Microprocessor Systems: Principles and Implementation

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Before We Start ...

❑ What is "hacker spirit?"

cracker

you can't change a hardwired system

❑ Jargon File: a hacker is a person who enjoys exploring the details of programmable systems and stretching their capabilities, as opposed to most users, who prefer to learn only the minimum necessary.
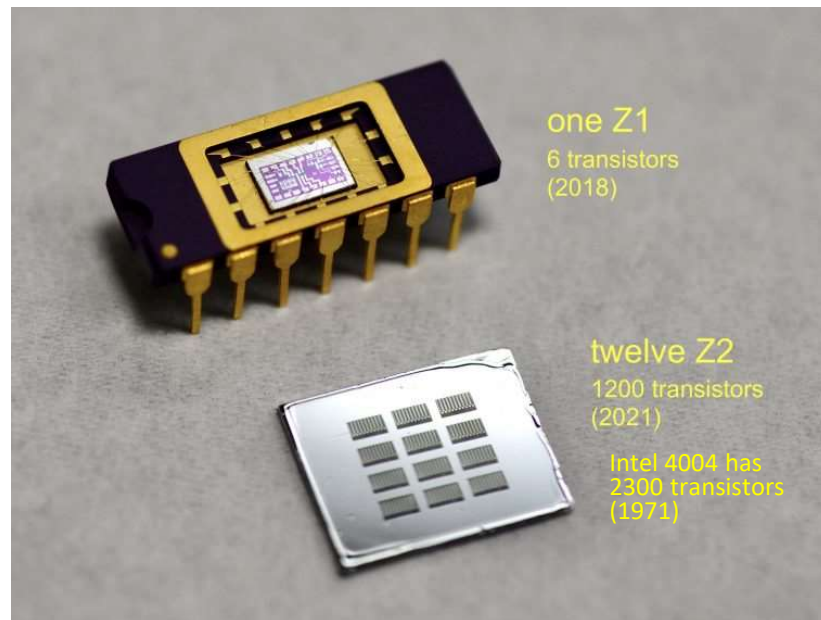
IETF *(Request for comments)*

❑ RFC-1392: a hacker is a person who delights in having an intimate understanding of the internal workings of a system, computers and computer networks in particular.

A Human Being Has No Limit

❑ A senior US high school student, Sam Zeloof, built an IC (an OP AMP in 5µm process) in a garage in 2018

❑ In 2021, he made an IC with the same 10µm polysilicon gate process used by Intel's 4004 CPU

one Z1
6 transistors
(2018)

twelve Z2
1200 transistors
(2021)

Intel 4004 has
2300 transistors
(1971)

(source URL: sam.zeloof.xyz)

Introduction to the Course

□ Lecture outline *ISA is not that important, but the design of micro Architecture*

- Introduction to the Course and Target Platform
- RISC-V Instruction Set Architecture *(vector)* → *Architecture (ISA).*
- Microprocessor Design: History and Review *micro Architecture.*
- Application Processors and Aquila SoC
- Memory Subsystem of Microprocessors → *& Domain Specific Accelerator*
- I/O Subsystem of Microprocessors *(DSA)*
- Operating System Support of Microprocessors
- Multicore Organization of Microprocessors

50MHz
ARM V7   *ARMV9.*
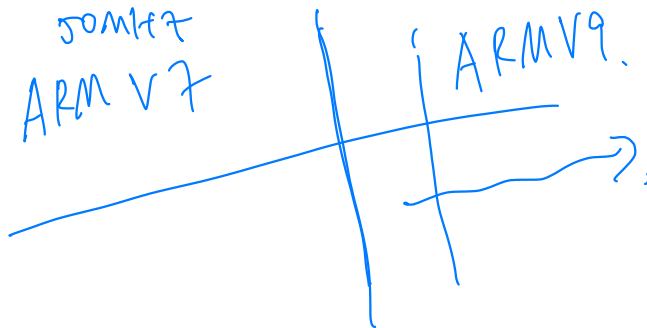
Homework & Grading

