



北京大学
PEKING UNIVERSITY

10010010

嵌入式系统编程与实践

2-从信息物理系统到嵌入式系统

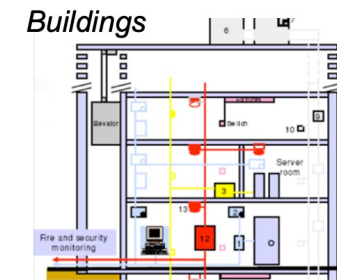
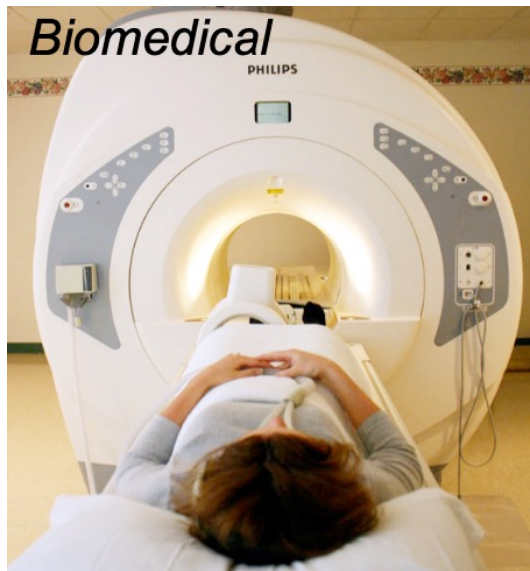
燕博南
2023秋

Outline

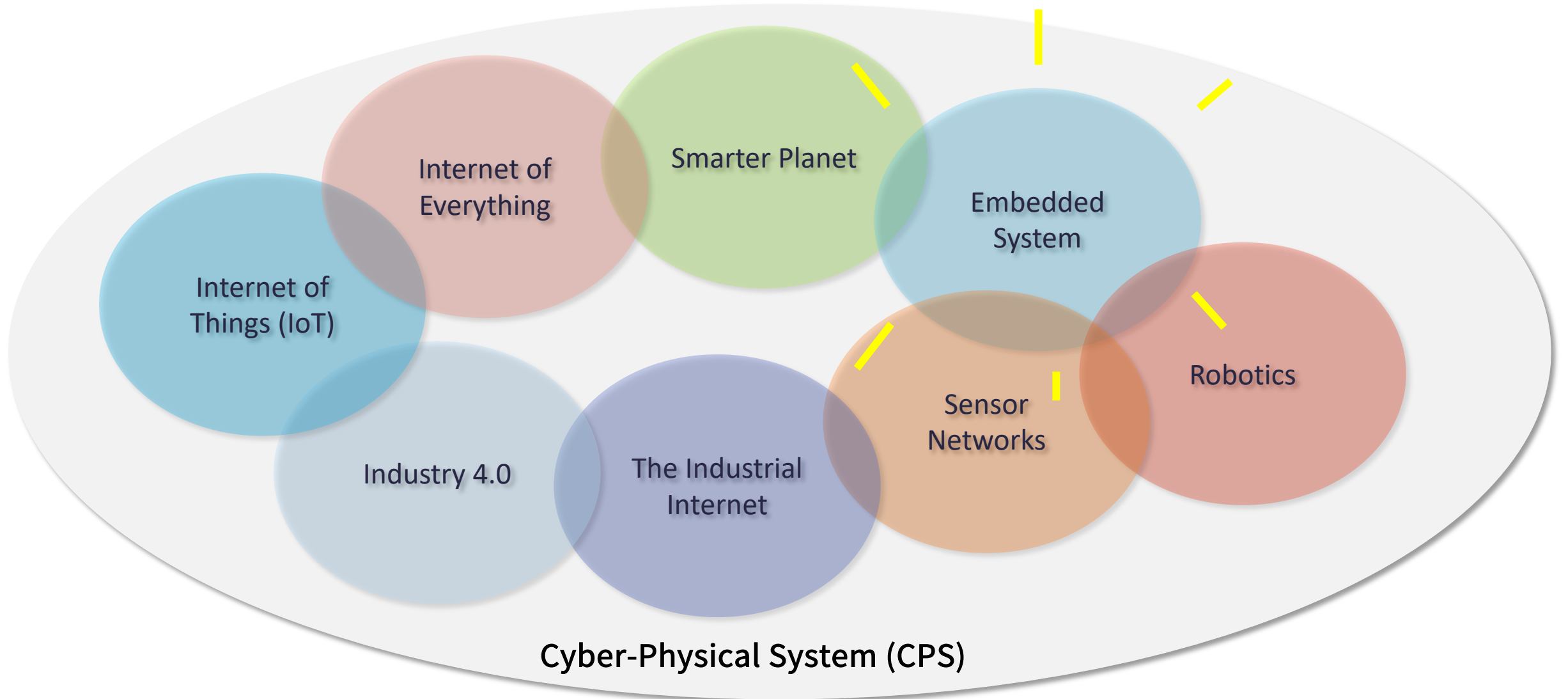
- Introduction to Cyber-Physical System (CPS)
- Introduction to Embedded System
- Embedded System Hierarchy
- Development Flow of Embedded System

Cyber-Physical System (CPS)

- Definition:
- Integration of **computation** with **physical processes**, defined by the intersection

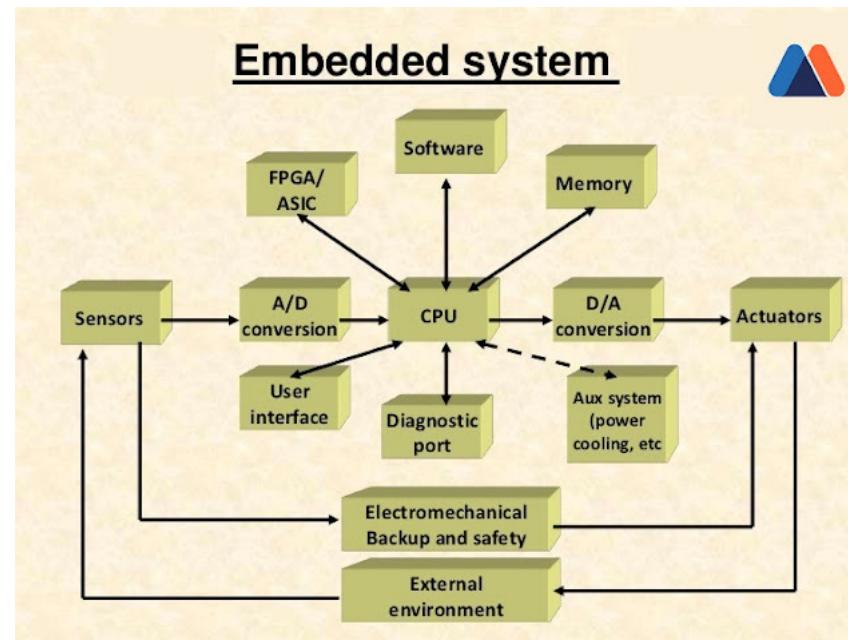


Cyber-Physical System (CPS)



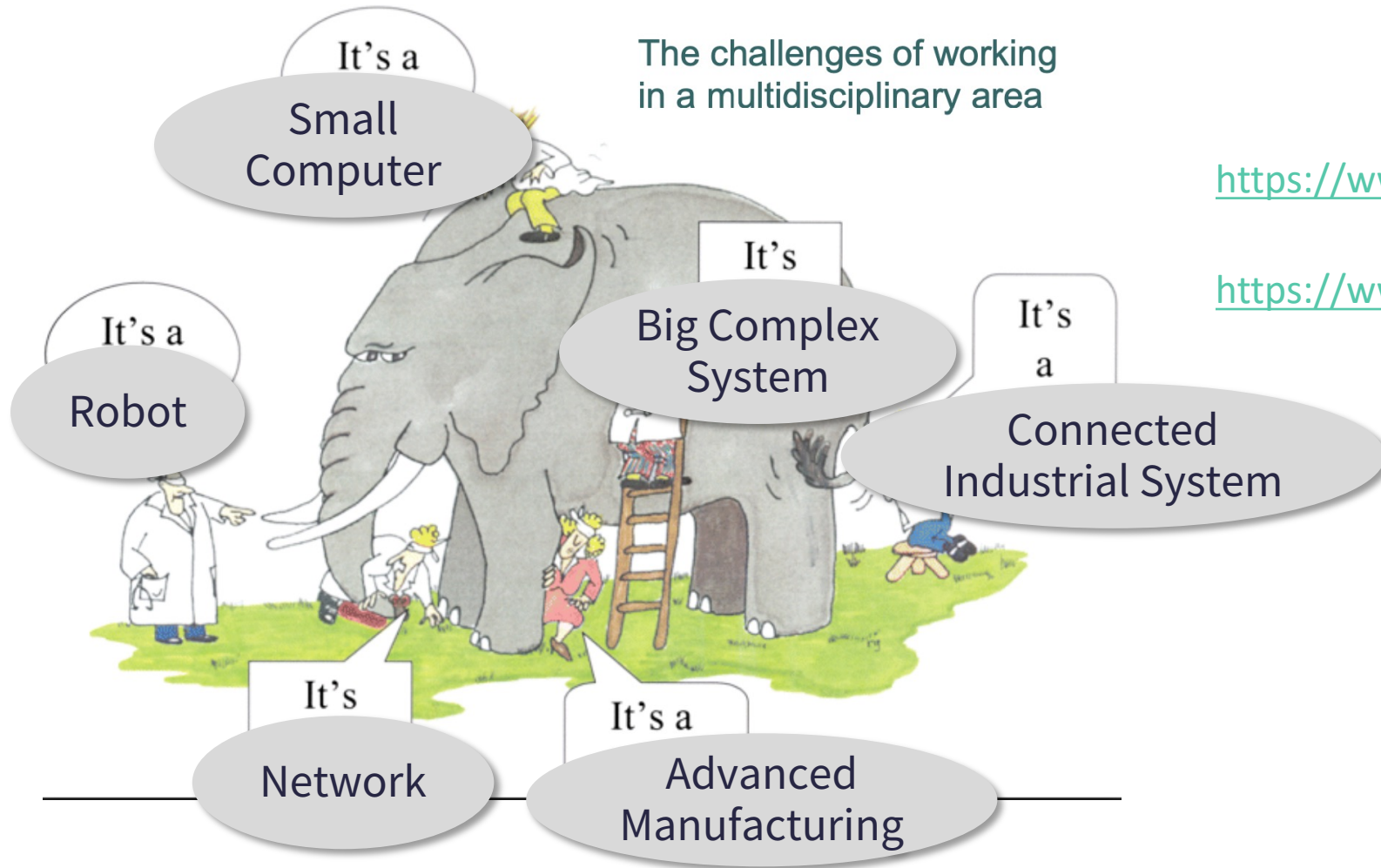
Embedded System

- An embedded system is a computer system—a combination of a computer processor, computer memory, and input/output peripheral devices—that has a dedicated function within a larger mechanical or electronic system.



