Embedded System Design

CSEE W4840

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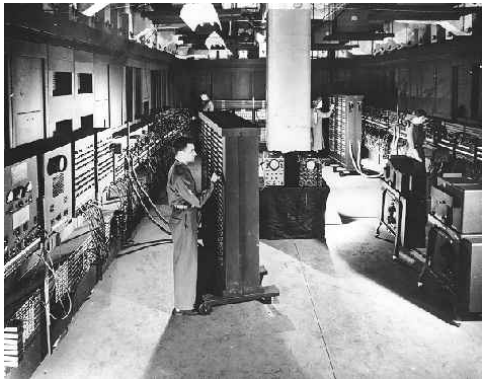
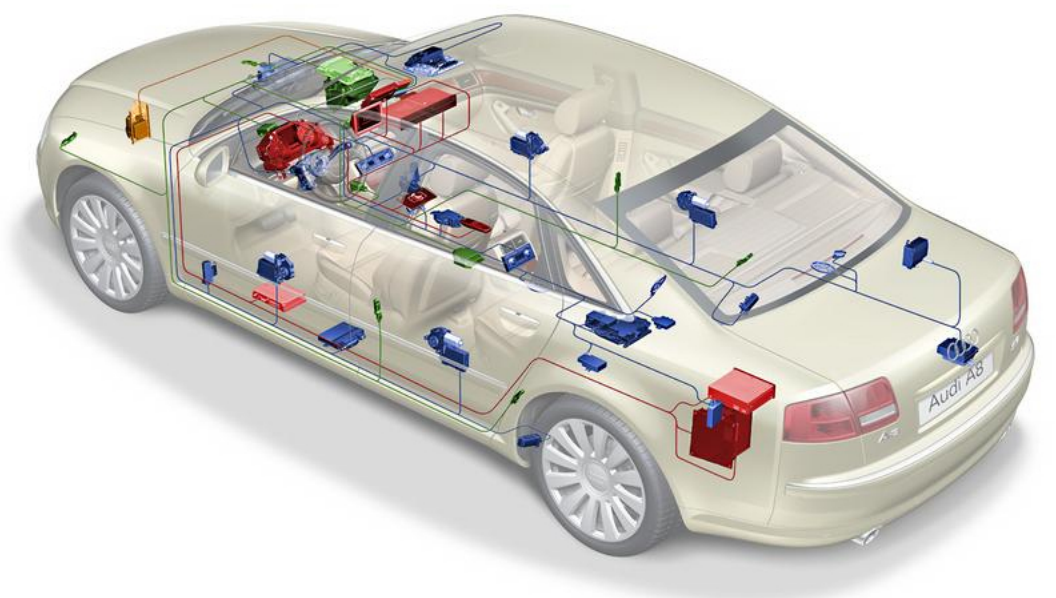
Columbia University

Spring 2026

Spot the Computer



Cars These Days...



Embedded Systems: Ubiquitous Computers

iPhone

Laser Keyboard

Nikon D5600

WiFi Light Bulb

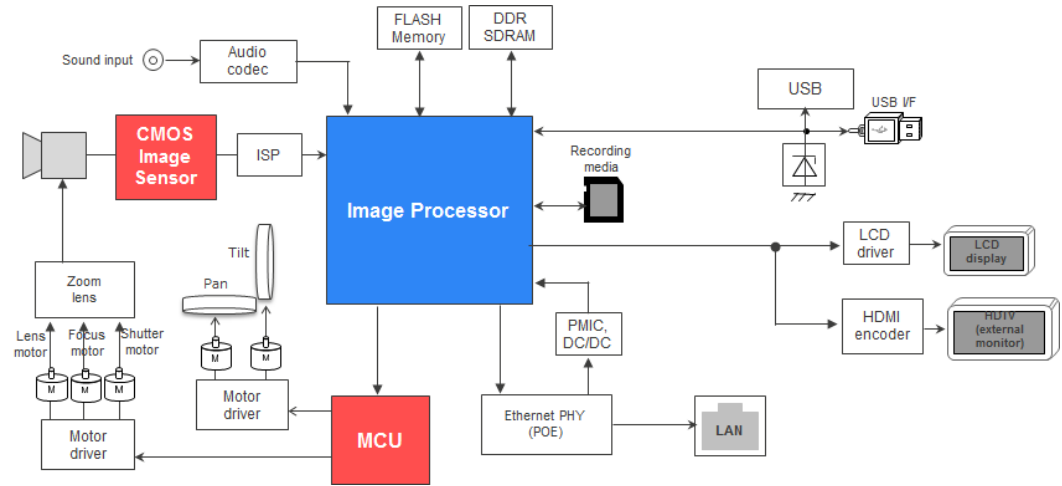
IP Phone

Playstation 5

PC Keyboard

Micro SD Card

Inside a Network Camera



Source: Renesas

Want an Optimal Device that Meets Constraints On

Price

Performance

Power

Maintainability

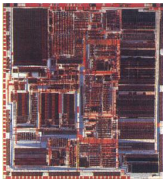
Functionality

Size

Time-to-market

Safety

Embedded System Technologies

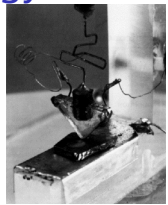


Integrated Circuits

Processing elements

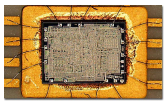
Design tools

IC Technology

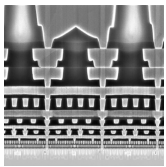


1947: First transistor (Shockley, Bell Labs)

