Low-Power Design Techniques for Computing Systems

運算系統之低功率設計技術

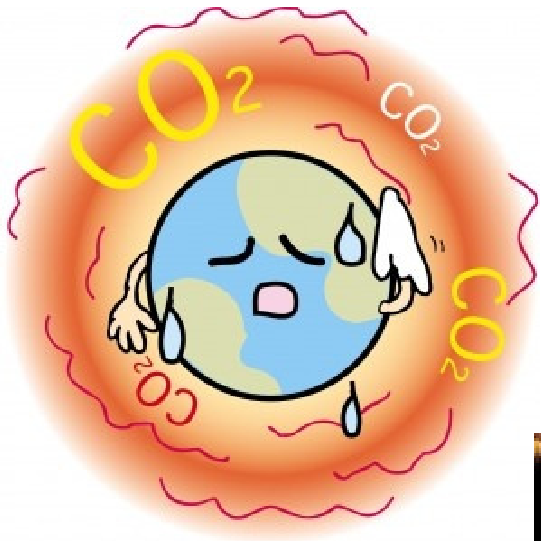
Shiann-Rong Kuang (鄺獻榮)

Dept. of Computer Science and Engineering
National Sun Yat-sen University

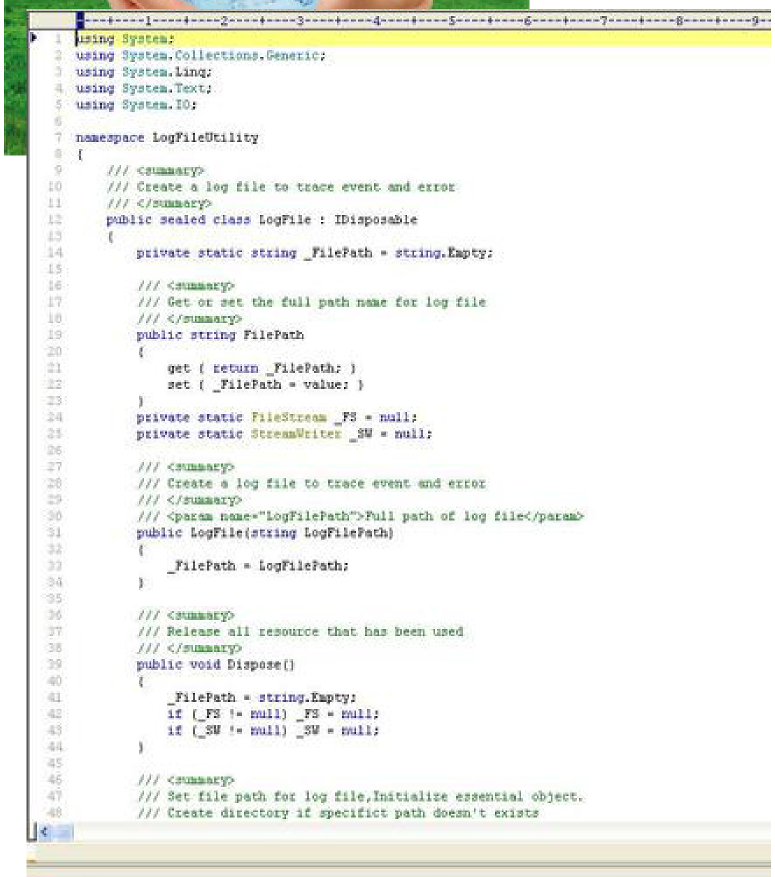
Outline

- **Low-Power Design ?**
- **Low-Power Design Techniques**
- **Power-Manageable Components**
  - *Clock Gating*
  - *Power Gating*
  - *Dynamic Voltage Scaling*
- **Case Study (3D GPU)**
- **Conclusion**

Global Warming



Energy Saving and Carbon Reduction

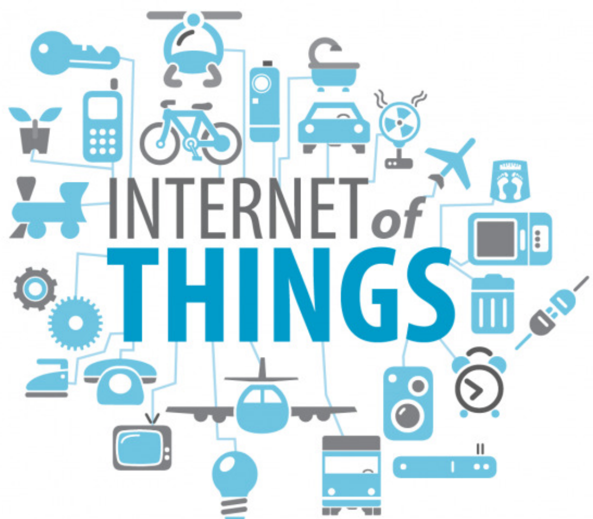


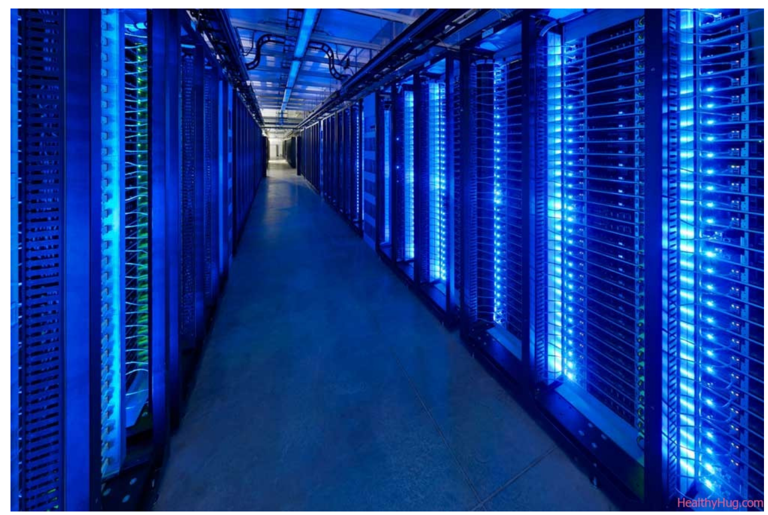
```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.IO;

namespace LogFileUtility
{
    /// <summary>
    /// Create a log file to trace event and error
    /// </summary>
    public sealed class LogFile : IDisposable
    {
        private static string _FilePath = string.Empty;

        /// <summary>
        /// Get or set the full path name for log file
        /// </summary>
        public string FilePath
        {
            get { return _FilePath; }
            set { _FilePath = value; }
        }
        private static FileStream _FS = null;
        private static StreamWriter _SW = null;

        /// <summary>
        /// Create a log file to trace event and error
        /// </summary>
        /// <param name="LogFilePath">Full path of log file</param>
        public LogFile(string LogFilePath)
        {
            _FilePath = LogFilePath;
        }

        /// <summary>
        /// Release all resource that has been used
        /// </summary>
        public void Dispose()
        {
            _FilePath = string.Empty;
            if (_FS != null) _FS = null;
            if (_SW != null) _SW = null;
        }

        /// <summary>
        /// Set file path for log file,Initialize essential object.
        /// Create directory if specifict path doesn't exists
```

Computing Systems

- **High-Performance Computers**
  - Supercomputer
    - Tianhe-2 (Milkyway-2)
    - AlphaGo
  - Data Center

- **Embedded Systems**





High-Performance Computers (1/3)

- **Tianhe-2 (Milkyway-2)**
  - 16,000個運算節點，每節點配備
    - 兩顆Xeon E5 12核心的中央處理器
    - 三個Xeon Phi 57核心的協同處理器
  - Intel Xeon E5-2692v2 12 中央處理器
    - 運作時脈為2.2GHz
    - 英特爾Ivy Bridge微架構
    - 22奈米製程
  - 運算速率
    - 33.86PFLOPS（實際峰值）、54.9PFLOPS（理論峰值）
      - PFLOPS：Peta Floating-Point Operations Per Second
      - 每秒一千兆（10^{15}）次的浮點運算
  - 消耗功率
    - 17.6MW（整機附帶散熱系統時為24MW）

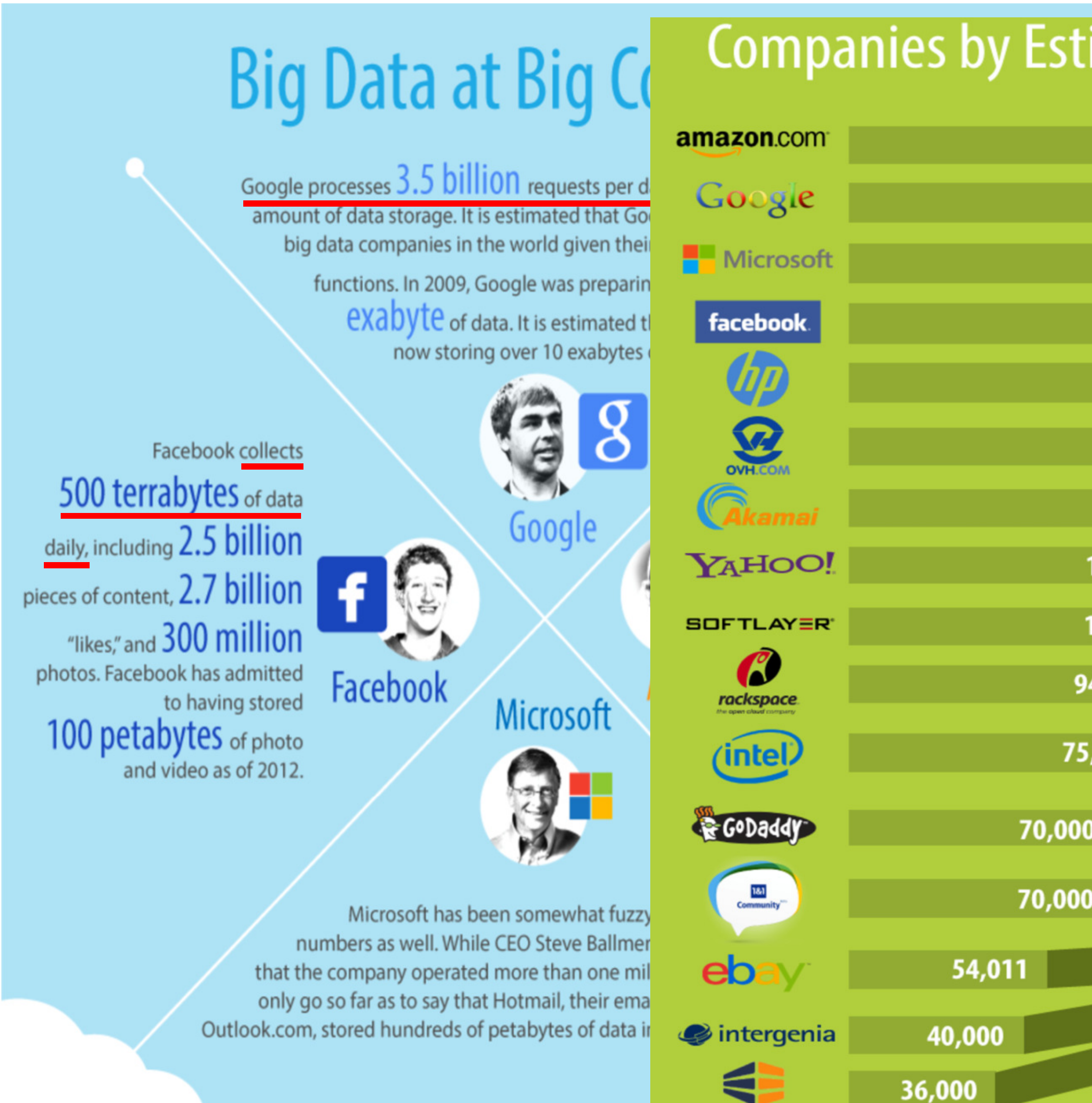
High-Performance Computers (2/3)

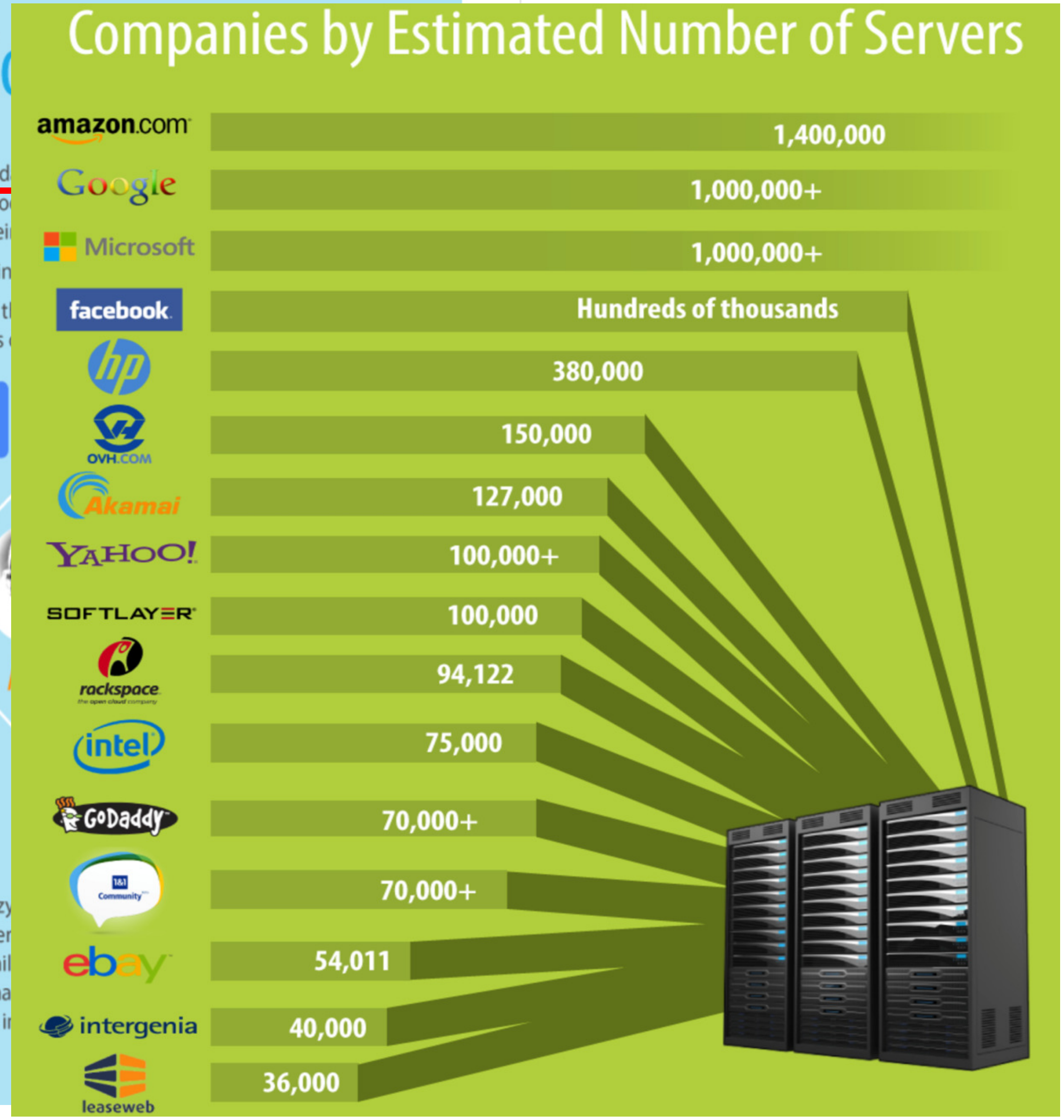
- **AlphaGo**
  - 1200個CPUs，一天能下100萬盤棋
  - 人工智慧系統是由 DeepMind 公司開發
    - 結合深度神經網路與蒙地卡羅樹狀搜尋