Source: <https://www.heavy.ai/technical-glossary/embedded-systems>

CPS is A Multidisciplinary Area



<https://www.bilibili.com/video/BV1ZA411e7Ff/>

<https://www.bilibili.com/video/BV1N14y1E741/>

Cyber-Physical System (CPS)

- DARPA: Symbiotic Design for Cyber Physical Systems (SDCPS), \$8.7M
- NSF: The CPS program aims to develop the core research needed to engineer these complex CPS, some of which may also require dependable, high-confidence, or provable behaviors, \$32.4M
- 我国重点研发计划：电网信息物理系统分析与控制的基础理论与方法

I. 项目背景

信息物理系统(Cyber Physical Systems, CPS)是实现计算、通信以及控制技术深度融合的系统,随着信息技术的深度应用,电网已成为典型的信息物理系统,而现有分析控制方法主要关注信息空间或物理系统本身,难以揭示二者交互影响所诱发的叠加风险,未能挖掘二者融合作用带来的能力提升。

本项目突破传统电网分析瓶颈,揭示电网信息物理过程交互机理,构建信息与能量高度融合的电网分析与控制理论体系,研发电网 CPS 综合仿真平台,为智能电网乃至新一代能源系统的运行控制提供理论支撑。

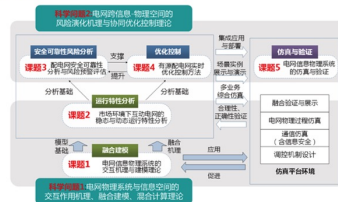


中华人民共和国科学技术部
Ministry of Science and Technology of the People's Republic of China



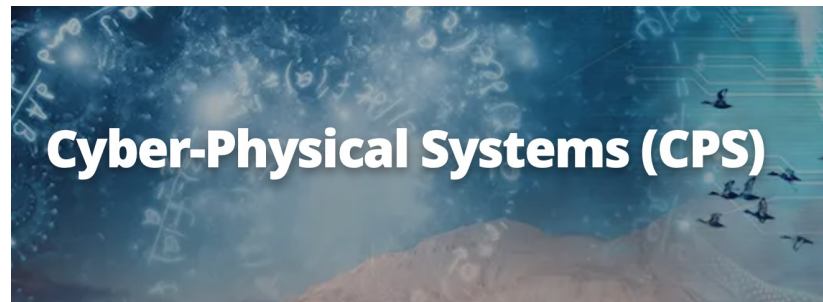
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

II. 科学问题与课题设置



III. 项目成效

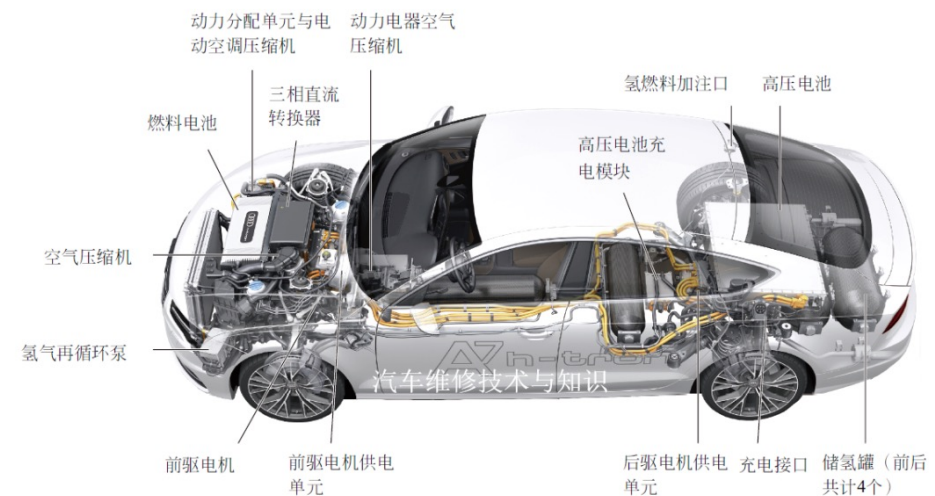
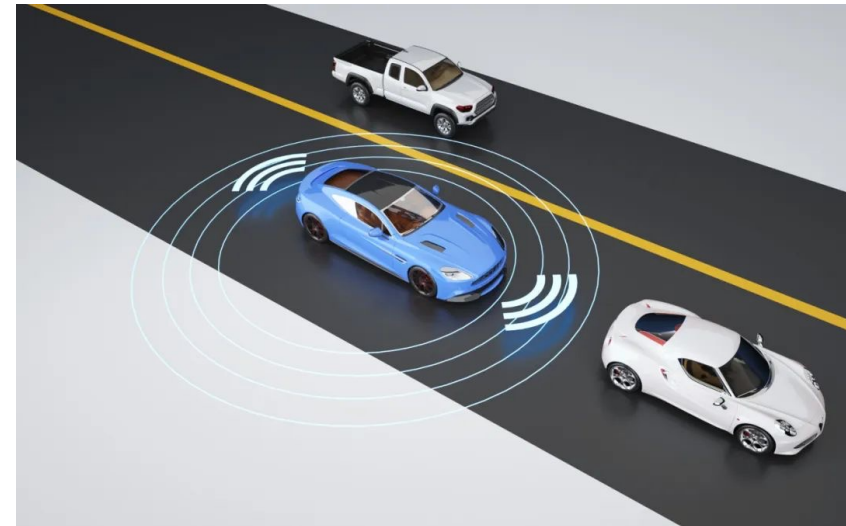
针对电网信息空间与物理系统交互影响带来的挑战与机遇,围绕“融合”解决CPS认知问题;围绕“高可靠”解决CPS应用问题。完成信息物理融合机理分析→建模与混成计算分析→配电网安全风险计算与自趋优控制→仿真验证平台。



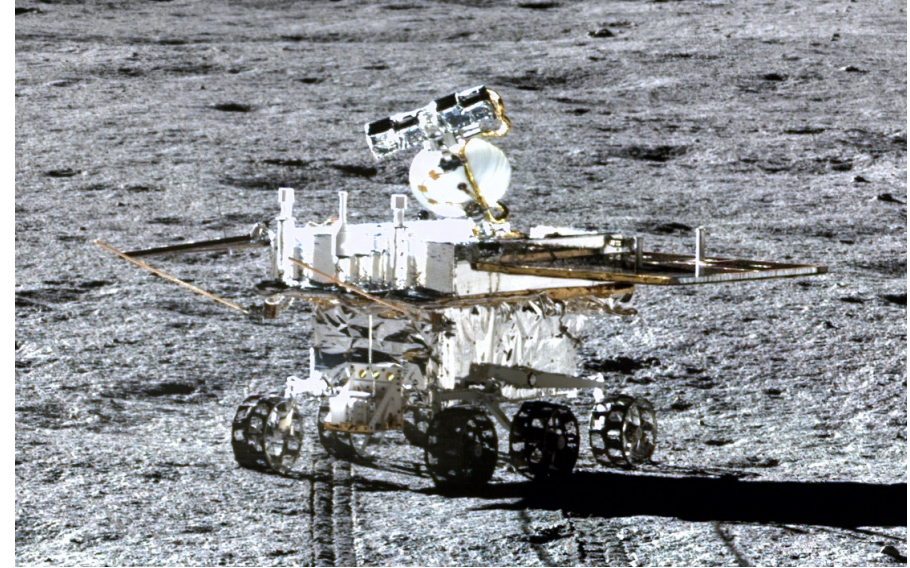
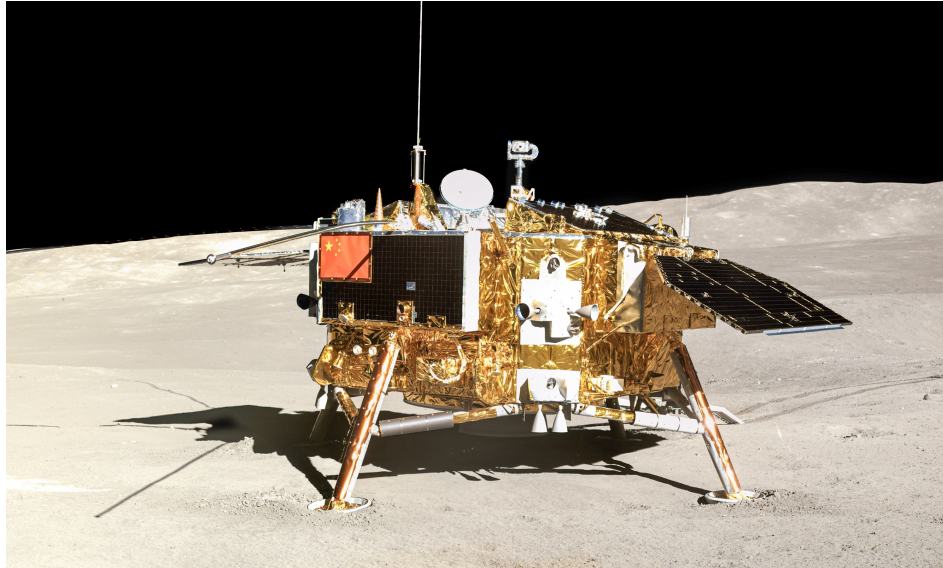
National Science Foundation

Example: Automotive CPS

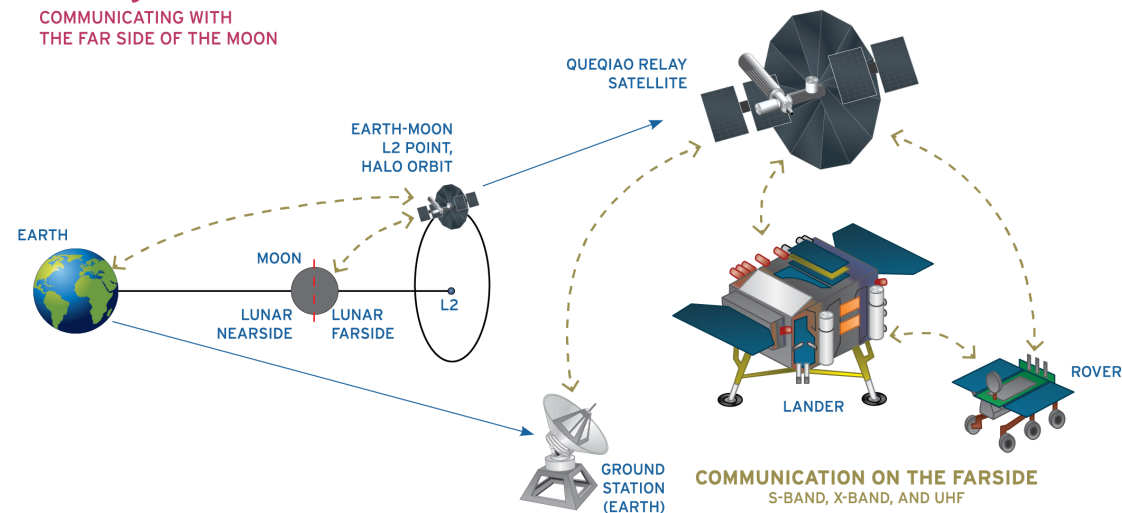
- Safer Transportation
- Reduced Emissions
- Smart Transportation
- Energy Efficiency
- Climate Change
- Human-Robot Collaboration



