effective chips doubles every 18 months



2005

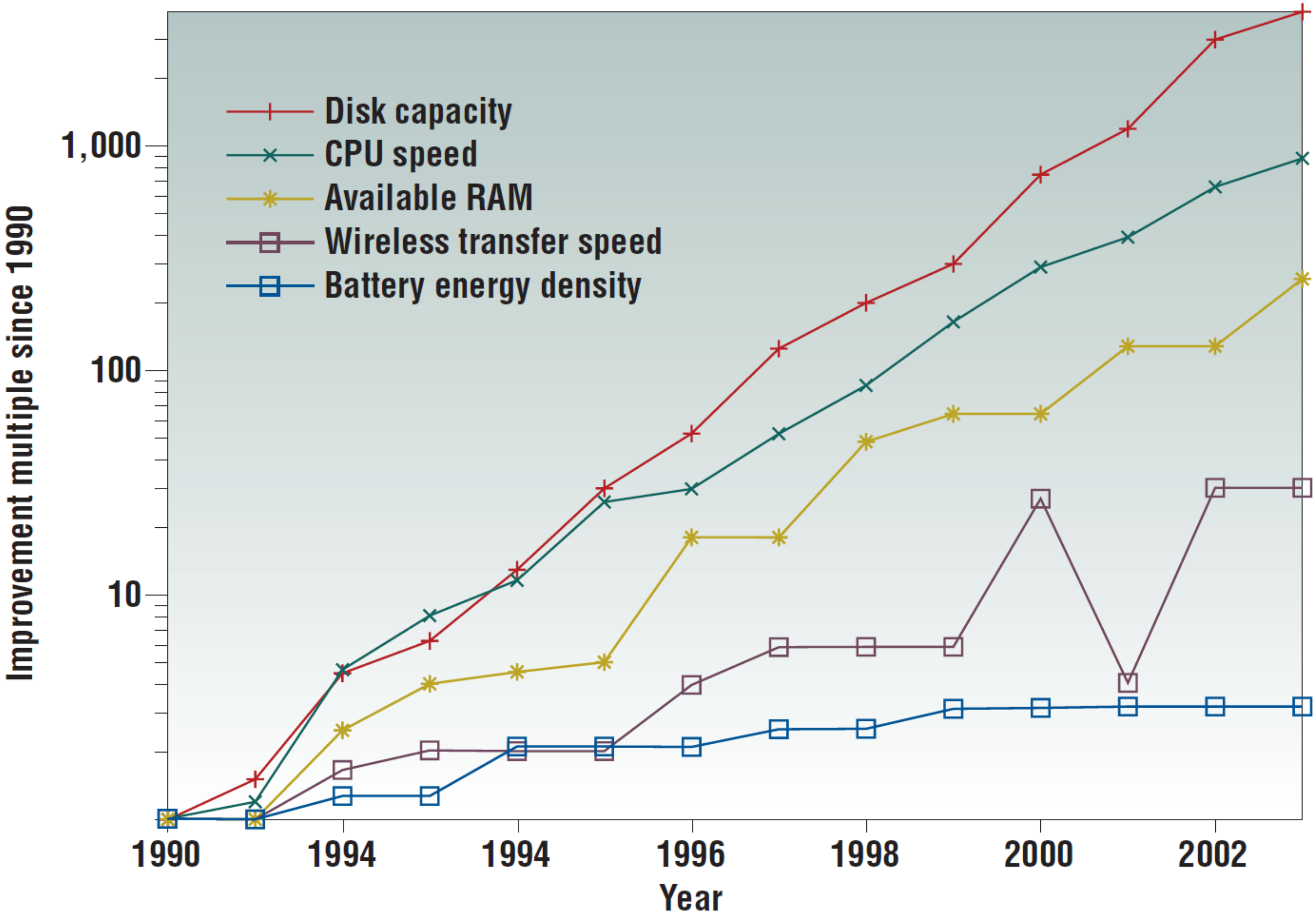


2011

- Today: millions of transistors per $
- Same fabrication technology provides CMOS radios for communication and micro-sensors
- Efficiency and leakage improvements at similar scale

Figure abridged from D. Culler

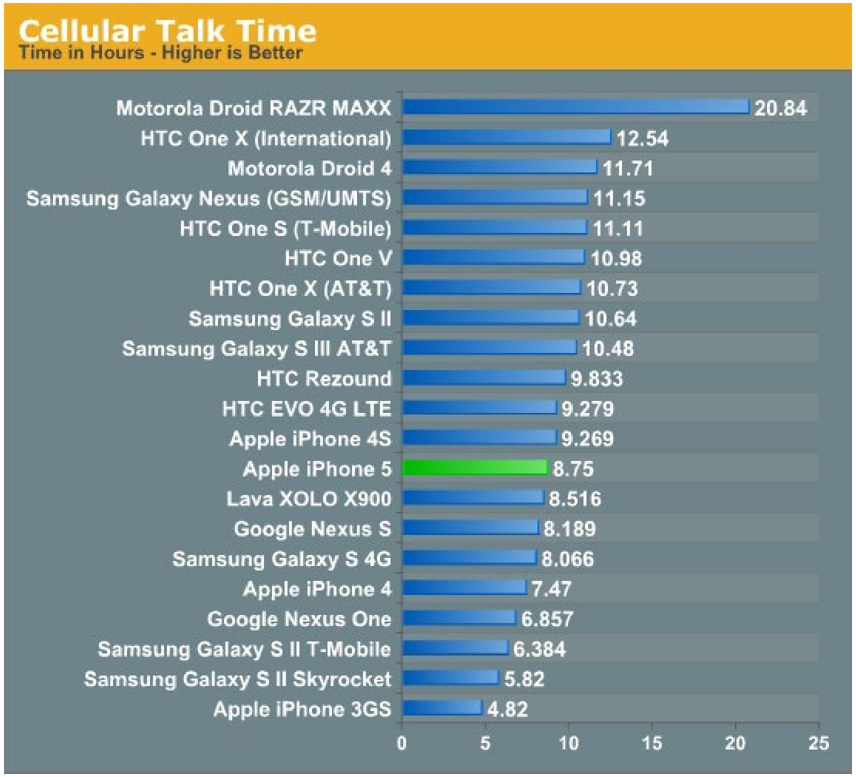
Battery Improvements are Slow



From J. Paradiso/T. Starner 2005

Slow increase in capacity: ~8% per year (Wh/cm^3)

