Ultra-Low Power Microcontrollers for Portable, Wearable, and Implantable Medical Electronics

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MCU Development

Texas Instruments, Inc.

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Outline

- Introduction
- MCUs in Today's Medical Applications
- System Architectures for the Next Generation
- Ultra-Low Voltage Operation
- Medical Embedded Processor System-on-Chip
- Summary and Conclusions

Semiconductors impact

Computing revolution

Communications revolution

Healthcare revolution

Computing transformed

1990s

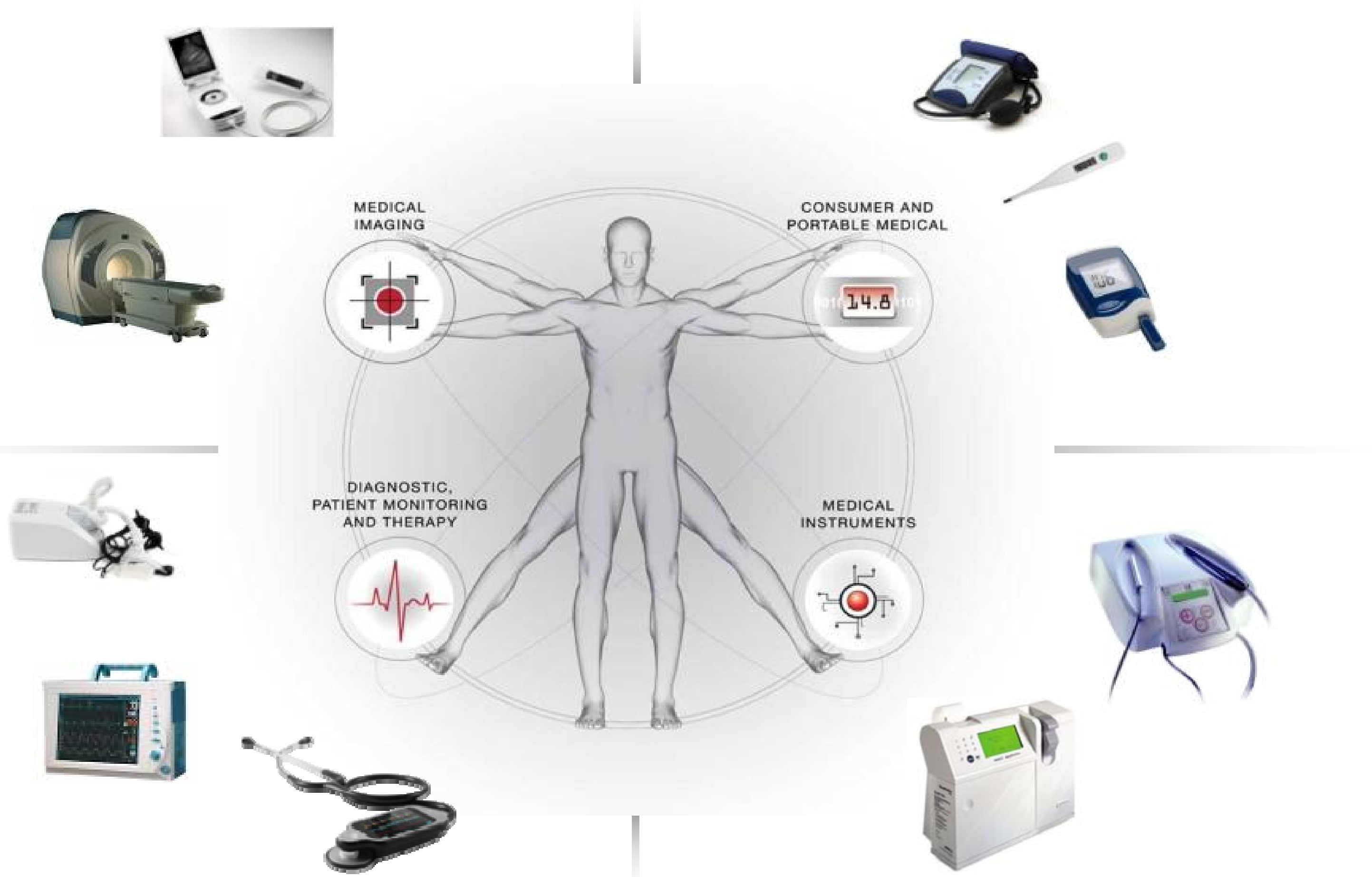
Communications transformed

2000s

Healthcare transformed

2010s

Applications of Medical Electronics



- Personal healthcare
  - 38% of medical semiconductor revenue in 2007 went into consumer medical devices

Factors Driving Consumer Medical Electronics

- Growing cost of Healthcare:
  - US Healthcare spending to grow from $2.4 trillion in 2008 to $3.1 trillion in 2012
  - US Healthcare spending is 16% of GDP
  - China healthcare expenditure increased 277% from 2006 to 2007
- Growth of Aging Populations:
  - US: 37.9M seniors in 2007
  - UK: By 2013 there will be more people over 65 yrs than people under age 16 yrs
  - By 2020, >1 billion people will be 60+ years
- Diet and Lifestyles:
  - Obesity and stress
  - Preventative Health and Wellness Management

Personal Health Devices

- Ultra-low power consumption is the key
- Battery life determines both form factor and ownership cost
- Reducing size and cost leads to more widespread use
- Microcontrollers (MCUs) provide the right combination of programmability, cost, performance, and power consumption

Portable
Blood glucose meter

Wearable
Heart rate monitor

Implantable
Retinal implant

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Today’s Microcontrollers

- Suited for portable and wearable applications
- Families of 16-bit and 32-bit MCUs are available to match memory and performance needs of various medical applications
- Excellent power consumption
  - Active power: 100-200 μA/MHz
  - Standby power: < 1 μA