High-Performance Computers (3/3)

- **IoT (Internet of Things) + Big Data (雲端運算)**
  - 預估2020前企業、個人都將處理比目前多五十倍的資料量
  - 雲端運算市場將於2020年前成長至兩千四百億美元（約七兆台幣），大約是今日個人電腦、半導體市場的八成規模
  - Google、亞馬遜、臉書、微軟皆在全球各地搶建資料中心
- **Google Data Center (2013)**
  - Google 在全世界一共有十二個資料中心
  - 每天約二十億人使用Google，三十五億筆搜尋
  - 平均一個Google搜尋只花四分之一秒
  - 所有伺服器的數量總計已累計超過一百萬台
  - 以低價錢購買大量硬體次級品，用軟體解決高故障率的問題
  - Google資料中心在 2012 年的耗電量占全世界用電量的 1.5%
  - 節能是資料中心最大的挑戰（用水來散熱）

Big Data at Big Companies

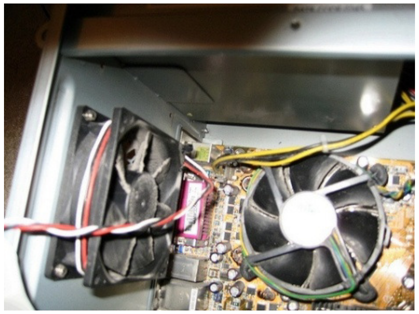


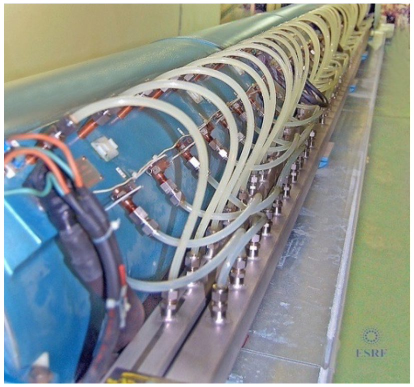


Google Data Center (1/2)

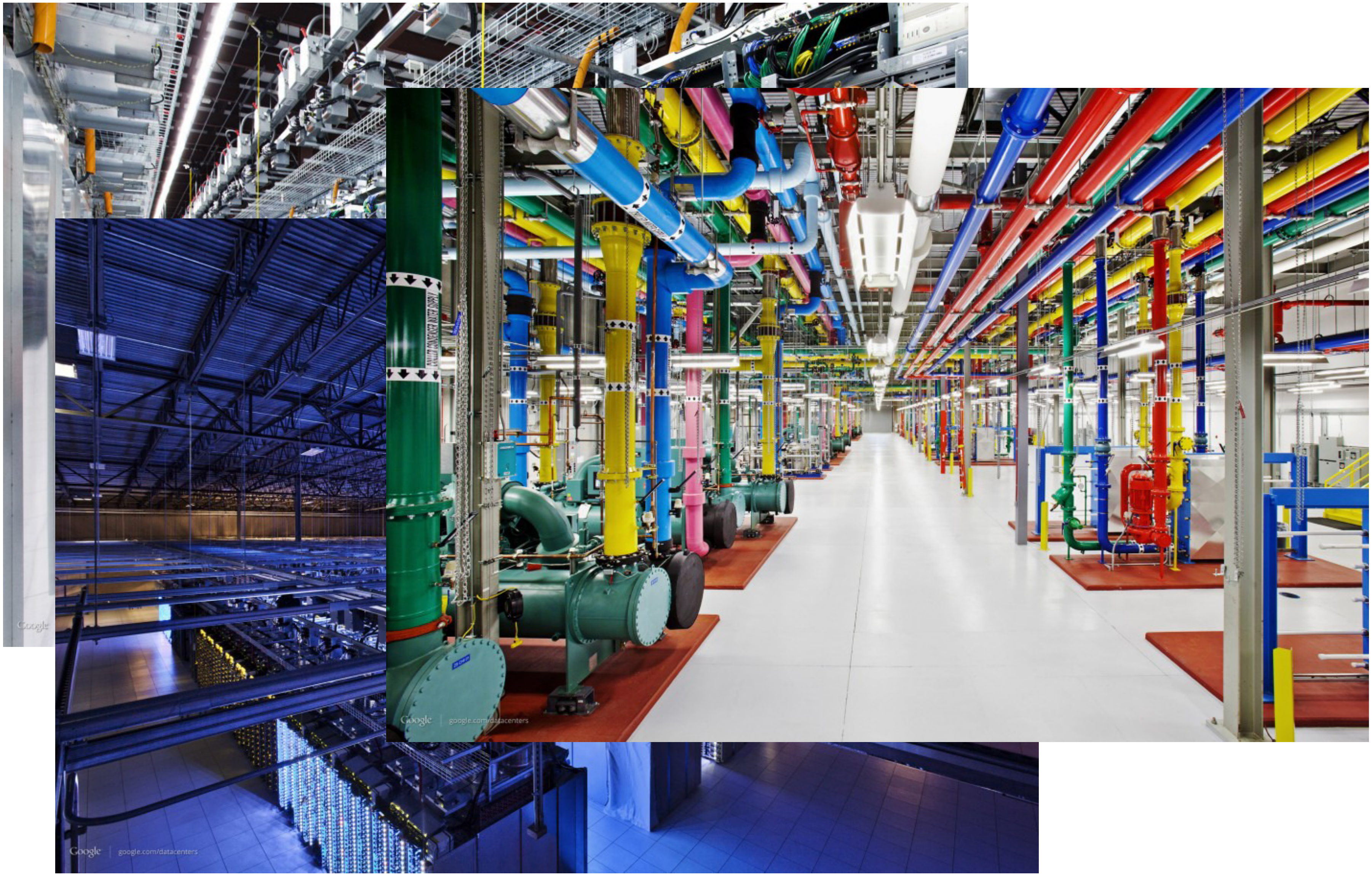
Google Data Center, Oregon

- Cost of large data centers solely determined by power bill …





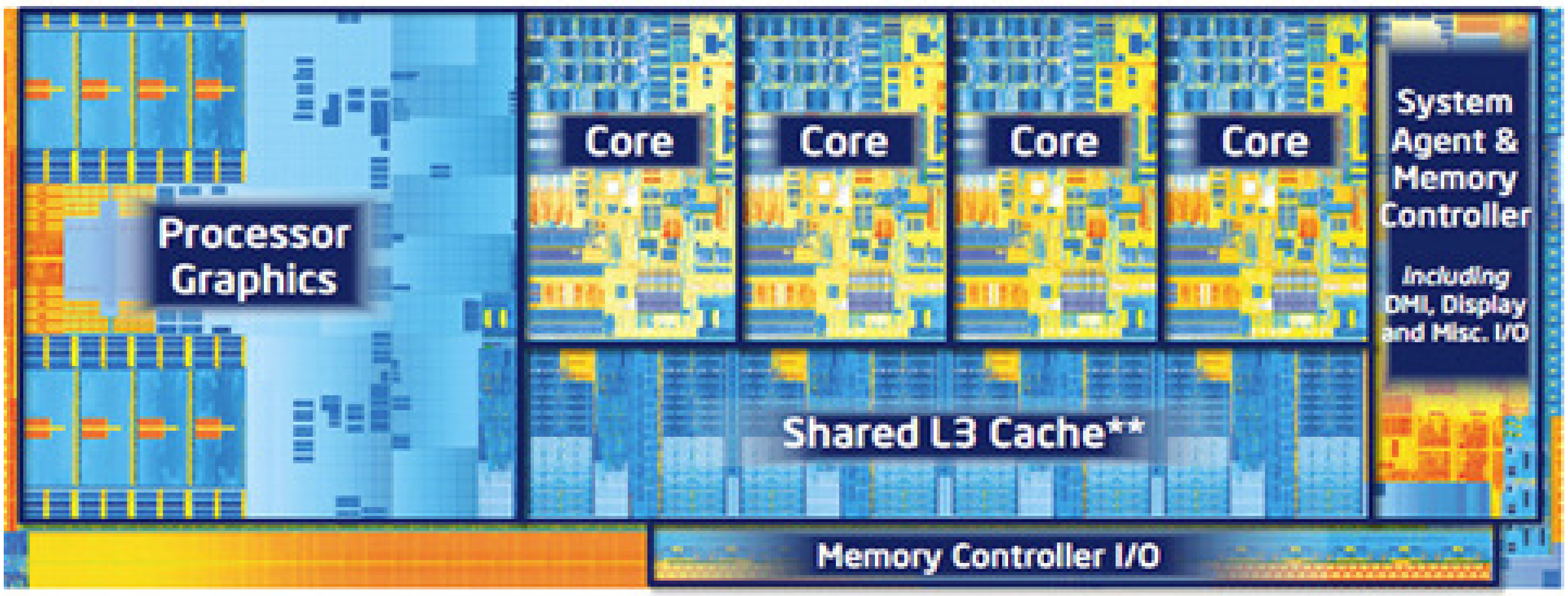
Google Data Center (2/2)



Intel Core i7 (1/2)

Newest Manufacturing Technology Delivers

3rd Generation Intel® Core™ Processor: 22nm Process



New architecture with shared cache delivering more performance and energy efficiency

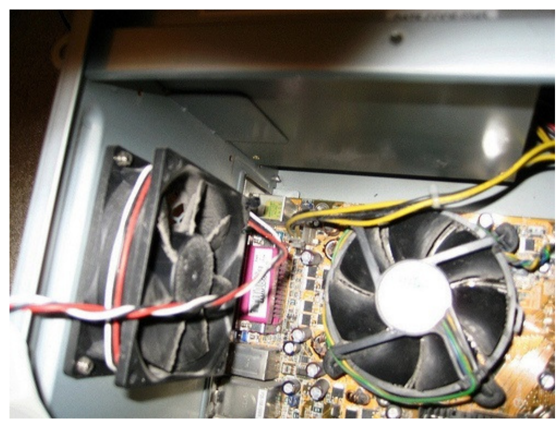
Quad Core die with Intel® HD Graphics 4000 shown above
Transistor count: 1.4Billion Die size: 160mm²
** Cache is shared across all 4 cores and processor graphics

Intel Core i7 (2/2)

Model	Core	Clock Speed	Thermal Design Power
Core i7-975 Extreme Edition	Bloomfield (45 nm)	3.333 GHz	130 W
Core i7-960	Bloomfield (45 nm)	3.2 GHz	130 W
Core i7-950	Bloomfield (45 nm)	3.067 GHz	130 W
Core i7-940	Bloomfield (45 nm)	2.933 GHz	130 W
Core i7-930	Bloomfield (45 nm)	2.8 GHz	130 W
Core i7-920	Bloomfield (45 nm)	2.667 GHz	130 W
Core i7-980X Extreme Edition	Gulftown (32 nm)	3.333 GHz @ 6 Cores	130 W
Core i7-970	Gulftown (32 nm)	3.2 GHz	130 W
Core i7-4790K	Haswell (22 nm)	4.0 GHz @ 4 Cores	88 W
Core i7-4770S	Haswell (22 nm)	3.1 GHz @ 4 Cores	65 W
Core i7-4770K	Haswell (22 nm)	3.5 GHz @ 4 Cores	84 W
Core i7-5960X Extreme Edition	Haswell-E (22 nm)	3 GHz @ 8 Cores	140 W
Core i7-5930K	Haswell-E (22 nm)	3.5 GHz @ 6 Cores	140 W
Core i7-5820K	Haswell-E (22 nm)	3.3 GHz @ 6 Cores	140 W
Core i7-3770T	Ivy Bridge (22 nm)	2.5 GHz @ 4 Cores	45 W
Core i7-3770S	Ivy Bridge (22 nm)	3.1 GHz @ 4 Cores	65 W
Core i7-3770K	Ivy Bridge (22 nm)	3.5 GHz @ 4 Cores	77 W
Core i7-3770	Ivy Bridge (22 nm)	3.4 GHz @ 4 Cores	77 W
Core i7-4960X Extreme Edition	Ivy Bridge-E (22 nm)	3.6 GHz @ 6 Cores	130 W
Core i7-4930K	Ivy Bridge-E (22 nm)	3.4 GHz @ 6 Cores	130 W
Core i7-4820K	Ivy Bridge-E (22 nm)	3.7 GHz @ 4 Cores	130 W

Power versus Energy (1/3)

- **Ampere:** 1 A = 1 Coulomb(庫倫)/sec
- **Volt:** 1 V = 1 Joule(焦耳) / Coulomb
- **Power consumption in Watts**
  - P (功率) = I (電流) • V (電壓) ⇒ 1 W = 1 A • V = 1 J/s
  - set packaging limits
- **Energy efficiency in Joules**
  - energy = power * delay (joules = watts * seconds)
  - 1 J = 1 W • s = 1 N • m = 0.239 Calorie (卡路里)

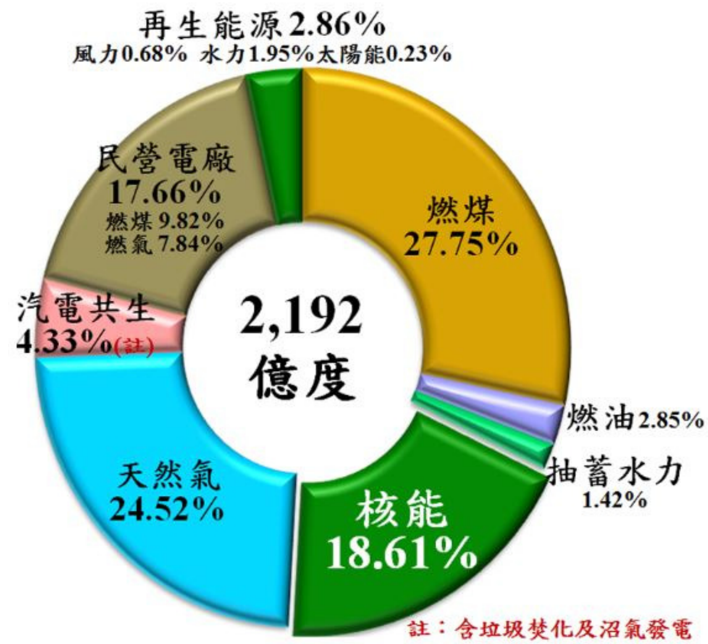


Power versus Energy (2/3)

- 發電機發電量 ： 瓩 (kW)
- **1度 = 1 kWh = 3.6×10^6 J**
  - 若1度電3元，則電腦一個月皆不關機需要多少電費？（假設主機滿載時耗電100W而且不包括螢幕等週邊設備耗電）
  - 0.1*24*30*3 = 216 元
- 天河二號 **17.6MW** （整機附帶散熱系統時為**24MW**）
  - 一個月電費： 17600*24*30*3 = 3801 萬元
- **Data Center (10萬台伺服器)**
  - 消耗功率：200W*100000 = 20000 kW = 20 MW
  - 一個月電費： 20000*24*30*3 = 4320 萬元
  - 一年耗電量： 20000 kW *24*365 = 0.175 G kWh

Power versus Energy (3/3)

- 第三核能發電廠
  - 年發電量：180億度
  - 機組：兩部反應爐
  - 裝置容量(輸出功率)
    - 每部機951MW (951000瓩)
  - 每部機組最大年發電量
    - 951000瓩×24×365
    - 8.33G kWh = 83.3億度
- 核能發電每部機組實際年發電量
  - 219.2 G kWh × 0.1861 ÷ 3 ÷ 2 = 6.8 G kWh
  - Year 2000: 0.16 Tera (10^{12}) kWh
    - ÷ 6.8 G kWh ≅ 23.5