Powering the Performance Increase



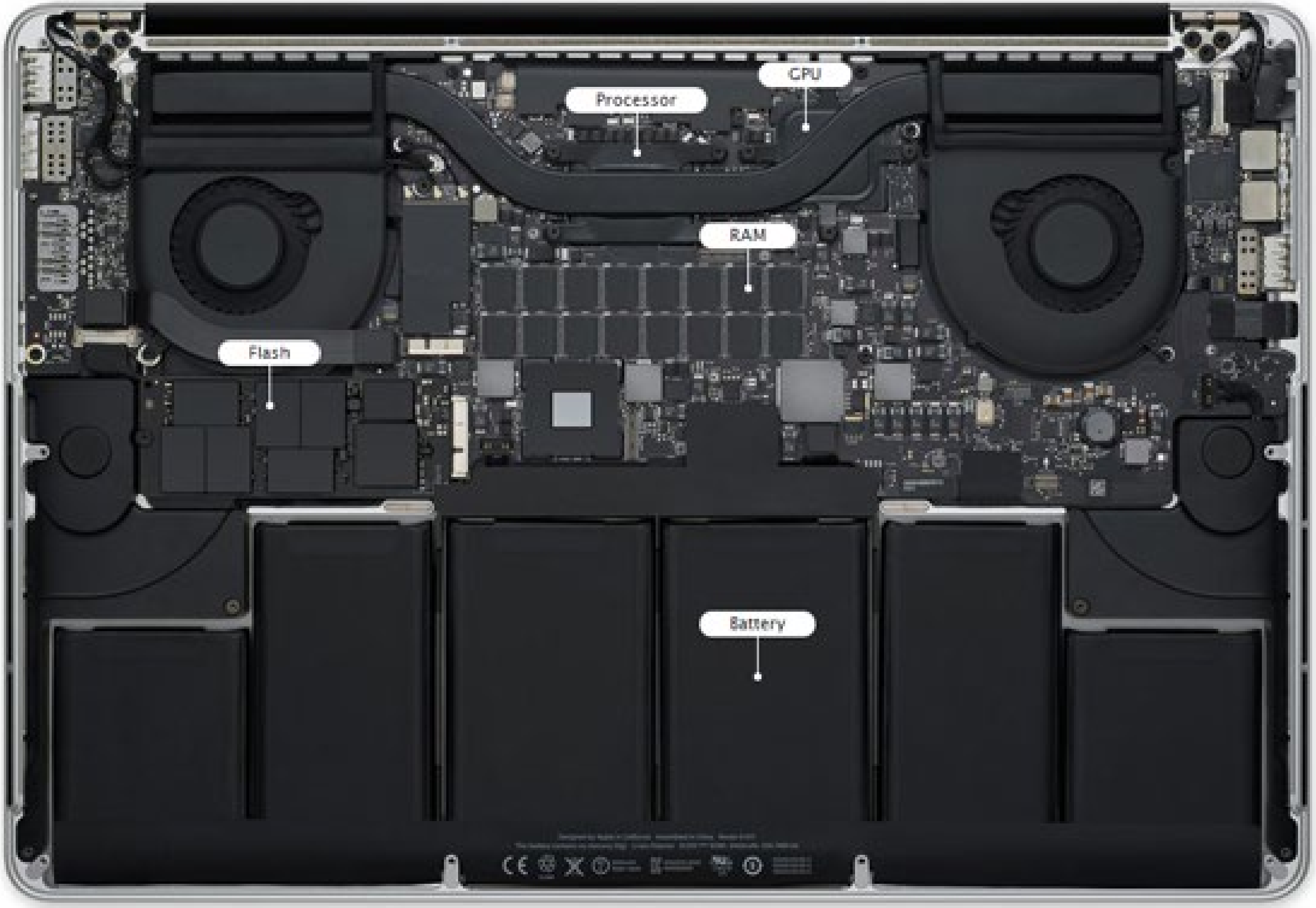
Batteries Use Up Most Space

From ifixit.com

Evolution 1.0 – Removable Packs

From ifixit.com

Higher Packing Density – Segmentation



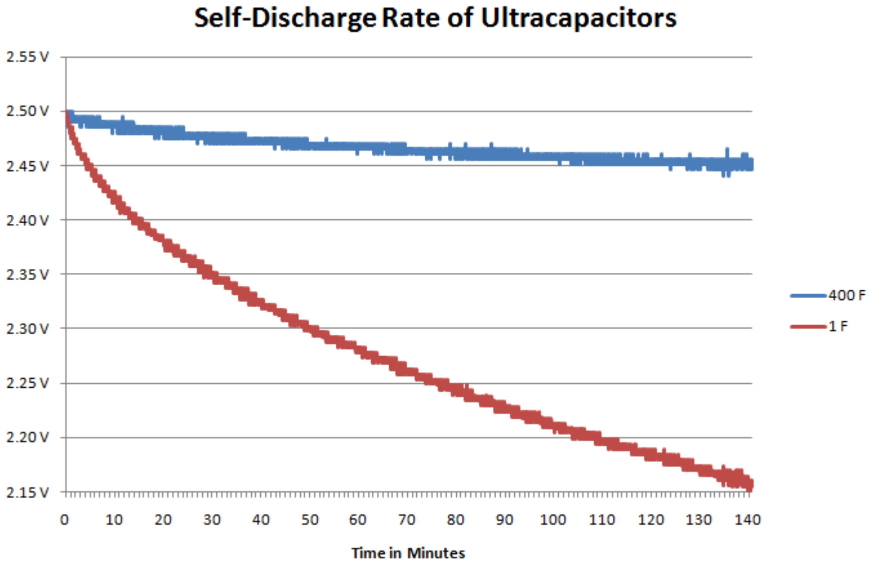
From ifixit.com

Latest – Glue-in Gel Pack Batteries

- **Integration Density**
  - **iPad 2:** 25Wh
  - **iPad 3:** 42.5Wh
- **Technology Push**
  - **iPhone 4S**
    3.7V @ 1432mAh = 5.3Wh
    Talk time: Up to 8 hours
    Standby: Up to 200 hours.
  - **iPhone 5**
    3.8V @ 1440mAh = 5.45Wh
    Talk time: Up to 8 hours
    Standby: Up to 225 hours

From ifixit.com

Storage Hierarchies Using Supercapacitors



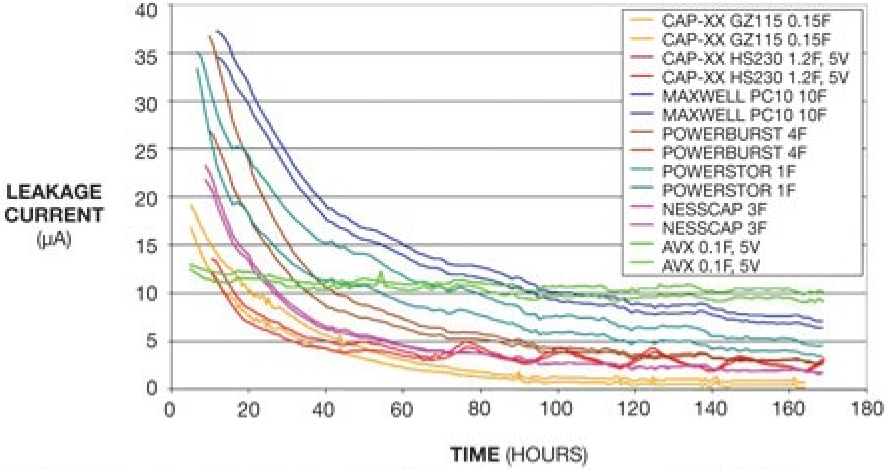
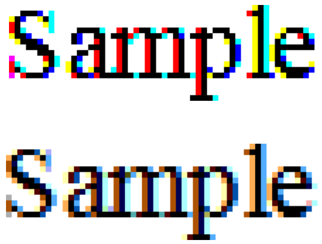


Figure 6 A rule of thumb for equilibrium-leakage-current CAP-XX supercapacitors at room temperature is 1 µA/F.

Unexpected Opportunities for Energy Improvements at System Level

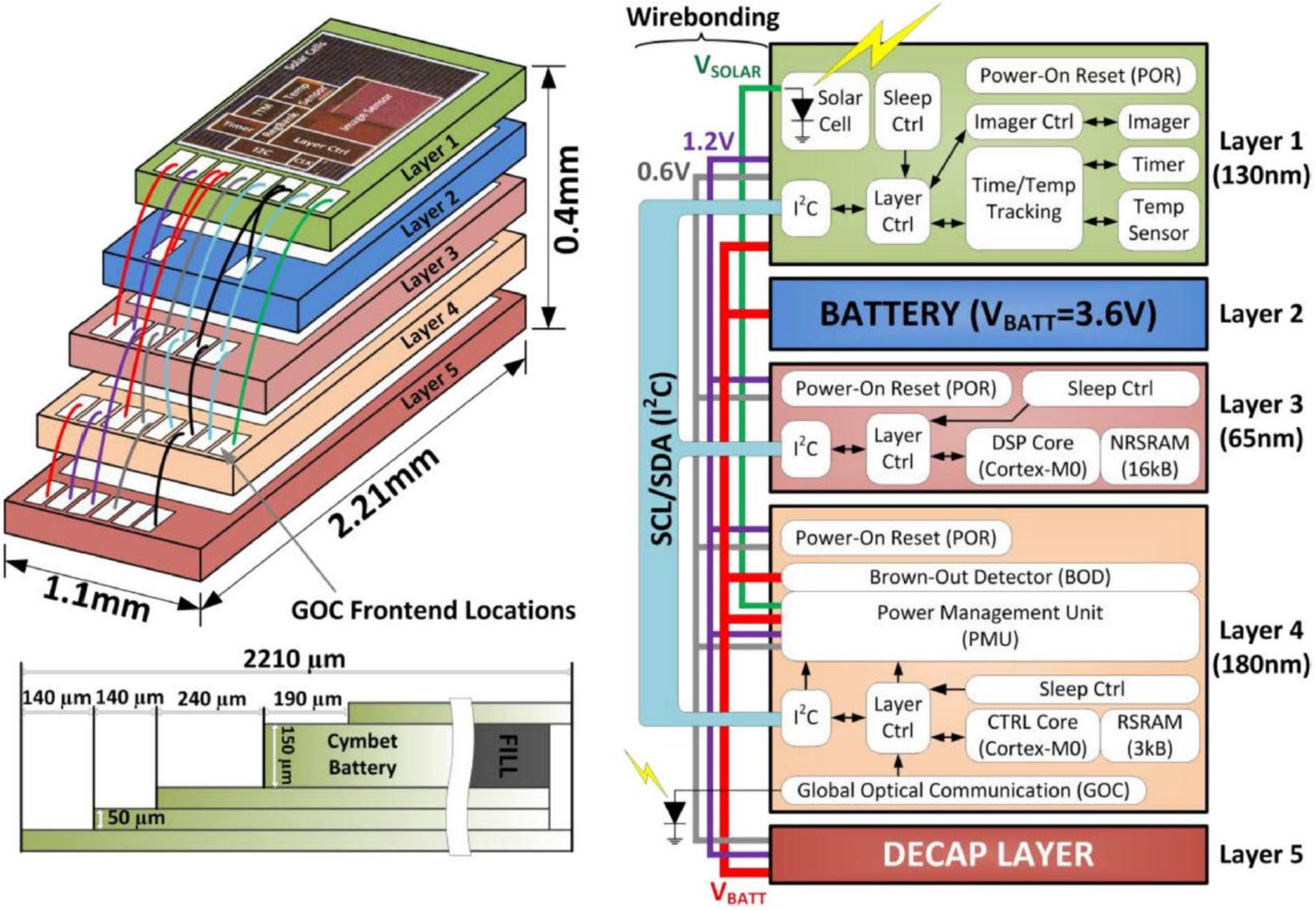
A More Energy Efficient Display

- Removal of display backlight
- Addition of white pixels
- RGBW subpixel rendering
  - Better image control
  - More contrast for outdoor viewing