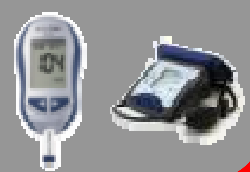
MSP430™
Ultra-low Power

Up to 25 MHz

Flash 1 KB to 256 KB

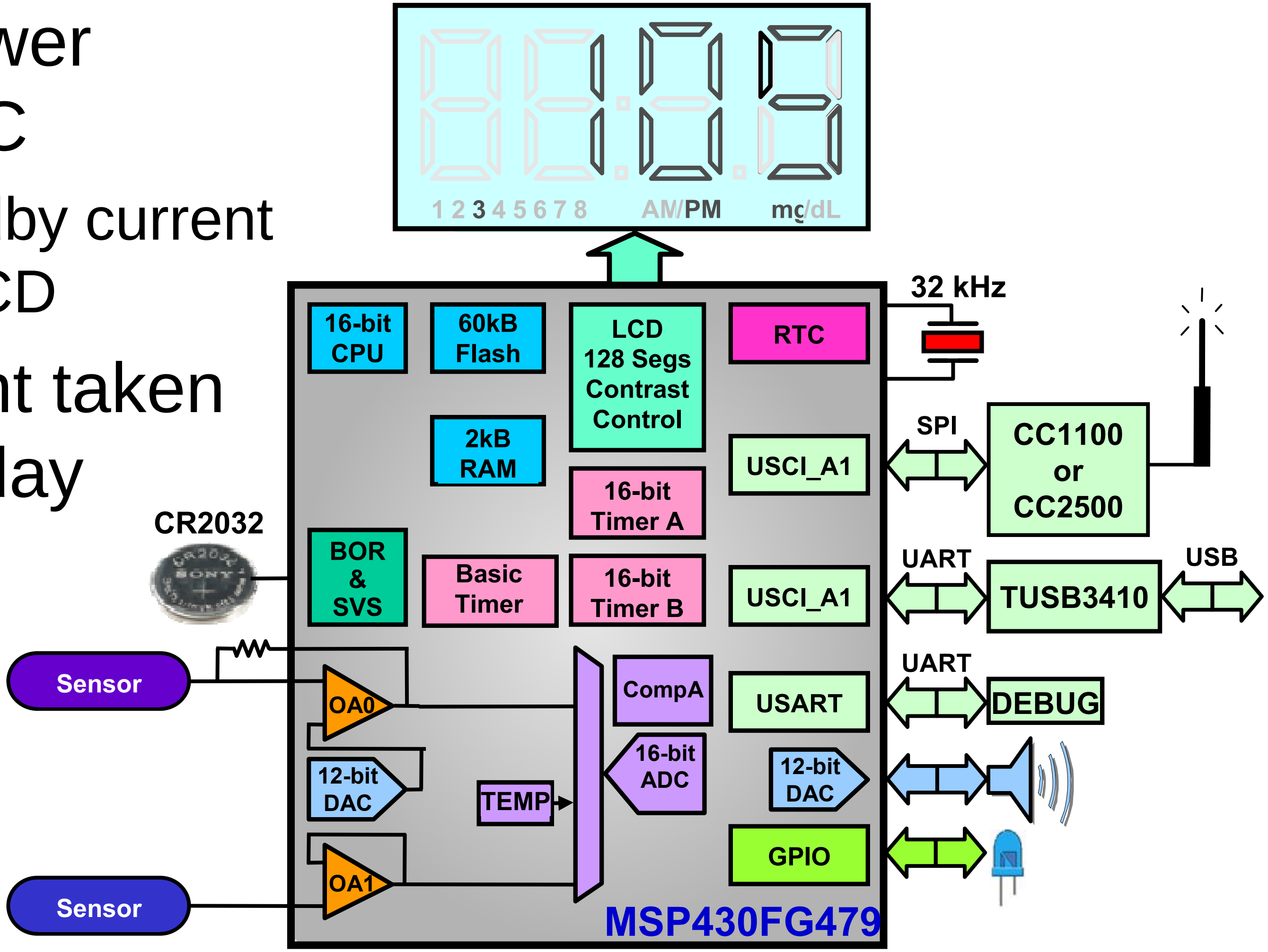
Analog I/O, ADC LCD, USB, RF

Measurement, Sensing, General Purpose



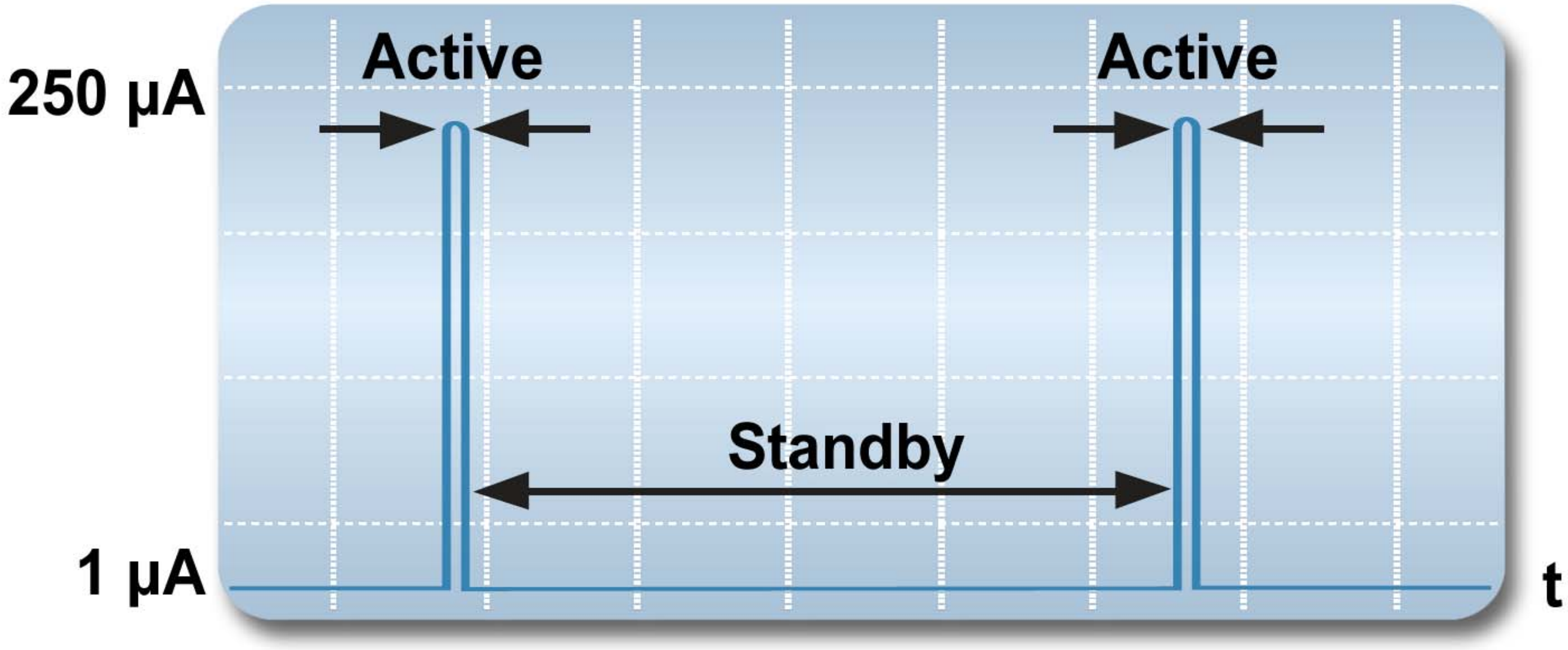
Portable Blood Glucose Meter

- Ultra-low power MSP430 SoC
  - ~2 uA standby current including LCD
- Measurement taken 4-6 times a day



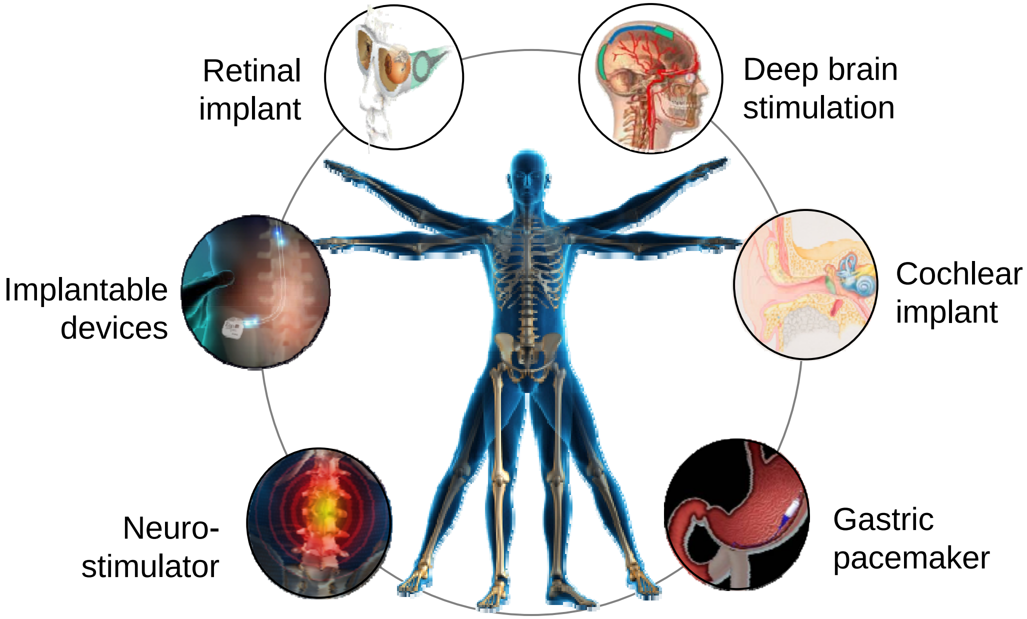
10-year life with 220 mAh coin-cell battery

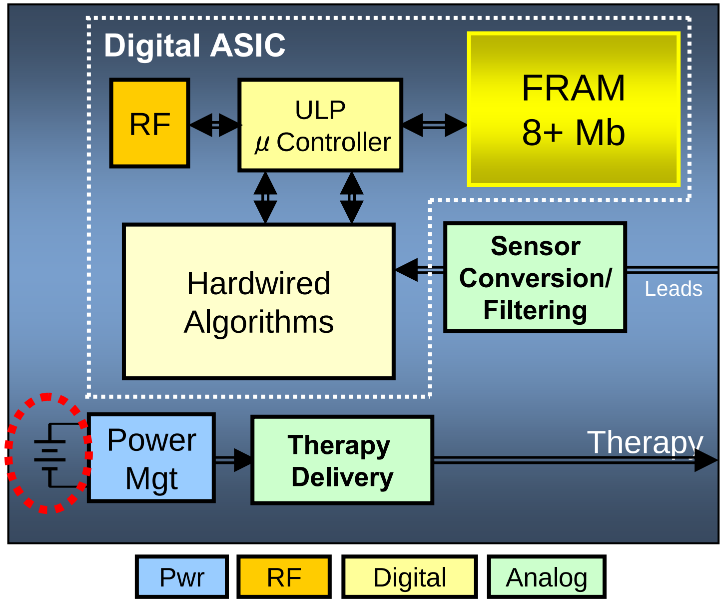
Activity Profile in Portable Devices



- Extended ultra-low power standby mode
- Minimum active duty cycle
- Interrupt driven performance with quick wake-up

Implantable Medical Devices





- Different activity profile compared to portable
  - MCU is active at all times
- Can we achieve 10-year life with 1Ah battery?
  - 10uA average power budget for entire system
  - ~2uA average active power budget for digital
- Yes, but requires innovation at all levels of SoC design

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Signal Processing in Medical Applications

- Many medical algorithms routinely employ signal processing operations
  - Finite impulse response (FIR) filtering to remove spurious frequencies from biomedical sensor data
  - Fast Fourier transform (FFT) is employed in epilepsy detection to identify data signatures in specific frequency bins.
- Two options to implement signal processing
  - Software running on MCU core
  - Dedicated hardware