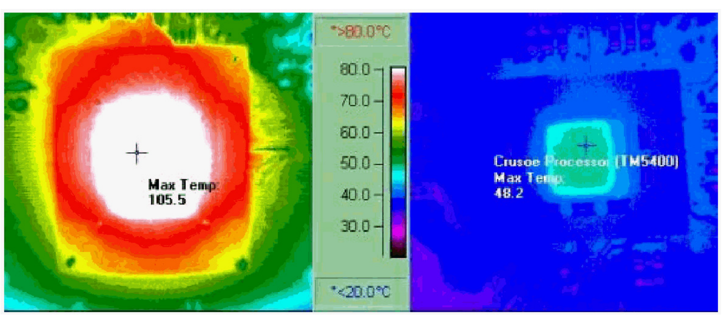


103年發電量占比圖


Wii U
Cyber-shot
SONY
SONY
Twitter
Email
Music
Weather
iPod

Embedded Systems (1/2)

- **Portable systems**
  - Long battery life, Low temperatures, Light weight, Small form factor, …
- **Packaging costs, Cooling costs**
- **Device reliability**
- **Performance**
  - 25°C ⇒ 105°C
  - loss of 30% of performance



Embedded Systems (2/2)

- Apple iPhone 6s Plus 64G : 2750 mAh
- Ah (Ampere-hour)
  - 電量單位
  - 1Ah = 1A・1h = 3,600 Coulomb(庫倫) (A・sec)
- Battery life (in portable systems)
  - P (功率) = I (電流)・V (電壓)
  - Nickel-Metal Hydride, "AA" sizes, 1600mAh, 1.2V
    - 1 W ⇒ ≅ 2 hours
      - 1.6Ah ÷ (1W÷1.2V)
    - 2.5 mW ⇒ ≅ a month

iPhone 5

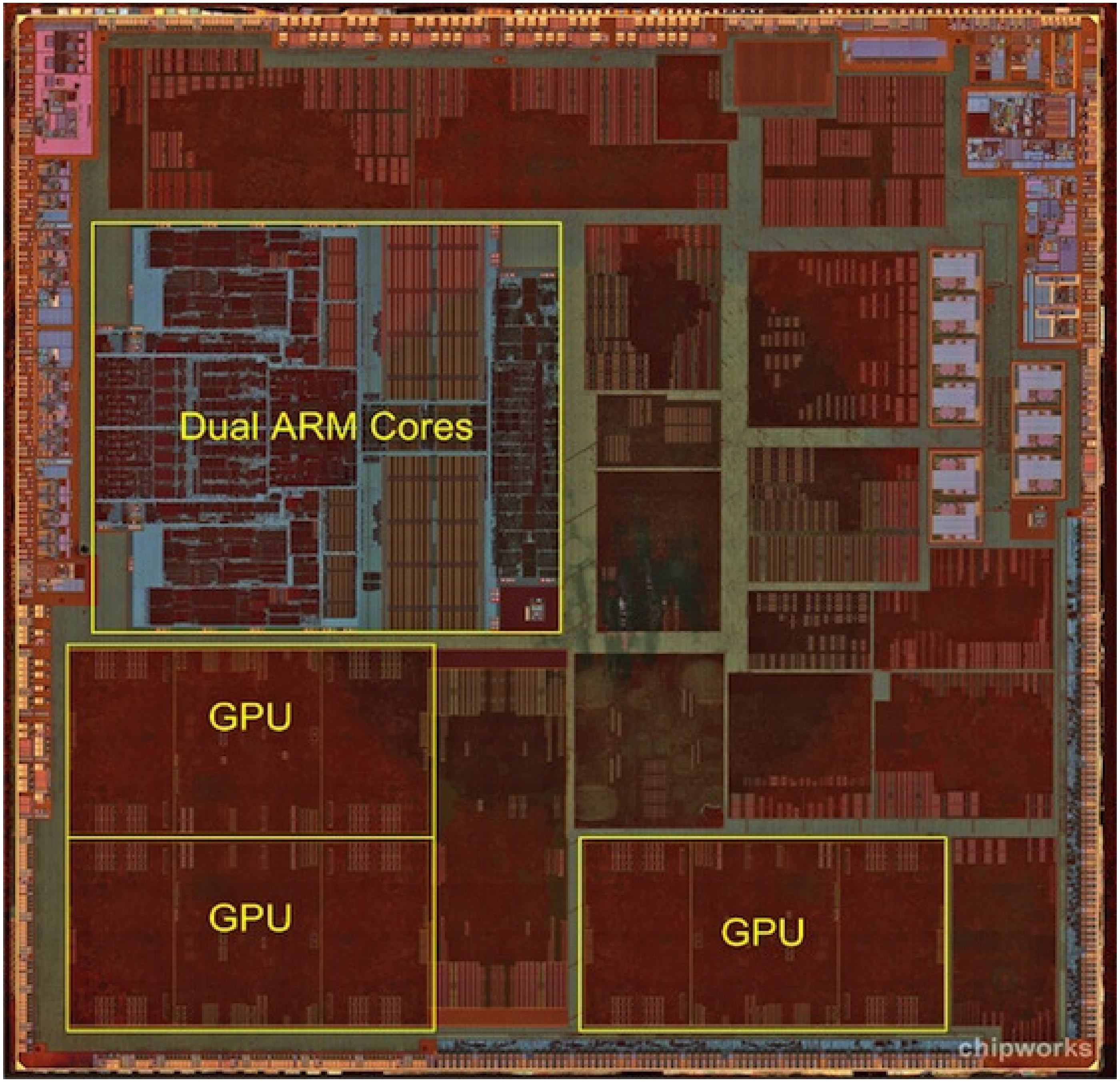

iPhone 5
Noch schneller, noch schöner, einfach noch besser!
iPhone


WARNING
Authorized Service Provider Only
Potential for fire or burning. Do not disassemble, puncture, crush, heat, or burn.
Li-ion Polymer Battery
3.8V ⎓ 5.92Whr
APN: 616-0728
VPN: 1852001-AL
Li-ion
iPhone
IFIXIT

TECHINSIGHTS

iPhone 6S


A6
N4PR1A3 1231

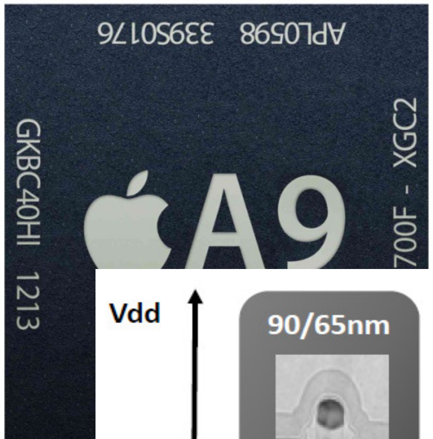

Dual ARM Cores
GPU
GPU
GPU
chipworks

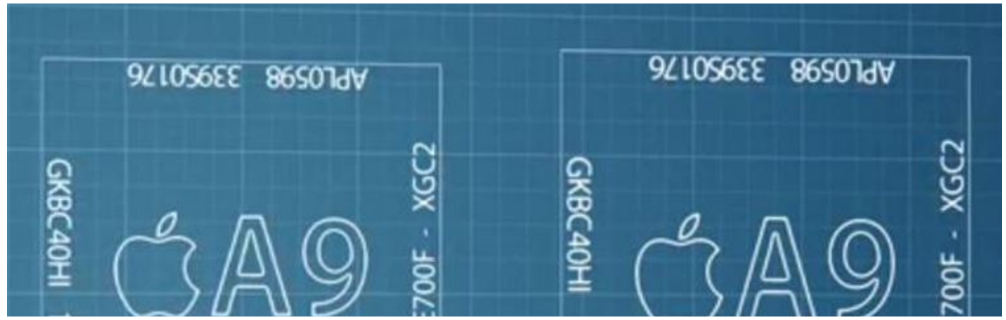
Apple A9 Processor (1/3)

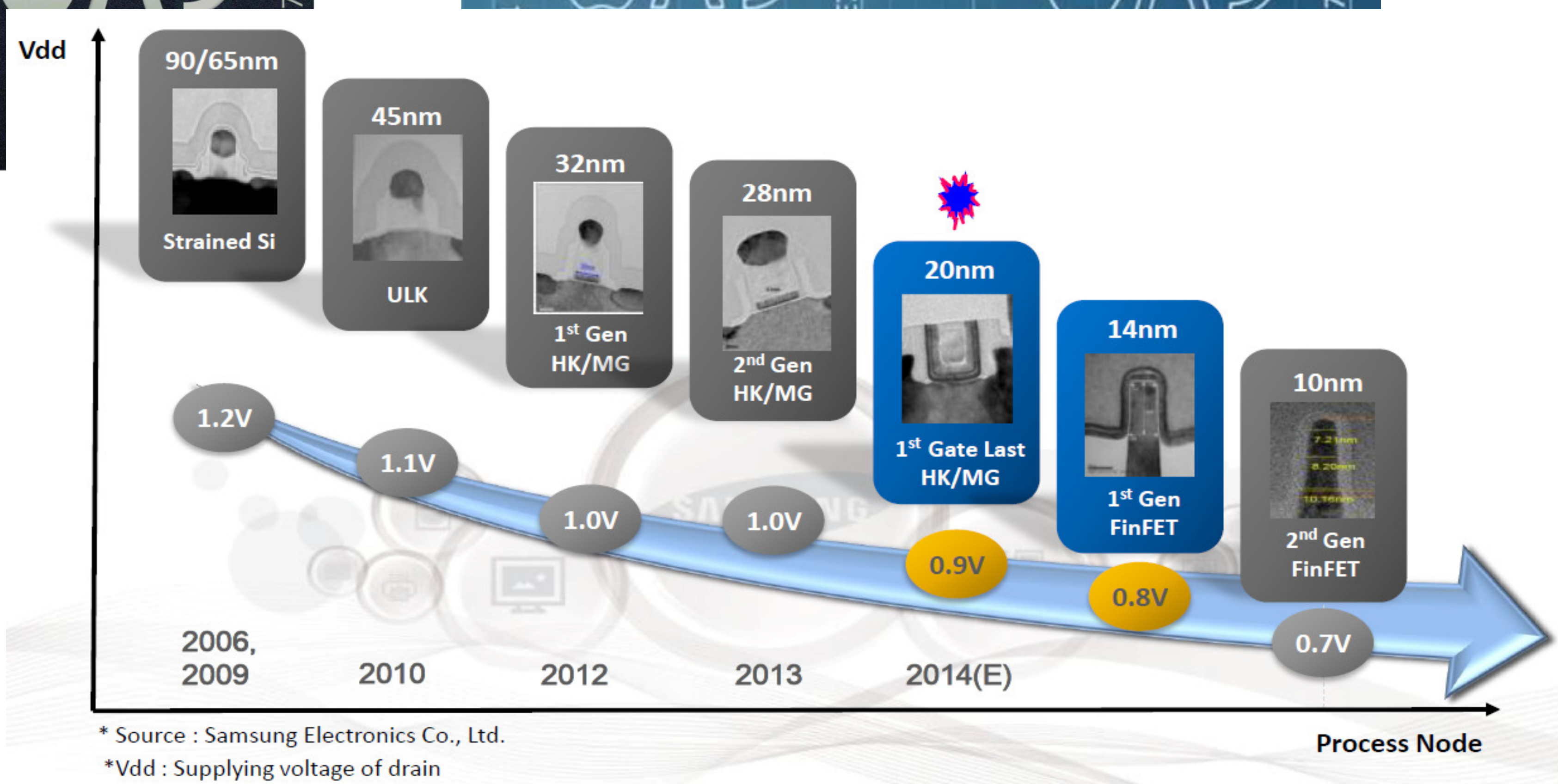
Apple SoC Comparison				
	A9X	A9	A8X	A6X
CPU	2x Twister	2x Twister	3x Typhoon	2x Swift
CPU Clockspeed	2.26GHz	1.85GHz	1.5GHz	1.3GHz
GPU	PVR 12 Cluster Series7	PVR GT7600	Apple/PVR GXA6850	PVR SGX554 MP4
RAM	4GB LPDDR4	2GB LPDDR4	2GB LPDDR3	1GB LPDDR2
Memory Bus Width	128-bit	64-bit	128-bit	128-bit
Memory Bandwidth	51.2GB/sec	25.6GB/sec	25.6GB/sec	17.1GB/sec
L2 Cache	3MB	3MB	2MB	1MB
L3 Cache	None	4MB	4MB	N/A
Manufacturing Process	TSMC 16nm FinFET	TSMC 16nm & Samsung 14nm	TSMC 20nm	Samsung 32nm

2 billion transistors

Apple A9 Processor (2/3)

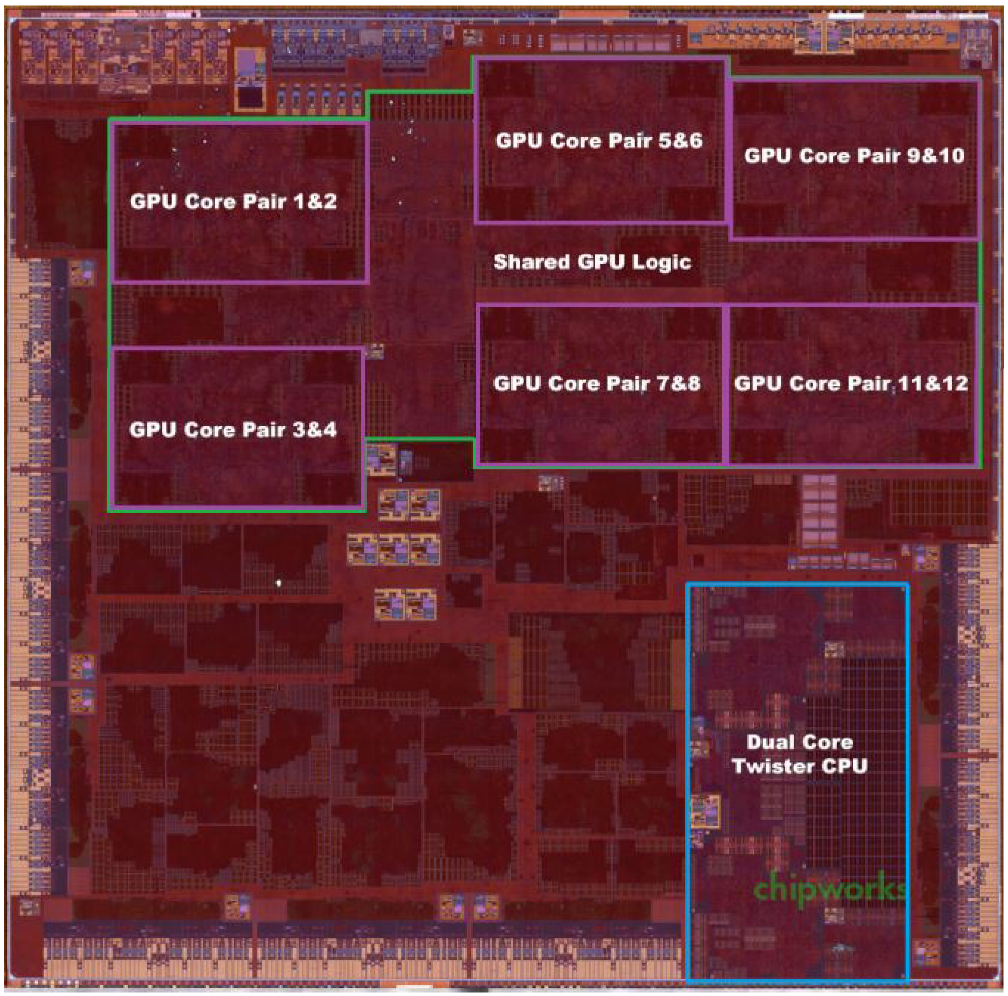






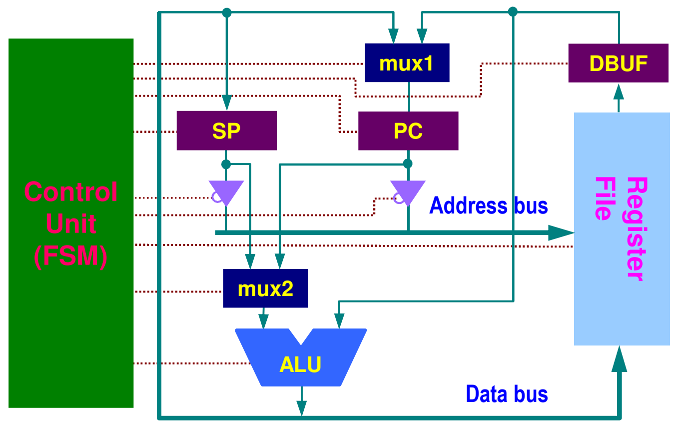
Apple A9 Processor (3/3)

