CS245 – Lecture 1

Embedded Systems Review

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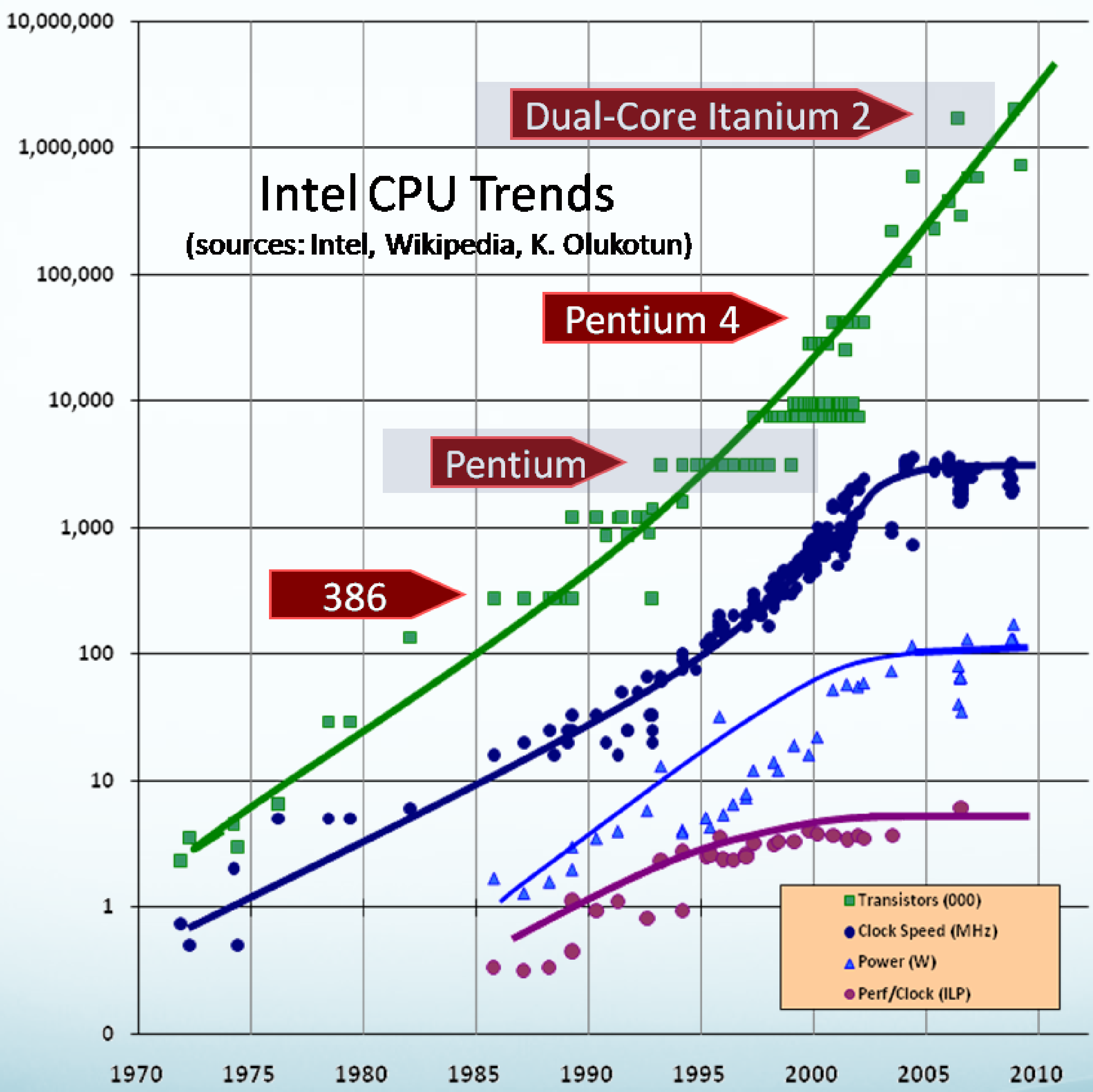
A Little History

- 1947 – Shockley, Brattain, and Bardeen invented the transistor at Bell Labs
- 1961 – First commercial IC by Fairchild/TI
- 1963 – CMOS invented
- 1965 – Moore’s law
- 1968 – State of the art: 64 transistor chip

Moore's Law

- "Transistor capacity doubles every 18 months."
- Driving force behind
  - Research and industry
  - Embedded systems
  - EDA
  - PCs
  - Internet
  - PDAs
  - Aerospace, Automobiles, Defense, …



Intel CPU Trends
(sources: Intel, Wikipedia, K. Olukotun)
Dual-Core Itanium 2
Pentium 4
Pentium
386
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
Transistors (000)
Clock Speed (MHz)
Power (W)
Perf/Clock (ILP)

