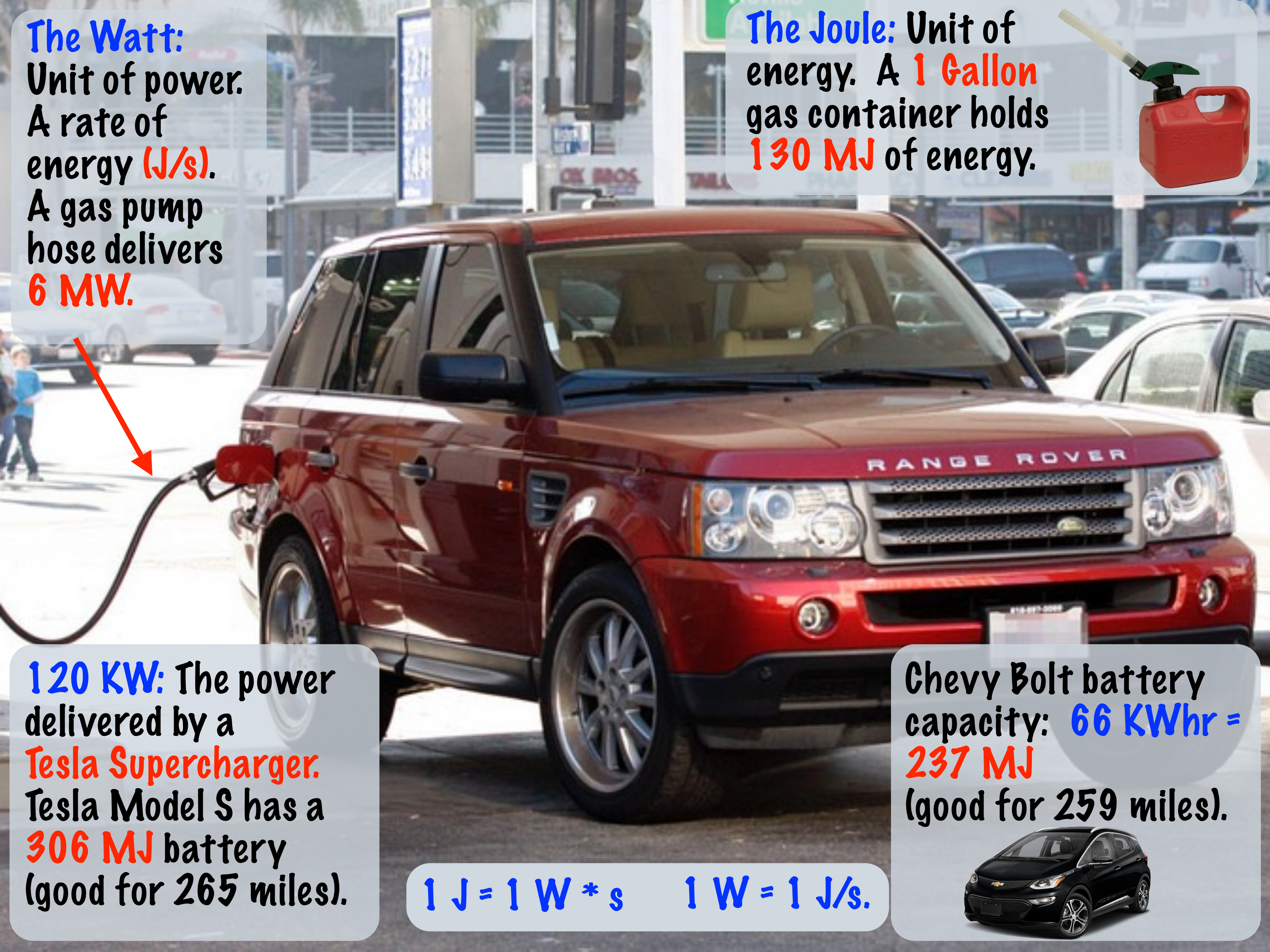
EECS 151/251A
Spring 2021
Digital Design and Integrated Circuits

Instructor:
John Wawrzynek

Lecture 16

Announcements

- Virtual Front Row today, 3/16:
  - *Power and Energy*
  - *Ben Tait*
  - *Khashayar Pirouzmand*
  - *Jennifer Zhou*
  - *ZItao Fang*
- HW7 to be posted later this week
- Midterm grading underway - grades posted by Thursday
- Feedback welcome!



The Watt: Unit of power. A rate of energy (J/s). A gas pump hose delivers 6 MW.

The Joule: Unit of energy. A 1 Gallon gas container holds 130 MJ of energy.

120 KW: The power delivered by a Tesla Supercharger. Tesla Model S has a 306 MJ battery (good for 265 miles).

1 J = 1 W * s   1 W = 1 J/s.

Chevy Bolt battery capacity: 66 KWhr = 237 MJ (good for 259 miles).

Energy and Power

Energy is the ability to do work (W).

Power is rate of expending energy.

$$P = \frac{dW}{dt}$$

Energy Efficiency: energy per operation

- ***Handheld and portable*** (battery operated):
  - Energy Efficiency - limits battery life
  - Power - limited by heat

- ***Infrastructure and servers*** (connected to power grid):
  - Energy Efficiency - dictates operation cost
  - Power - heat removal contributes to TCO

Remember: P = IV

Sad fact: Computers turn electrical energy into heat. Computation is a byproduct.

Energy and Performance

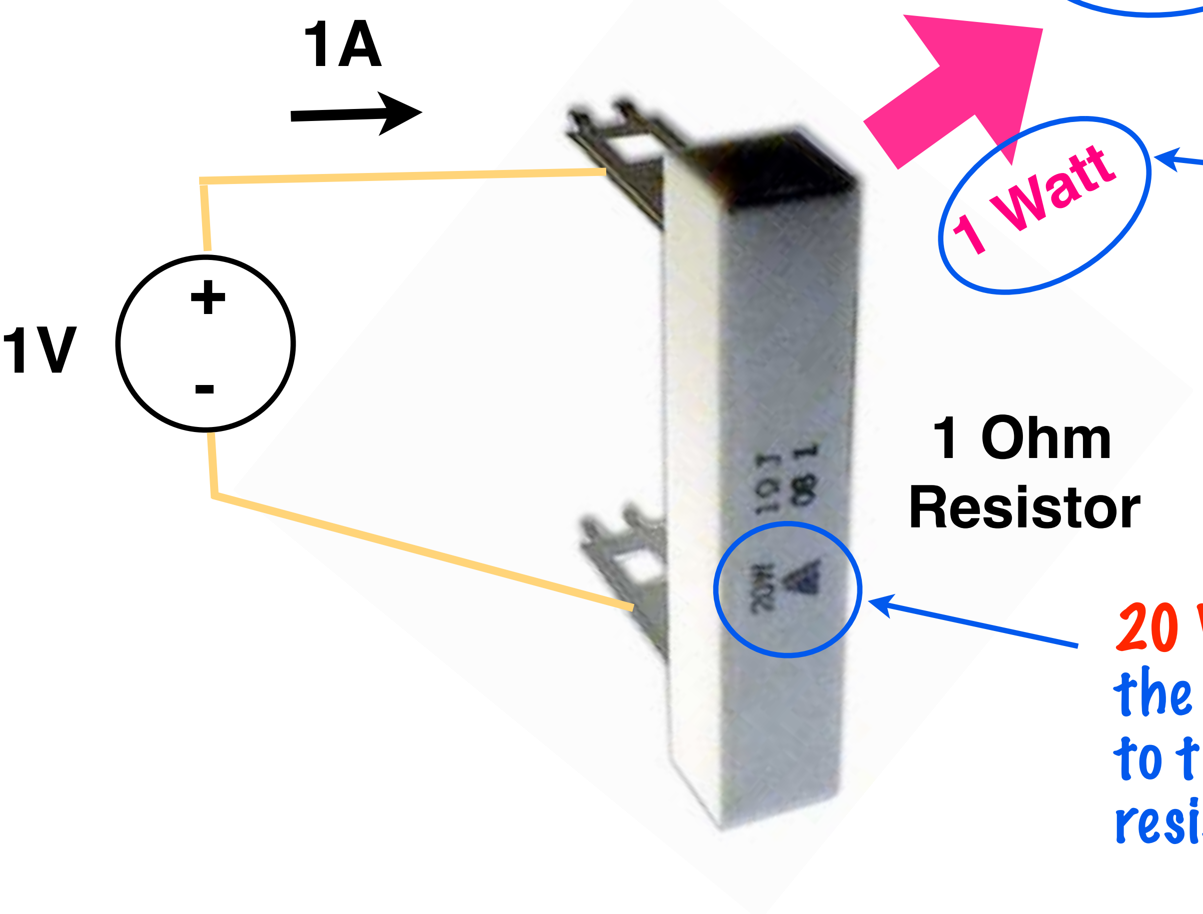
Air or water carries heat away, or chip melts.

The Joule: Unit of energy. Can also be expressed as **Watt-Seconds.** Burning 1 Watt for 100 seconds uses 100 Watt-Seconds of energy.

This is how electric tea pots work ...

1 Joule heats 1 gram of water
0.24 degree C

1 Joule of Heat Energy
per Second



The Watt: Unit of power. The rate at which energy dissipated in the resistor.

20 W rating: Maximum power the package is able to transfer to the air. Exceed rating and resistor **burns.**

Old example: Cooling an iPod nano ...

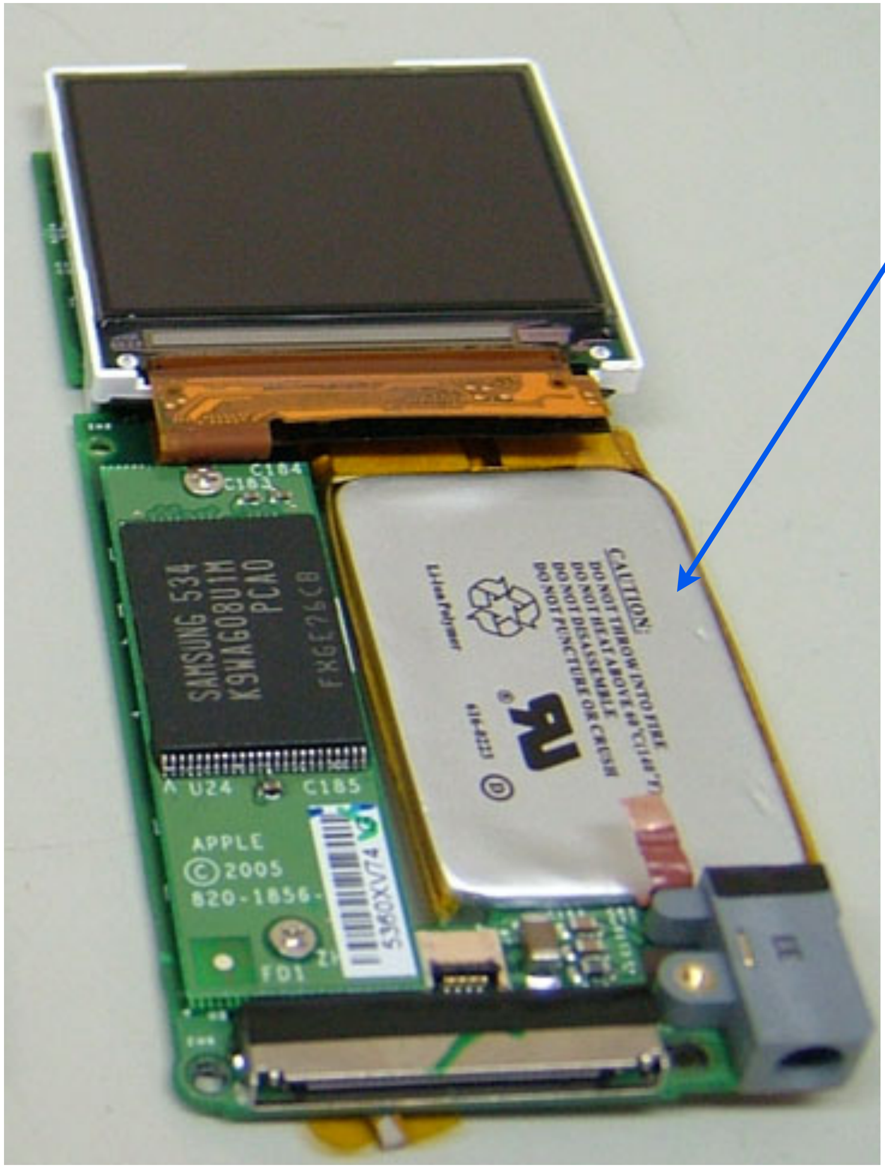
Like resistor on last slide, iPod relies on passive transfer of heat from case to the air.

Why? Users don't want fans in their pocket ...

To stay "cool to the touch" via passive cooling, power budget of 5 W.

If iPod nano used 5W all the time, its battery would last 15 minutes ...

Powering an iPod nano (2005 edition)


C184
C183
SAMSUNG 534
K9WAG08U1M
PCA0
U24
C185
APPLE
©2005
820-1856-
FD1
CAUTION
Li-ion Polymer

1.2 W-hour battery:
Can supply 1.2 watts
of power for 1 hour.

$1.2\ \text{W-hr} / 5\ \text{W} \approx$ 15 minutes.

More W-hours require bigger battery
and thus bigger “form factor” --
it wouldn’t be “nano” anymore :-).

Real specs for iPod nano :

14 hours for music,

4 hours for slide shows.

85 mW for music.

300 mW for slides.

What's happened since 2005?

2010 nano

0.74 ounces (50% of 2005 Nano)

"Up to" 24 hours audio playback.

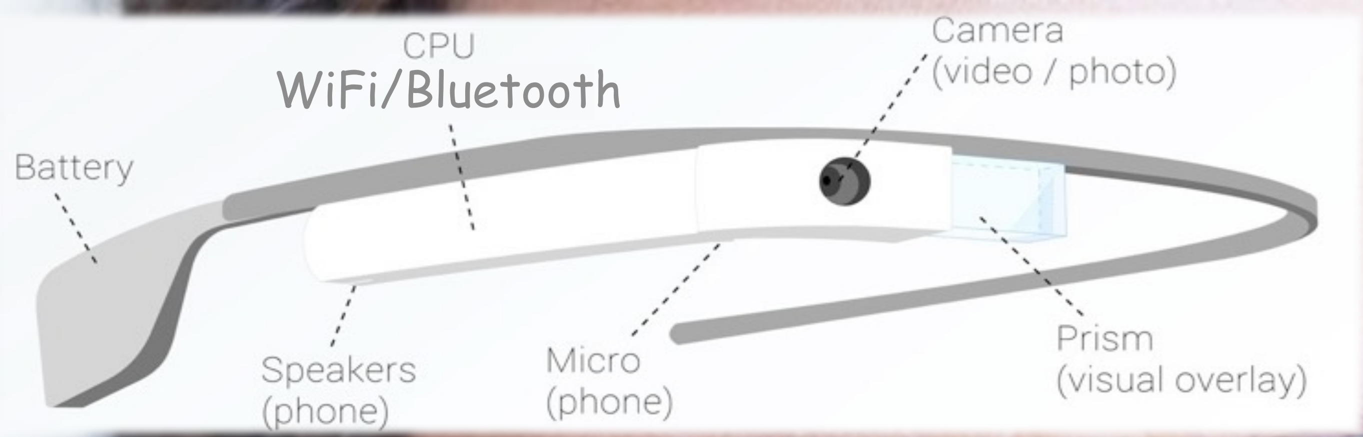
70% improvement from 2005 nano.

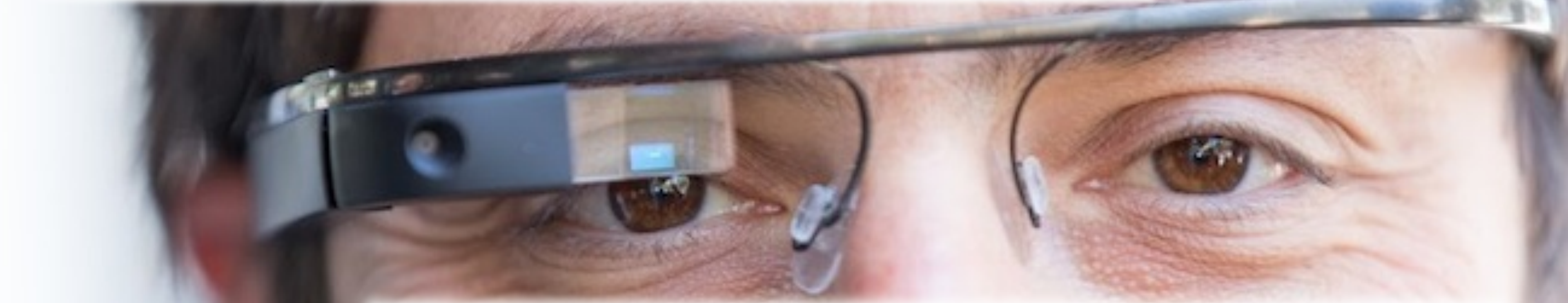
0.39 W Hr (33% of 2005 Nano)

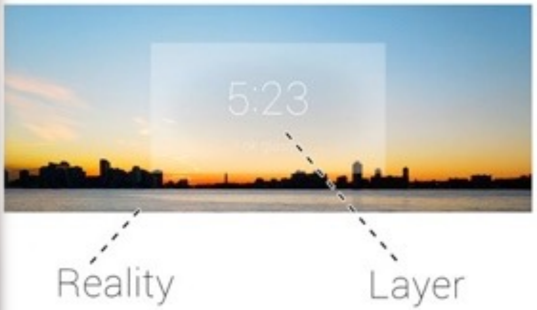
2015

Apple
Watch
LON 5:09
15:00
12PM LUNCH WITH KEN

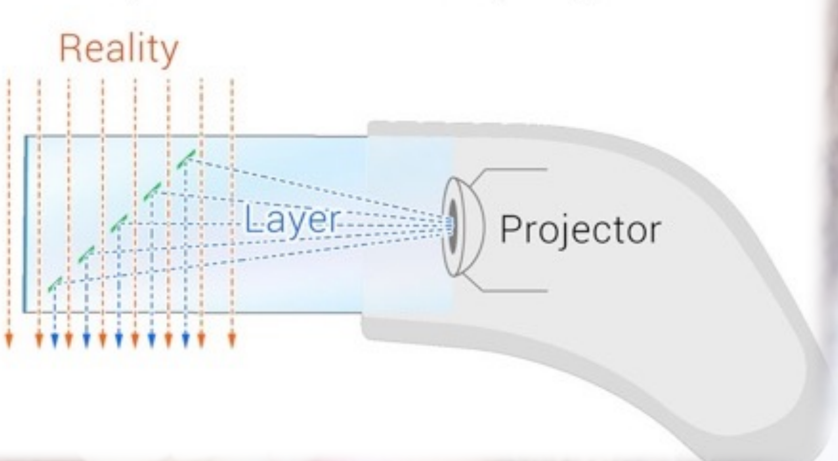
3.8 V, 0.78 Wh lithium-ion battery on 38mm model. Apple claims the 205 mAh battery should provide up to 18 hours of use (which translates to 6.5 hours of audio playback, 3 hours of talk time, or 72 hours of Power Reserve mode.)


CPU
WiFi/Bluetooth
Camera (video / photo)
Battery
Speakers (phone)
Micro (phone)
Prism (visual overlay)



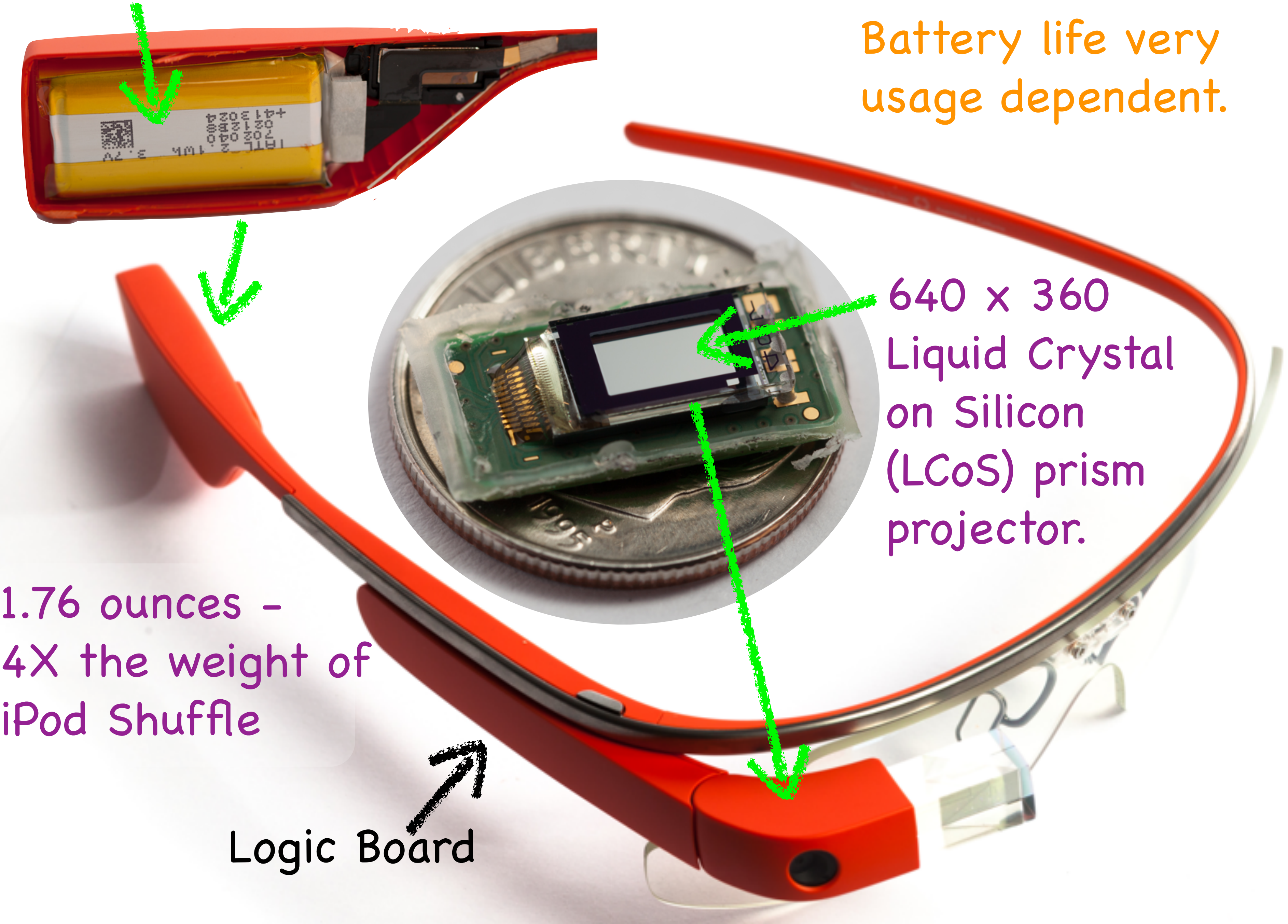

5:23
Reality
Layer

A clever prism projects a layer over reality light.


Reality
Layer
Projector

2.1 Wh battery - 5.3x as much energy as 2010 Nano.

Battery life very usage dependent.



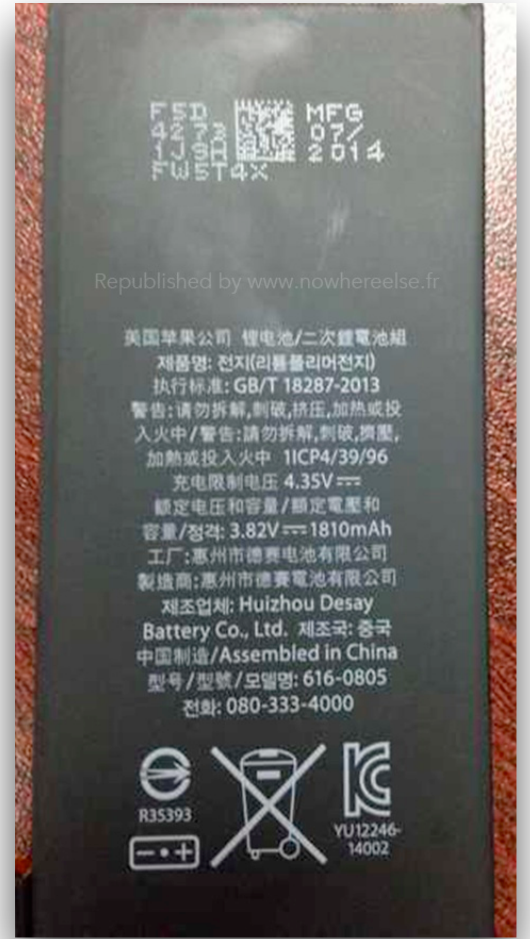
640 x 360 Liquid Crystal on Silicon (LCoS) prism projector.

