

16.480/552

- Course web
 - <http://yanluo.github.io/teaching/16.480.552/>
- Course discussion forum
 - We use the web based forum on piazza.com (please search the course number 16.480)
- Lectures and lab sessions
 - mandatory
- Lab assignments, reports, and demo
 - Hardware/software design, debugging, testing
- Exams
 - Two in-class 90-minute exams
- Grading
 - Labs-60%, Exams-40%,
 - 16.480 and 16.552 graded in separate scale

Introduction to Embedded Systems



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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

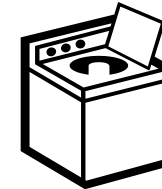
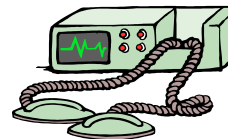
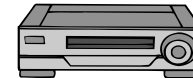
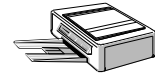
- Embedded computing systems
 - Computing systems embedded within electronic devices
 - Hard to define. Nearly any computing system other than a desktop computer
 - Billions of units produced yearly, versus millions of desktop units
 - Perhaps 50 per household and per automobile



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

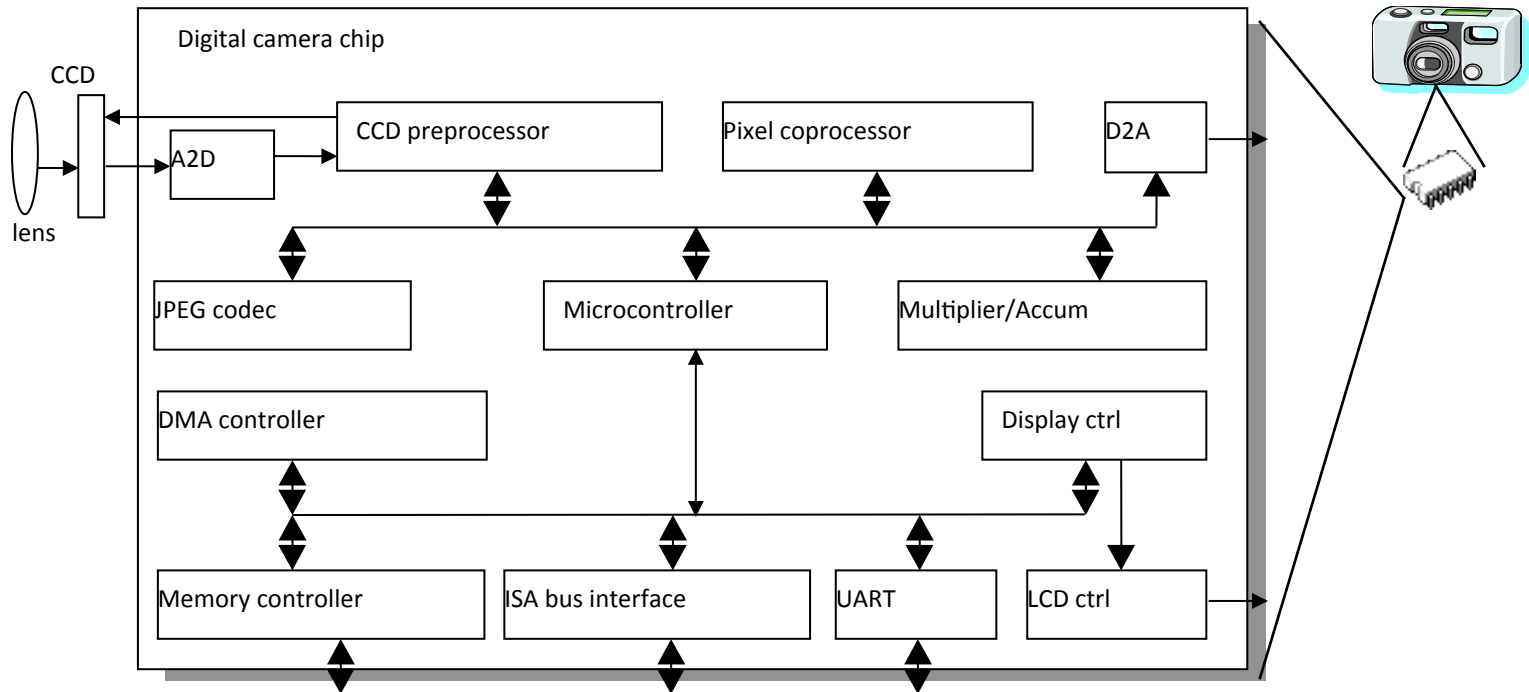


And the list goes on and on

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

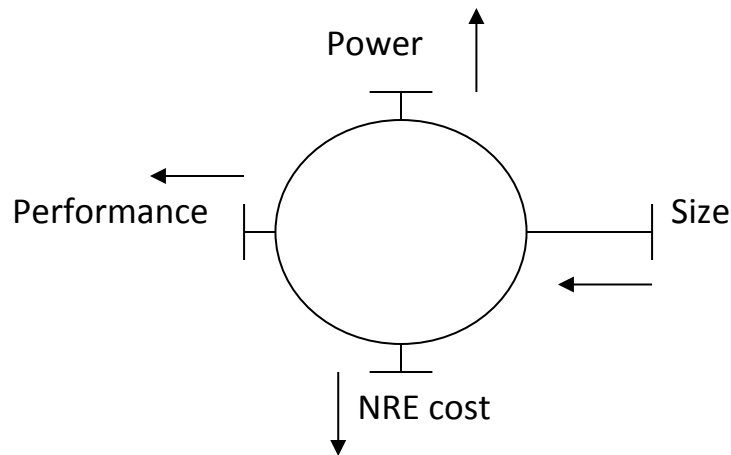
- Common metrics

- **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

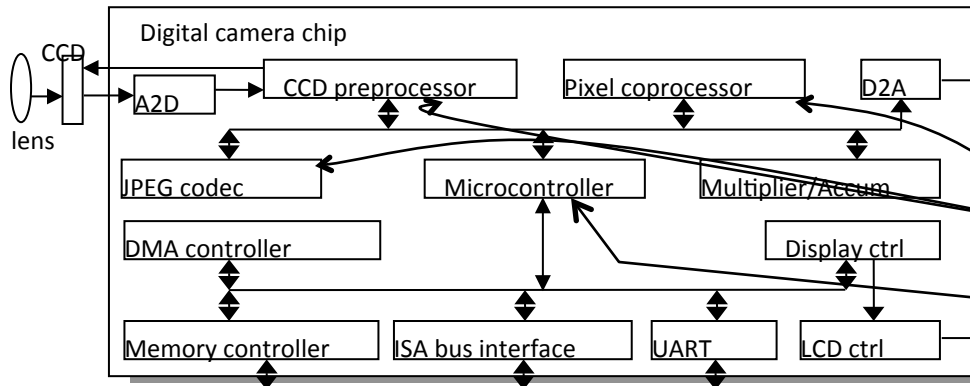
Design challenge – optimizing design metrics

