

# Embedded System Design

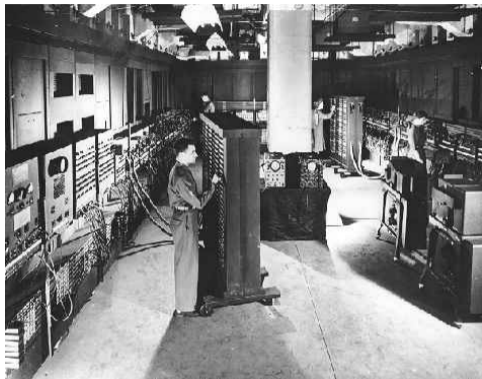
CSEE W4840

Stephen A. Edwards

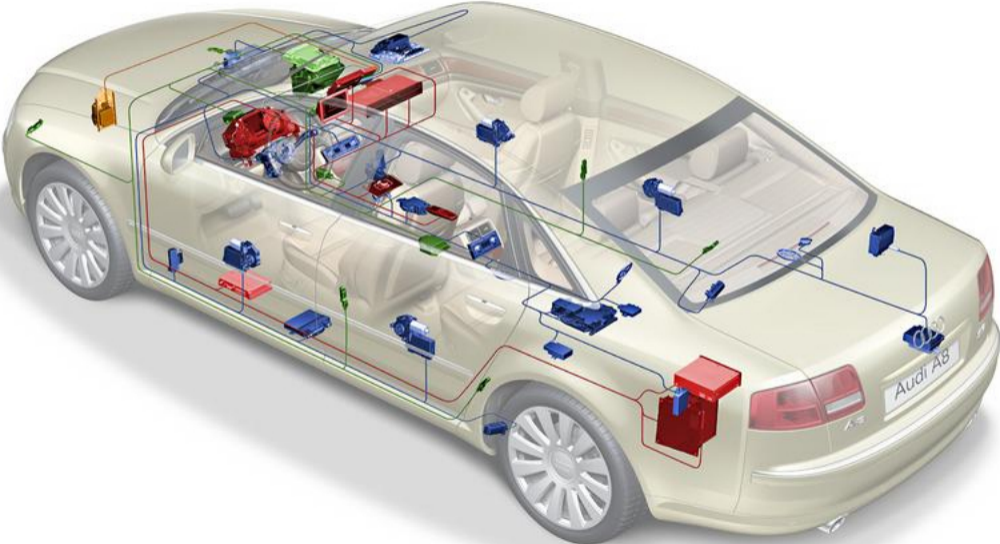
Columbia University

Spring 2025

# Spot the Computer



# Cars These Days...



# Embedded Systems: Ubiquitous Computers



iPhone



Laser Keyboard



Nikon D5600



WiFi Light Bulb



IP Phone



Playstation 5

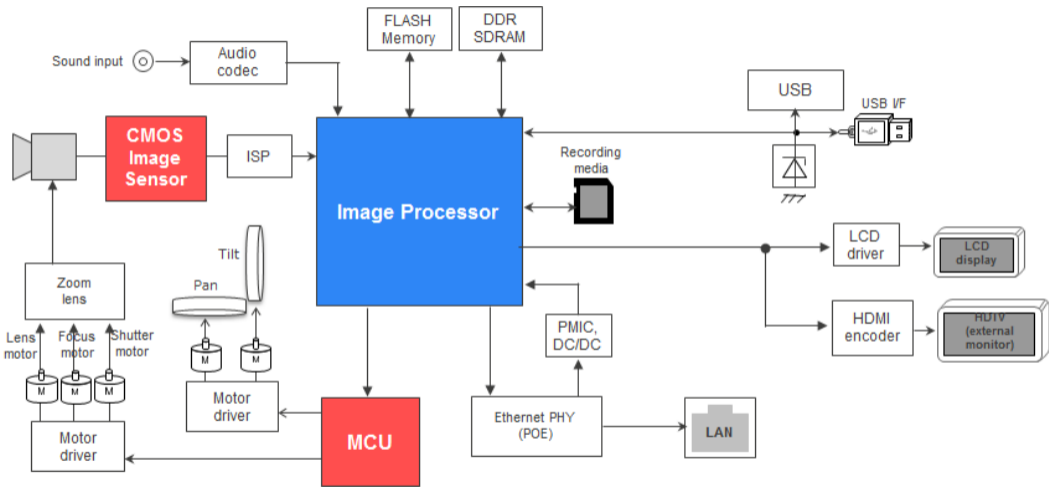


PC Keyboard



Micro SD Card

# Inside a Network Camera



Source: Renesas

# Want an Optimal Device that Meets Constraints On



Price



Functionality



Performance



Size



Power



Time-to-market

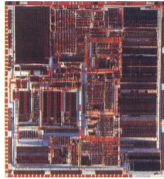


Maintainability



Safety

# Embedded System Technologies



Integrated Circuits

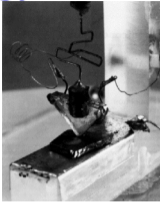


Processing elements



Design tools

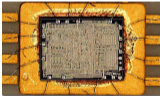
# IC Technology



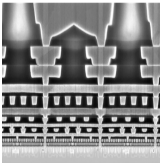
1947: First transistor (Shockley, Bell Labs)