1.76 ounces - 4X the weight of iPod Shuffle

Logic Board

iPhone6

4.7 inch iPhone6:
1,810mAh battery
@3.8V = 6.88 Wh



FSD 4273 1J9H FW5T4X
MFG 07/ 2014

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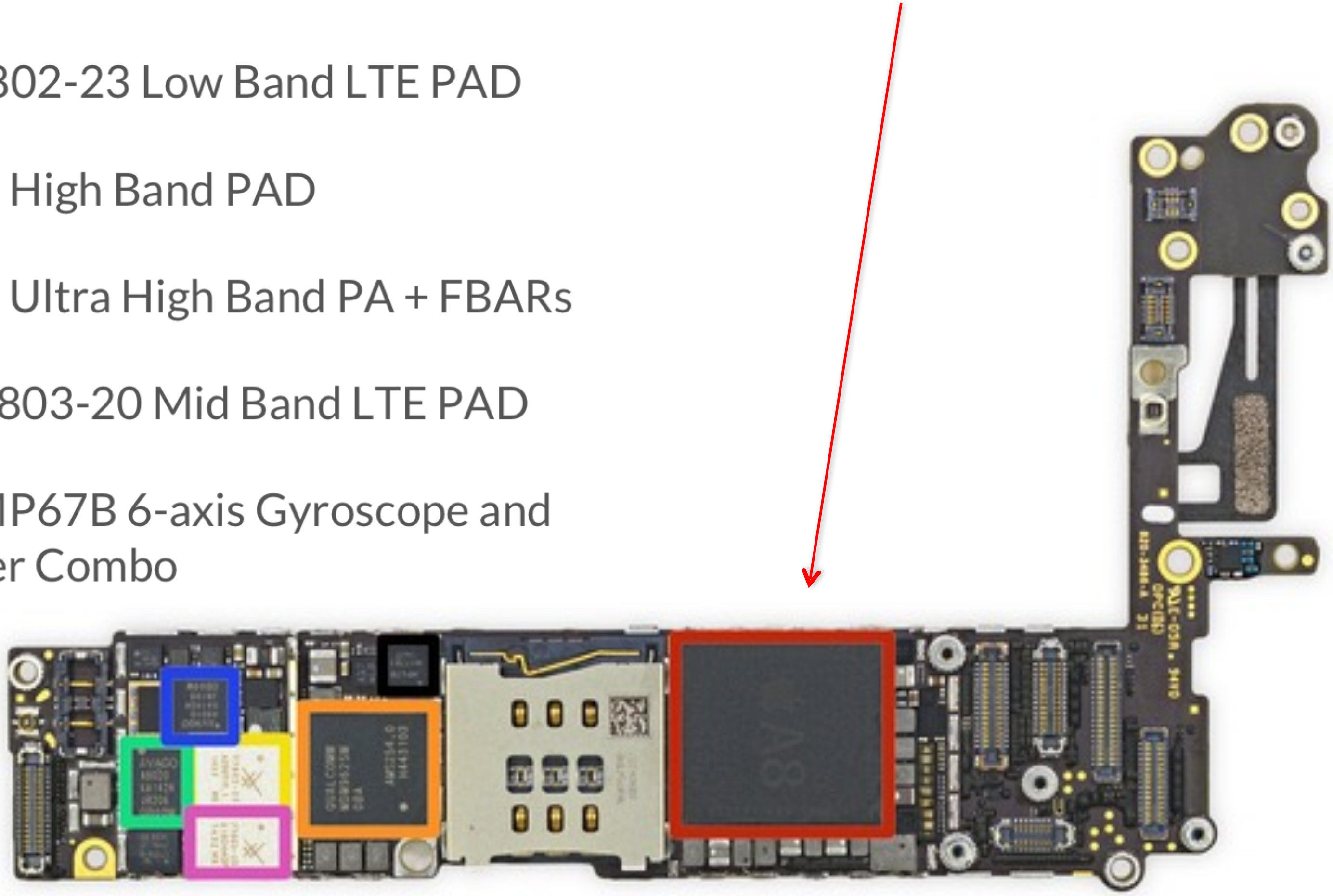
美国苹果公司 锂电池/二次鋰電池組
제품명: 전지(리튬폴리머전지)
执行标准: GB/T 18287-2013
警告:请勿拆解,刺破,挤压,加热或投
入火中 / 警告:請勿拆解,刺破,擠壓,
加熱或投入火中 1ICP4/39/96
充电限制电压 4.35V ⎓
额定电压和容量 / 額定電壓和
容量/정격: 3.82V ⎓ 1810mAh
工厂:惠州市德赛电池有限公司
製造商:惠州市德賽電池有限公司
제조업체: Huizhou Desay
Battery Co., Ltd. 제조국: 중국
中国制造/Assembled in China
型号 / 型號 / 모델명: 616-0805
전화: 080-333-4000

iPhone 5s: 1570mAh
@3.8V = 6 Wh

- The front side of the logic board:
  - 🔴 Apple A8 APL1011 SoC + SK Hynix RAM as denoted by the markings H9CKNNN8KTMRWR-NTH (we presume it is 1 GB LPDDR3 RAM, the same as in the iPhone 6 Plus)
  - 🟠 Qualcomm MDM9625M LTE Modem
  - 🟡 Skyworks 77802-23 Low Band LTE PAD
  - 🟢 Avago A8020 High Band PAD
  - 🔵 Avago A8010 Ultra High Band PA + FBARs
  - 🟣 SkyWorks 77803-20 Mid Band LTE PAD
  - ⚫ InvenSense MP67B 6-axis Gyroscope and Accelerometer Combo

The A8 is manufactured on a 20 nm process by TSMC. It contains 2 billion transistors. Its physical size is 89 mm^2.] It has 1 GB of LPDDR3 RAM included in the package. It is dual core, and has a frequency of 1.38 GHz.

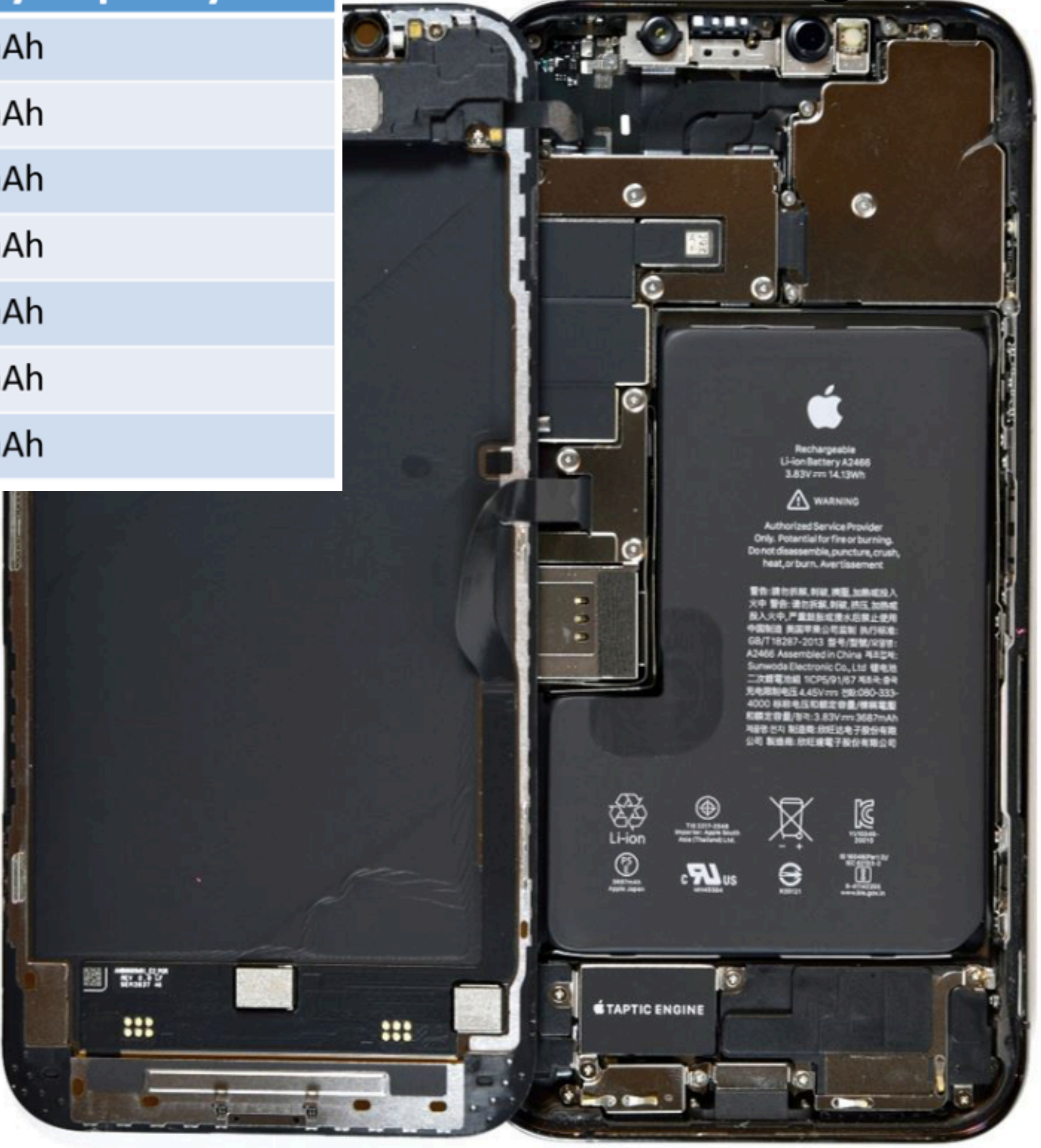


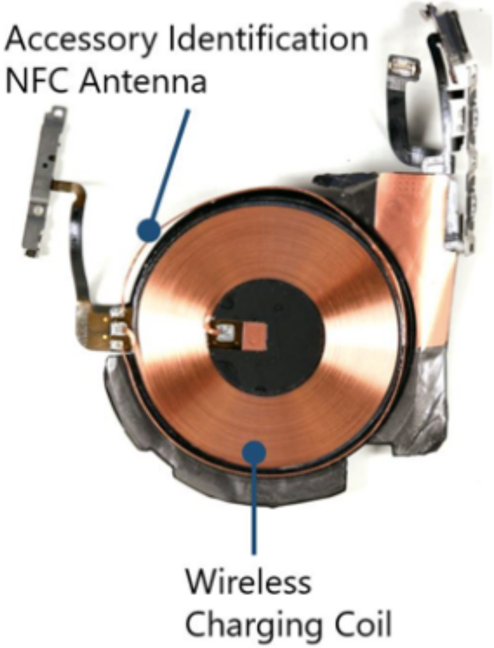
Iphone 12:

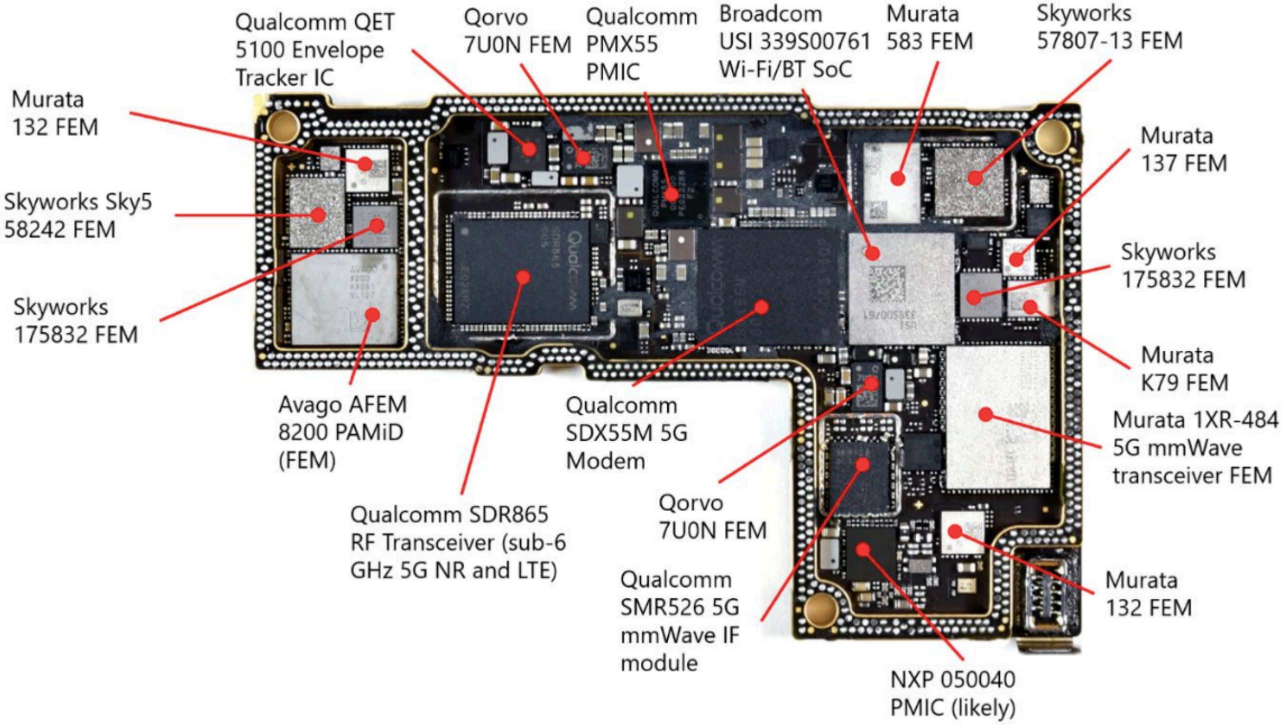
https://unitedlex.com/insights/apple-iphone-12-pro-max-teardown-report

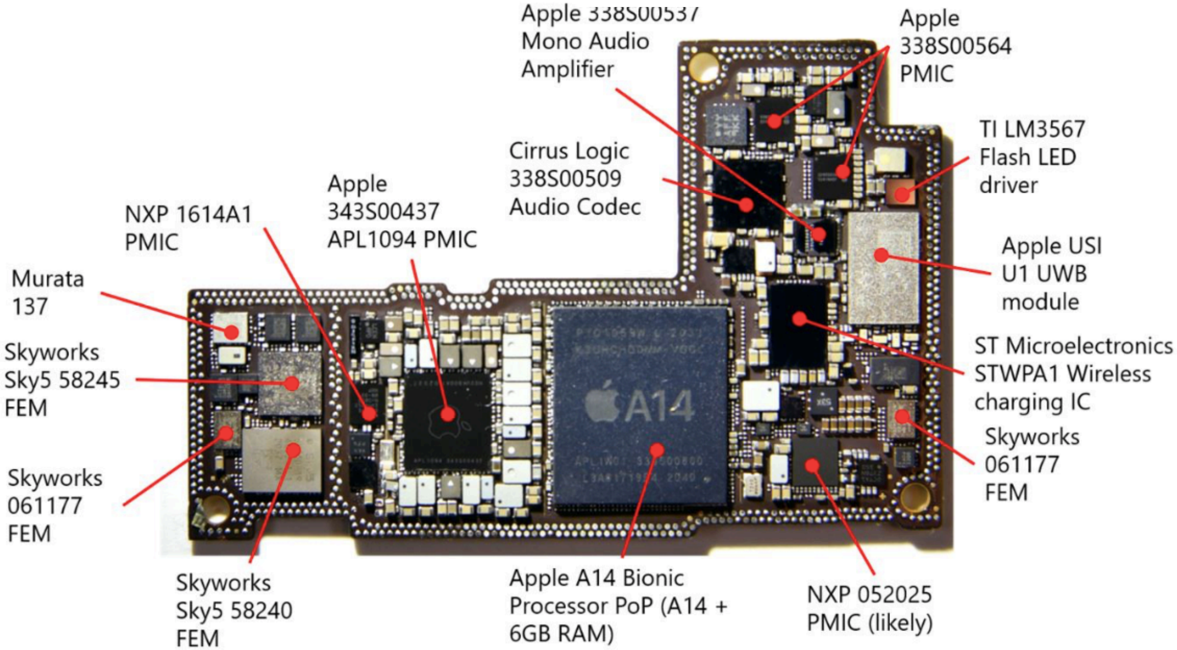
iPhone Model	Battery Capacity
iPhone 12 Mini	2,227 mAh
iPhone 12	2,815 mAh
iPhone 12 Pro	2,815 mAh
iPhone 12 Pro Max	3,687 mAh
iPhone 11	3,110 mAh
iPhone 11 Pro	3,046 mAh
iPhone 11 Pro Max	3,969 mAh

14.13 Wh @ 3.8V


Rechargeable
Li-ion Battery A2466
3.83V ⎓ 14.13Wh
WARNING
Authorized Service Provider Only. Potential for fire or burning. Do not disassemble, puncture, crush, heat, or burn. Avertissement
Li-ion
TAPTIC ENGINE

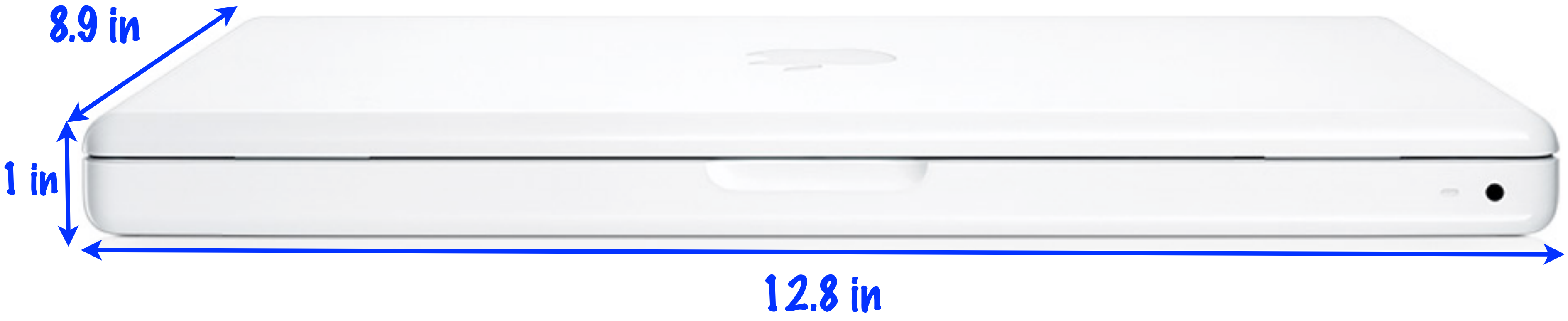

Accessory Identification NFC Antenna
Wireless Charging Coil


Qualcomm QET 5100 Envelope Tracker IC
Qorvo 7U0N FEM
Qualcomm PMX55 PMIC
Broadcom USI 339S00761 Wi-Fi/BT SoC
Murata 583 FEM
Skyworks 57807-13 FEM
Murata 132 FEM
Murata 137 FEM
Skyworks Sky5 58242 FEM
Skyworks 175832 FEM
Skyworks 175832 FEM
Murata K79 FEM
Avago AFEM 8200 PAMiD (FEM)
Qualcomm SDX55M 5G Modem
Murata 1XR-484 5G mmWave transceiver FEM
Qorvo 7U0N FEM
Qualcomm SDR865 RF Transceiver (sub-6 GHz 5G NR and LTE)
Qualcomm SMR526 5G mmWave IF module
Murata 132 FEM
NXP 050040 PMIC (likely)


Apple 338S00537 Mono Audio Amplifier
Apple 338S00564 PMIC
TI LM3567 Flash LED driver
Cirrus Logic 338S00509 Audio Codec
Apple 343S00437 APL1094 PMIC
NXP 1614A1 PMIC
Apple USI U1 UWB module
Murata 137
Skyworks Sky5 58245 FEM
ST Microelectronics STWPA1 Wireless charging IC
Skyworks 061177 FEM
Skyworks 061177 FEM
Skyworks Sky5 58240 FEM
Apple A14 Bionic Processor PoP (A14 + 6GB RAM)
NXP 052025 PMIC (likely)

Notebooks ... as designed in 2006 ...

2006 Apple MacBook -- 5.2 lbs



- **Performance:** Must be “close enough” to desktop performance ... most people no longer used a desktop (even in 2006).
- **Size and Weight.** Ideal: paper notebook.
- **Heat:** No longer “laptops” -- top may get “warm”, bottom “hot”. Quiet fans OK.

Battery: Set by size and weight limits ...

46x more energy than iPod nano battery. And iPod lets you listen to music for 14 hours!

Battery rating: 55 W-hour.

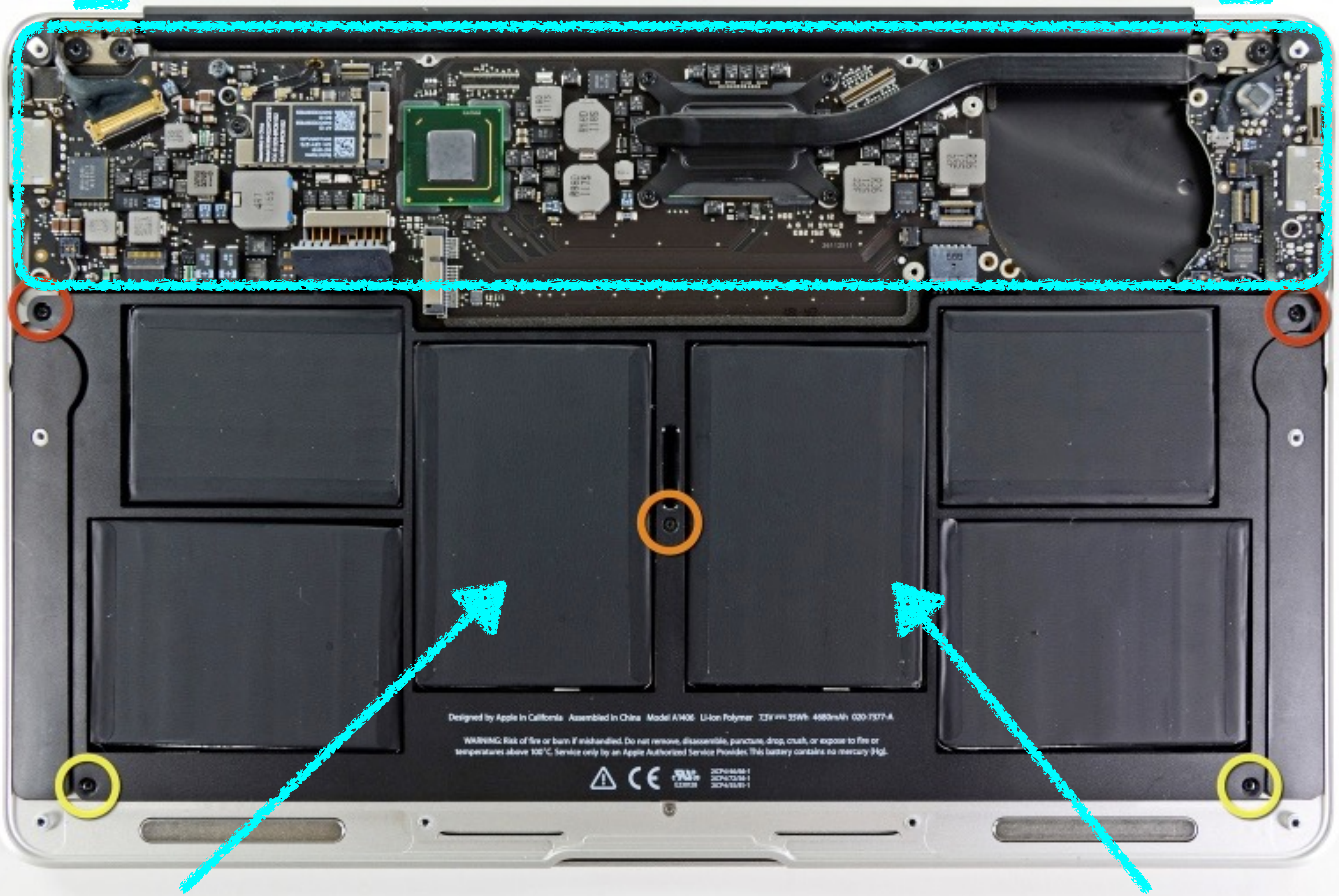
At 2.3 GHz, Intel Core Duo CPU consumes 31 W running a heavy load - under 2 hours battery life! And, just for CPU!