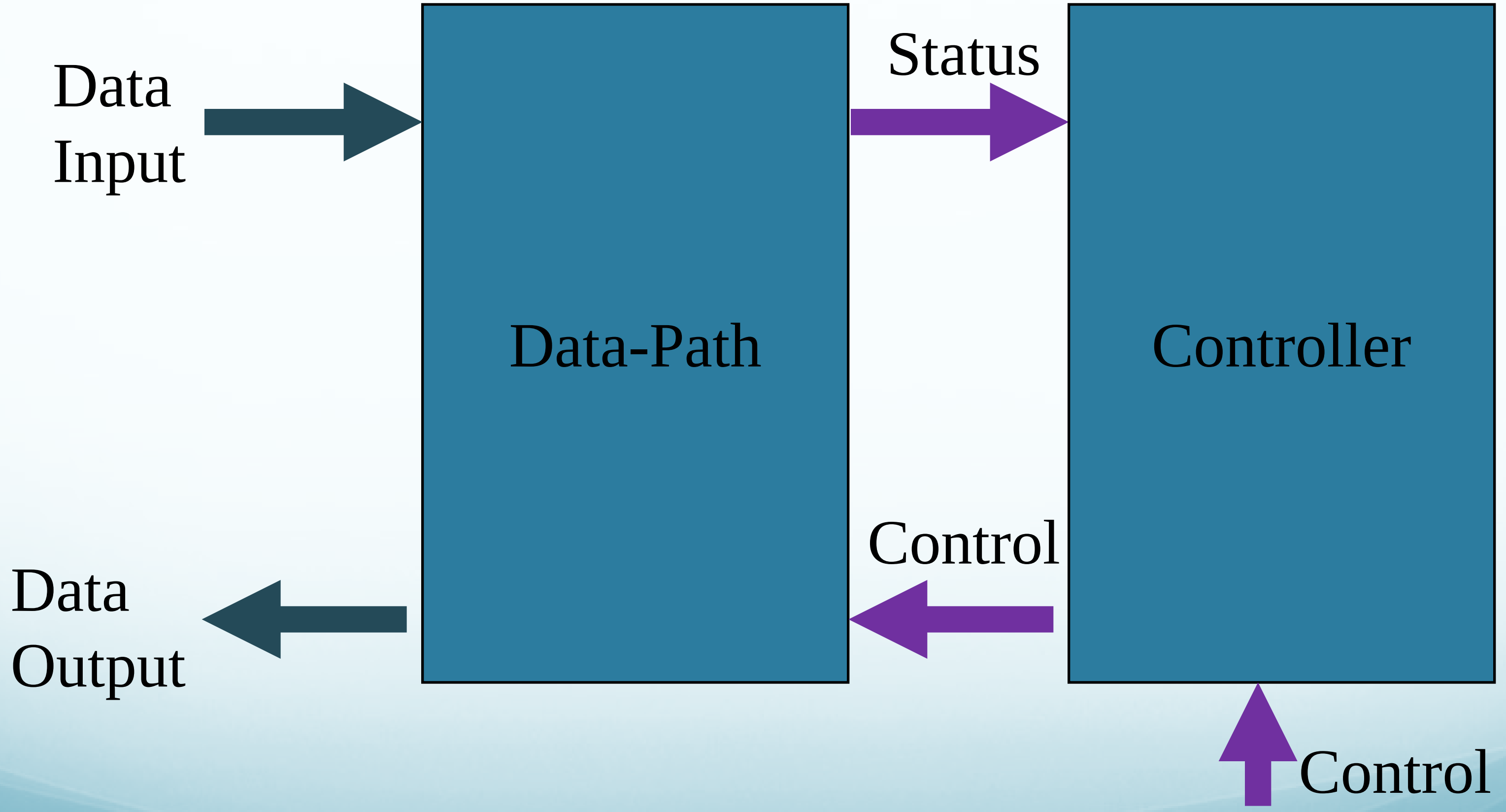
Embedded Systems

- Devices other than desktop PCs, servers, and notebooks
  - Electricity running through
  - Perform something intelligent
- Hardware/software which form a component of a larger system, but are concealed from user
- Computers camouflaged as non-computers
- The future of computing!

Processors

- What is a processor?
  - Artifact that computes (runs algorithms)
  - Controller and data-path
- General-purpose (GP) processors:
  - Variety of computation tasks
  - Functional flexibility
  - Slow and power hungry
- Single-purpose (SP) processors:
  - One computation task
  - Functional inflexibility
  - Fast and power efficient

GP/SP Processor Architecture



GP vs. SP Processors

GP:

- Programmable controller
  - Control logic is stored in memory
  - Fetch/decode overhead
- Highly general data-path
  - Typical bit-width (8, 16, 32, 64)
  - Complete set of arithmetic/logic units
  - Large set of registers

SP:

- Hardwired controller
  - No need for program memory and cache
  - No fetch/decode overhead
- Highly tuned data-path
  - Custom bit-width
  - Custom arithmetic/logic units
  - Custom set of registers

