

# Embedded Systems: Concepts and Practices Part 1

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# Outline (Part 1)

- Definitions and Examples
- Hardware Engineering Challenges
- Embedded Processor Examples
  - TI MSP430F2001
  - TI OMAP DM3730
  - Atmel ATtiny4
  - Xilinx FPGAs/MicroBlaze/Zynq-7000
  - Microsemi IGLOO FPGA
- Closing Comments
- Preview of Part 2 (April 22nd)

# Embedded System

## Historical Definition

- A dedicated computer performing a specific function as a part of a larger system
- Saw commercial use beginning in the 1970s as an alternative to hard-wired control and logic circuitry (engine controls, guidance systems, industrial process controllers)
- Essential Goal: Turn hardware problems into software problems.

# Embedded System

## Modern Definition

- High-reliability systems operating in a resource-constrained environment (typically cost, space & power)
- Excludes general-purpose computers, and non-computerized devices (now rare!)
- Smartphones are computers, but technical challenges are the same (ES may not be a very meaningful term any more, since it applies to so much of the ECE/CS universe!)

# Are ES Software or Hardware?

“Yes”

- No externally-visible difference between hardware and software functions
- Well-defined, fundamental, and extremely performance-sensitive functions are generally implemented in hardware.
- Complex, non-performance-sensitive, and/or subject-to-change functions are generally implemented in software.

# Embedded Systems

## Examples

### Consumer

- Cellular Handsets
- Game Consoles
- Media Players
- TV Set-Top Boxes
- Kitchen Appliances

### Vehicular

- Engine Control
- Driveline Control
- Anti-Lock Braking
- GPS Receivers
- Tire monitoring
- "Infotainment"

### Infrastructure

- Utility meters
- Traffic signal control
- Structure monitoring
- Surveillance
- HVAC control
- Parking meters
- Battery Management
- Generator controls
- Pipeline Safety



### Medical

- Pacemakers
- Measurement
- Drug Delivery

### Industry

- PLCs
- Motor Control
- Process Control

### Defense

- Vision Enhancers
- Communications
- UAV Systems

### Computing

(computers within computers!)

# Ford EEC

## "Old School"

- EEC-I (1978, about same time as Apple II)  
Proprietary 12-bit processor @ 3 MHz  
"PM-11" after the DEC PDP-11  
4K bytes of ROM, 256 bytes of RAM  
Ignition timing, EGR valve & smog pump

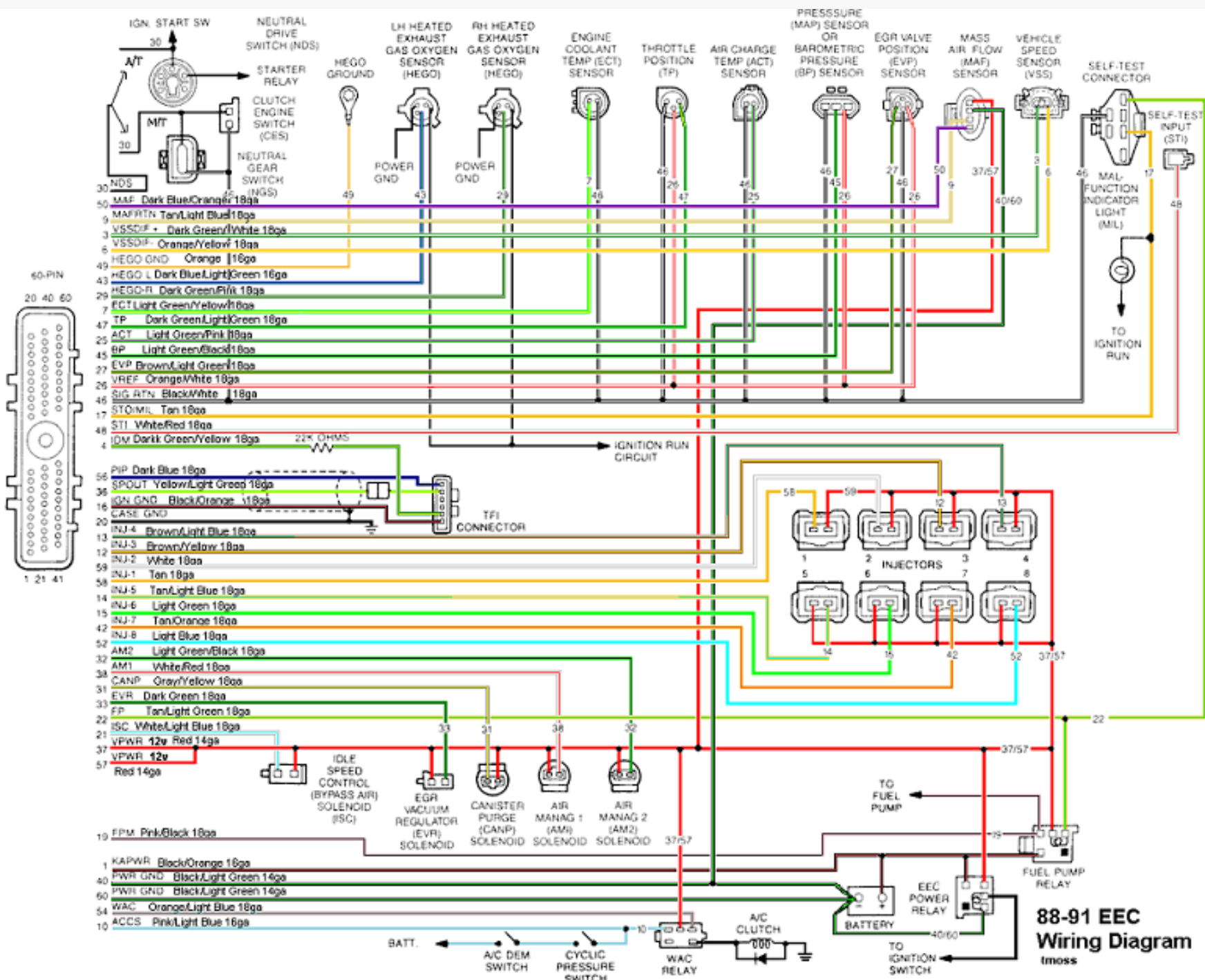


- EEC-IV (1983 through 1990s)  
Intel 8061 8/16 bit processor @ 15 MHz  
8K bytes of ROM, 256 bytes of RAM  
Controlled 8 vehicle functions