❑ Homework (based on RISC-V processor for FPGA):

  ■ 0: Simulation of a HW-SW platform

  ■ 1: Real-time debugging of a HW-SW platform

  ■ 2: Branch predictor analysis and improvement

  ■ 3: Cache analysis and improvement

  ■ 4: Multithread synchronization improvement under RTOS

  ■ 5: Domain-specific accelerator for application processors

❑ Grading

  ■ HW# 1 ~ 5: 70%

  ■ Midterm online test: 5%, Final online test: 25%

The Open-Source Aquila SoC

❑ In this course, our homework will be based on the open-source Aquila SoC:

http://github.com/eisl-nctu/aquila

❑ The Aquila SoC is an open-source processor core:
- Developed at the EISLab, Dept. of CS, NYCU (NCTU)
- RISC-V RV32-IMA compliant
- In-order, single-issue, five-stage pipeline microarchitecture
- Capable of running multi-threading RTOS
- 0.97 Dhrystone MIPS/MHz

GCC 8.2...   GCC 1.0 10.2.1.

A Short Table of DMIPS/MHz

❑ Dhrystone is one of the oldest CPU benchmarks:

Computer/CPU	Year	Clock (MHz)	DMIPS/MHz
UNIVAC I (first ISA computer)	1951	2.25	0.0008
Intel 4004 (first microprocessor)	1971	0.74	0.124
IBM PC/Intel 8088 (begins the fall of mainframes)	1979	4.77	0.145
PDP-11/70 (where UNIX & C were created)	1970	? (~ 10)	0.15
Apple II (origin of Taiwan's PC industry)	1977	1	0.43
Alpha 21064 (descendent used in SunWay)	1993	150	0.675
ARM 7 (popular for 2G mobile phones)	1994	45	0.889
ARM Cortex M4 (intended for microcontrollers)	2010	200	1.25
Cray I (first super computer)	1975	80	2.0
ARM Cortex A53 (popular in 4G smartphones)	2014	1500	2.24
ARM Cortex A9 (popular for 3G feature phones)	2009	1500	2.5
ARM Cortex A76 (popular in 4G smartphones)	2018	3000	12.4
Intel i9-9900K	2018	4700	10.96

Handwritten annotations: 2300 transistor; First SuperComputer microchip; ← Aquila (1.00); ← Falco (1.84) 0.1.0; ← MediumBoom (2.18); ← Boom (3.9); DGC; Apple Dual Core ARM 7. 100MHz; big LITTLE; Cortex: SuperScalar
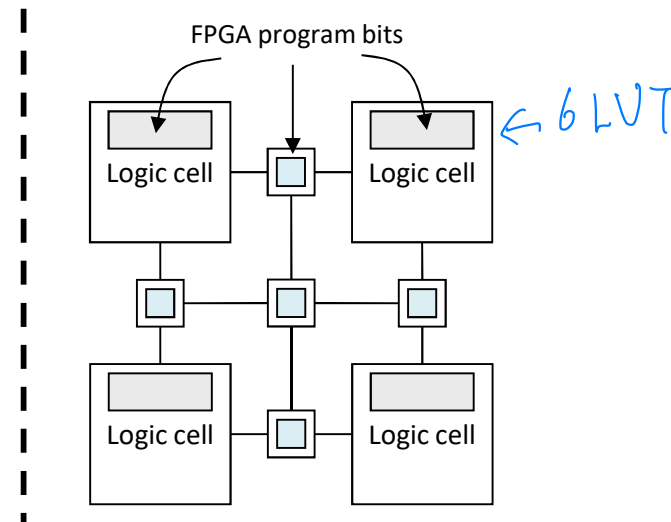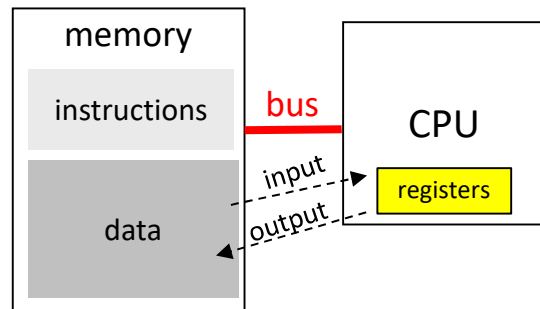
Skill Requirements