1958: First integrated circuit (Kilby, TI)



1971: First microprocessor (4004: Intel)

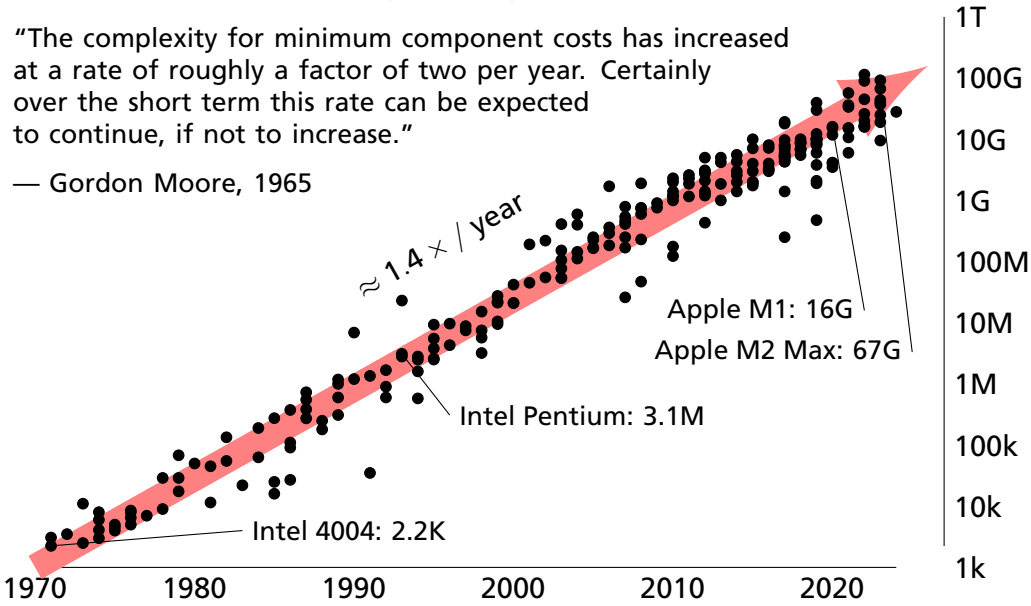


2018: Intel “10 nm” process, 12 layers

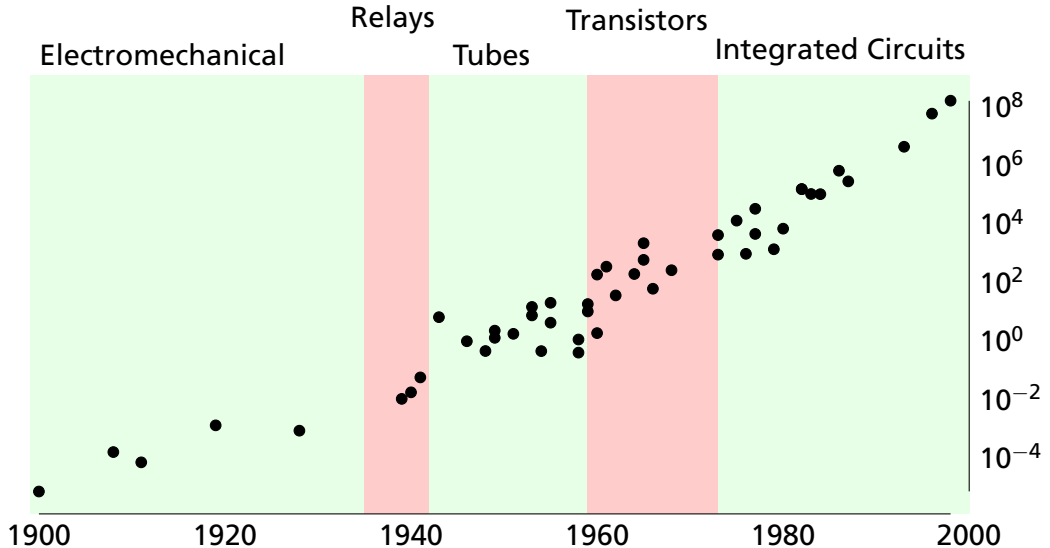
Moore's Law: Transistors per chip

"The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not to increase."

— Gordon Moore, 1965

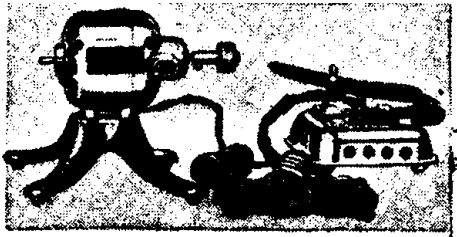


$1000 Buys You This Many Cycles per Second



Source: Ray Kurzweil, *The Age of Spiritual Machines*

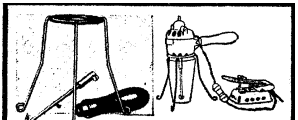
1918 Sears Roebuck Catalog



Home Motor.