System Architecture Considerations

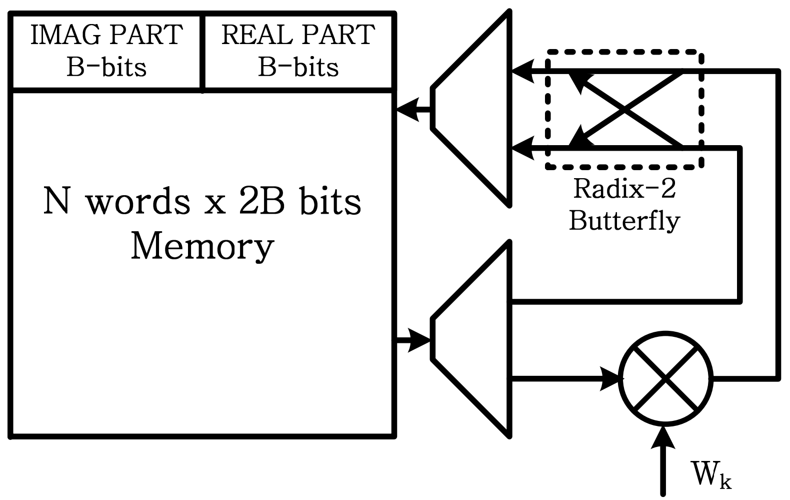
- System architecture needs to incorporate a judicious combination of programmable and hard-wired processing elements
  - Ensures the ability to map different algorithms
  - Depending on the targeted applications, a single hardware accelerator or a suite of accelerators is appropriate.
  - Dedicated hardware can lower power consumption by orders of magnitude

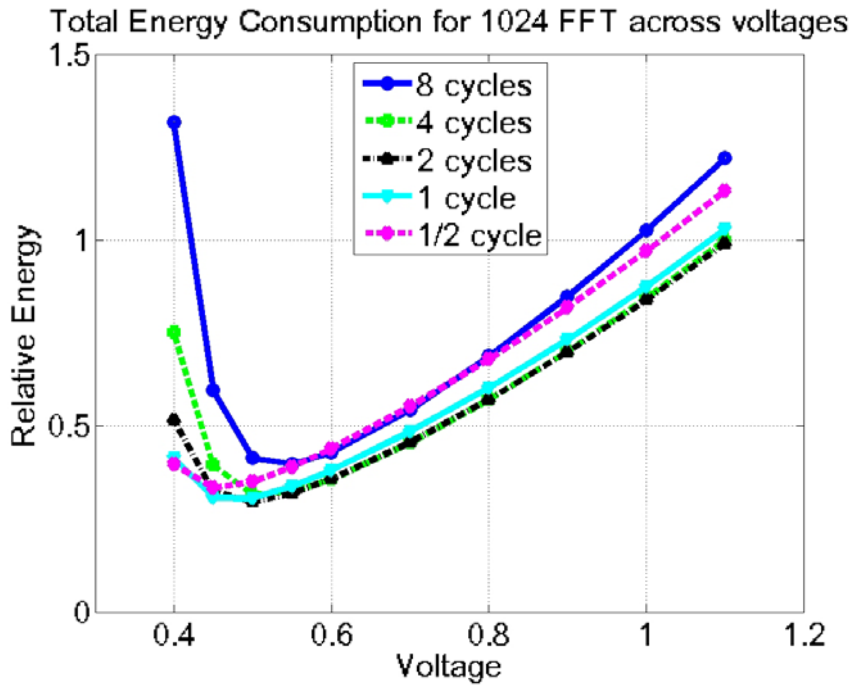
Energy (measured at 1V)			
Operation	MSP430 Software (nJ)	Dedicated Hardware (nJ)	Reduction
32-tap FIR	176.1	1.2	144.4x
512-pt FFT	82147.9	616.1	133.3x
sin(x)	279.4	1.3	215.2x
65-pt Median	114.0	0.8	144.9x

Reference: J. Kwong, ESSCIRC, 2010

Microarchitecture Considerations

- Example: FFT Processor
- How many cycles should one radix-2 FFT butterfly and twiddle factor multiplier take?
  - Proportional increase in memory bandwidth is needed to match the datapath throughput.
- 4-cycle radix-2 butterfly provides the best energy and performance trade-off
  - It requires a single memory access per cycle
  - It is within ~ 3% of 1 cycle butterfly and better than ½ cycle butterfly in terms of energy requirement





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What's Different about Medical Implantable Applications?

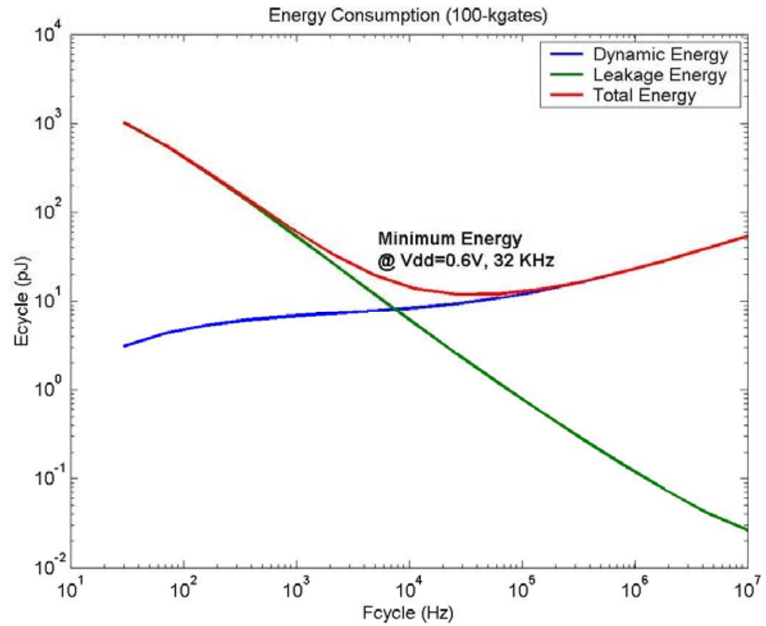
	Networking	Consumer	Implantable	units
Node	65nm	40nm	**130nm**	
Gates	41,000	15,000	300	K
Memory	32	9	8	Mb
Area	251	40	24	mm^2
Freq	900	400	**1**	MHz
Dynamic Power	65	2.6	.000002 (2uW)	W
Leakage	10	0.4	0.0000002 (200nW)	W
Temp	125	85	37	C

or 40, if you have a fever

- 1 MHz processing frequency is sufficient for many applications as biomedical signals tend to have useful information at frequencies less than 1 kHz

