16.480/552

- Course web
  - http://piazza.com/uml/fall2015/16480552/home
  - Course discussion forum
    - We use the web based forum on piazza.com
- Lectures and lab sessions
  - mandatory
- Lab assignments, reports, and demo
  - Hardware/software design, debugging, testing
- Exams
  - One in-class 90-minute exam and a final exam
- Grading
  - Labs-60%, Exams-40%,
  - 16.480 and 16.552 graded in separate scale

Introduction to Embedded Systems

Prof. Yan Luo

For UMass Lowell 16.480/552

Outline

- Overview of Embedded Systems
- Design Challenges
- Design methodology
- Embedded processors
- Numbering system

Embedded systems overview

- Computing systems are everywhere
- Most of us think of “desktop” computers
  - PC’s 
  - Laptops 
  - Mainframes
  - Servers
- But there’s another type of computing system
  - Far more common...

***Acknowledgement: Slides 4-36 are based on “Embedded Systems Design: A Unified Hardware/Software” by* Vahid/Givargis**

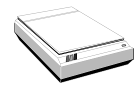
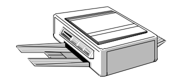
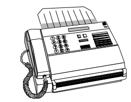
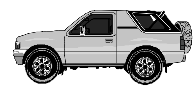
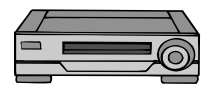
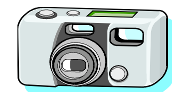
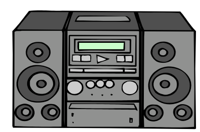
Embedded systems overview

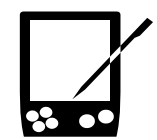
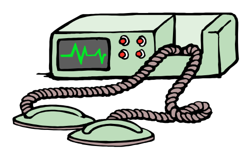
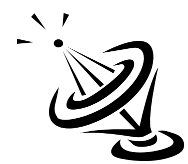
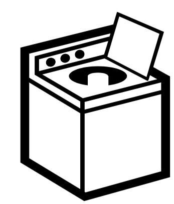
- Embedded computing systems
  - Computing systems embedded within electronic devices
  - Hard to define. Nearly any computing system other than a desktop computer
  - Billions of units produced yearly, versus millions of desktop units
  - Perhaps 50 per household and per automobile

A “short list” of embedded systems

Anti-lock brakes
Auto-focus cameras
Automatic teller machines
Automatic toll systems
Automatic transmission
Avionic systems
Battery chargers
Camcorders
Cell phones
Cell-phone base stations
Cordless phones
Cruise control
Curbside check-in systems
Digital cameras
Disk drives
Electronic card readers
Electronic instruments
Electronic toys/games
Factory control
Fax machines
Fingerprint identifiers
Home security systems
Life-support systems
Medical testing systems

Modems
MPEG decoders
Network cards
Network switches/routers
On-board navigation
Pagers
Photocopiers
Point-of-sale systems
Portable video games
Printers
Satellite phones
Scanners
Smart ovens/dishwashers
Speech recognizers
Stereo systems
Teleconferencing systems
Televisions
Temperature controllers
Theft tracking systems
TV set-top boxes
VCR’s, DVD players
Video game consoles
Video phones
Washers and dryers

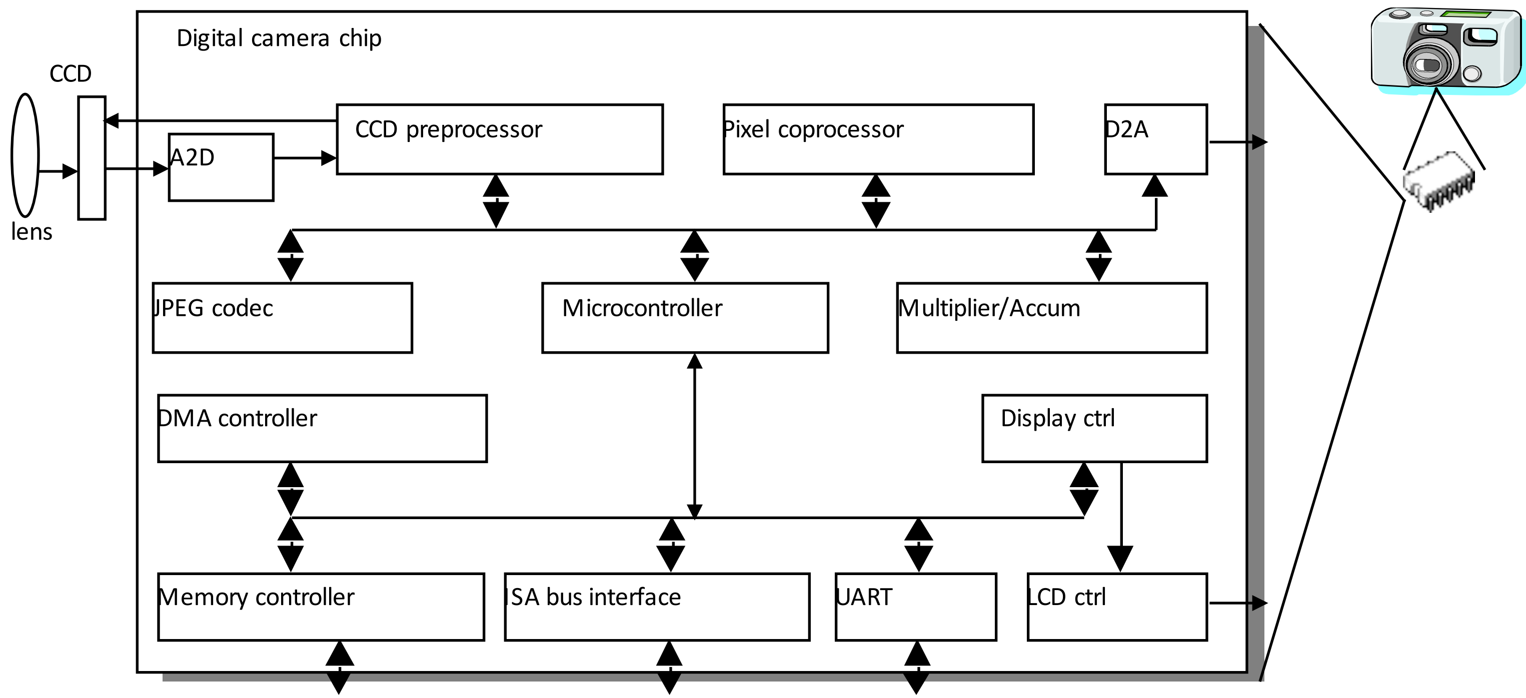





And the list goes on and on

Some common characteristics of embedded systems

- Single-functioned
  - Executes a single program, repeatedly
- Tightly-constrained
  - Low cost, low power, small, fast, etc.
- Reactive and real-time
  - Continually reacts to changes in the system's environment
  - Must compute certain results in real-time without delay

An embedded system example -- a digital camera



- Single-functioned -- always a digital camera
- Tightly-constrained -- Low cost, low power, small, fast
- Reactive and real-time -- only to a small extent

Design challenge – optimizing design metrics

- Obvious design goal:
  - Construct an implementation with desired functionality
- Key design challenge:
  - Simultaneously optimize numerous design metrics
- Design metric
  - A measurable feature of a system's implementation
  - Optimizing design metrics is a key challenge

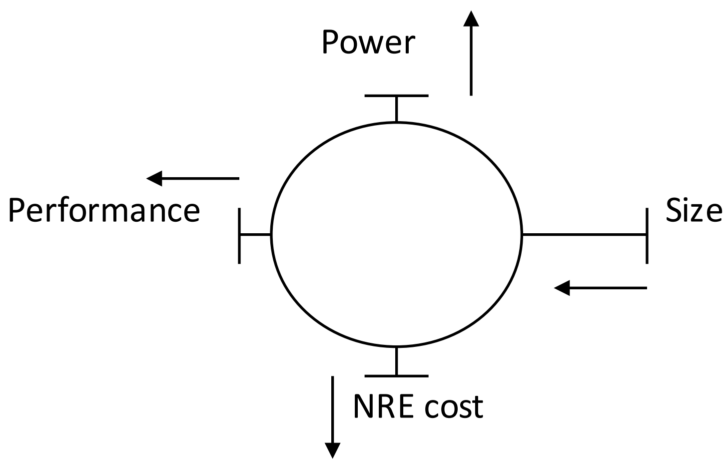
Design challenge – optimizing design metrics

- Common metrics
  - Unit cost: the monetary cost of manufacturing each copy of the system, excluding NRE cost
  - NRE cost (Non-Recurring Engineering cost): The one-time monetary cost of designing the system
  - Size: the physical space required by the system
  - Performance: the execution time or throughput of the system
  - Power: the amount of power consumed by the system
  - Flexibility: the ability to change the functionality of the system without incurring heavy NRE cost