- 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



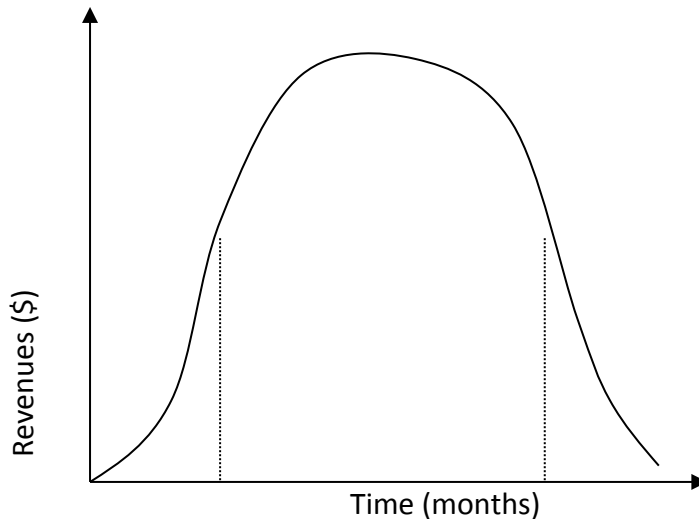
- Expertise with both **software and hardware** is needed to optimize design metrics
 - Not just a hardware or software expert, as is common
 - A designer must be comfortable with various technologies in order to choose the best for a given application and constraints



Hardware

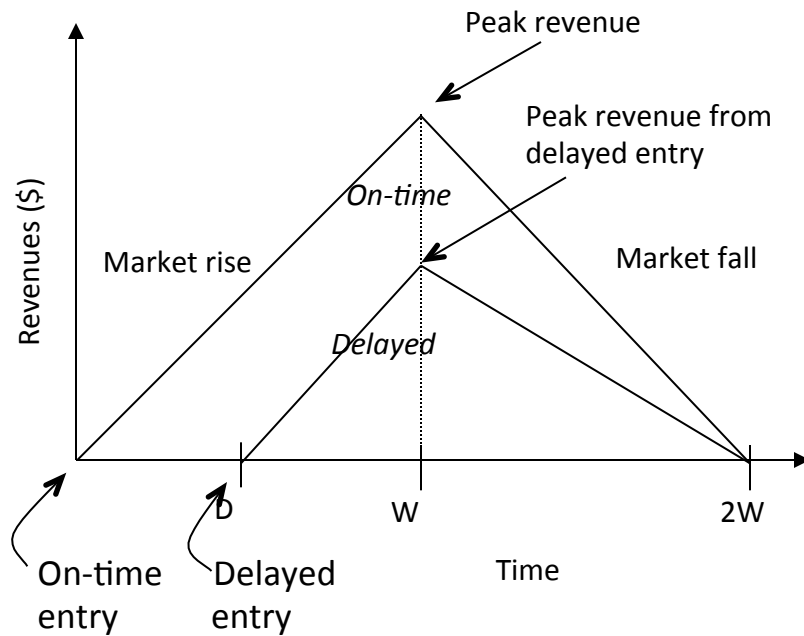
Software

Time-to-market: a demanding design metric



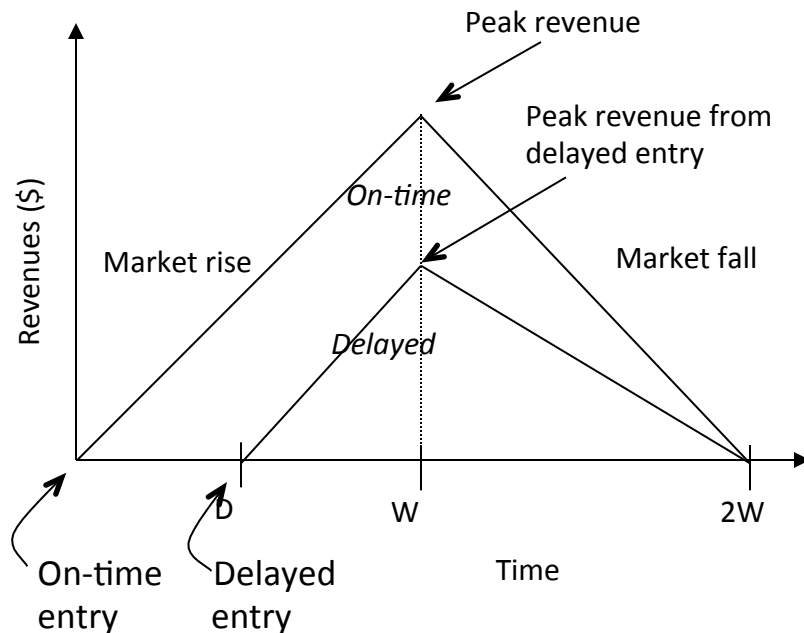
- Time required to develop a product to the point it can be sold to customers
- Market window
 - Period during which the product would have highest sales
- Average time-to-market constraint is about 8 months
- Delays can be costly

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 = $\frac{1}{2} * \text{base} * \text{height}$
 - On-time = $\frac{1}{2} * 2W * W$
 - Delayed = $\frac{1}{2} * (W-D+W)*(W-D)$
- 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!

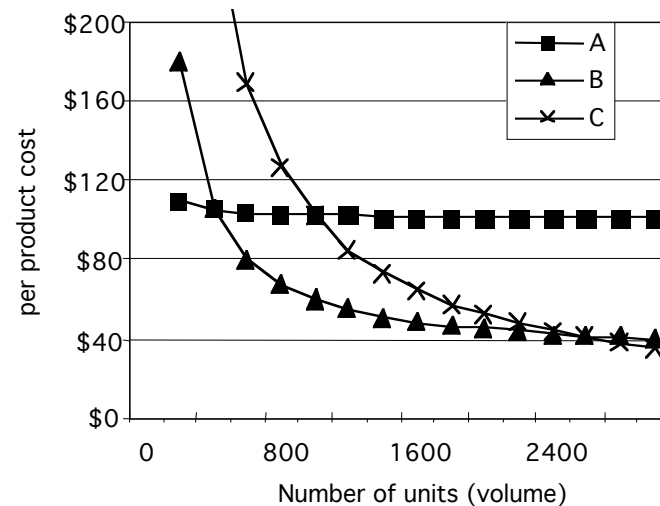
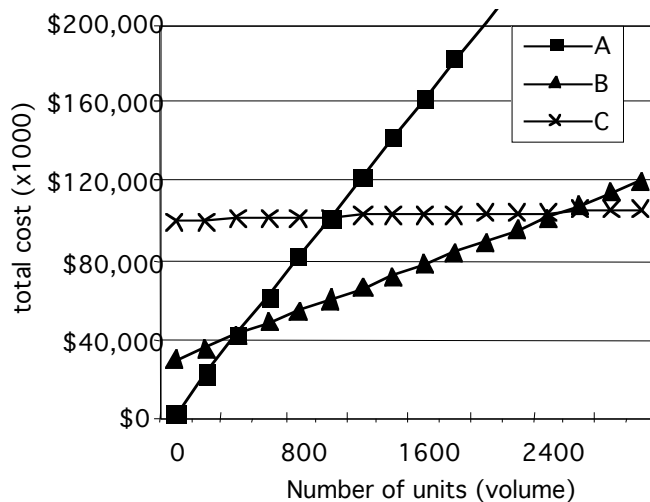
NRE and unit cost metrics