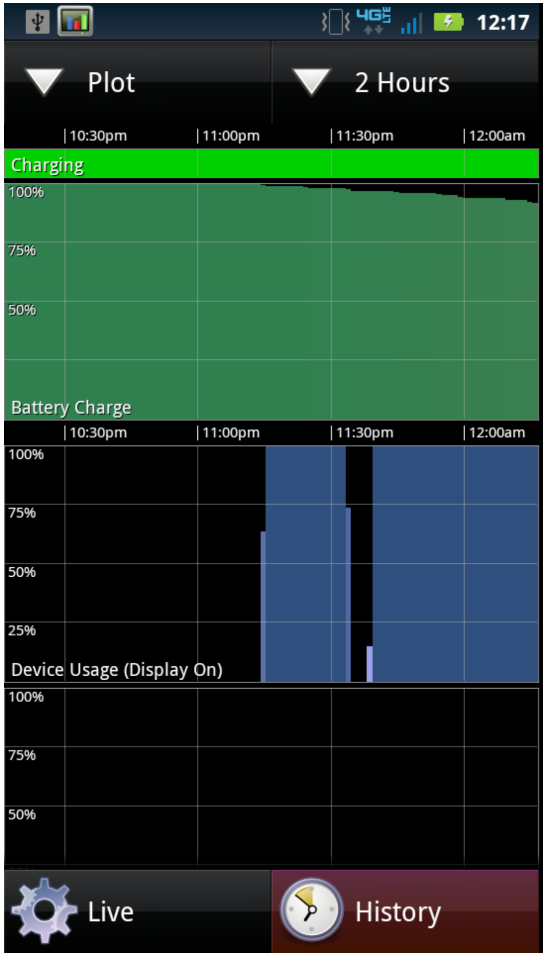
  - Significant power savings

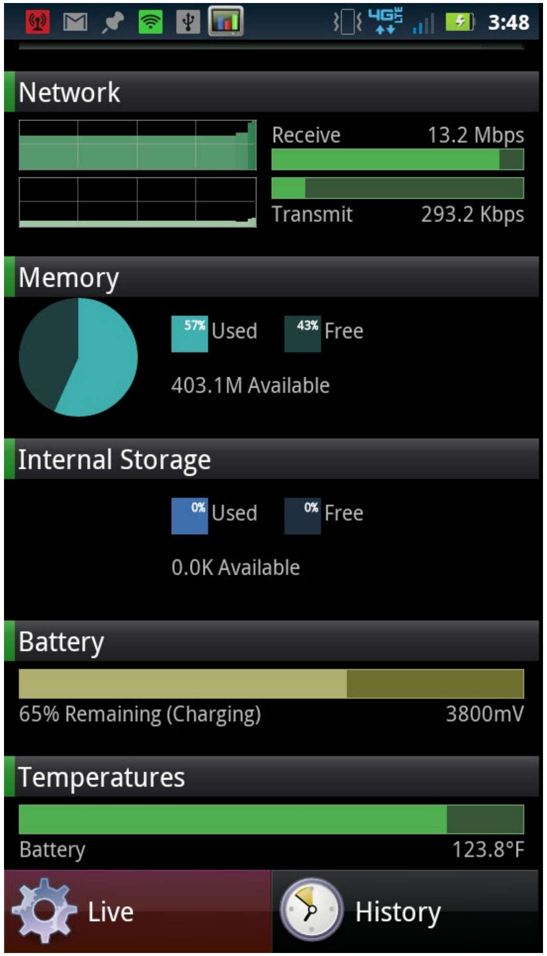
Leveraging Ambient Energy Sources: Miniaturized Zero-Power Systems



IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 48, NO. 1, JANUARY 2013

Largest Gains – Power Aware Software





Receive 13.2 Mbps

Transmit 293.2 Kbps

57% Used 43% Free

403.1M Available

0% Used 0% Free

0.0K Available

65% Remaining (Charging) 3800mV

Battery 123.8°F

Low-Power System Design

GENERAL TERMINOLOGY

Power and Energy

- Energy is a property of objects.

SI unit for energy = joule [J]

$$1\ \mathrm{J} = 1\ \mathrm{N{\cdot}m} = 1\ \mathrm{kg{\cdot}m2}/s2 = 1\ \mathrm{V{\cdot}C} = 1\ \mathrm{W{\cdot}s}$$

In engineering the unit of energy is the watt-hour [Wh]

$$1\ \mathrm{J} = 1\ \mathrm{W{\cdot}s} = 2.7 \times 10^{-4}\ \mathrm{W{\cdot}h}$$

$$1\ \mathrm{W{\cdot}h} = 3600\ \mathrm{J}$$

- Energy is our limited resource, and power is the rate at which we consume (or replenish) that resource.

SI unit for power = watt [W]

$$1\ \mathrm{W} = 1\ \mathrm{J/s} = \mathrm{V{\cdot}C/s} = \mathrm{V{\cdot}A}$$

Electric Power

- Electric potential energy = charge x voltage

$$U = Q \cdot V$$

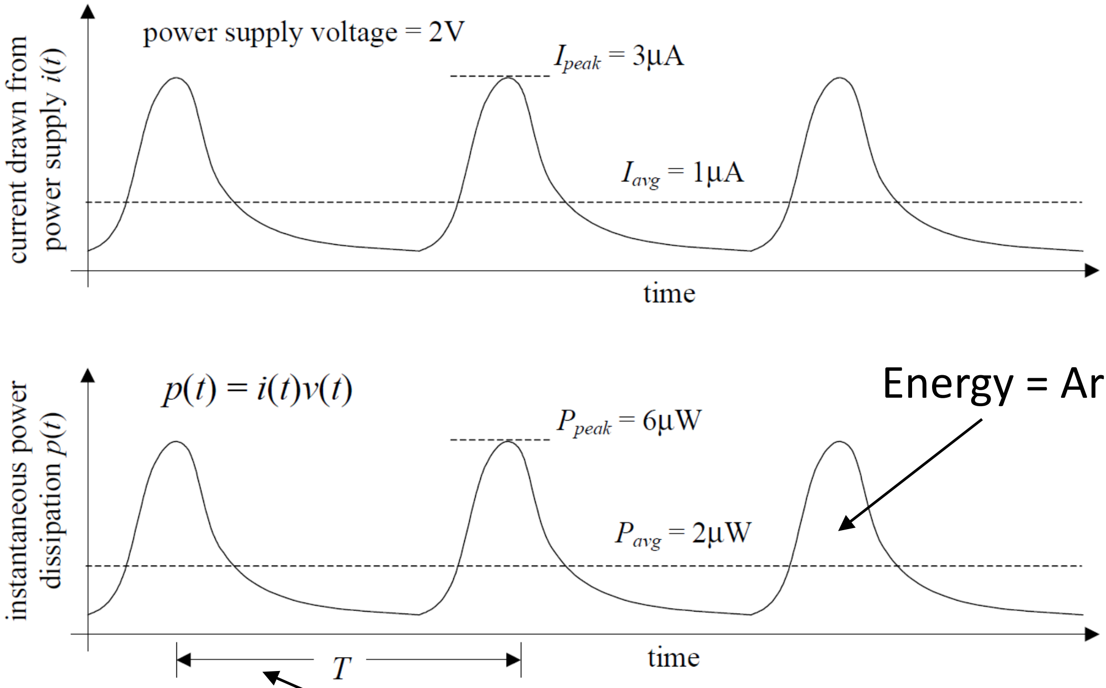
- Remember power is the rate of doing work
- Electrical power equals energy/per unit time

$$P = \frac{U}{t} = \frac{QV}{t} = V \cdot I$$

Q: How much energy does a 1-watt system consume per second/per hour?