Ultra-Low Voltage operation

- ULV: sub-V_t to $2V_t$
- Low-performance applications enable ULV operation
  - System and micro architecture innovations further reduce the peak clock frequency
- Leakage energy increases with reduction in voltage and frequency



- Total energy reaches a minima after which increase in leakage energy is higher than decrease in dynamic energy
- Operate at or above the optimum supply voltage

Key Challenges in ULV Operation

- SRAM reliability
  - Random bit failures due to process variation
- Power delivery
  - Efficient power delivery is necessary to ensure full benefit of voltage scaling
- Leakage minimization
  - Minimum achievable energy depends on leakage
- Timing closure
  - Hold violations occur due to increased skew

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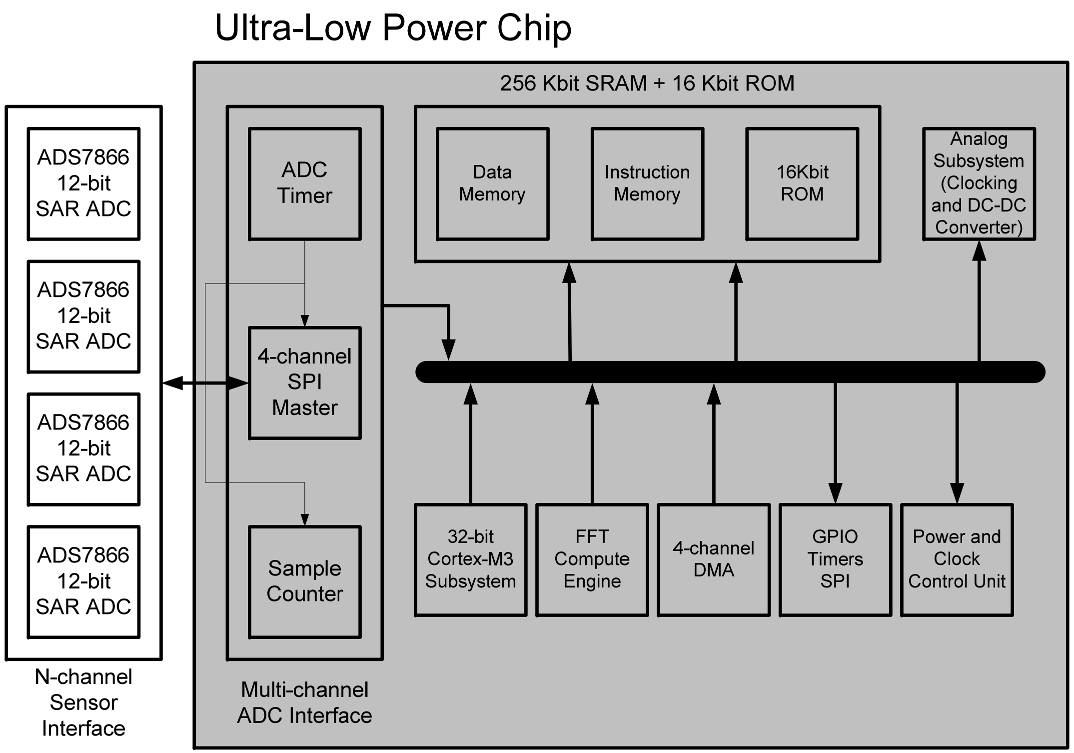
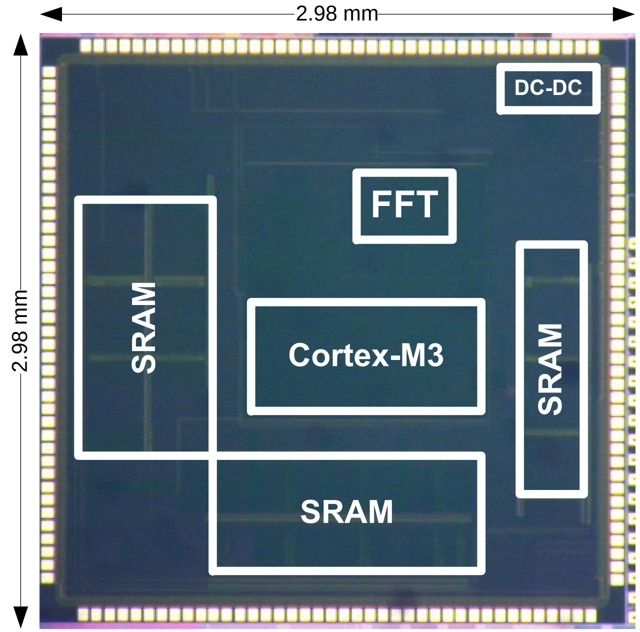
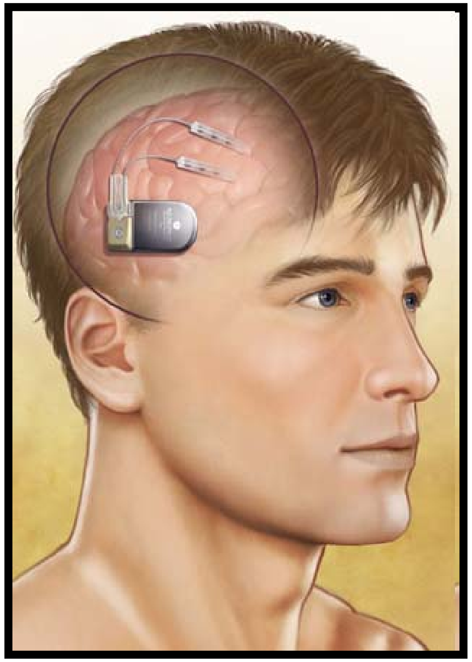
Embedded Processor Platform