Almost full 1 inch depth. Width and height set by available space, weight.

At 1 GHz, CPU consumes 13 Watts. "Energy saver" option uses this mode ...

MacBook Air … design the laptop like an iPod

Mainboard: fills about 25% of the laptop


Designed by Apple in California Assembled in China Model A1406 Li-Ion Polymer 7.3V 35Wh 4680mAh 020-7377-A
WARNING: Risk of fire or burn if mishandled. Do not remove, disassemble, puncture, drop, crush, or expose to fire or temperatures above 100°C. Service only by an Apple Authorized Service Provider. This battery contains no mercury (Hg).

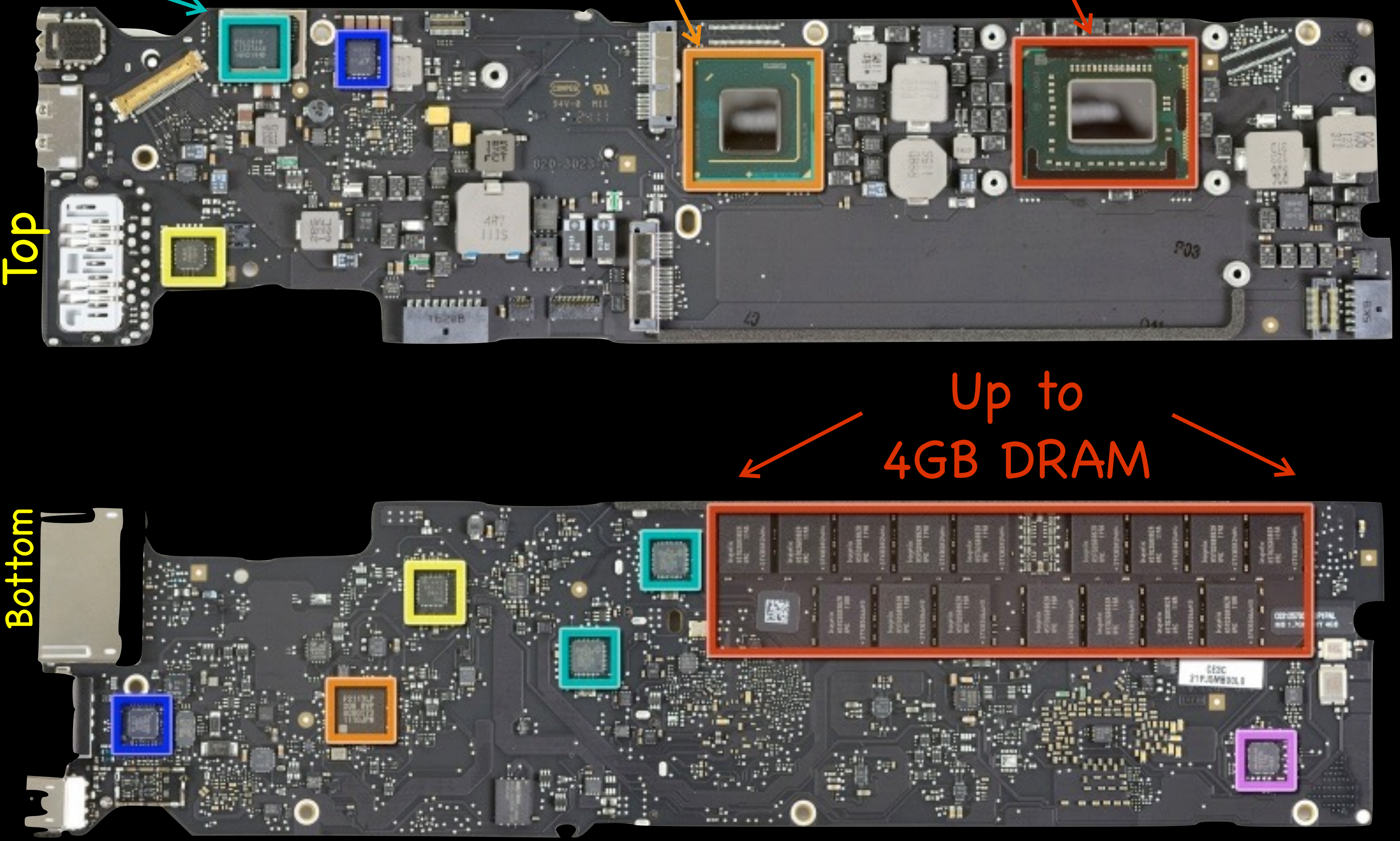
35 W-h battery: 63% of 2006 MacBook's 55 W-h

MacBook Air: Full PC

Thunderbolt I/O

Platform Controller Hub

Core i5 CPU/GPU



Up to 4GB DRAM

50Wh is 180,000 Joules!

Servers: Total Cost of Ownership (TCO)

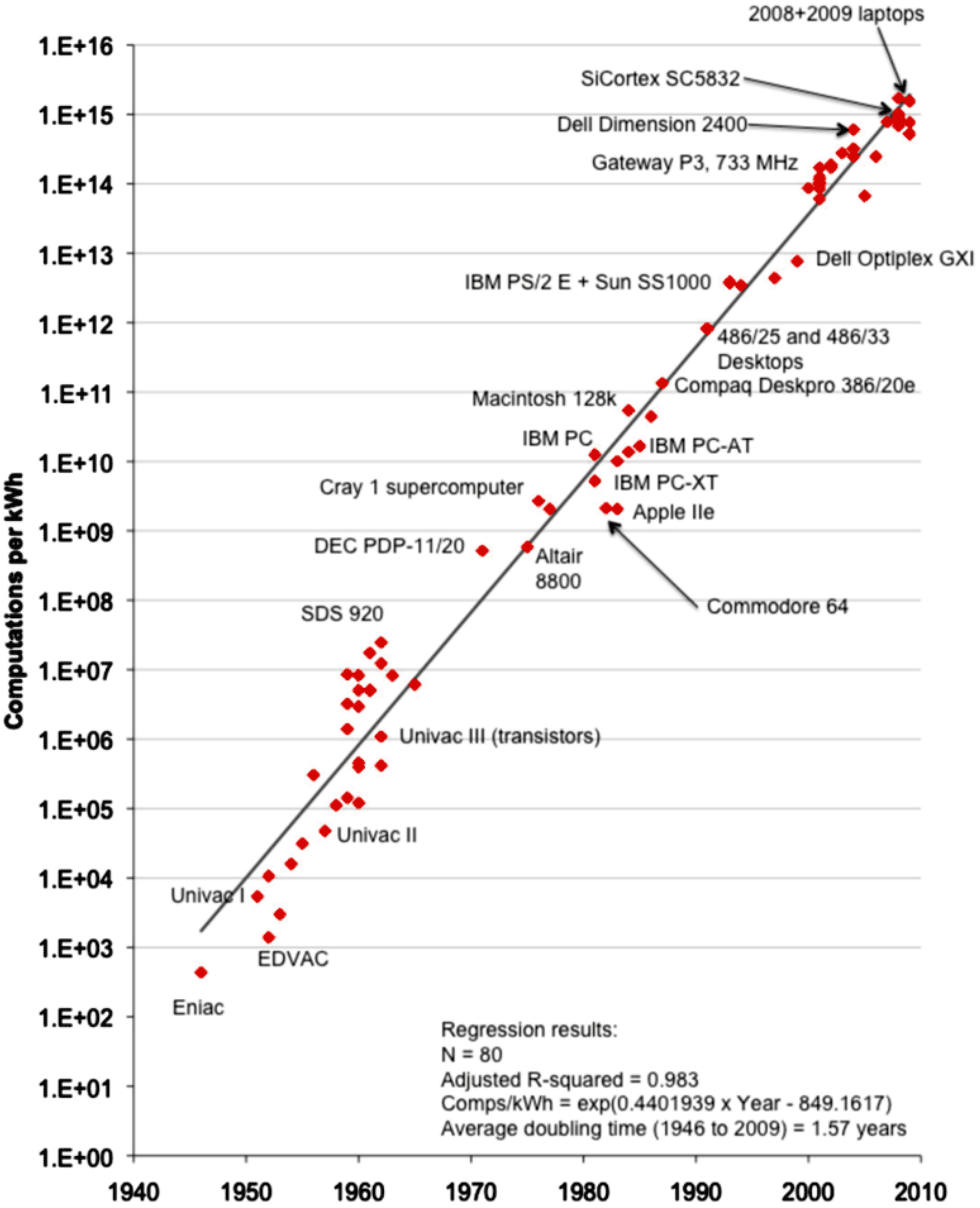
Machine rooms are expensive. Removing heat dictates how many servers to put in a machine room.

Electric bill adds up! Powering the servers + powering the air conditioners is a big part of TCO.

Reliability: running computers hot makes them fail more often.

Computations per W-h doubles every 1.6 years, going back to the first computer.

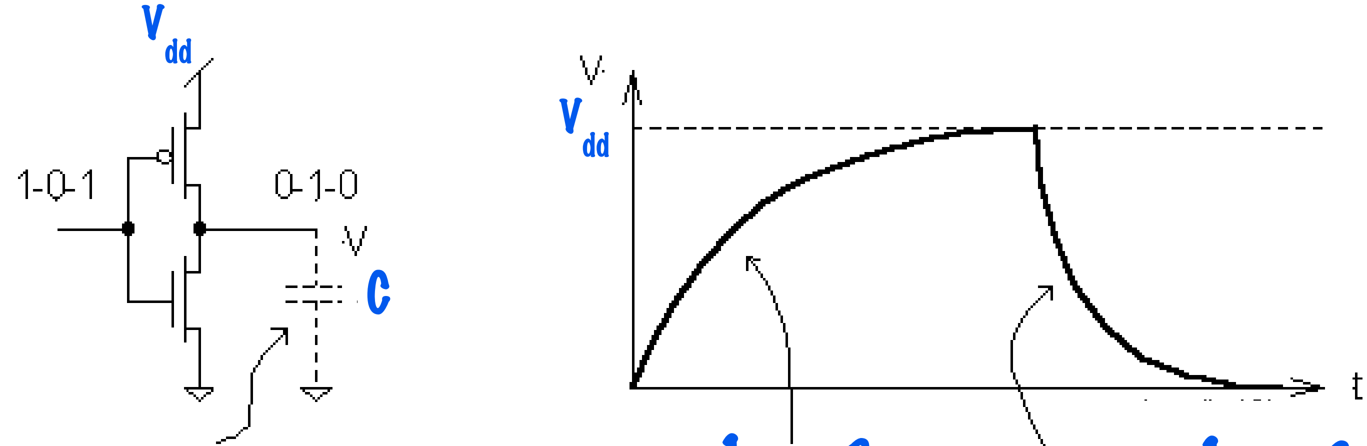
(Jonathan Koomey, Stanford).



CMOS Circuits and Energy

Switching Energy: Fundamental Physics

Every logic transition dissipates energy.



Models inputs to other gates & wire capacitance

$$E_{0\to 1} = \frac{1}{2} C V_{dd}^2 \qquad E_{1\to 0} = \frac{1}{2} C V_{dd}^2$$

Strong result: Independent of technology.

How can we limit switching energy?

(1) Reduce # of clock transitions. But we have work to do ...

(2) Reduce Vdd. But lowering Vdd limits the clock speed ...

(3) Fewer circuits. But more transistors can do more work.

(4) Reduce C per node. One reason why we scale processes.

Chip-Level “Dynamic” Power

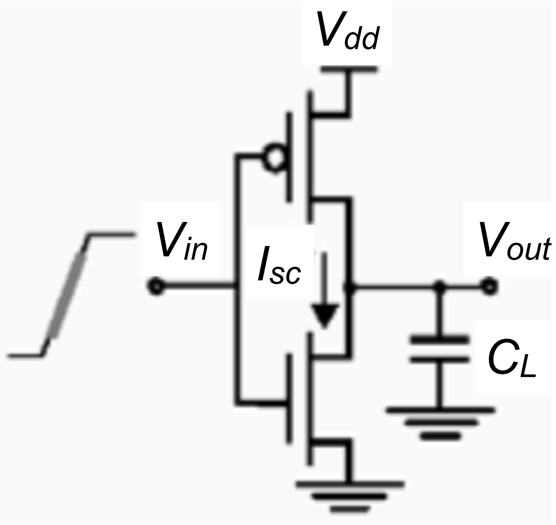
$$P_{sw} = 1/2\ \alpha\ C\ V_{dd}^{2}\ F$$

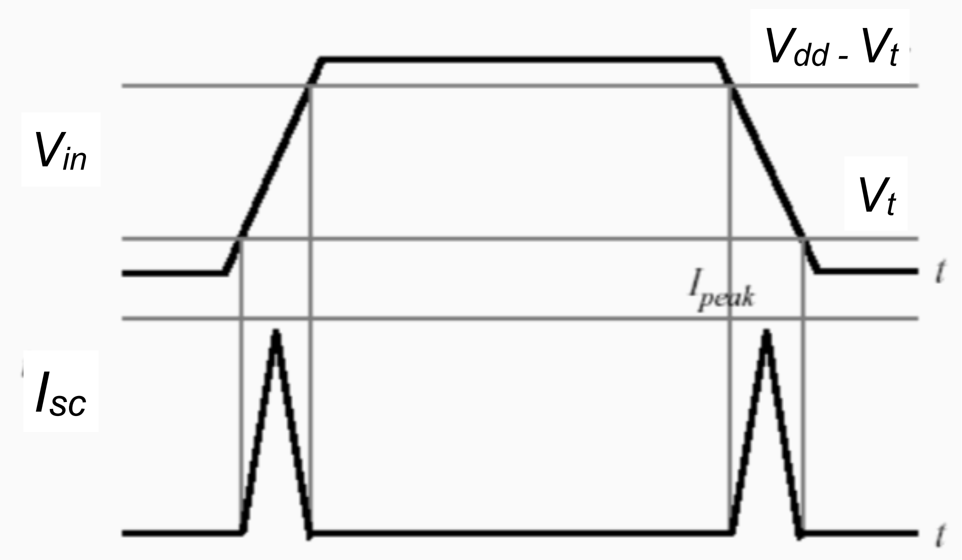
“activity factor”, average percentage of capacitance switching per cycle (~ number of nodes to switch)

Total chip capacitance to be switched

Clock Frequency

Additional Dynamic Power - “short circuit current”



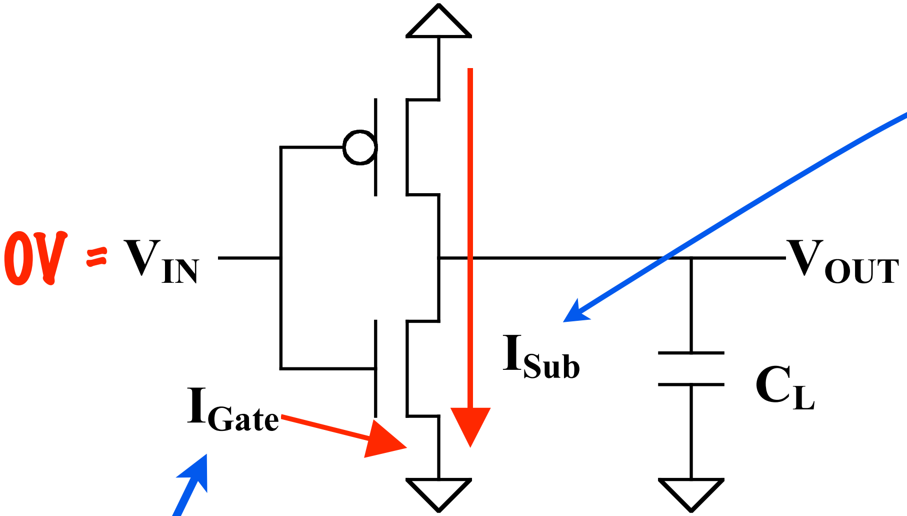


When gate switches, brief period when both pullup network and pulldown network could be on.

Worse when input is changing slowly compared to the output.

Another Factor: Leakage Currents

Even when a logic gate isn't switching, it burns power.

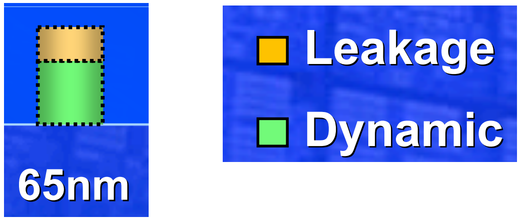


Isub: Even when this nFet is off, it passes an Ioff leakage current.

We can engineer any Ioff we like, but a lower Ioff also results in a lower Ion, and thus a lower maximum clock speed.

Igate: Ideal capacitors have zero DC current. But modern transistor gates are a few atoms thick, and are not ideal.

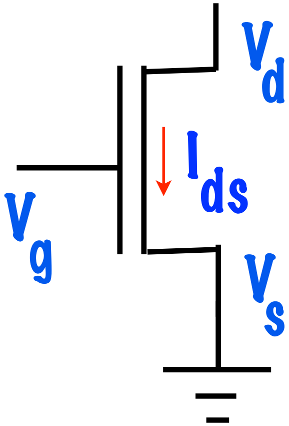
Intel's 2006 processor designs, leakage vs switching power



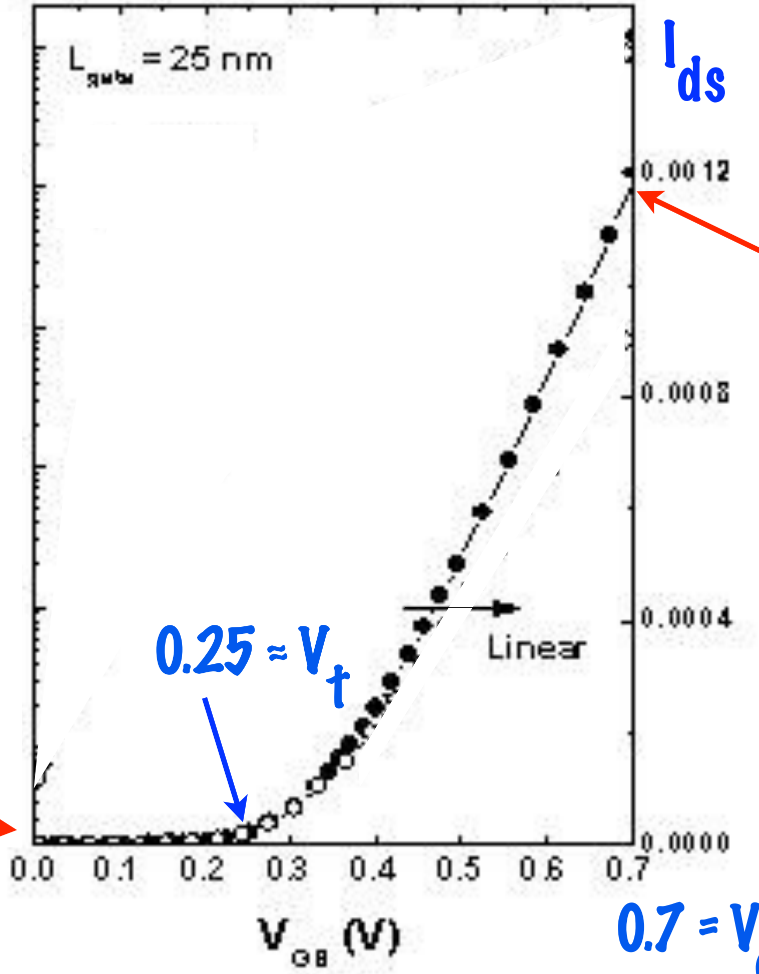
A lot of work was done to get a ratio this good ... 50/50 is common.

Bill Holt, Intel, Hot Chips 17.

Engineering “On” Current at 25 nm ...



We can increase I_{on} by raising V_{dd} and/or lowering V_t.



I_{ds}

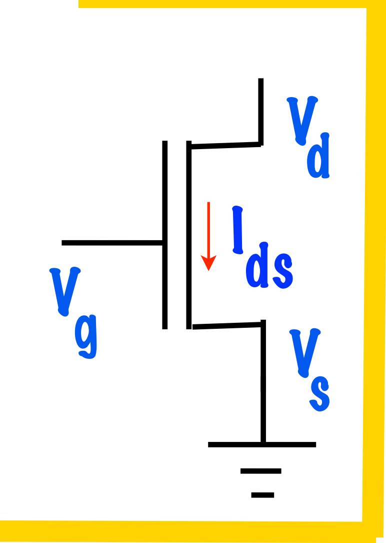
1.2 mA = I_{on}

0.25 ≈ V_t

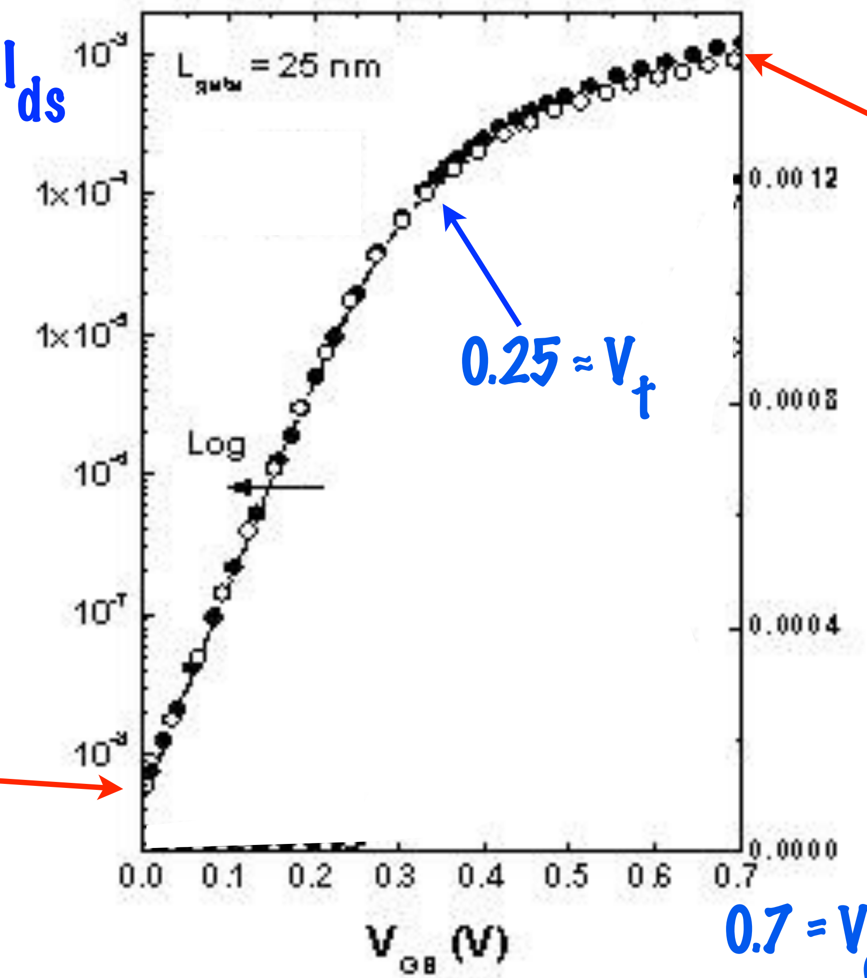
I_{off} = 0 ???

0.7 = V_{dd}

Plot on a “Log” Scale to See “Off” Current



We can decrease I_{off} by raising V_t - but that lowers I_{on}.