❑ Verilog programming for HW design

- Using FPGA as digital design target
- Using waveform simulator for functional debugging
- Using embedded logic analyzer for live debugging

❑ C programming for SW design

- Using GCC toolchain for SW development
- Using linker script usage for SW memory organization
- Tracing assembly code for SW debugging

Implementation of Computing Systems

❑ All computing systems are used to compute functions
- A function can be implemented in software, hardware, or both
- Software: processor instructions or FPGA program bits

stored program concept.

memory

instructions — bus — CPU

input → registers

data ← output

FPGA program bits

Logic cell   Logic cell   ← 6 LUT

Logic cell   Logic cell

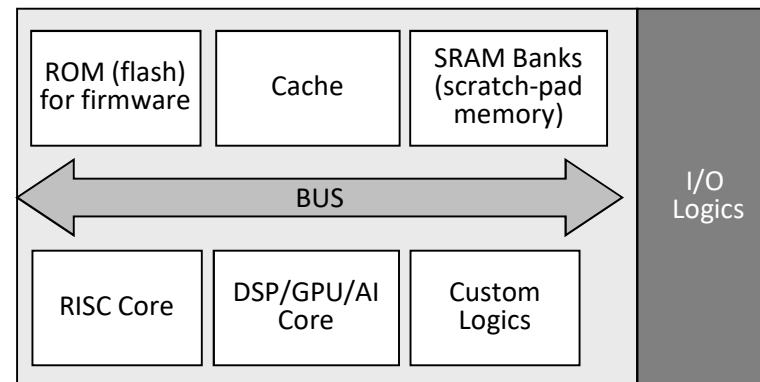- Hardware: analog circuits or digital circuits

Hardwired.

Board-Level System Implementation

❑ Integrate different ICs on a printed circuit board (PCB):
  ◾ A PCB has multiple layers
  ◾ Trace layers: connecting IC ports to other IC ports
  ◾ Power layers: supply power to circuit components on the PCB
  ◾ Ground layers: provide electrical grounds for signals

❑ Each IC implement analog and/or digital functions
  ◾ Digital ICs: data processing, buffering, signal arbitration and bridging, etc.
  ◾ Analog ICs: voltage regulation, AD/DA, signal amplification, etc.

Chip-Level System Implementation

❑ A System-on-Chip (SoC) is a complex IC that integrates the major functional components of a computing system into a single chip

❑ The SoC design typically incorporates several computing components (aka IPs) *Intellectual Property*

- Embedded processor cores (RISC/DSP/GPU/AI)
- On-chip memory blocks
- Accelerator Logic blocks
- I/O logic blocks
- Embedded software

ROM (flash) for firmware	Cache	SRAM Banks (scratch-pad memory)	I/O Logics
BUS			
RISC Core	DSP/GPU/AI Core	Custom Logics	

# "Board-level" vs. "Chip-level" Design

- ❑ Board-level Design
  - ■ More flexible in development cycle
  - ■ High manufacturing cost for large quantities
  - ■ Larger form factor and higher power consumption

- ❑ Chip-level Design (i.e. SoC)
  - ■ More demanding in design, debug, and verification
  - ■ Low cost for large quantities
  - ■ Smaller form factor and lower power consumption

- ❑ A new trend: package-level design, aka system-in-package
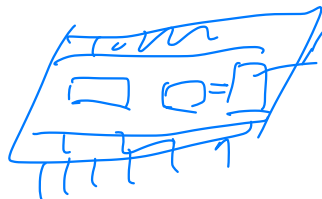
Application Processor Concept

❑ You probably have learned the following terms:

- CPU
- Microprocessor
- Microcontroller
- . . .