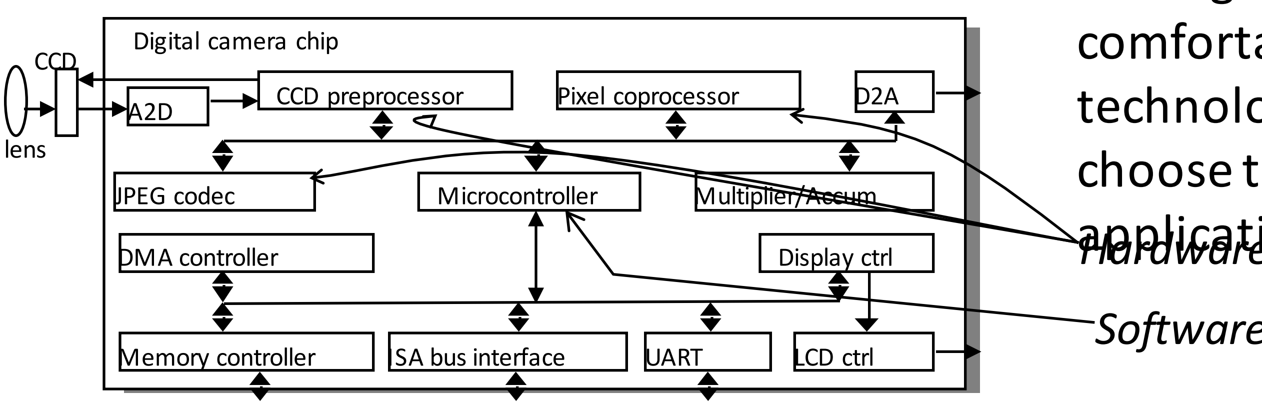
Design challenge – optimizing design metrics

- Common metrics (continued)
  - Time-to-prototype: the time needed to build a working version of the system
  - Time-to-market: the time required to develop a system to the point that it can be released and sold to customers
  - Maintainability: the ability to modify the system after its initial release
  - Correctness, safety, many more

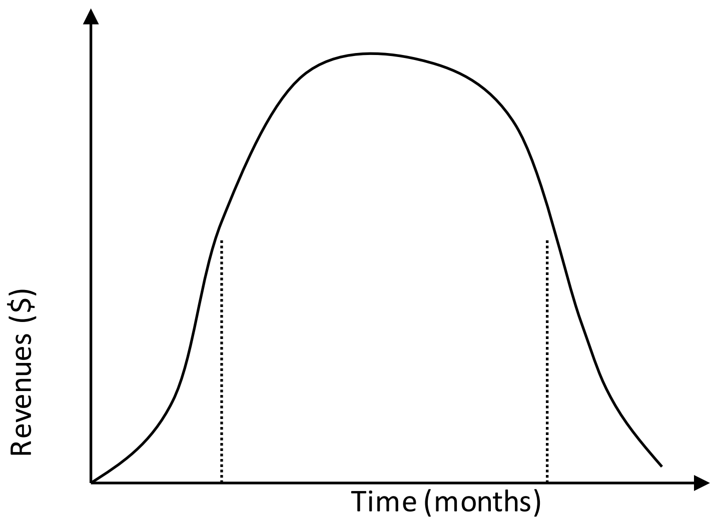
Design metric competition -- improving one may worsen others



- Expertise with both **software and hardware** is needed to optimize design metrics
  - Not just a hardware or software expert, as is common
  - A designer must be comfortable with various technologies in order to choose the best for a given application and constraints

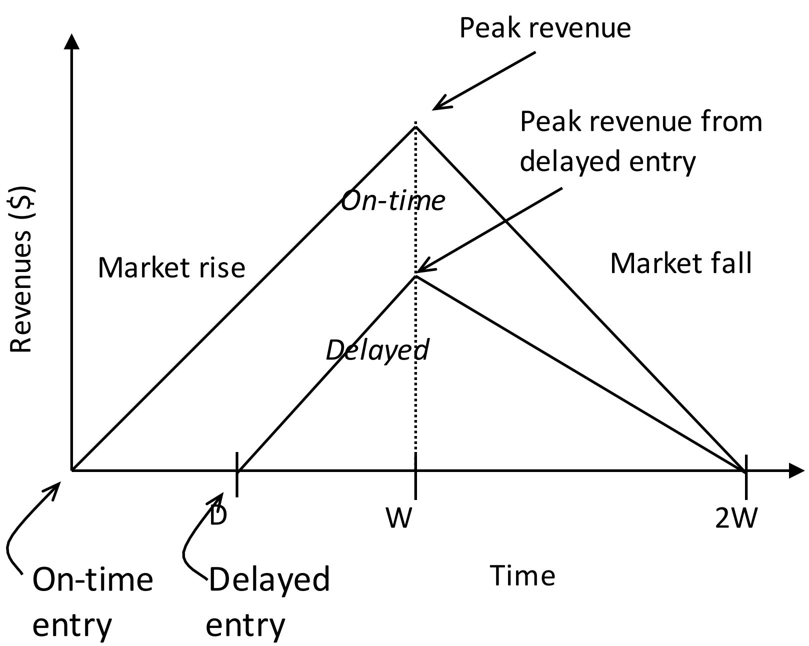


Time-to-market: a demanding design metric



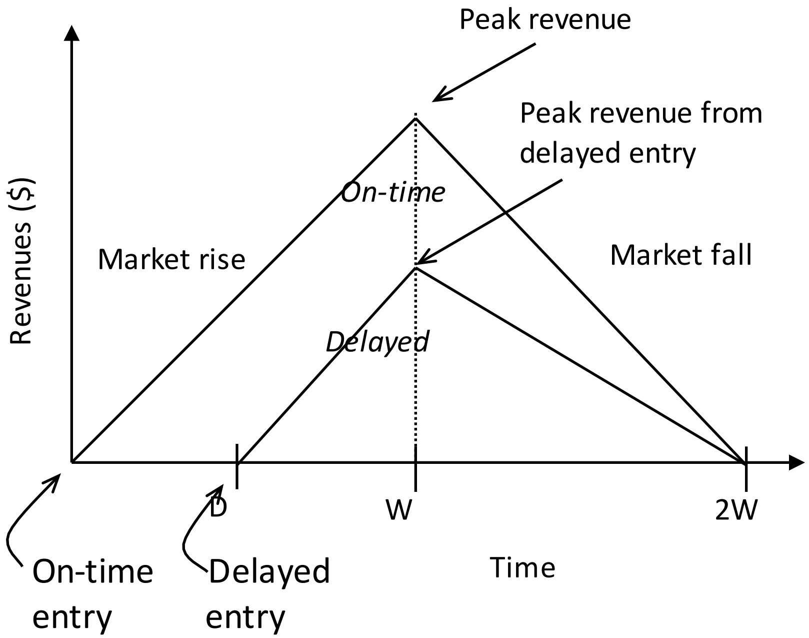
- Time required to develop a product to the point it can be sold to customers
- Market window
  - Period during which the product would have highest sales
- Average time-to-market constraint is about 8 months
- Delays can be costly

Losses due to delayed market entry



- Simplified revenue model
  - Product life = 2W, peak at W
  - Time of market entry defines a triangle, representing market penetration
  - Triangle area equals revenue
- Loss
  - The difference between the on-time and delayed triangle areas

Losses due to delayed market entry (cont.)



- Area = 1/2 * base * height
  - On-time = 1/2 * 2W * W
  - Delayed = 1/2 * (W-D+W)*(W-D)
- Percentage revenue loss = $(D(3W-D)/2W^2)*100\%$
- Try some examples
  - Lifetime 2W=52 wks, delay D=4 wks
  - (4*(3*26 –4)/2*26^2) = 22%
  - Lifetime 2W=52 wks, delay D=10 wks
  - (10*(3*26 –10)/2*26^2) = 50%
  - Delays are costly!