Example: 嫦娥四号着陆器+探测器

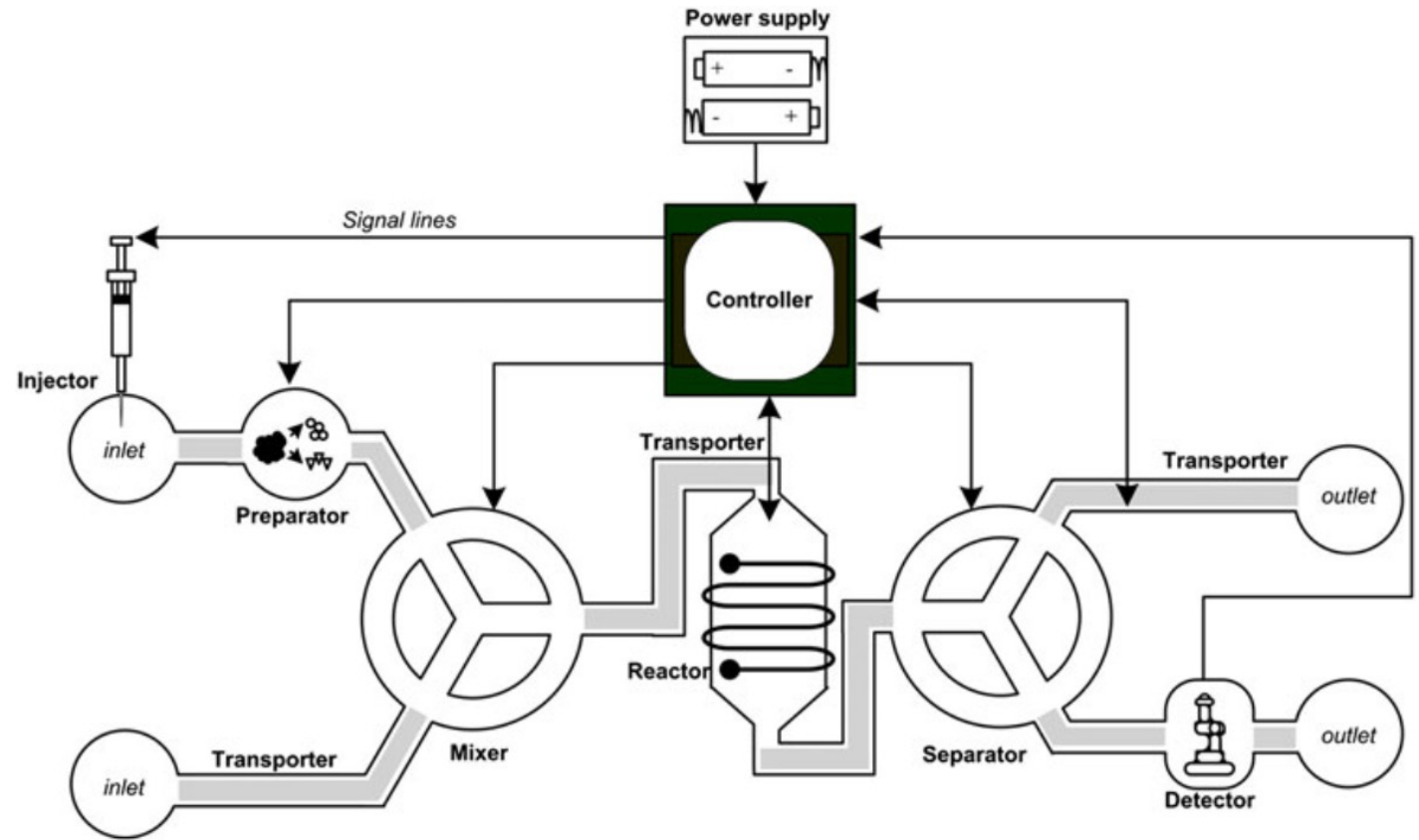
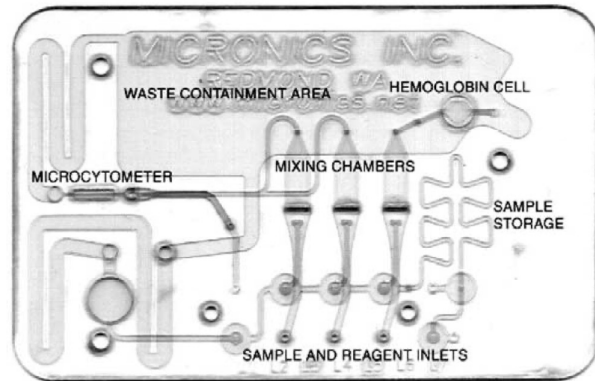


Chang'e-4
COMMUNICATING WITH
THE FAR SIDE OF THE MOON



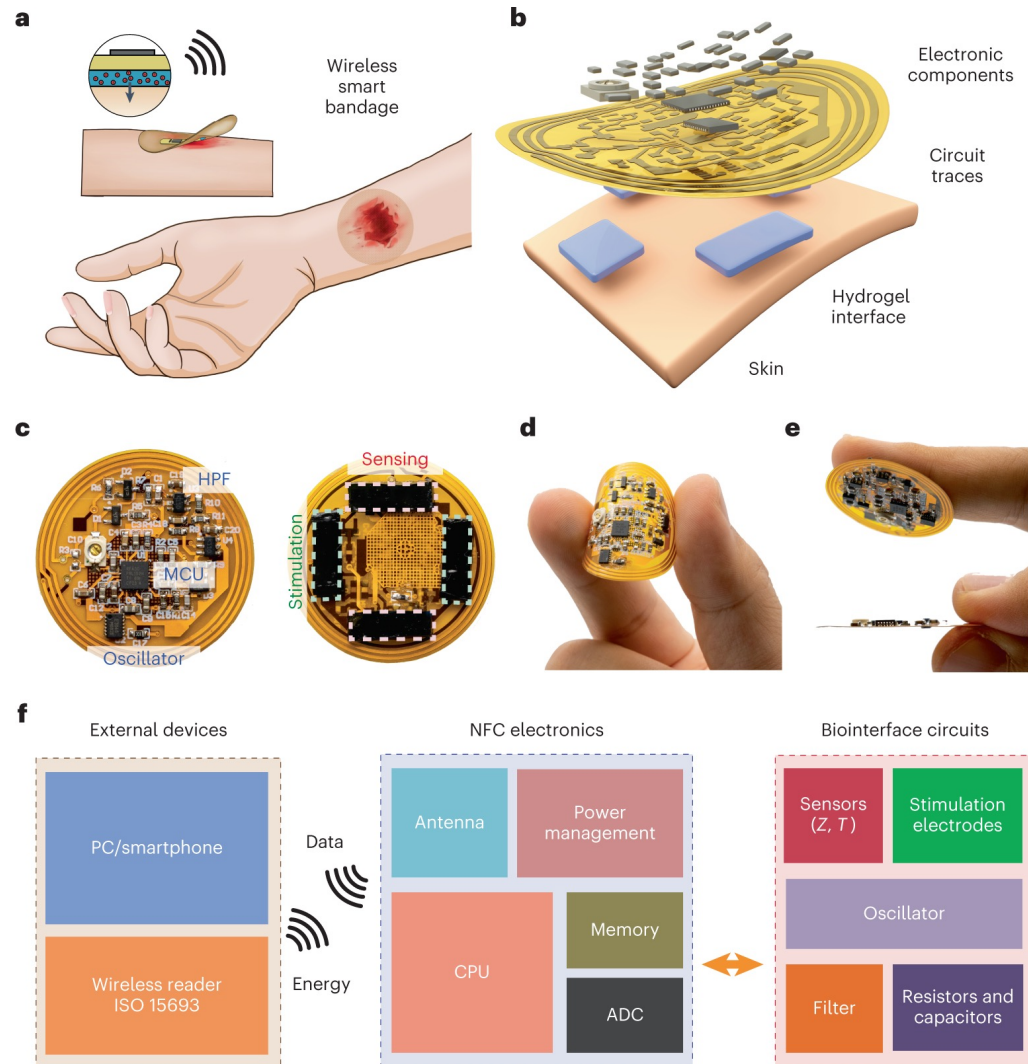
Example: Lab-on-a-chip

- Precise droplet control
- Real-time analysis



Source: Lab-on-a-chip: a component view

Example: Smart Bandage



- Intersection of:
- Material science
- Electronics
- Embedded Systems

Jiang, Y., Trotsyuk, A.A., Niu, S. *et al.* *Nat Biotechnol* **41**, 652–662 (2023).

Development Flow of CPS

- **Modeling** is the process of gaining a deeper understanding of a system through imitation. Models express **what** a system does or should do.
- **Design** is the structured creation of artifacts. It specifies **how** a system does what it does.
- **Analysis** is the process of gaining a deeper understanding of a system through dissection. It specifies **why** a system does what it does (or fails to do what a model says it should do).

Motivating Example of a Cyber-Physical System

- (see Chapter 1 in book)



STARMAC quadrotor aircraft (Tomlin, et al.)
多旋翼无人机

Modeling:

- Flight dynamics (ch2)
- Modes of operation (ch3)
- Transitions between modes (ch4)
- Composition of behaviors (ch5)
- Multi-vehicle interaction (ch6)

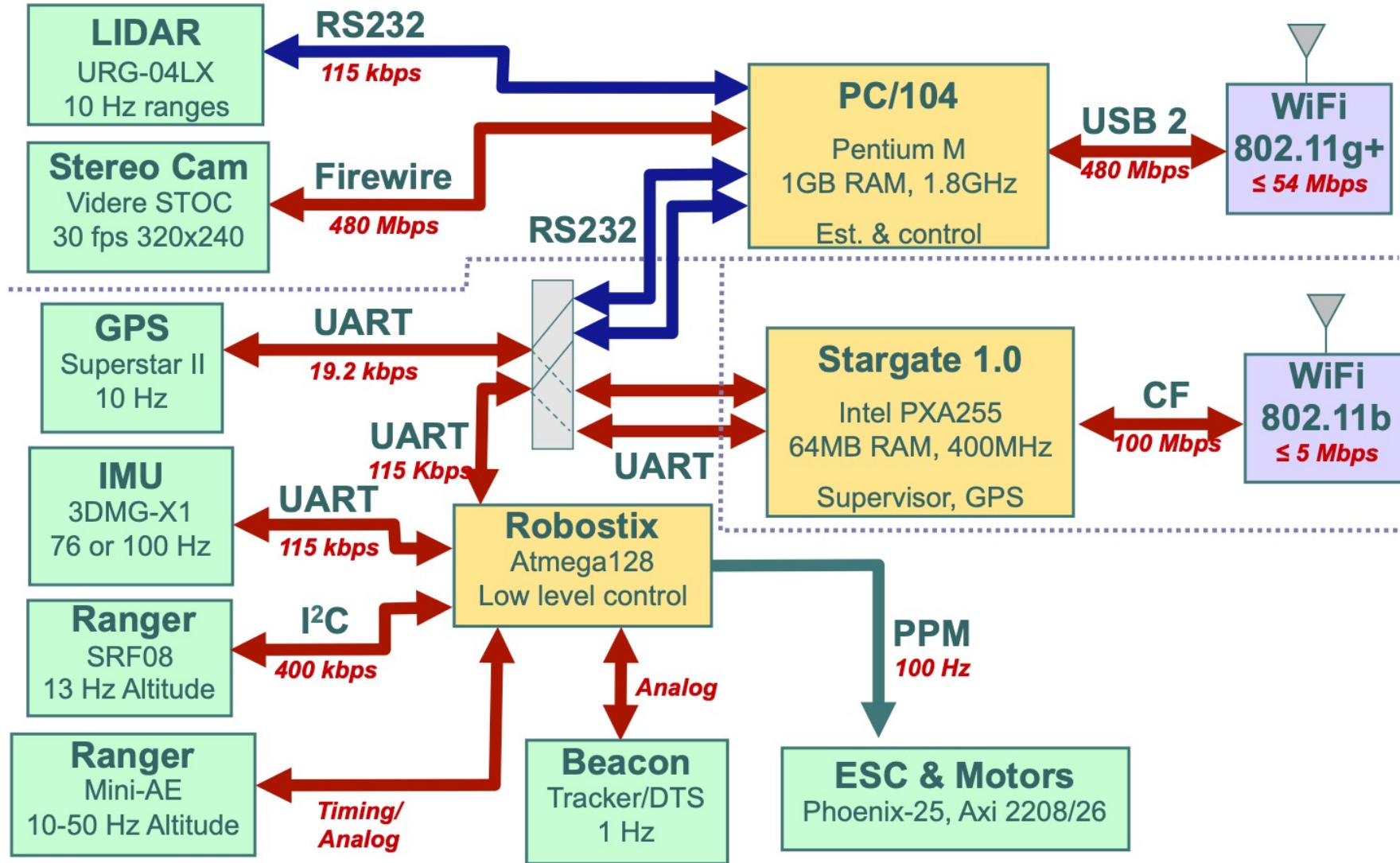
Design:

- Sensors and Actuators (ch7)
- Processors (ch8)
- Memory system (ch9)
- Sensor interfacing (ch10)
- Concurrent software (ch11)
- Real-time scheduling (ch12)

Analysis

- Specifying safe behavior (ch13)
- Achieving safe behavior (ch14)
- Verifying safe behavior (ch15)
- Guaranteeing timeliness (ch16)
- Security and privacy (ch17)

Design of STARMAC Design



Think Critically

- Any course that purports to teach you how to design embedded systems is misleading you
- The technology will change, rapidly!
- Our goal is to teach you how things are done today, and why that is not good enough.