1958: First integrated circuit (Kilby, TI)



1971: First microprocessor (4004: Intel)



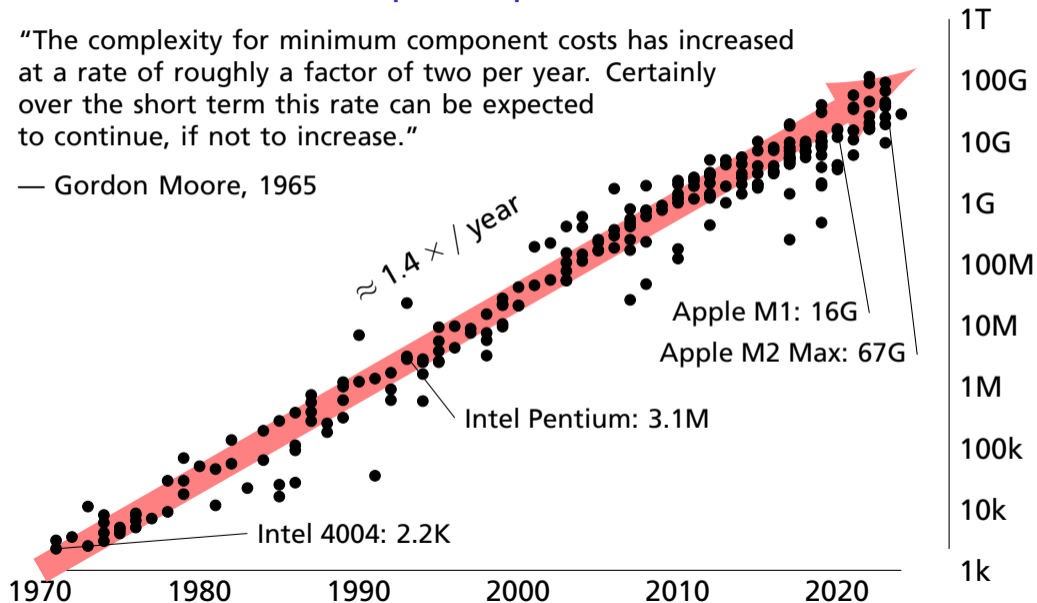
2018: Intel "10 nm" process, 12 layers



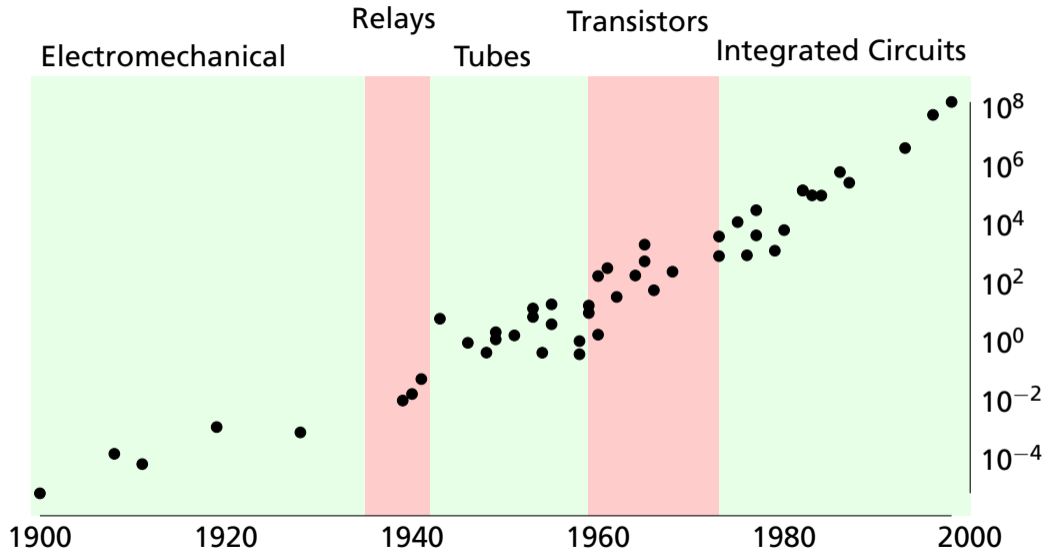
# Moore's Law: Transistors per chip

"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

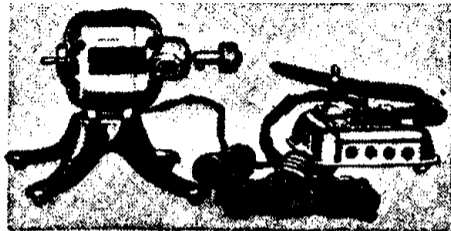


# \$1000 Buys You This Many Cycles per Second



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

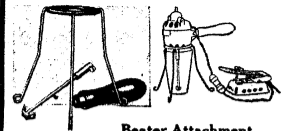
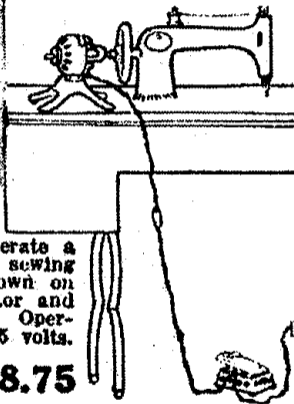
# 1918 Sears Roebuck Catalog



## 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.

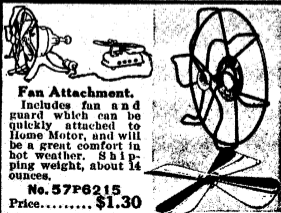