Storage

- What is a memory?
  - Artifact that stores bits
  - Storage fabric and access logic
- Write-ability
  - Manner and speed a memory can be written
- Storage-permanence
  - ability of memory to hold stored bits after they are written
- Many different types of memories
  - Flash, SRAM, DRAM, etc.
- Common to compose memories

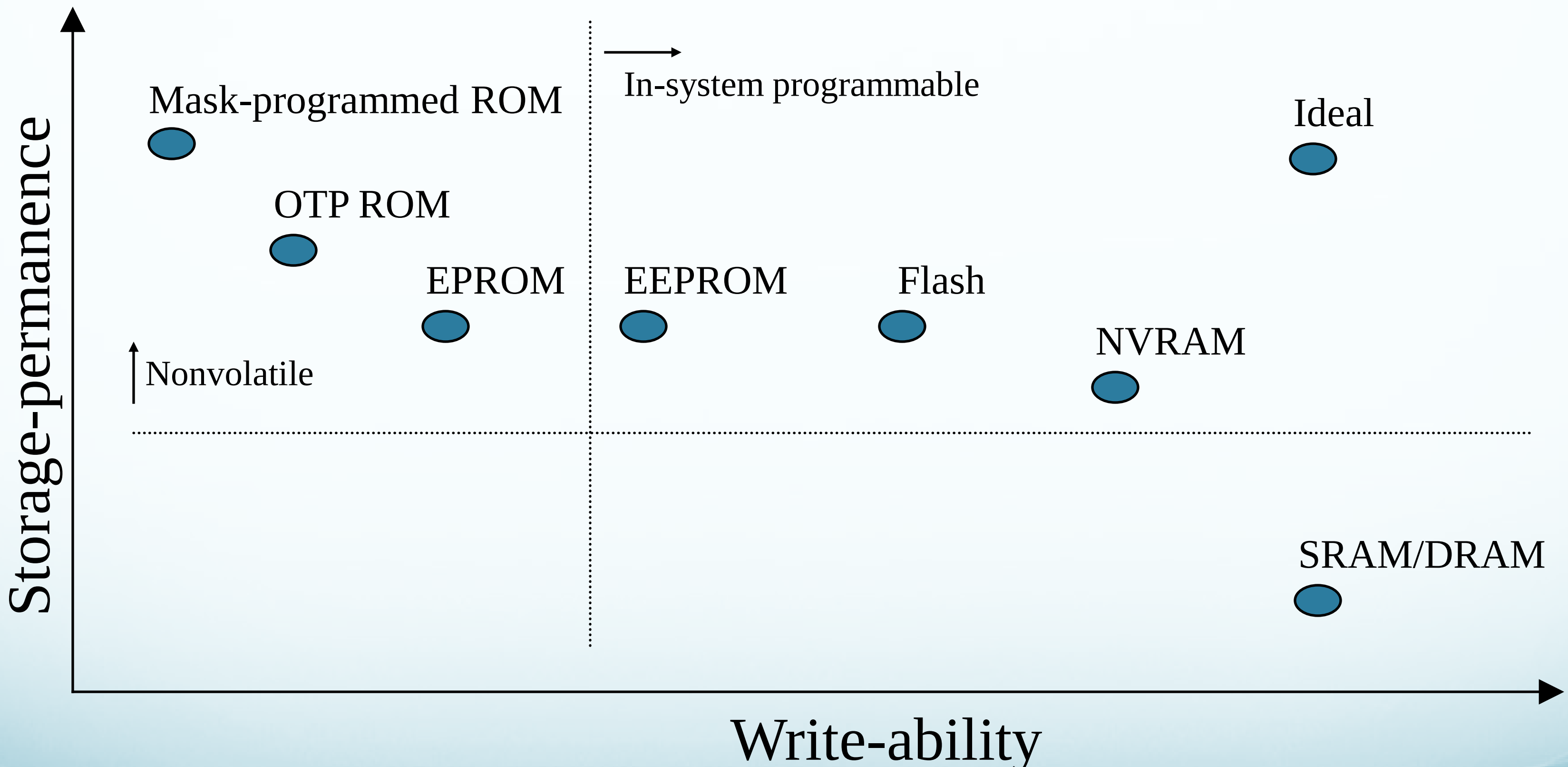
Write-ability

- Ranges of write-ability
  - High end
    - Processor writes to memory simply and quickly
    - E.g., RAM
  - Middle range
    - Processor writes to memory, but slower
    - E.g., FLASH, EEPROM
  - Lower range
    - Special equipment, “programmer”, must be used to write to memory
    - E.g., EPROM, OTP ROM
  - Low end
    - Bits stored only during fabrication
    - E.g., Mask-programmed ROM

Storage-permanence

- Range of storage-permanence
  - High end
    - Essentially never loses bits
    - E.g., mask-programmed ROM
  - Middle range
    - Holds bits days/months/years after memory's power source turned off
    - E.g., NVRAM
  - Lower range
    - Holds bits as long as power supplied to memory
    - E.g., SRAM
  - Low end
    - Begins to lose bits almost immediately after written
    - E.g., DRAM

Memory Types



Communication

- What is a bus?
  - An artifact that transfers bits
  - Wires, air, or fiber and interface logic
- Associated with a bus, we have:
  - Connectivity scheme
    - Serial Communication
    - Parallel Communication
    - Wireless Communication
  - Protocol
    - Ports
    - Timing Diagrams
    - Read and write cycles
  - Arbitration scheme, error detection/correction, DMA, etc.