NRE and unit cost metrics

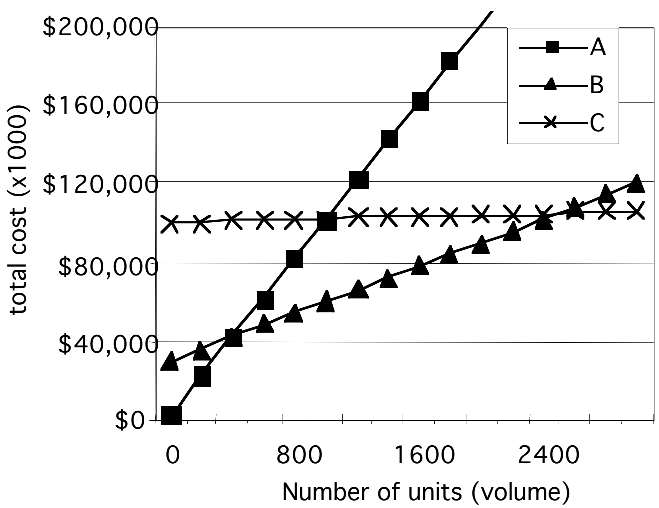
- Costs:
  - Unit cost: the monetary cost of manufacturing each copy of the system, excluding NRE cost
  - NRE cost (Non-Recurring Engineering cost): The one-time monetary cost of designing the system
  - *total cost = NRE cost + unit cost * # of units*
  - *per-product cost = total cost / # of units*
    = (NRE cost / # of units) + unit cost

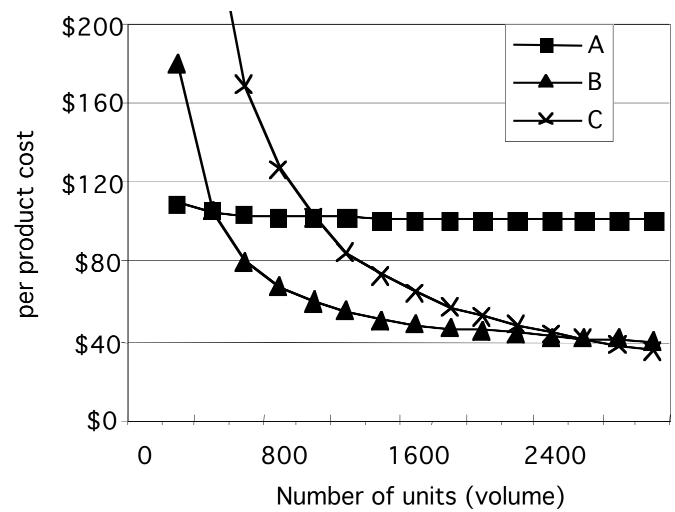
- Example
  - NRE=$2000, unit=$100
  - For 10 units
    - total cost = $2000 + 10*$100 = $3000
    - per-product cost = $2000/10 + $100 = $300

Amortizing NRE cost over the units results in an additional $200 per unit

NRE and unit cost metrics

- Compare technologies by costs -- best depends on quantity
  - Technology A: NRE=$2,000, unit=$100
  - Technology B: NRE=$30,000, unit=$30
  - Technology C: NRE=$100,000, unit=$2





- But, must also consider time-to-market

The performance design metric

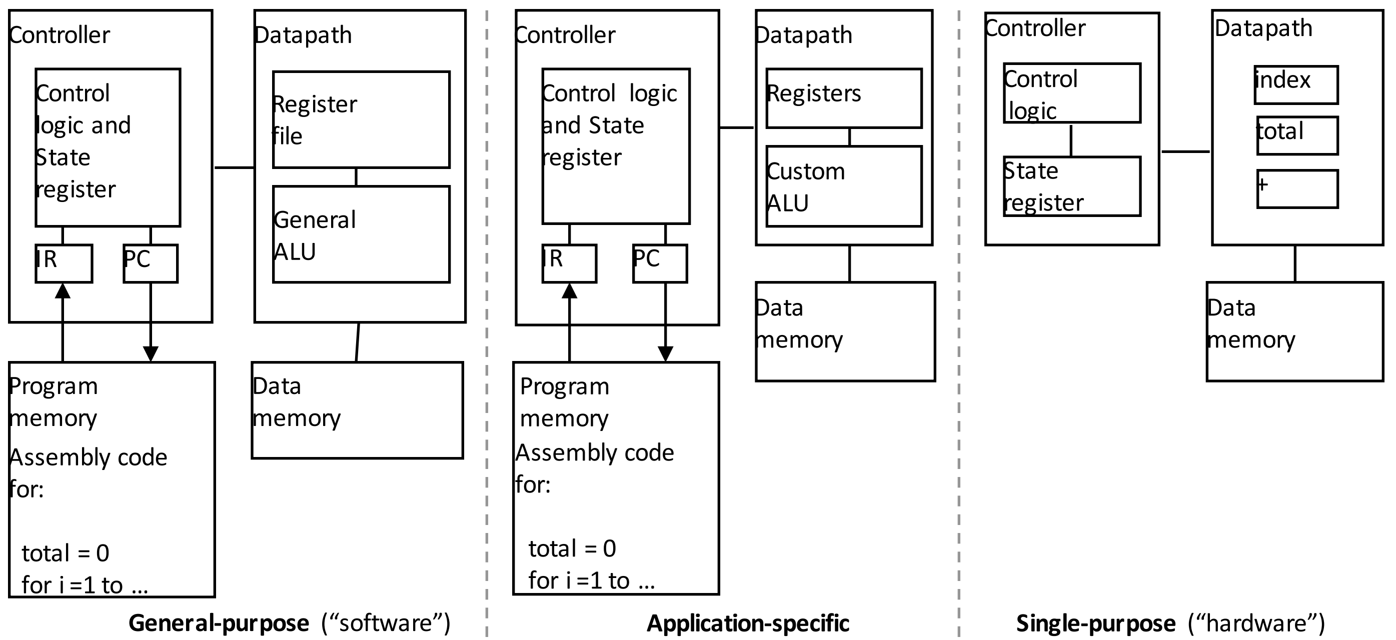
- Widely-used measure of system, widely-abused
  - Clock frequency, instructions per second – not good measures
  - Digital camera example – a user cares about how fast it processes images, not clock speed or instructions per second
- Latency (response time)
  - Time between task start and end
  - e.g., Camera's A and B process images in 0.25 seconds
- Throughput
  - Tasks per second, e.g. Camera A processes 4 images per second
  - Throughput can be more than latency seems to imply due to concurrency, e.g. Camera B may process 8 images per second (by capturing a new image while previous image is being stored).
- *Speedup* of B over S = B's performance / A's performance
  - Throughput speedup = 8/4 = 2

Three key embedded system technologies

- Technology
  - A manner of accomplishing a task, especially using technical processes, methods, or knowledge
- Three key technologies for embedded systems
  - Processor technology
  - IC technology
  - Design technology

Processor technology

- The architecture of the computation engine used to implement a system's desired functionality
- Processor does not have to be programmable
  – "Processor" *not* equal to general-purpose processor

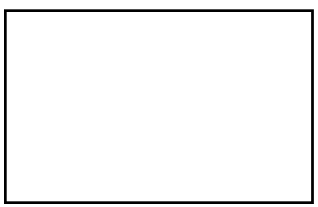


Processor technology

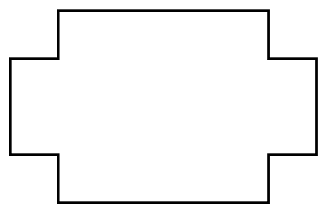
- Processors vary in their customization for the problem at hand

Desired functionality

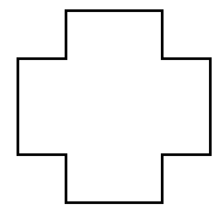
```
total = 0
for i = 1 to N  loop
   total += M[i]
end loop
```



General-purpose processor



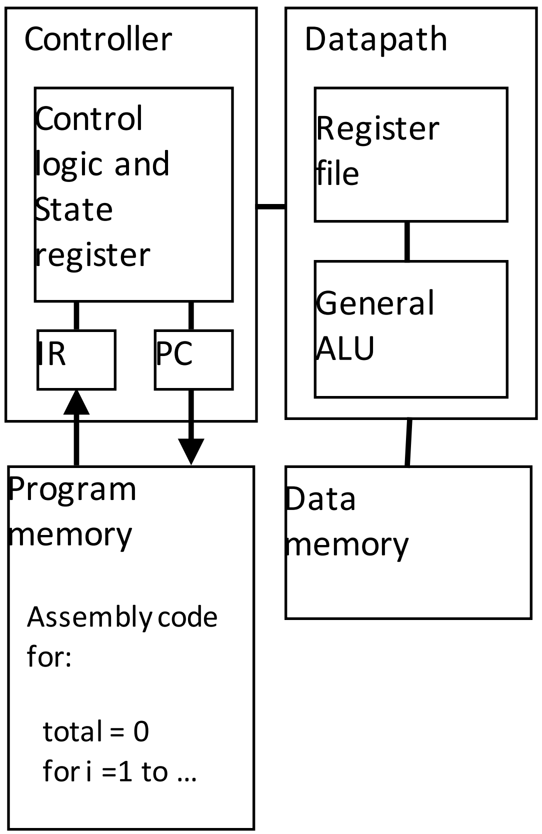
Application-specific processor



Single-purpose processor

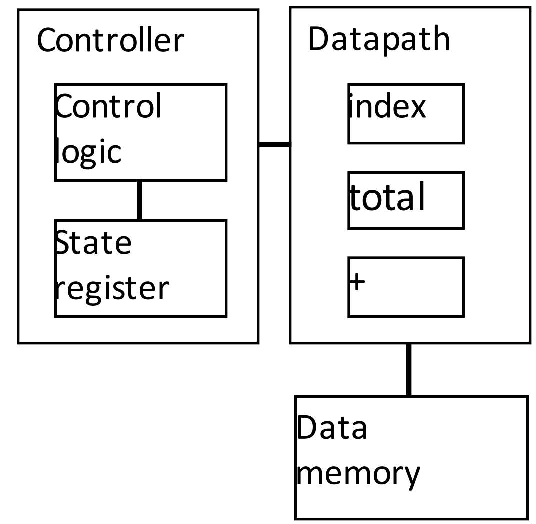
General-purpose processors

- Programmable device used in a variety of applications
  - Also known as "microprocessor"
- Features
  - Program memory
  - General datapath with large register file and general ALU
- User benefits
  - Low time-to-market and NRE costs
  - High flexibility
- "Pentium" the most well-known, but there are hundreds of others