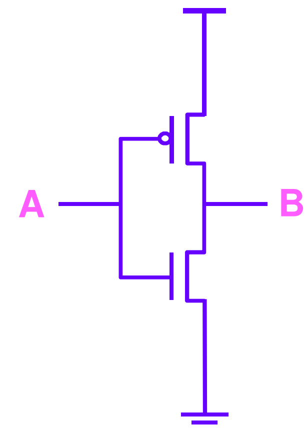
- **A9X Die**

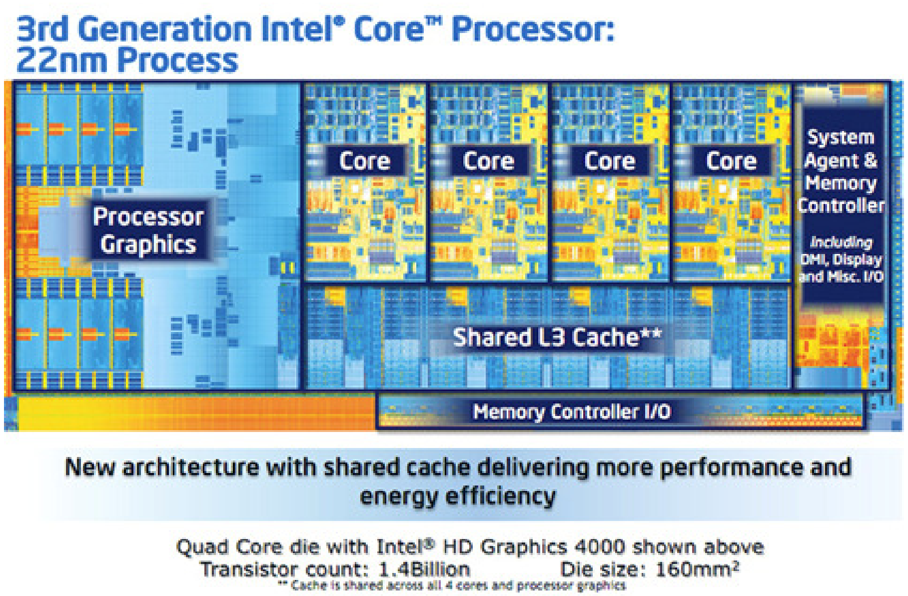


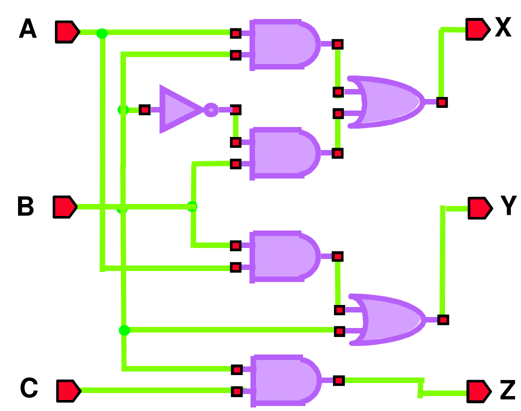
Apple iPad Pro

Sources of Power Dissipation (1/2)



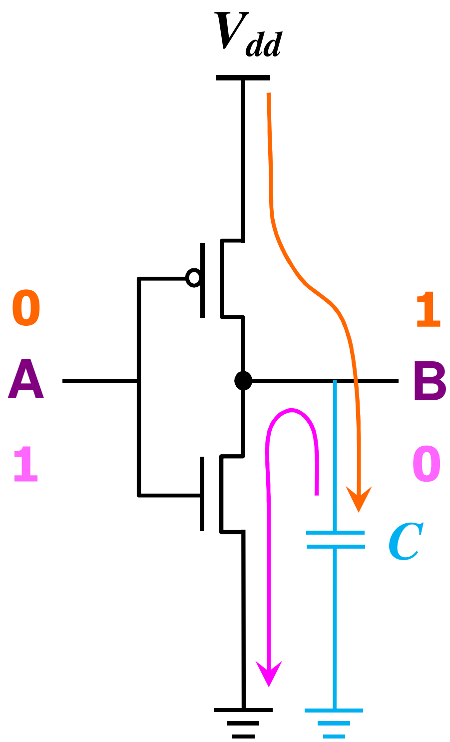


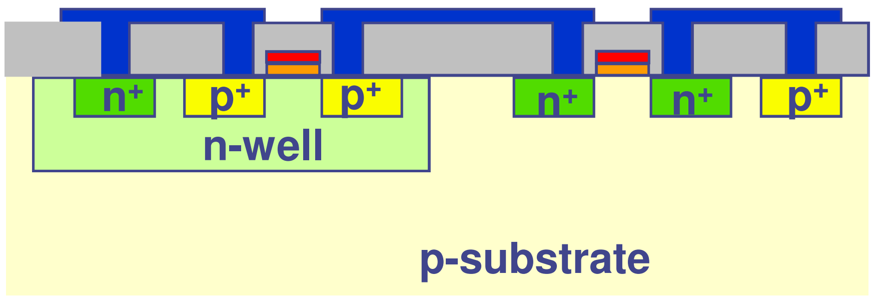




Sources of Power Dissipation (2/2)

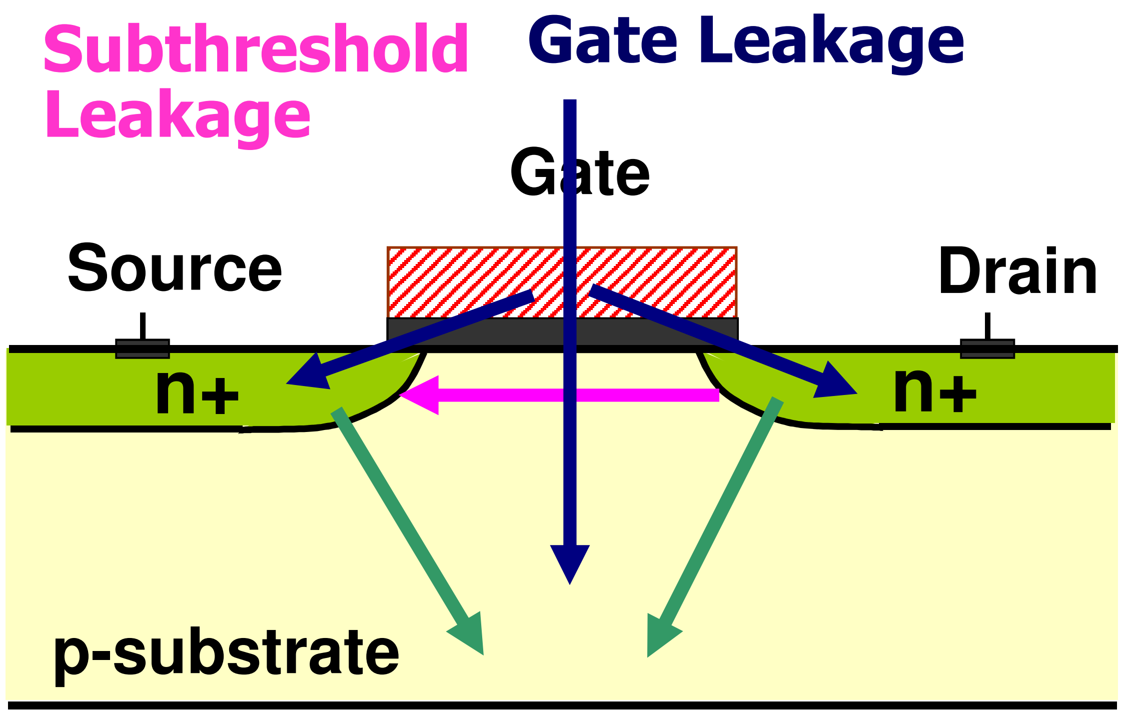
- Dynamic power, Short circuit power, Leakage power





$$P = \boxed{C \cdot V_{dd}^{2} \cdot f} + \boxed{V_{dd} \cdot I_{leak}}$$

Leakage Power



Levels for Low-Power Processor Design

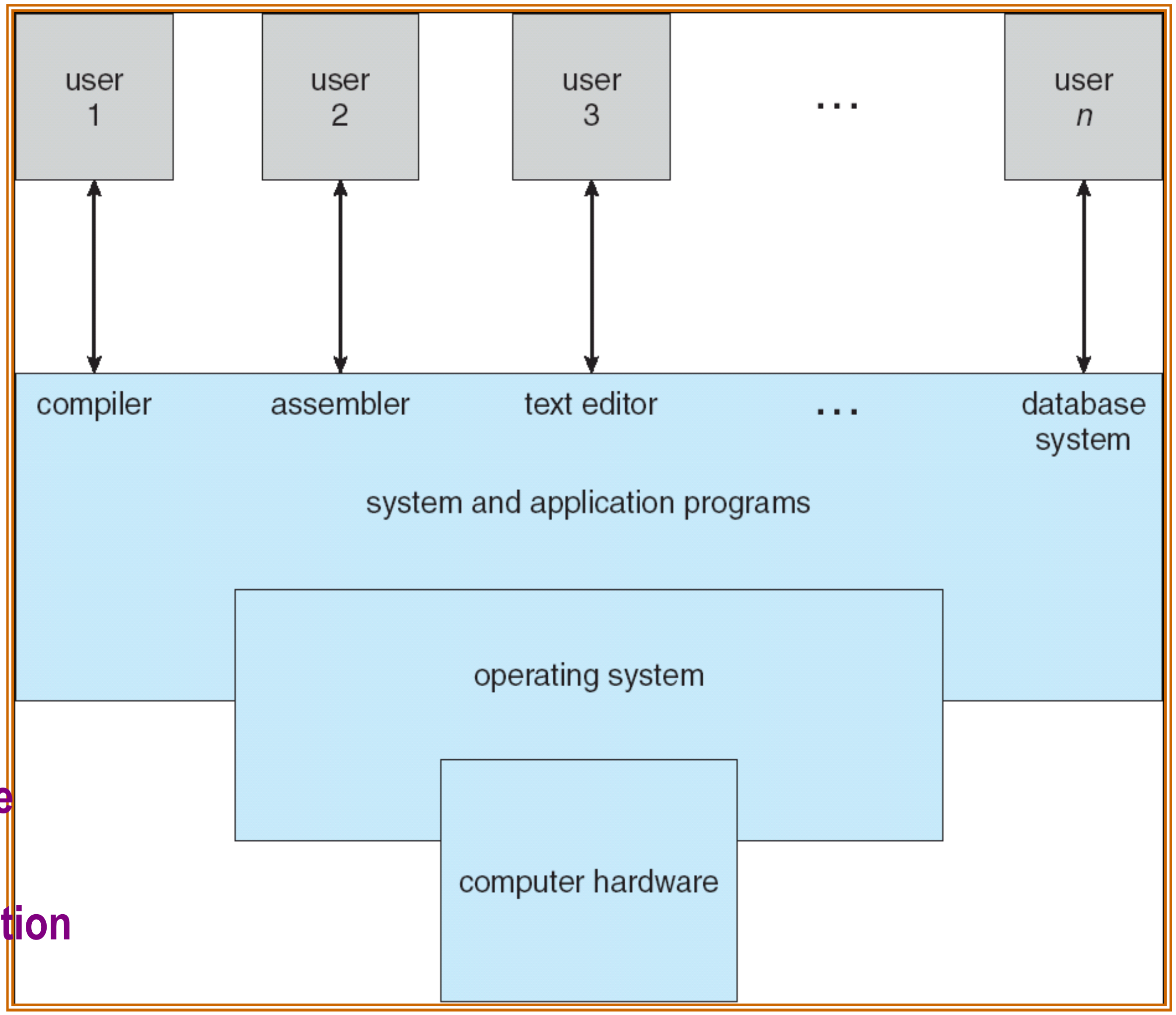
Application

Compiler

OS

Architecture

Implementation



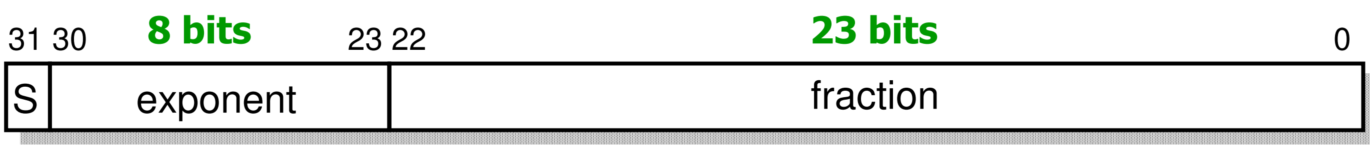
Application Level Low-Power Techniques

- **Selection of an algorithm to perform a function**
  - Locality of reference (spatially and temporally)
  - Multiplication versus shift operation
  - A*B+A*C $\Rightarrow$ A*(B+C)

```
FOR i :=1 TO N DO
   B[i] := f(A[i]);
FOR i:=1 TO N DO
   C[i] := g(B[i]);
```

```
FOR i :=1 TO N DO  BEGIN
   B[i] := f(A[i]);
   C[i] := g(B[i]);
END
```

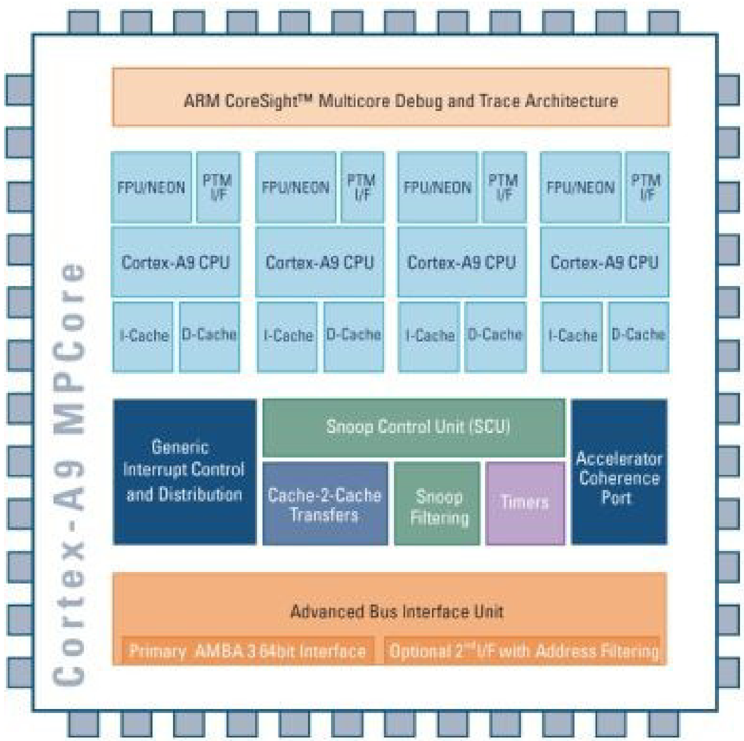
- **Algorithms can have approximate implementations**
  - Integer or floating-point number, single or double-precision
  - Fixed-point or floating-point representation