Courtesy: UC Berkeley EECS149

Outline

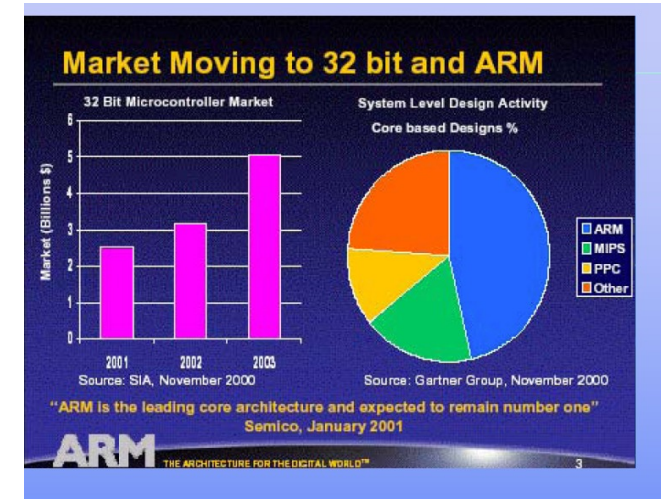
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Historic Perspective: Embedded System Depends on IC Technology

嵌入式系统教学讲义 (何广强)



一些典型的嵌入式系统应用实例



计算机的发展



1.3.5 嵌入式外围接口电路和设备接口

根据外围设备的功能可分为以下5类

- 存储器类型
- 通信接口
- 输入输出设备
- 设备扩展接口
- 电源及辅助设备

1.3.1 嵌入式系统软件的层次结构

具有操作系统的嵌入式软件层次

- 驱动层程序
- 实时操作系统 (RTOS)
- 操作系统的应用程序接口 (API)
- 应用程序

1.3.2 启动程序BootLoader介绍

Historic Perspective: Embedded System Depends on IC Technology

泛在通用人工智能计算时代

2025-2035

大型计算机
科学计算时代
1965以前

牵引应用：
• 军事应用
• 科学计算

个人电脑
小型化时代
1965-2000

牵引应用：
• 图文办公
• 自动控制

互联网时代
2000-2007

牵引应用：
• Web1.0/2.0
• 网络服务

移动计算时代
2007-2017

牵引应用：
• 智能手机
• 移动互联网

高性能计算/
感知智能时代
2017-2027

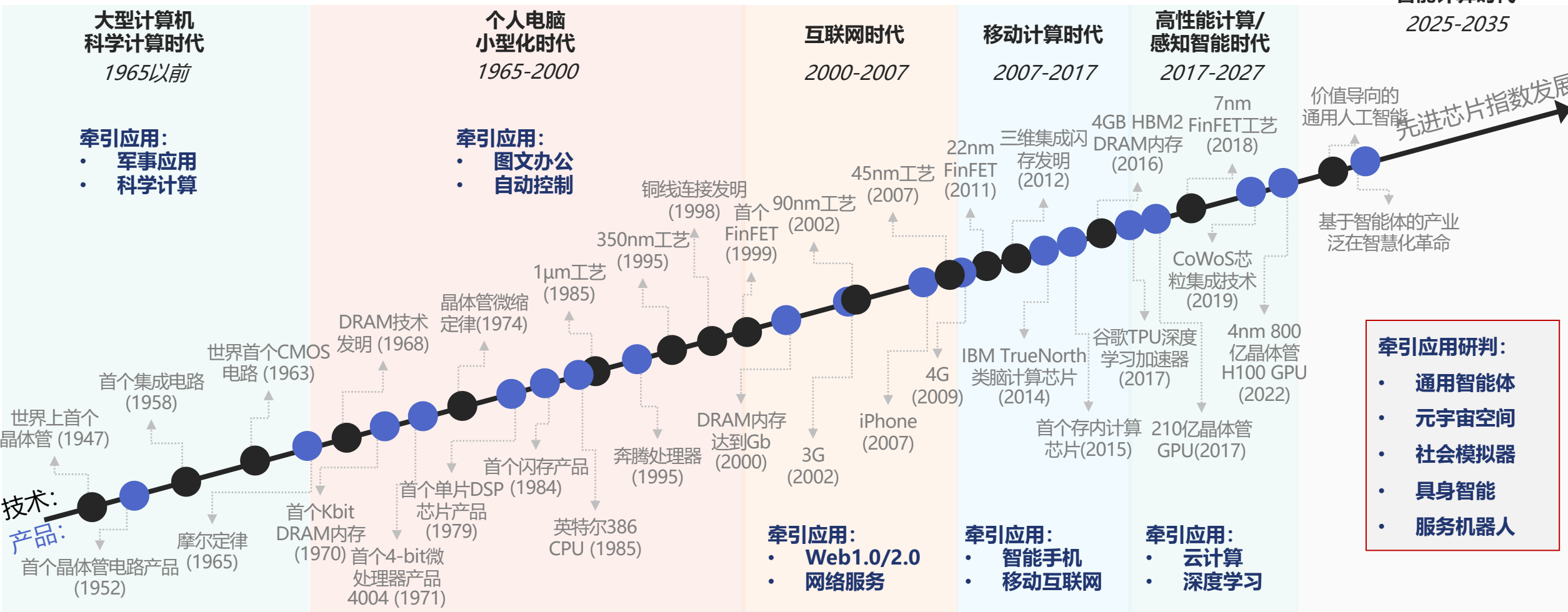
牵引应用：
• 云计算
• 深度学习

价值导向的
通用人工智能
先进芯片指数发展

基于智能体的产业
泛在智慧化革命

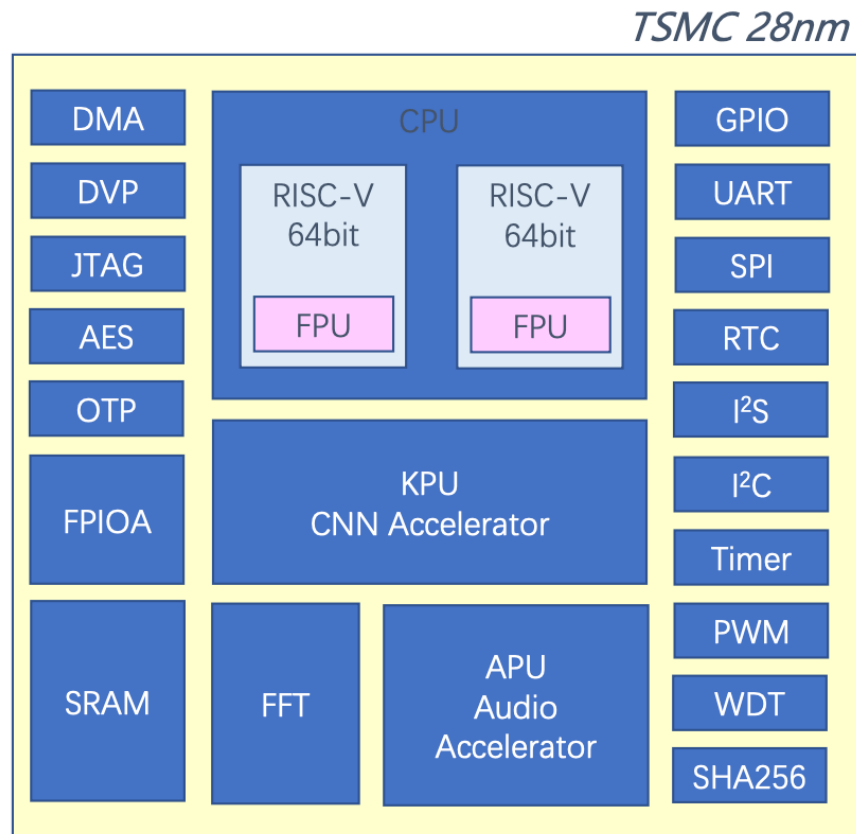
牵引应用研判：

- 通用智能体
- 元宇宙空间
- 社会模拟器
- 具身智能
- 服务机器人



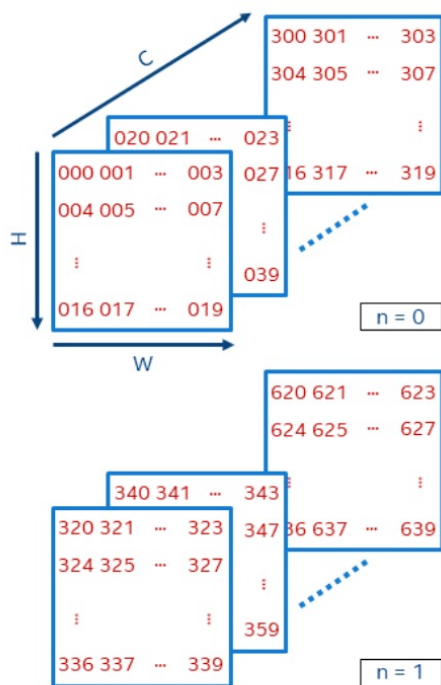
K210 Architecture

- CPU x2
 - 额定运行频率400MHz，各自带独立FPU（单精度浮点）
- KPU x1: 神经网络加速器
 - 卷积、池化、激活
- APU x1: 语音处理单元
 - Beam-forming、降采样、FIR、FFT
 - 最多支持8路音频数据，16个方向
- SRAM x1: 8MB
 - 其中2MB为KPU专用，剩余6MB由用户程序和模型数据共用
- DVP x1: 摄像头接口（8位并口）
 - 输入：RGB565、YUV422
 - 输出：RGB565、RGB888、YUV422的Y分量
 - 支持的最大分辨率1920*1023
- DMA x6: 6个通道

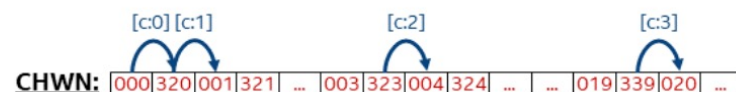


KPU运行卷积深度学习网络

- 网络输入或者中间的feature map尺寸不大于320*256，不小于4*4
- 与tensorflow支持的数据排布格式NHWC不同， KPU支持的数据排布格式为NCHW



Physical data layout
NCHW, NHWC, and CHWN layouts



KPU

- 支持的普通二维卷积

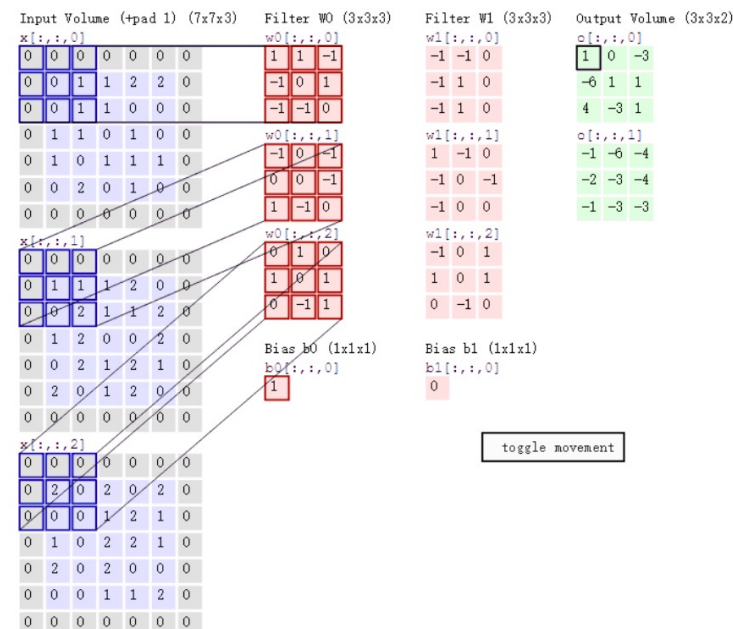
ksize	stride	required tensorflow padding
1*1	1	same或valid
3*3	1	same
3*3	2	卷积前将feature map手动padding一圈，然后卷积时padding方式用valid

- 支持的depthwise二维卷积

ksize	stride	required tensorflow padding
3*3	1	same
3*3	2	卷积前将feature map手动padding一圈，然后卷积时padding方式用valid

- 支持的pooling

ksize	stride	required tensorflow padding
2*2	1	same
2*2	2	如果feature map size是ksize的整数倍， same或valid； 否则valid
4*4	4	如果feature map size是ksize的整数倍， same或valid； 否则valid