Power Consumption

- In most circuits, the power supply voltage is constant. In circuits where the current varies with time, we must make a distinction between **instantaneous power** and **average power.**

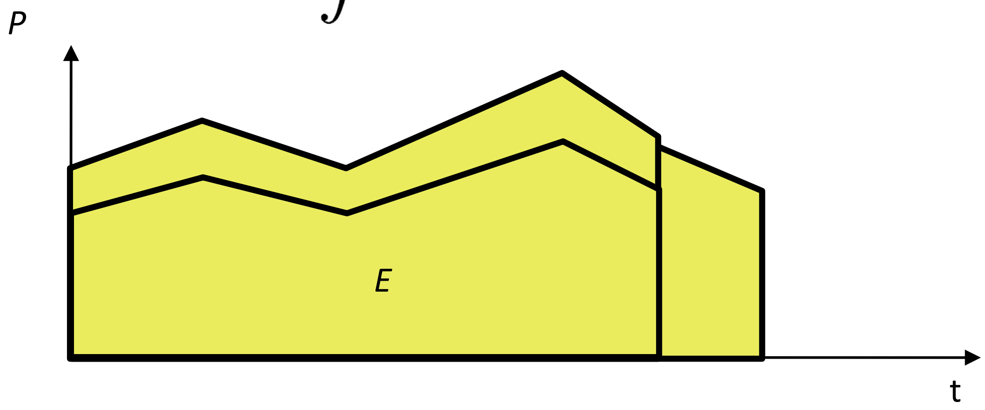


Energy = Area under curve

$$P_{avg} = \frac{1}{T}\int_0^T p(t)dt = \frac{V_{supply}}{T}\int_0^T i_{supply}(t)dt$$

Dynamics of Power and Energy

$$E = \int P(t)dt$$



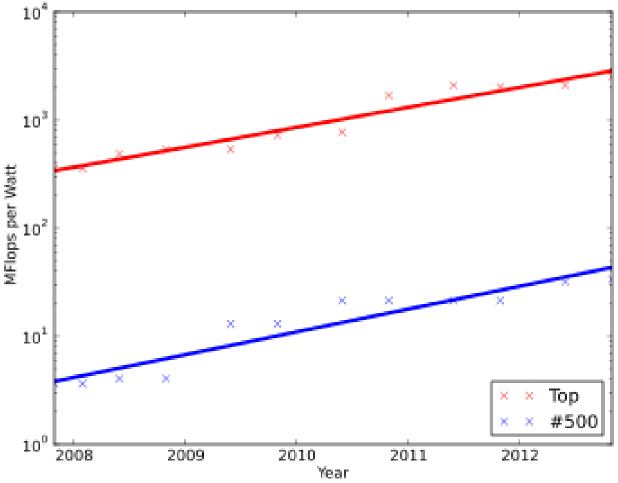
- In some cases, faster execution also means less energy, but the opposite may be true if power has to be increased to allow for a faster execution.

Power and Efficiency

- The **efficiency** of is defined as useful power output divided by the total electrical power consumed.

$$\eta = \frac{Useful\ power\ output}{Total\ power\ input}$$

- **Performance-per-watt** is a typical to describe energy efficiency in computing hardware.

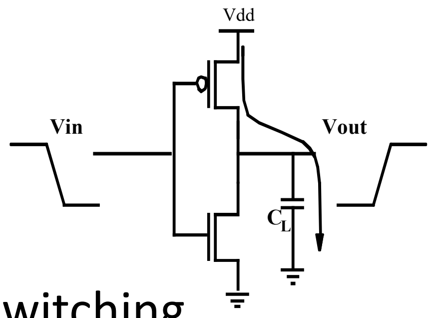


Example:
Supercomputer
Performance

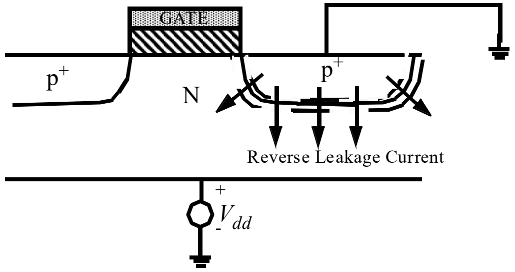
Low Power vs. Low Energy

- Minimizing the ***power consumption*** is important for
  - the design of the power supply and voltage regulators
  - the dimensioning of interconnect between power supply and components
  - cooling (short term cooling)
    - high cost
    - limited space
- Minimizing the ***energy consumption*** is important for
  - restricted availability of energy (mobile systems)
  - limited battery capacities (only slowly improving)
  - very high costs of energy (energy harvesting, solar panels)
  - long lifetimes, low temperatures

Where Does Power Go in CMOS?



- Dynamic Power Consumption
  - Charging and discharging capacitors
- Short Circuit Currents
  - Short circuit path between supply rails during switching
- Leakage
  - Leaking diodes and transistors

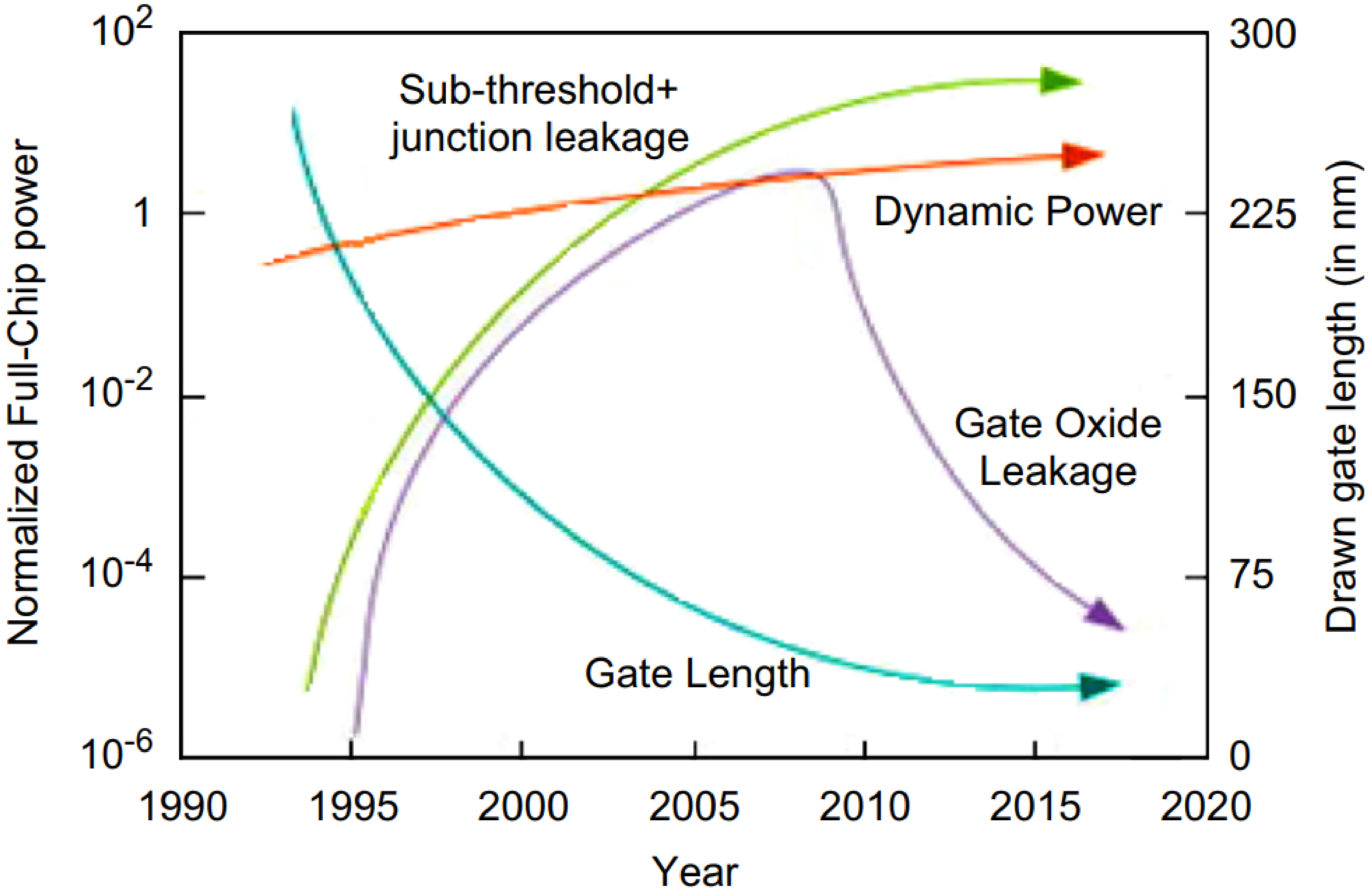


$I_{DL} = J_S \times A$

- Most of it is thermal energy in the end

- Countermeasures
  - Prime choice: Reduce voltage!
  - Reduce switching activity
  - Reduce physical capacitance

Where Does Power Go in CMOS?