- 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
 - $\text{total cost} = \text{NRE cost} + \text{unit cost} * \# \text{ of units}$
 - $\text{per-product cost} = \text{total cost} / \# \text{ of units}$
 $= (\text{NRE cost} / \# \text{ of units}) + \text{unit cost}$
- Example
 - NRE=\$2000, unit=\$100
 - For 10 units
 - $\text{total cost} = \$2000 + 10 * \$100 = \$3000$
 - $\text{per-product cost} = \underbrace{\$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

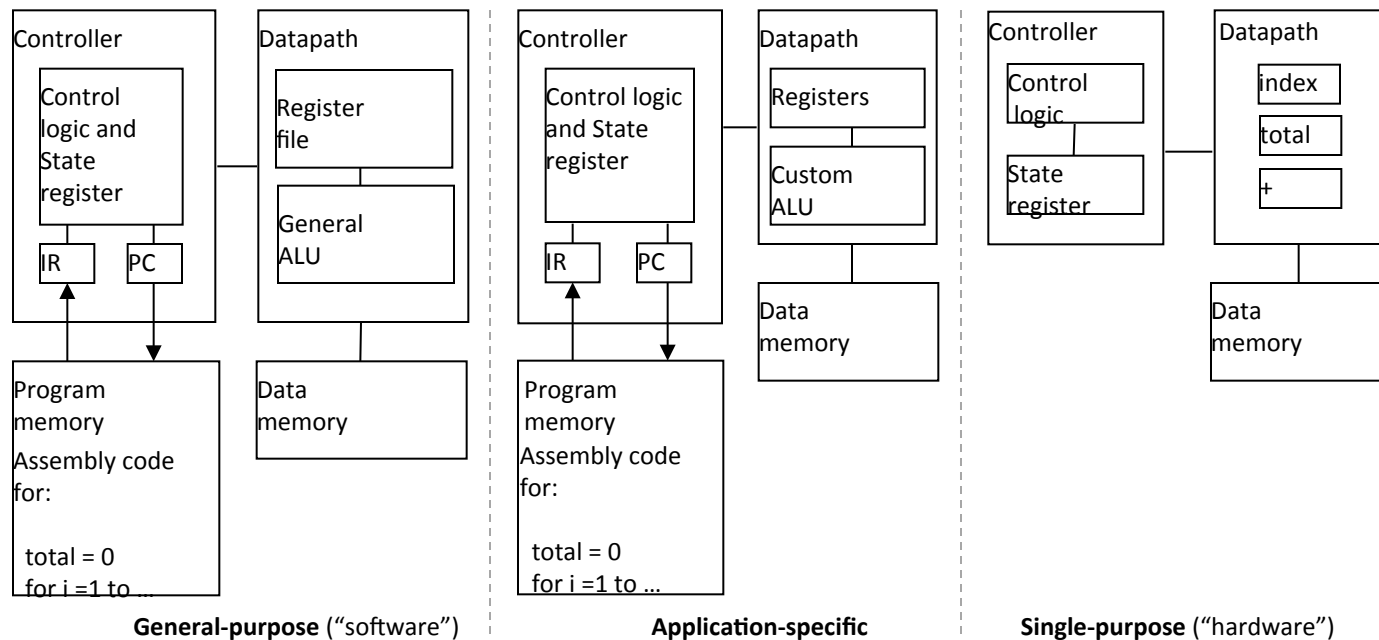
- Widely-used measure of system, widely-abused
 - Clock frequency, instructions per second – not good measures
 - Digital camera example – a user cares about how fast it processes images, not clock speed or instructions per second
- Latency (response time)
 - Time between task start and end
 - e.g., 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

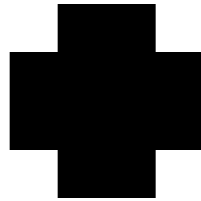
Processor technology

- 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

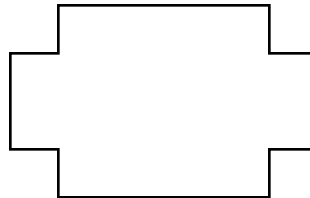


Desired
functionality

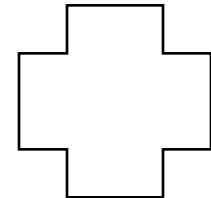
```
total = 0
for i = 1 to N loop
  total += M[i]
end loop
```