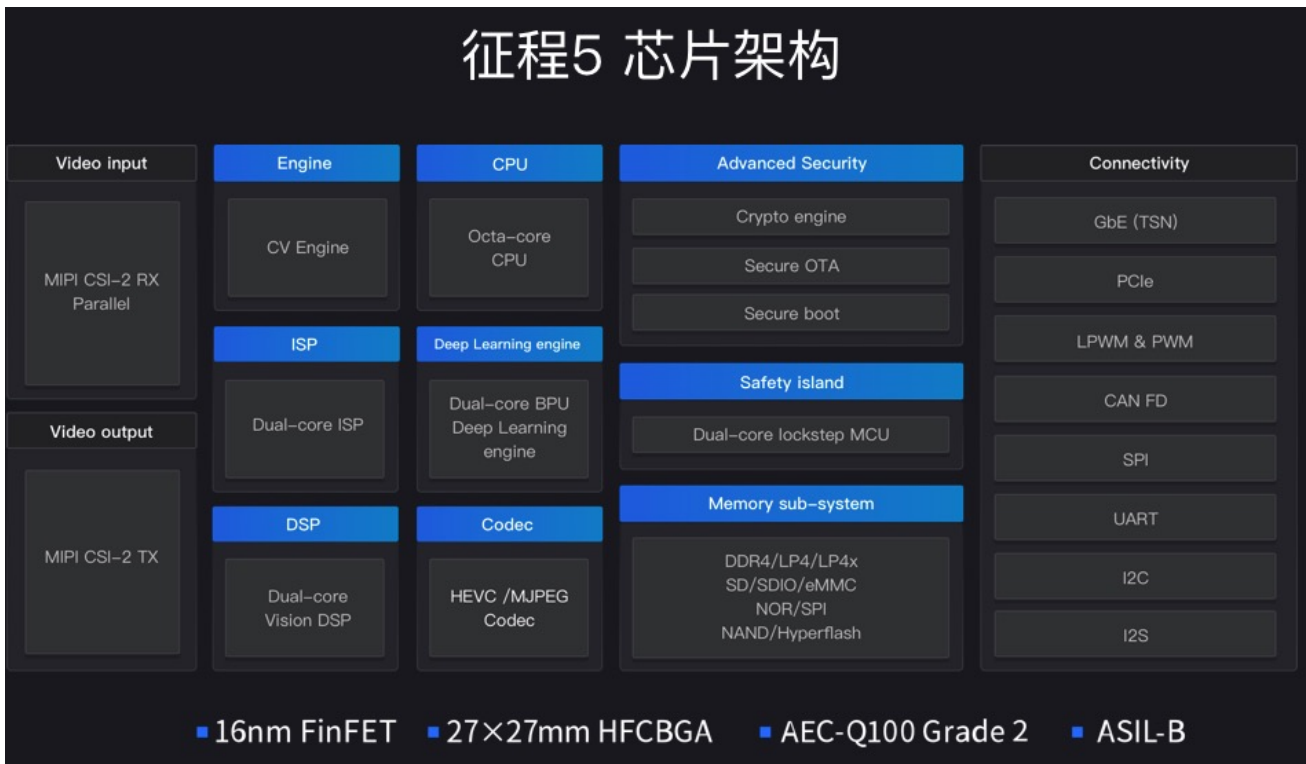
KPU工作流程

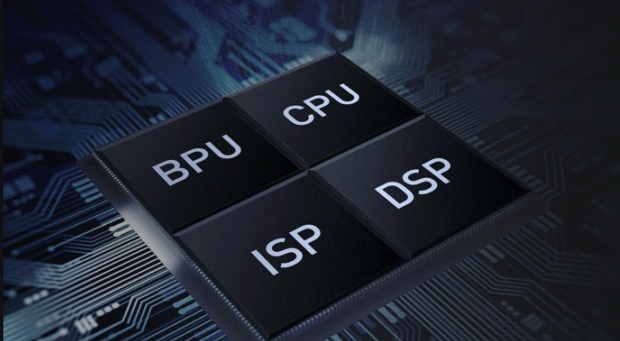
用于将主流训练框架按照特定限制规则训练出来的浮点模型量化转化为K210可运行的格式

- 支持的训练框架
 - Tensorflow、Caffe、Paddlepaddle
- 量化位数
 - 8bit、16bit
- 支持的操作
 - Conv2d、DepthwiseConv2d、FullyConnected、Add、MaxPool2d、AveragePool2d、GlobalAveragePool2d、BatchNormalization、BiasAdd、Relu、Relu6、LeakyRelu、Concatenation、L2Normalization、Softmax、Flatten、ResizeNearestNeighbor

其它例子：地平线征程5

征程5 芯片架构






丰富异构计算

- BPU、DSP 和 CPU 无缝支持复杂计算任务
- 低延迟 CV 引擎
- HEVC/JPEG 硬件编解码



面向自动驾驶场景设计的 I/O 接口

- PCIe 3.0 高速信号接口
- 双路千兆实时以太网(TSN) 为多传感同步融合提供硬件级支持(PTP)
- 多路 CAN-FD 接口简化整车智能计算平台系统架构



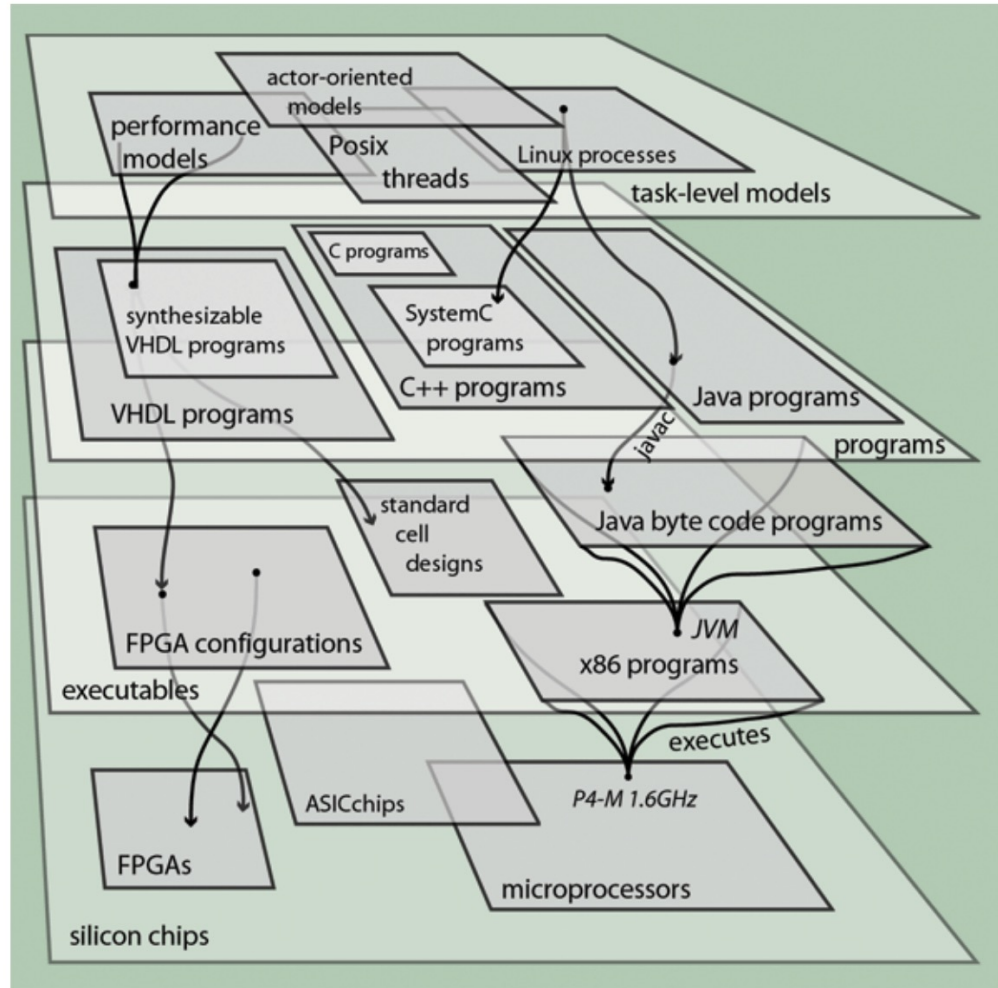
全面的功能安全和信息安全保障

- 安全岛，软硬件安全功能
- 涵盖计算和 I/O 接口
- ARM 信任区，硬件Crypto加速引擎

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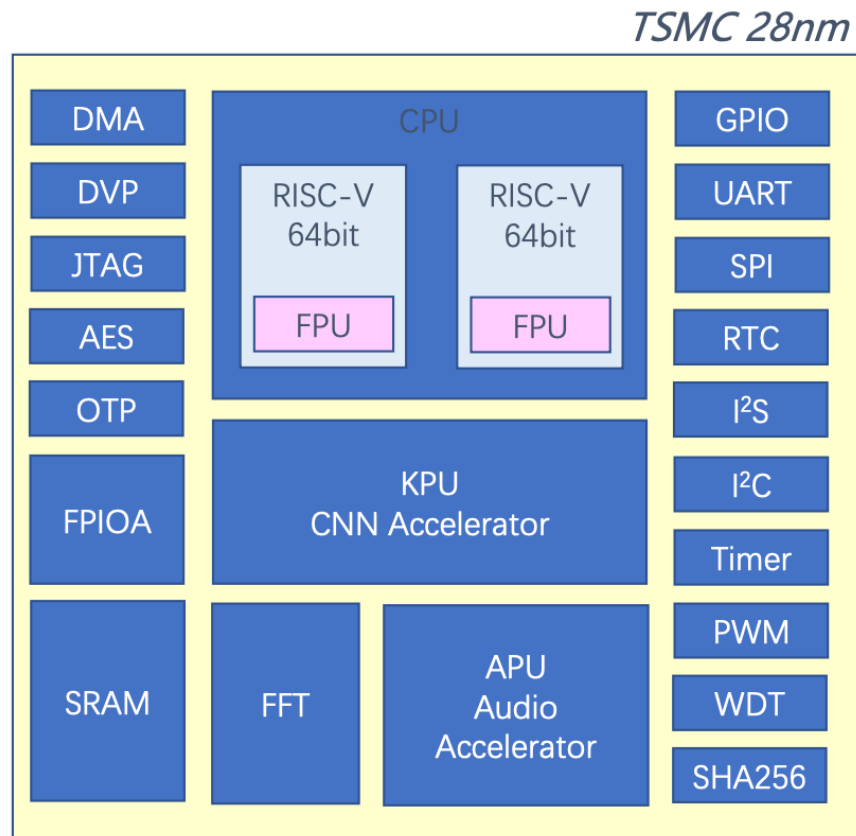
Embedded System Abstraction



The purpose of an abstraction is to hide details of the implementation below and provide a platform for design from above.