This motor, as shown above, will operate a sewing machine. Easily attached; makes sewing a pleasure. The many attachments shown on this page may be operated by this motor and help to lighten the burden of the home. Operates on usual city current of 105 to 115 volts. Shipping weight, about 5 pounds.

No. 57P7564 Price, complete, as shown..... **$8.75**



Beater Attachment.

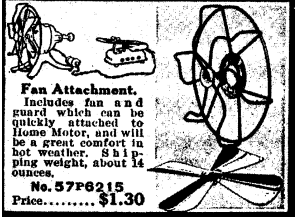
Whips cream and beats eggs, and many other uses will be found for these attachments when used in connection with the Home Motor. Parts include the stand, handle and the beater. Shipping weight, about 14 ounces.

No. 57P7585 Price..... **$1.30**

Churn and Mixer Attachment.

Used in connection with the Home Motor, makes a small churn and mixer for which you will find many uses. The attachments include the base, supports, mixer, handle and special cover for jar. Shipping weight, about 1¾ pounds.

No. 57P7582 Price..... **$1.30**



Fan Attachment.

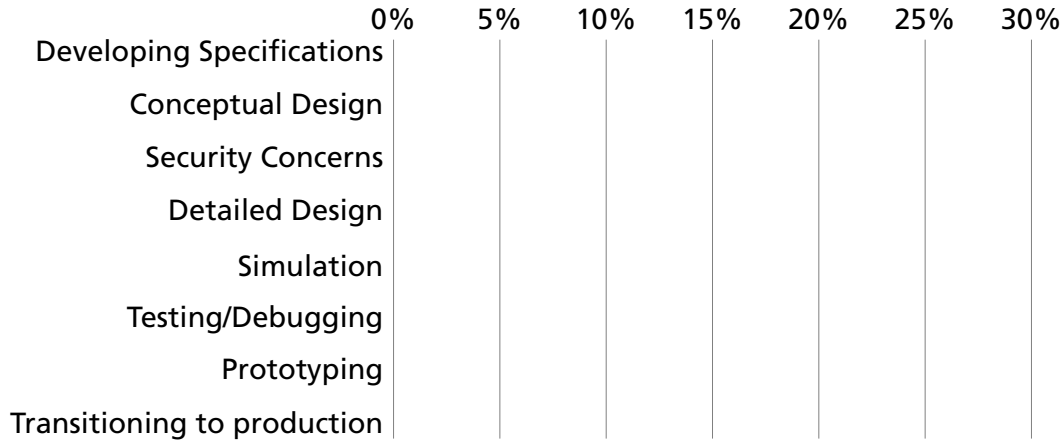
Includes fan and guard which can be quickly attached to Home Motor, and will be a great comfort in hot weather. Shipping weight, about 14 ounces.

No. 57P6215
Price..... **$1.30**

About $150 in 2022 dollars.

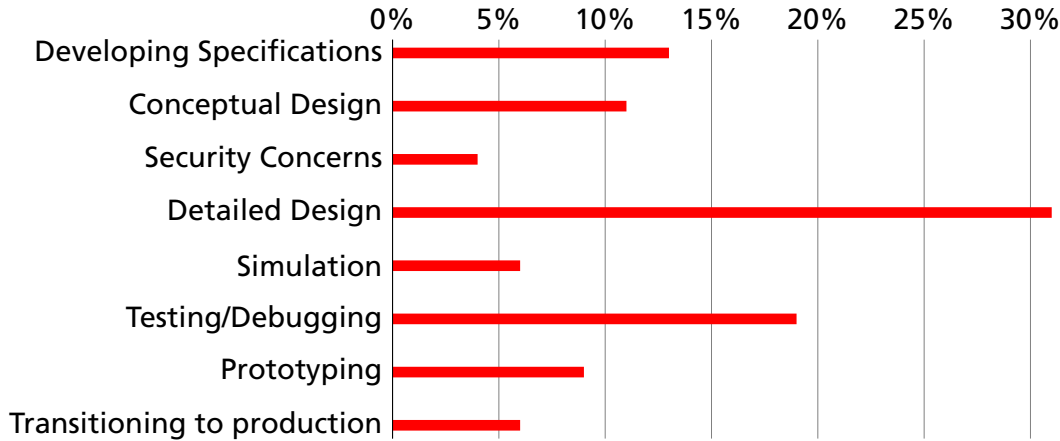
From Donald Norman, *The Invisible Computer*, 1998.

What Percentage of Time Do You Spend...



Source: 2019 Embedded Market Study

What Percentage of Time Do You Spend...