No. 57P7585 Price..... **\$1.30**



### 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 1 1/2 pounds.

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



### Fan Attachment.

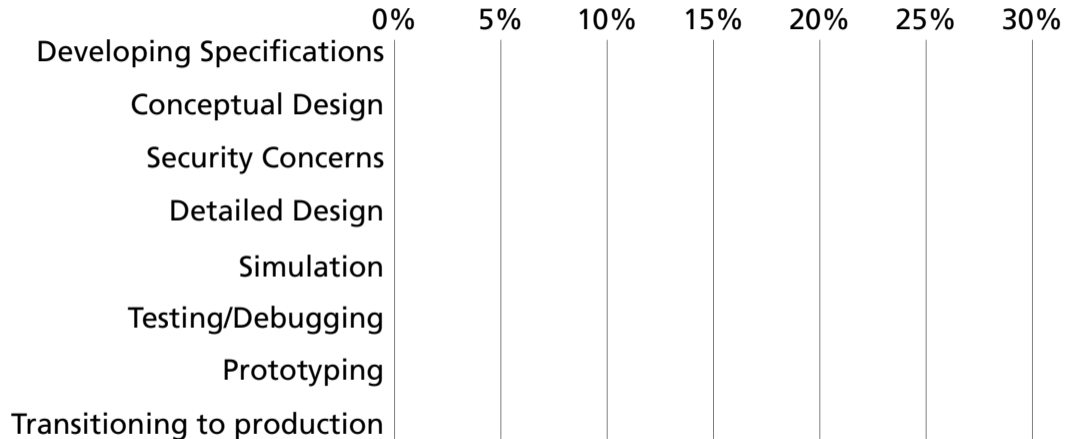
Includes fan and guard which can be quickly attached to Home Motor, and will be a great comfort in hot weather. Shipping weight, about 14 ounces.

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

About \$150 in 2022 dollars.

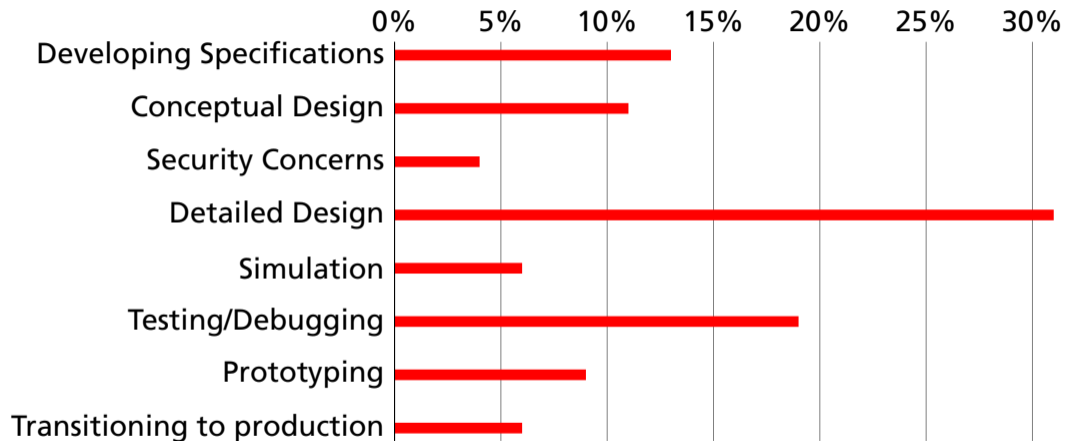
From Donald Norman, *The Invisible Computer*, 1998.