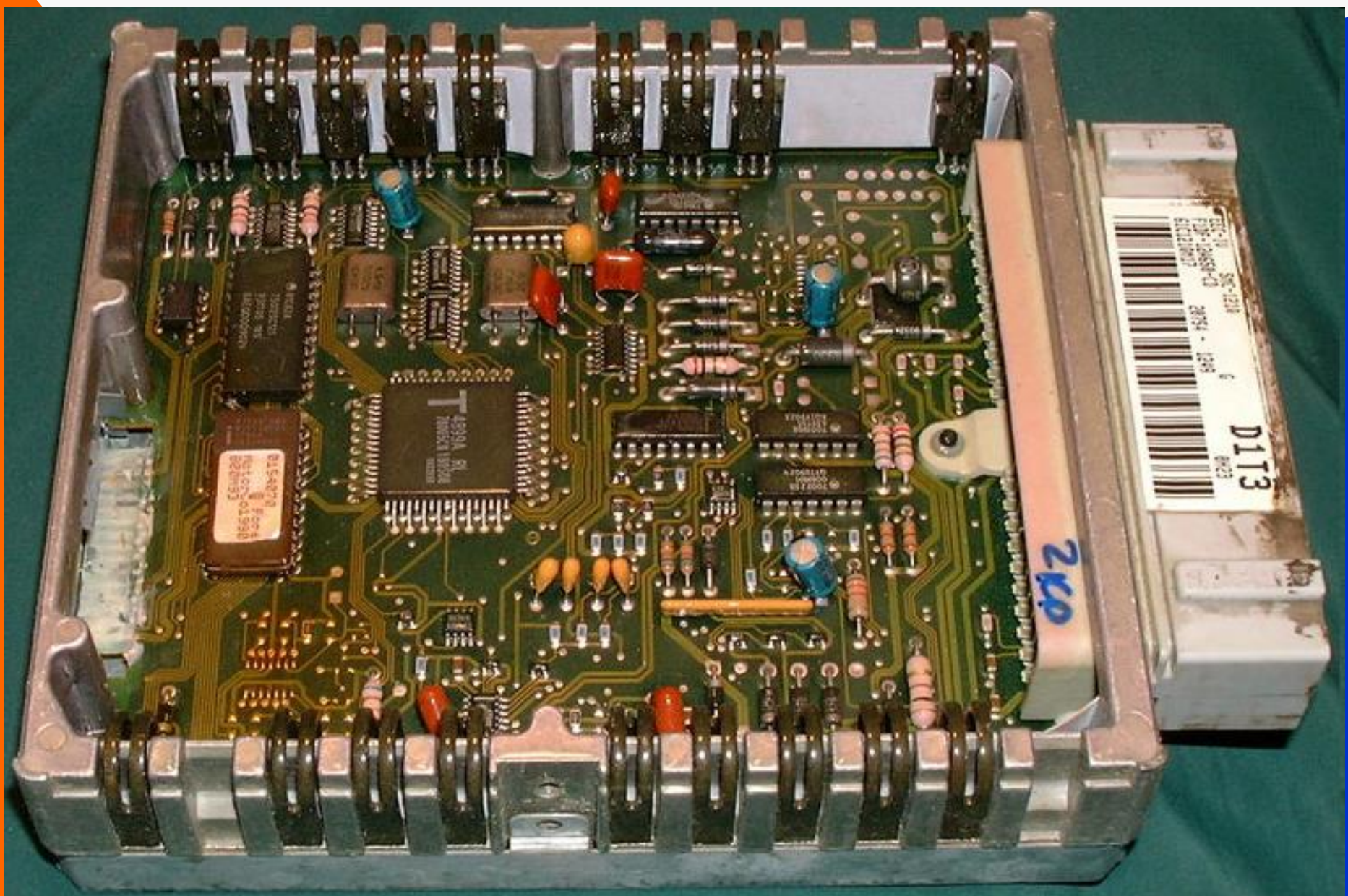
# Old School (Ford Motor Co. EEC)







**88-91 EEC  
Wiring Diagram**  
tmoss



75111 56-1218  
F30-2088-03 2034 - 1218  
00210017  
D1T3  
8023

210

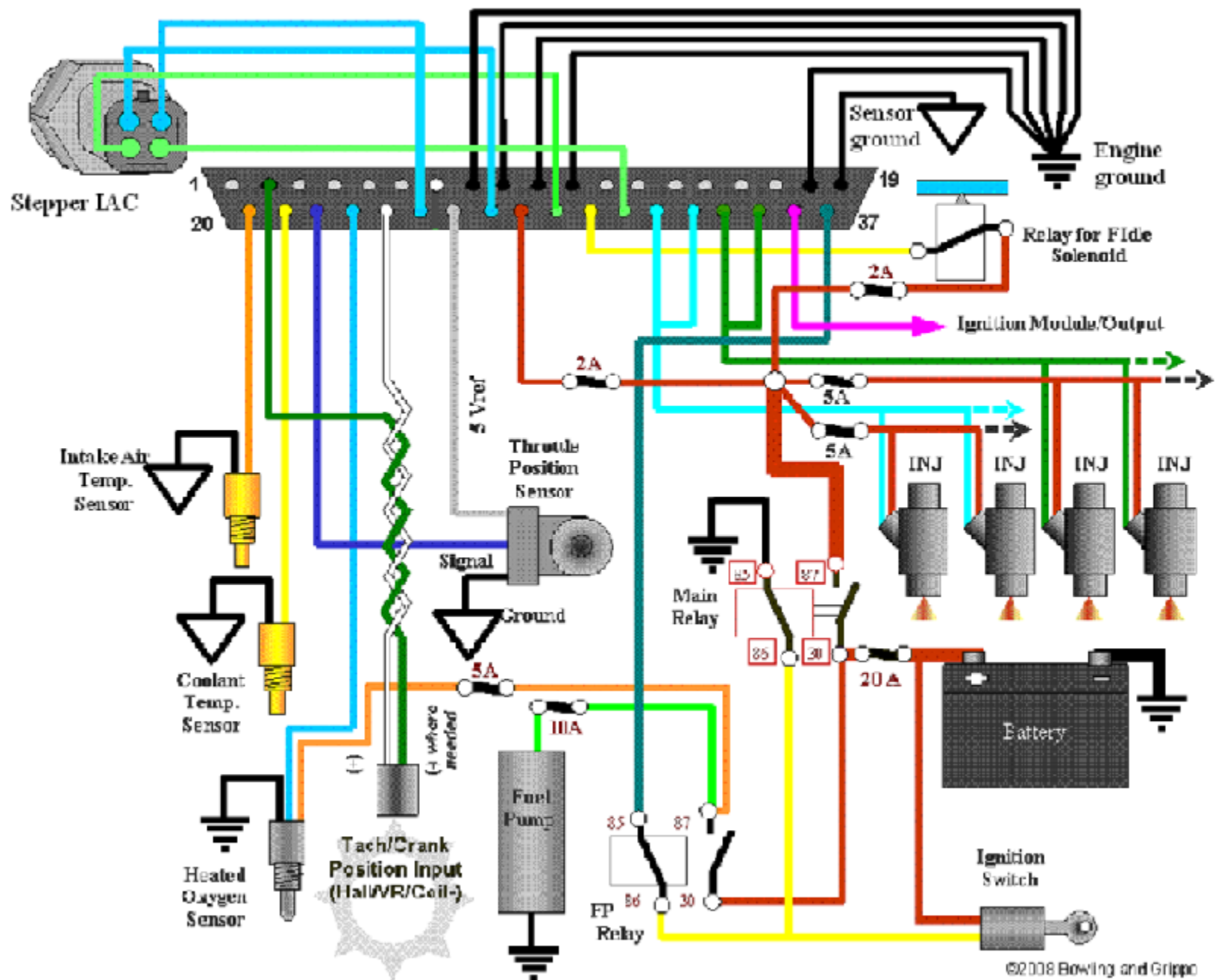


# “Megasquirt”

Open Source Fuel Injection Controller



# MegaSquirt V3.0 Main Board External Wiring Diagram



# Automotive Trends

ECUs/vehicle, 2018

- Economy: 20+
- Volume Luxury: 50+
- Ultra Luxury: 100+

Communication via CANBus, Ethernet, wireless and other networks

After engine and transmission, the 3<sup>rd</sup> heaviest component in a modern automobile is the wiring harness

# Lines of Code

## Two F-Series Vehicles

- "Turn hardware problems into software problems" ...a *lot* of software problems.
- Lockheed Martin F-35 Lightning II: 30 million LOC
- Ford F-150, as per a claim made at the 2016 CES:



# Complexity

## Two F-Series Vehicles

- "Turn hardware problems into software problems" ...a *lot* of software problems.
- Lockheed Martin F-35 Lightning II: 30 million LOC
- Ford F-150, as per a claim made at the 2016 CES: 150 million LOC



# DJI NAZA N3

## UAV Flight Controller

- 32-bit DSP, GPS, compass, gyro, power management, external LED driver, etc.
- Up to 8 rotors; street price \$300





# Engineering Challenges

## Constraints typical in many ES designs

- **Form Factor**  
(size, shape, weight)
- **Environment**  
(shock, vibration, temperature, moisture, radiation, RF)
- **Power**  
(battery life, heat dissipation, surges)

## Reliability, Security, Safety

Failures may cause injuries or property damage

Mission critical but often inaccessible

- **Cost**  
\$ (or ¢!)