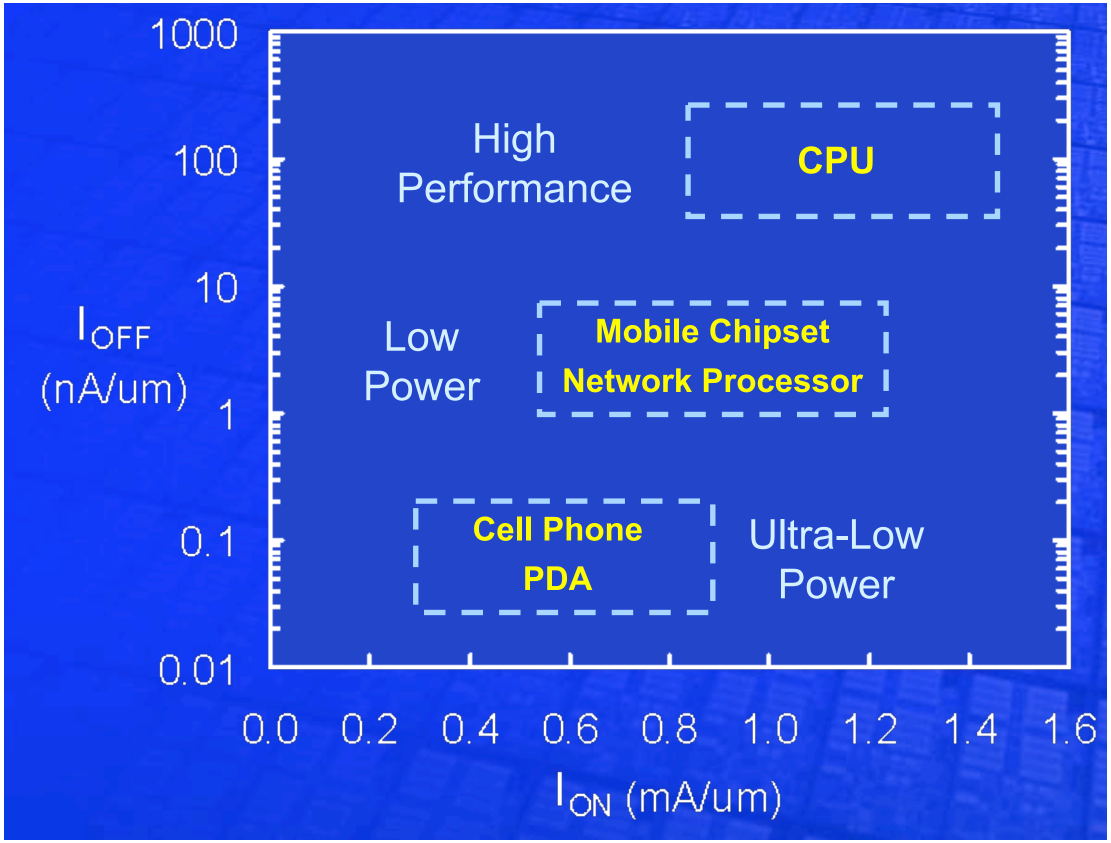
1.2 mA = I_{on}

0.25 ≈ V_t

I_{off} ≈ 10 nA

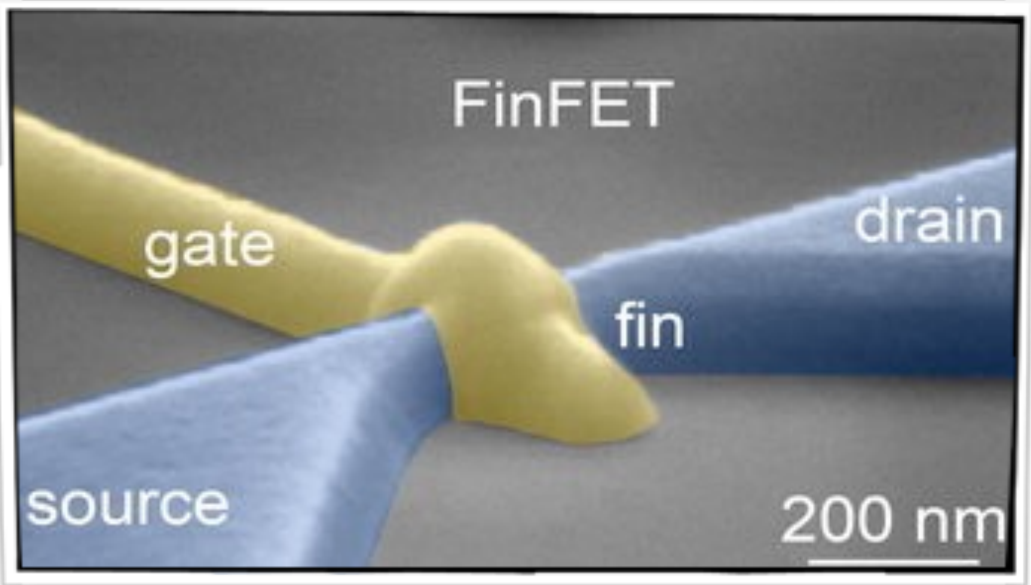
0.7 = V_{dd}

Customize processes for product types ...



From: “Facing the Hot Chips Challenge Again”, Bill Holt, Intel, presented at Hot Chips 17, 2005.

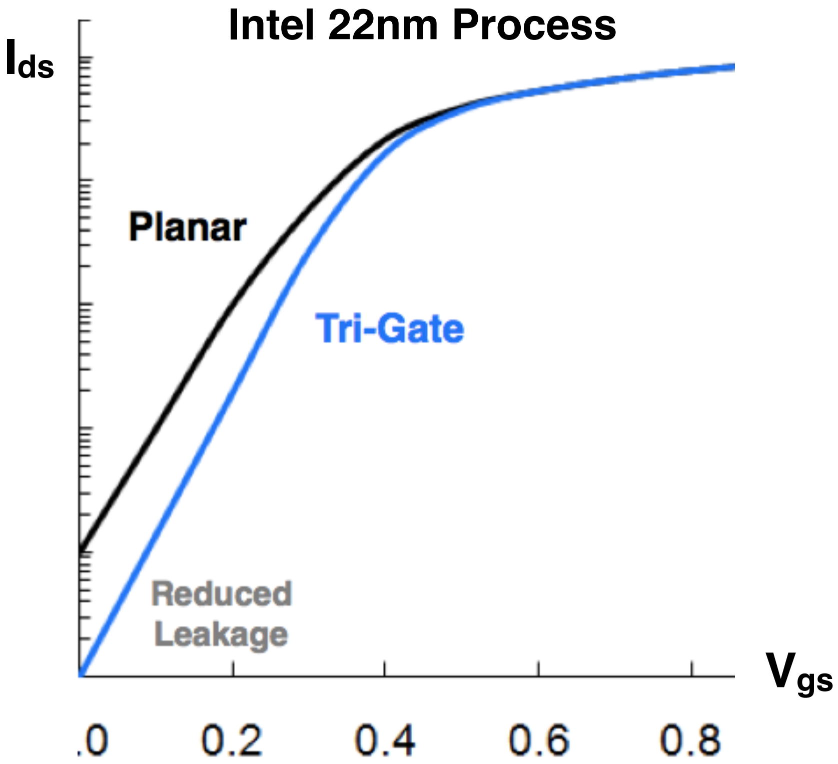
- *Vt is controlled by channel doping.*
- *Modern IC processes have 2 or 3 different Vt values available.*
- *Standard cell libraries offer low Vt and high Vt versions of cells so that the tools can optimize on a per instance basis.*
- *(If high performance not needed then use high Vt to reduce leakage).*

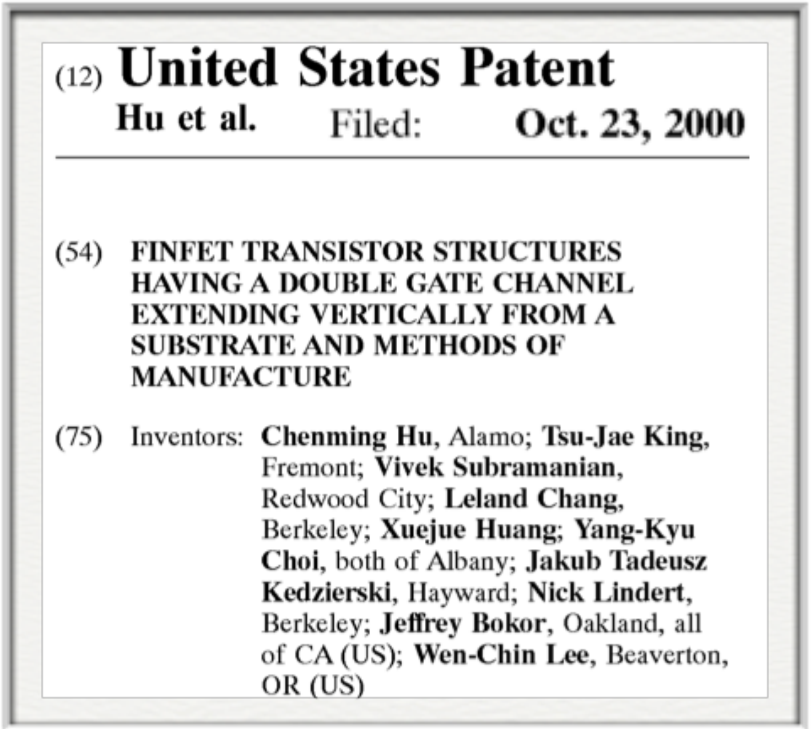


Transistor channel is a raised fin.

Gate controls channel from sides and top.

Channel depth is fin width. 12-15nm for L=22nm.

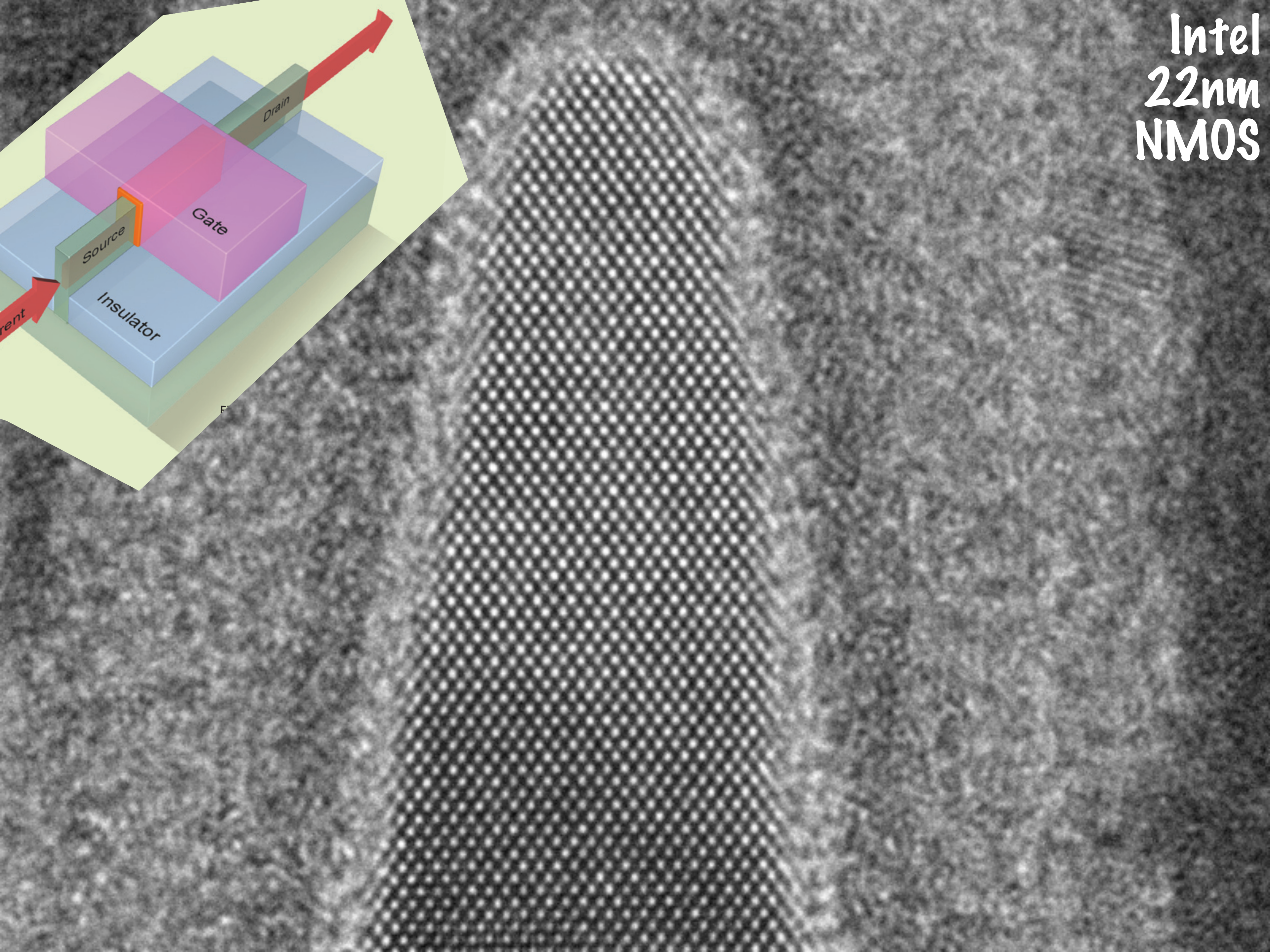




(12) **United States Patent**
Hu et al. Filed: **Oct. 23, 2000**

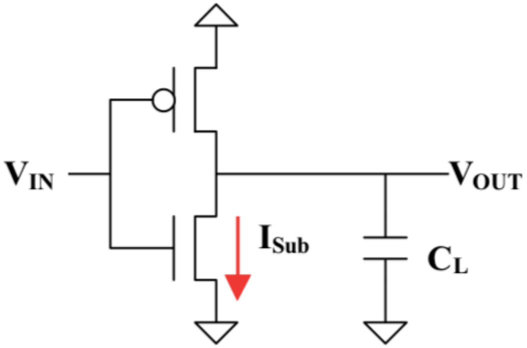
(54) **FINFET TRANSISTOR STRUCTURES HAVING A DOUBLE GATE CHANNEL EXTENDING VERTICALLY FROM A SUBSTRATE AND METHODS OF MANUFACTURE**

(75) Inventors: **Chenming Hu**, Alamo; **Tsu-Jae King**, Fremont; **Vivek Subramanian**, Redwood City; **Leland Chang**, Berkeley; **Xuejue Huang**; **Yang-Kyu Choi**, both of Albany; **Jakub Tadeusz Kedzierski**, Hayward; **Nick Lindert**, Berkeley; **Jeffrey Bokor**, Oakland, all of CA (US); **Wen-Chin Lee**, Beaverton, OR (US)

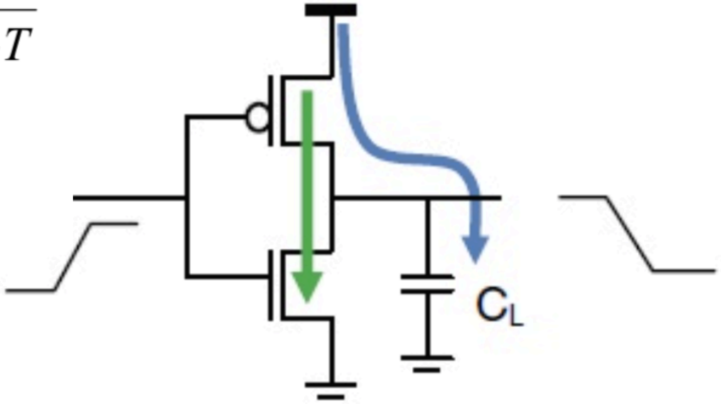

Drain
Gate
Source
Insulator
rent

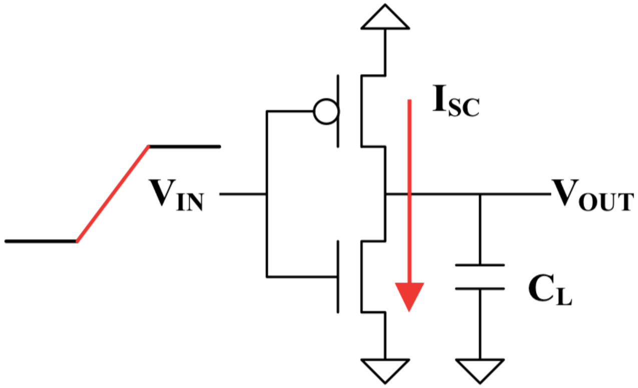
Intel
22nm
NMOS

Total Power = $P_{switching} + P_{short\text{-}circuit} + P_{leakage}$


V_{IN}
V_{OUT}
I_{Sub}
C_L

$$I_{DSub} = k \cdot e^{\frac{-q\cdot V_T}{a\cdot k_a\cdot T}}$$




I_{SC}
V_{IN}
V_{OUT}
C_L

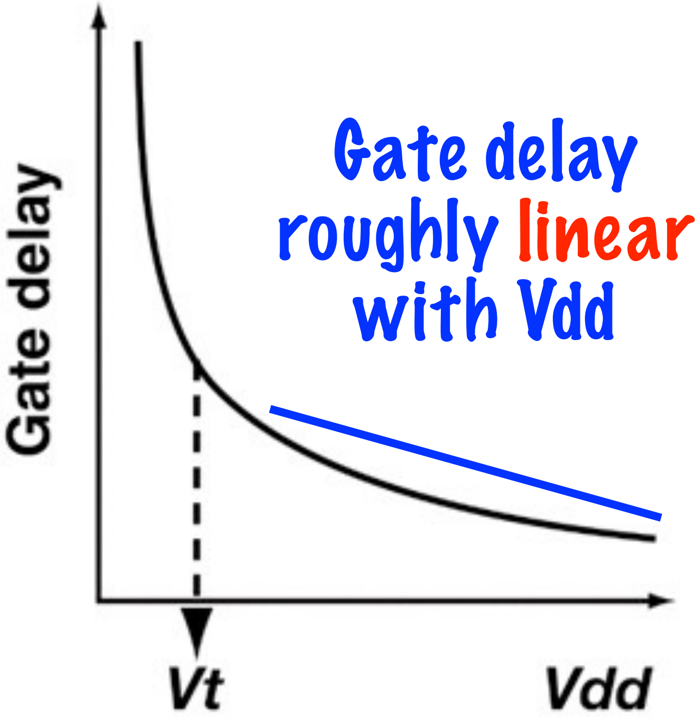
Some low-power design techniques

- Parallelism and pipelining
- Power-down idle transistors
- Slow down non-critical paths
- Clock gating
- Thermal management

Design Technique #1 (of 5)

Trading Hardware for Power

via Parallelism and Pipelining ...



Gate delay roughly linear with Vdd

And so, we can transform this:

Vdd

Logic Block

$P \sim F \times V_{dd}^2$

$P \sim 1 \times 1^2$

Freq = 1
Vdd = 1
Throughput = 1
Power = 1
Area = 1
Pwr Den = 1

Block processes stereo audio. 1/2 of clocks for "left", 1/2 for "right".

Into this:

Top block processes "left", bottom "right".

Vdd/2

Logic Block

Logic Block

Freq = 0.5
Vdd = 0.5
Throughput = 1
Power = 0.25
Area = 2
Pwr Den = 0.125

$P \sim \#blks \times F \times V_{dd}^2$

$P \sim 2 \times 1/2 \times 1/4 = 1/4$

CV^2 power only

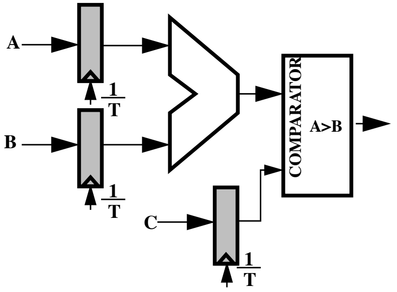
THIS MAGIC TRICK BROUGHT TO YOU BY CORY HALL ...

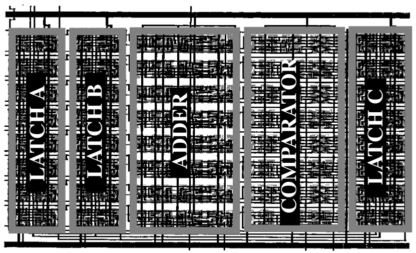
Chandrakasan & Brodersen (UCB, 1992)

Architecture	Power (normalized)
Simple	1
Parallel	0.36
Pipelined	0.39
Pipelined-Parallel	0.2

Architecture	Area (normalized)
Simple	1
Parallel	3.4
Pipelined	1.3
Pipelined-Parallel	3.7

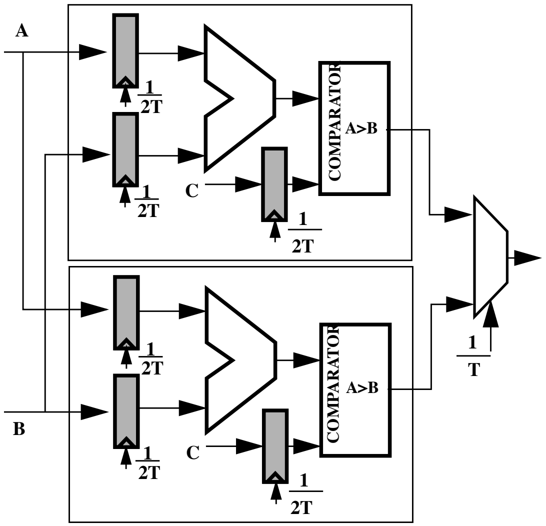
Architecture	Voltage
Simple	5V
Parallel	2.9V
Pipelined	2.9V
Pipelined-Parallel	2.0

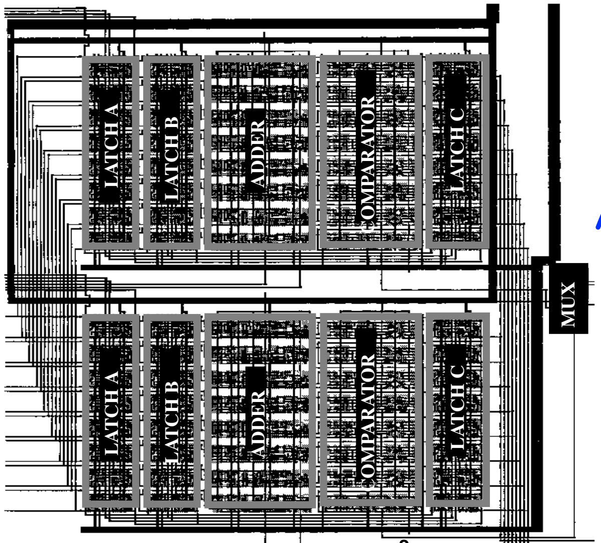

A
B
C
$\frac{1}{T}$
COMPARATOR
A>B


LATCH A
LATCH B
ADDER
COMPARATOR
LATCH C

Area = 636 x 833 μ^2

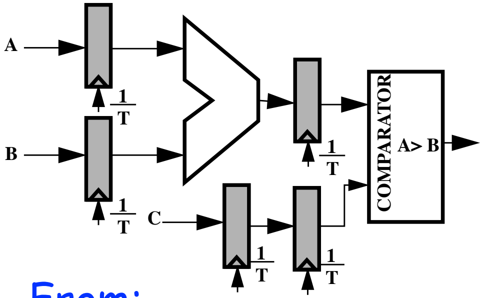
Simple

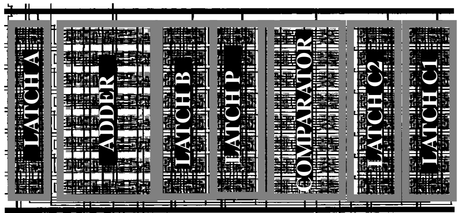

A
B
C
$\frac{1}{2T}$
$\frac{1}{T}$
COMPARATOR
A>B


LATCH A
LATCH B
ADDER
COMPARATOR
LATCH C
MUX

Area = 1476 x 1219 μ^2

Parallel


A
B
C
$\frac{1}{T}$
COMPARATOR
A> B


LATCH A
ADDER
LATCH B
LATCH P
COMPARATOR
LATCH C2
LATCH C1

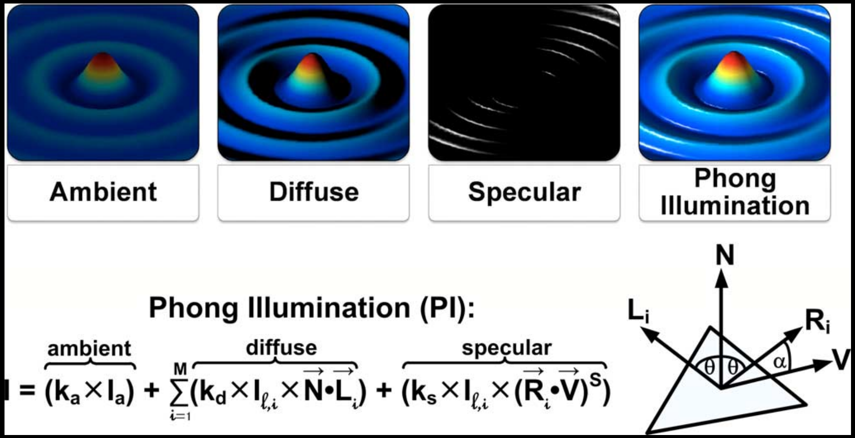
Area = 640 x 1081 μ^2

Pipelined

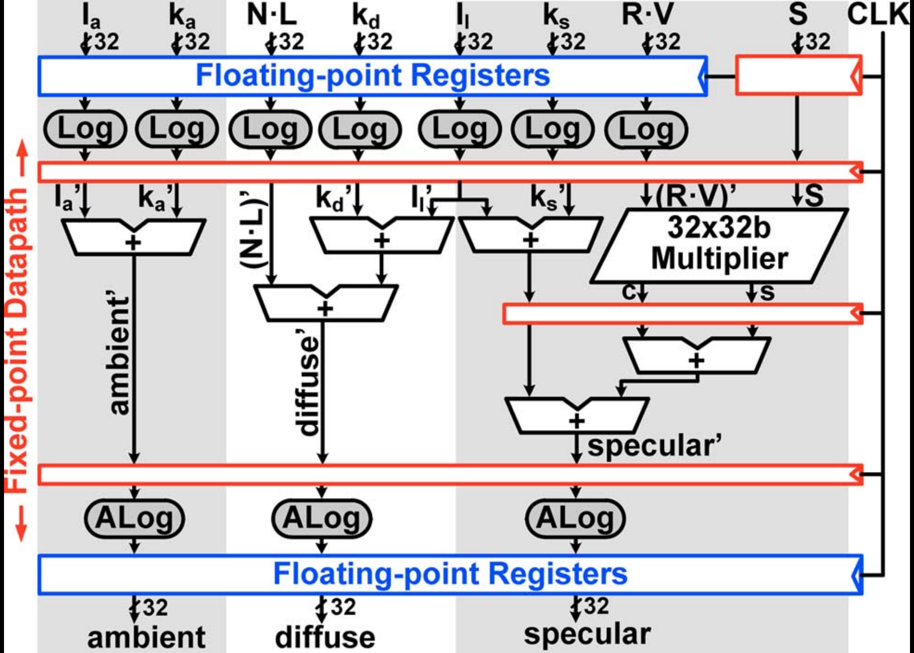
From:

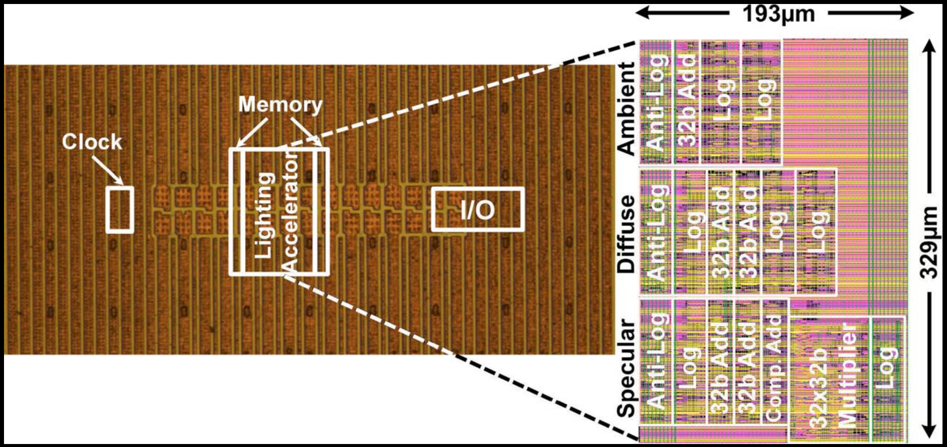
Minimizing Power Consumption in CMOS Circuits Anantha P. Chandrakasan, Robert W. Brodersen

Example: Intel Graphics Pipeline IP


Ambient
Diffuse
Specular
Phong Illumination
Phong Illumination (PI):
ambient
diffuse
specular
N
L_i
R_i
V
θ
θ
α

$$I = \underbrace{(k_a \times I_a)}_{\text{ambient}} + \underbrace{\sum_{i=1}^{M}(k_d \times I_{\ell,i} \times \vec{N} \bullet \vec{L}_i)}_{\text{diffuse}} + \underbrace{(k_s \times I_{\ell,i} \times (\vec{R}_i \bullet \vec{V})^S)}_{\text{specular}}$$

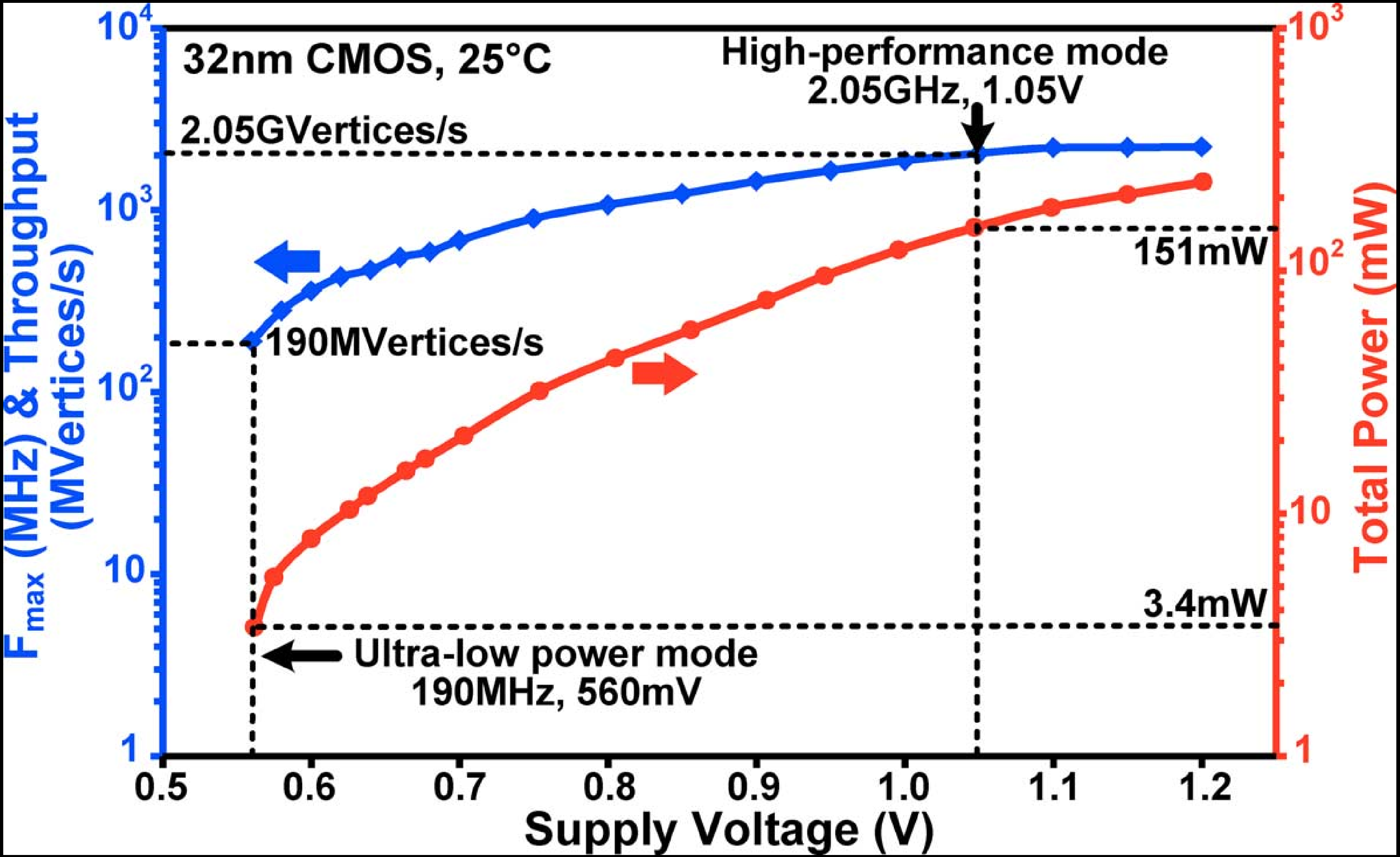

I_a
k_a
N·L
k_d
I_l
k_s
R·V
S
CLK
32
Floating-point Registers
Log
I_a'
k_a'
(N·L)'
k_d'
I_l'
k_s'
(R·V)'
S
32x32b Multiplier
c
s
+
ambient'
diffuse'
specular'
Fixed-point Datapath
ALog
Floating-point Registers
ambient
diffuse
specular


Clock
Memory
Lighting Accelerator
I/O
193μm
329μm
Ambient
Anti-Log
32b Add
Log
Log
Diffuse
Anti-Log
Log
32b Add
32b Add
Log
Log
Specular
Anti-Log
Log
32b Add
32b Add
Comp. Add
32x32b Multiplier
Log

A 2.05 GVertices/s 151 mW Lighting Accelerator
for 3D Graphics Vertex and Pixel Shading
in 32 nm CMOS

Farhana Sheikh, *Member, IEEE*, Sanu K. Mathew, *Member, IEEE*, Mark A. Anders, *Member, IEEE*, Himanshu Kaul, *Member, IEEE*, Steven K. Hsu, *Member, IEEE*, Amit Agarwal, *Member, IEEE*, Ram K. Krishnamurthy, *Fellow, IEEE*, and Shekhar Borkar, *Fellow, IEEE*

Clock Rate and Power vs Voltage



A 2.05 GVertices/s 151 mW Lighting Accelerator
for 3D Graphics Vertex and Pixel Shading
in 32 nm CMOS

Farhana Sheikh, *Member, IEEE*, Sanu K. Mathew, *Member, IEEE*, Mark A. Anders, *Member, IEEE*,
Himanshu Kaul, *Member, IEEE*, Steven K. Hsu, *Member, IEEE*, Amit Agarwal, *Member, IEEE*,
Ram K. Krishnamurthy, *Fellow, IEEE*, and Shekhar Borkar, *Fellow, IEEE*

Multiple Cores for Low Power

Trade hardware for power, on
a large scale ...

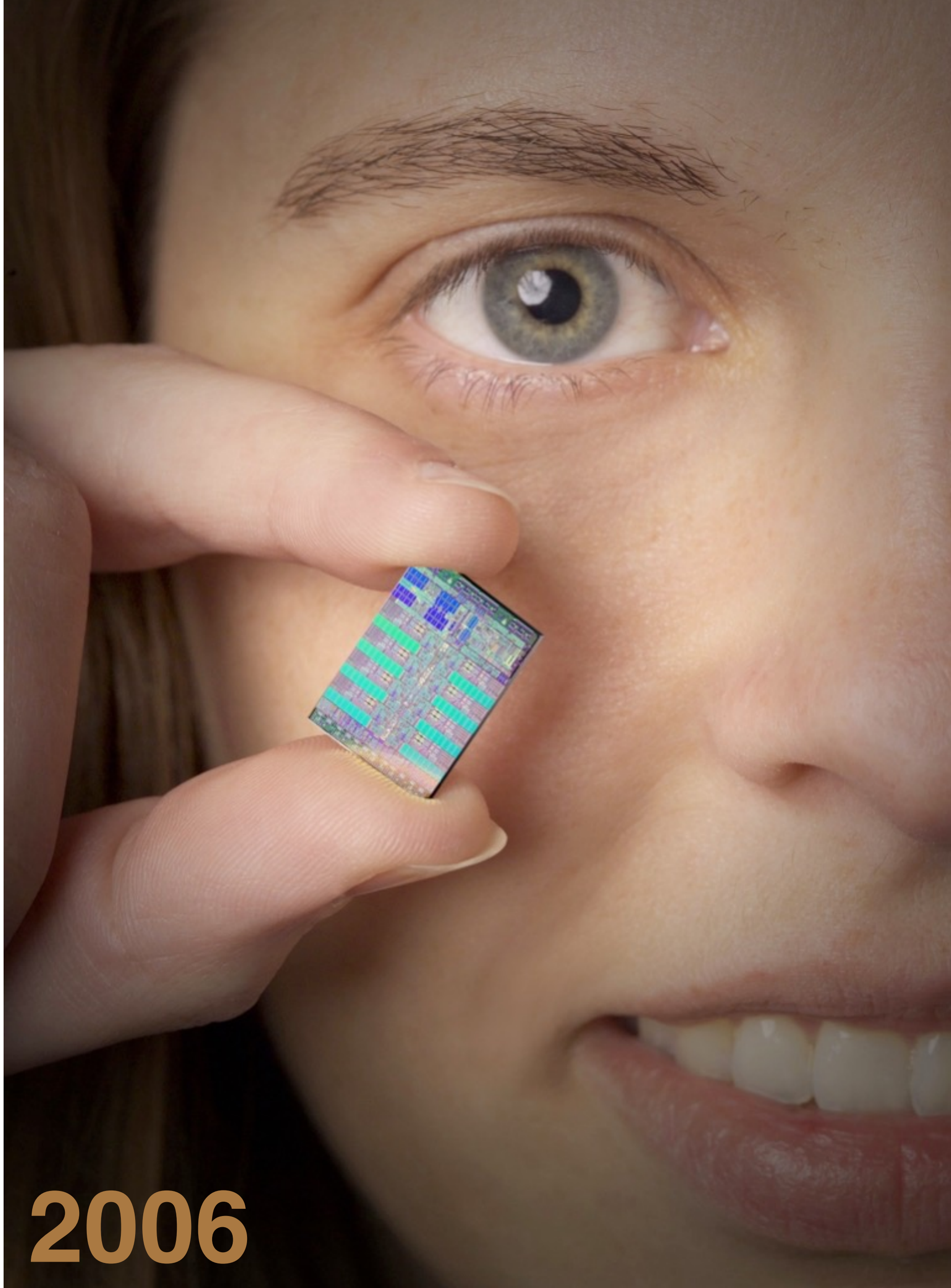
Cell:
The PS3 chip

IBM

SONY

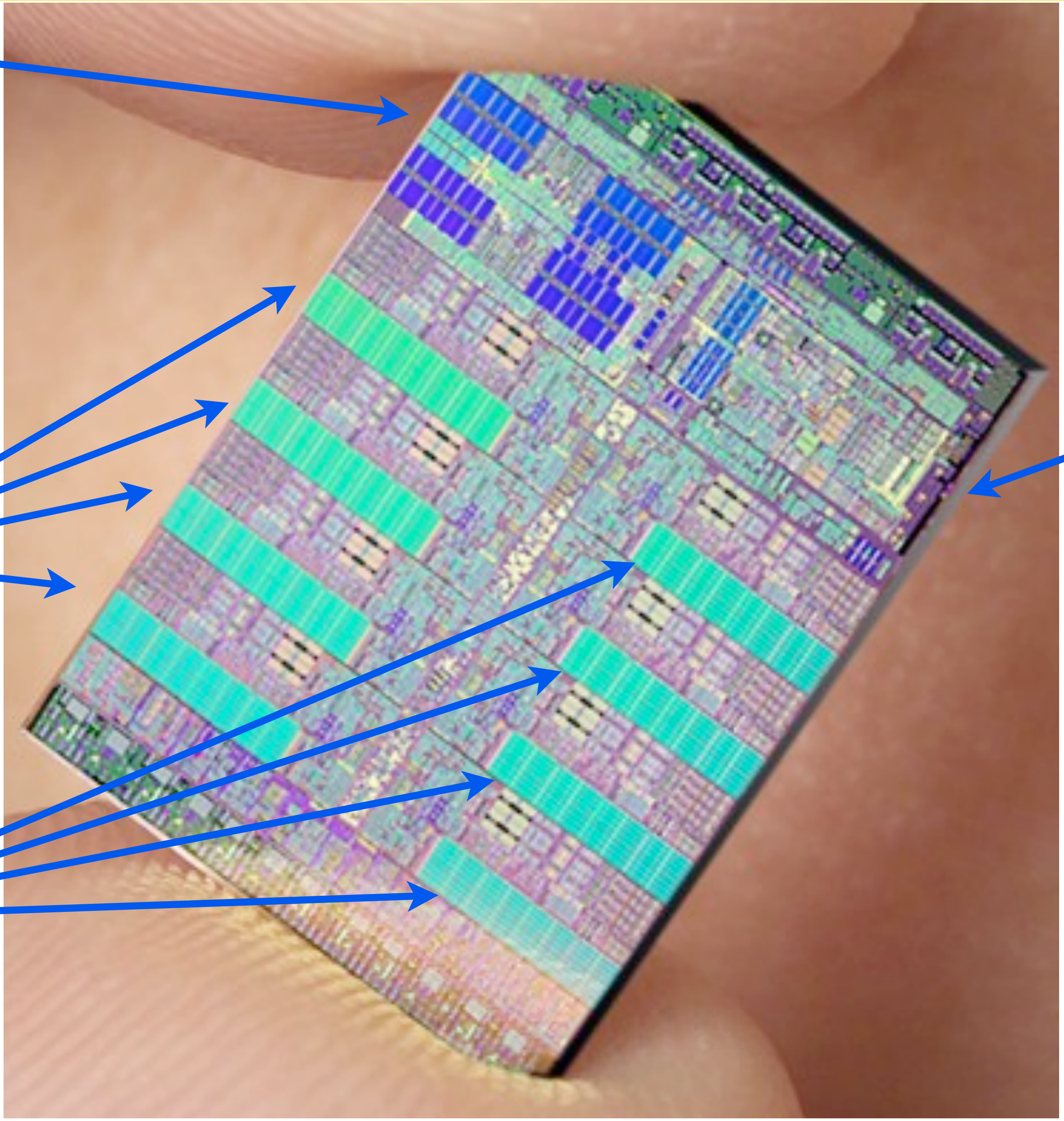
COMPUTER
ENTERTAINMENT

TOSHIBA



2006

Cell (PS3 Chip): 1 CPU + 8 “SPUs”



L2 Cache 512 KB

PowerPC

8 Synergistic Processing Units (SPUs)

IBM

SONY COMPUTER ENTERTAINMENT

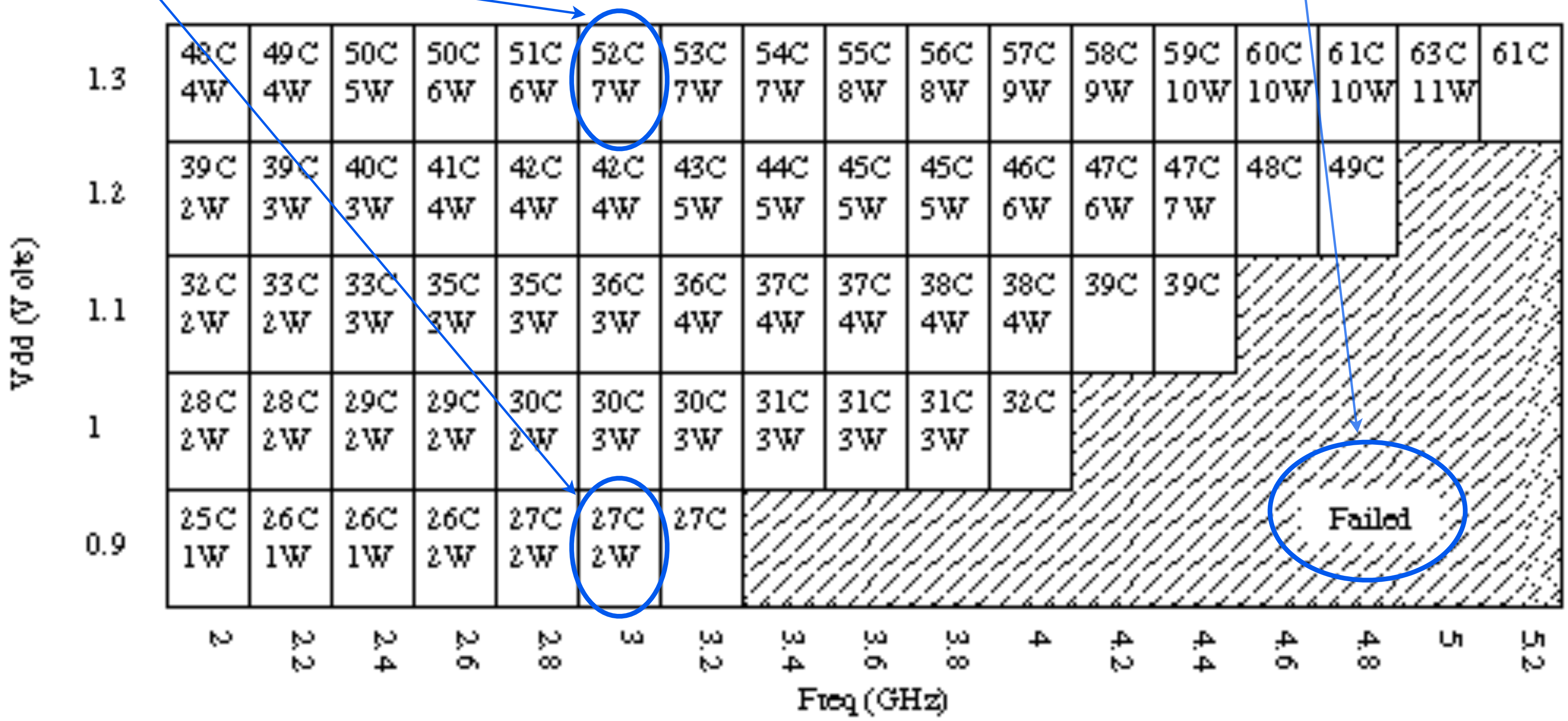
TOSHIBA

A “Schmoo” plot for a Cell SPU ...

The lower Vdd, the less dynamic energy consumption.

$E_{0\text{->}1} = \frac{1}{2} \; C \, V_{dd}^2$ $E_{1\text{->}0} = \frac{1}{2} \; C \, V_{dd}^2$

The lower Vdd, the longer the maximum clock period, the slower the clock frequency.