HW-SW Codesign

❑ The concept of "Application Processor (AP)" comes from the big boom of smartphones

❑ An AP is an SoC that contains:

- Processor cores
- Optimized domain-specific accelerators (DSAs)
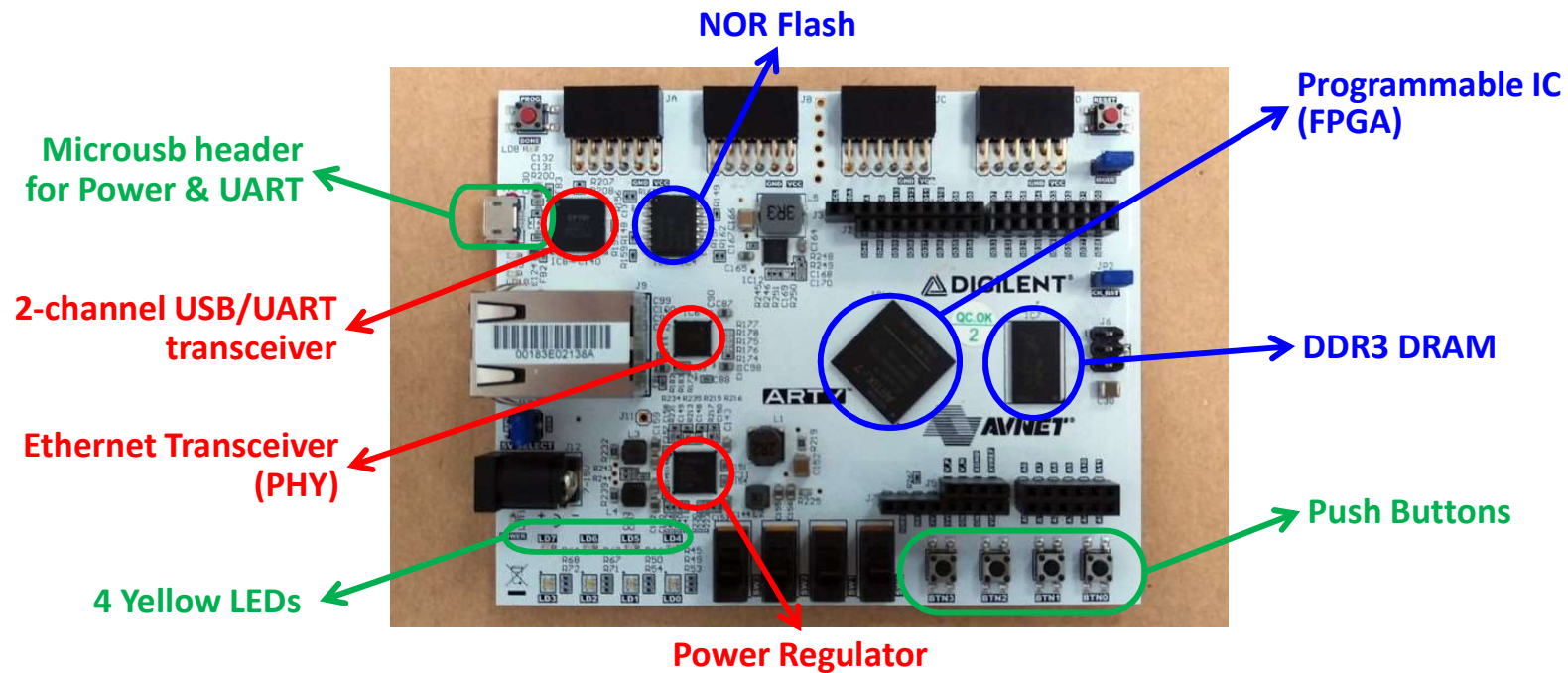- An efficient memory subsystem