# Hardware Challenges

## Form Factor

- **Space Limitations**

- Enclosure design often drives hardware design
  - Highly-integrated chips minimize parts count  
(if you can turn off what you don't need!)

- **Close collaboration with Mechanical Engineers is critical to project success**

- **3D Printing/Rapid Prototyping gets better every day, and can avoid costly mistakes later in production**

# Hardware Challenges

## Form Factor

- Exotic PCB materials and techniques may be required
  - Flexible circuits
  - Very fine feature sizes
  - Via-in-pad, laser-drilled microvias
- Tiny SMT devices, BGAs, etc. save space, but watch ratings, manufacturability and rework issues

(01005 is really small, and it's tough to solder that kludge wire dead-center under a BGA package...)

# Hardware Challenges

## Environment

- Exotic PCB materials and techniques again  
High-temperature/pressure substrates  
(there's a reason FR-4 is cheap)  
Conformal coating  
(moisture, Pb-free Sn whiskers)
- "Shake and Bake"  
Shock Mounting  
Ingress Prevention (IP-xx standards)

# Hardware Challenges

## Environment

### Electromagnetic Compatibility (EMC)

#### Emission:

Your device makes other devices not work

#### Susceptibility:

Other devices make your device not work

- Both are bad
- Requires careful attention to electronic and mechanical design to ensure compliance

# Hardware Challenges

## Power

- Minimize power consumption for...
  - Battery life (per-charge and lifetime)
  - Heat Dissipation
  - Operating Cost
- Designing for Power Management
  - (Not just a 5V rail and ground!)
  - Many switchable power domains
  - Integrated current and voltage monitoring
  - Voltage and clock speed scaling

# Hardware Challenges

## Power

- Not just "off" and "on"  
Low-power sleep modes  
Wake-up receivers, Bluetooth Low Energy, etc.  
Challenge: naming all the power modes!
- Beware of battery-draining "sneak paths"  
"Disabled" or "shut down" doesn't mean "off"  
Check those data sheets!
- External power has its own problems; design for and test extreme cases (surges, undervoltage, cranking).

# Hardware Challenges

## Reliability/Security/ Safety

- For critical applications, redundant systems with a "computer third party" to disable failing units
- Power-On Self Test (POST) capabilities, self-diagnostics, system health reporting
- Predict how systems may fail (risk assessment, fault tree analysis, etc.)
- Minimize effects ("fail in the right direction")



# Hardware Challenges

## Reliability/Security/ Safety

- Recover from software failures  
"watchdog" timers to restart after a crash
- Authentication and/or encryption to prevent or detect tampering with soft components
- Wireless or Internet-connected systems require added attention to security issues
- Audit and manage supply/manufacturing chain to ensure authenticity and quality of components

# Hardware Challenges

## Cost

"To define it rudely but not inaptly, engineering is the art of doing that well with one dollar, which any bungler can do with two after a fashion."

--Arthur Mellen Wellington, c. 1887

# Hardware Architecture

## Embedded Processors

- Architecture Options for Every Design
  - 8-, 16-, 32-, 64-bit
  - Optional floating-point, memory management
- High Integration
  - Dedicated on-chip peripherals and coprocessors
  - Minimizing chip count speeds design, saves power
- Complex, powerful power management
  - Separate core, I/O, peripheral power
  - Multiple low-power sleep/standby modes
  - Companion PMICs for higher-end devices

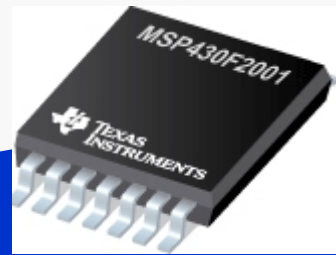
# Hardware Architecture

## Embedded Processors

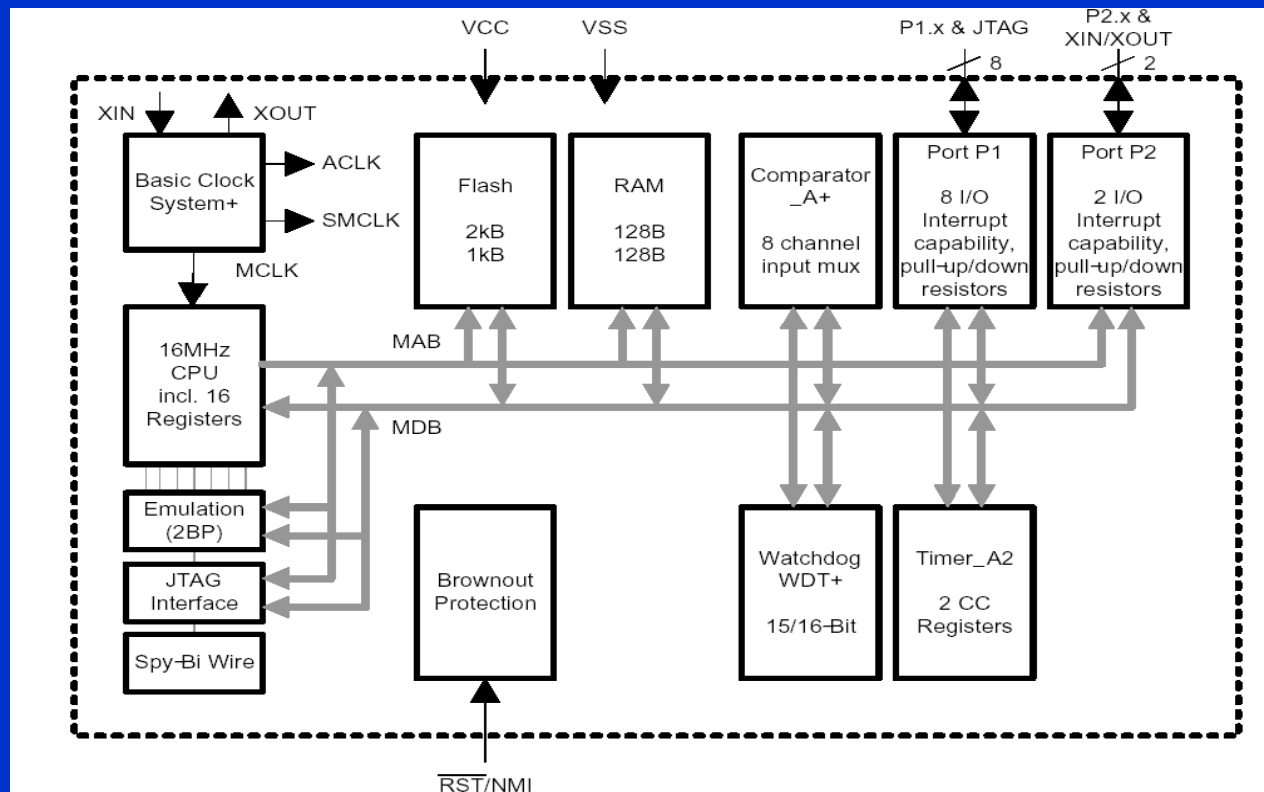
- **Sophisticated Timing**
  - Accurate timing for realtime performance
  - Fast wake-up time
  - Very low power timers
  - Watchdog timers to recover after failures
- **Pin Multiplexing**
  - Driving pins takes a lot of a chip's power budget
  - Multiplex out test signals, unused chip functions