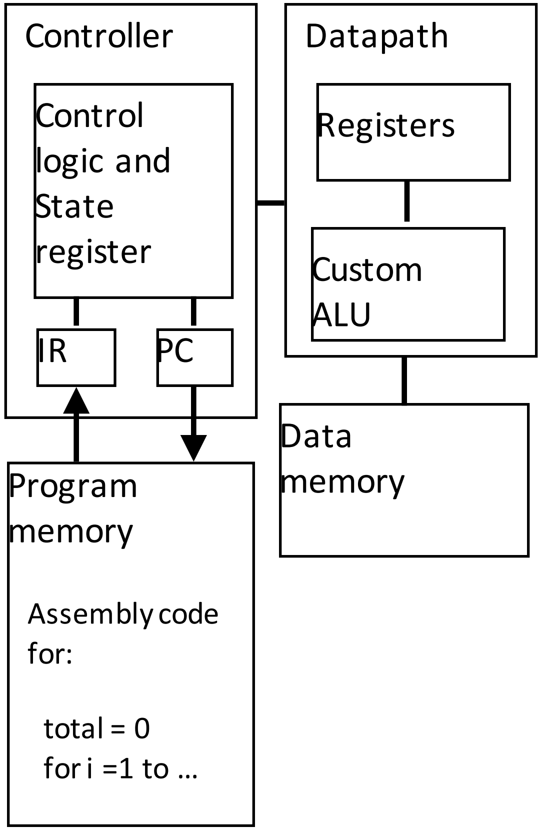
Single-purpose processors

- Digital circuit designed to execute exactly one program
  - a.k.a. coprocessor, accelerator or peripheral
- Features
  - Contains only the components needed to execute a single program
  - No program memory
- Benefits
  - Fast
  - Low power
  - Small size



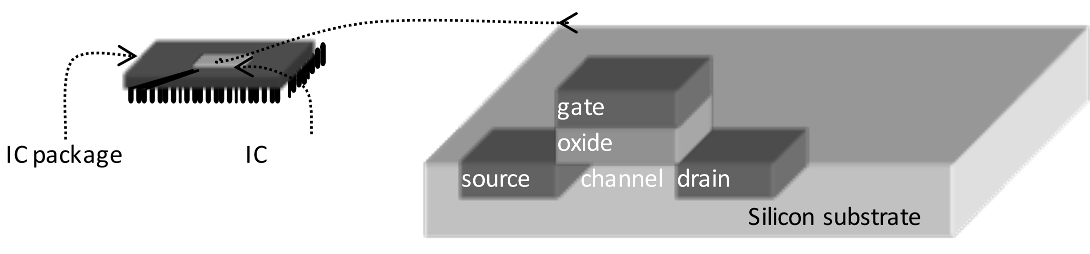
Application-specific processors

- Programmable processor optimized for a particular class of applications having common characteristics
  - Compromise between general-purpose and single-purpose processors
- Features
  - Program memory
  - Optimized datapath
  - Special functional units
- Benefits
  - Some flexibility, good performance, size and power



IC technology

- The manner in which a digital (gate-level) implementation is mapped onto an IC
  - IC: Integrated circuit, or “chip”
  - IC technologies differ in their customization to a design
  - IC’s consist of numerous layers (perhaps 10 or more)
    - IC technologies differ with respect to who builds each layer and when



IC technology

- Three types of IC technologies
  - Full-custom/VLSI
  - Semi-custom ASIC (gate array and standard cell)
  - PLD (Programmable Logic Device)

Full-custom/VLSI

- All layers are optimized for an embedded system's particular digital implementation
  - Placing transistors
  - Sizing transistors
  - Routing wires
- Benefits
  - Excellent performance, small size, low power
- Drawbacks
  - High NRE cost (e.g., $300k), long time-to-market

Semi-custom

- Lower layers are fully or partially built
  - Designers are left with routing of wires and maybe placing some blocks
- Benefits
  - Good performance, good size, less NRE cost than a full-custom implementation (perhaps $10k to $100k)
- Drawbacks
  - Still require weeks to months to develop

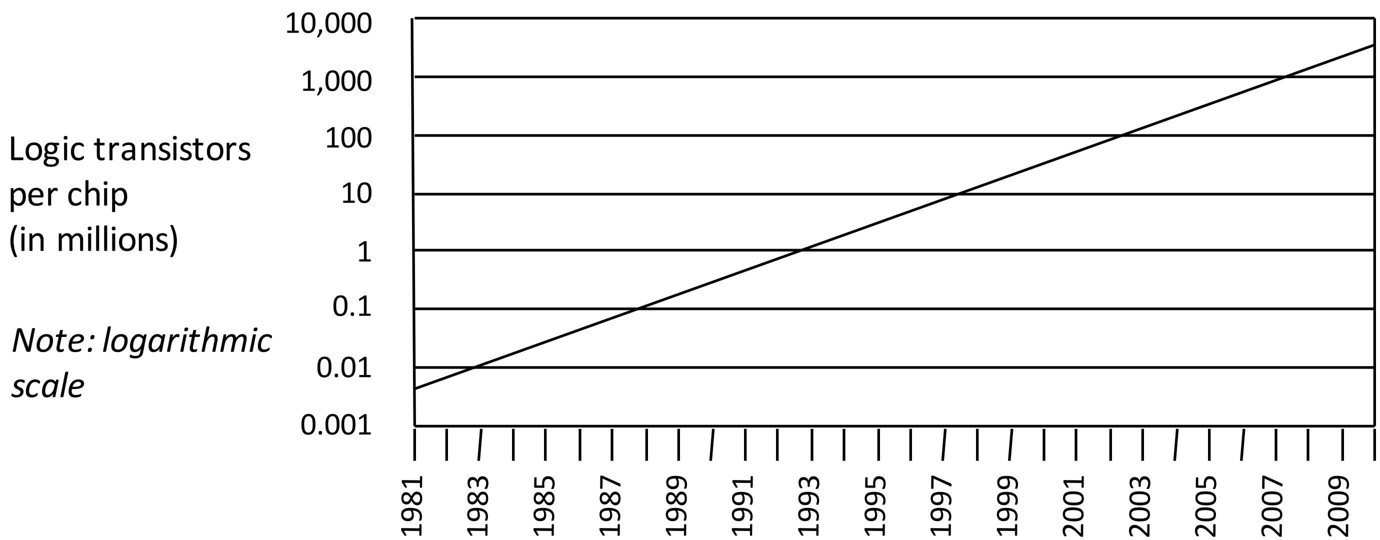
PLD (Programmable Logic Device)

- All layers already exist
  - Designers can purchase an IC
  - Connections on the IC are either created or destroyed to implement desired functionality
  - Field-Programmable Gate Array (FPGA) very popular
- Benefits
  - Low NRE costs, almost instant IC availability
- Drawbacks
  - Bigger, expensive (perhaps $30 per unit), power hungry, slower

Moore's law

- The most important trend in embedded systems
  - Predicted in 1965 by Intel co-founder Gordon Moore

    IC transistor capacity has doubled roughly every 18 months for the past several decades