[J. Xue, T. Li, Y. Deng, Z. Yu, Full-chip leakage analysis for 65 nm CMOS technology and beyond, Integration VLSI J. 43 (4) (2010) 353–364]

Low-Power Hardware Design Rules

$$P_{dyn} = \alpha \underset{\substack{\uparrow \\ \text{flexible}}}{f} C + V^2 \underset{\substack{\uparrow \\ \text{fixed by project}}}{f}$$

- Reduction of dynamic power
  - α: clock gating, sleep modes
  - C: small transistors (esp. on clock), short wires
  - V_{dd}: lowest suitable voltage
  - f: lowest suitable frequency

  - Main application: DVFS (Dynamic Voltage and Frequency Scaling)
    e.g. Intel Core/Xeon, ARM cores, multiprocessor systems…

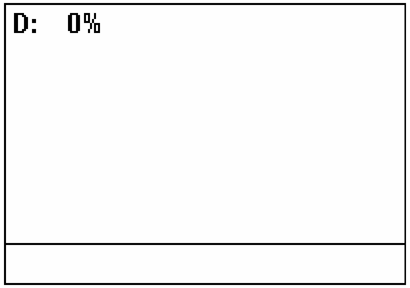
- Reduction of static power
  - Power gating
  - Selectively use ratioed circuits (weak pull-up and strong pull-down)
  - Selectively use low V_t devices
  - Leakage reduction: stacked devices, body bias, low temperature

Reduction of Switching Activity

- Primary mean in LP systems is **duty cycling** of subsystems
  - **Dynamic voltage scaling** and **dynamic frequency scaling** is a typical technique to reduce CPU power consumption.

- A **duty cycle** is defined as the ratio between activity and the period given as percentage.

$$D = \frac{T}{P} * 100\%$$



- Obvious impact on system performance
  - Throughput
  - Latency
  - Reactivity

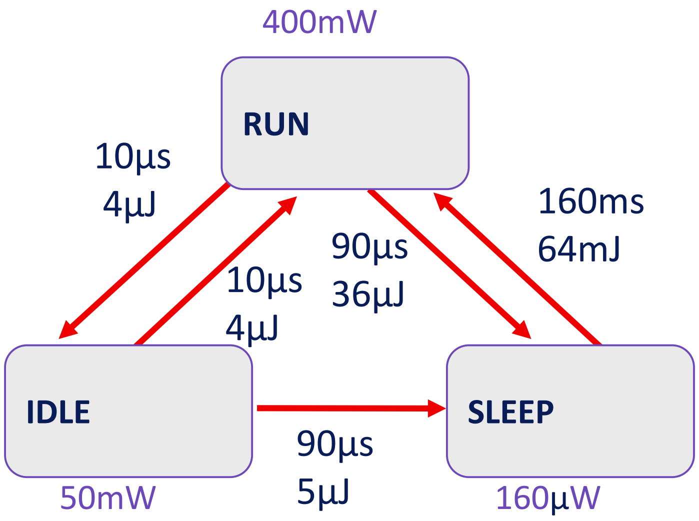
Dynamic Power Management (DPM)

- Dynamic power management tries to assign optimal **power saving states during program execution**
- DPM requires hardware and software support

RUN: operational

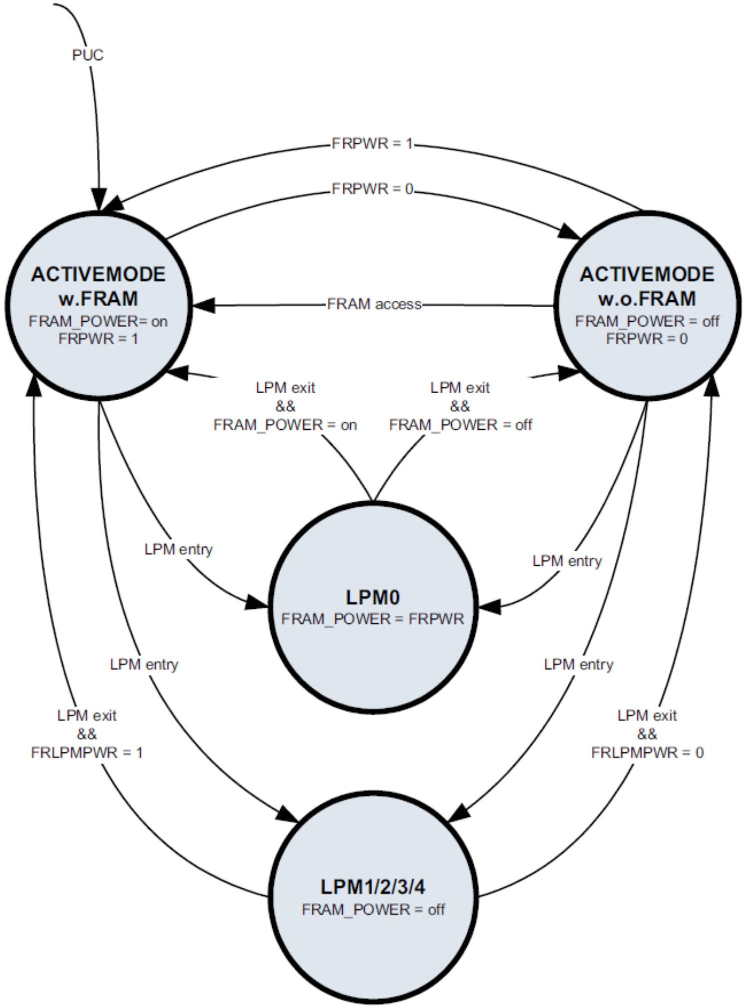
IDLE: a SW routine may stop the CPU when not in use, while monitoring interrupts