# TI MSP430F2001

## Block Diagram

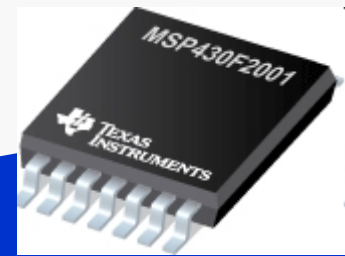


16-bit embedded CPU with Flash,  
Comparator, 10 I/O Lines, Serial Port  
Low Performance, Low Price (\$0.50)



# TI MSP430F2001

## Form Factor

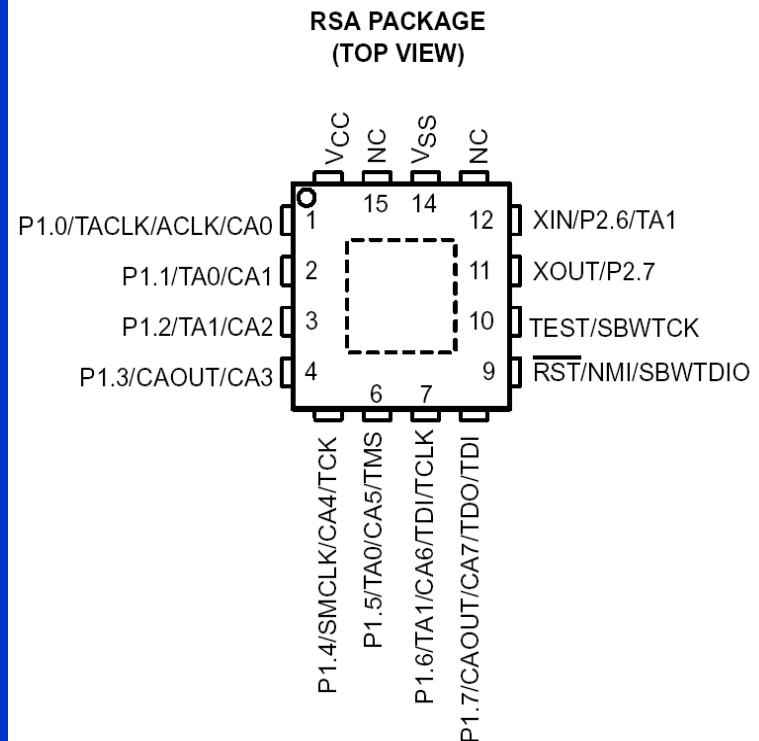
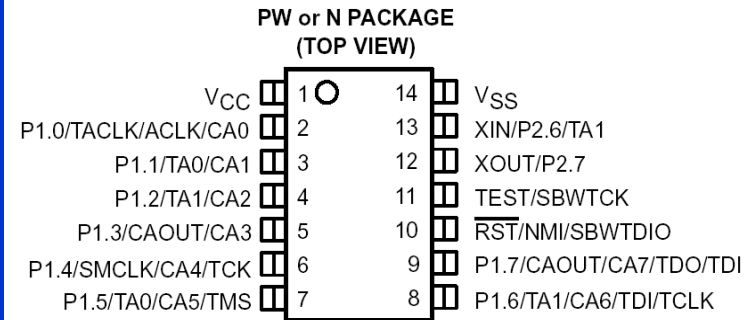


14-pin TSSOP or 16-pin  
PQFP, 0.25 cm<sup>2</sup>

Software configurable  
pinout (up to 5 choices  
for some pins)

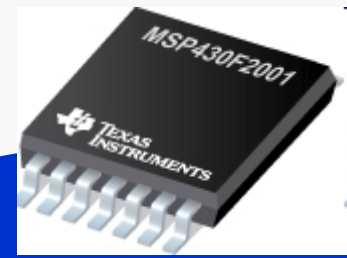
JTAG support for in-  
circuit testability

(Dozens of other designs  
available)



# TI MSP430F2001

## Power Management



### 6 Power Modes

Externally triggered  
wake-up in  $< 1\mu\text{s}$

220 $\mu\text{A}$  active;  
0.1-0.5 $\mu\text{A}$  standby

The following six operating modes can be configured by software:

- Active mode AM;
  - All clocks are active
- Low-power mode 0 (LPM0);
  - CPU is disabled  
ACLK and SMCLK remain active. MCLK is disabled
- Low-power mode 1 (LPM1);
  - CPU is disabled  
ACLK and SMCLK remain active. MCLK is disabled  
DCO's dc-generator is disabled if DCO not used in active mode
- Low-power mode 2 (LPM2);
  - CPU is disabled  
MCLK and SMCLK are disabled  
DCO's dc-generator remains enabled  
ACLK remains active
- Low-power mode 3 (LPM3);
  - CPU is disabled  
MCLK and SMCLK are disabled  
DCO's dc-generator is disabled  
ACLK remains active
- Low-power mode 4 (LPM4);
  - CPU is disabled  
ACLK is disabled  
MCLK and SMCLK are disabled  
DCO's dc-generator is disabled  
Crystal oscillator is stopped

# TI MSP430F2001

## Software Environment



- 16-MHz MSP430 Processor Core  
1,280 bytes of flash, 128 bytes of RAM  
Small assembly or C programs  
“Bare metal” (no operating system)

Typical applications:

Utility metering

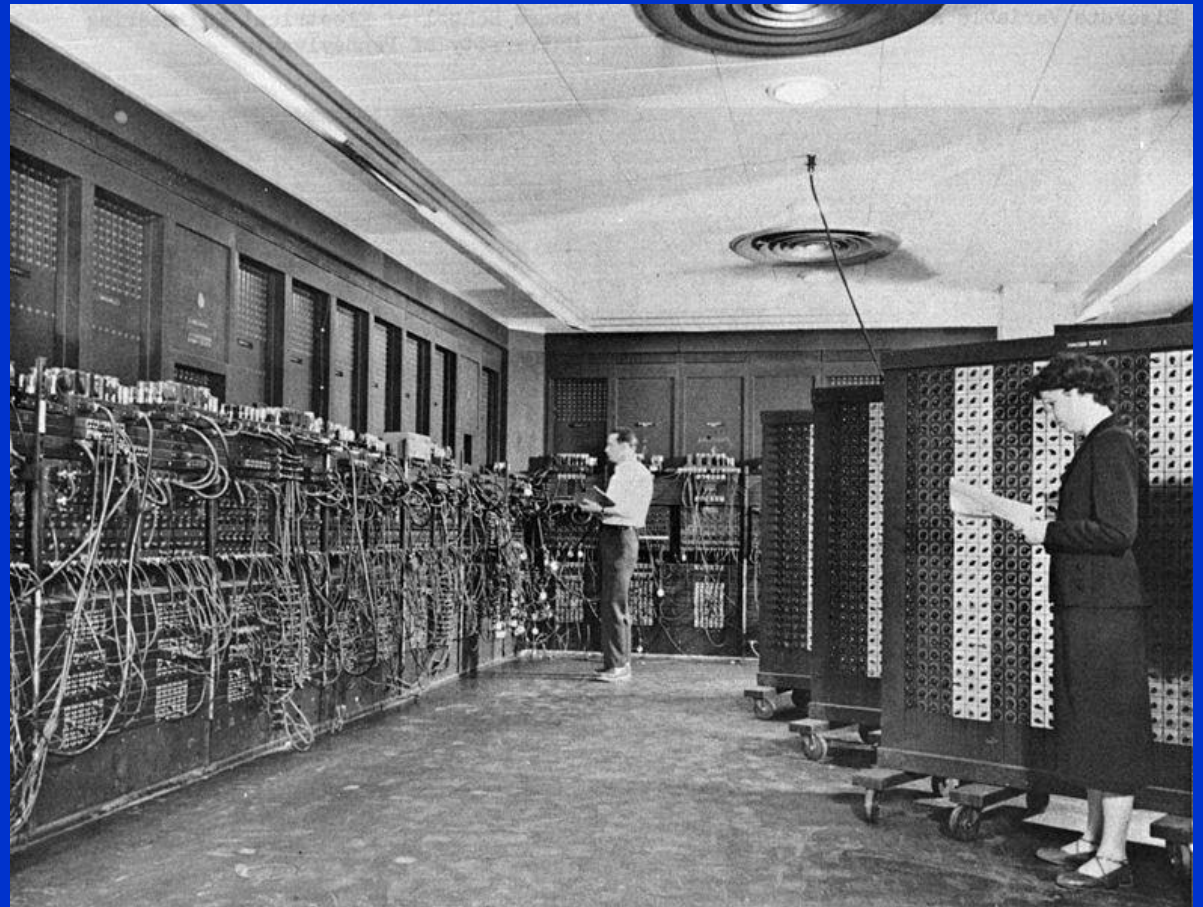
Simple portable medical devices

Sensor networks



# TI MSP430F2001 Comparables

ENIAC, circa 1946  
Aberdeen Proving  
Ground, Maryland



# TI OMAP DM3730

## Overview



Embedded CPU with ARM, DSP cores

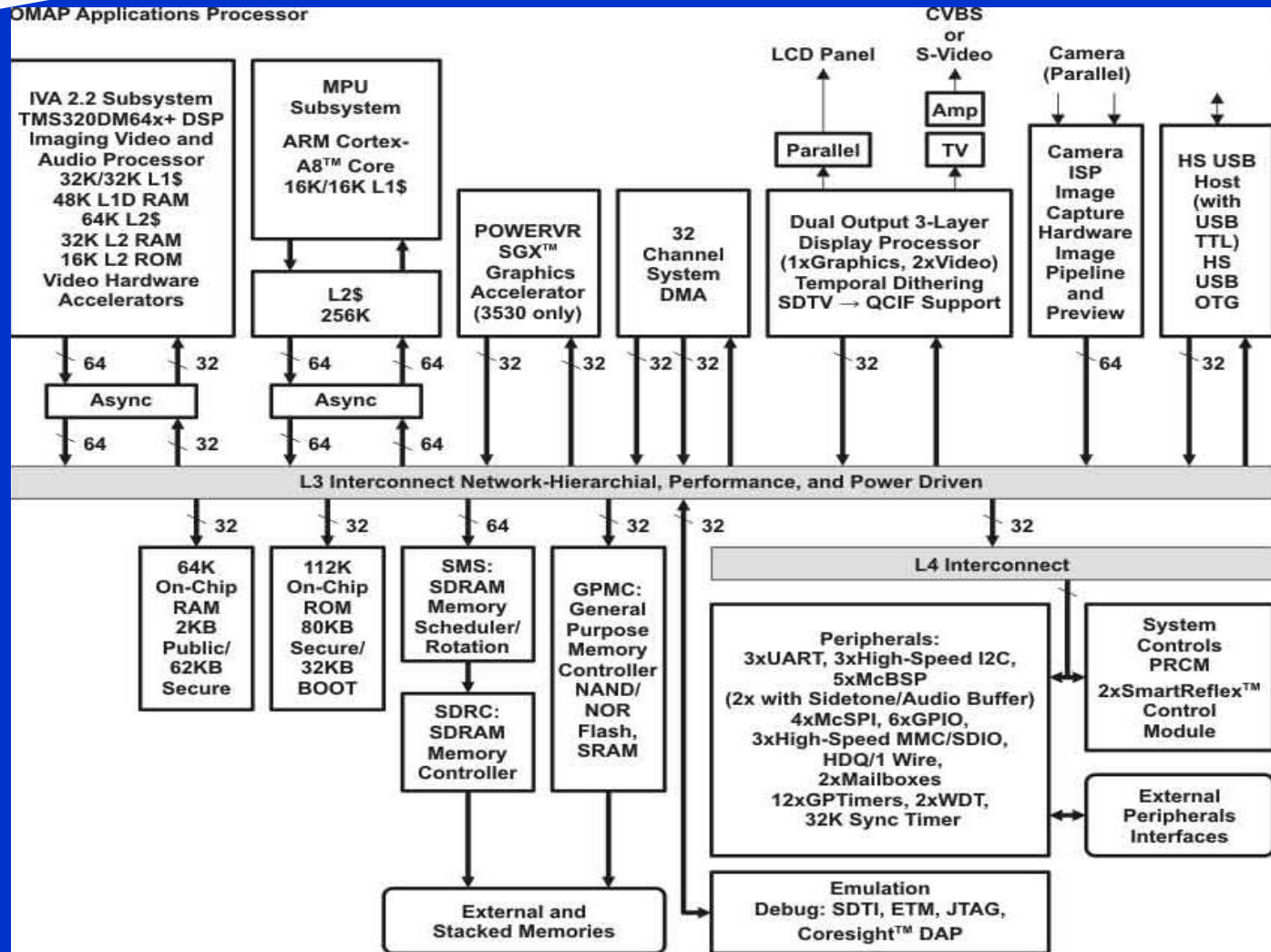
“Kitchen Sink” onboard peripheral set  
video display interface and acceleration  
camera interface  
high speed serial interfaces  
multiple USB interfaces  
optimized for smartphone handsets

JTAG interface for debugging

High Performance = High Price (\$35)