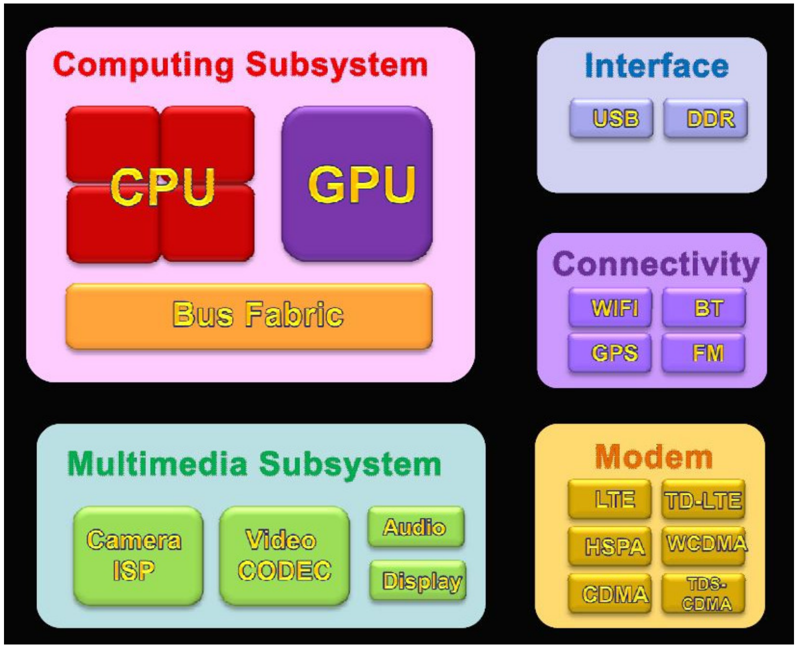


OS Level Low-Power Techniques (1/3)

Dynamic Power Management

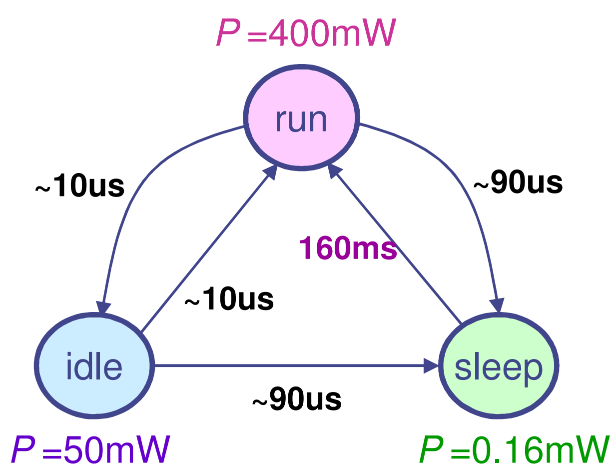
- selectively turn off or slow down system components





OS Level Low-Power Techniques (2/3)

- **Power-manageable Components**
  - Can be modeled as power state machine (PSM)
- **Processors, Memories, HD, Hardware Accelerators, Displays, …**



StrongARM SA-1100 processor

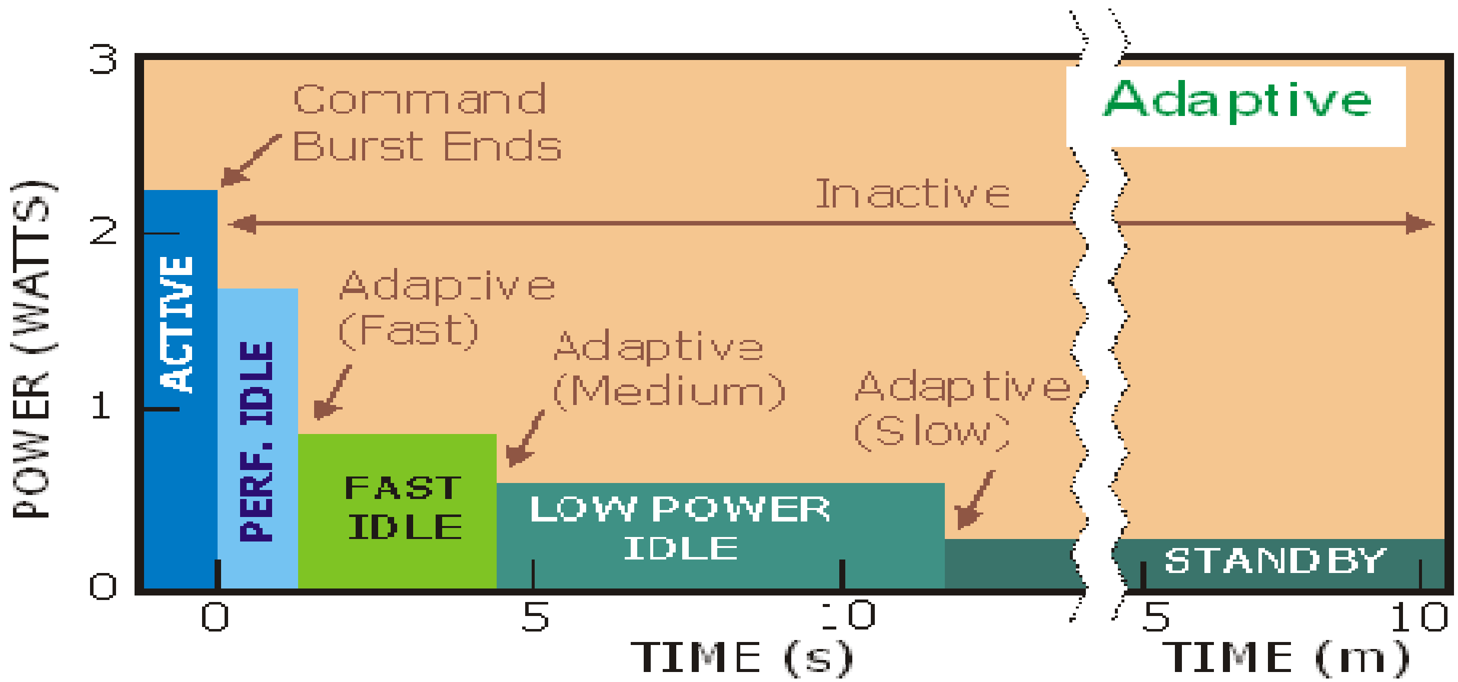
run: normal operating mode

idle: allow a software application to stop the CPU

sleep: the lowest level of available functionality

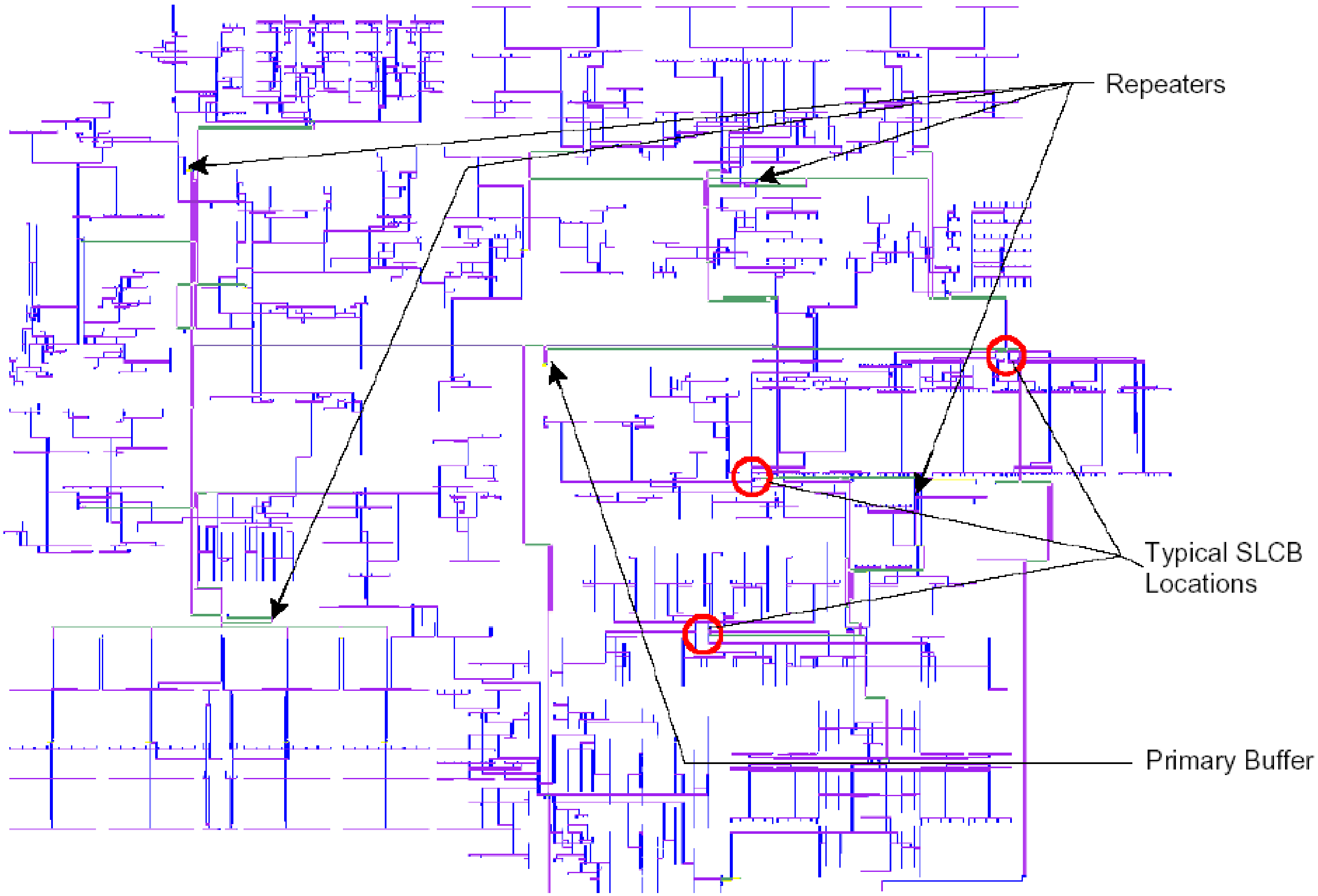
OS Level Low-Power Techniques (3/3)

- **Design of Power-Manageable Components**
  - **Clock Gating**
  - **Power Gating**
  - **Dynamic Voltage Scaling**



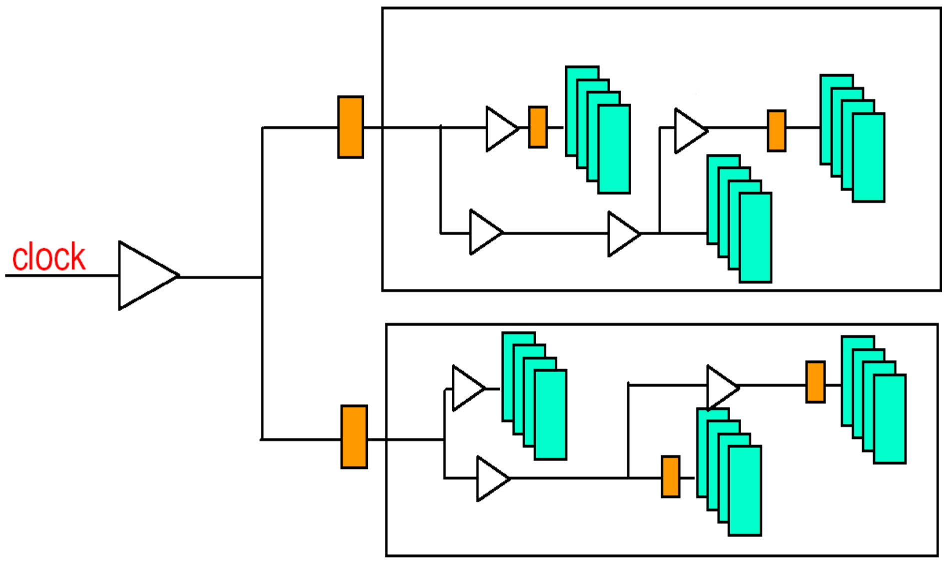
Clock Gating (1/2)

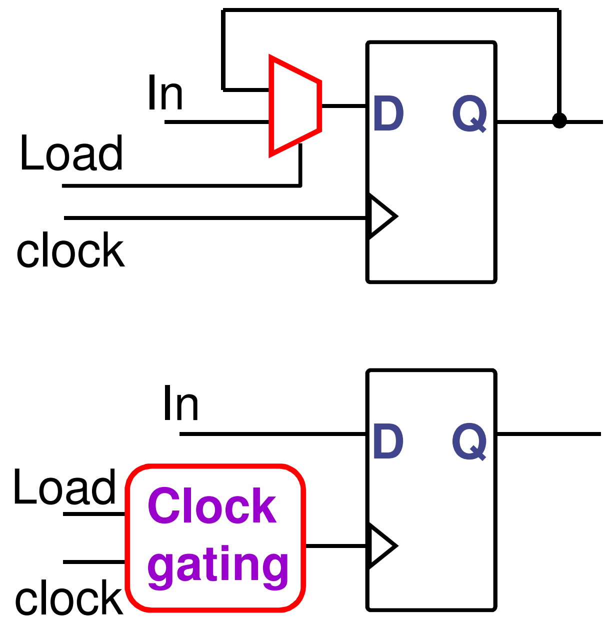
Itanium 2 H-Tree



Clock Gating (2/2)