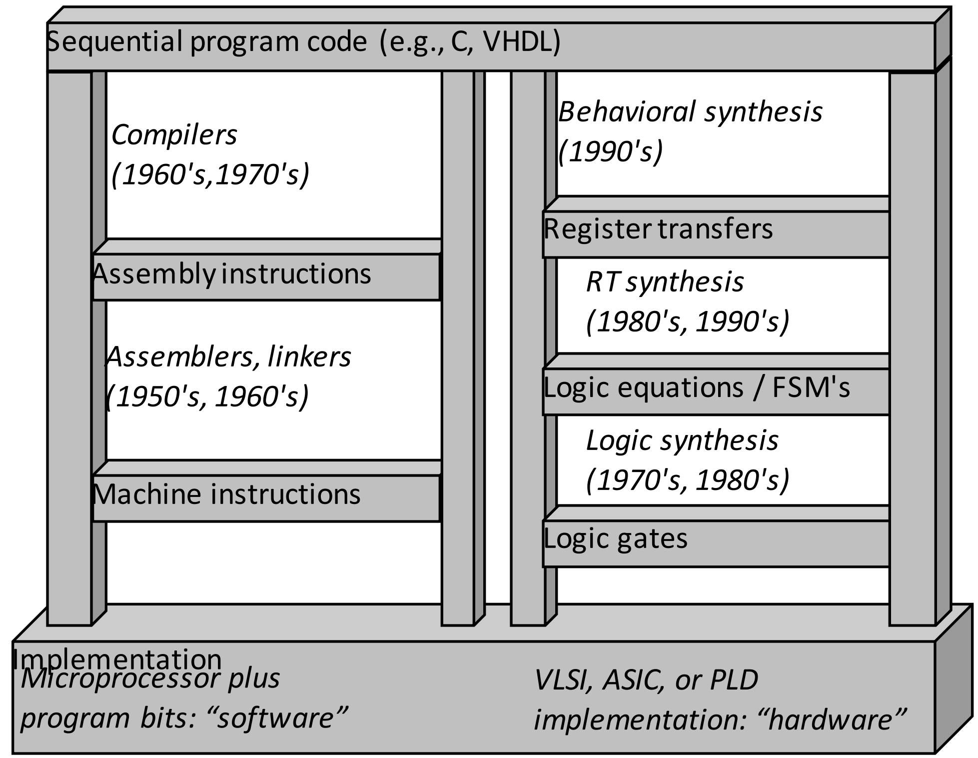


The Future of Moore's law

- Does Moore's Law still hold?
  - This growth rate has been steady until ~2005
  - Factors limiting transistor counts
    - *Power consumption (leakage power)*
    - *Temperature*
    - *Development of new technology (65nm, 45nm, 30nm…)*
  - Transistor density growth slows down
- New Trend
  - Multiple computing cores
  - Not significant higher frequency
  - Nanotechnology

The co-design ladder

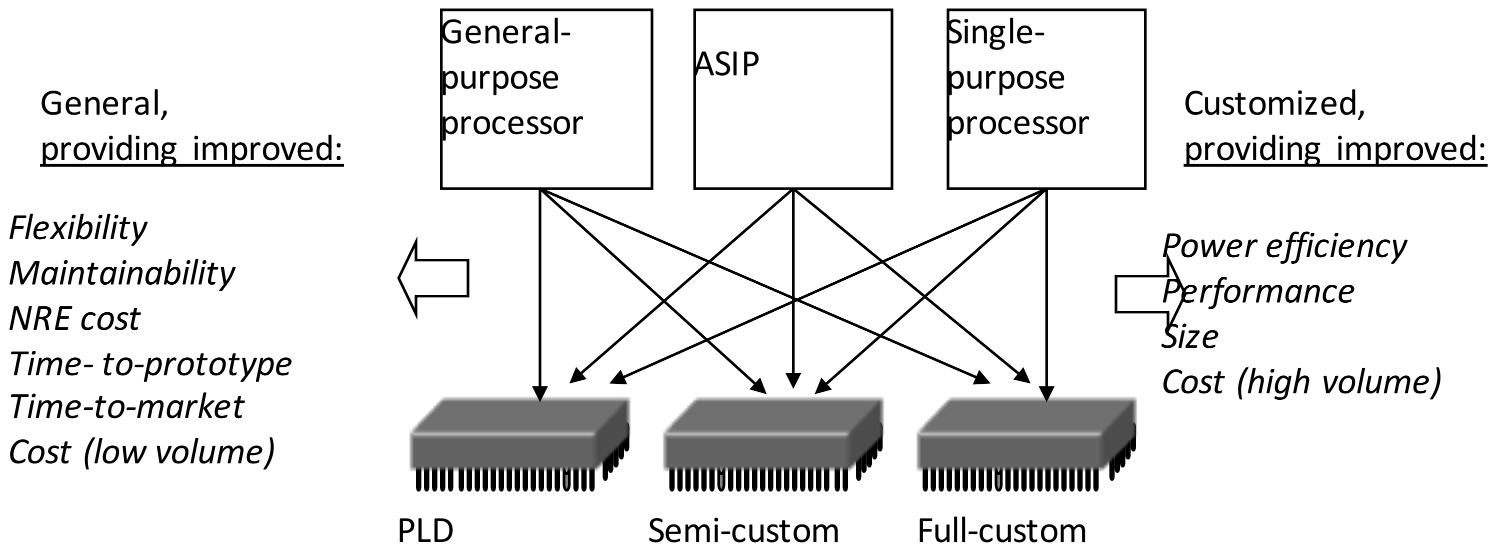
- In the past:
  - Hardware and software design technologies were very different
  - Recent maturation of synthesis enables a unified view of hardware and software
- Hardware/software "codesign"



The choice of hardware versus software for a particular function is simply a tradeoff among various design metrics, like performance, power, size, NRE cost, and especially flexibility; there is no fundamental difference between what hardware or software can implement.

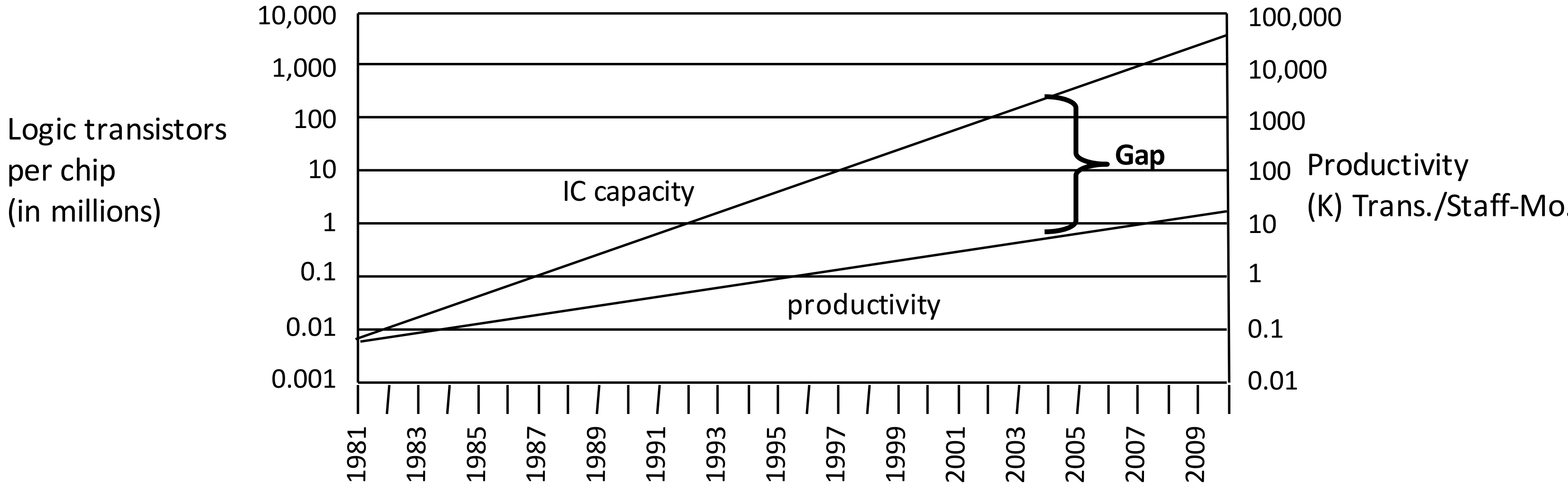
Independence of processor and IC technologies

- Basic tradeoff
  - General vs. custom
  - With respect to processor technology or IC technology
  - The two technologies are independent



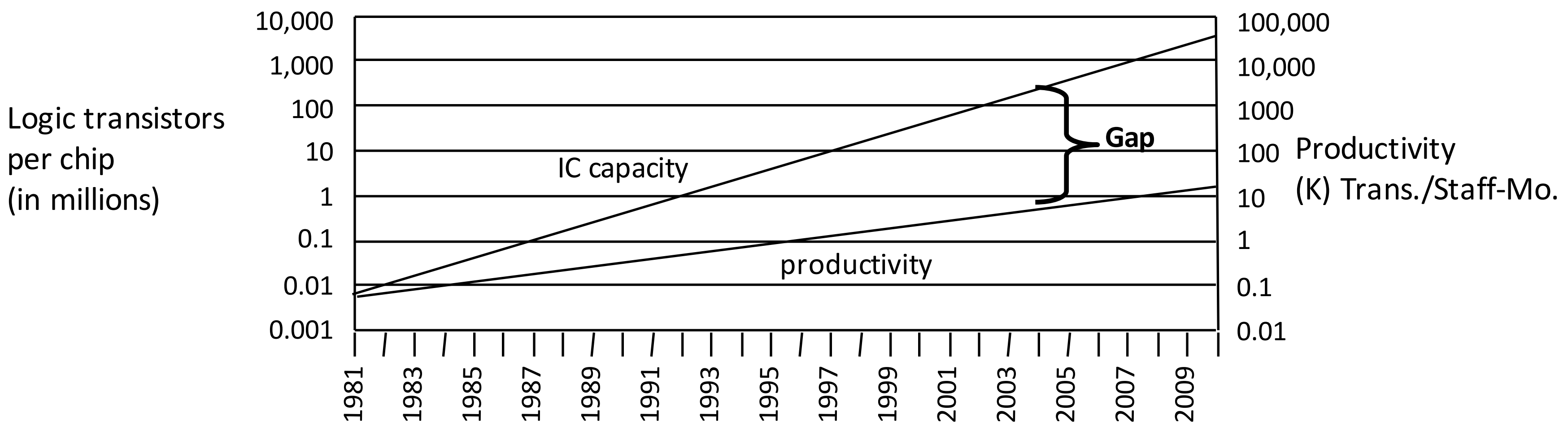
Design productivity gap

- While designer productivity has grown at an impressive rate over the past decades, the rate of improvement has not kept pace with chip capacity