SLEEP: Shutdown of on-chip activity

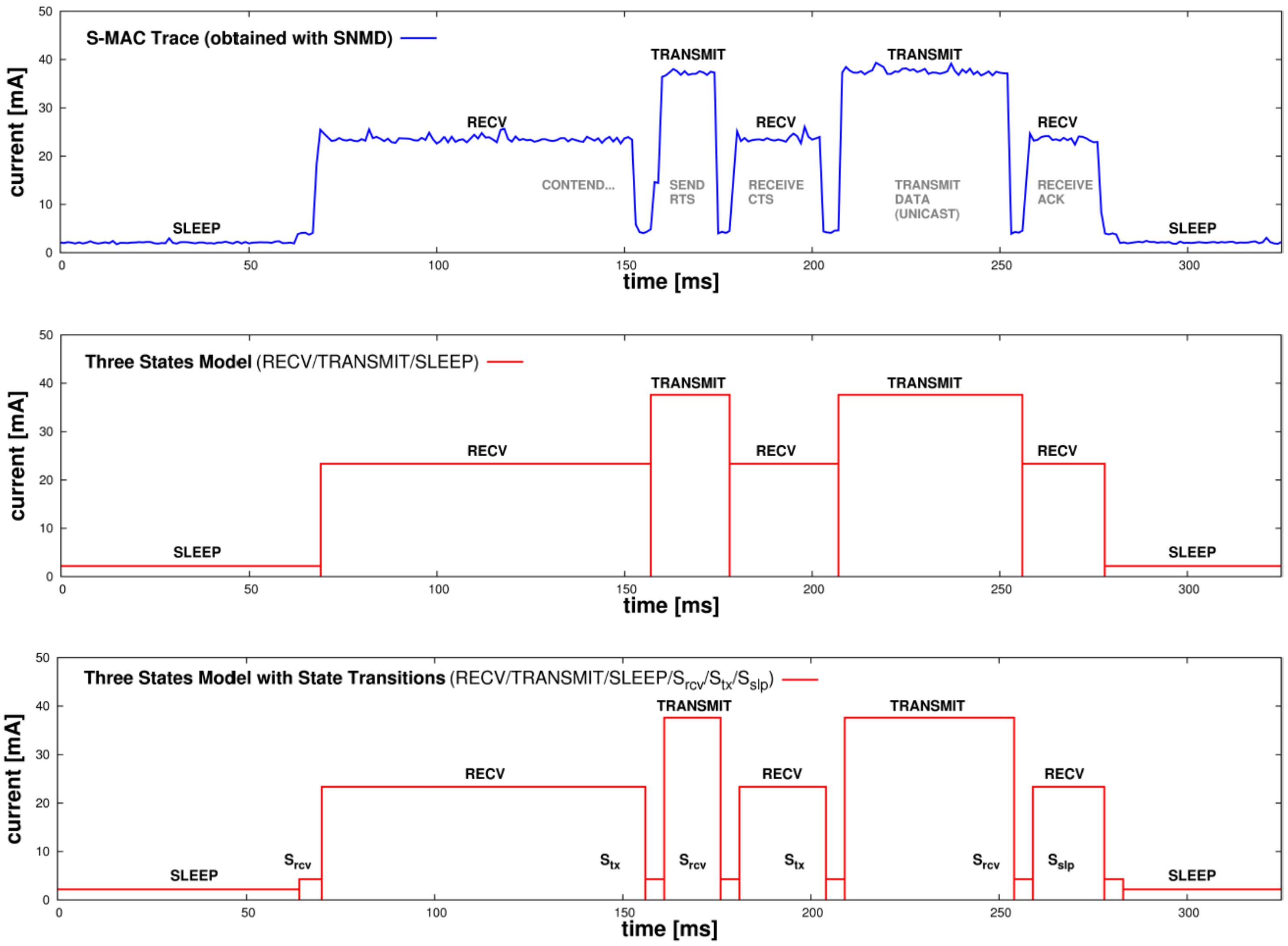


Example: StrongARM SA1100

Example: Low Power States in uC

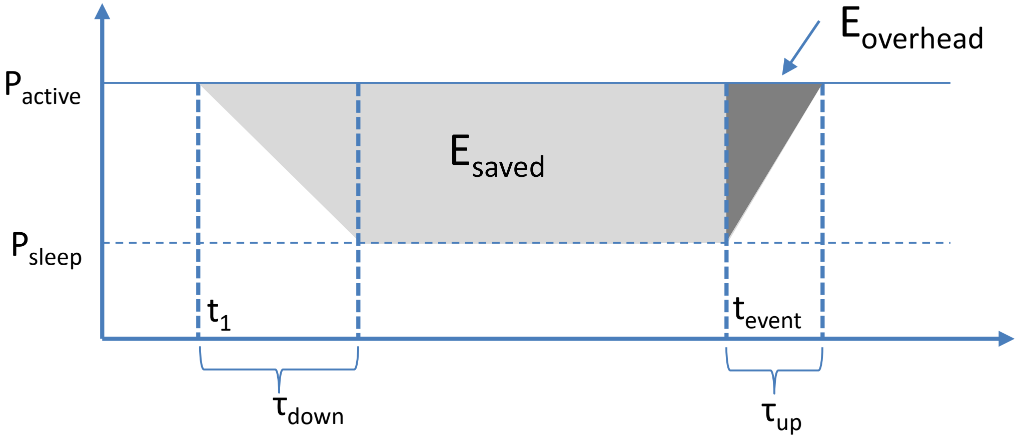


Dynamic Power Management



[Philipp Hurni 2011]

Modelling Low Power State Changes



- The energy saving on entering a sleep mode is

$$E_{saved} = (t_{event} - t_1)P_{active} - \frac{\tau_{down}\left(P_{active} + P_{sleep}\right)}{2} + (t_{event} - t_1 - \tau_{down})P_{sleep}$$

- With the overhead

$$E_{overhead} = \frac{\tau_{up(P_{active}+P_{sleep})}}{2}$$

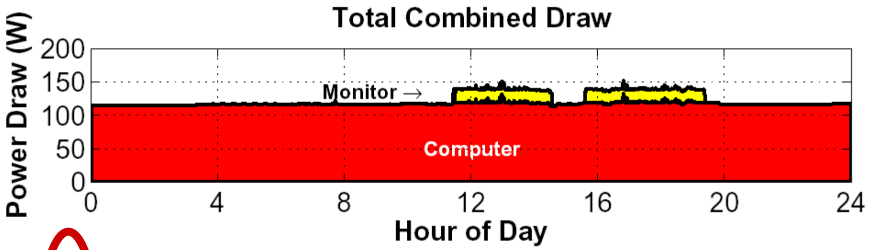
- This is only beneficial if $E_{overhead} < E_{saved}$ or

$$(t_{event} - t_1) > \frac{1}{2}(\tau_{down} + \frac{P_{active} + P_{sleep}}{P_{active} - P_{sleep}}\tau_{up})$$

Examples: Duty-Cycle Operation

Time Scale

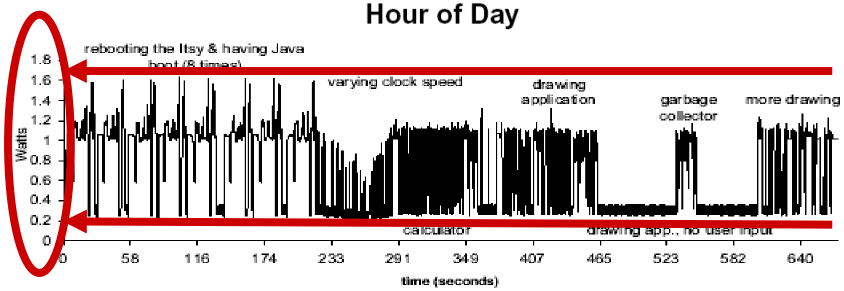
PC



86,400,000 ms

Handheld

[Farkas 2000]

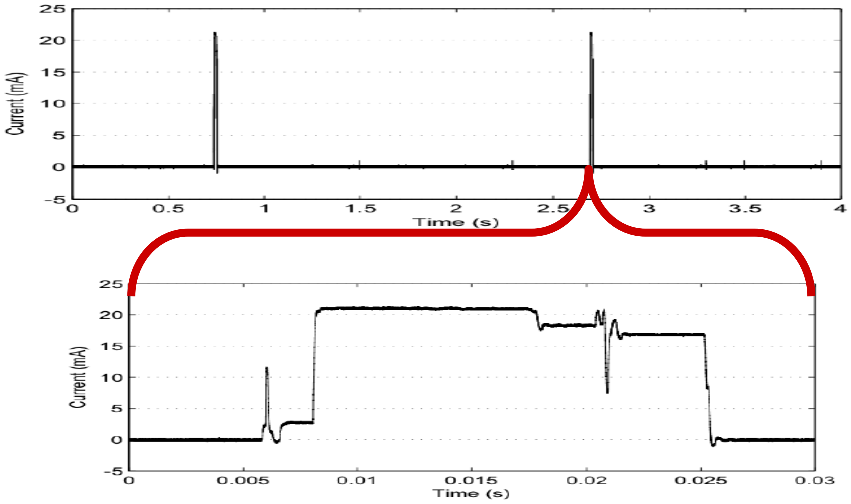


640,000 ms

Sensor Node

[Dutta 2008]

TX packet at 1% duty cycle (20 ms / 2 s)