Serial Communication

- A single wire used for data transfer
- One or more additional wires used for control (but, some protocols may not use additional control wires)
- Higher throughput for long distance communication
  - Often across processing node
- Lower cost in terms of wires (cable)
- E.g., USB, Ethernet, PCIe, RS232, I^2C, etc.

Parallel Communication

- Multiple wires used for data transfer
- One or more additional wires used for control
- Higher throughput for short distance communication
  - Data misalignment problem
  - Often used within a processing node
- Higher cost in terms of wires (cable)
- E.g., ISA, AMBA, PCI, etc.

Wireless Communication

- Infrared (IR)
  - Electronic wave frequencies just below visible light spectrum
  - Diode emits infrared light to generate signal
  - Infrared transistor detects signal, conducts when exposed to infrared light
  - Cheap to build
  - Need line of sight, limited range
- Radio frequency (RF)
  - Electromagnetic wave frequencies in radio spectrum
  - Analog circuitry and antenna needed on both sides of transmission
  - Line of sight not needed, transmitter power determines range

Peripherals

- Perform specific computation task
- *Custom* single-purpose processors
  - Designed by us for a unique task
- *Standard* single-purpose processors
  - “Off-the-shelf”
  - pre-designed for a common task

Timers/Counters

- Timers: measure time intervals
  - To generate timed output events
  - To measure input events
  - Top: max count reached
- Range and resolution
- Counters: like a timer, but count pulses on a general input signal rather than clock
  - e.g., count cars passing over a sensor
  - Can often configure physical device as either a timer or counter

Watchdog Timers

- Must reset timer every X time units, else timer generates a signal
- Common use: detect failure, self-reset

Pulse Width Modulators

- Generate pulses with specific high/low times
- Duty cycle: % time high
  - Square wave: 50% duty cycle
- Common use: control average voltage to electric device
  - Simpler than DC-DC converter or digital-analog converter
  - DC motor speed, dimmer lights

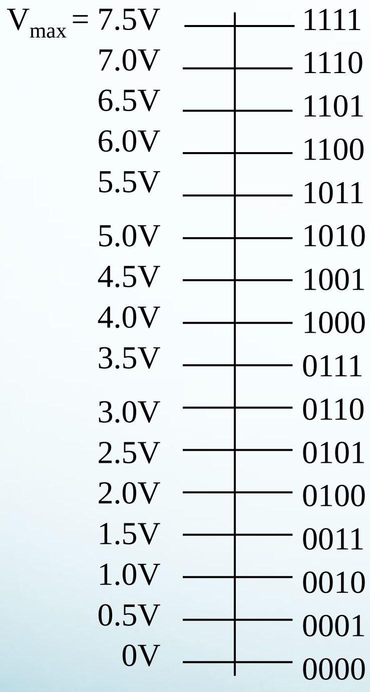
Displays & Keypads

- N rows by M columns
- Controller may be build into the LCD module or managed in software
- Display: challenge is to reverse polarity and scan the pixels at a high rate
- Keypad: challenge is to scan at a high rate

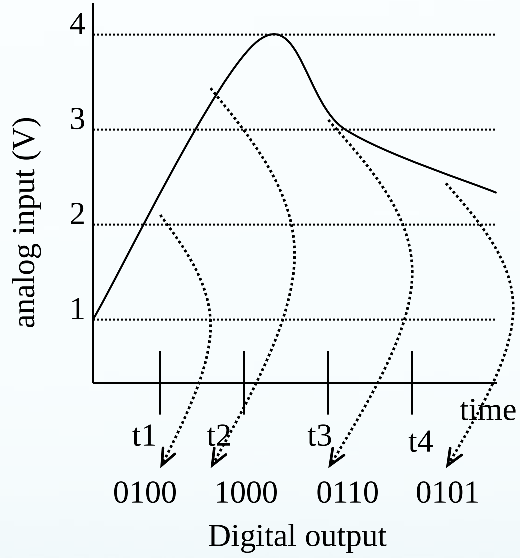
Stepper Motor Controller

- Stepper motor: rotates fixed number of degrees when given a “step” signal
  - In contrast, DC motor just rotates when power applied, coasts to stop
- Rotation achieved by applying specific voltage sequence to coils
- Controller greatly simplifies this