Design productivity gap

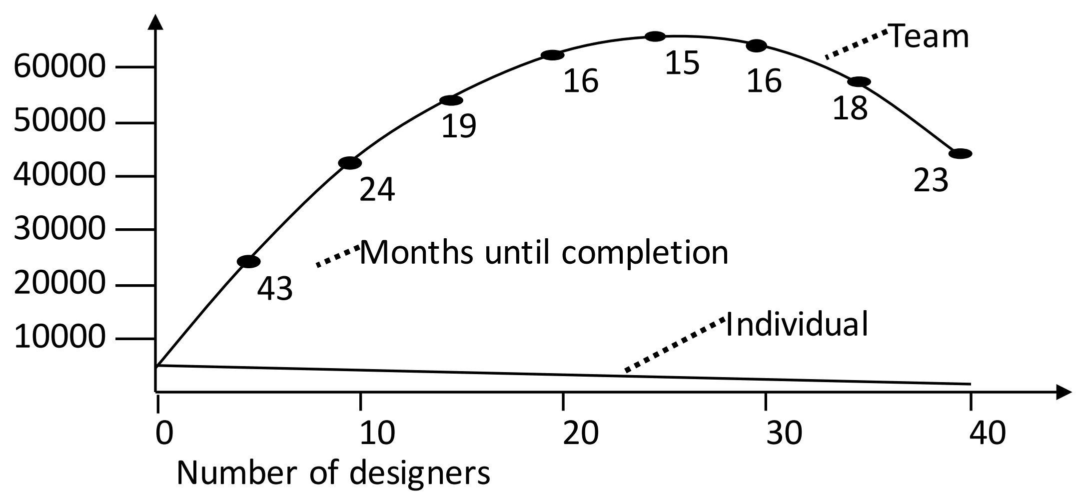
- 1981 leading edge chip required 100 designer months
  - 10,000 transistors / 100 transistors/month
- 2002 leading edge chip requires 30,000 designer months
  - 150,000,000 / 5000 transistors/month
- Designer cost increase from $1M to $300M



The mythical man-month

- The situation is even worse than the productivity gap indicates
- In theory, adding designers to team reduces project completion time
- In reality, productivity per designer decreases due to complexities of team management and communication
- In the software community, known as “the mythical man-month” (Brooks 1975)
- At some point, can actually lengthen project completion time! (“Too many cooks”)

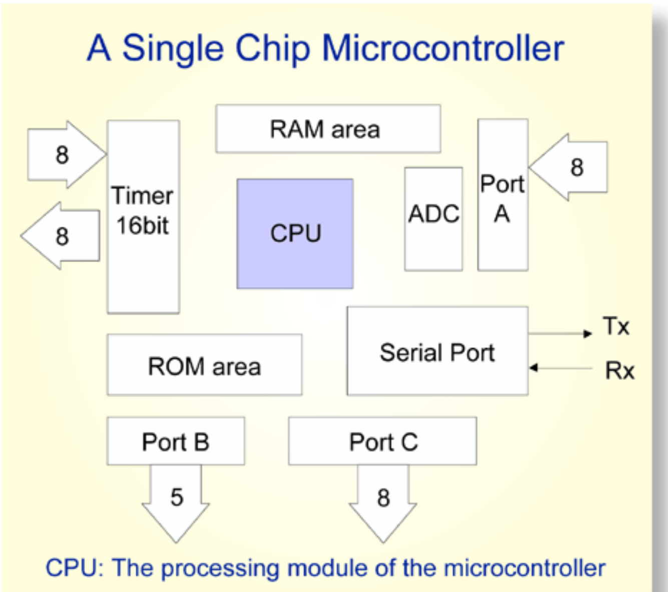
- 1M transistors, 1 designer=5000 trans/month
- Each additional designer reduces for 100 trans/month
- So 2 designers produce 4900 trans/month each

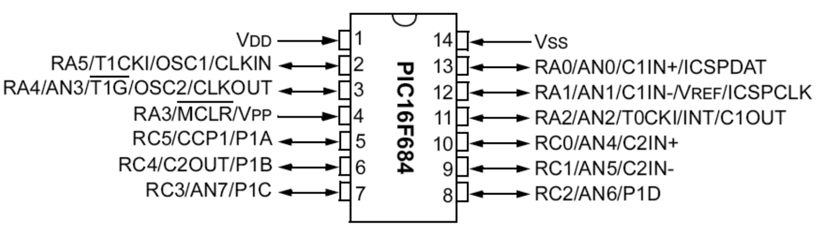


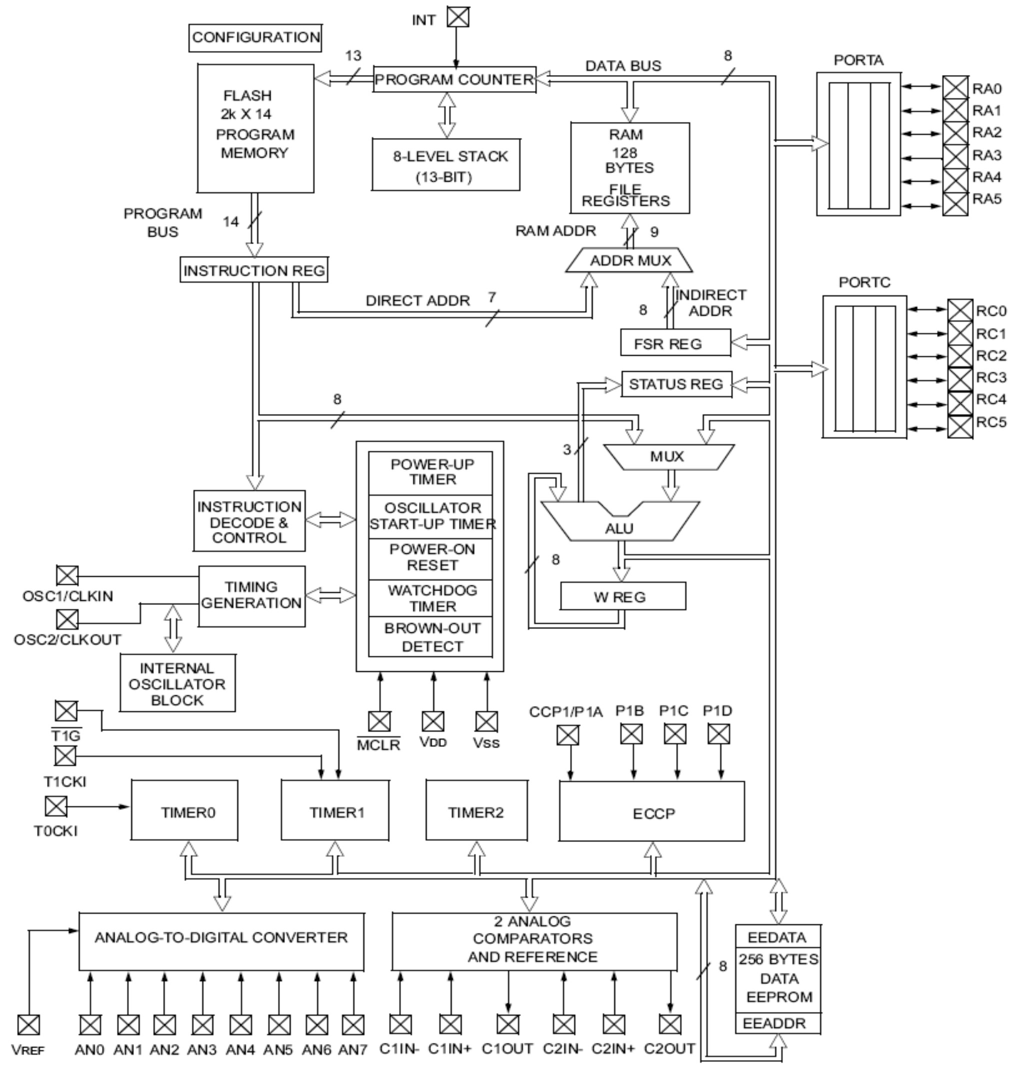
Embedded Processors

- Requirements for embedded processors
  - Low power consumption
  - Programmable
  - Low cost
- Examples
  - Microcontroller-type:
    - self-contained (mem, I/O, ADC, etc.), GPIO,
    - no OS, less interactive environment e.g. sensor data acquisition
    - Microchip PIC, Intel 8051, Parallex Propeller, Atmel AVR, TI MSP430
  - Microprocessor-type:
    - SoC, demux address/data buses, co-processor, standard system buses
    - often with OS, more interactive environment e.g. set-top box, in-vehicle entertainment system
    - Intel Atom/Quark, TI OMAP4, Nvidia Tegra, Apple A8