Source: 2019 Embedded Market Study

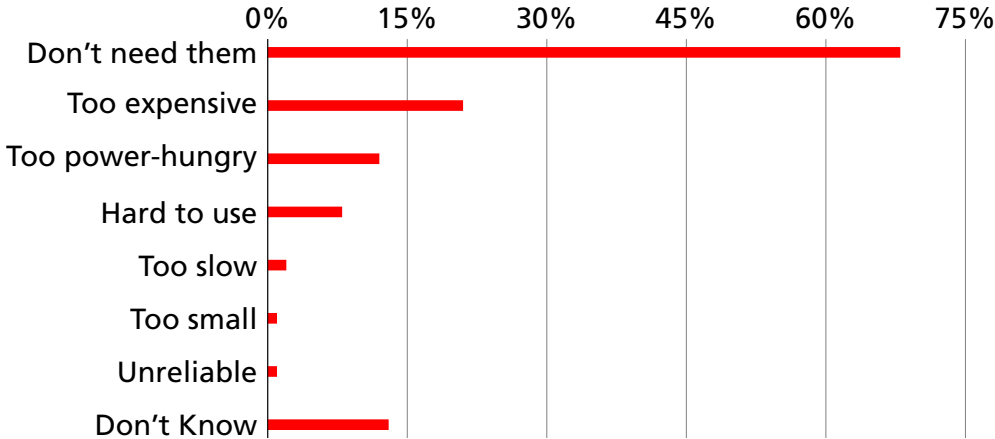
Does Your Current Project Contain FPGAs?