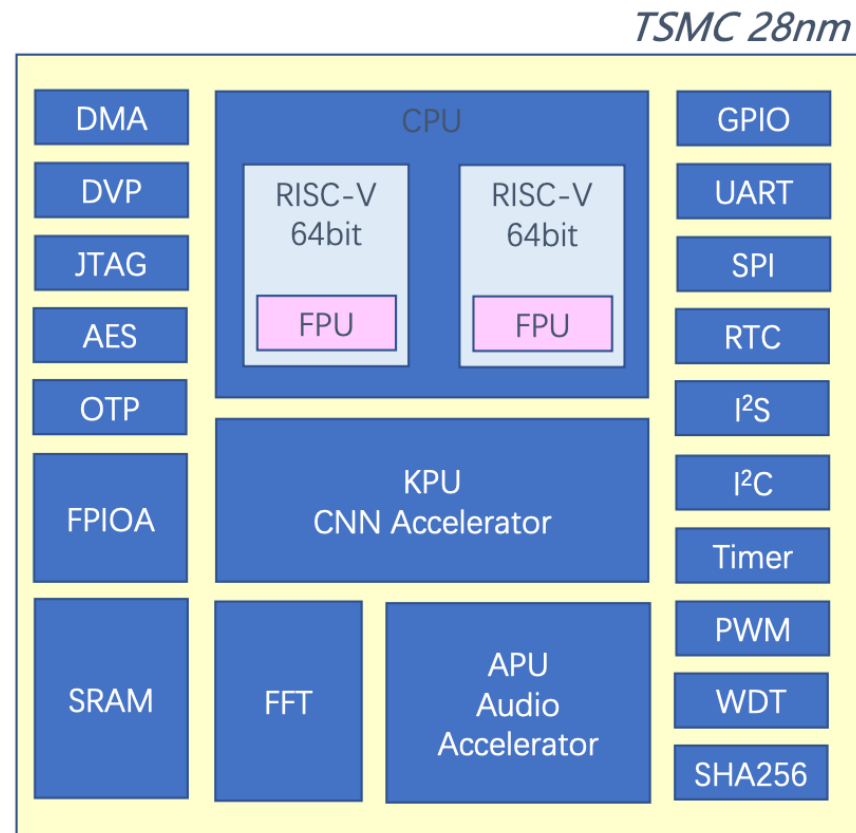
K210 Hardware (Revisit)

- CPU x2
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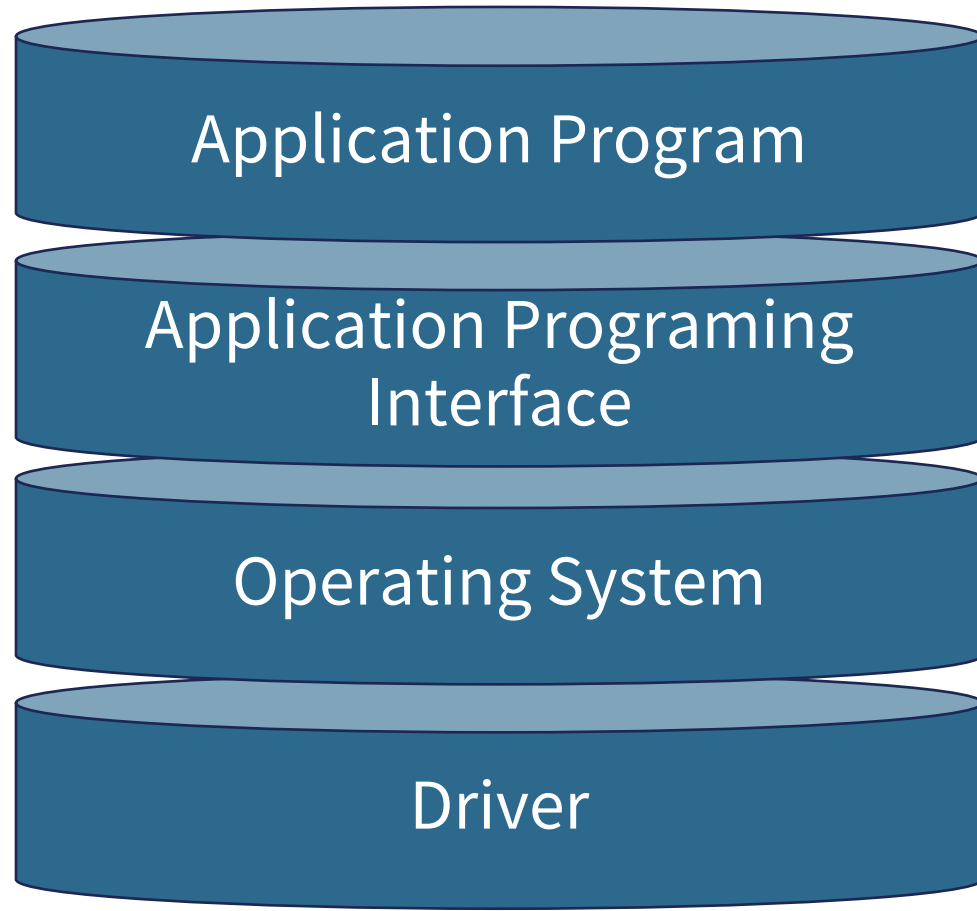


K210 Hardware (Revisit)

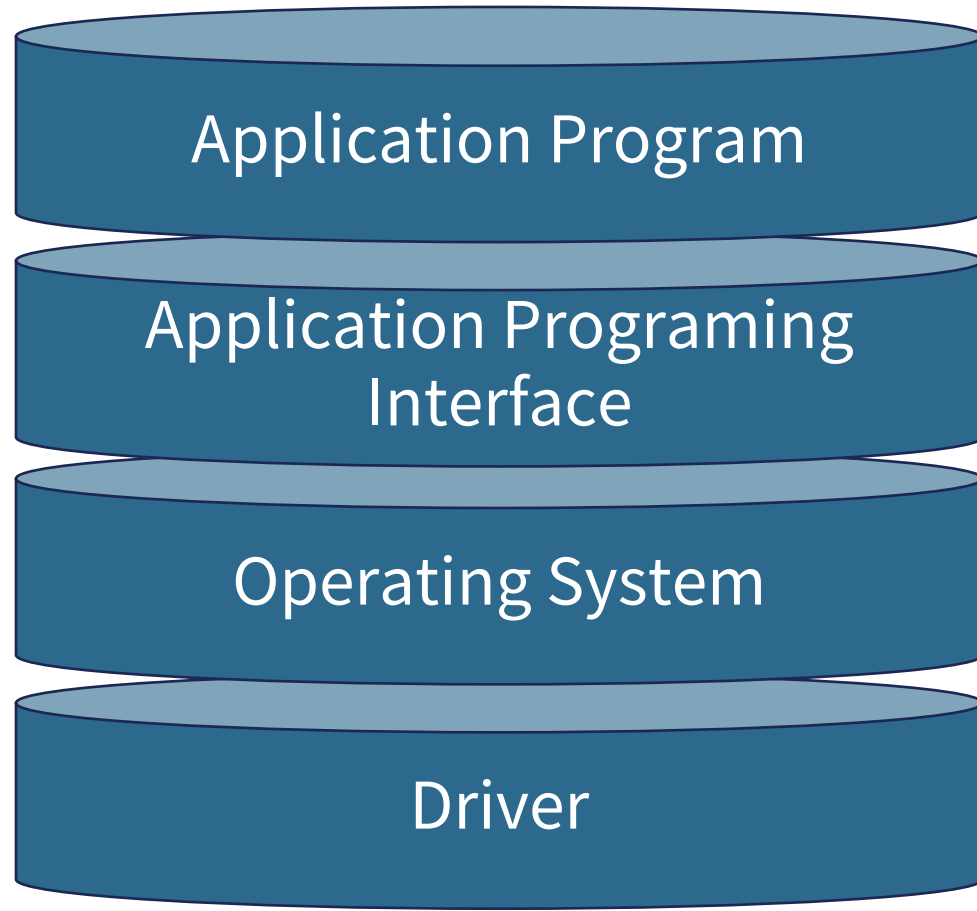
- FPIOA x1: 现场可编程IO阵列
 - 用于将芯片内部功能映射到48个物理IO上
- GPIO x40
- UART x4
 - 推荐使用UART1、UART2、UART3, 波特率达5Mbps
 - 推荐UART0仅用于调试
- SPI x4
 - SPI0、SPI1、SPI3为master, SPI2为slave
 - SPI3固定接片外FLASH, SPI0通常接屏幕
 - Master时钟速度达80MHz, slave时钟速度达30MHz
- I2S x3
 - 每个I2S最多可接8路音频数据
 - I2S0可以连接到APU
- I2C x3
- 定时器 x3, WDT x2, RTC x1
- FFT x1, SHA256 x1, AES x1



Software for Embedded Systems



Software for Embedded Systems

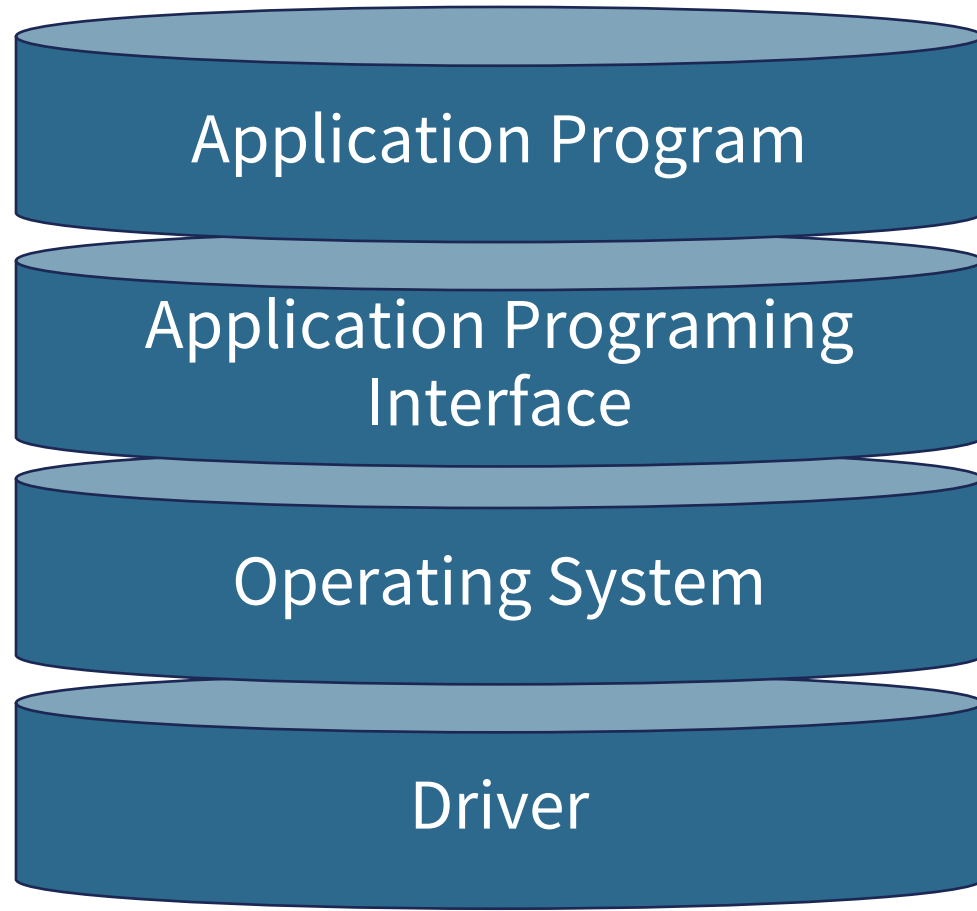


Example: FT2232H



- Single chip USB to dual channel UART (RS232, RS422 or RS485).
- Single chip USB to dual channel FIFO.
- Likewise Single chip USB to dual channel JTAG.
- Single chip USB to dual channel SPI.
- Additionally Single chip USB to dual channel I2C.
- Single chip USB to dual channel Bit-Bang.