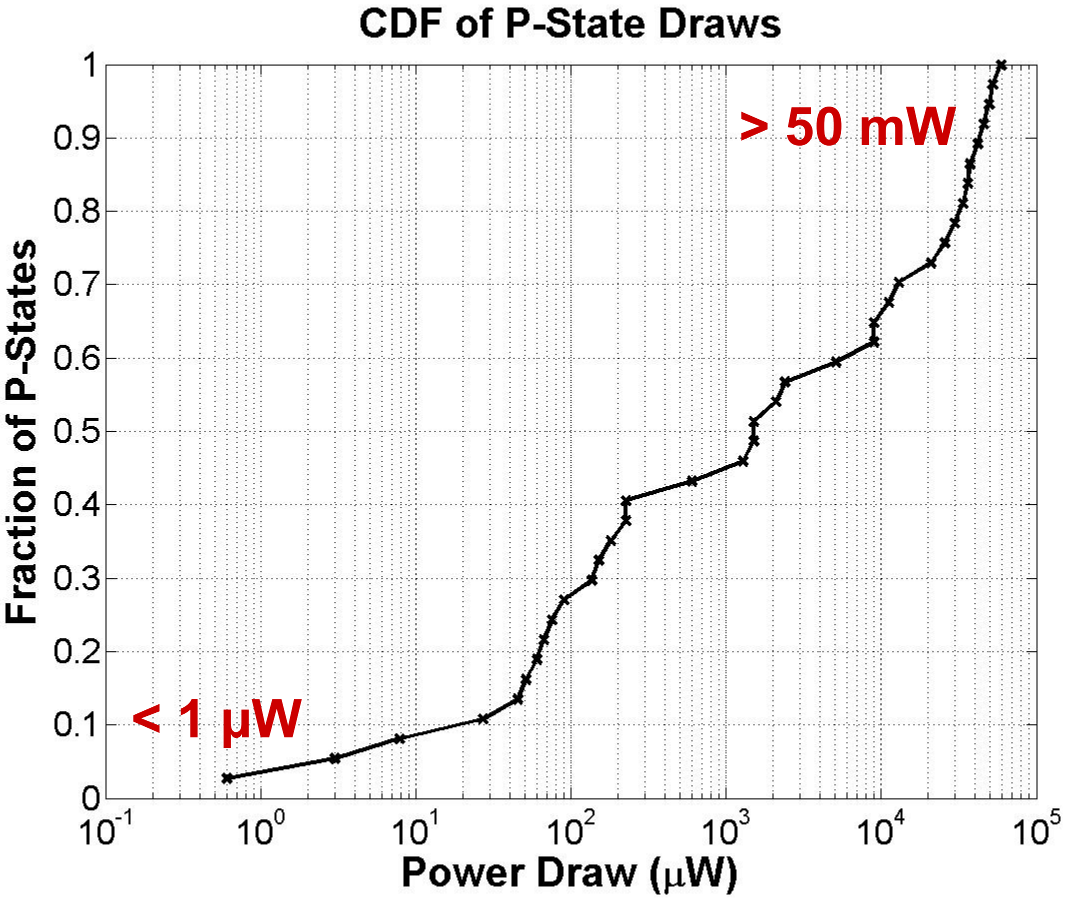


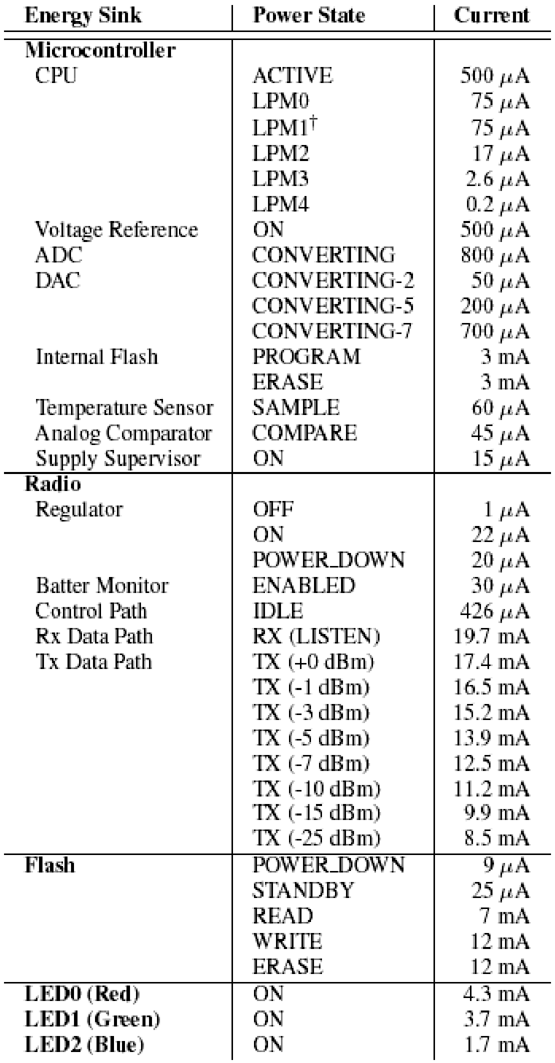
4,000 ms

30 ms

Slide abridged from P. Dutta, U Michigan

Dynamic Range Exceeds 10,000:1





Energy Sink	Power State	Current
Microcontroller		
CPU	ACTIVE	500 µA
	LPM0	75 µA
	LPM1†	75 µA
	LPM2	17 µA
	LPM3	2.6 µA
	LPM4	0.2 µA
Voltage Reference	ON	500 µA
ADC	CONVERTING	800 µA
DAC	CONVERTING-2	50 µA
	CONVERTING-5	200 µA
	CONVERTING-7	700 µA
Internal Flash	PROGRAM	3 mA
	ERASE	3 mA
Temperature Sensor	SAMPLE	60 µA
Analog Comparator	COMPARE	45 µA
Supply Supervisor	ON	15 µA
Radio		
Regulator	OFF	1 µA
	ON	22 µA
	POWER_DOWN	20 µA
Batter Monitor	ENABLED	30 µA
Control Path	IDLE	426 µA
Rx Data Path	RX (LISTEN)	19.7 mA
Tx Data Path	TX (+0 dBm)	17.4 mA
	TX (-1 dBm)	16.5 mA
	TX (-3 dBm)	15.2 mA
	TX (-5 dBm)	13.9 mA
	TX (-7 dBm)	12.5 mA
	TX (-10 dBm)	11.2 mA
	TX (-15 dBm)	9.9 mA
	TX (-25 dBm)	8.5 mA
Flash	POWER_DOWN	9 µA
	STANDBY	25 µA
	READ	7 mA
	WRITE	12 mA
	ERASE	12 mA
LED0 (Red)	ON	4.3 mA
LED1 (Green)	ON	3.7 mA
LED2 (Blue)	ON	1.7 mA

Slide abridged from P. Dutta, U Michigan

Radio Power Budget Basics

- Free-space path loss according to Friis equation

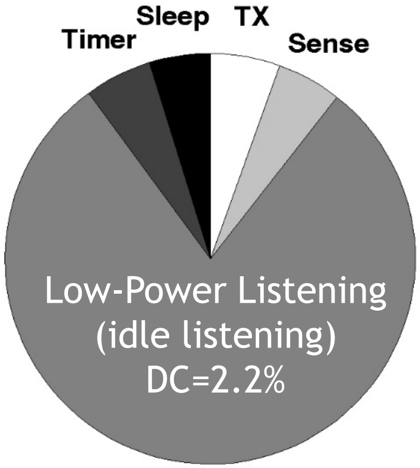
$$P_r = P_T G_T G_R \left(\frac{\lambda}{4pid}\right)^2$$

- Exponent depends on environment

– Free space	2
– Urban cellular	2.7-3.5
– Indoor typical	3-4
– Indoor worst case	4-6

- Multi-hop networking reduces demand in TX power considerably

A typical multi-hop system example



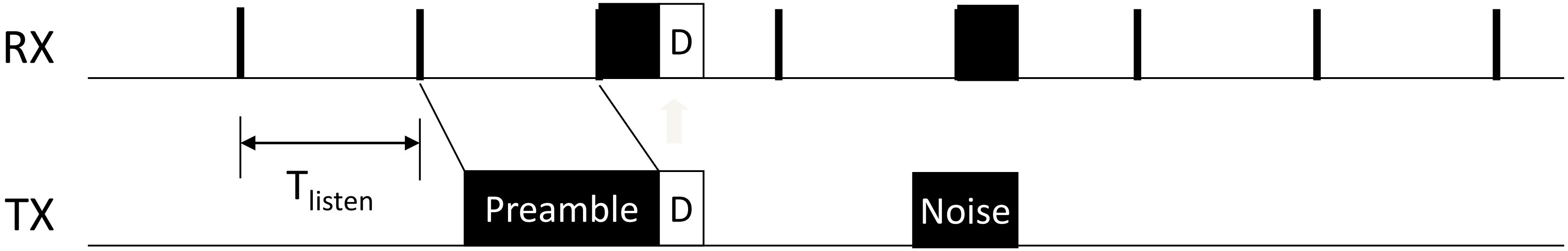
R. Szewczyk, A. Mainwaring, J. Polastre, D. Culler, "An Analysis of a Large Scale Habitat Monitoring Application", ACM SenSys' 04, November, 2004.

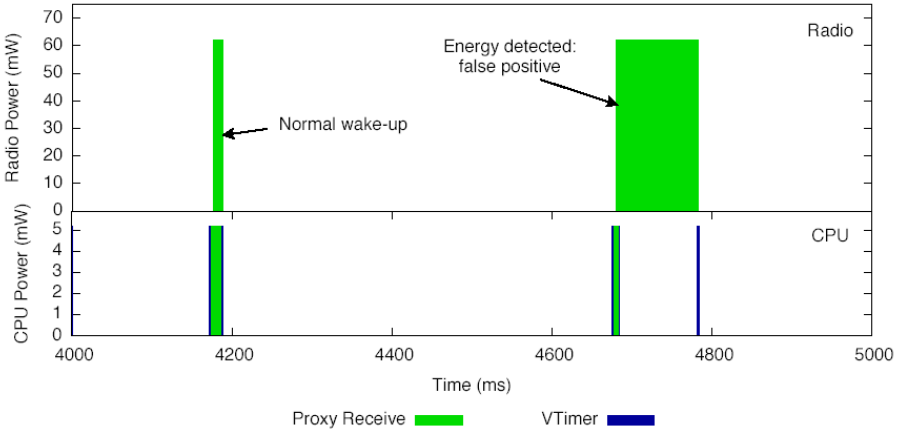
- Idle listening dominates the power budget even at radio duty cycles of just 1 to 2%