33% Yes

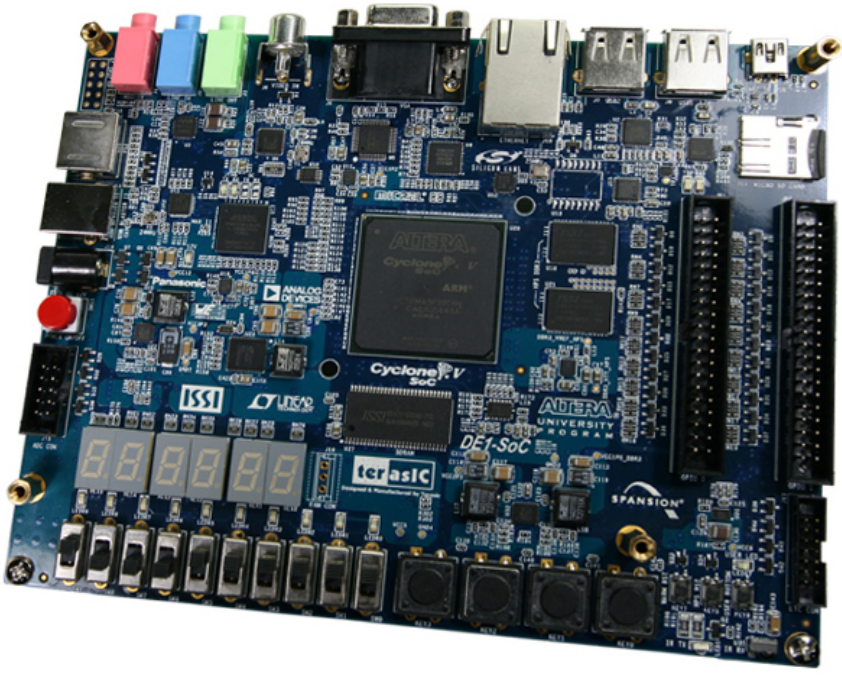
67% No

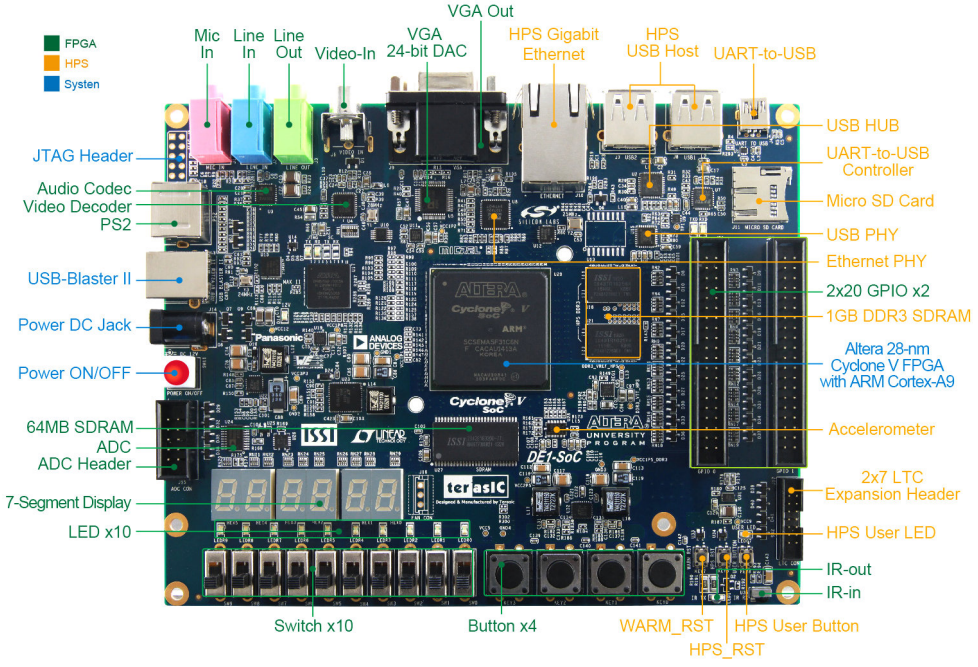
Source: 2019 Embedded Market Study

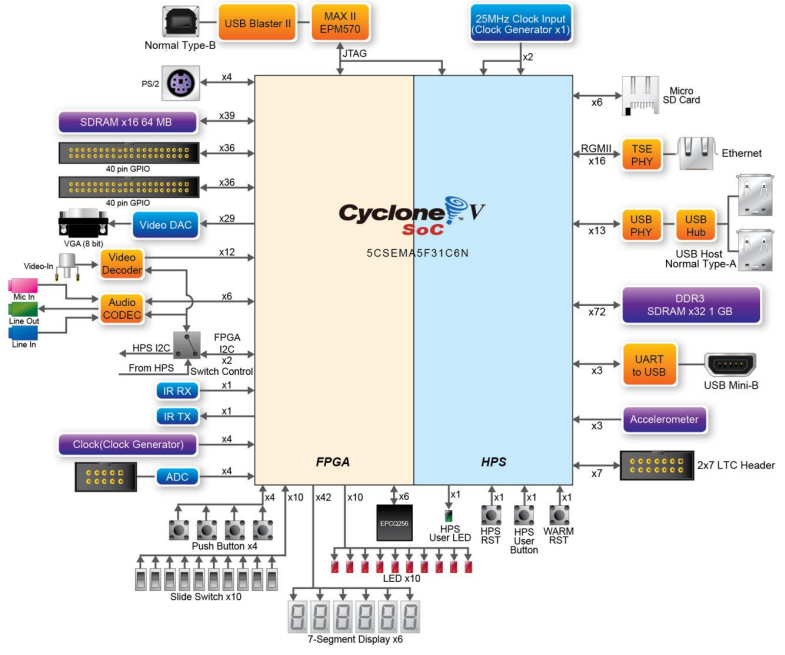
Why Won't Your *Next* Project Use FPGAs?



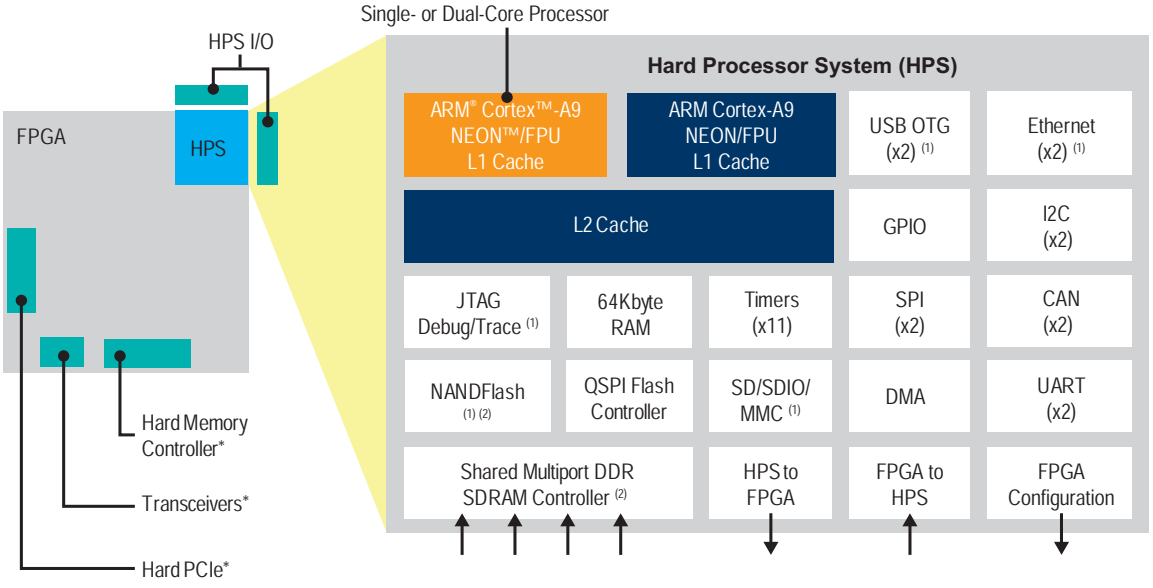
Source: 2009 Embedded Market Study


Cyclone V SoC
DE1-SoC
terasIC
ALTERA
UNIVERSITY PROGRAM
Panasonic
ANALOG DEVICES
ISSI
SPANSION