# What Percentage of Time Do You Spend...



Source: 2019 Embedded Market Study

## What Percentage of Time Do You Spend...



Source: 2019 Embedded Market Study

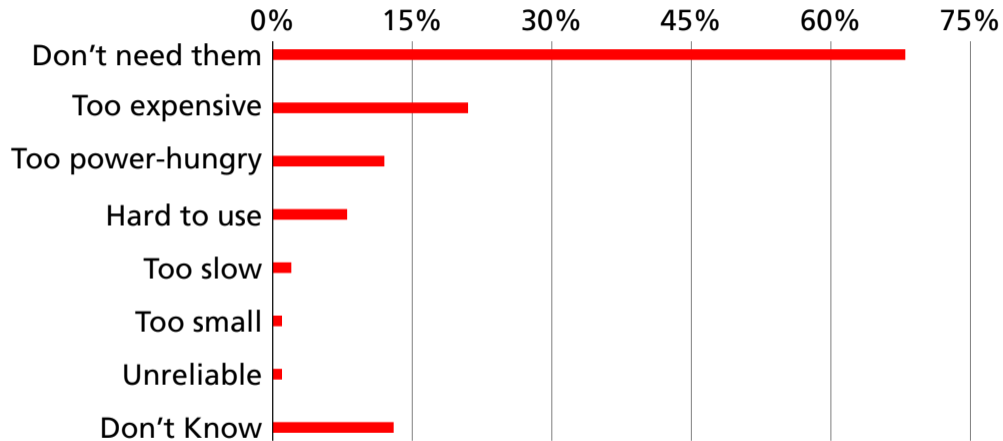
## Does Your Current Project Contain FPGAs?