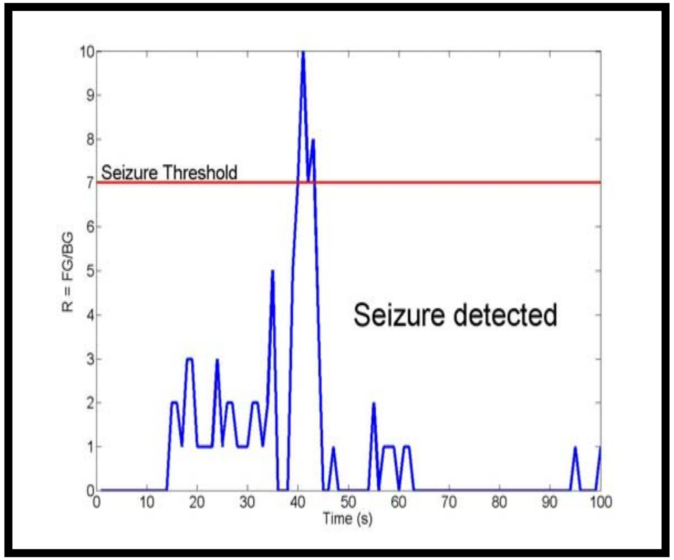


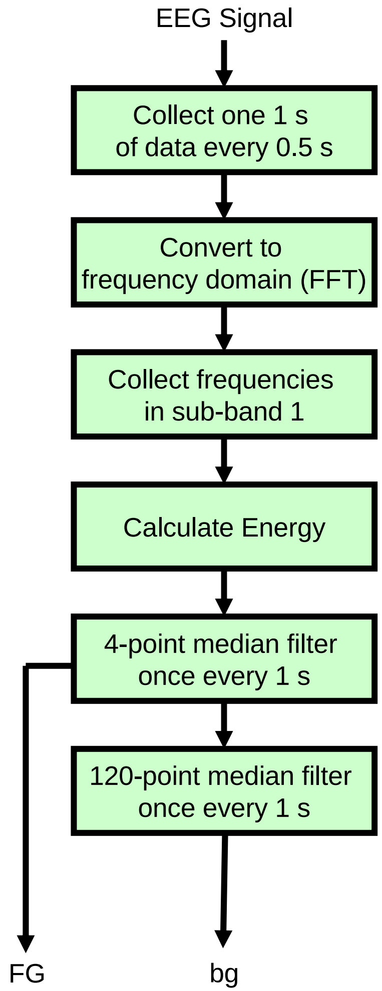


- Key components
  - ARM Cortex-M3 32-bit MCU
  - Fast Fourier transform (FFT) accelerator
  - SRAM
  - DC-DC Converter

Epileptic Seizure Detection







1 μW per Channel

BG = α bg[n] + (1-α) bg[n-1]

R = FG/BG

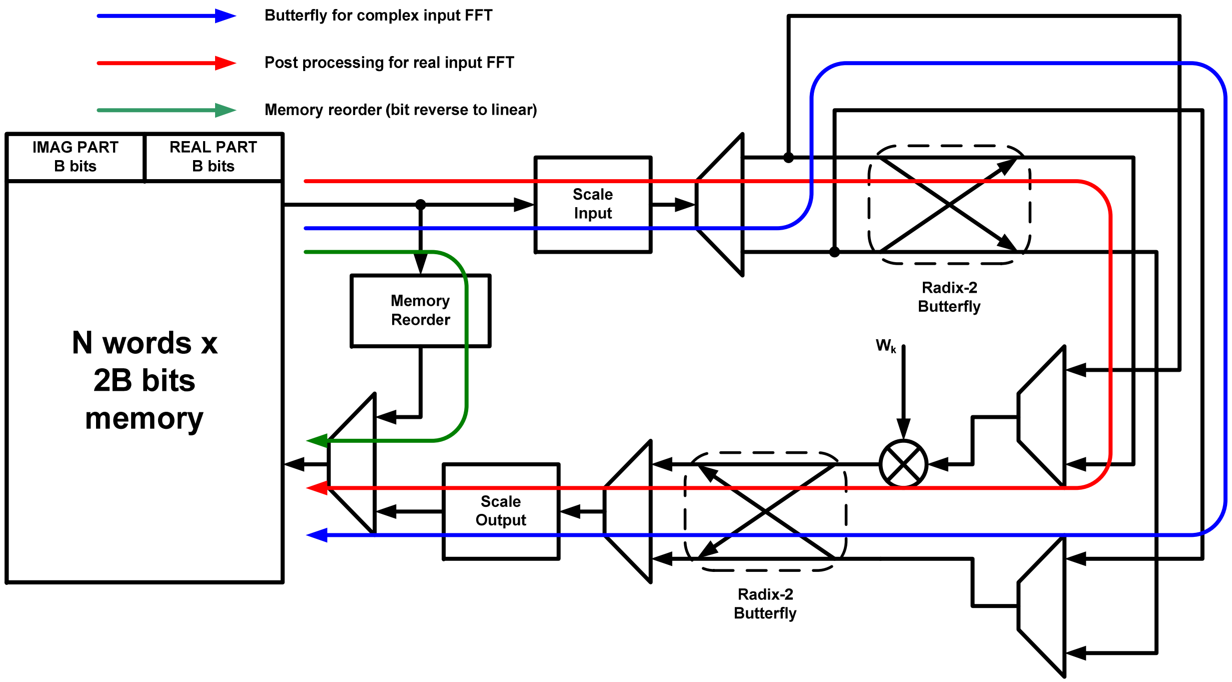
Seizure Detection: R > THRESHOLD

Ref: S. Ravindran, et al., ISABEL, 2009

How Did We Achieve 1 μW?