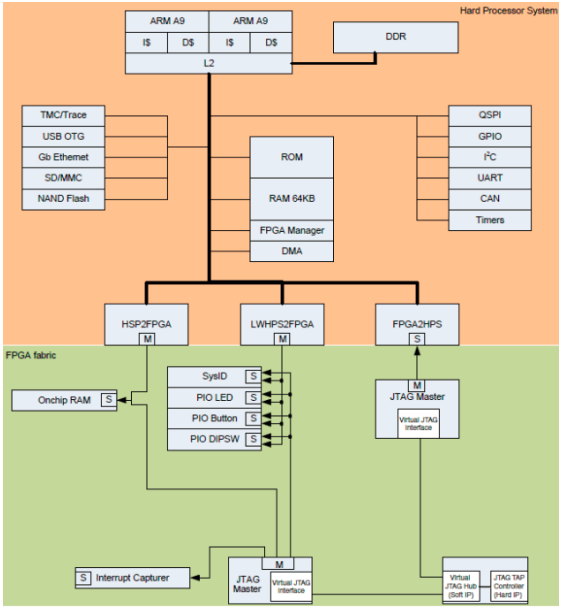

FPGA
HPS
Systen
Mic In
Line In
Line Out
Video-In
VGA 24-bit DAC
VGA Out
HPS Gigabit Ethernet
HPS USB Host
UART-to-USB
JTAG Header
Audio Codec
Video Decoder
PS2
USB-Blaster II
Power DC Jack
Power ON/OFF
64MB SDRAM
ADC
ADC Header
7-Segment Display
LED x10
Switch x10
Button x4
WARM_RST
HPS_RST
HPS User Button
IR-out
IR-in
HPS User LED
2x7 LTC Expansion Header
Accelerometer
Altera 28-nm Cyclone V FPGA with ARM Cortex-A9
1GB DDR3 SDRAM
2x20 GPIO x2
Ethernet PHY
USB PHY
Micro SD Card
UART-to-USB Controller
USB HUB
DE1-SoC


Normal Type-B
USB Blaster II
MAX II EPM570
JTAG
25MHz Clock Input (Clock Generator x1)
x2
PS/2
x4
SDRAM x16 64 MB
x39
40 pin GPIO
x36
40 pin GPIO
x36
VGA (8 bit)
Video DAC
x29
Video-In
Video Decoder
x12
Mic In
Line Out
Line In
Audio CODEC
x6
HPS I2C
FPGA I2C
x2
From HPS
Switch Control
IR RX
x1
IR TX
x1
Clock(Clock Generator)
x4
ADC
x4
Cyclone V SoC
5CSEMA5F31C6N
FPGA
HPS
x6
Micro SD Card
RGMII x16
TSE PHY
Ethernet
x13
USB PHY
USB Hub
USB Host Normal Type-A
x72
DDR3 SDRAM x32 1 GB
x3
UART to USB
USB Mini-B
x3
Accelerometer
x7
2x7 LTC Header
x4
Push Button x4
x10
Slide Switch x10
x42
x10
EPCQ256
x6
LED x10
x1
HPS User LED
x1
HPS RST
x1
HPS User Button
x1
WARM RST
7-Segment Display x6

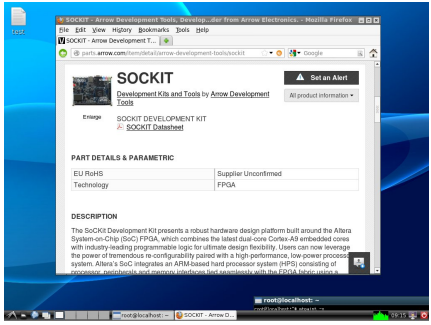
Inside the Cyclone V: Dual ARM processors + FPGA



An Example System



Linux + Custom Hardware



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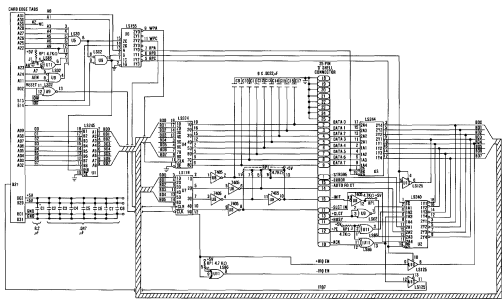


Class Structure

Three Introductory Labs: 2 weeks each

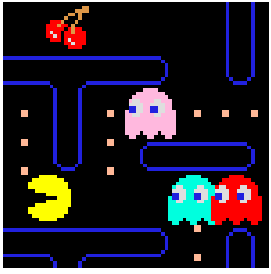
1. Hardware: Test the Collatz Conjecture
2. Software: A simple Internet chat client
3. HW + SW: A video bouncing ball

The project: **Design-your-own**

Work in groups

Broadly: C + SystemVerilog + peripheral(s)

Broad Project Idea: Video Game

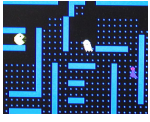
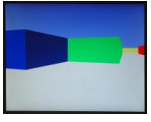
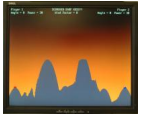


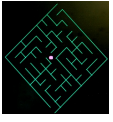
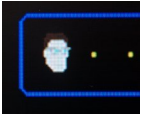
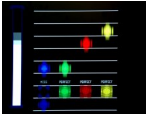
Implement graphics in custom hardware

Put game logic in software

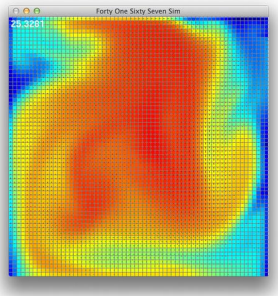
Interface with USB HID (Joystick, etc.)