33% Yes

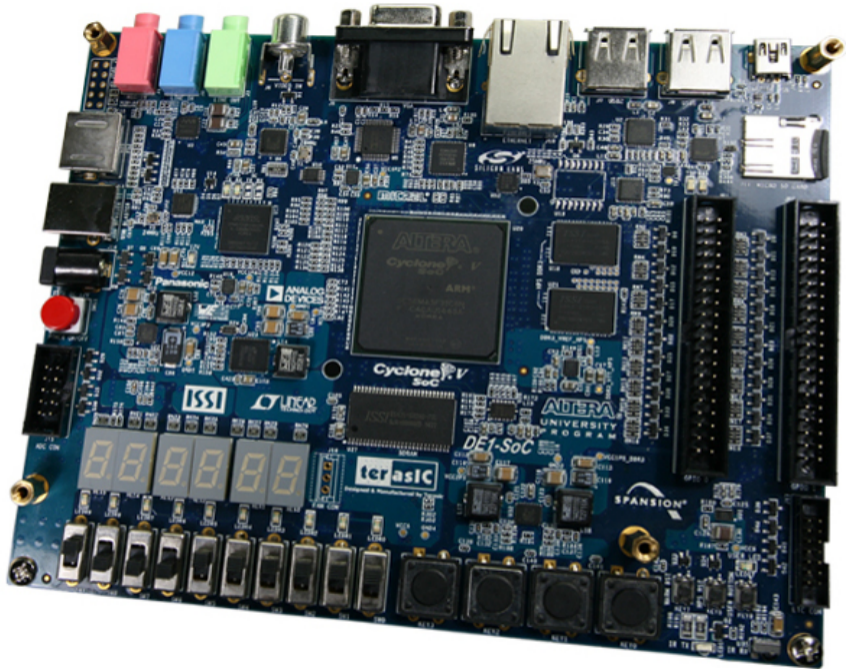
67% No

Source: 2019 Embedded Market Study

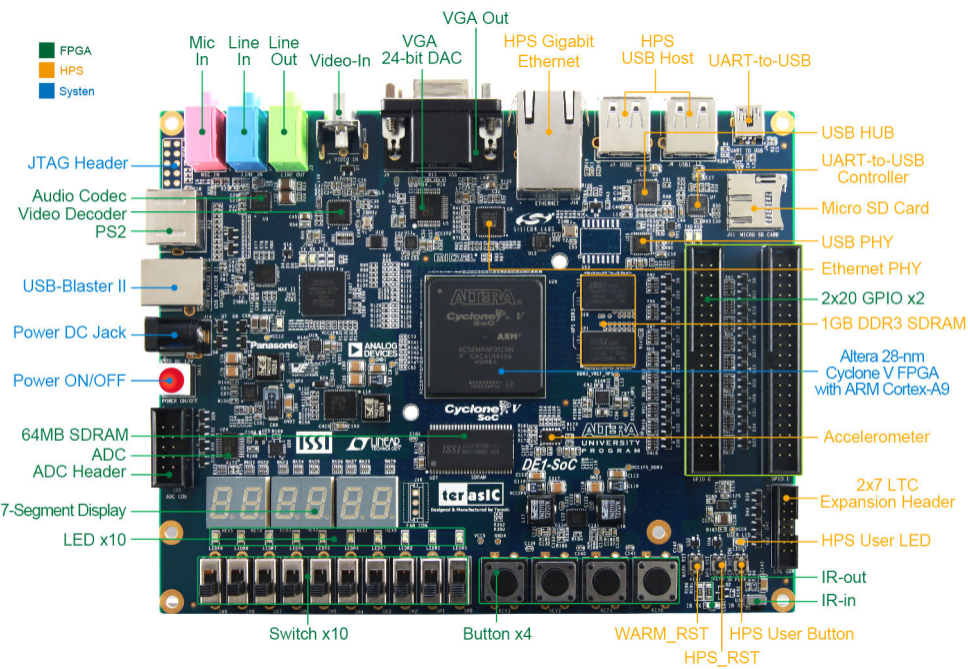
## Why Won't Your Next Project Use FPGAs?