The Architecture of the Aquila SoC

❑ The Aquila SoC specification on Arty A7-100T:

  ■ A 32-bit RISC-V core @ 41.6667 MHz
    – L1 4-way set associative I/D-caches
  ■ 64KB tightly-coupled memory (TCM) / 256MB DDR3 DRAM
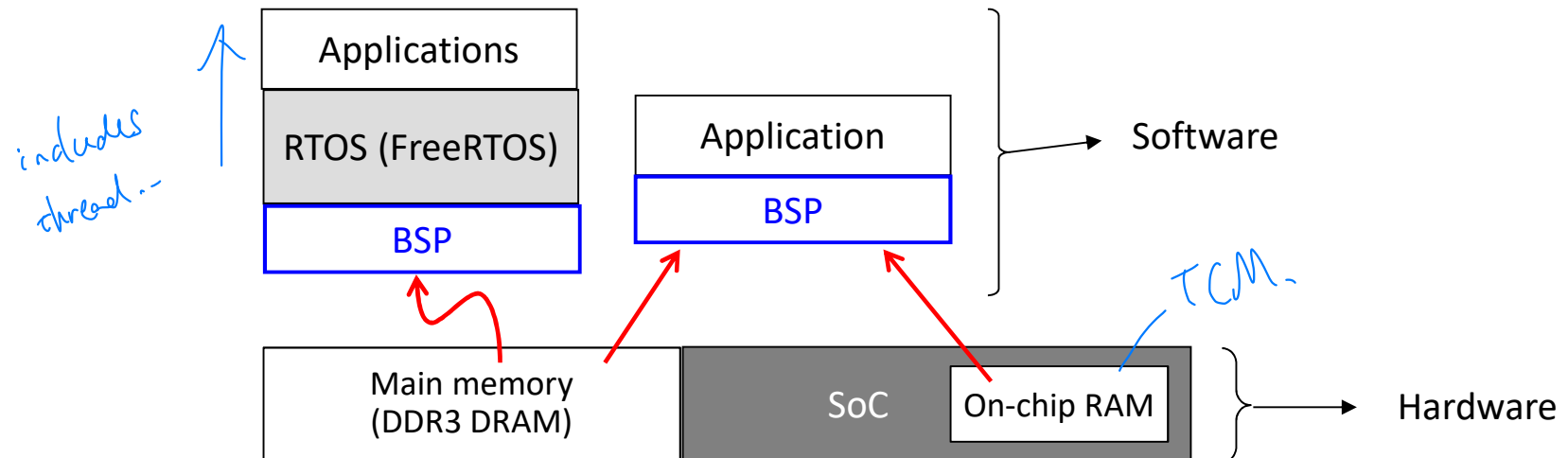 ■ Integrated UART, Timer, and device controllers
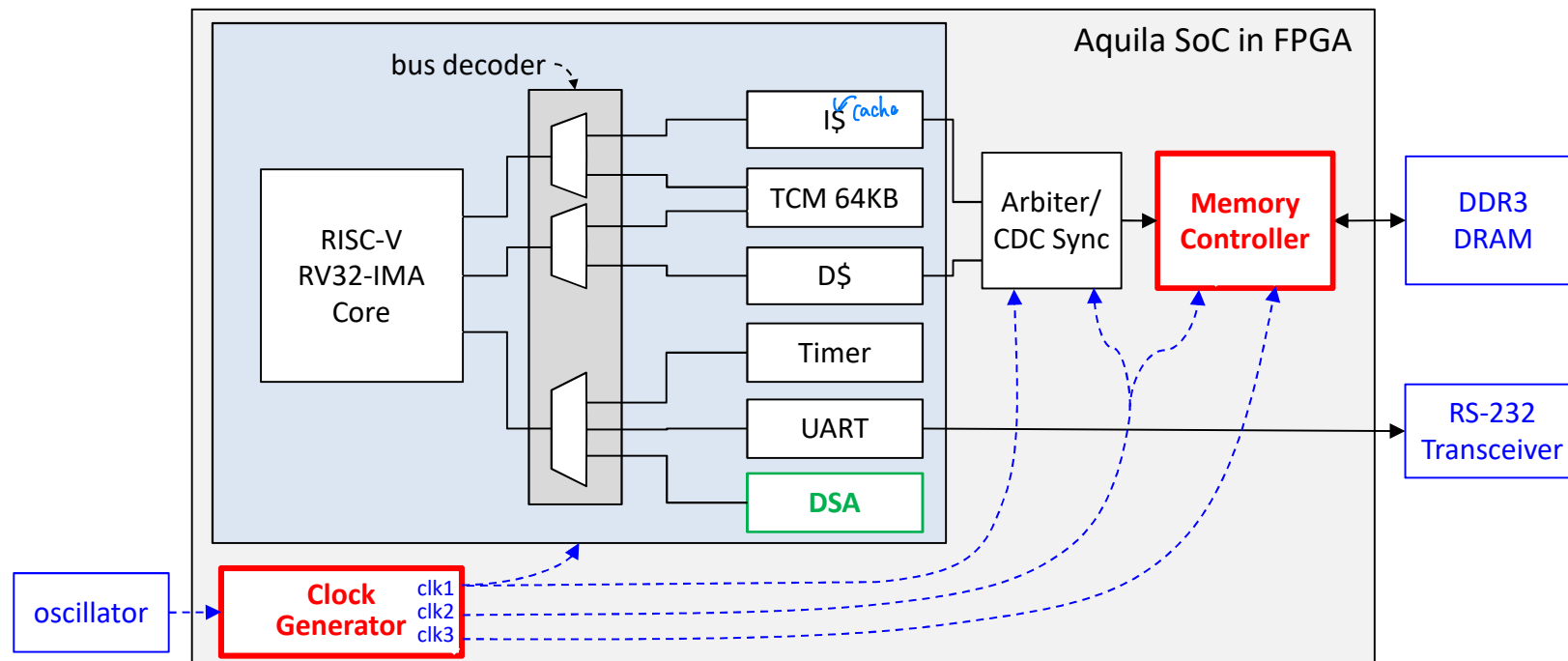
The Target Development Board