General-purpose
processor



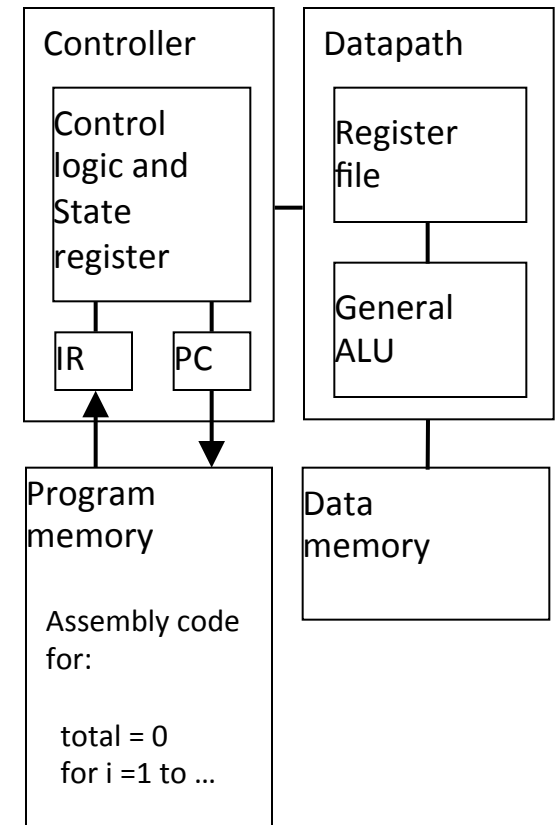
Application-specific
processor



Single-purpose
processor

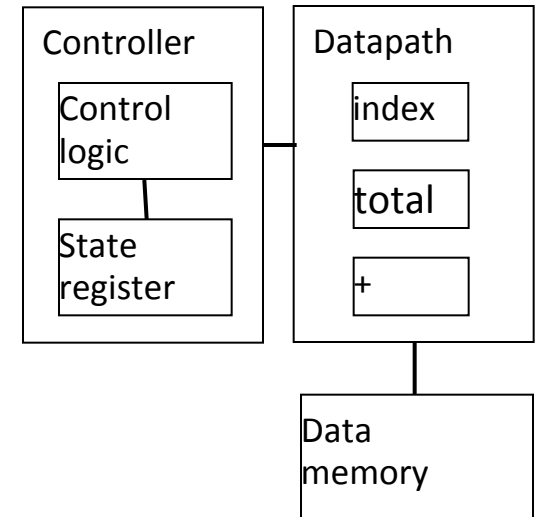
General-purpose processors

- 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



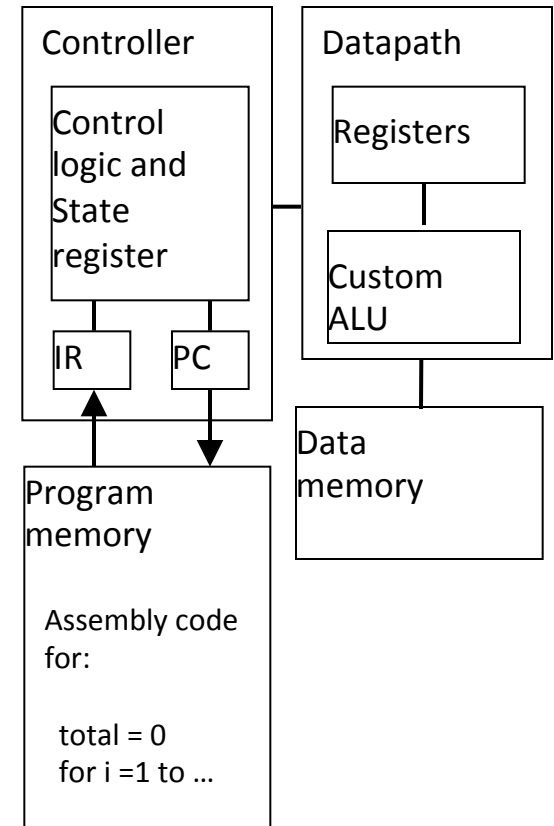
Single-purpose processors

- 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



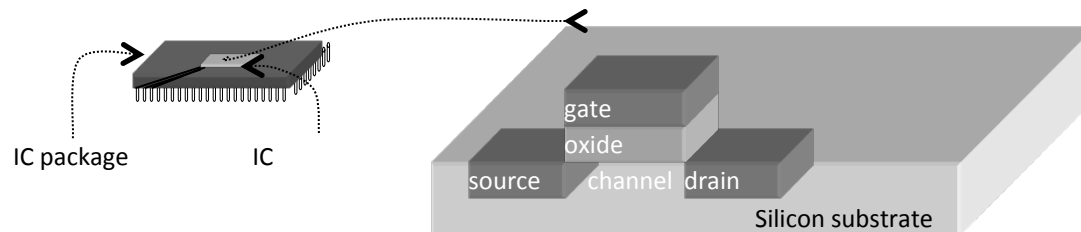
Application-specific processors

- 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

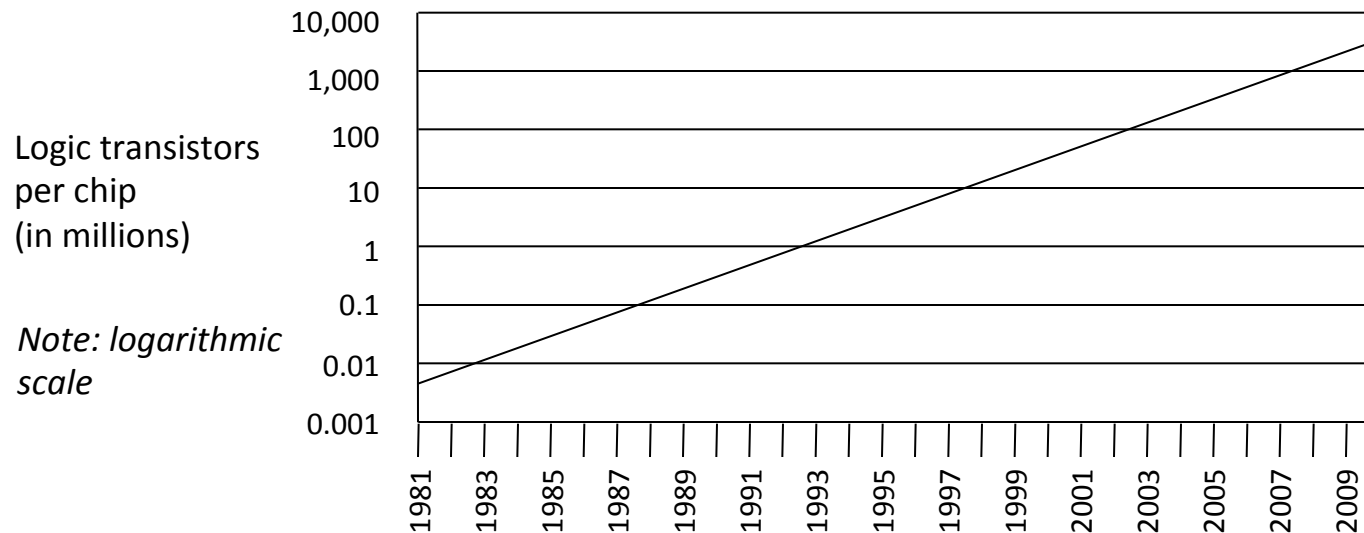
- Lower layers are fully or partially built
 - Designers are left with routing of wires and maybe placing some blocks
- Benefits
 - Good performance, good size, less NRE cost than a full-custom implementation (perhaps \$10k to \$100k)
- Drawbacks
 - Still require weeks to months to develop