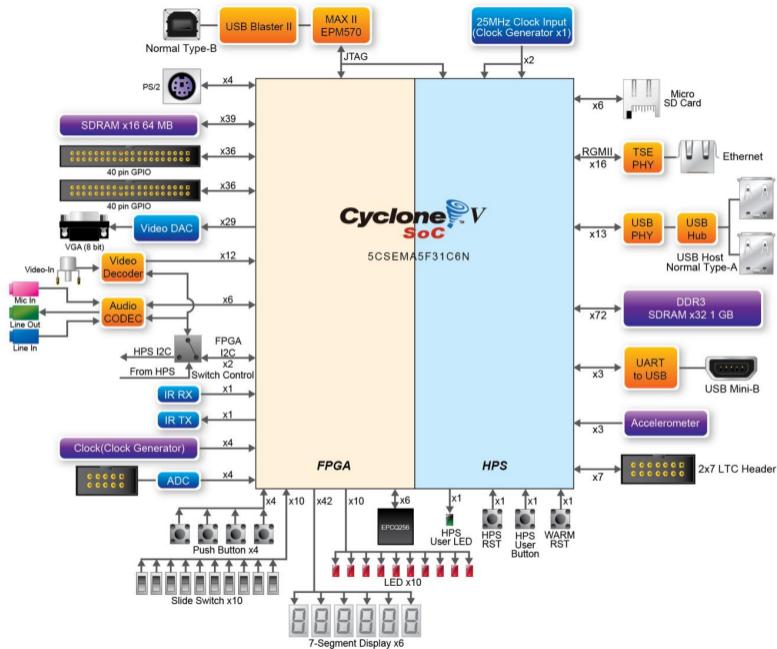


Source: 2009 Embedded Market Study

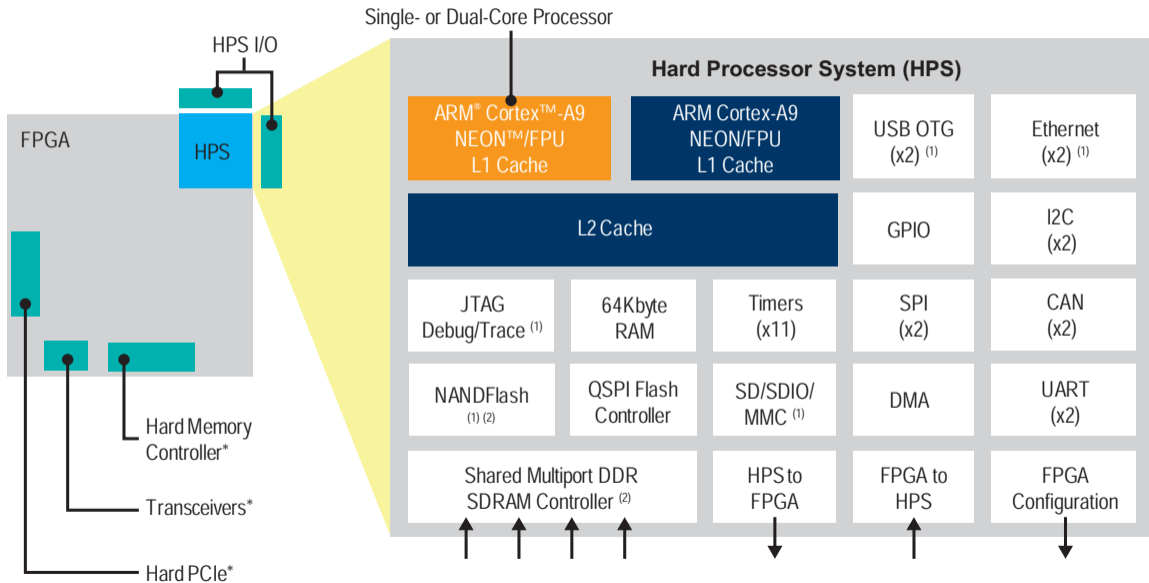




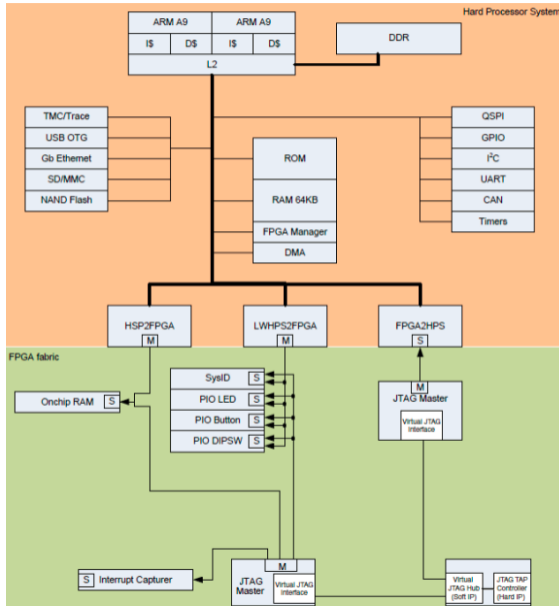




# Inside the Cyclone V: Dual ARM processors + FPGA



# An Example System



# Linux + Custom Hardware

The screenshot shows a Mozilla Firefox browser window with the URL `parts.arrow.com/item/detail/arrow-development-tools/sockit`. The page title is "SOCKIT Development Kits and Tools by Arrow Development Tools". It features a "Set an Alert" button and a "All product information" link. The main content area is titled "SOCKIT DEVELOPMENT KIT" and includes a "SOCKIT Datasheet" link. Below this, there is a "PART DETAILS & PARAMETRIC" section with a table:

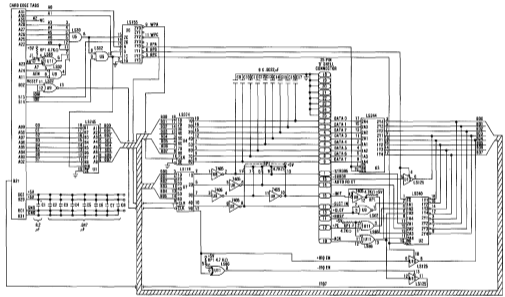
EU RoHS	Supplier Unconfirmed
Technology	FPGA

The "DESCRIPTION" section contains the following text:

The SoCKit Development Kit presents a robust hardware design platform built around the Altera System-on-Chip (SoC) FPGA, which combines the latest dual-core Cortex-A9 embedded cores with industry-leading programmable logic for ultimate design flexibility. Users can now leverage the power of tremendous re-configurability paired with a high-performance, low-power processor system. Altera's SoC integrates an ARM-based hard processor system (HPS) consisting of processor, peripherals, and memory interfaces tied seamlessly with the FPGA fabric.

The browser's address bar shows the user is logged in as `root@localhost`.

+



# Class Structure

Three Introductory Labs: 2 weeks each

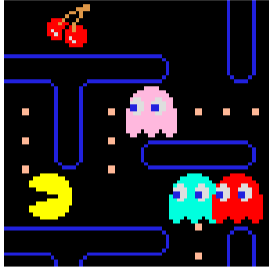
1. Hardware: Test the Collatz Conjecture
  2. Software: A simple Internet chat client
  3. HW + SW: A video bouncing ball
- 

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

Work in groups

Broadly: C + SystemVerilog + peripheral(s)

# Broad Project Idea: Video Game

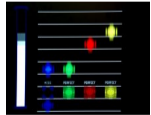
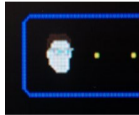
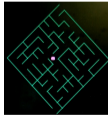
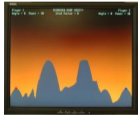


Implement graphics in custom hardware

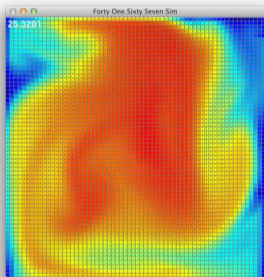
Put game logic in software

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

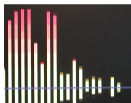
E.g., Smoke simulator, inverse kinematics for robotics, Bitcoin miner