E.g., Pac-man, 2.5D maze game, tank, worms

Broad Project Idea: Computational Accelerator



Pick a computationally intensive algorithm

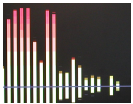
Implement its core in custom hardware

Write software and device drivers that pass data to and from the accelerator

E.g., Smoke simulator, inverse kinematics for robotics, Bitcoin miner

More Ideas

Digital tone control



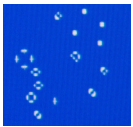
Spectrum analyzer

Internet radio

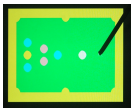
Speech Synthesizer

MIDI synthesizer

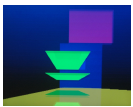
Accelerated JPEG



Game of Life



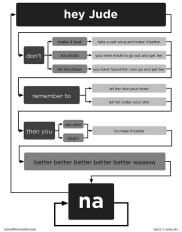
Pool game



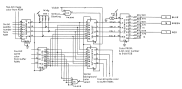
Real-time ray tracer

The Three Main Challenges of Embedded Systems

Coping with Real-World Sensor Data

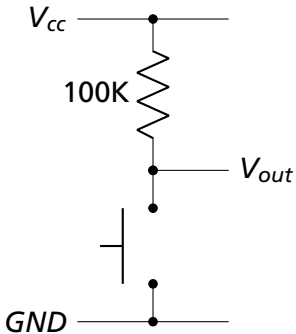


Algorithm Design



Implementation Details

What Happens When You Press the Switch?



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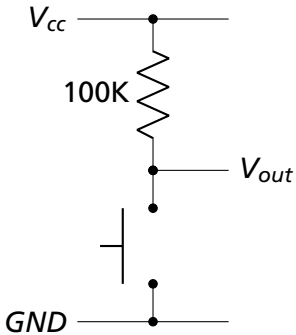
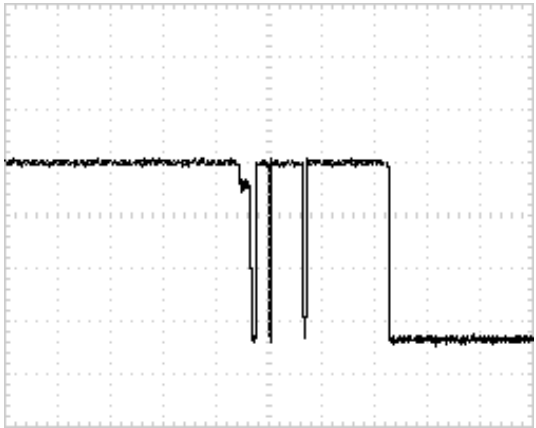
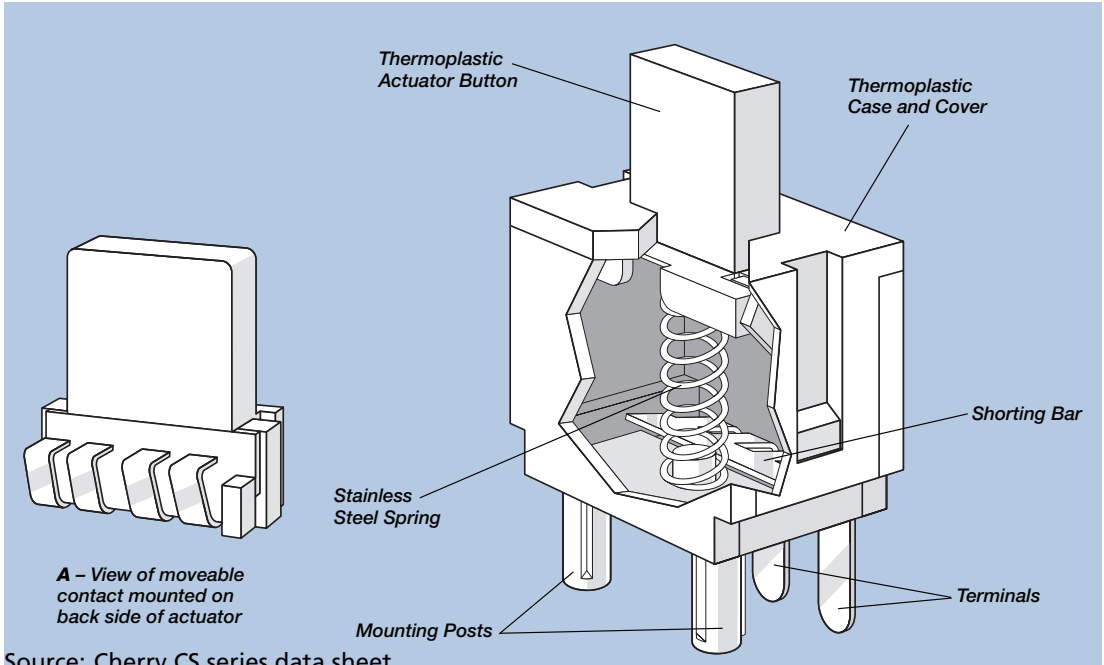