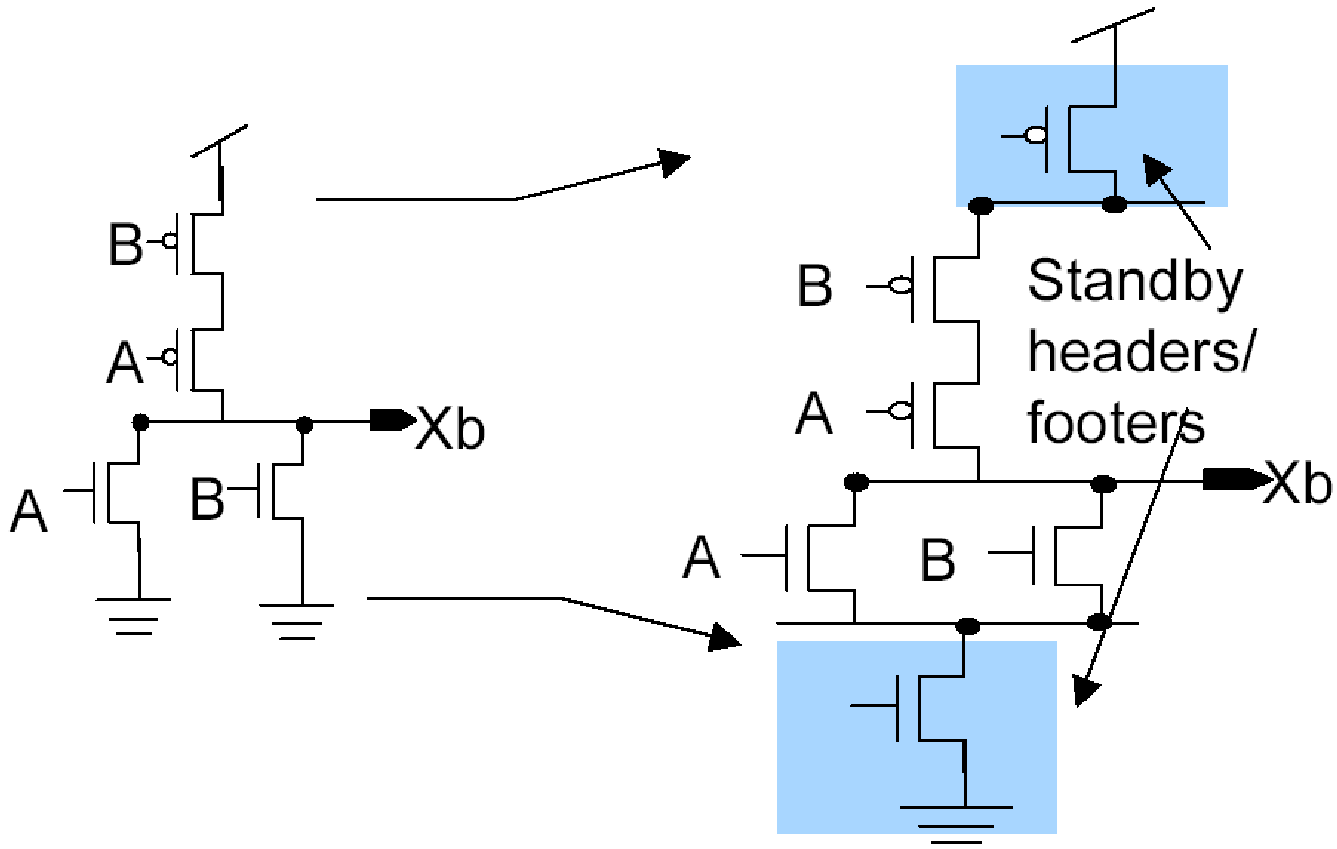
- **Clock gating**
  - **> 50%** power consumed in clock network reported
  - gate the clock to a flip-flop





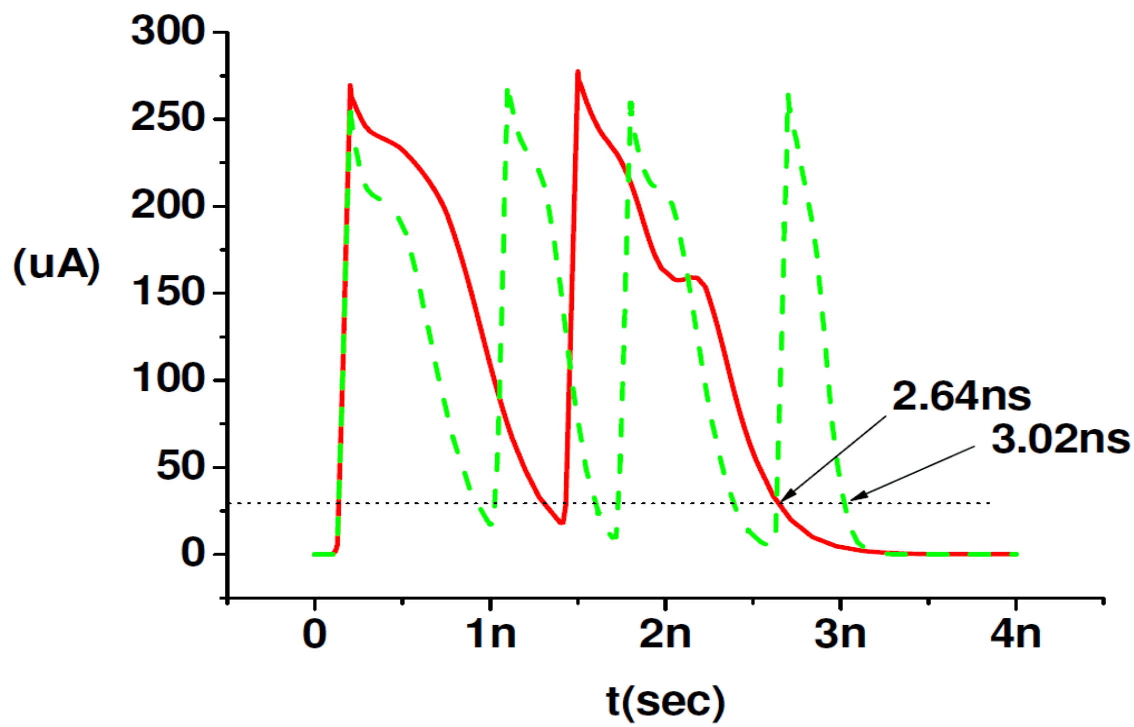
Power Gating (1/2)

- Use header and/or footer switches to disconnect supplies when inactive



Power Gating (2/2)

- **Simultaneous switching capacitance**
- **Loss of state**
  - preserve the state before a module shuts down
  - scan out data to a RAM, then scan it back in

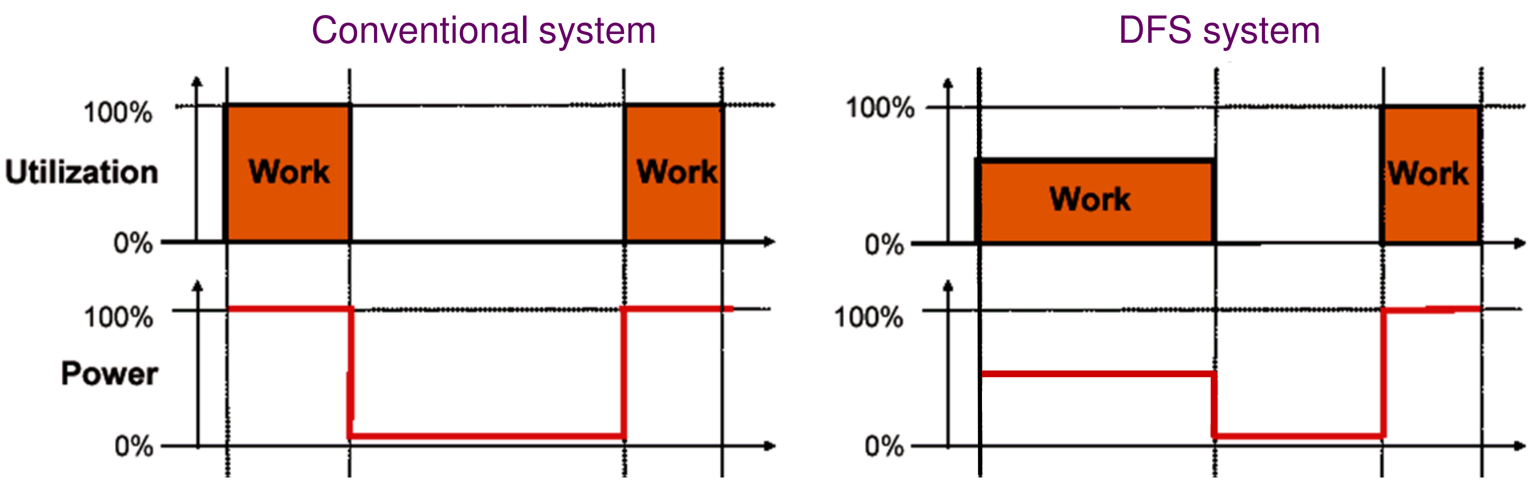


Dynamic Voltage Scaling (1/2)

Dynamic Frequency Scaling (DFS)

- lower power linearly
- does NOT improve energy efficiency
- avoid thermal problems

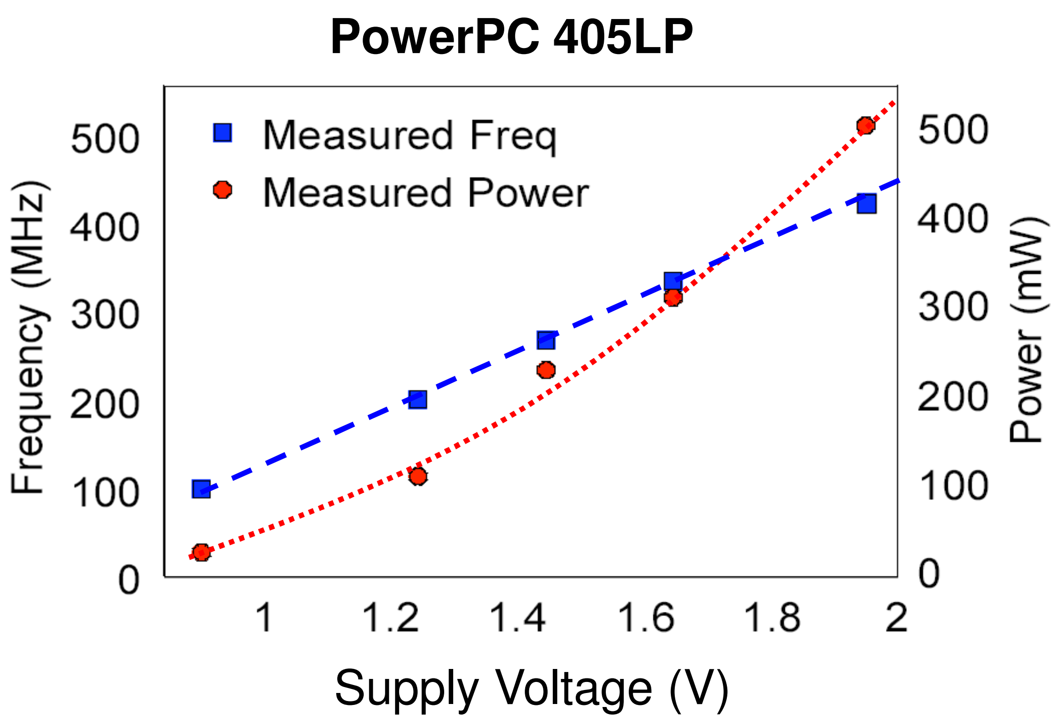
$$P = C \cdot V_{dd}^2 \cdot f + V_{dd} \cdot I_{leak}$$



Dynamic Voltage Scaling (2/2)

Dynamic Voltage Scaling (DVS)

- is often combined with frequency scaling (DVFS)



$$P = C \cdot V_{dd}^2 \cdot f + V_{dd} \cdot I_{leak}$$

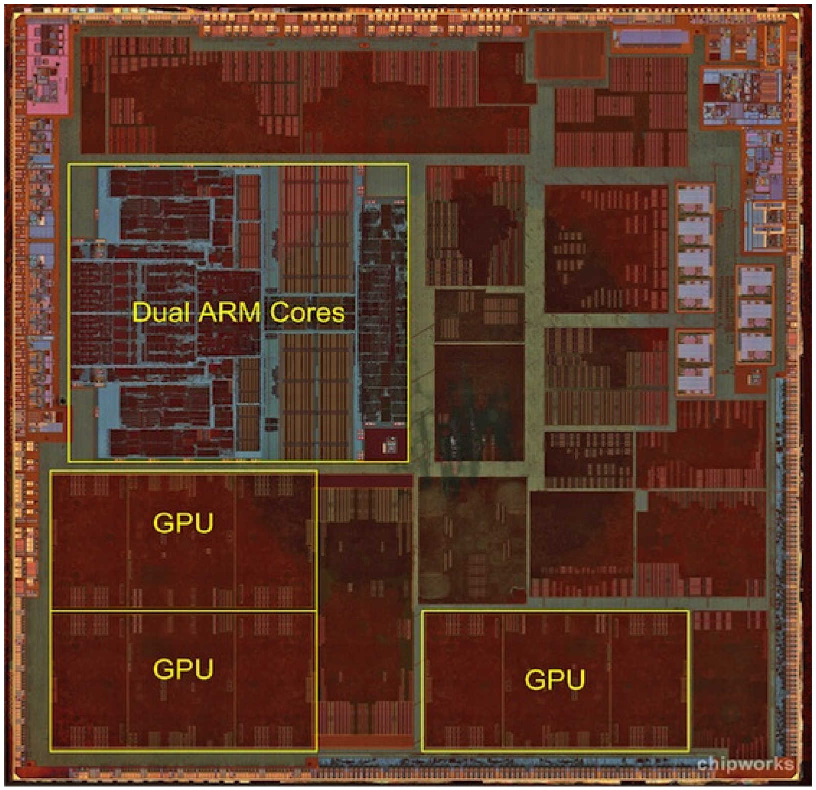
$$f \sim (V_{dd} - V_t)^2 / V_{dd}$$

f : $(2-0.5)^2/2$: $(1-0.5)^2/1$ = 4.5 : 1

P : $2^2 \times 4.5$: 1 = 18 : 1

E : 18×1 : 1×4.5 = 4 : 1

Low-power Design of 3D GPU (1/2)

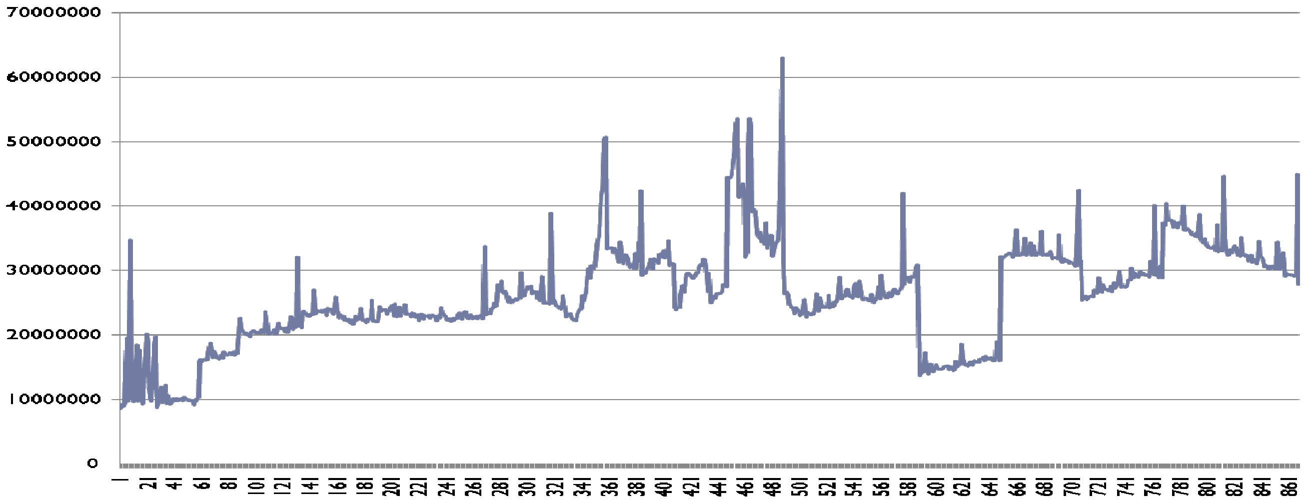


Low-power Design of 3D GPU (2/2)