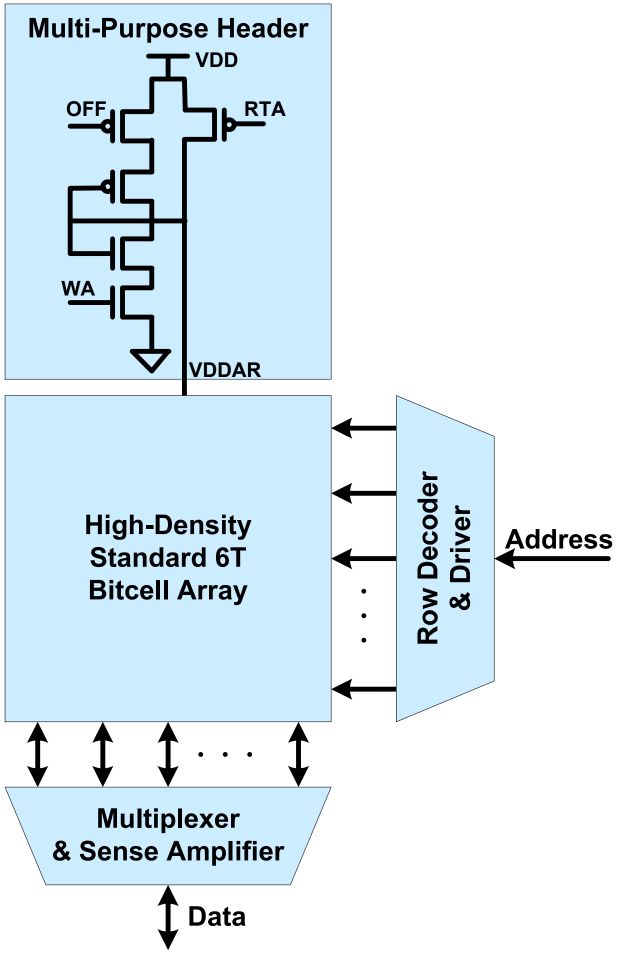
- System Architecture
  - 32-bit CortexM3 based platform
  - 100-nW FFT accelerator
  - Enables ULV operation
- Reliable 0.5-V SRAM
  - By using circuit assist techniques
- 90%-efficient power delivery
  - Self-tuning DC-DC Converter
- Leakage minimization and timing closure
  - By using an ultra-low voltage digital implementation flow

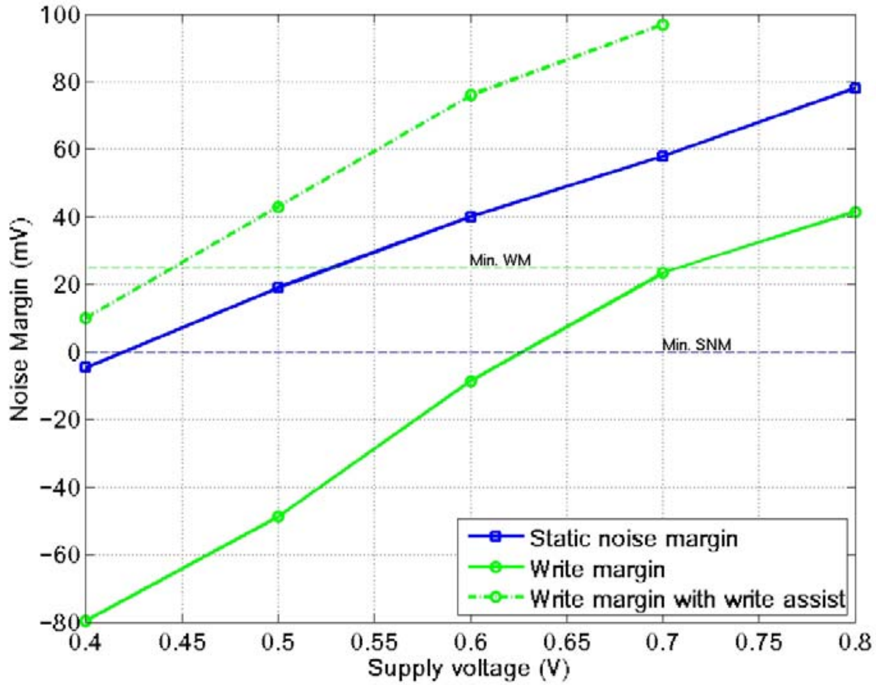
Energy-Optimal FFT Architecture



- Block floating point architecture for optimizing data bit widths
- 16-bit data achieve 65 dB SQNR
- 2x reduction in power for real-input FFT
- Energy consumption of 100 nJ for 256-point real FFT