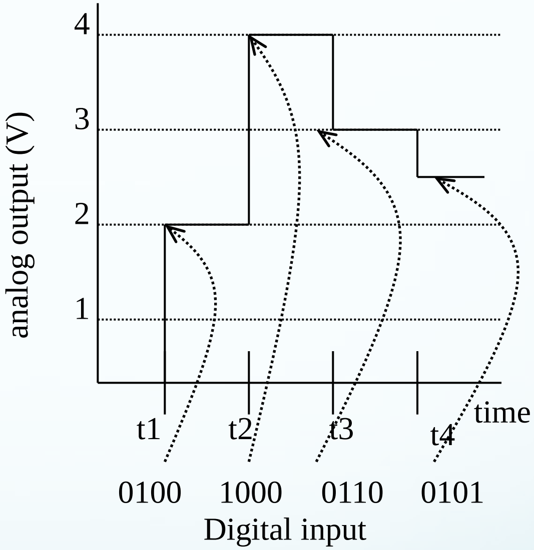
Analog-to-Digital Converter



proportionality



analog to digital



digital to analog

Real-time Systems

- A real-time system has to produce correct result at the right time (deadline driven)
- A real-time system imposes stringent timing requirements in addition to correctness
  - Hard real-time
  - Firm real-time
  - Soft real-time

Hard Real-time

- System designed to meet all deadlines
- A missed deadline is a design flaw
- Examples:
  - Shuttle navigation system
  - Nuclear reactor monitoring system
- System hardware (over) designed for worst-case performance
- System software vigorously tested
- Formal proofs used to guaranty timing correctness

Firm Real-time

- System designed to meet all deadlines, but
  - "Occasional" missed deadline is allowed
    - Sometimes statistically quantified (e.g., 5% misses)
  - No need to compute further once a deadline is missed
- Examples:
  - Multimedia systems
- System hardware designed for average case performance
- System software tested under average (ideal) conditions

Soft Real-Time

- System designed to meet as many deadlines as possible
  - Best effort to complete within specified time, but may be late
- Examples:
  - Network switch or router
- System hardware designed for average case performance
- System software tested under average (ideal) conditions

Embedded Operating Systems

- Must provide means for dynamic task creation
  - Create, join, and cancel
- Must provide means for task synchronization and communication
  - Shared memory vs. message passing
  - Semaphore and condition variables vs. monitors
- Posix threads a common standard provides thread creation and synchronization