Software for Embedded Systems

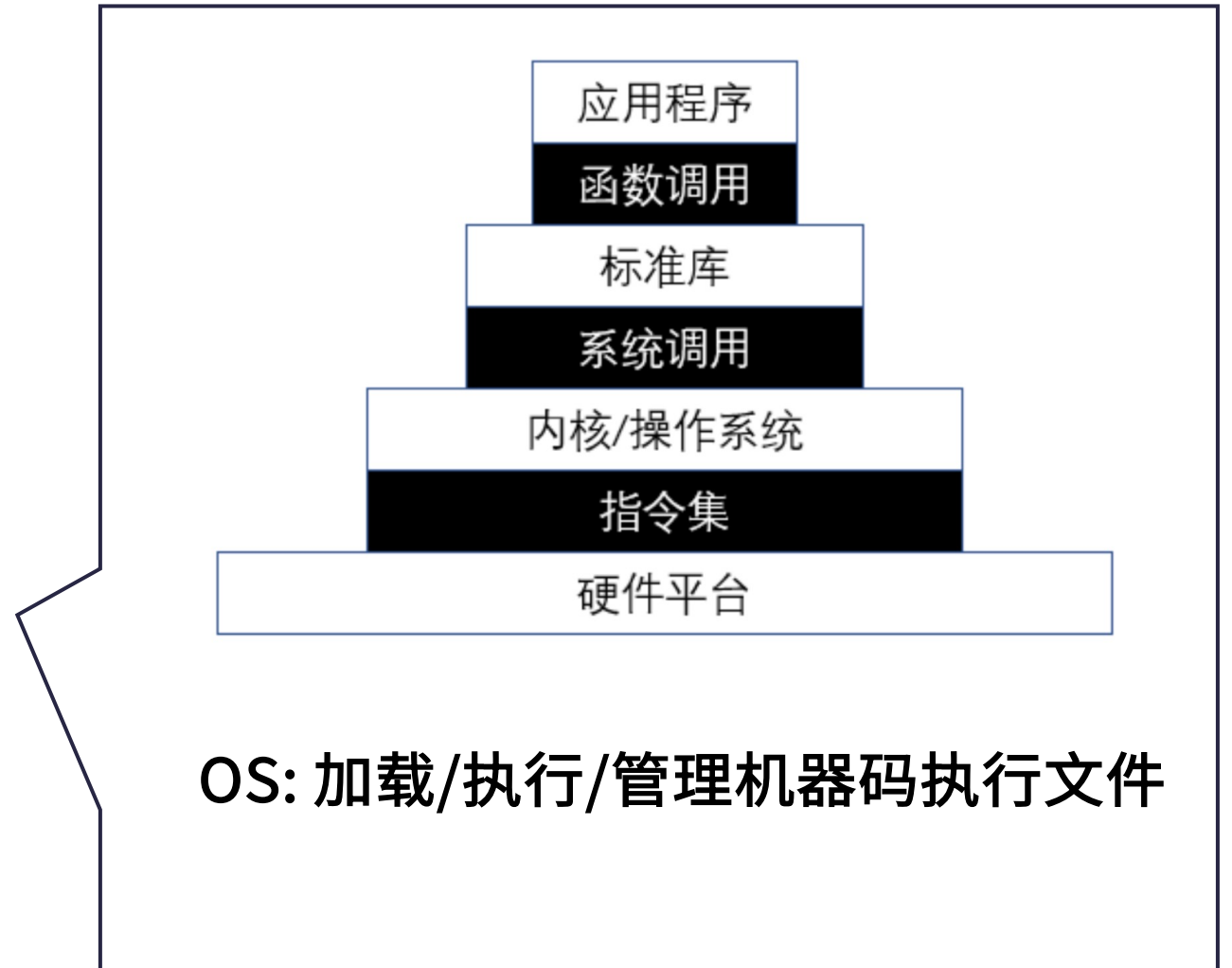
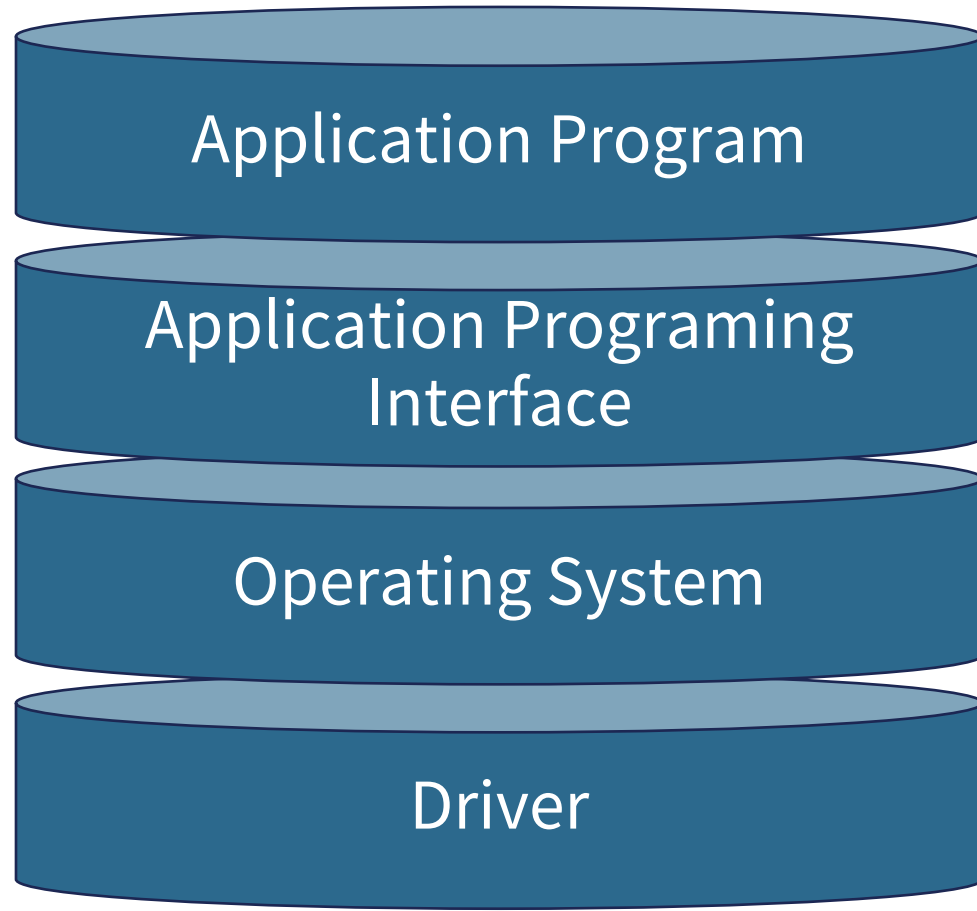


Example: FT2232H

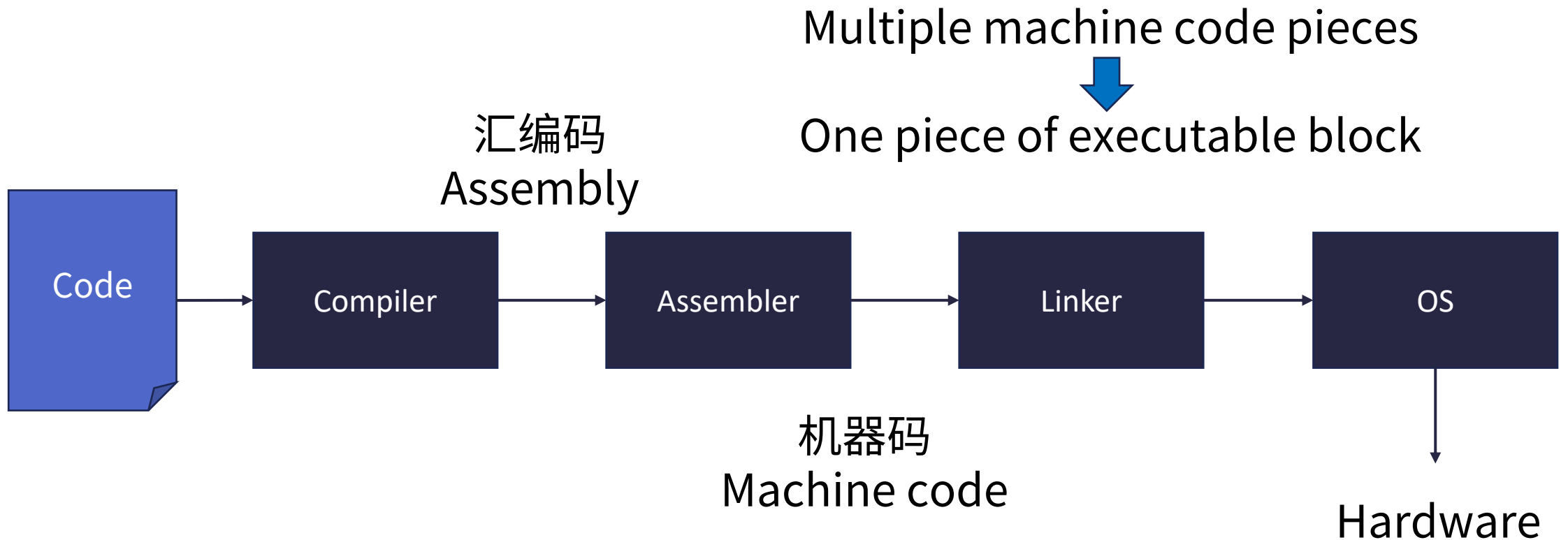


- The device allows for configurable I/O drive strength and slew rate, and it incorporates a highly integrated design with a built-in +1.8V LDO regulator for V_{CORE}, power-on-reset (POR) function, and an on-chip clock multiplier PLL.

Software for Embedded Systems



Type I - Compilation Work Flow



Type II – MicroPython + Bare Metal Program

- MicroPython was created by Damien George, with initial release launched on May 3, 2014.
- It is actually a program that runs on MicroControllers, and is itself written in C language.

Proper Python with hardware-specific modules

MicroPython is a full Python compiler and runtime that runs on the bare-metal. You get an interactive prompt (the REPL) to execute commands immediately, along with the ability to run and import scripts from the built-in filesystem. The REPL has history, tab completion, auto-indent and paste mode for a great user experience.

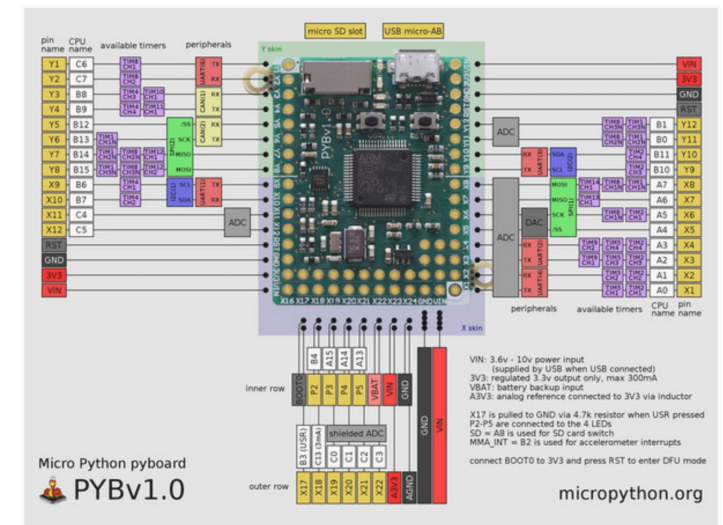
MicroPython strives to be as compatible as possible with normal Python (known as CPython) so that if you know Python you already know MicroPython. On the other hand, the more you learn about MicroPython the better you become at Python.

In addition to implementing a selection of core Python libraries, MicroPython includes modules such as "machine" for accessing low-level hardware.

```
from machine import Pin

# create an I/O pin in output mode
p = Pin('X1', Pin.OUT)

# toggle the pin
p.high()
p.low()
```

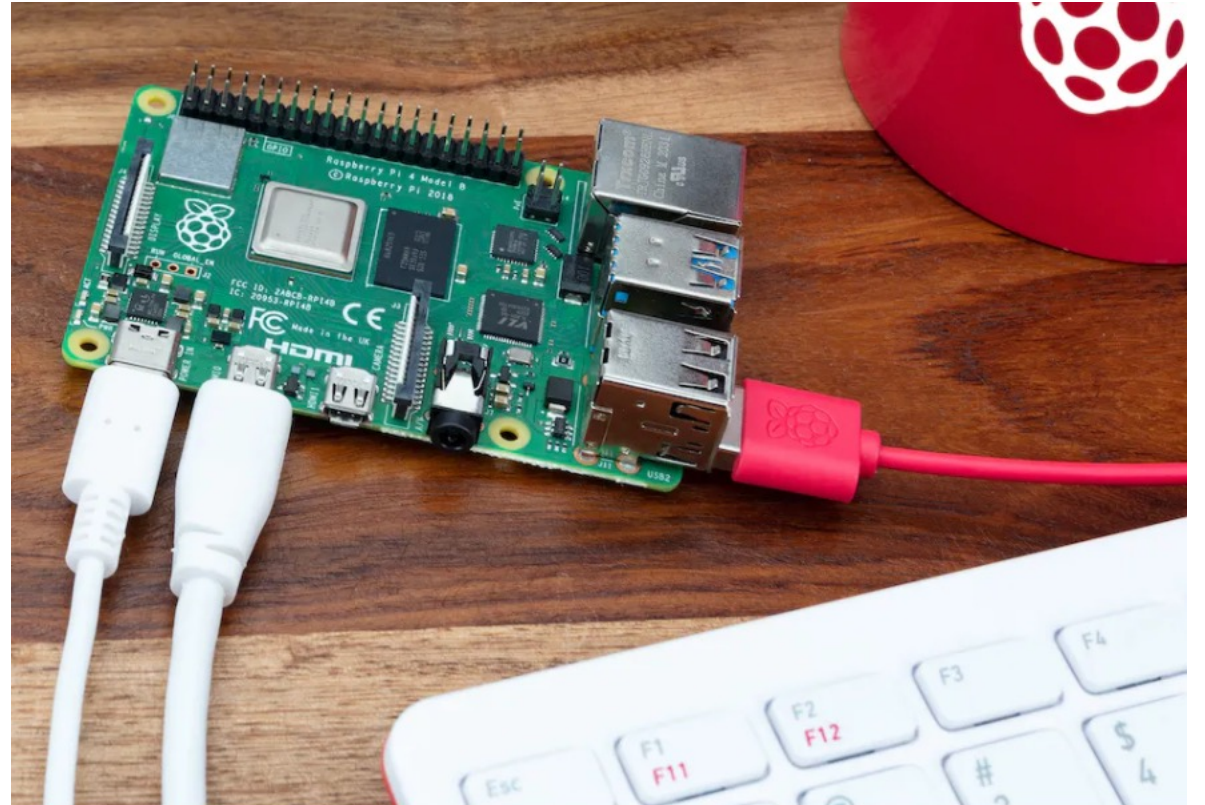


Type III – OS + Python

Raspberry Pi OS

Your Raspberry Pi needs an operating system to work. This is it. Raspberry Pi OS (previously called Raspbian) is our official supported operating system.