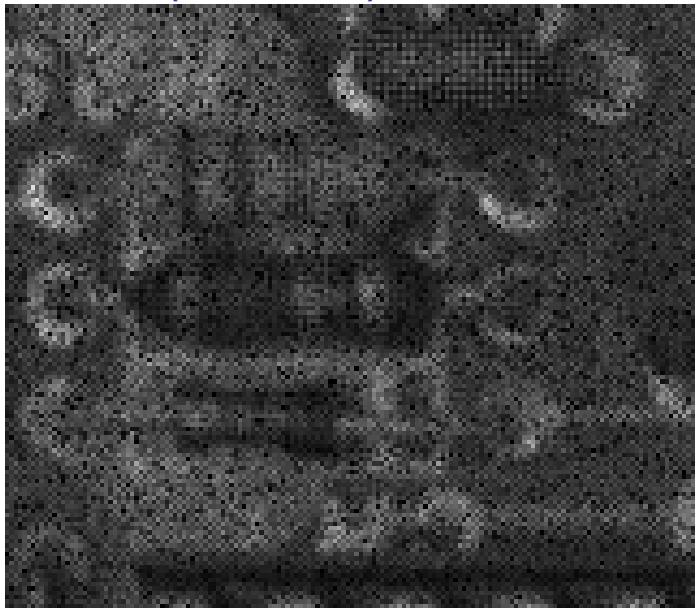




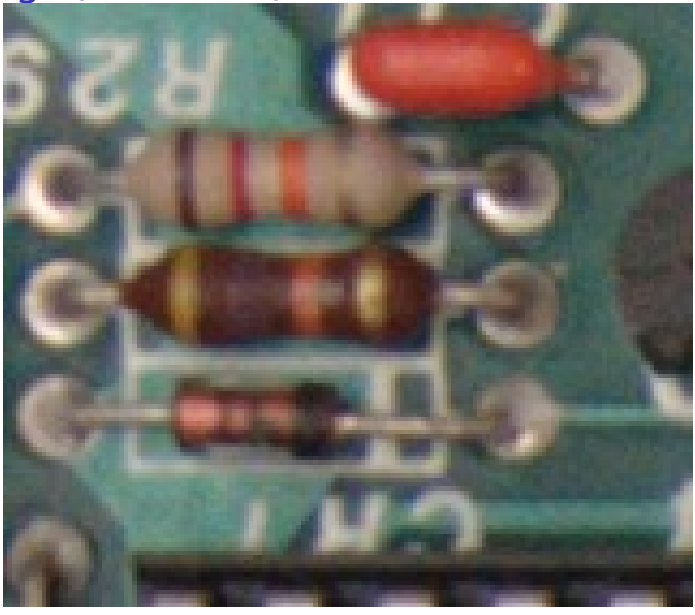
***A** – View of moveable contact mounted on back side of actuator*

Source: Cherry CS series data sheet

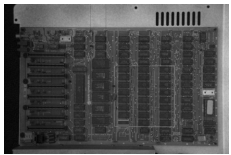
Raw Data from a CCD (zoomed in)



Corrected Image (zoomed in)



Correcting Data from CCDs

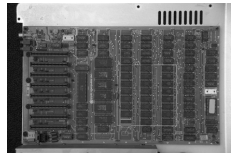


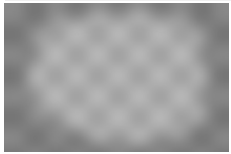
Raw

−

Dark Frame

=





Flat Field

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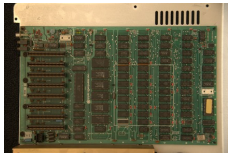
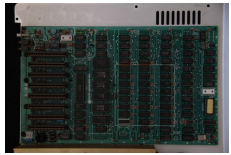
Bias

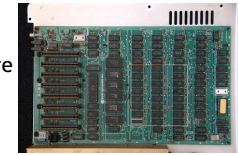
Color →



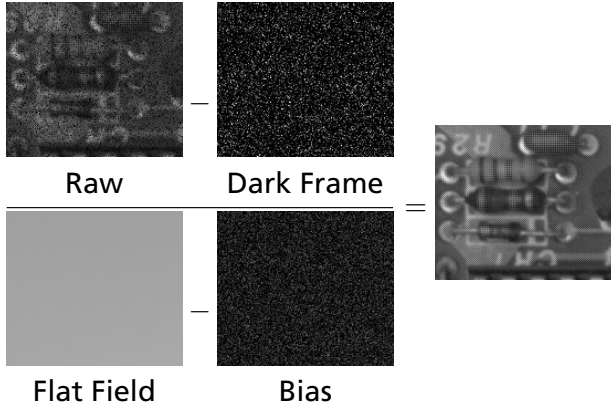
Temp. →



Exposure →



Correcting Data from CCDs



Where Does This Noise Come From?

Nikon D300: 23.6 mm $\times$ 15.8 mm
12.3 megapixel CMOS sensor

Pixels are 5.5 μm on a side

A/D sampling of 12 bits per pixel measures

ISO:	LO	200	400	800	1600	3200
G	7.1	5.5	2.7	1.3	0.65	0.33
B	5.8	4.6	2.3	1.1	0.55	0.27
R	4.7	4.5	2.2	1.1	0.54	0.26

The units: *electrons per ADU* (digital unit).

Emil Martinec, *A comparison of the Nikon D300 and Canon 40D sensors*, 2007.

The Two Big Challenges

- Design the algorithm
  1. Acquire representative input (sensor) data
  2. Conceive of an algorithm
  3. Prototype the algorithm using your favorite language
- Implement the algorithm
  1. Choose a hardware/software partition based on performance and resource constraints
  2. Develop software and hardware architectures
  3. Define interface between software and hardware
  4. Implement the hardware and software
  5. Test, test, test...