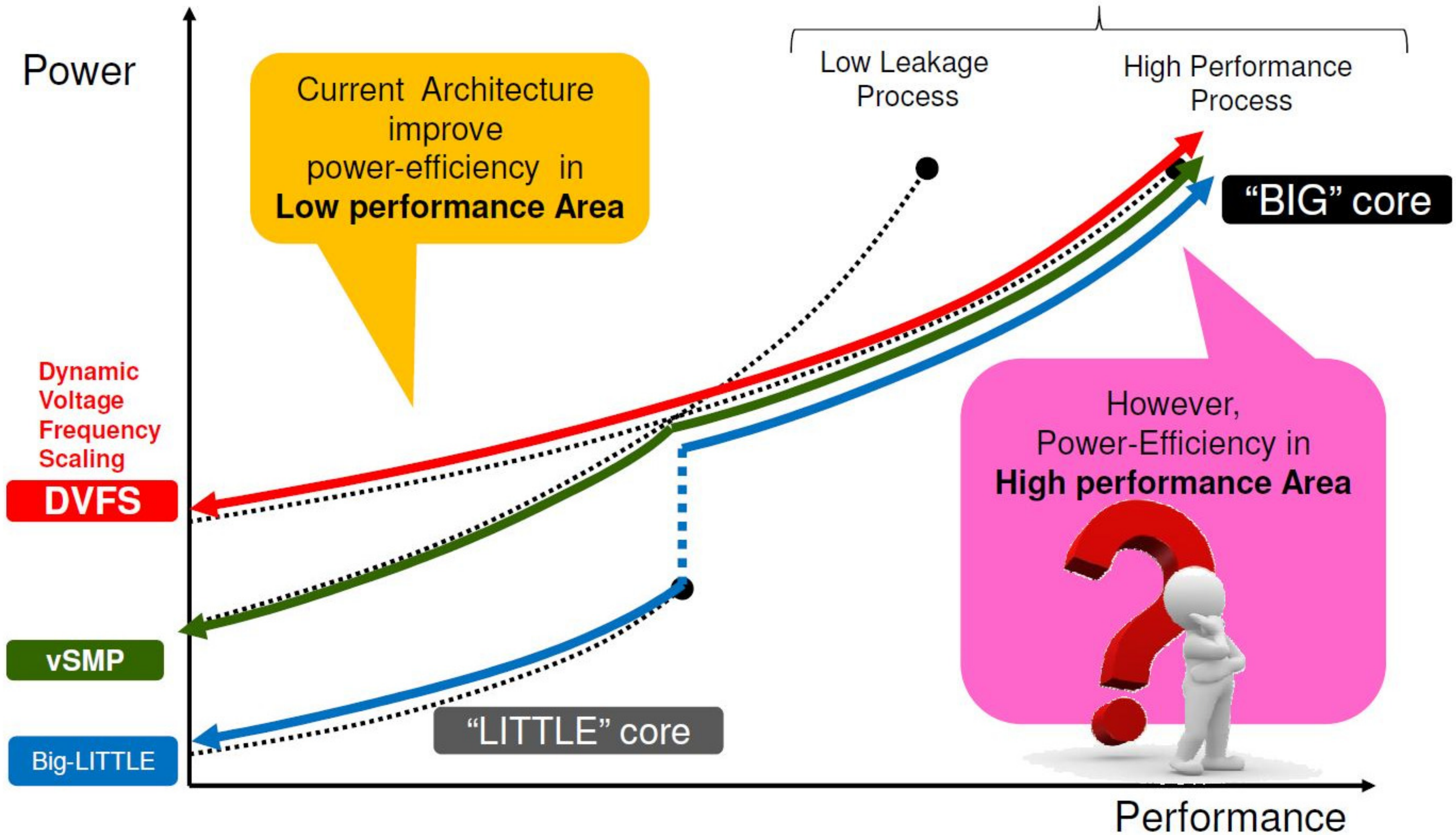
- **Dynamic Voltage/Frequency Scaling**
  - Workload Prediction for DVFS
- **Multiple-Precision Graphics Processing Unit**
  - Multiple-Precision Floating-Point (FP) Arithmetic Units

Workload Prediction

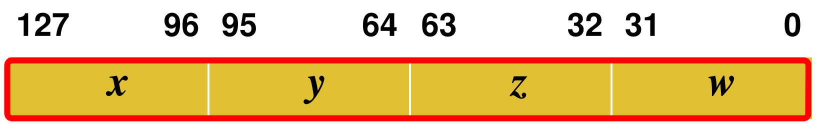
- **Workload Prediction for Power Management**
  - Predict the complexity of future frames
- **History-based Workload Prediction**
  - Predict the workload of next frame by the workloads of previous frames
  - UW1, UW5, and UW1_5
  - …

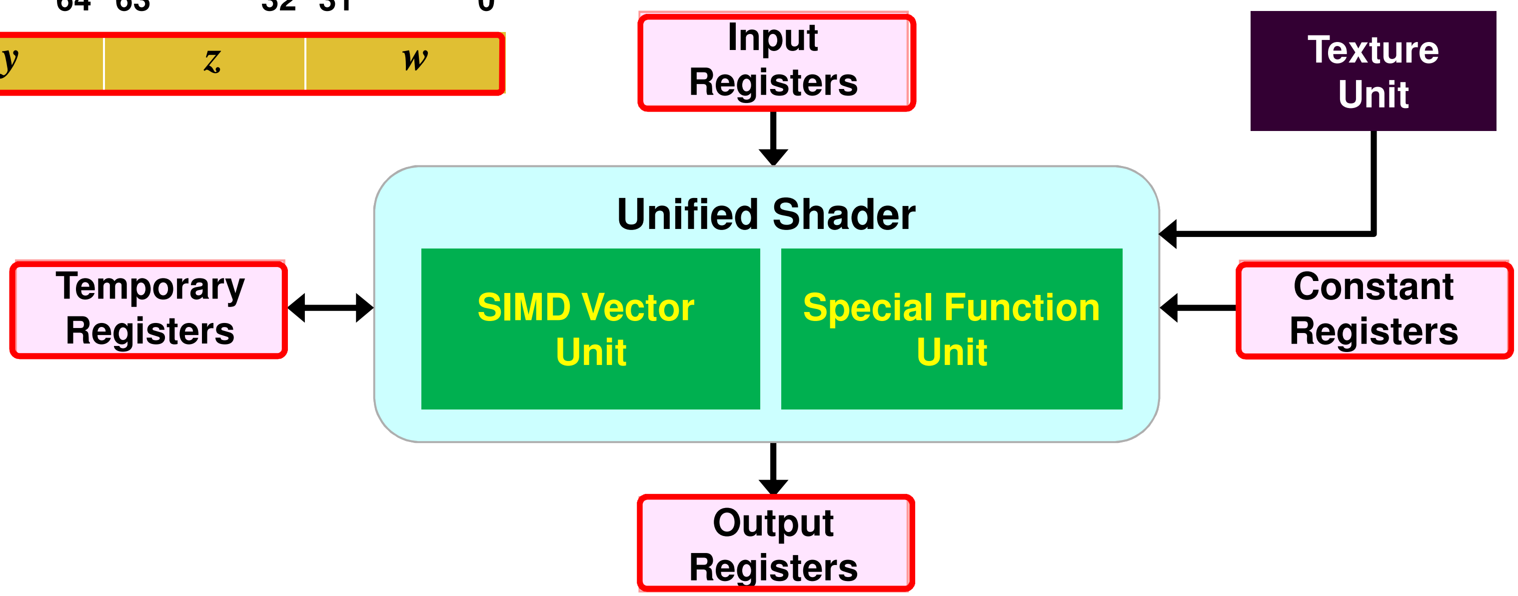


Power-Efficient Architecture of Smartphone

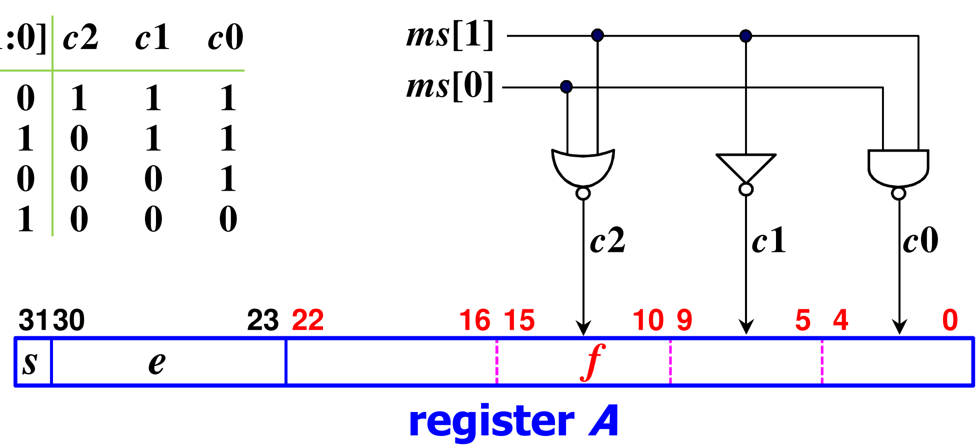


Unified Shader Architecture



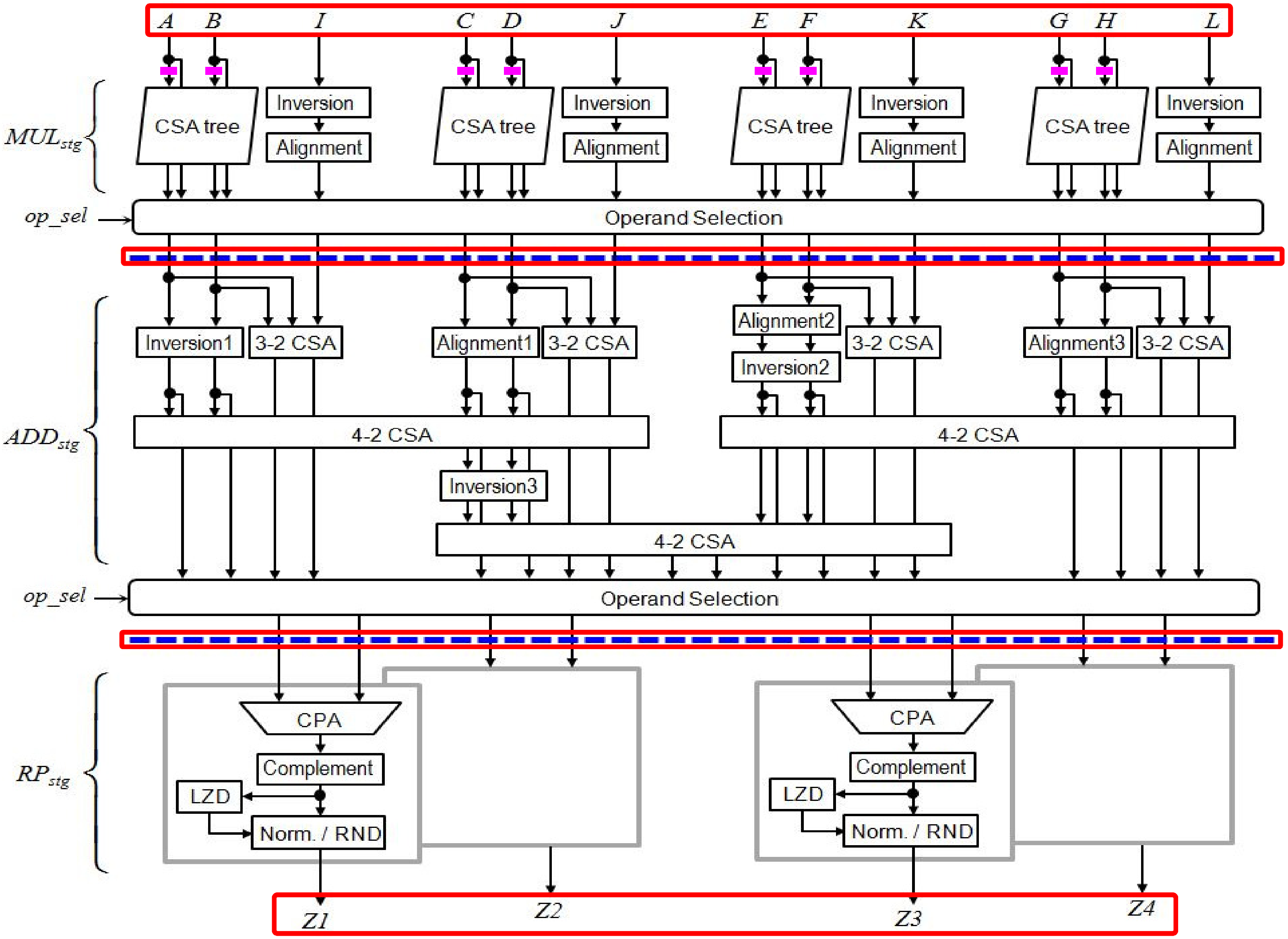


	$ms[1:0]$		$c2$	$c1$	$c0$
$PM3$ (23-bit)	0	0	1	1	1
$PM2$ (18-bit)	0	1	0	1	1
$PM1$ (13-bit)	1	0	0	0	1
$PM0$ (7-bit)	1	1	0	0	0



MPDP4 (1/2)

$$Z1 = AB + CD + EF + GH$$

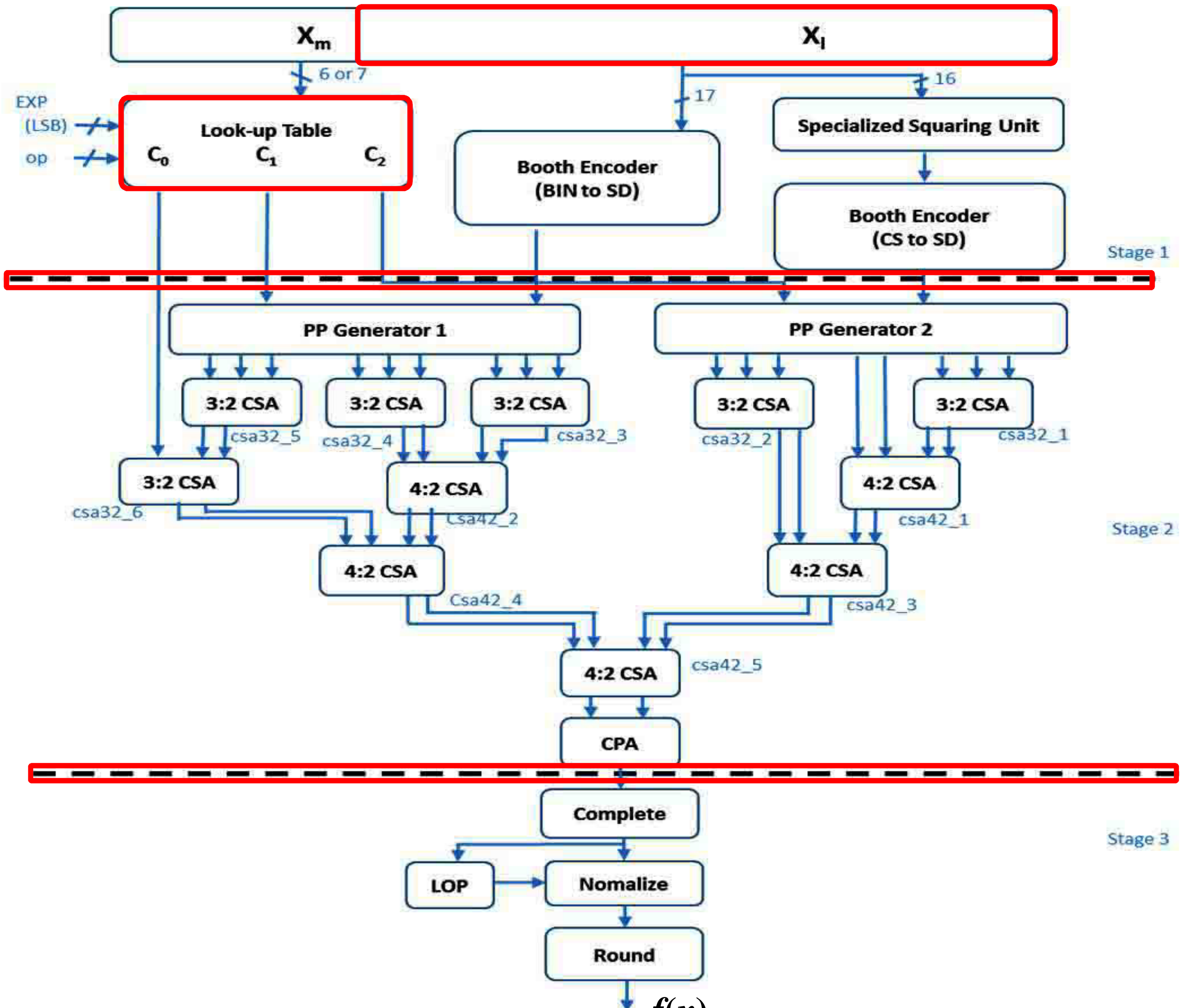


MPDP4 (2/2)