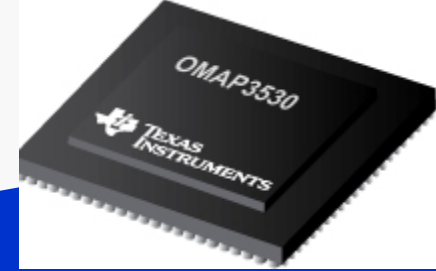
# TI OMAP DM3730

## Block Diagram



# TI OMAP DM3730

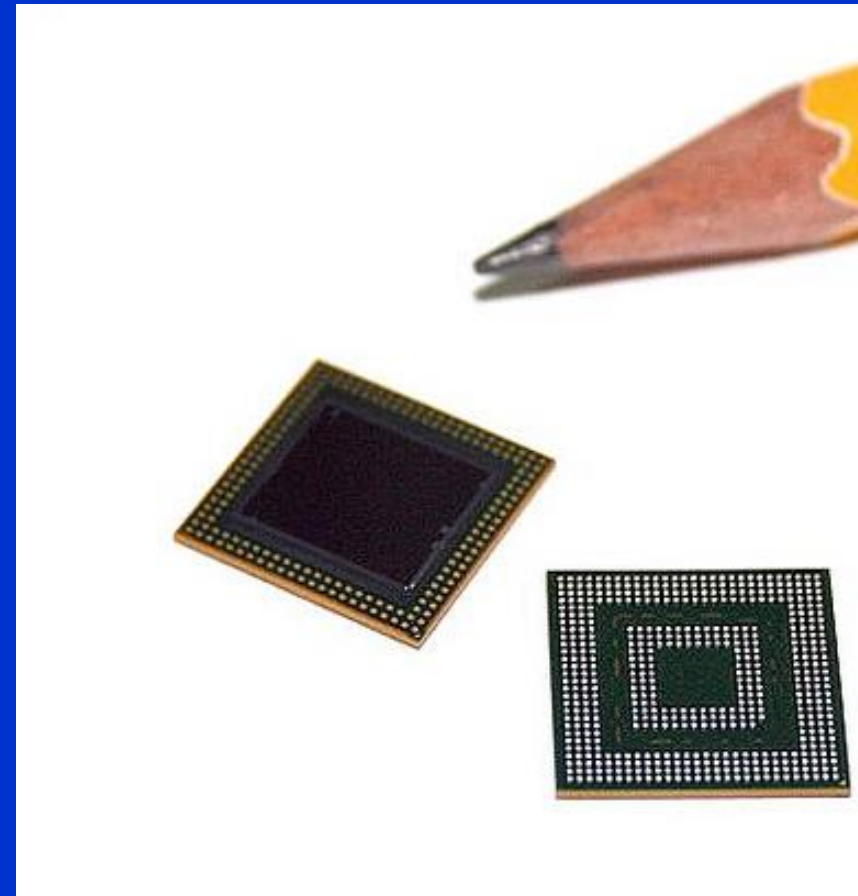
## Form Factor



515-pin Ball Grid Array (BGA), 1 cm

347 pins on bottom, 168 pins on top for P-O-P memory chip

Software configurable pinout (up to 8 choices for some pins)



# TI OMAP DM3730

## Power Management



9 Top Level Power Domains with independent supplies

PRCM (Power, Reset and Clock Module) “brain stem” can turn domains on and off

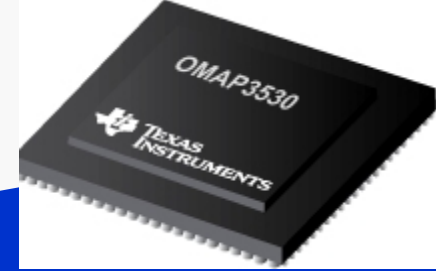
“SmartReflex” power and clock speed scaling

Up to 2W fully active; a few mW in standby modes

Companion power management chip (TPS65960) contains multiple power regulators, battery charger support, etc.

# TI OMAP DM3730

## Software Environment



- ARM Cortex A8 Processor
  - Full memory management
  - Linux main-line kernel tree support
  - Supervisory and User Interface functions
- TMS320C64x DSP Core
  - Access to private and system memory and I/O
  - Supervised by ARM, but autonomous
  - Dedicated DSP functions
- Task: Maximize efficiency by intelligent allocation of functions among ARM and DSP



# Atmel ATtiny4

8-bit CPU in SOT-23

- Atmel ATtiny4
  - 6 pins, 512b flash, \$0.44
  - 200uA @ 1.8V (active)
  - 25uA @ 1.8V (idle)
  - 0.1uA @ 1.8V (power-down)

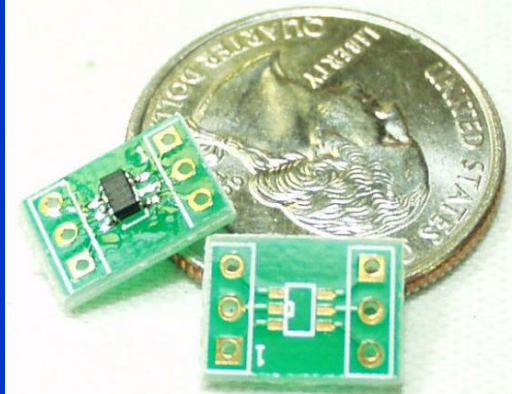
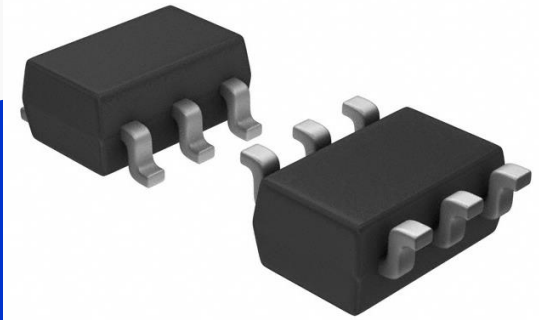
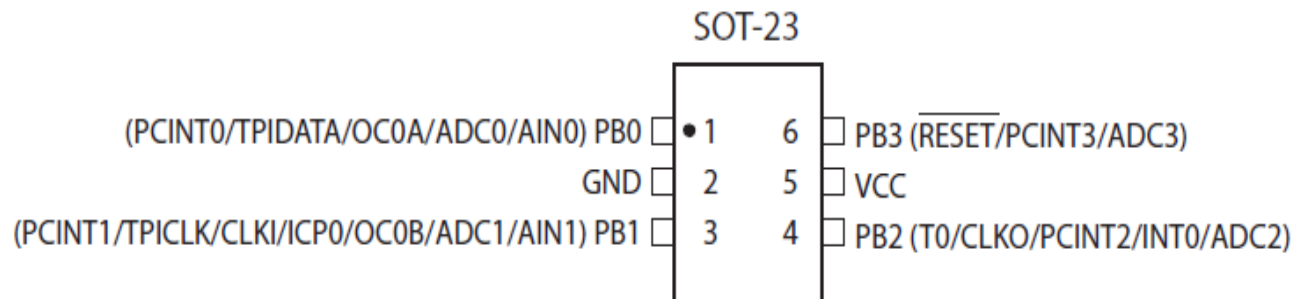


Figure 1-1. Pinout of ATtiny4/5/9/10



# FPGA Technology

- Field Programmable Gate Array
- “Grab Bag” of hardware on a single chip
- Configures itself on power-up, usually from a specialized low-cost serial FLASH memory
- Often used as a “front end” to reduce CPU processing demand or pin count

Xilinx ([www.xilinx.com](http://www.xilinx.com))

Intel, ex-Altera ([www.intel.com](http://www.intel.com))



# FPGA Technology

## (continued)

- Powerful design tools generate FPGA “code” using software-like descriptions in Hardware Description Languages (VHDL, Verilog)
- Designs can be extensively simulated
- Designs can be converted into ASICs (Application Specific Integrated Circuit) for lower cost in very high volume products

# FPGA Technology

## (continued)

- Many hardware functions can be purchased as IP (intellectual property) “Cores”--FPGA code that can be securely dropped into an existing FPGA design.

(Audio/video codecs, network communication, radio modulation/demodulation, encryption/decryption...)