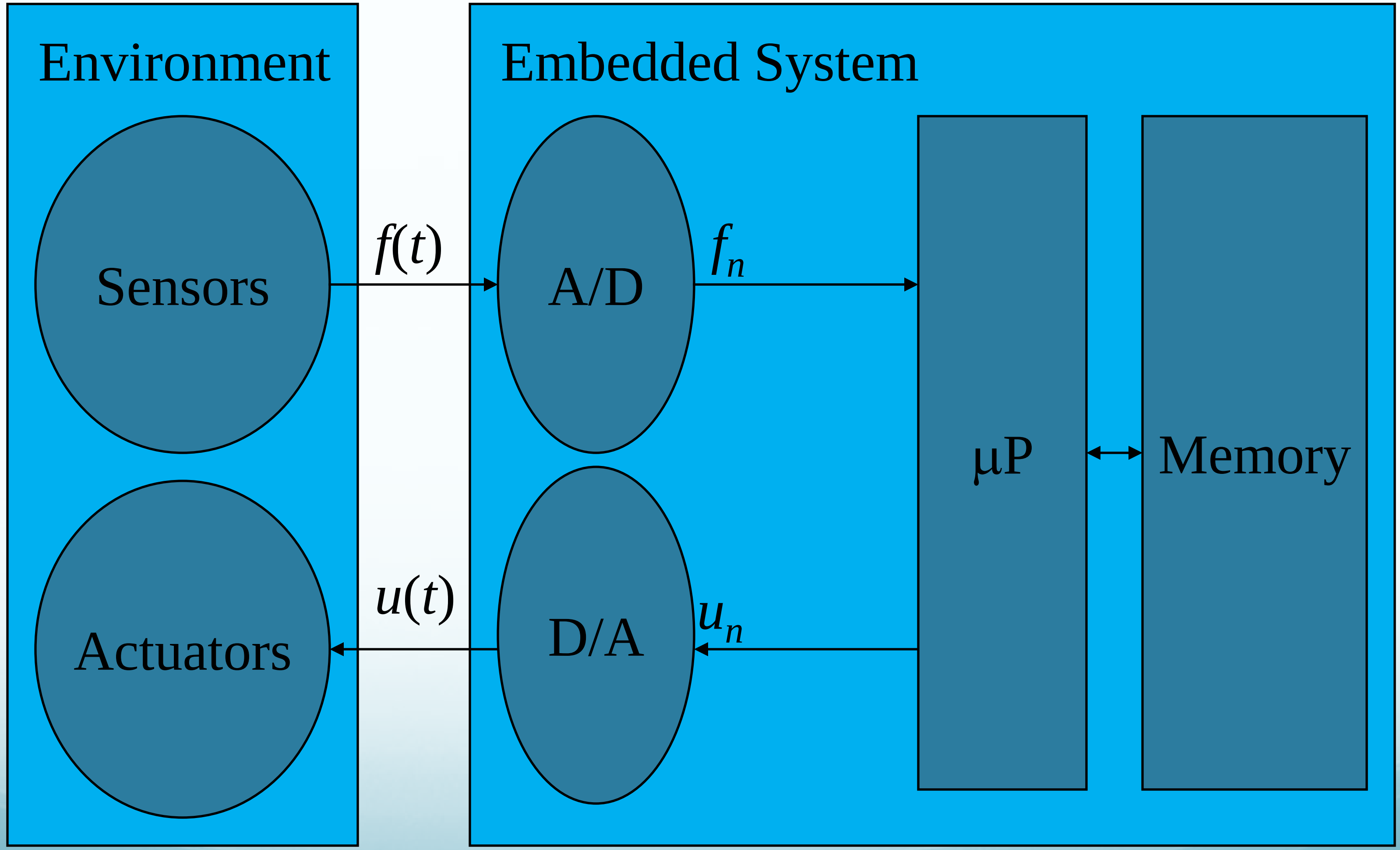
Fixed Point Arithmetic

- Using integer math to emulate floating point numbers and operations
- Determine *range* and *precision* (i.e., *m*.*n*)
- Define +, -, ×, and /
- Analyze for overflow
- Use tables for common math functions, e.g., sine, cosine, etc.

Digital Signal Processing

- Any interesting embedded system has to process some input signals and generate some output signals
  - We use the term *signal* in a general way
- Digital devices process signals in digital form
  - A uniformly sampled stream of data spread in time (e.g., audio) or space (e.g., image)

General DSP Architecture



Sensors and Actuators

- Sensors:
  - Capture physical stimulus (e.g., heat, light, sound, pressure, magnetism, or other mechanical motion)
  - Typical generate a proportional electrical current
  - May require analog interface
- Actuators
  - Convert a command to a physical stimulus (e.g., heat, light, sound, pressure, magnetism, or other mechanical motion)
  - May require analog interface

solenoid

mic

speaker

laser diode/transistor

compass

dc motor

accelerometer

Analog / Digital Domain Conversion

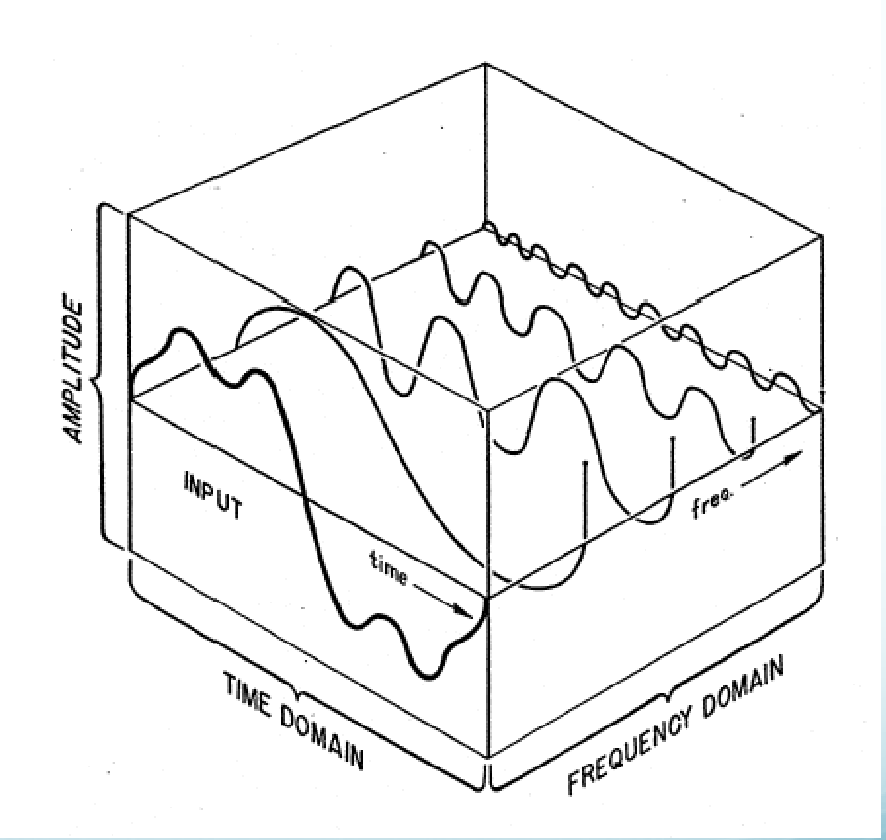
- Sampling: how often is the signal converted?
  - Twice as high as the highest frequency signal present in the input
  - As much as 10 to 20 times for even better results
- Quantization: how many bits used to represent a sample?
  - Sufficient to provide required dynamic range (measured as dB)
    - E.g., 16-bit A/D ➔ $20 \times \log_{10}(2^{16}) = 96$ dB (human ear limit)
  - Under-loading: dynamic range not used properly
  - AC coupling: a DC offset renders some of dynamic range unusable
  - Clipping: input signal beyond the dynamic range
- Aliasing: erroneous signals, not present in analog domain, but present in digital domain
  - Use anti-aliasing filters
  - Sample at higher than necessary rate
  - Remember the spinning bicycle wheel