## More Ideas



Digital tone control



Spectrum analyzer



Internet radio



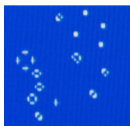
Speech Synthesizer



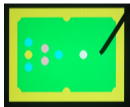
MIDI synthesizer



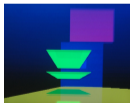
Accelerated JPEG



Game of Life



Pool game

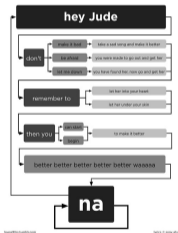


Real-time ray tracer

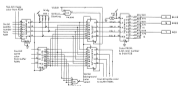
# The Three Main Challenges of Embedded Systems



Coping with Real-World Sensor Data

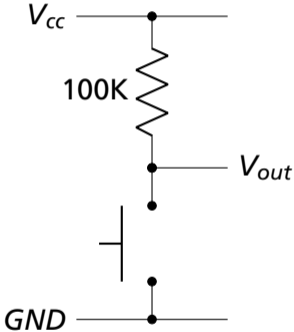


Algorithm Design

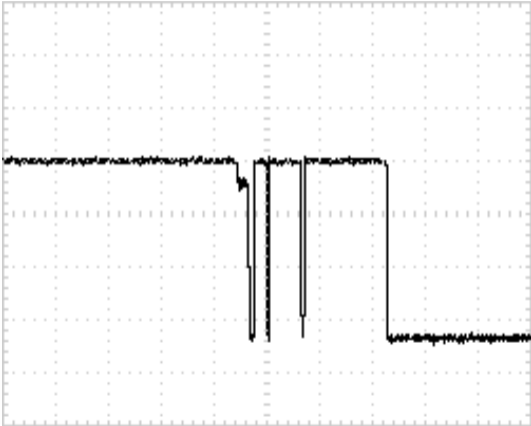
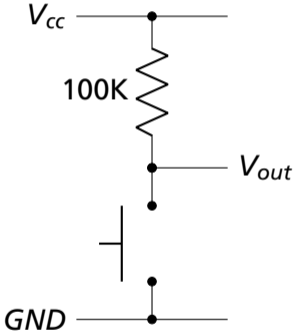