- The third-party marketplace for FPGA intellectual property has created a means to monetize design innovations without having to build hardware

# FPGA Technology

## (continued)

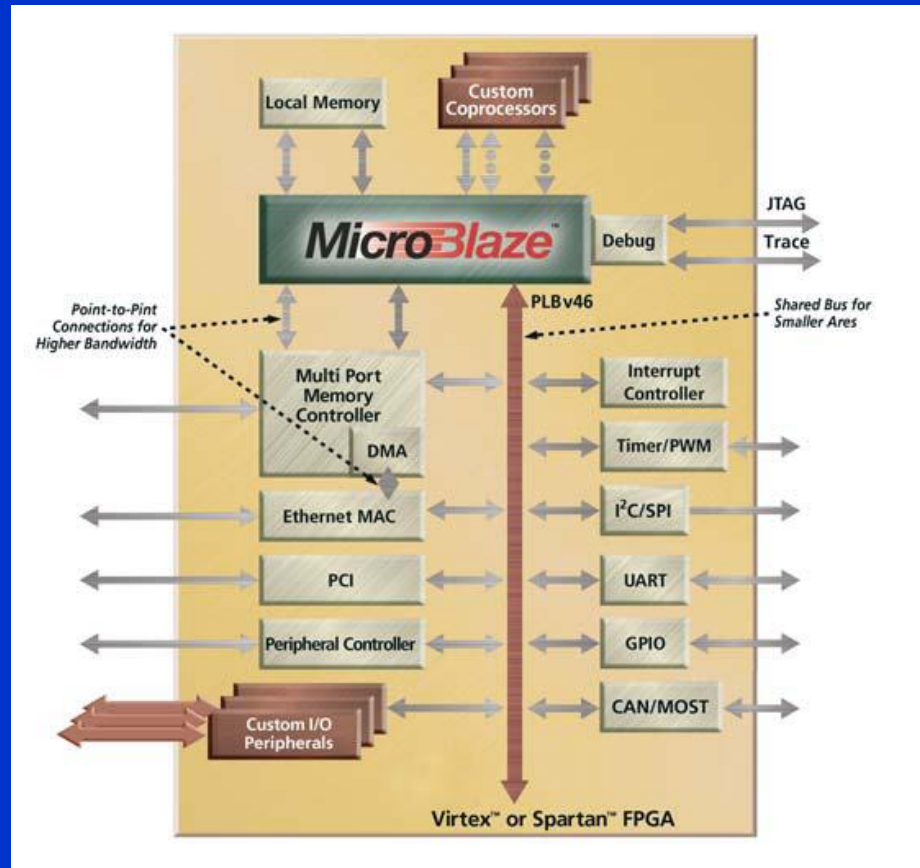
- A “Soft Core” CPU and peripherals can be implemented on an FPGA
- Some CPU architectures are available as IP (intellectual property)--VHDL or Verilog code
- IP also available for complicated I/O tasks (USB, FireWire, Ethernet, audio and video encoding/decoding, memory controllers, etc.)
- True single-chip solution for some systems

# Xilinx MicroBlaze™

## Soft-Core Processor

- Implemented on a Xilinx FPGA
- Any combination of standard, custom or user-modified peripherals
- Shares FPGA with other user-defined hardware

Intel's Nios II is comparable



# Xilinx MicroBlaze™

## On Spartan-3E FPGA

- Spartan XC3S1600E (~\$50)
  - 376-pin BGA package (23mm x 23mm)
  - 33,192 “Logic Cells” (4-input LUTs)
  - 36 dedicated multipliers
  - 36 4K-byte RAM blocks
- MicroBlaze core itself uses ~1,000 LUTs
- Peripherals use additional space
  - Parallel port (23), Ethernet (1,800)
- Typical instance is ~25% of a 1600E,  
75% remaining for user hardware

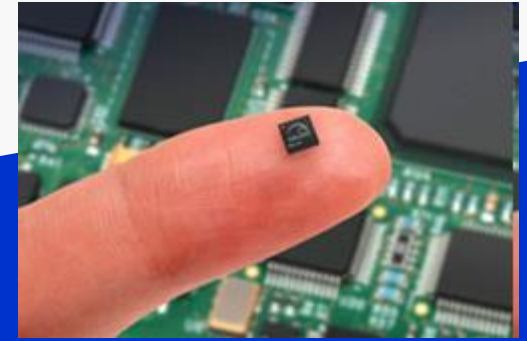
# Xilinx MicroBlaze™

## On Spartan-6 FPGA

- Spartan-6 LX and LXT Series
  - 144 to 900 pins (8x8mm to 31x31 mm)
  - 3,800 to 147,000 Logic Cells (LUTs)
  - \$10-\$320 (Q1K)
- Some units have PCI Express endpoints, multi-gigabit SerDes, DDR3 controller)
- Footprint compatibility for scalability (same board layout, different chips)

# Microsemi Igloo Nano

## Ultra low-power FPGA

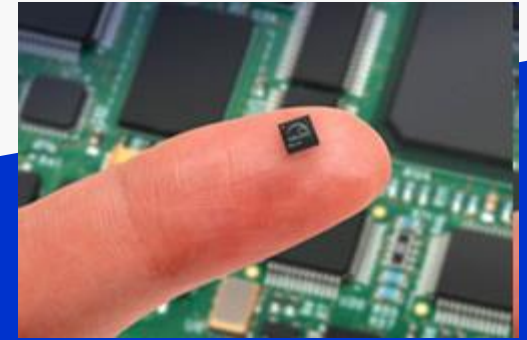


- Range of form factors
  - 36 to 100 pins (3x3 mm to 14x14 mm)
  - 260 to 6,144 "VersaTiles" (D flip-flops)
  - \$4-\$15
- Self-configuring from onboard Flash
- As low as 1.2V power supply
- 2 uW standby power in "freeze mode"