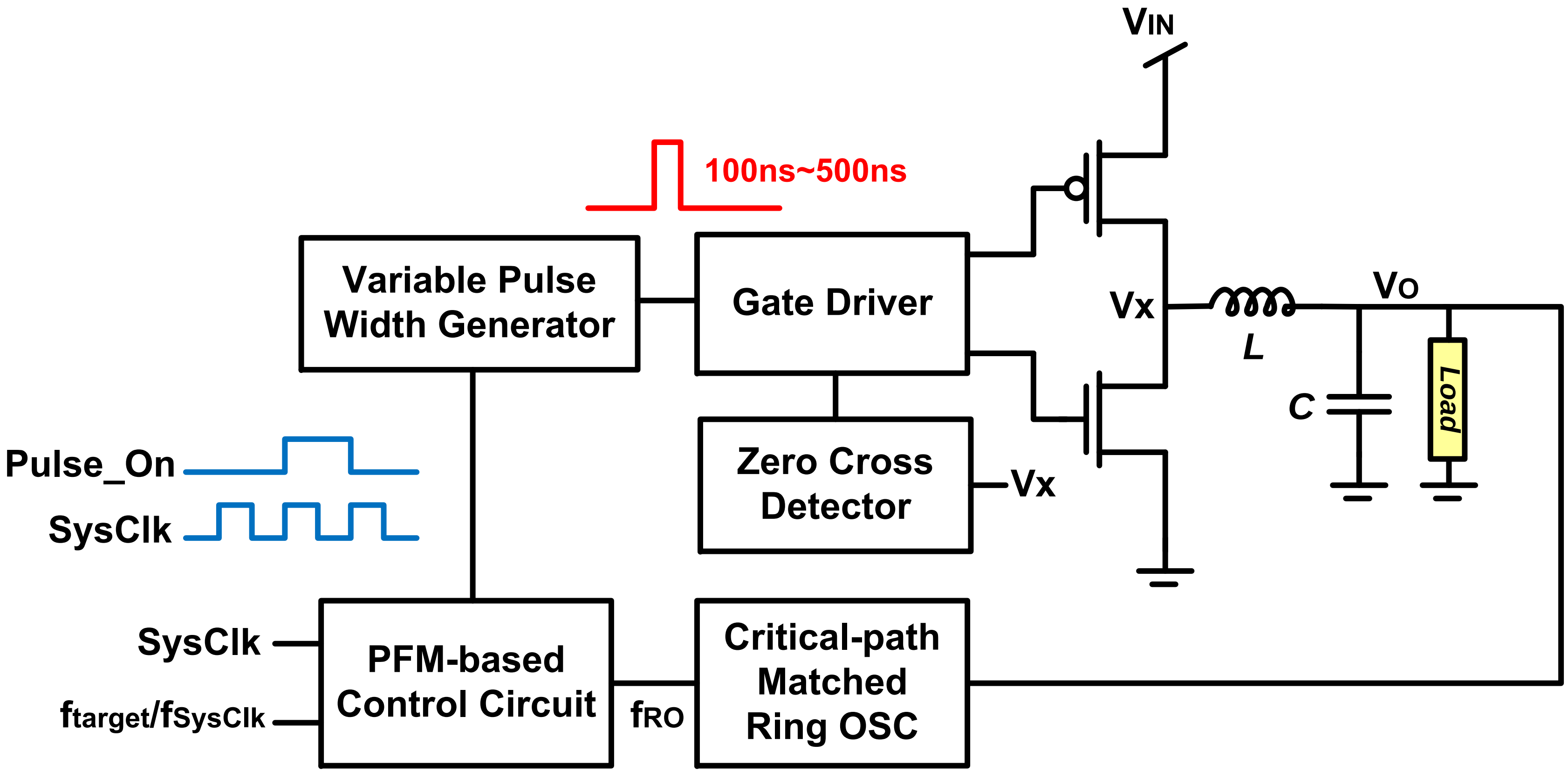
SRAM with Multi-Purpose Header Switch





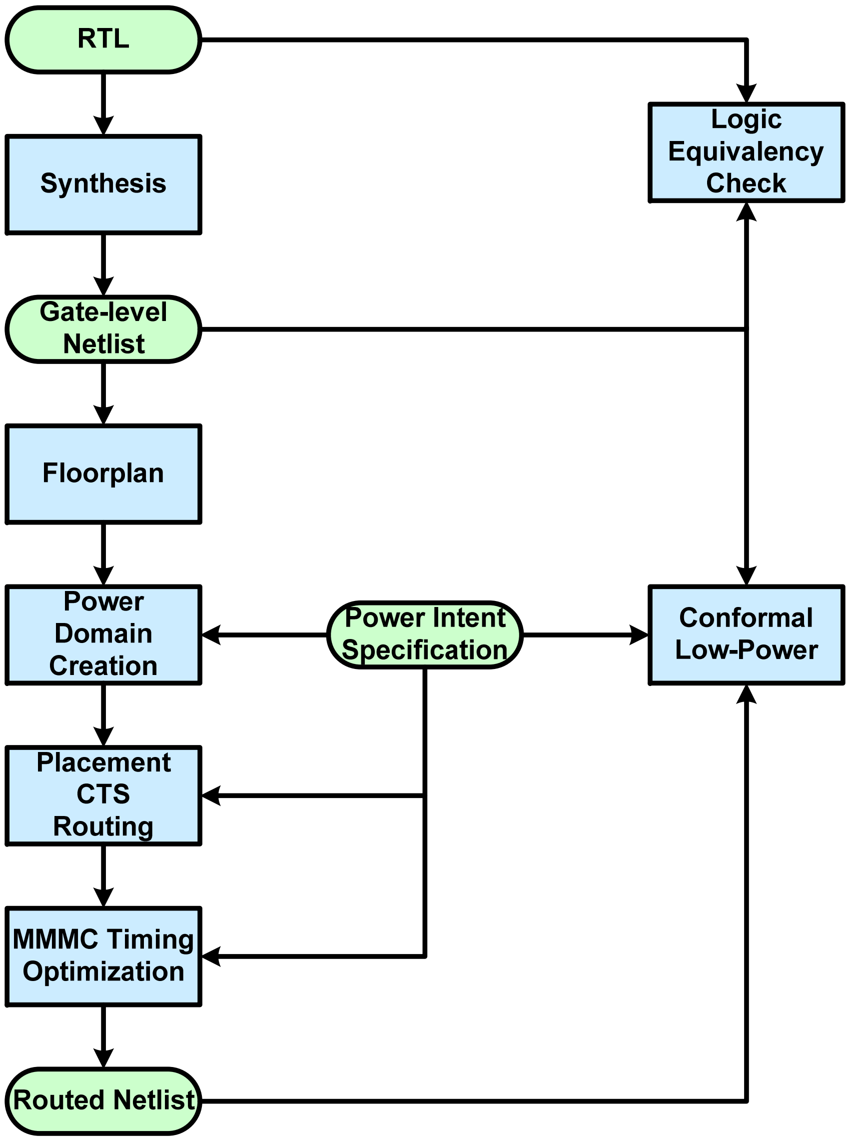
- Power gating, retention-till-access, and write assist features are achieved using header switch.
- 5 nW/kHz active power and 28 fW/bit leakage power

Self-Tuning DC-DC Converter



- Track the PVT variation by ring oscillator
- Regulate voltage by comparing f_{target}/f_{SysClk} and f_{RO}/f_{SysClk}
- Low-power analog and digital control circuit

Ultra-Low Voltage Digital Implementation



- Extensive use of power intent specification
- Power domains for leakage reduction when FFT is not used
- Near minimum-width standard cells in the data path to reduce gate capacitance and leakage

Design Automation Challenges

- Efficient but accurate timing closure at ultra-low voltages. Improvements needed in:
  - Statistical static timing analysis
  - Current source based delay modeling
  - Hold violation fixing
- Clock tree synthesis for ULV designs
- Automation of minimum energy optimization
  - Trade-off between dynamic and leakage energy for total energy minimization while meeting constraints on frequency and area.

Summary and Conclusions

- Microcontrollers play a key role in enabling portable, wearable, and implantable medical electronics. MCUs are a major force behind putting healthcare literally into patients' hands.
- The ultra-low power consumption of MCUs extends the battery life of these personal health devices.
- Further reduction in power consumption in embedded MCU SoCs is possible via novel system architectures and low-voltage operation.
- Such ultra-low power operation is a must in enabling advanced signal processing algorithms for the next generation battery-powered medical devices.
- The innovative medical platform MCU demonstrates the first sub-microwatt EEG seizure detection.