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**

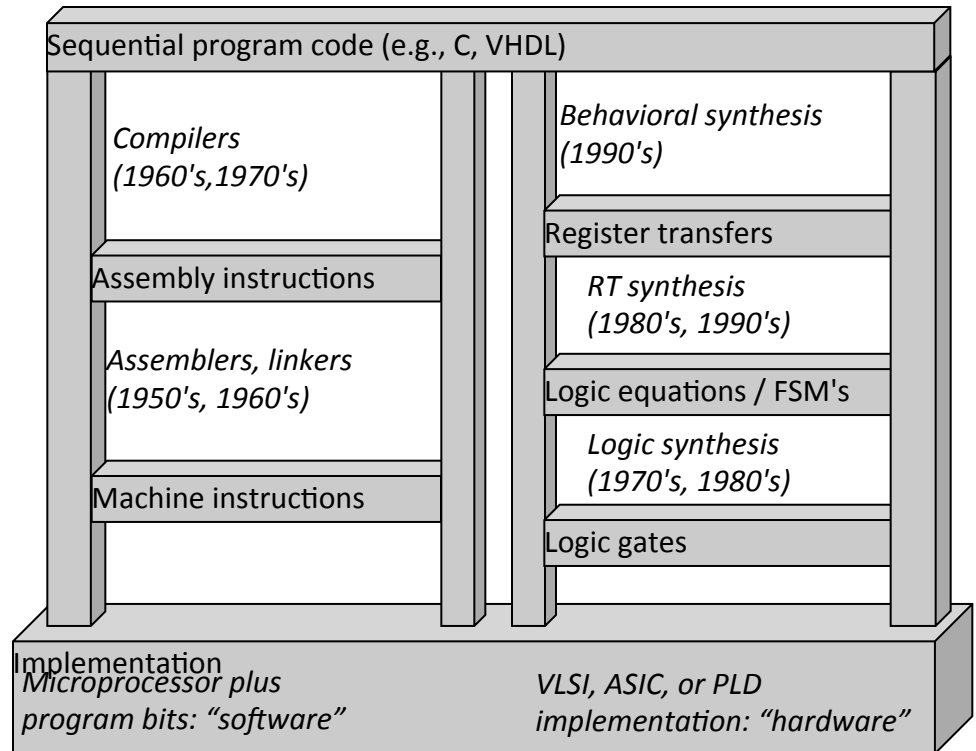


The Future of Moore's law

- 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

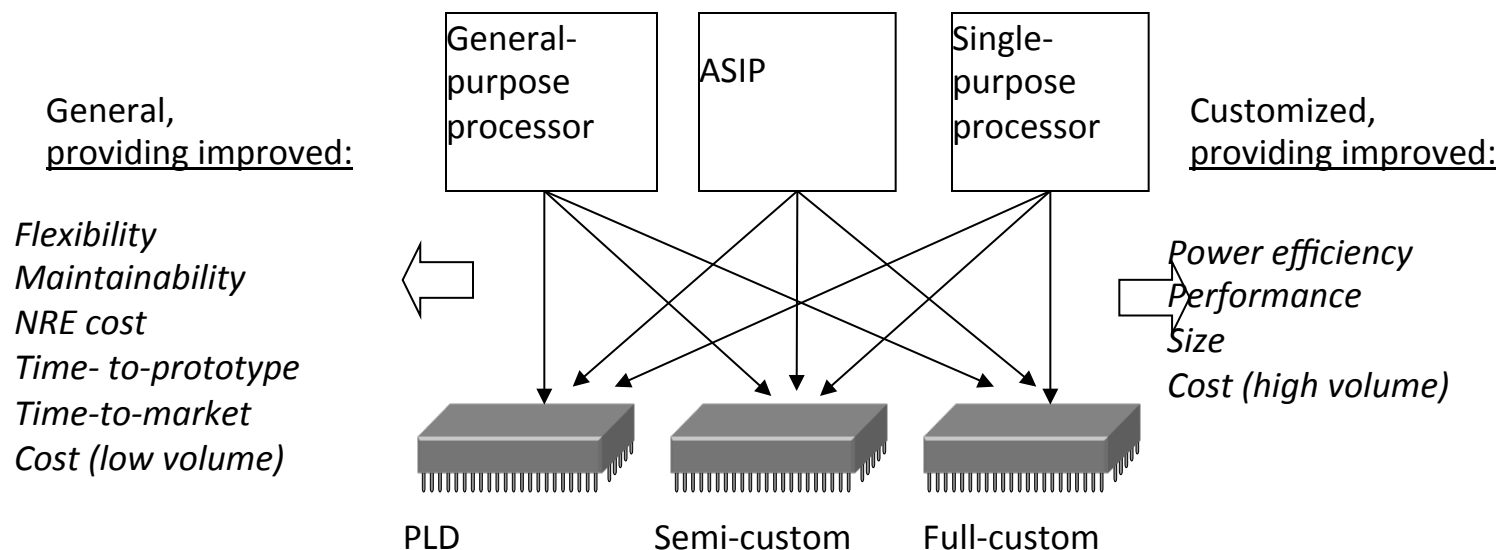
- In the past:
 - Hardware and software design technologies were very different
 - Recent maturation of synthesis enables a unified view of hardware and software
- Hardware/software “codesign”



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.

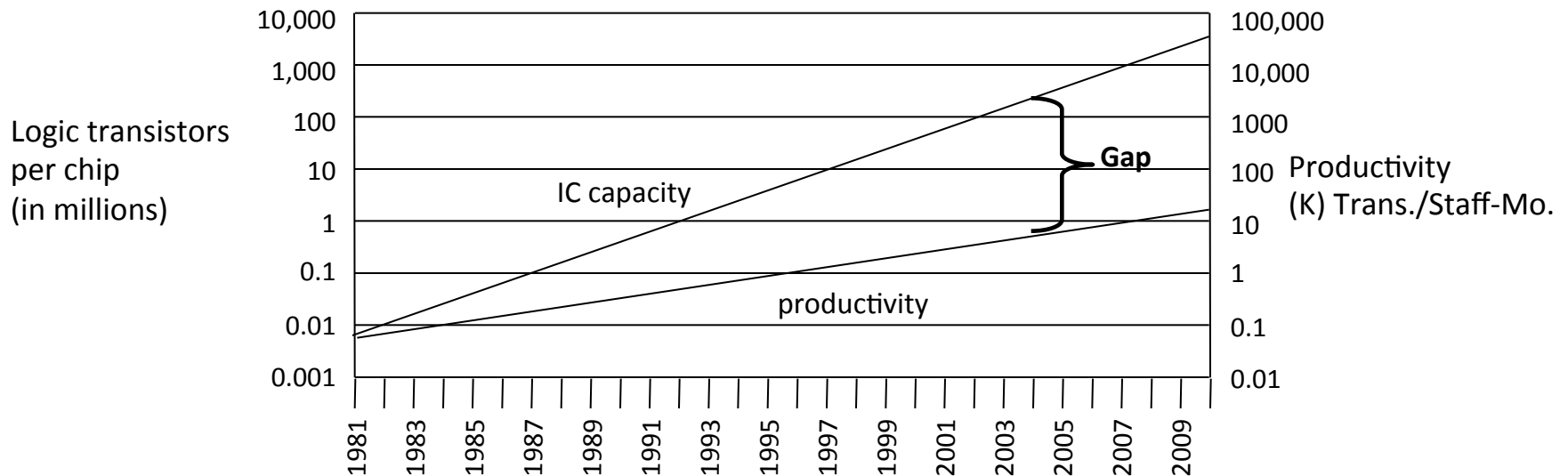
Independence of processor and IC technologies