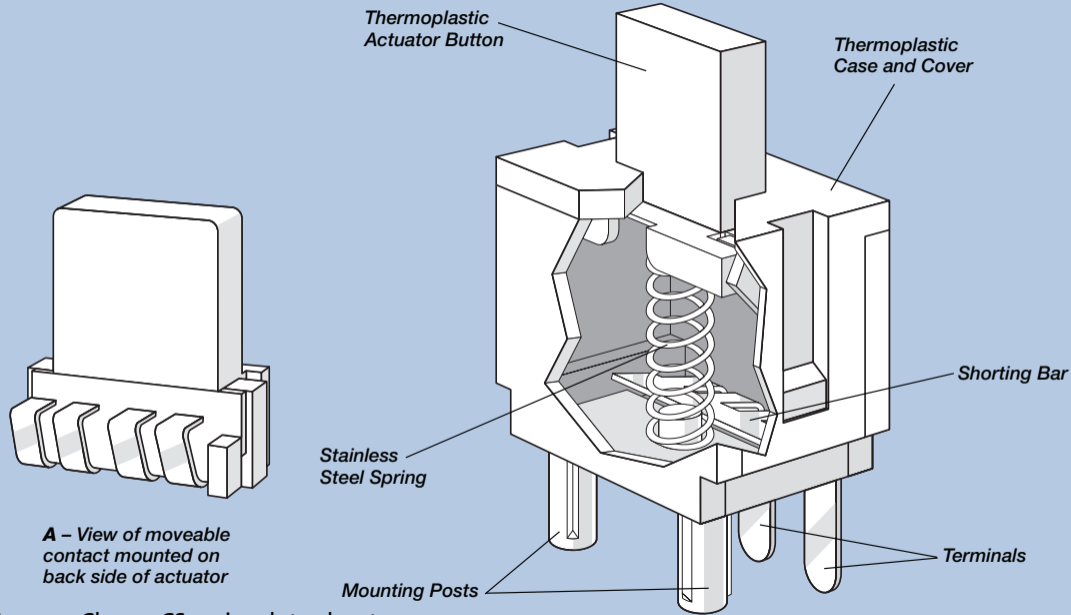
Implementation Details

# What Happens When You Press the Switch?



# What Happens When You Press the Switch?



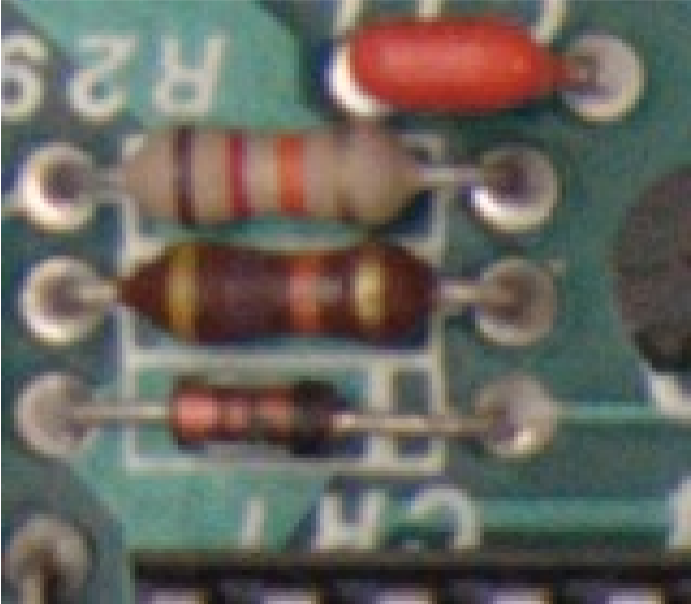


Source: Cherry CS series data sheet

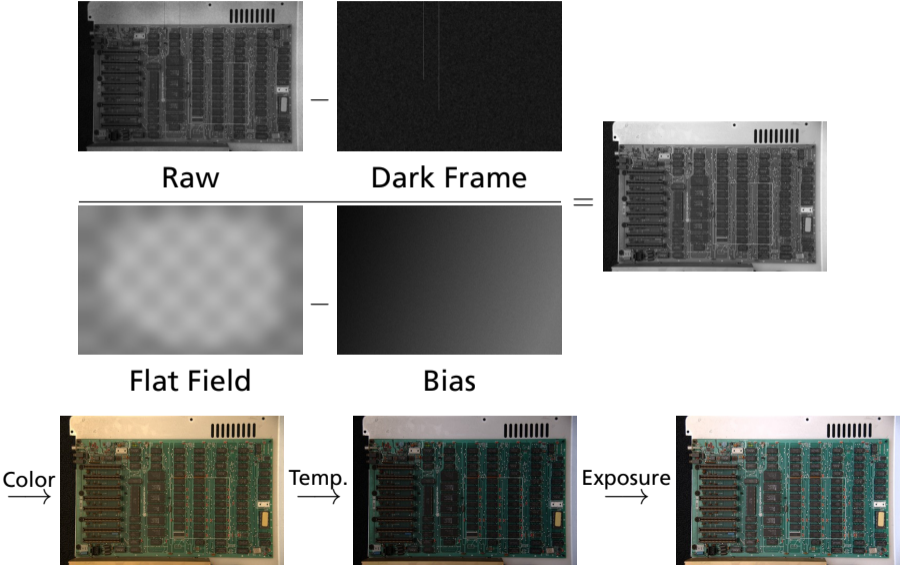
Raw Data from a CCD (zoomed in)



Corrected Image (zoomed in)

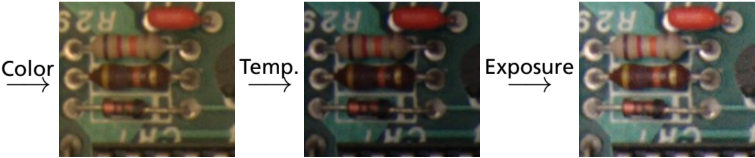
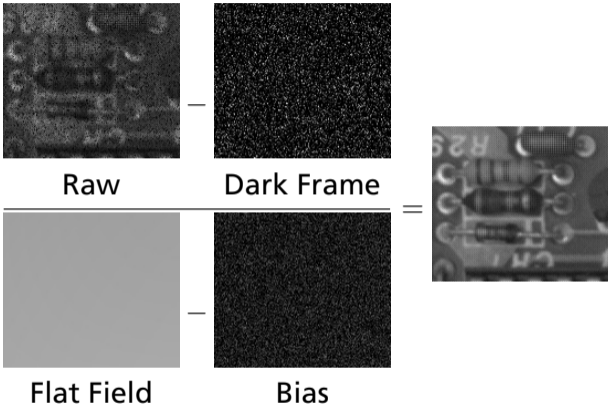


# Correcting Data from CCDs





# Correcting Data from CCDs



# Where Does This Noise Come From?

Nikon D300: 23.6 mm × 15.8 mm  
12.3 megapixel CMOS sensor

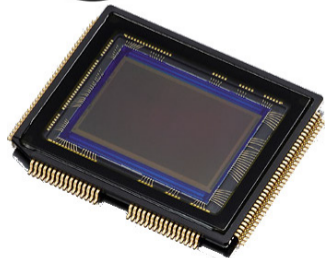
Pixels are 5.5  $\mu\text{m}$  on a side

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...