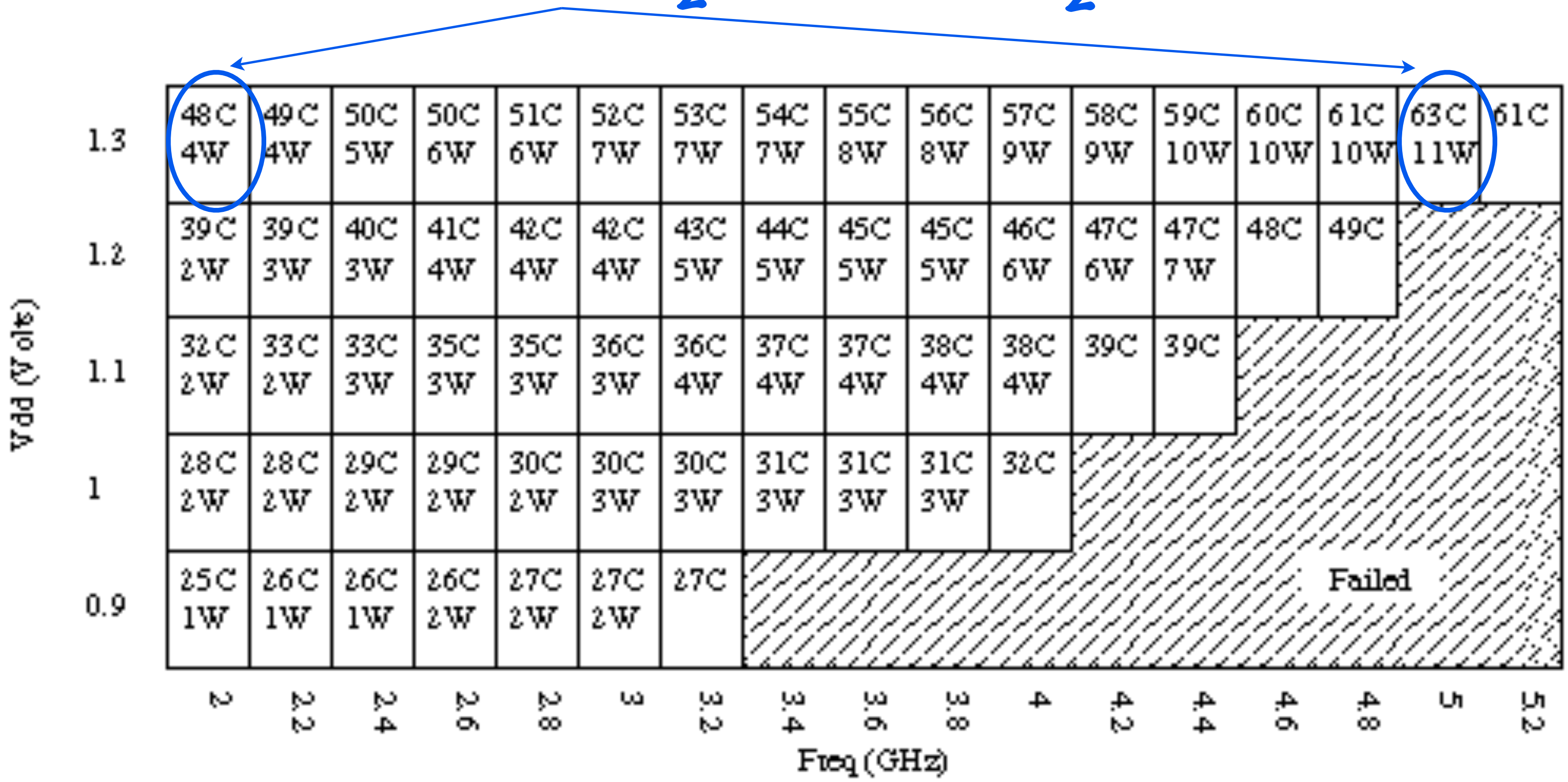


Vdd (Volts) \ Freq (GHz)	2	2.2	2.4	2.6	2.8	3	3.2	3.4	3.6	3.8	4	4.2	4.4	4.6	4.8	5	5.2
1.3	48C 4W	49C 4W	50C 5W	50C 6W	51C 6W	52C 7W	53C 7W	54C 7W	55C 8W	56C 8W	57C 9W	58C 9W	59C 10W	60C 10W	61C 10W	63C 11W	61C
1.2	39C 2W	39C 3W	40C 3W	41C 4W	42C 4W	42C 4W	43C 5W	44C 5W	45C 5W	45C 5W	46C 6W	47C 6W	47C 7W	48C	49C	▨	▨
1.1	32C 2W	33C 2W	33C 3W	35C 3W	35C 3W	36C 3W	36C 4W	37C 4W	37C 4W	38C 4W	38C 4W	39C	39C	▨	▨	▨	▨
1	28C 2W	28C 2W	29C 2W	29C 2W	30C 2W	30C 3W	30C 3W	31C 3W	31C 3W	31C 3W	32C	▨	▨	▨	▨	▨	▨
0.9	25C 1W	26C 1W	26C 1W	26C 2W	27C 2W	27C 2W	27C	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Clock speed alone doesn't help E/op ...

But, lowering clock frequency while keeping voltage constant spreads the same amount of work over a longer time, so chip stays cooler ...

$$E_{0\to1} = \frac{1}{2} C V_{dd}^2 \qquad E_{1\to0} = \frac{1}{2} C V_{dd}^2$$



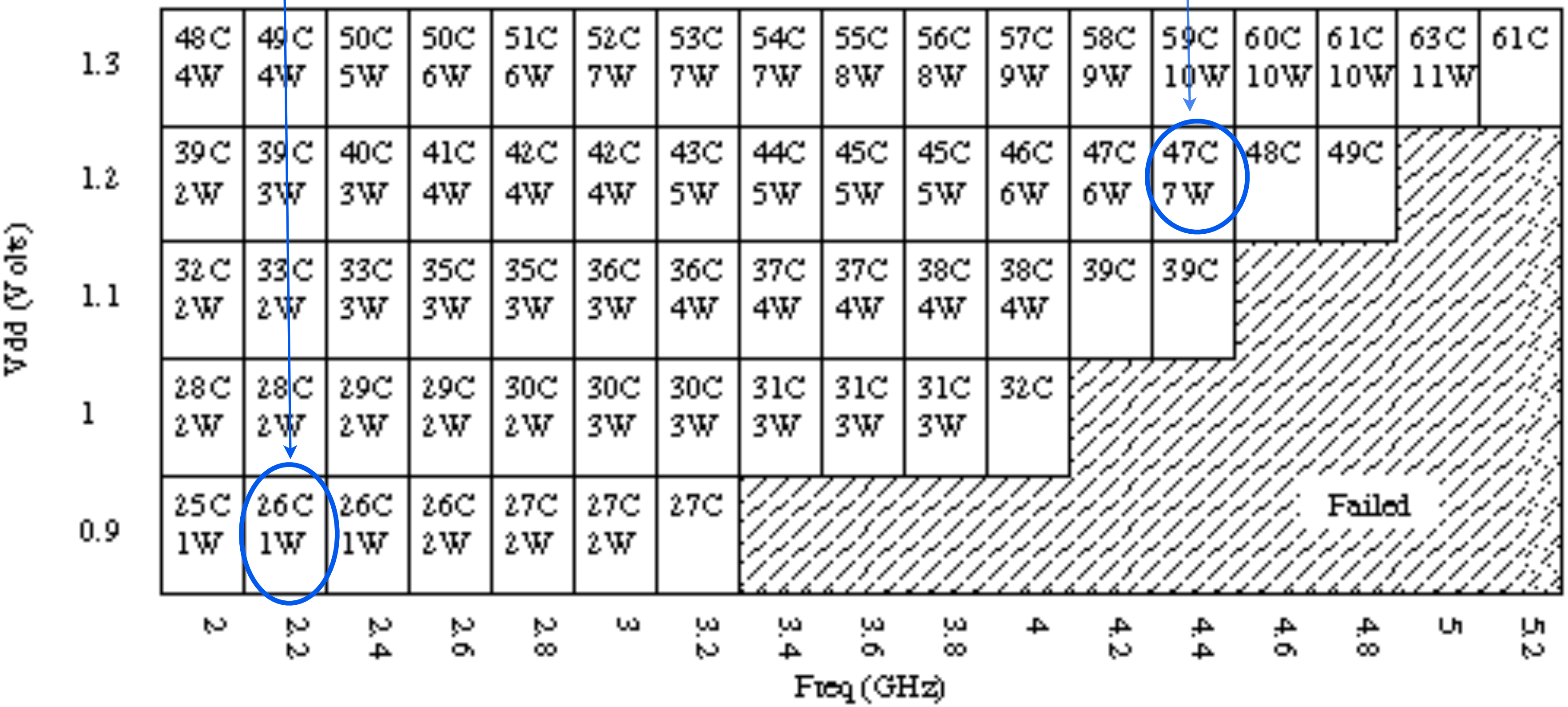
Vdd (Volts) \ Freq (GHz)	2	2.2	2.4	2.6	2.8	3	3.2	3.4	3.6	3.8	4	4.2	4.4	4.6	4.8	5	5.2
1.3	48C 4W	49C 4W	50C 5W	50C 6W	51C 6W	52C 7W	53C 7W	54C 7W	55C 8W	56C 8W	57C 9W	58C 9W	59C 10W	60C 10W	61C 10W	63C 11W	61C
1.2	39C 2W	39C 3W	40C 3W	41C 4W	42C 4W	42C 4W	43C 5W	44C 5W	45C 5W	45C 5W	46C 6W	47C 6W	47C 7W	48C	49C	▨	▨
1.1	32C 2W	33C 2W	33C 3W	35C 3W	35C 3W	36C 3W	36C 4W	37C 4W	37C 4W	38C 4W	38C 4W	39C	39C	▨	▨	▨	▨
1	28C 2W	28C 2W	29C 2W	29C 2W	30C 2W	30C 3W	30C 3W	31C 3W	31C 3W	31C 3W	32C	▨	▨	▨	▨	▨	▨
0.9	25C 1W	26C 1W	26C 1W	26C 2W	27C 2W	27C 2W	27C	▨	▨	▨	▨	▨	▨	▨	▨ Failed	▨	▨

Scaling V and f *does* lower energy/op

1 W to get 2.2 GHz performance. 26 C die temp.

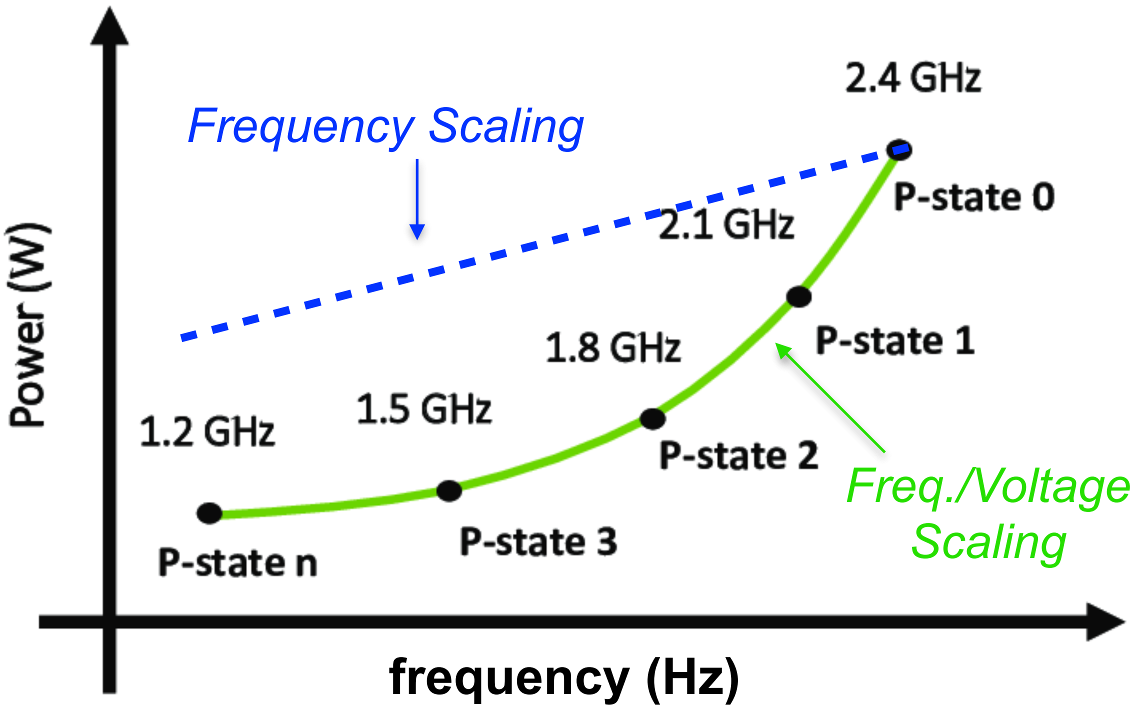
7W to reliably get 4.4 GHz performance. 47C die temp.

If a program that needs a 4.4 Ghz CPU can be recoded to use two 2.2 Ghz CPUs ... big win.



Vdd (Volts) \ Freq (GHz)	2	2.2	2.4	2.6	2.8	3	3.2	3.4	3.6	3.8	4	4.2	4.4	4.6	4.8	5	5.2
1.3	48C 4W	49C 4W	50C 5W	50C 6W	51C 6W	52C 7W	53C 7W	54C 7W	55C 8W	56C 8W	57C 9W	58C 9W	59C 10W	60C 10W	61C 10W	63C 11W	61C
1.2	39C 2W	39C 3W	40C 3W	41C 4W	42C 4W	42C 4W	43C 5W	44C 5W	45C 5W	45C 5W	46C 6W	47C 6W	47C 7W	48C	49C		
1.1	32C 2W	33C 2W	33C 3W	35C 3W	35C 3W	36C 3W	36C 4W	37C 4W	37C 4W	38C 4W	38C 4W	39C	39C				
1	28C 2W	28C 2W	29C 2W	29C 2W	30C 2W	30C 3W	30C 3W	31C 3W	31C 3W	31C 3W	32C						
0.9	25C 1W	26C 1W	26C 1W	26C 2W	27C 2W	27C 2W	27C								Failed		

Dynamic Voltage/Frequency Scaling (DVFS)



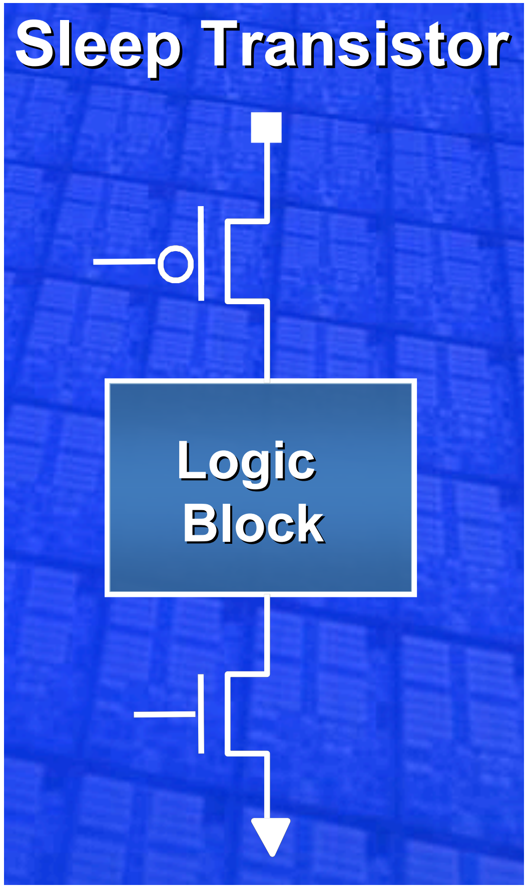
Many modern processors have controls for dynamically changing operating frequency and voltage.

Intel power states

- BIO/OS software can adjust frequency to reduce heat and/or improve power efficiency with high performance not needed.
- Adjusting both voltage and frequency helps improve energy efficiency and allows higher frequency for a given power level.

Powering down idle circuits

Add “sleep” transistors to logic ...


Sleep Transistor
Logic Block

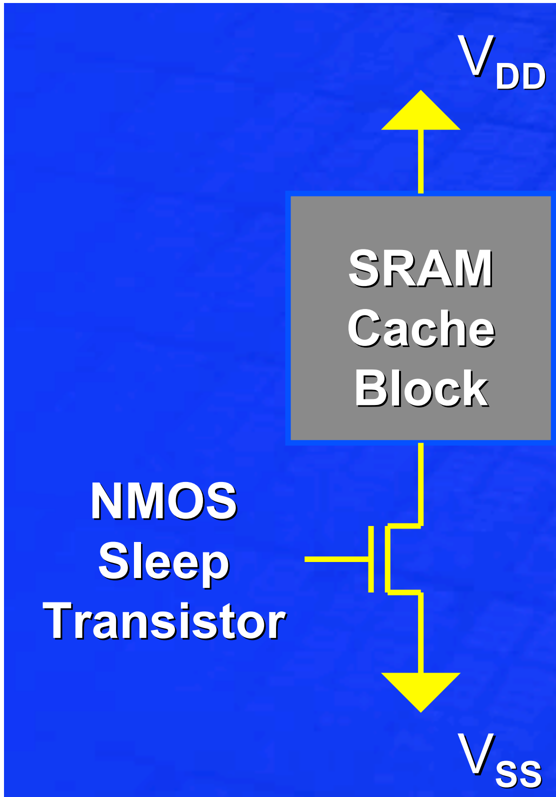
Example: Floating point unit logic.

When running fixed-point instructions, put logic “to sleep”.

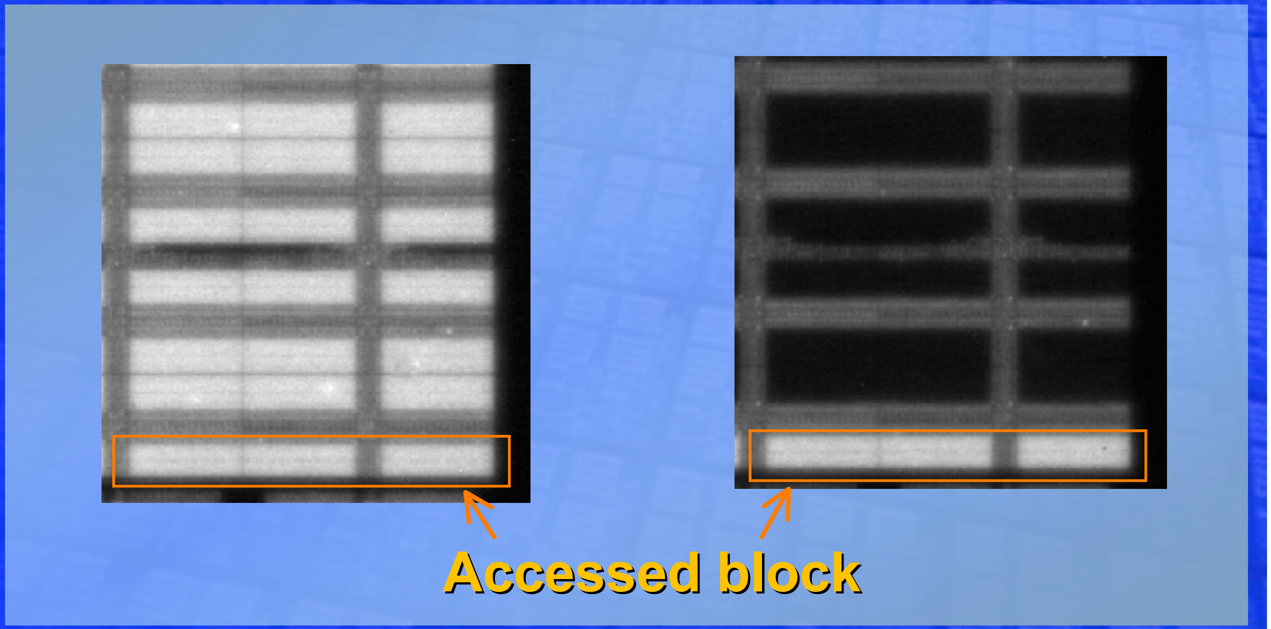
+++ When “asleep”, leakage power is dramatically reduced.

--- Presence of sleep transistors slows down the clock rate when the logic block is in use.

Intel example: Sleeping cache blocks


V_{DD}
SRAM Cache Block
NMOS Sleep Transistor
V_{SS}

70 Mbit SRAM leakage current map


Accessed block

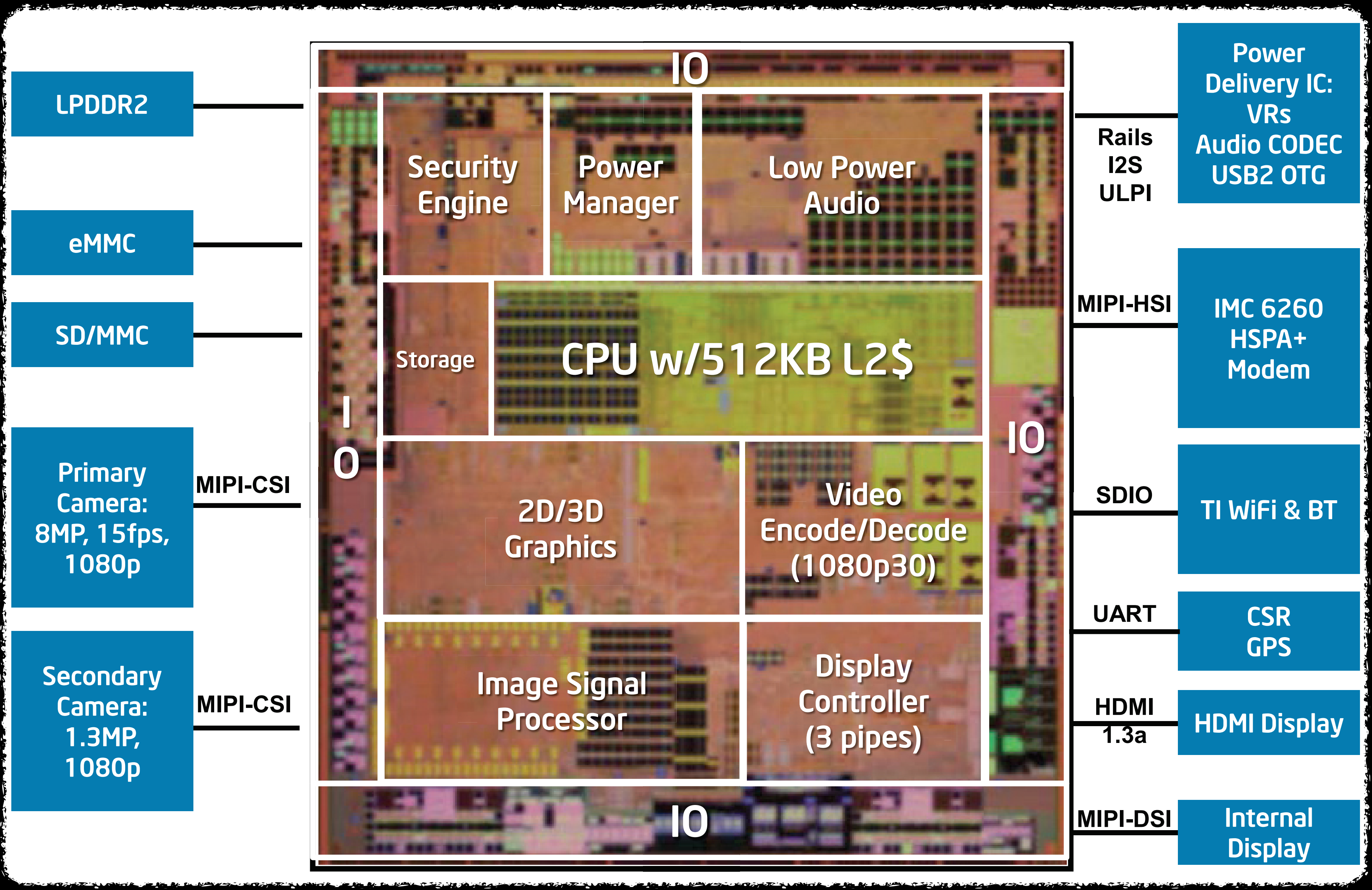
Without sleep transistor **With sleep transistor**

>3x SRAM leakage reduction on inactive blocks

A tiny current supplied in "sleep" maintains SRAM state.

From: "Facing the Hot Chips Challenge Again", Bill Holt, Intel, presented at Hot Chips 17, 2005.