Operation	MFDP4	MPDP4			
		*PM*3	*PM*2	*PM*1	*PM*0
ADD	50.5	25.5 (–49.5%)	23.6 (–53.3%)	22.2 (–56.0%)	20.2 (–60.0%)
MUL	50.7	49.0 (–3.4%)	40.8 (–19.5%)	31.4 (–38.1%)	20.9 (–58. 8%)
MAD	52.2	62.0 (+18.8%)	56.0 (+7.3%)	48.7 (– 6.7%)	38.0 (–27.2%)
DP3	47.8	47.2 (–1.3%)	41.3 (–13.6%)	33.1 (–30.8%)	23.3 (–51.3%)
DP4	49.3	48.8 (–1.0%)	42.5 (–13.8%)	34.4 (–30.2%)	23.9 (–51.5%)
Average	50.1	46.5 (–7.2%)	40.8 (–18.5%)	34.0 (–32.2%)	25.3 (–49.6%)

MPSFU (1/2)

$f(x)=C_0+C_1X_l+C_2X_l^2$



MPSFU (2/2)

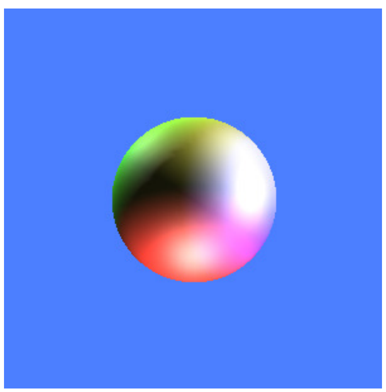
Operation	SFU	MPSFU			
		PM3	*PM2*	*PM1*	*PM0*
EXP	7.92	5.42 (–31.6%)	3.86 (–51.3%)	2.70 (–65.9%)	1.013 (–87.2%)
REC	7.67	5.62 (–26.7%)	4.00 (–47.8%)	2.72 (–64.5%)	0.888 (–88.4%)
LOG	7.71	5.62 (–27. 1%)	3.99 (–48.1%)	2.75 (–64.3%)	0.884 (–88.5%)
RSR_odd	7.62	5.43 (–28.7%)	3.84 (–49.5%)	2.59 (–66.1%)	0.844 (–88.9%)
RSR_even	7.64	5.49 (–28.1%)	3.92 (–48.7%)	2.63 (–65.5%)	0.862 (–88.7%)

Results of Multiple-Precision 3D GPU (1/3)

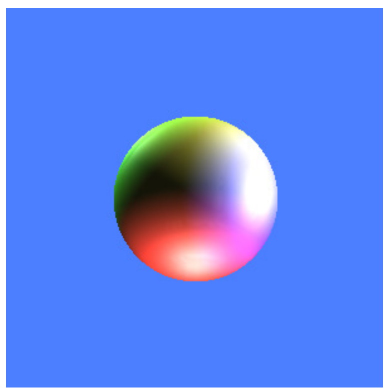
Mode 3

Mode 2

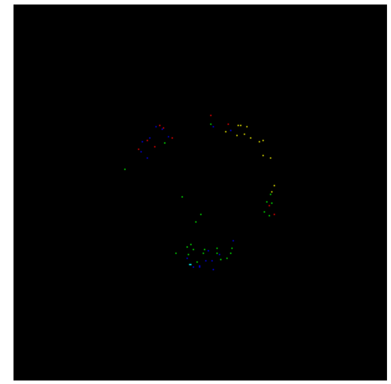
Mode 1



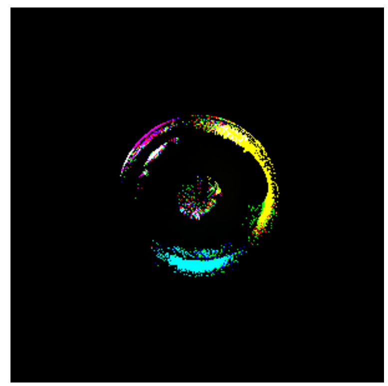
Mode 0



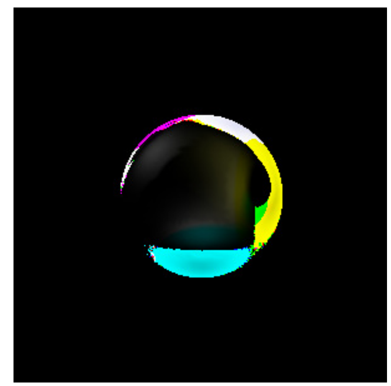
Mode 2



Mode 1



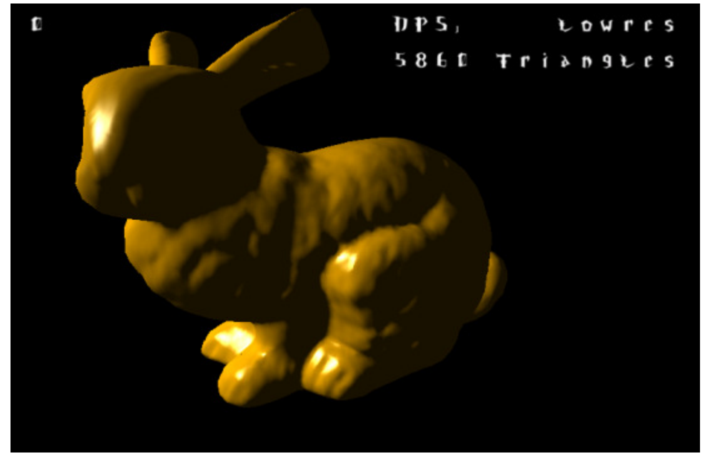
Mode 0



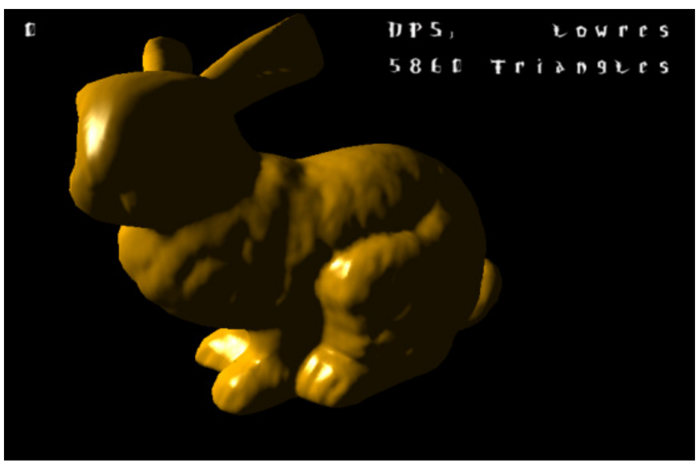
Results of Multiple-Precision 3D GPU (2/3)

Mode 3

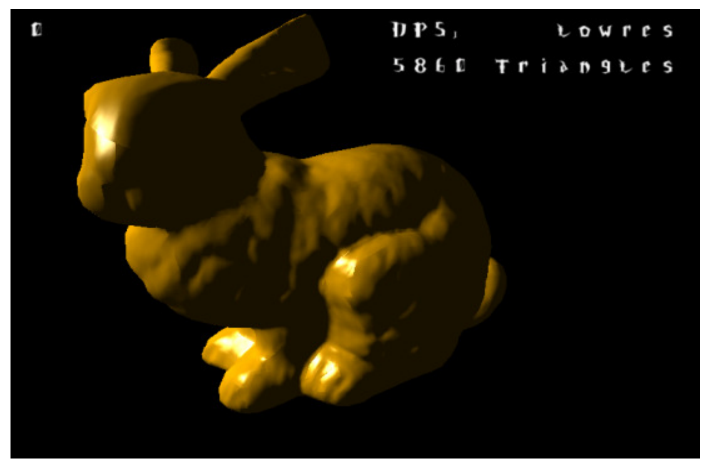
Mode 2



Mode 1



Mode 0

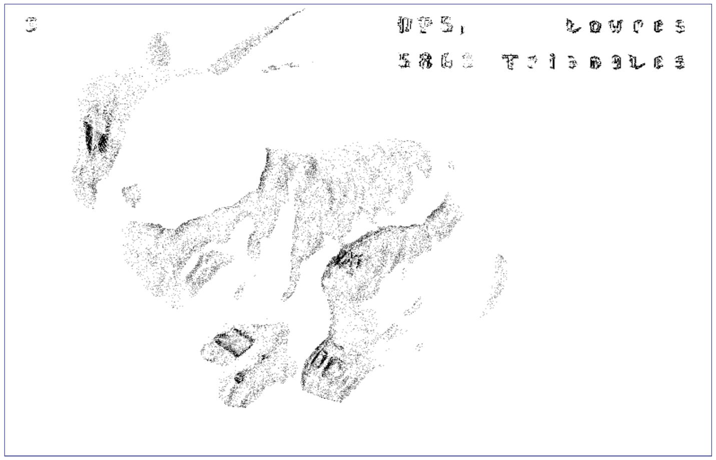


Results of Multiple-Precision 3D GPU (3/3)

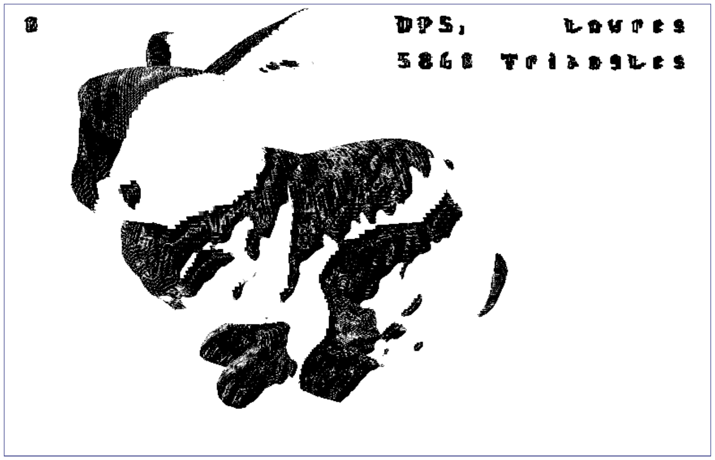
Mode 3

Mode 2

Mode 1

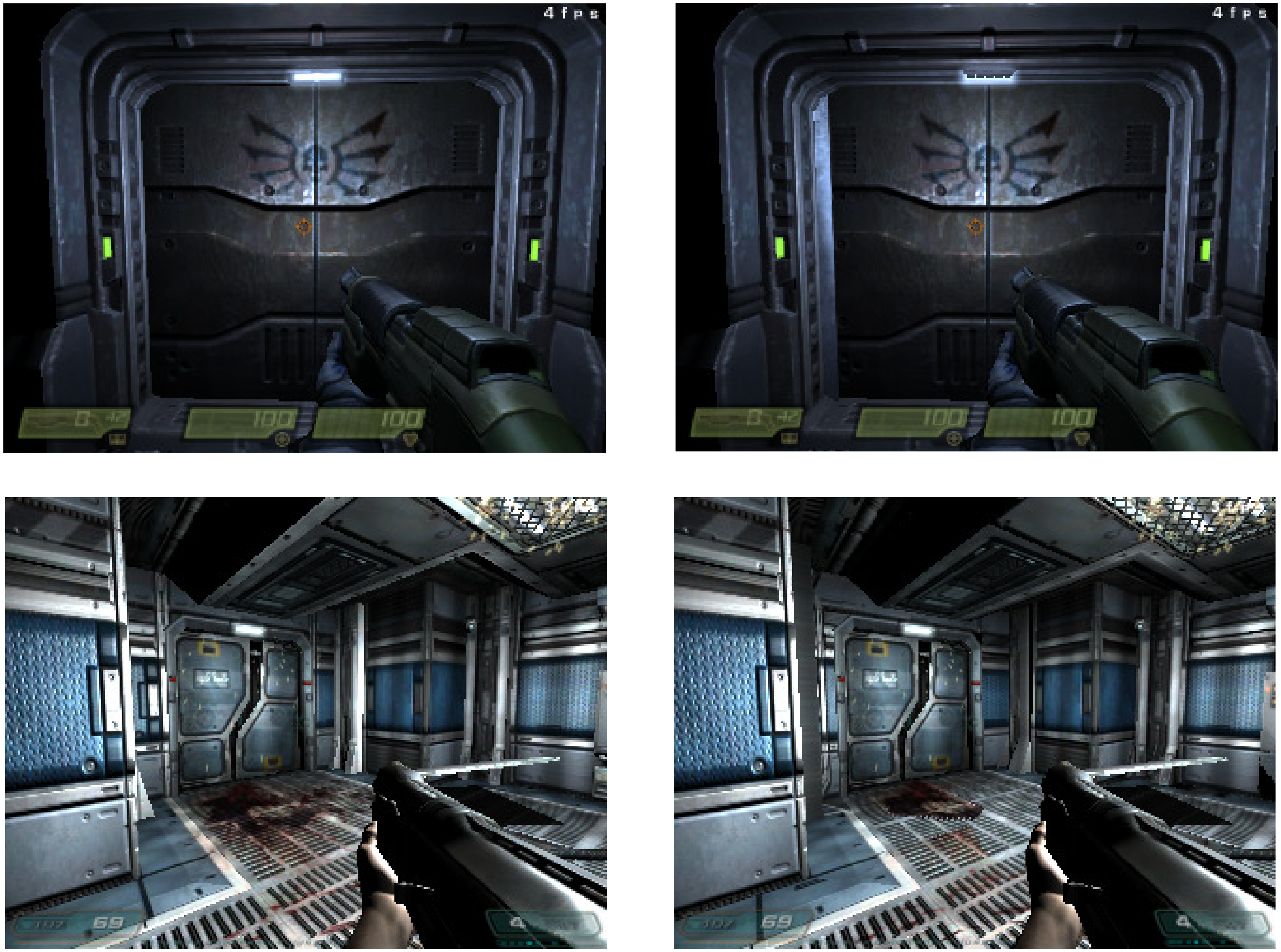


Mode 0



Rendering Results of Doom3 Benchmark

Rendering Results of Quake4 Benchmark



Conclusion

- Power consumption has become one of the most critical factors in the continued development of the microelectronics
- Minimizing power consumption calls for conscious effort at each abstraction level and at each phase of the design process