Signal Processing

- Digital signal S_0, S_1, S_2 … $S_{n\text{-}1}$
- What can we do with it?
  - Transpose: e.g., $Z_i = S_i + K$
  - Amplify: e.g., $Z_i = S_i \times \alpha$
  - Compose: e.g., $Z_i = (S^1{}_i \times \alpha^1 + K^1) + (S^2{}_i \times \alpha^2 + K^2)$
  - Filter: e.g, $Z_i = (S_i + S_{i+1}) / 2$
  - Compress: e.g., using Huffman codes
  - Archive, match against database, etc.
- Or, process after converting to frequency domain
  - Spectral analysis

Frequency Domain

- Any continues time varying signal can be represented as the sum o cosine functions of different amplitude and frequency
  - E.g., input signal captured as the sum of 4 cosine functions
- Once in frequency domain, certain manipulations become trivial (e.g., filtering)

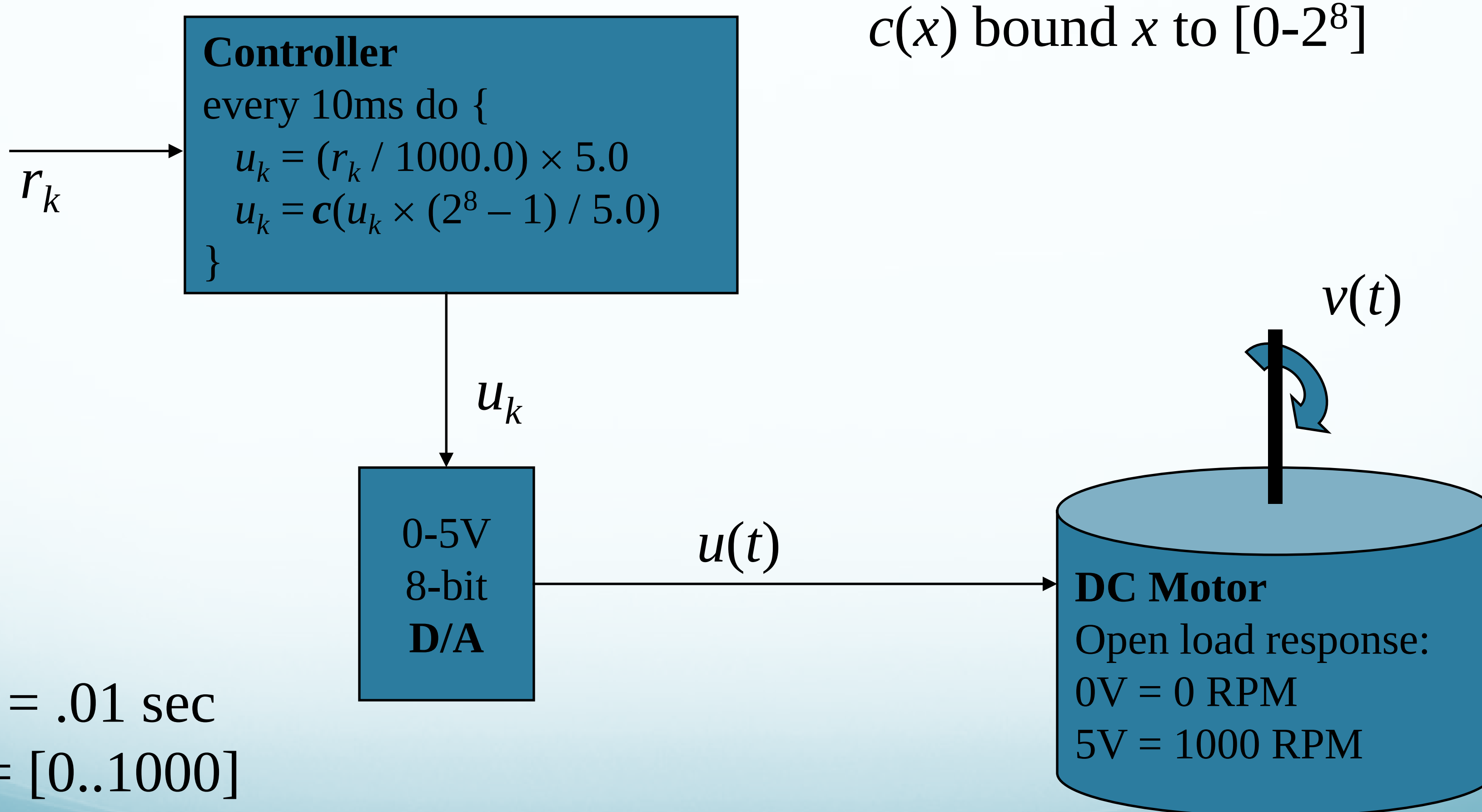


Control Systems

- Control systems are a common class of embedded systems
- Goal is to make a system’s output track a desired reference value
  - Cruise control, thermostat, VCR tape speed, etc.
- We’ll take a look at open-loop and closed-loop control systems
- We’ll take a look at PID control