Intel Medfield


IO
Security Engine
Power Manager
Low Power Audio
I O
Storage
CPU w/512KB L2$
IO
2D/3D Graphics
Video Encode/Decode (1080p30)
Image Signal Processor
Display Controller (3 pipes)
IO

LPDDR2

eMMC

SD/MMC

Primary Camera: 8MP, 15fps, 1080p

MIPI-CSI

Secondary Camera: 1.3MP, 1080p

MIPI-CSI

Rails
I2S
ULPI

Power Delivery IC: VRs
Audio CODEC
USB2 OTG

MIPI-HSI

IMC 6260 HSPA+ Modem

SDIO

TI WiFi & BT

UART

CSR GPS

HDMI 1.3a

HDMI Display

MIPI-DSI

Internal Display

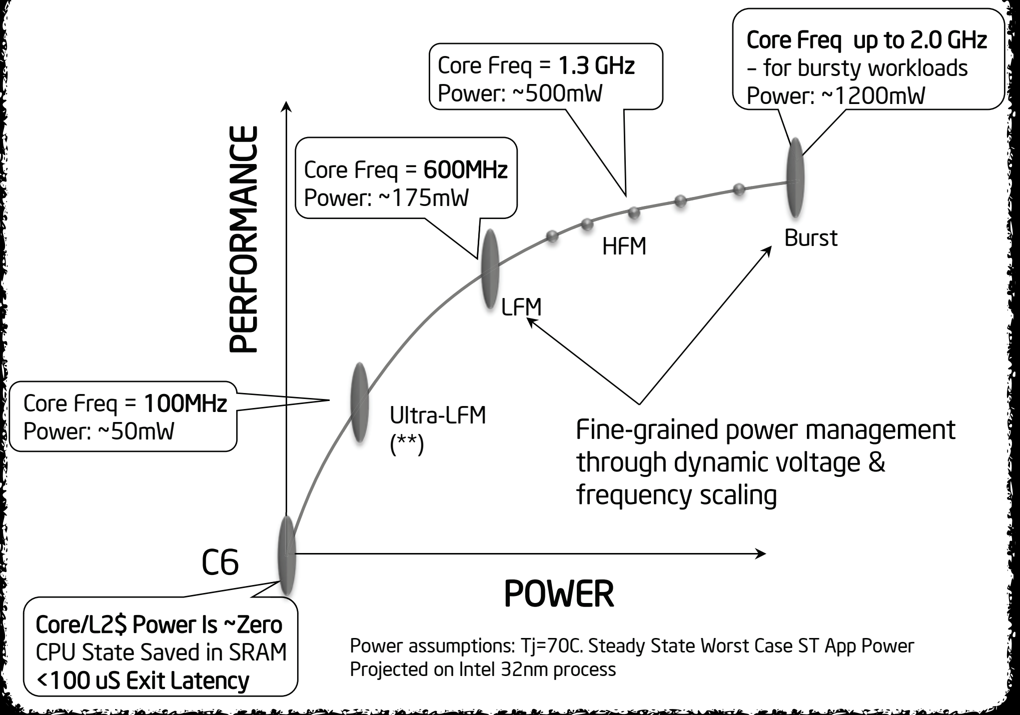
Intel Medfield

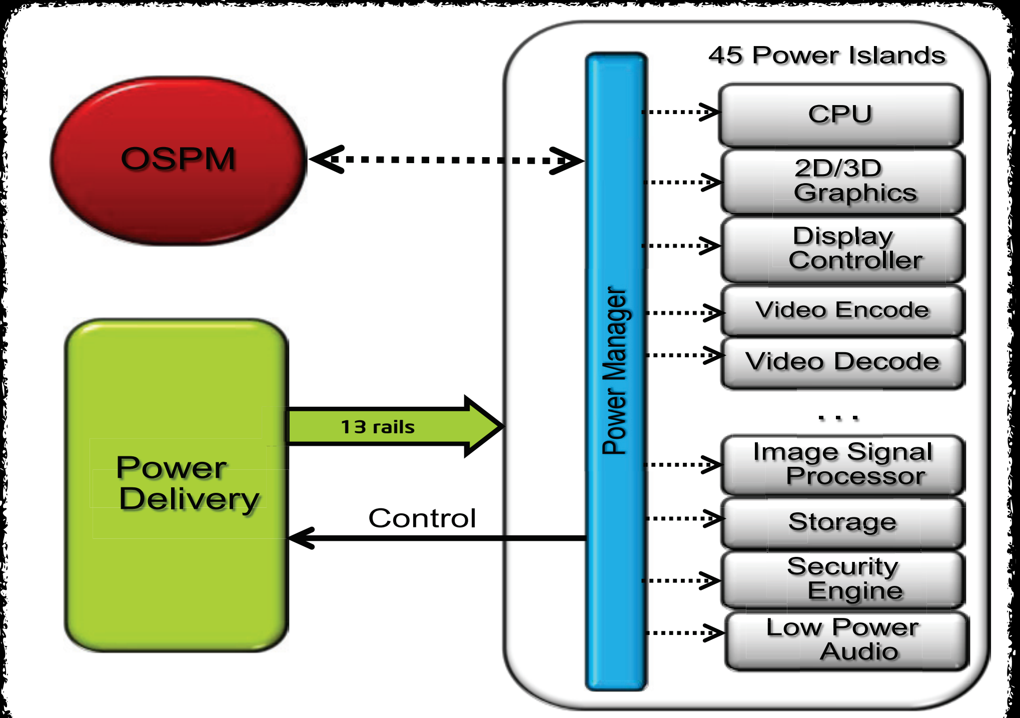
Switches 45 power "islands."

Fine-grained control of leakage power, to track user activity.

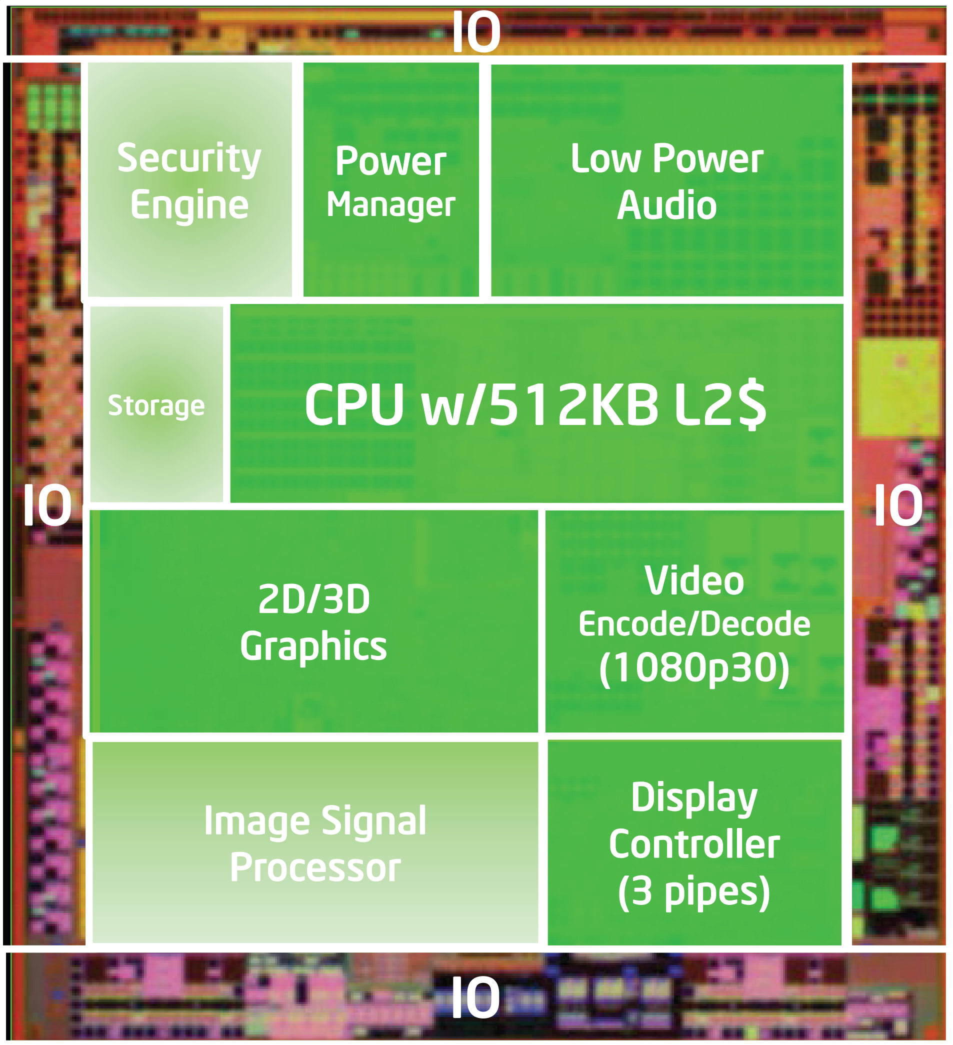
"Race to idle" strategy -- finish tasks quickly, to get to power down.

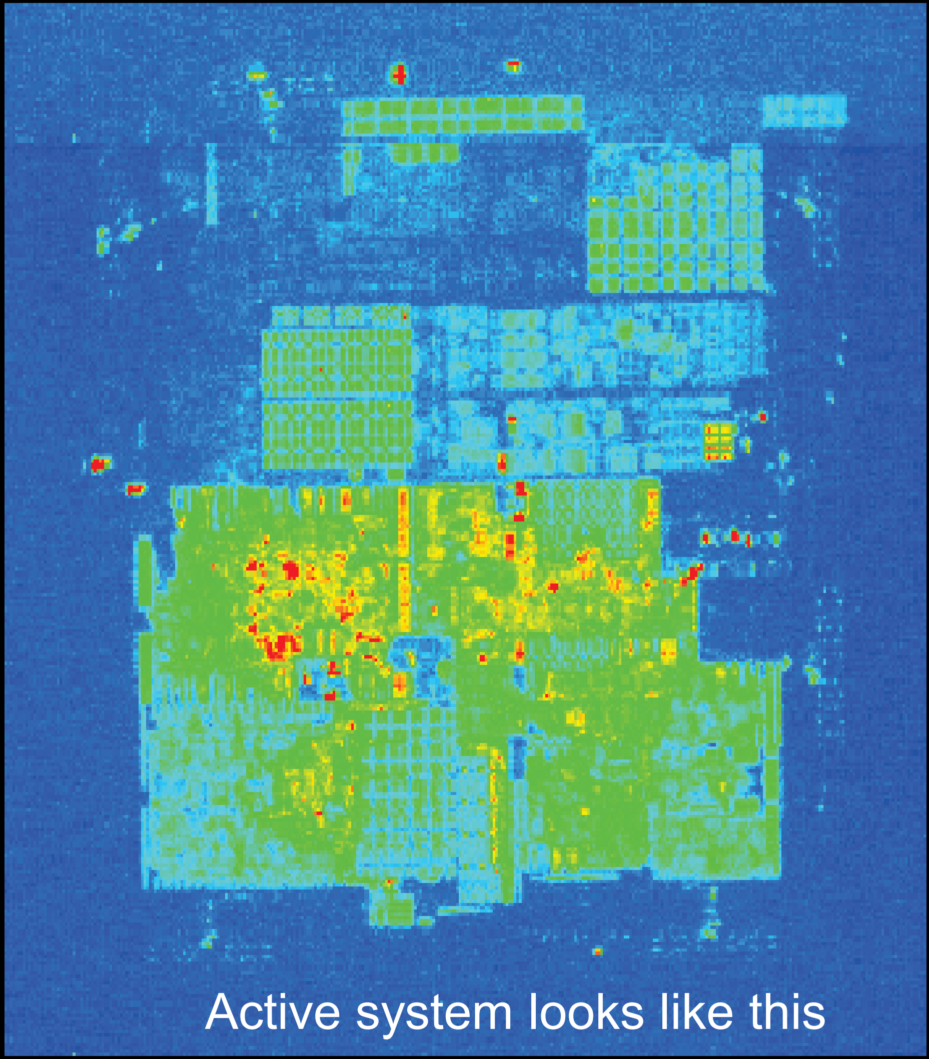
Intel® Smartphone Reference Design



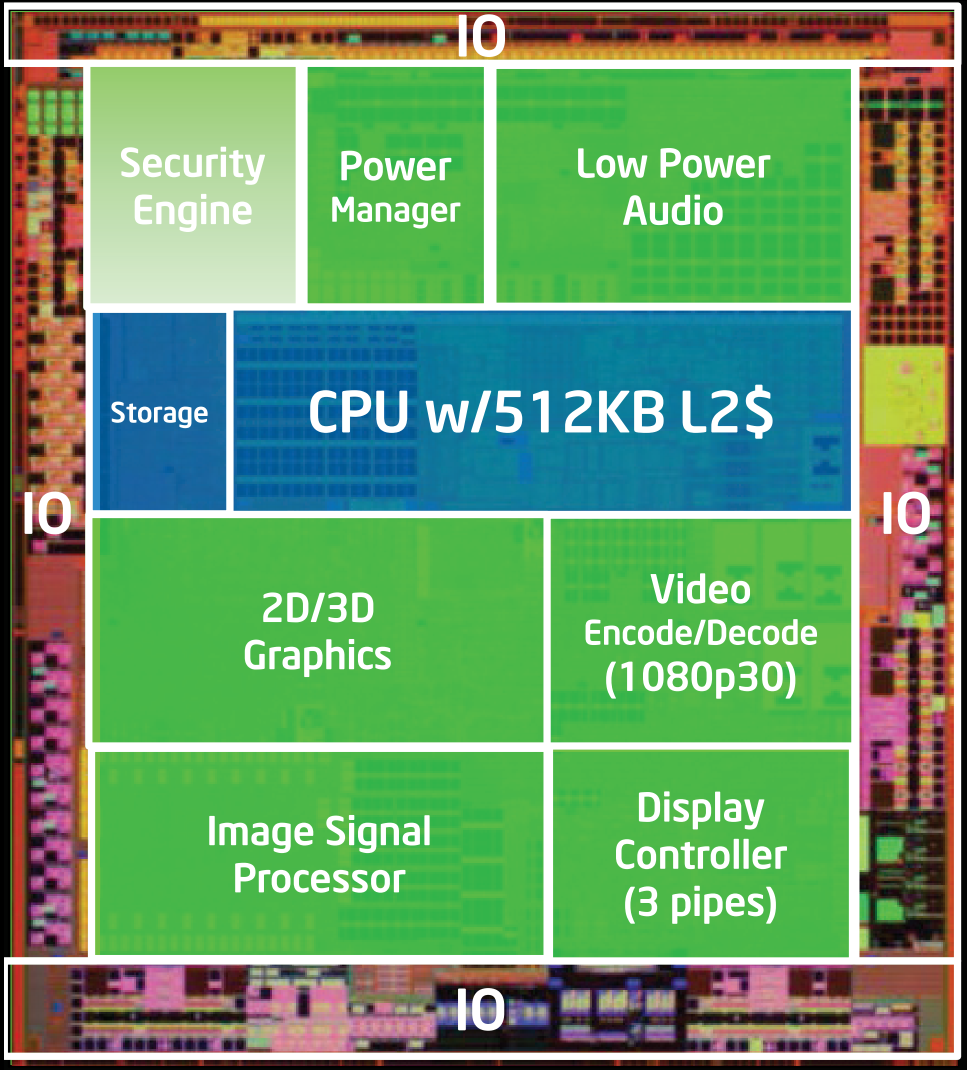

OSPM
45 Power Islands
Power Manager
CPU
2D/3D Graphics
Display Controller
Video Encode
Video Decode
. . .
Image Signal Processor
Storage
Security Engine
Low Power Audio
Power Delivery
13 rails
Control

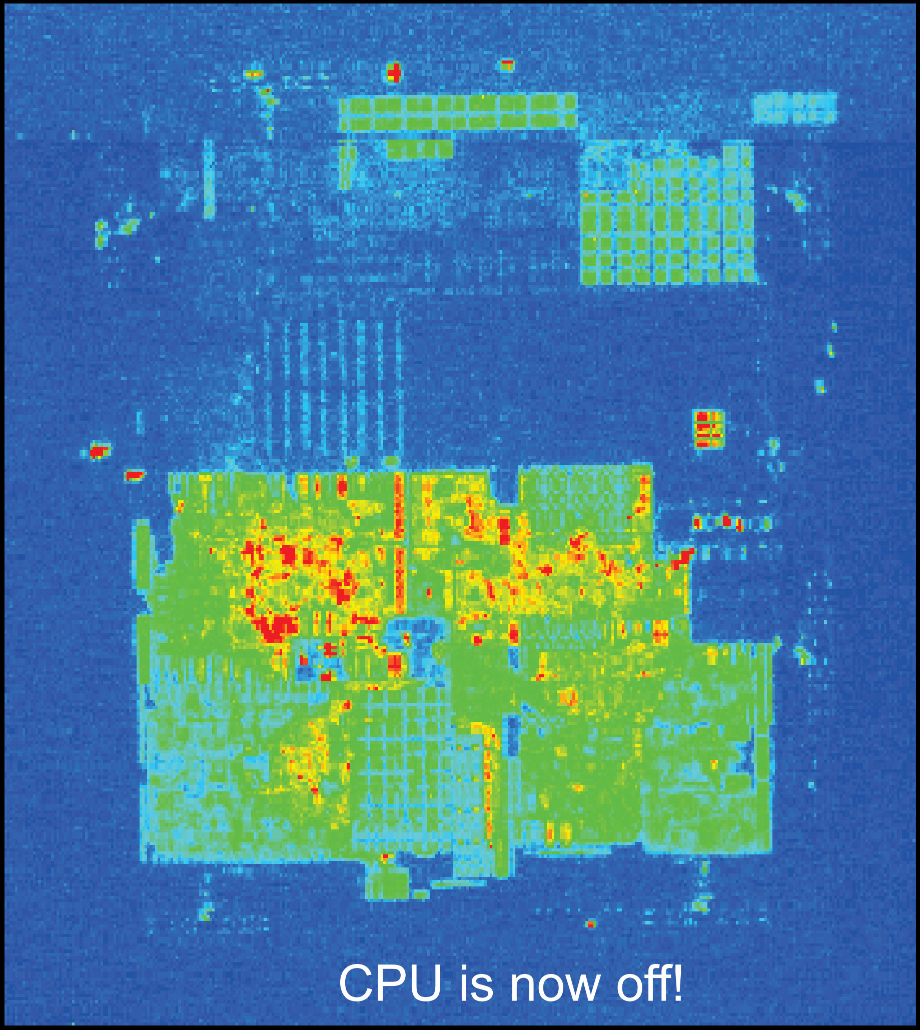
Playing a game …


IO
Security Engine
Power Manager
Low Power Audio
Storage
CPU w/512KB L2$
IO
IO
2D/3D Graphics
Video Encode/Decode (1080p30)
Image Signal Processor
Display Controller (3 pipes)
IO


Active system looks like this

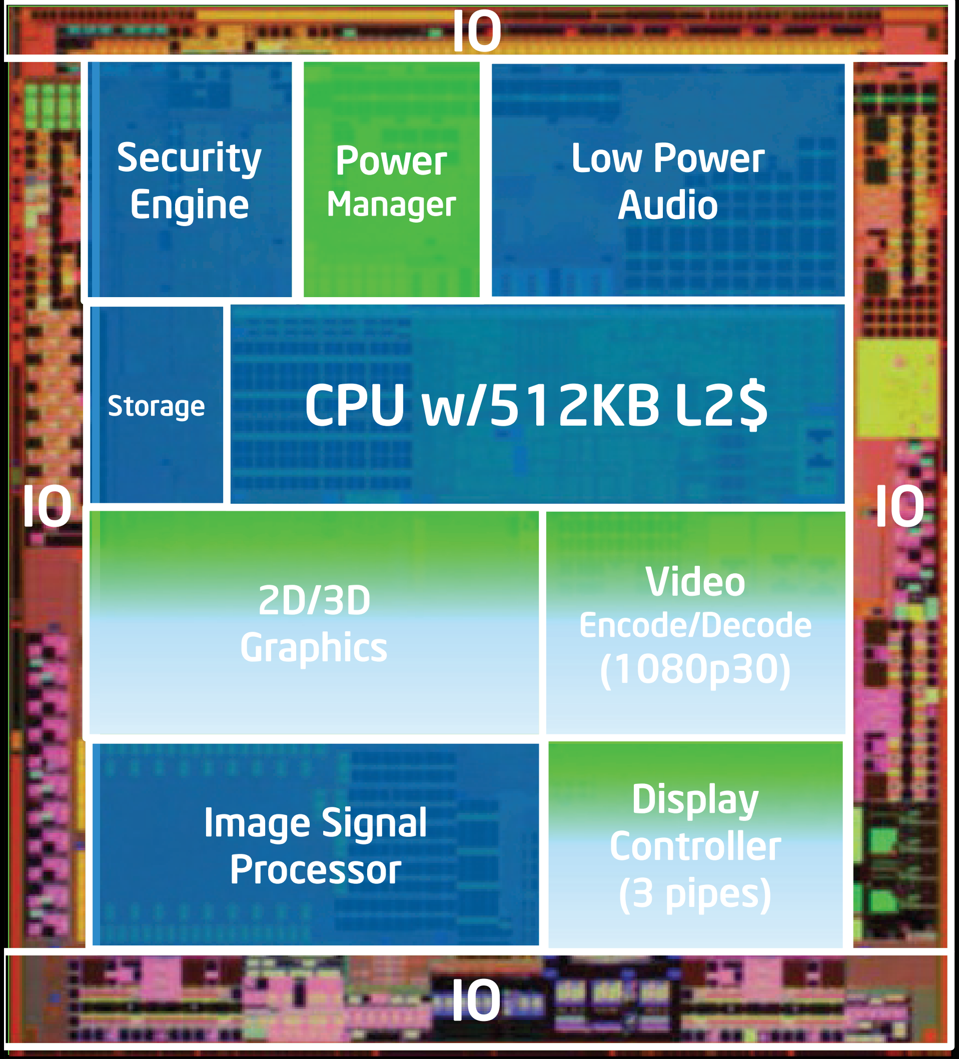
Watching a video …

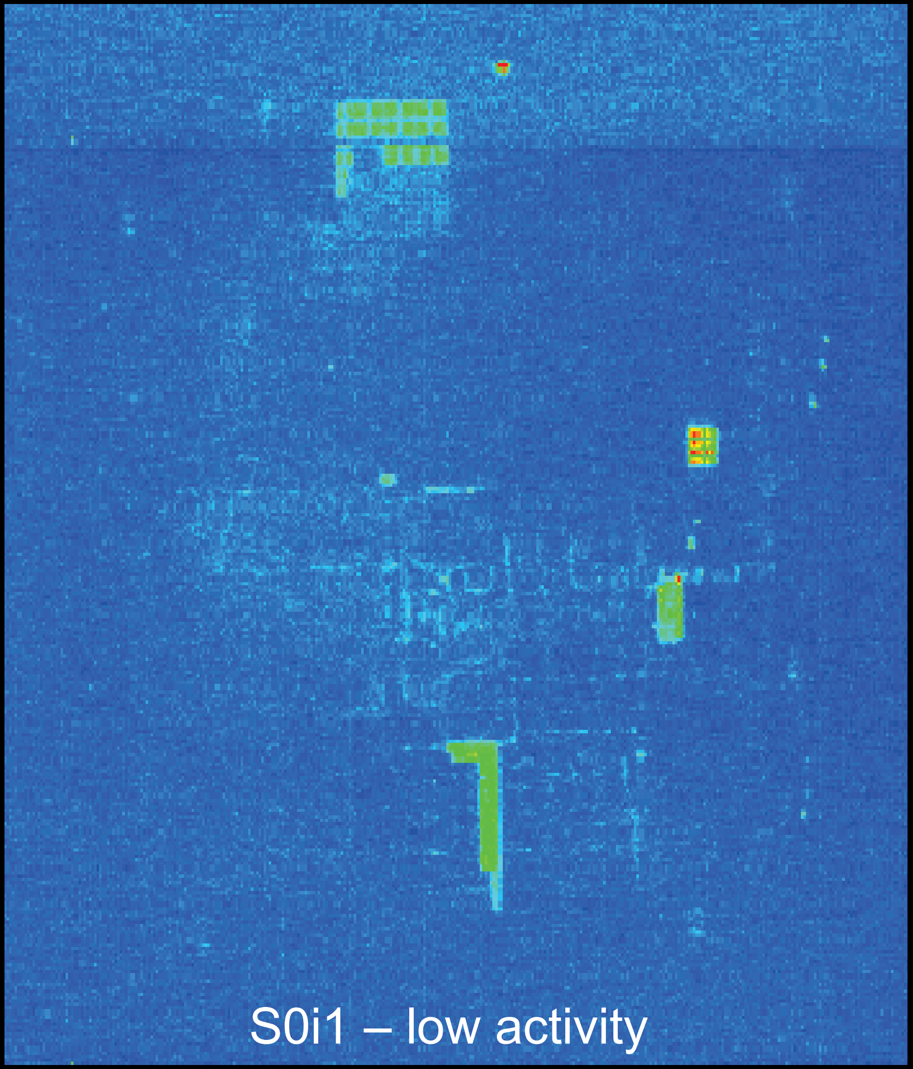

IO
Security Engine
Power Manager
Low Power Audio
Storage
CPU w/512KB L2$
IO
IO
2D/3D Graphics
Video Encode/Decode (1080p30)
Image Signal Processor
Display Controller (3 pipes)
IO



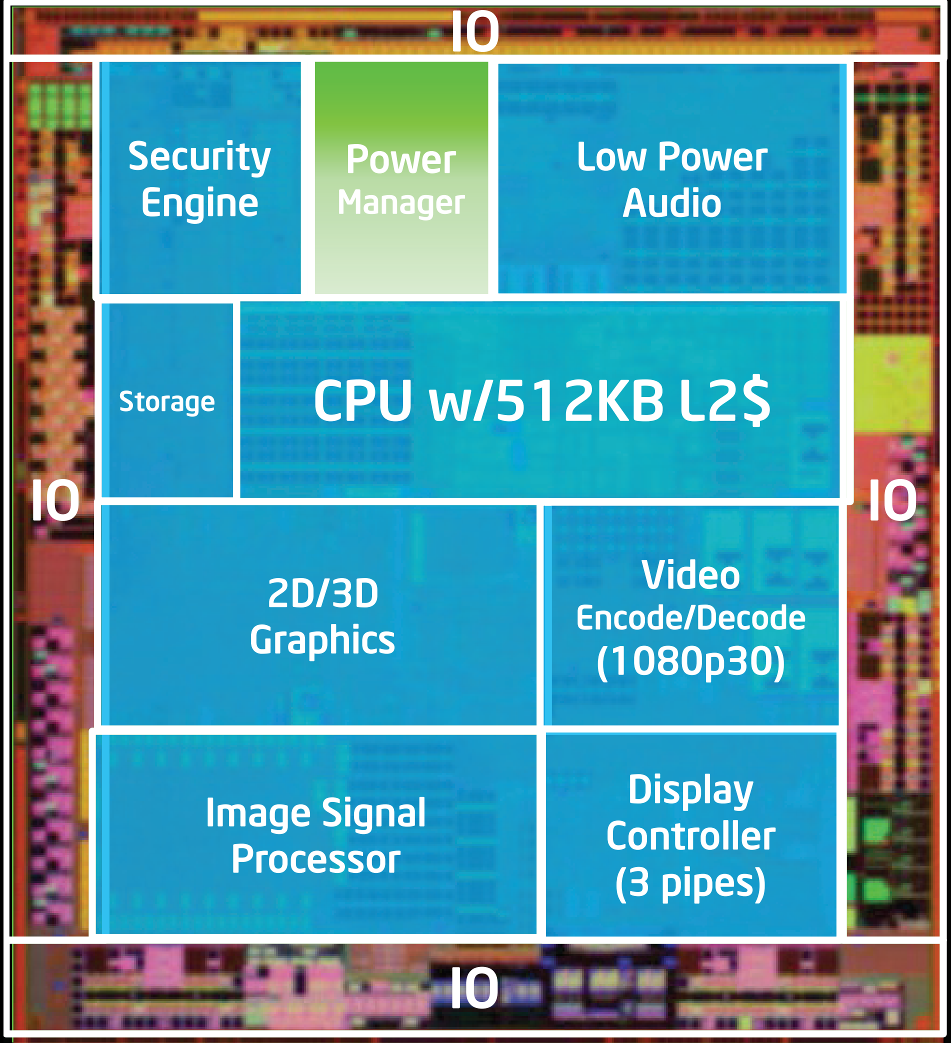
CPU is now off!