Based on Debian Linux distribution



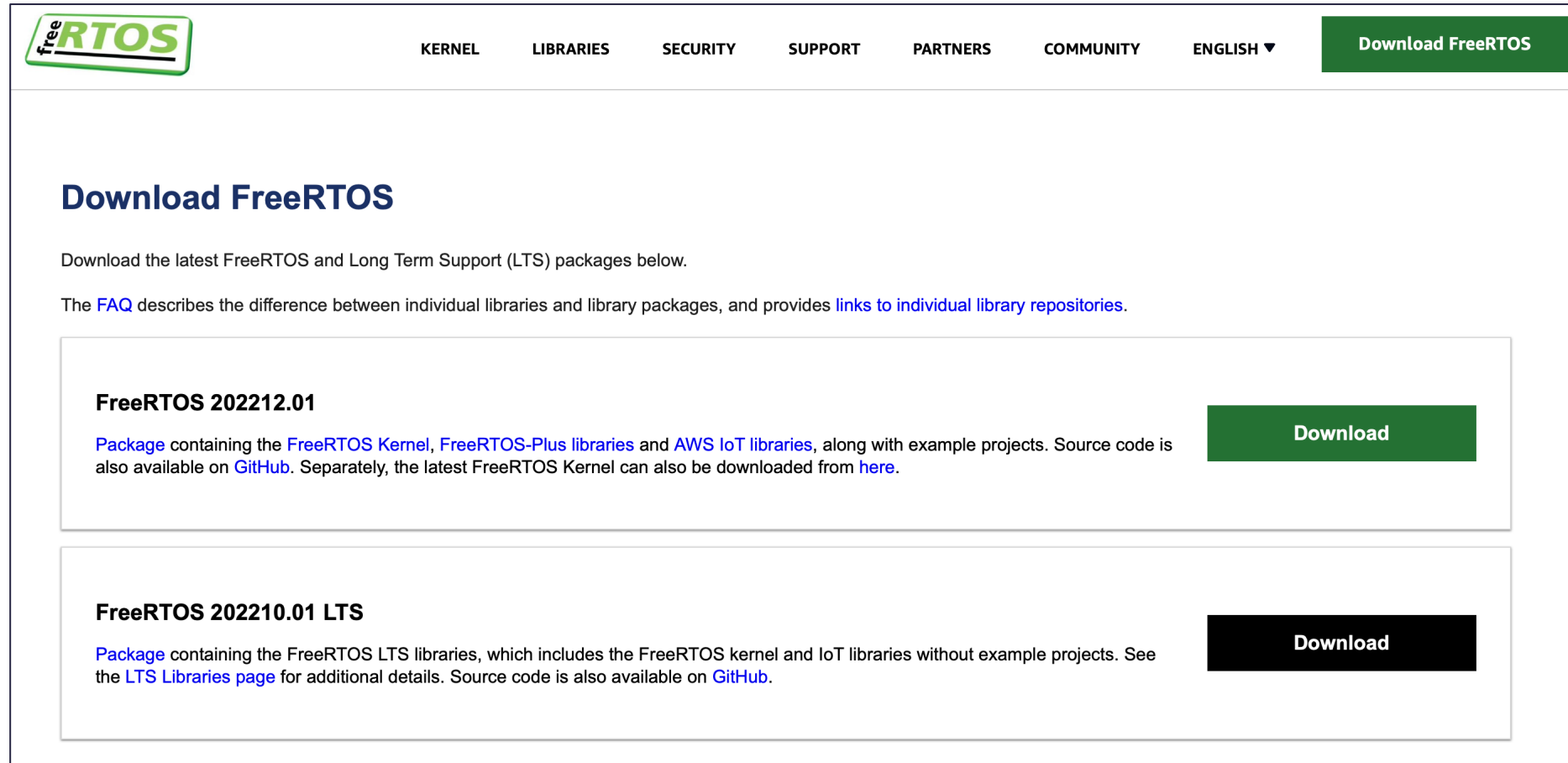
Software for Embedded Systems



火星探测车：勇气号

美国NASA自20世纪80年代末以来，就一直在航天器中采用实时操作系统，从最早的“火星登陆者”到“勇气号”都采用了RTOS (VxWorks)。勇气号采用的嵌入式软件——在仅仅128MB的空间里存放了其最核心的程序

Real-Time Operating System (RTOS) Example



The screenshot shows the FreeRTOS website's download page. At the top left is the FreeRTOS logo. The navigation menu includes links for KERNEL, LIBRARIES, SECURITY, SUPPORT, PARTNERS, COMMUNITY, and ENGLISH. A prominent green button labeled "Download FreeRTOS" is in the top right. The main heading is "Download FreeRTOS". Below it, text instructs users to download the latest FreeRTOS and Long Term Support (LTS) packages. A link to the FAQ is provided for more details. Two download options are listed in separate boxes: "FreeRTOS 202212.01" with a green "Download" button, and "FreeRTOS 202210.01 LTS" with a black "Download" button. Each option includes a brief description of the package contents and source code availability.

FreeRTOS 202212.01

Package containing the [FreeRTOS Kernel](#), [FreeRTOS-Plus libraries](#) and [AWS IoT libraries](#), along with example projects. Source code is also available on [GitHub](#). Separately, the latest FreeRTOS Kernel can also be downloaded from [here](#).

FreeRTOS 202210.01 LTS

Package containing the FreeRTOS LTS libraries, which includes the FreeRTOS kernel and IoT libraries without example projects. See the [LTS Libraries page](#) for additional details. Source code is also available on [GitHub](#).

<https://www.freertos.org>, as of 2023

Real-Time Operating System (RTOS) Feature

Regular OS	Real-Time OS (RTOS)
Complex	Simple
Best effort	Guaranteed response
Fairness	Strict Timing constraints
Average Bandwidth	Minimum and maximum limits
Unknown components	Components are known
Unpredictable behavior	Predictable behavior
Plug and play	RTOS is upgradable

Software for Embedded Systems

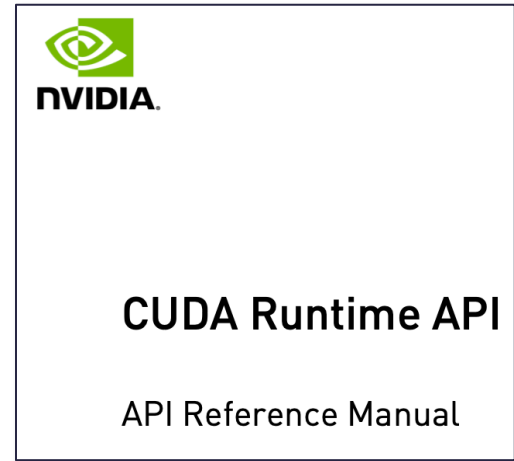
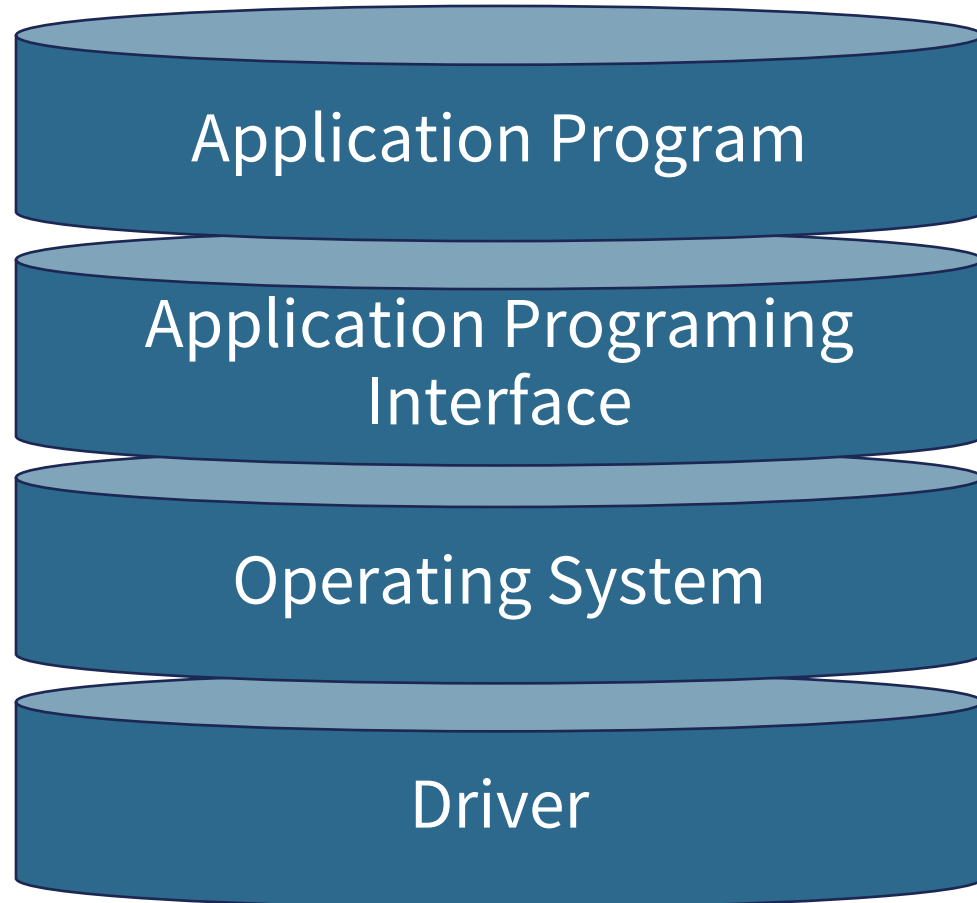


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Development of Embedded Systems

- 开发环境
 - IDE (Intergrated Development Environment) : 交叉开发软件一般为一个整合编辑、编译汇编链接、调试、工程管理及函数库等功能模块
 - 在线调试 (On-Chip Debugging, OCD)
 - 基于JTAG的ICD (In-Circuit Debugger)
 - 软件模拟环境 (如QEMU)
 - 评估电路板 (开发板)

Hardware/Software Codesign

- 嵌入式系统设计是使用一组物理硬件和软件来完成所需功能的过程。系统是指任何由硬件、软件或者两者的结合来构成的功能设备。
- 由于嵌入式系统是一个专用的系统，所以嵌入式产品的设计过程中，软件设计和硬件设计是紧密结合、相互协调的。这就产生了一种全新的发展中的设计理论软硬件协同设计
- 这种方法的特点是在设计时，从系统功能的实现考虑，把实现时的软硬件同时考虑进去，硬件设计包括芯片级“功能定制”设计。既可以最大限度的利用有效资源、缩短开发周期，又能取得更好的设计效果。