PIC16F684


A Single Chip Microcontroller
8
8
Timer 16bit
RAM area
CPU
ADC
Port A
8
ROM area
Serial Port
Tx
Rx
Port B
Port C
5
8
CPU: The processing module of the microcontroller


VDD 1
RA5/T1CKI/OSC1/CLKIN 2
RA4/AN3/T1G/OSC2/CLKOUT 3
RA3/MCLR/VPP 4
RC5/CCP1/P1A 5
RC4/C2OUT/P1B 6
RC3/AN7/P1C 7
PIC16F684
14 VSS
13 RA0/AN0/C1IN+/ICSPDAT
12 RA1/AN1/C1IN-/VREF/ICSPCLK
11 RA2/AN2/T0CKI/INT/C1OUT
10 RC0/AN4/C2IN+
9 RC1/AN5/C2IN-
8 RC2/AN6/P1D


CONFIGURATION
INT
13
PROGRAM COUNTER
DATA BUS
8
PORTA
RA0
RA1
RA2
RA3
RA4
RA5
FLASH 2k X 14 PROGRAM MEMORY
8-LEVEL STACK (13-BIT)
RAM 128 BYTES FILE REGISTERS
PROGRAM BUS
14
RAM ADDR
9
INSTRUCTION REG
ADDR MUX
DIRECT ADDR
7
INDIRECT ADDR
8
FSR REG
PORTC
RC0
RC1
RC2
RC3
RC4
RC5
STATUS REG
8
3
MUX
POWER-UP TIMER
OSCILLATOR START-UP TIMER
POWER-ON RESET
WATCHDOG TIMER
BROWN-OUT DETECT
INSTRUCTION DECODE & CONTROL
ALU
8
OSC1/CLKIN
TIMING GENERATION
W REG
OSC2/CLKOUT
INTERNAL OSCILLATOR BLOCK
MCLR
VDD
VSS
CCP1/P1A
P1B
P1C
P1D
T1G
T1CKI
T0CKI
TIMER0
TIMER1
TIMER2
ECCP
ANALOG-TO-DIGITAL CONVERTER
2 ANALOG COMPARATORS AND REFERENCE
8
EEDATA
256 BYTES DATA EEPROM
EEADDR
VREF
AN0
AN1
AN2
AN3
AN4
AN5
AN6
AN7
C1IN-
C1IN+
C1OUT
C2IN-
C2IN+
C2OUT

PIC18F45K20

PDIP

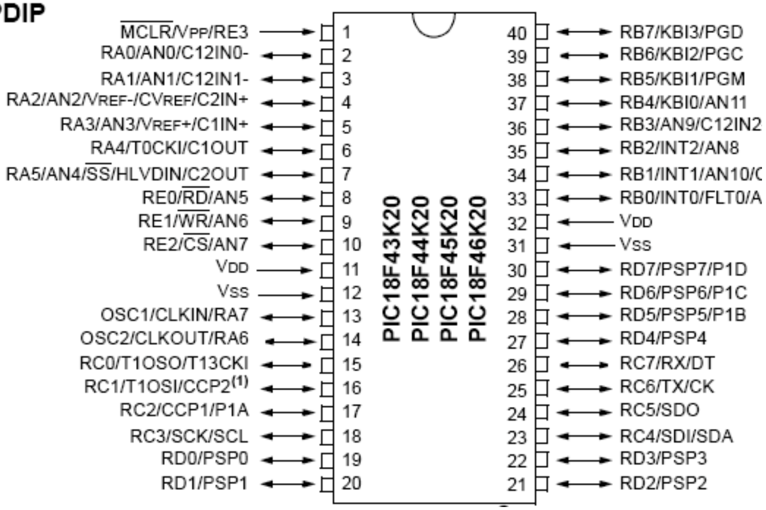
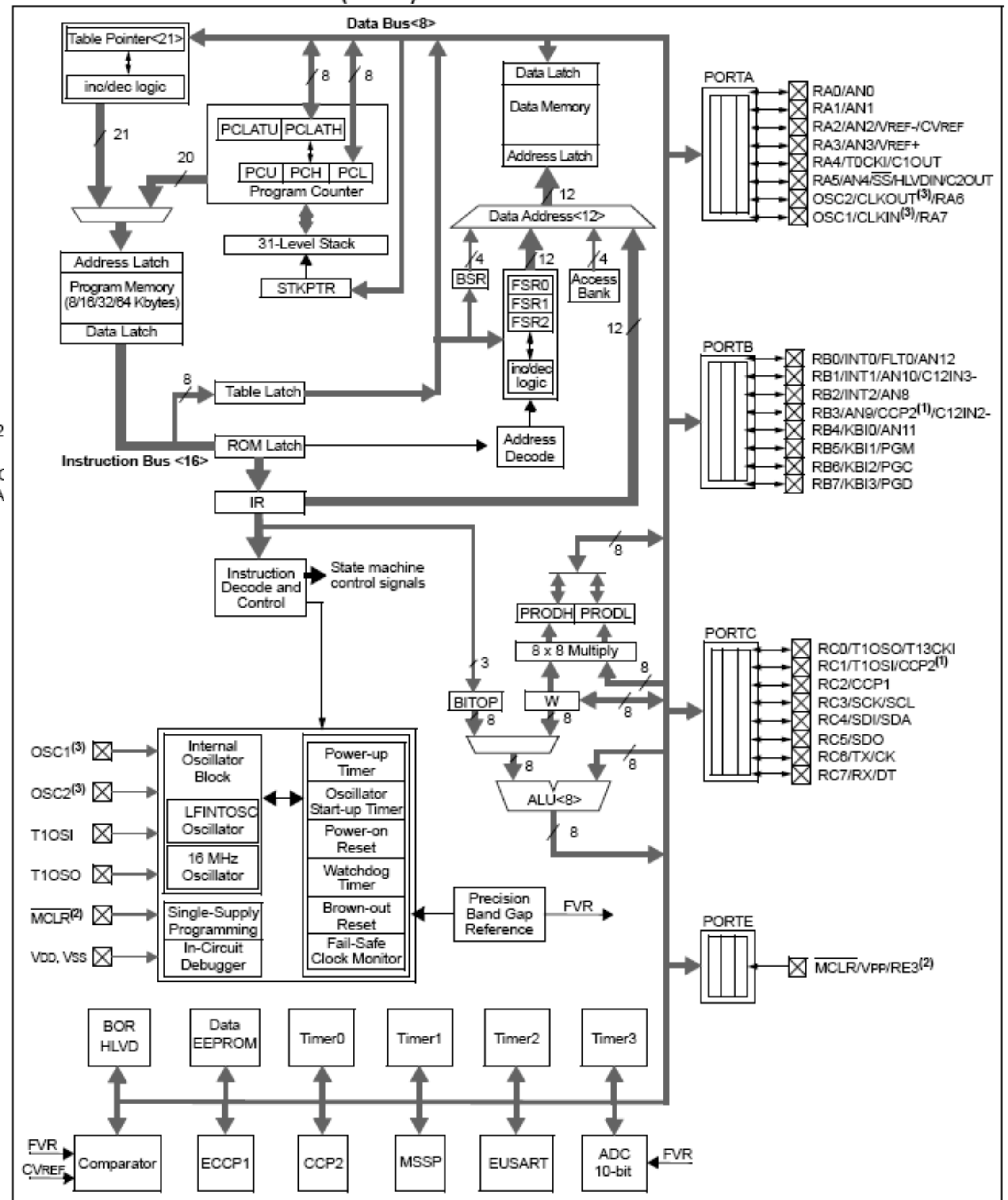
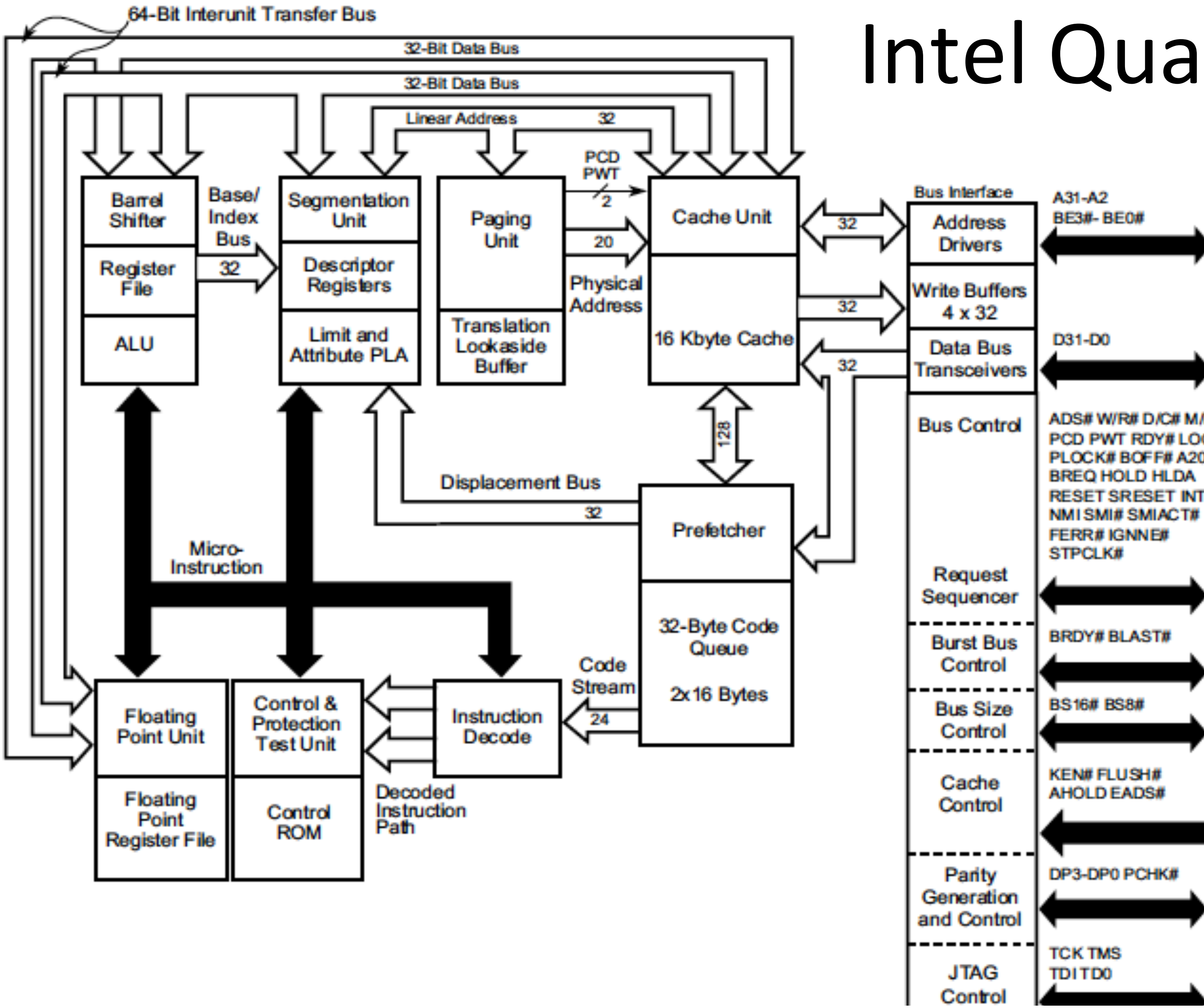