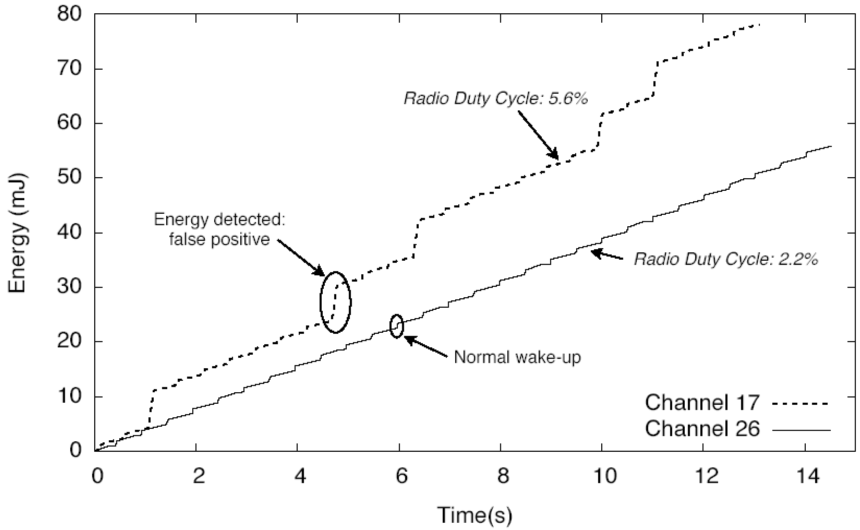
Slide abridged from P. Dutta, U Michigan

Therefore, the radio is kept mostly off

Low-Power Listening







Overhearing adds significant unpredictability to node lifetime

Slide abridged from P. Dutta, U Michigan

Today’s Hot Researcher & Paper

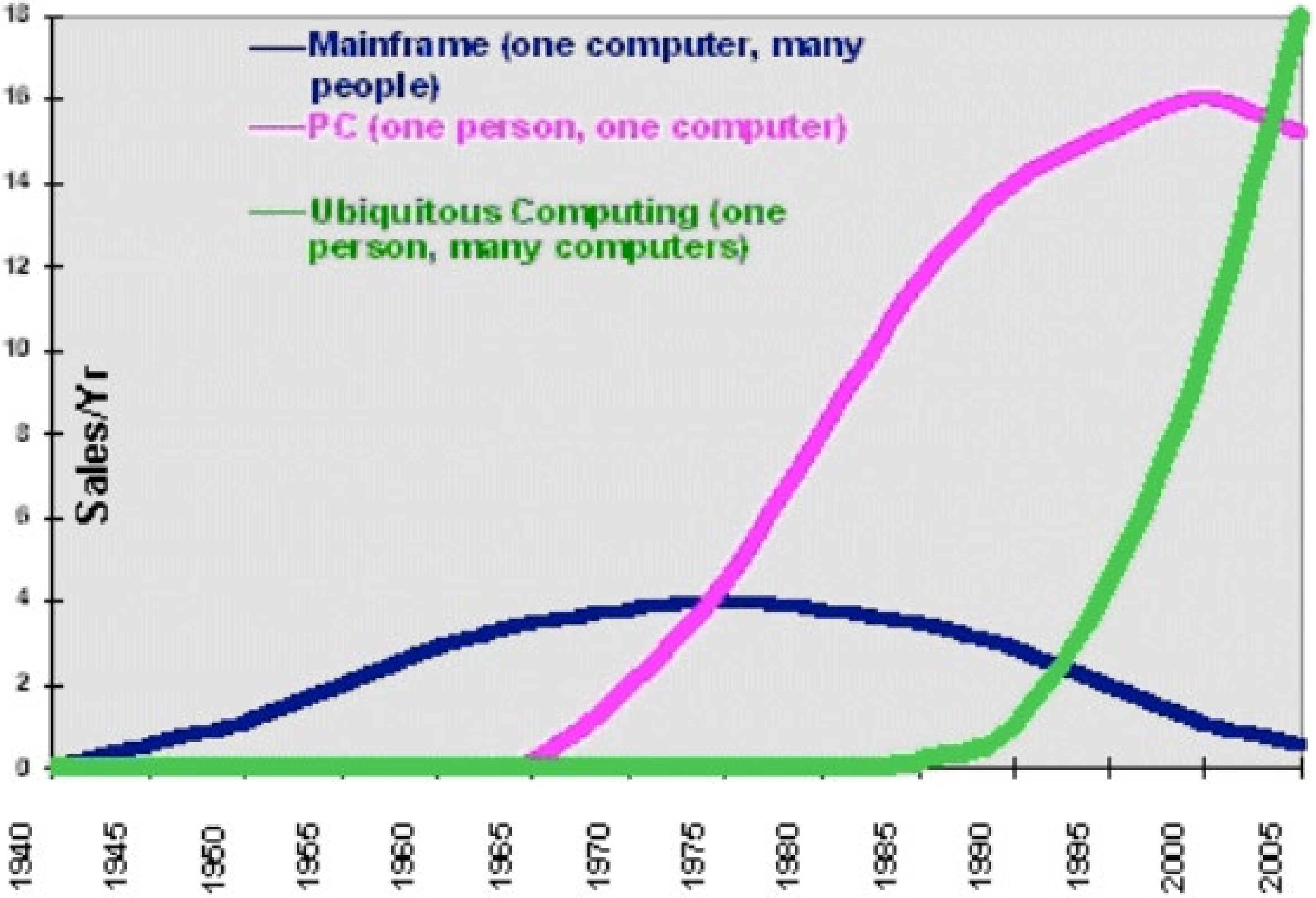
- Mark Weiser (1952-1999)
  - Chief scientist at Xerox PARC in the US
  - Considered to be the father of ubiquitous computing

“Ubiquitous computing names the third wave in computing, just now beginning. First were mainframes, each shared by lots of people. Now we are in the personal computing era, person and machine staring uneasily at each other across the desktop. Next comes ubiquitous computing, or the age of calm technology, when technology recedes into the background of our lives.”

—Mark Weiser

- Mark Weiser: “The Computer for the 21st Century" - Scientific American Special Issue on Communications, Computers, and Networks, September, 1991

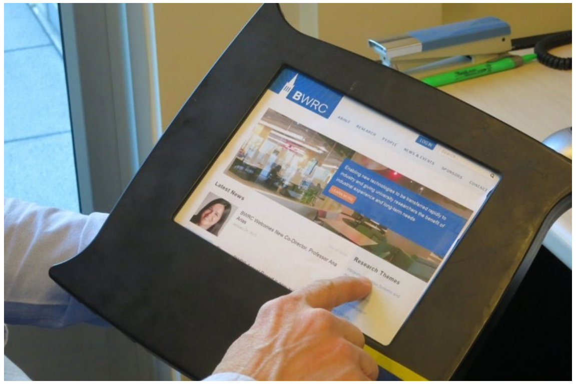
Weisers Ubicomp Vision



The Evolution of Weiser’s Idea

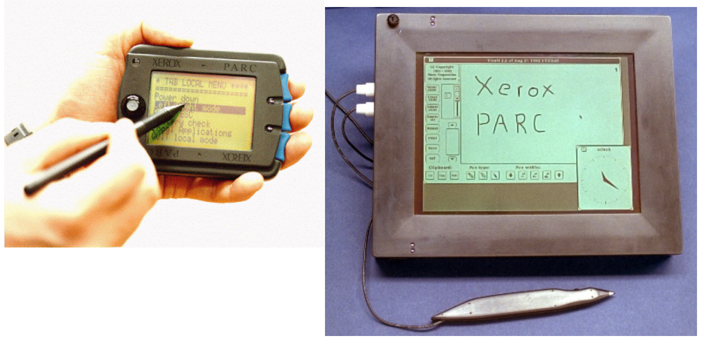
InfoPad

[UC Berkeley 1999]



PARC Tab
and
PARC Pad

[XEROX PARC 1988-1995]



Tablet 2014

Recap of Today

- **Lowering the energy footprint** of systems is an increasingly important topic.
- Apart from using advances in modern LP hardware good **system design** and **software support** are crucial. This requires a system view.
- Increasing demand for **networked interactions**, **mobility** and **constant availability** complicate system design.

Energy-efficiency affects all layers of system design.

Recap of Today

- **Power** is defined as the rate of **energy transfers**.
- It is required to differentiate between **instantaneous** and **average power consumption**.

- Low-power wireless systems are **highly resource constrained**.
- **Limited energy** availability is the **main resource obstacle**.

- In order to prolong functionality **power management** e.g. by duty-cycling is necessary. This introduces **further complexity** to the system (design).