Open-Loop Control Example

$c(x)$ bound x to $[0\text{-}2^8]$

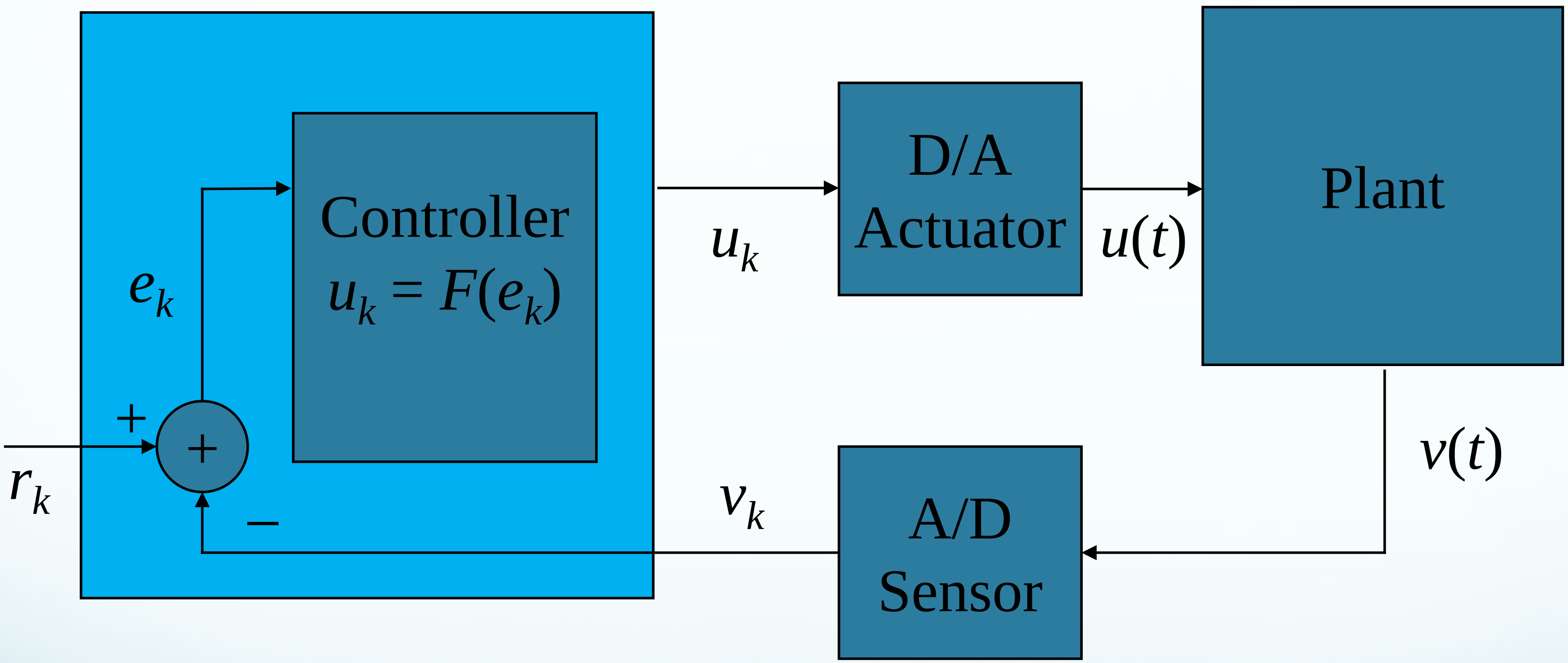


$\Delta T = .01$ sec

$r_k = [0..1000]$

What if a load is placed on the motor?

Closed-Loop Control



r_k is the reference (to be controlled) value
k is a discrete time variable
$t = k \times \Delta T$ is a continues time variable
$e_k = r_k - v_k$ is plant error

Proportional Integral Derivative (PID) Controllers

- Proportional control: A controller that multiplies the error by a constant
  - $u_k = e_k \times P$
- Integral control: A controller that considers the integral of error over time (using history)
  - $u_k = (e_0 + e_1 + \ldots + e_k) \times I$
- Derivative control: A controller that considers the differential of error over time (predict future)
  - $u_k = (e_k - e_{k-1}) \times D$

Conclusion

- Introduction to embedded systems
- Hardware
  - Processors
  - Memories
  - Communication
  - Peripherals
- Software
  - Real-time operating systems
  - Application domains (DSP, control)