❑ Arty A7-100T contains an XC7A100T FPGA:
  ▪ 63,400 LUTs, 126,800 FFs, 600KB BRAMs, and 220 DSPs
❑ Aquila core uses 7,300 LUTs, 5,000 FFs, and 4 DSPs

NOR Flash

Programmable IC (FPGA)

Microusb header for Power & UART

2-channel USB/UART transceiver

Ethernet Transceiver (PHY)

DDR3 DRAM

Push Buttons

4 Yellow LEDs

Power Regulator

The System HW-SW Layers

Scratch Pad memory –

❑ The layered structure of the HW-SW in this course:

■ BSP stands for Board Support Package, it contains a basic set of I/O routines, usually for C programs (similar to BIOS for PC)

includes thread –

Applications
RTOS (FreeRTOS)
BSP

Application
BSP

→ Software

Main memory (DDR3 DRAM)	SoC	On-chip RAM

TCM –

→ Hardware

❑ For FPGAs, the on-chip RAM can be initialized with a program (such as boot code).

O.1d

System Convergence

❑ Today, smart devices have many things in common:
- Powerful processors and accelerators
- Sensor integrations
- Audio/video recording and/or playback
- Complex feedback control of motors
- Wireless communication capabilities

❑ One platform for all devices (Drones, ADAS, etc.)?
- Application Processor
- GPS
- AV codecs
- Motor control
- Wi-Fi and BT

Discussions

❑ This course tries to teach you the entire HW-SW system, with almost all source code exposed to you

❑ Taiwan has an IT industry today because back in 1977, the co-funder of Apple, Steve Wozniak, insisted that the entire source code and the schematics of the Apple II computer should be available to users