FIGURE 1-1: PIC18F2XK20 (28-PIN) BLOCK DIAGRAM

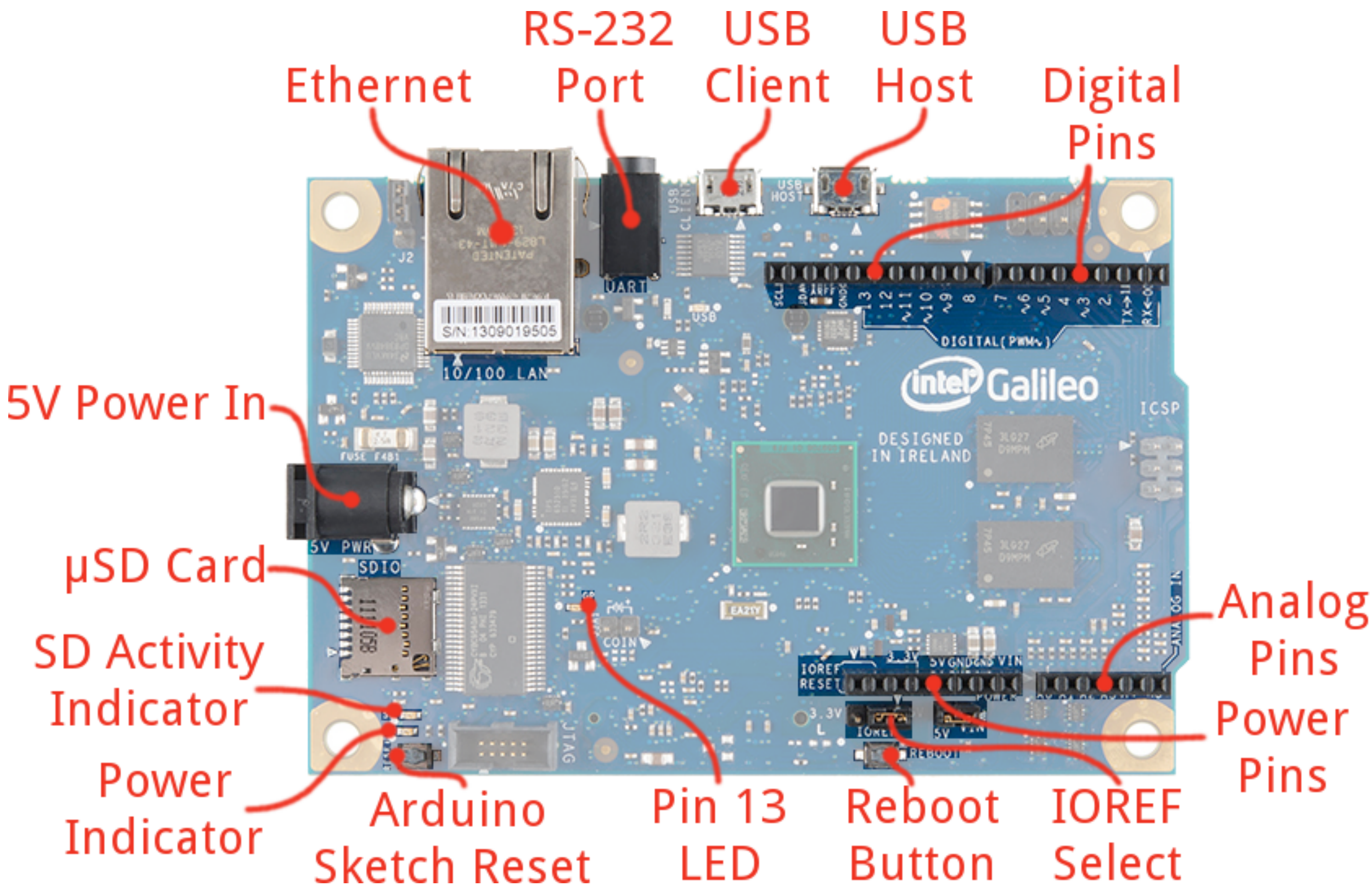


Intel Quark



64-Bit Interunit Transfer Bus
32-Bit Data Bus
32-Bit Data Bus
Linear Address
32
PCD
PWT
2
20
Physical Address
Barrel Shifter
Register File
ALU
Base/ Index Bus
32
Segmentation Unit
Descriptor Registers
Limit and Attribute PLA
Paging Unit
Translation Lookaside Buffer
Cache Unit
16 Kbyte Cache
32
32
32
Bus Interface
Address Drivers
Write Buffers 4 x 32
Data Bus Transceivers
Bus Control
Request Sequencer
Burst Bus Control
Bus Size Control
Cache Control
Parity Generation and Control
JTAG Control
A31-A2
BE3#- BE0#
D31-D0
ADS# W/R# D/C# M/IO#
PCD PWT RDY# LOCK#
PLOCK# BOFF# A20M#
BREQ HOLD HLDA
RESET SRESET INTR
NMI SMI# SMIACT#
FERR# IGNNE#
STPCLK#
BRDY# BLAST#
BS16# BS8#
KEN# FLUSH#
AHOLD EADS#
DP3-DP0 PCHK#
TCK TMS
TDI TD0
128
Displacement Bus
32
Prefetcher
32-Byte Code Queue
2x16 Bytes
Code Stream
24
Micro-Instruction
Floating Point Unit
Floating Point Register File
Control & Protection Test Unit
Control ROM
Instruction Decode
Decoded Instruction Path

Intel Galileo Development Board



Source: https://learn.sparkfun.com/tutorials/galileo-getting-started-guide

Summary

- Embedded systems are everywhere
- Key challenge: optimization of design metrics
  - Design metrics compete with one another
- A unified view of hardware and software is necessary to improve productivity
- Three key technologies
  - Processor: general-purpose, application-specific, single-purpose
  - IC: Full-custom, semi-custom, PLD, Moore's Law
  - Design: hw/sw co-design, design productivity
- Embedded Processors: architecture and applications