\*formerly Actel

# Microsemi Igloo Nano

## Ultra low-power FPGA



- No-cost, Royalty-Free Processor Cores

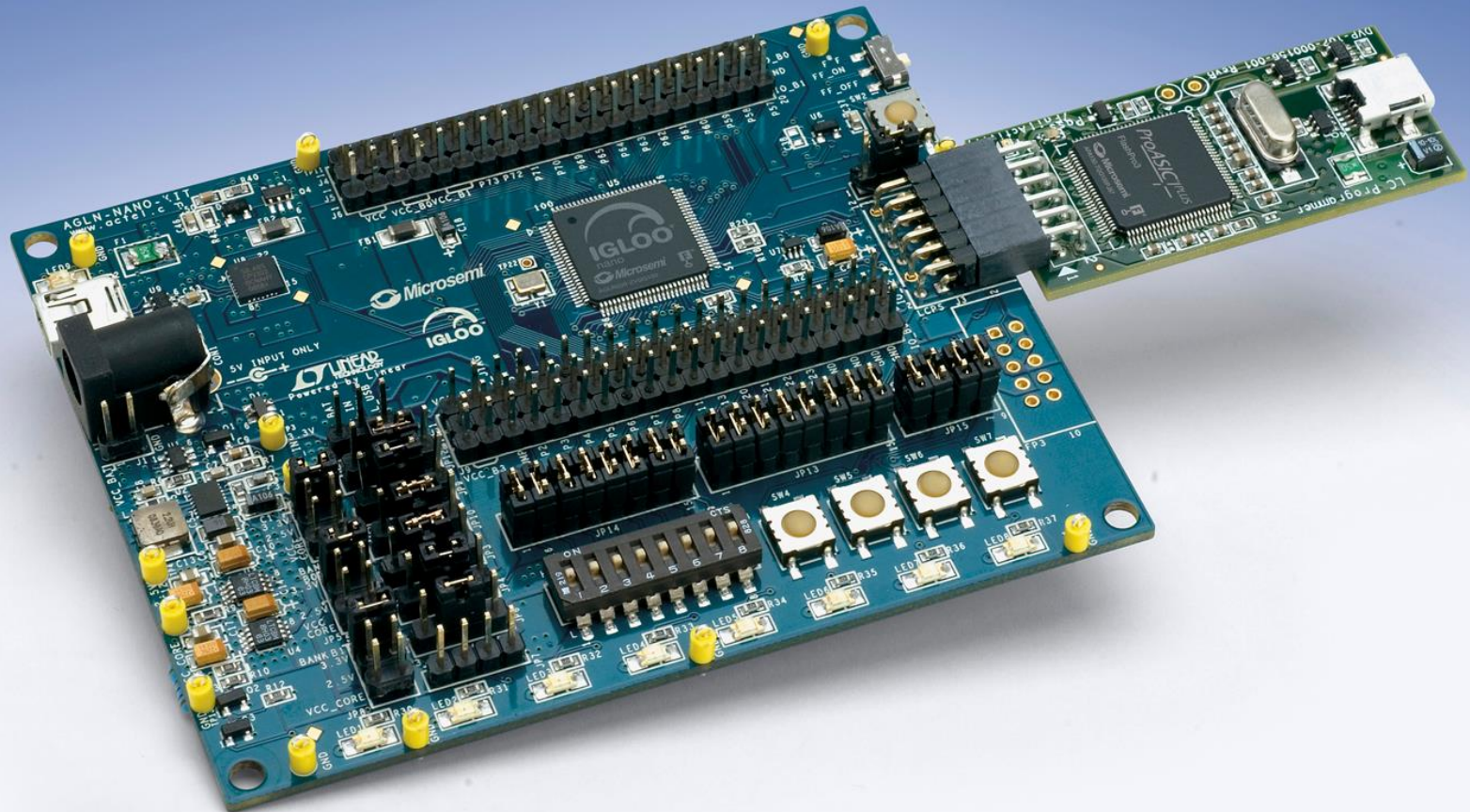
CoreABC: Very simple, programmed in assembly language, internal memory

Core8051, CoreM1: More complex, programmed in C, external memory

APB Bus: Lots of peripherals (UART, SPI, I2C, GPIO, Timers, 10/100 Ethernet, etc.)



# Microsemi Igloo Nano Starter Kit (\$99)



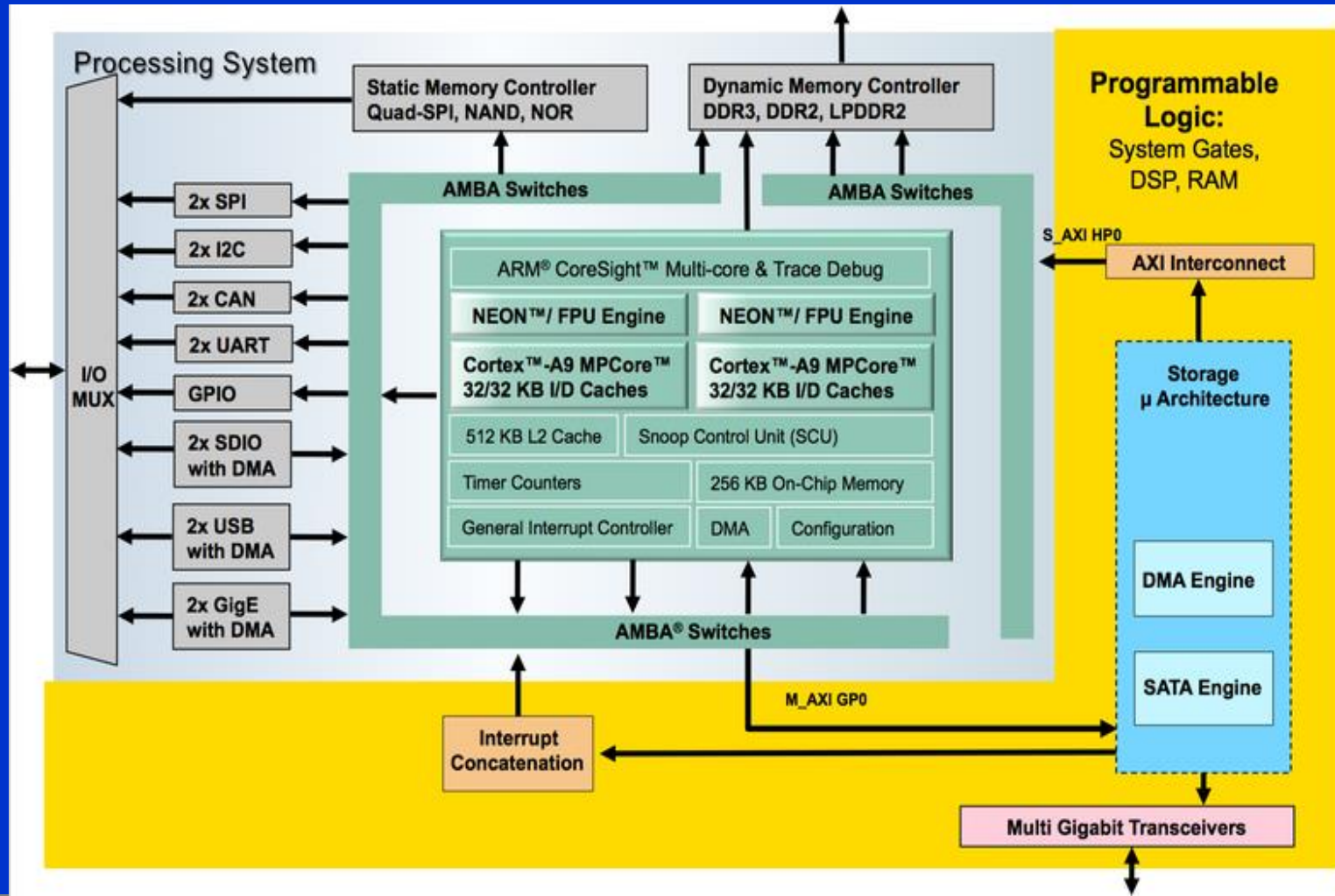
# Xilinx Zynq-7000

## Hybrid FPGA

- "PS" (Processor Subsystem): 2 ARM Cortex-A9 procesors and a lot of useful peripherals
- "PL" (Programmable Logic): Configurable FPGA logic blocks (multiple sizes available)
- Standard buses connecting PS and PL; interrupts
- Some I/O pins accessible directly by PS, so can be used prior to loading FPGA bitstream
- Best of both worlds (for some designs)

# Xilinx Zynq-7000

## Hybrid FPGA



# Closing Comments

- Embedded systems are found in almost all product areas due to the power of being able to combine hardware and software in the most appropriate way to solve a given problem
- ES present significant engineering challenges in terms of physical design, environment, power, reliability, security, safety and cost
- Developing embedded systems requires balancing many competing factors
- Many specialized processors and support chips are optimized specifically for embedded applications

# Part 2 Preview (Software)

- ARM and DSP Architectures
- Software challenges in Embedded Systems
- Key decisions in ES software development
- ARM and DSP Architectures
- Low-cost ES Prototyping Platforms
- Trends and opportunities in the ES industry

# Questions

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