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



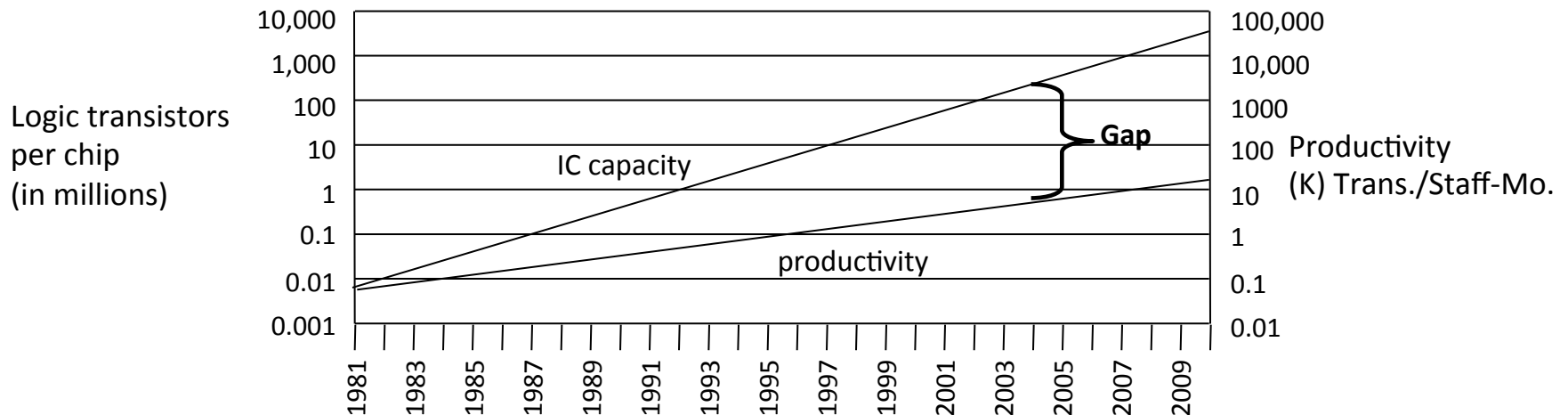
Design productivity gap

- 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

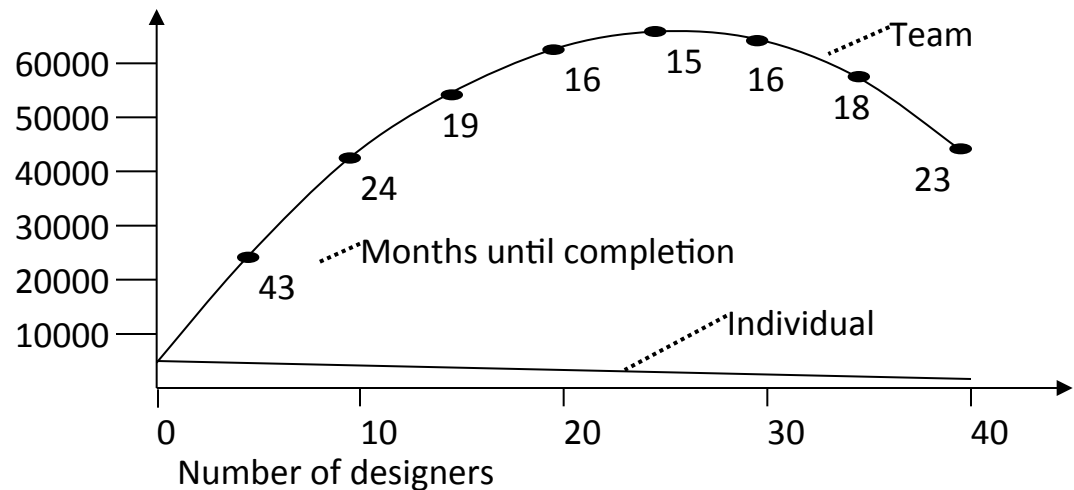
- 1981 leading edge chip required 100 designer months
 - 10,000 transistors / 100 transistors/month
- 2002 leading edge chip requires 30,000 designer months
 - 150,000,000 / 5000 transistors/month
- Designer cost increase from \$1M to \$300M



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

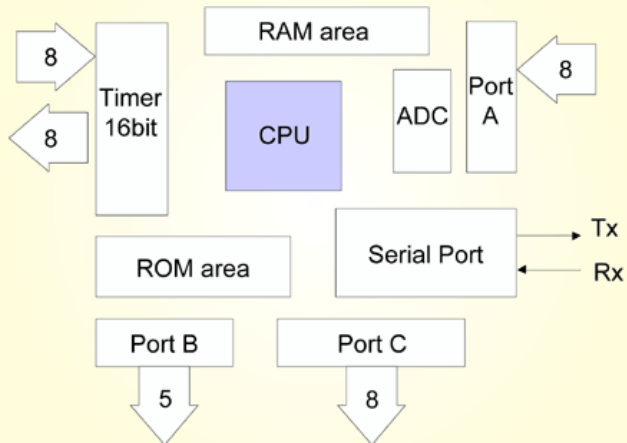


Embedded Processors

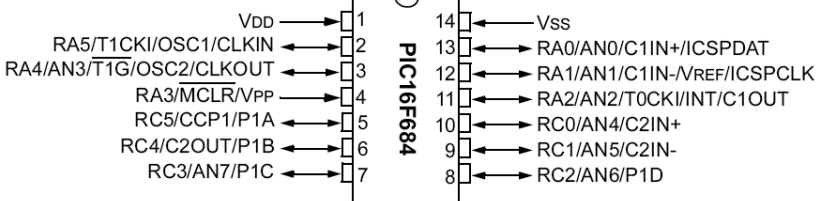
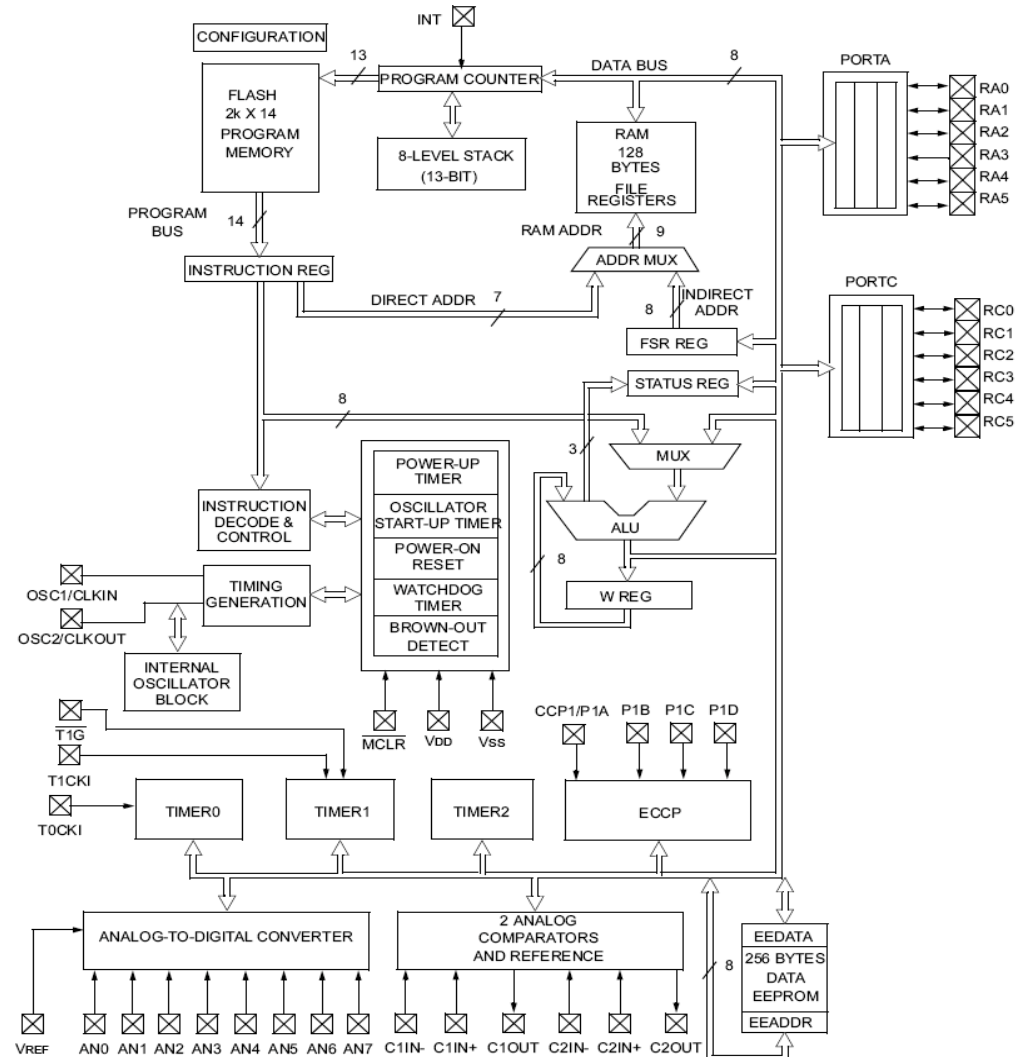
- Requirements for embedded processors
 - Low power consumption
 - Programmable
 - Low cost
- Examples
 - Microcontroller-type:
 - self-contained (mem, I/O, ADC, etc.), GPIO,
 - no OS, less interactive environment e.g. sensor data acquisition
 - Microchip PIC, Intel 8051, Parallax Propeller, Atmel AVR, 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