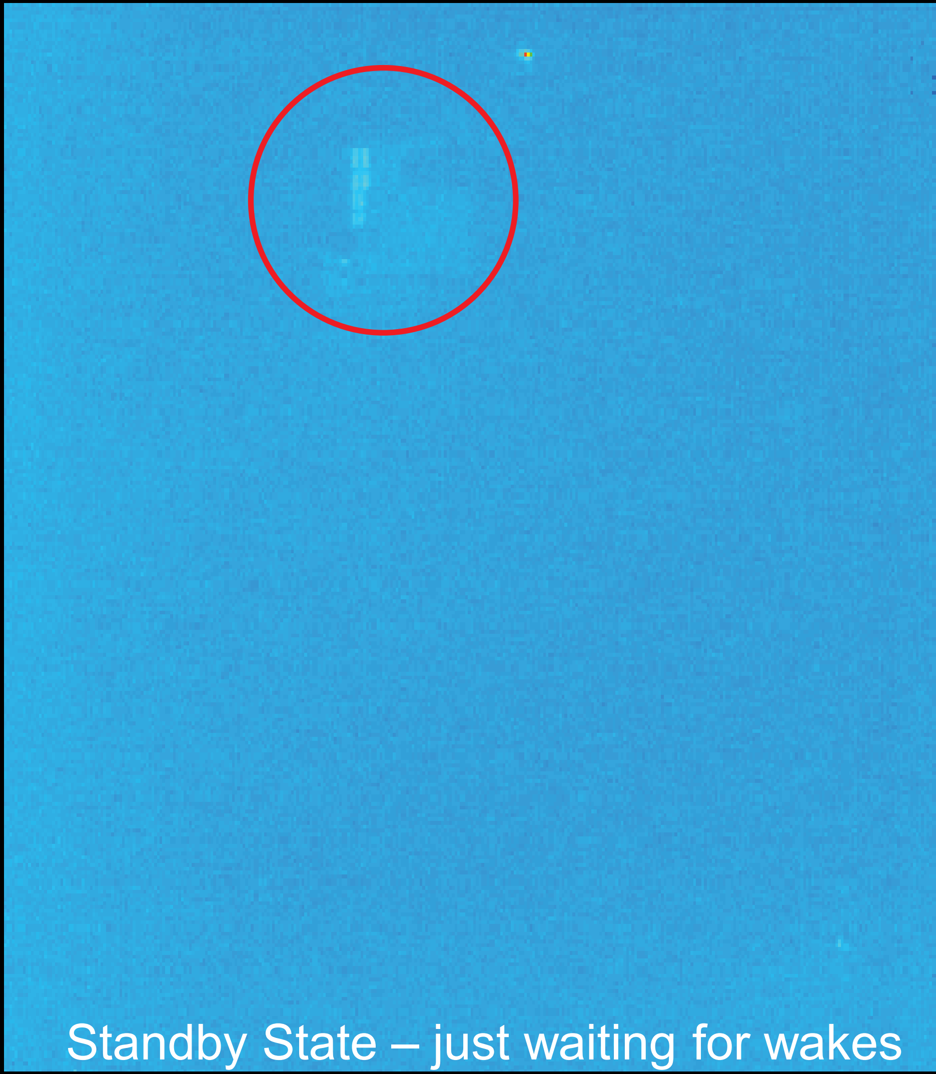
Looking at phone screen, not doing anything …


IO
Security Engine
Power Manager
Low Power Audio
Storage
CPU w/512KB L2$
IO
IO
2D/3D Graphics
Video Encode/Decode (1080p30)
Image Signal Processor
Display Controller (3 pipes)
IO


S0i1 – low activity

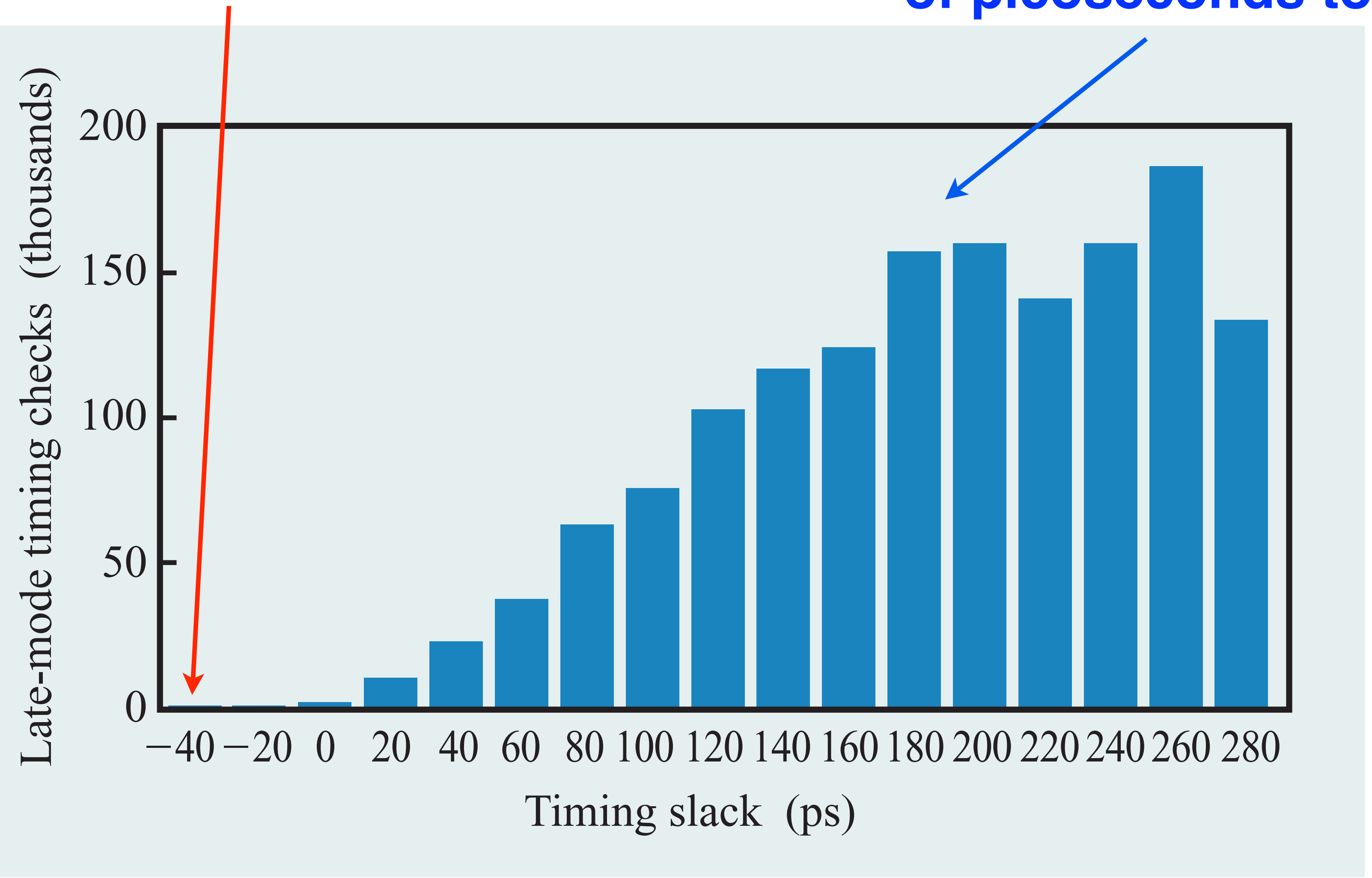
Phone in your pocket, waiting for a call …


IO
Security Engine
Power Manager
Low Power Audio
Storage
CPU w/512KB L2$
IO
IO
2D/3D Graphics
Video Encode/Decode (1080p30)
Image Signal Processor
Display Controller (3 pipes)
IO


Standby State – just waiting for wakes

Slow down “slack paths”

Fact: Most logic on a chip is “too fast”

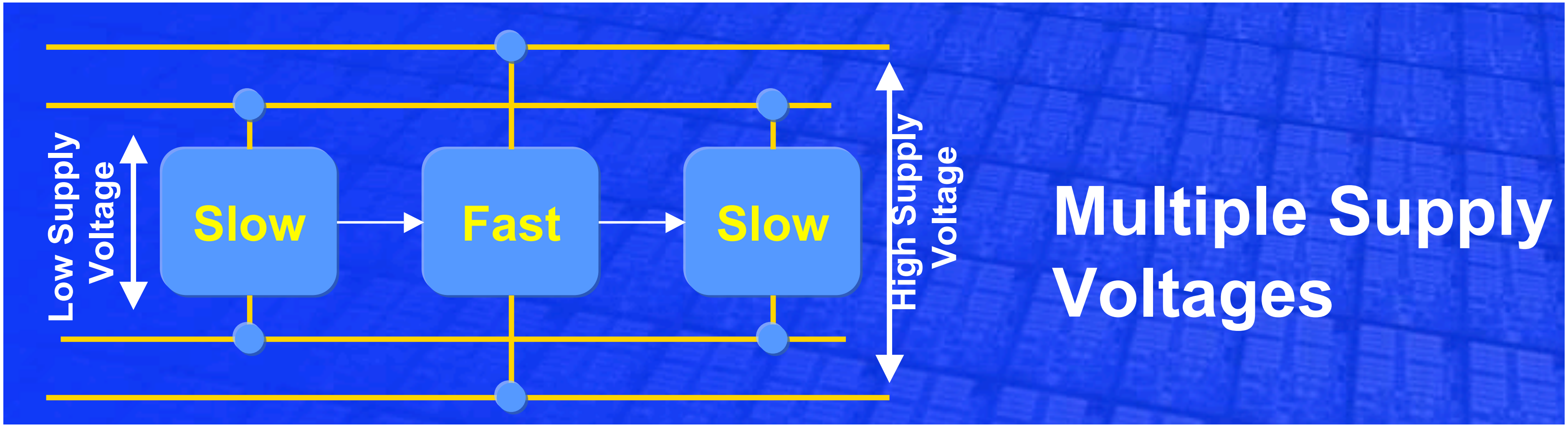


The critical path

Most wires have hundreds of picoseconds to spare.

From “The circuit and physical design of the POWER4 microprocessor”, IBM J Res and Dev, 46:1, Jan 2002, J.D. Warnock et al.

Use several supply voltages on a chip ...


Low Supply Voltage
Slow
Fast
Slow
High Supply Voltage

Multiple Supply Voltages

Why use multi-Vdd? We can reduce dynamic power by using low-power Vdd for logic off the critical path.

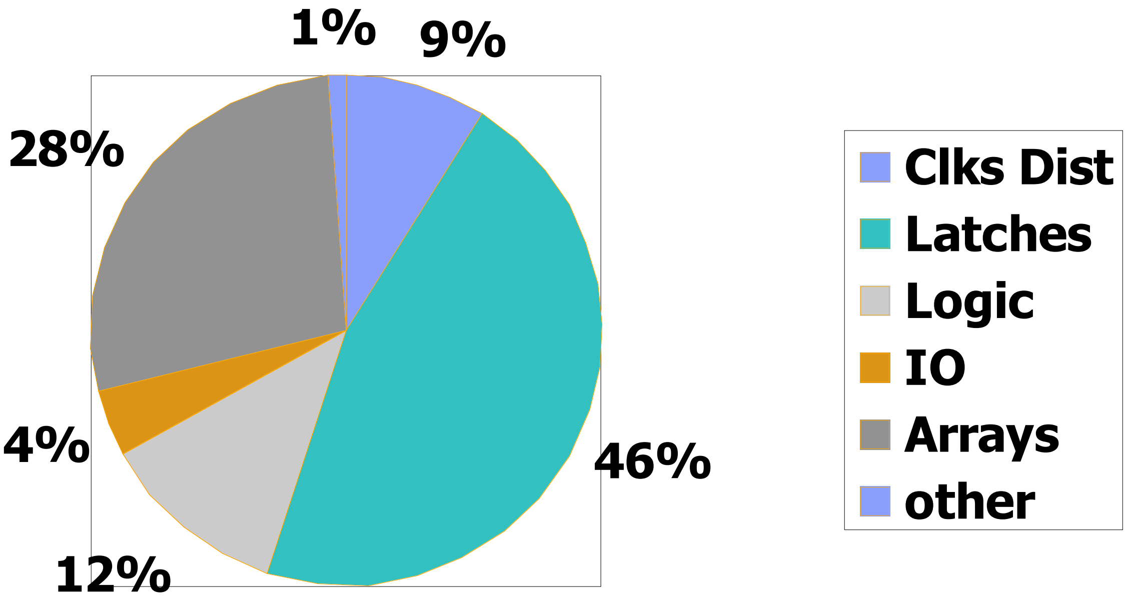
What if we can't do a multi-Vdd design?
In a multi-Vt process, we can reduce leakage power on the off critical path logic by using high-Vth transistors.

From: "Facing the Hot Chips Challenge Again", Bill Holt, Intel, presented at Hot Chips 17, 2005.

Design Technique #4 (of 5)

Gating clocks to save power

On a CPU, where does the power go?



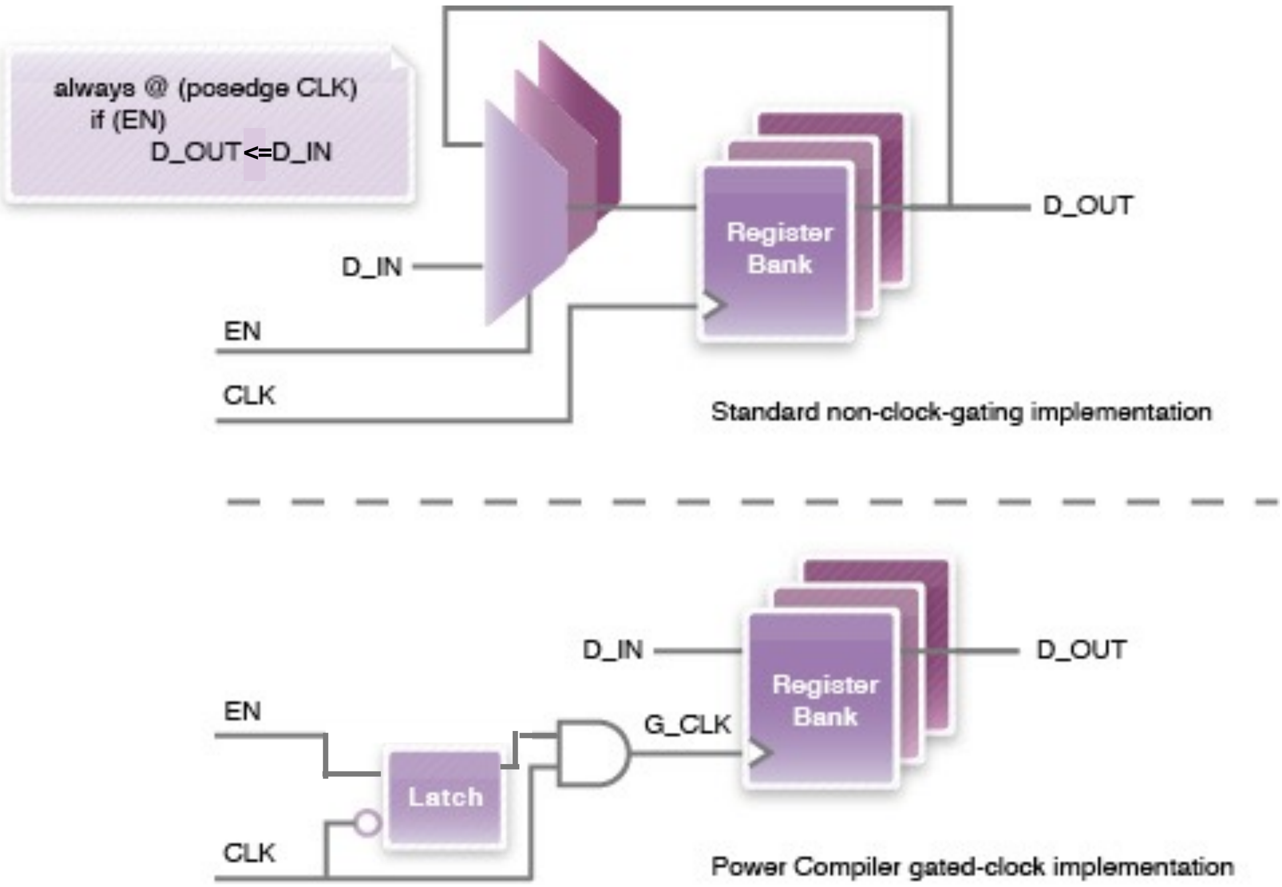
Half of the power goes to latches (Flip-Flops).

Most of the time, the latches don't change state.

So "gated" clocks are a big win.
But, done with CAD tools in a disciplined way.

From: Bose, Martonosi, Brooks: Sigmetrics-2001 Tutorial

Synopsis Design Compiler can do this ...


always @ (posedge CLK)
if (EN)
D_OUT<=D_IN
D_IN
EN
CLK
Register Bank
D_OUT
Standard non-clock-gating implementation
D_IN
EN
CLK
Latch
G_CLK
Register Bank
D_OUT
Power Compiler gated-clock implementation

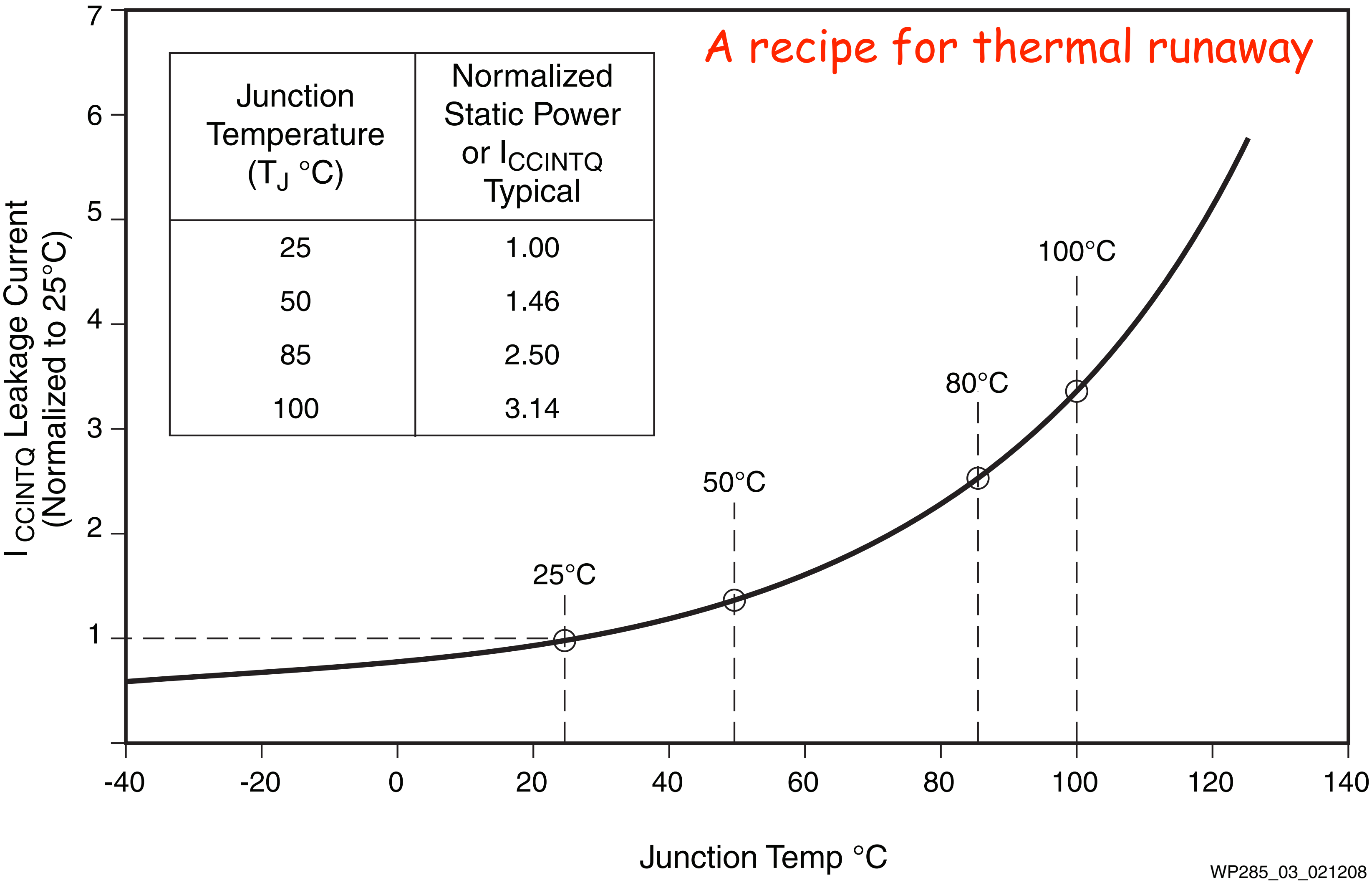
"Up to 70% power savings at the block level, for applicable circuits"

Synopsis Data Sheet

Design Technique #5 (of 5)

Thermal Management

Keep chip cool to minimize leakage power



Junction Temperature (T_J °C)	Normalized Static Power or I_{CCINTQ} Typical
25	1.00
50	1.46
85	2.50
100	3.14

A recipe for thermal runaway

Figure 3: **I_{CCINTQ} vs. Junction Temperature with Increase Relative to 25°C**

Five low-power design techniques

- Parallelism and pipelining
- Power-down idle transistors
- Slow down non-critical paths
- Clock gating
- Thermal management