CPU: The processing module of the microcontroller



PIC18F45K20

PDIP

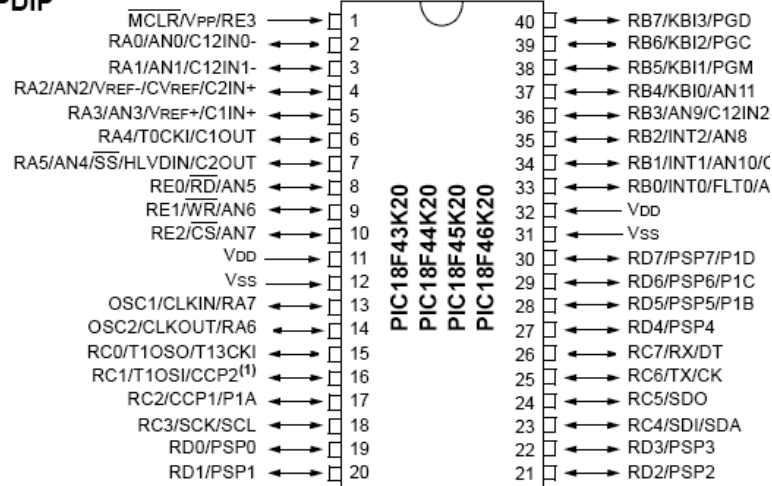
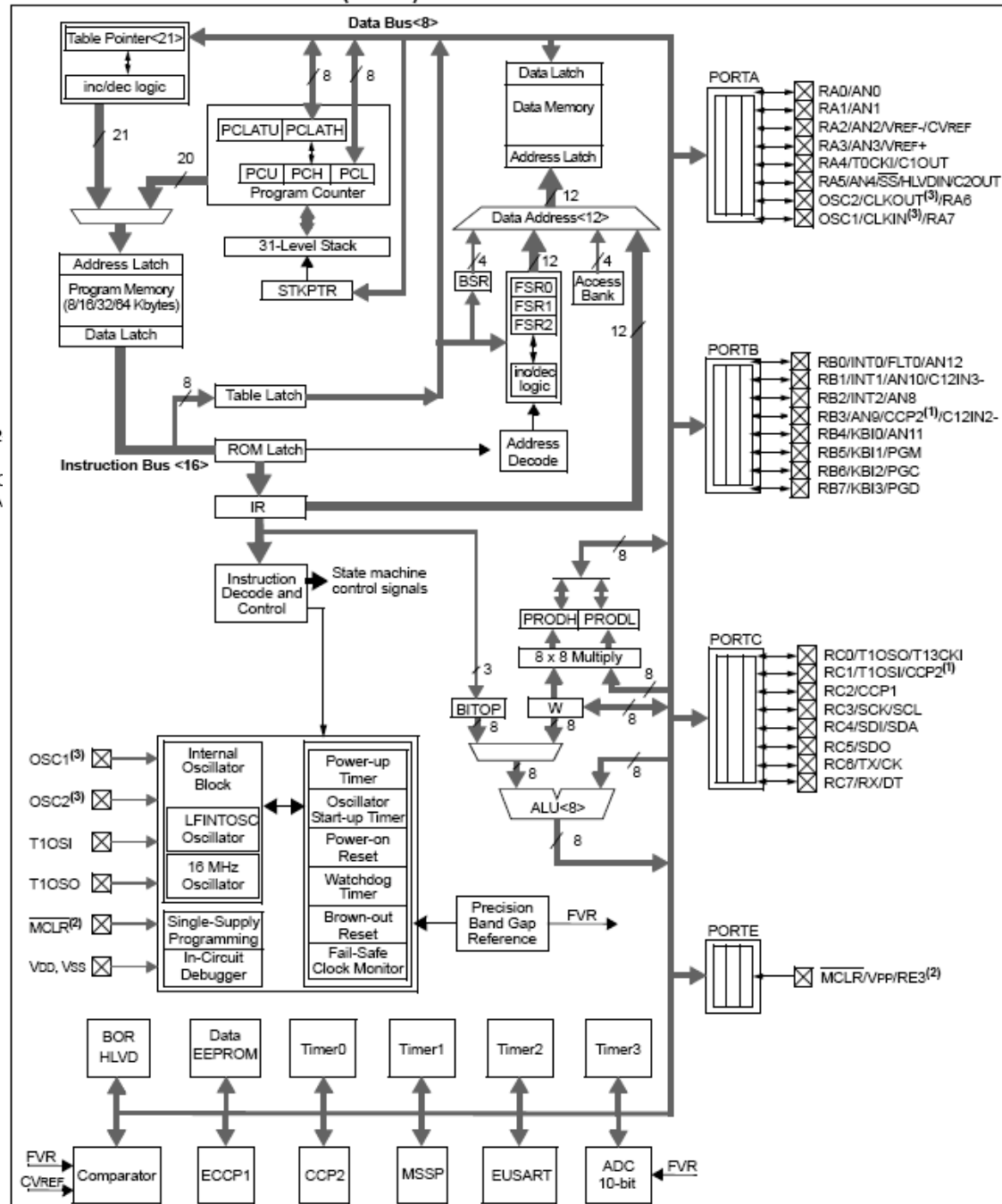
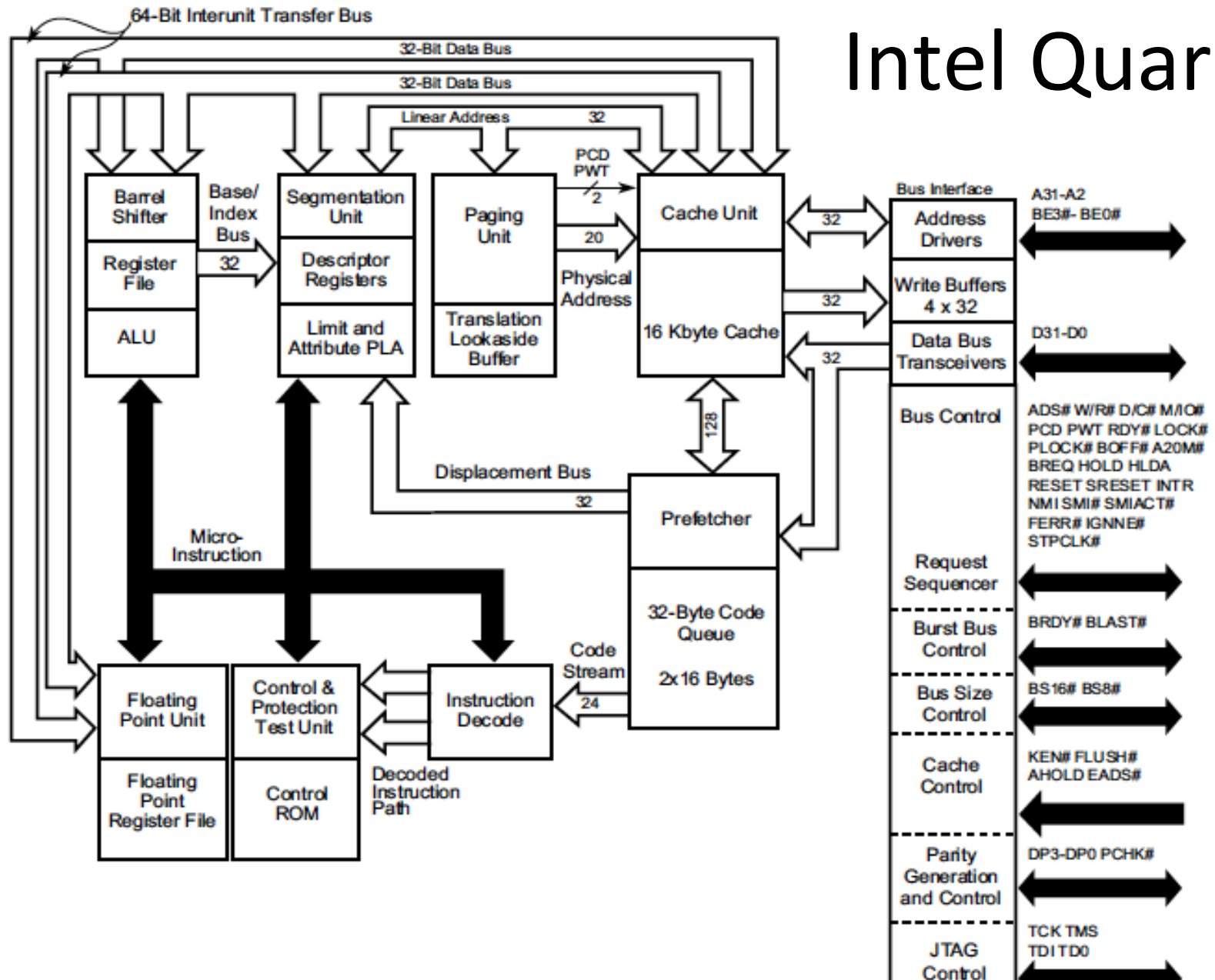


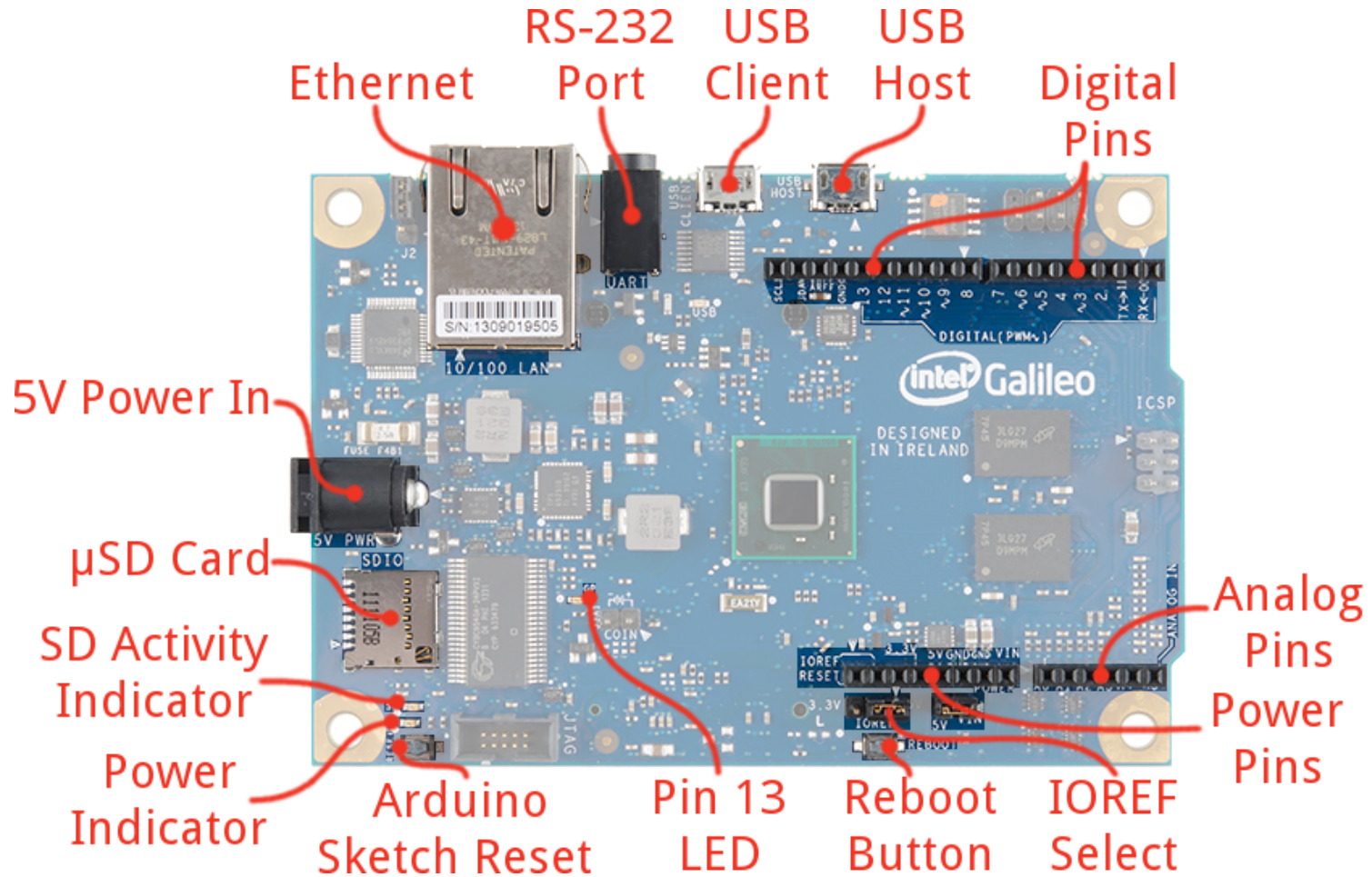
FIGURE 1-1: PIC18F2XK20 (28-PIN) BLOCK DIAGRAM



Intel Quark



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