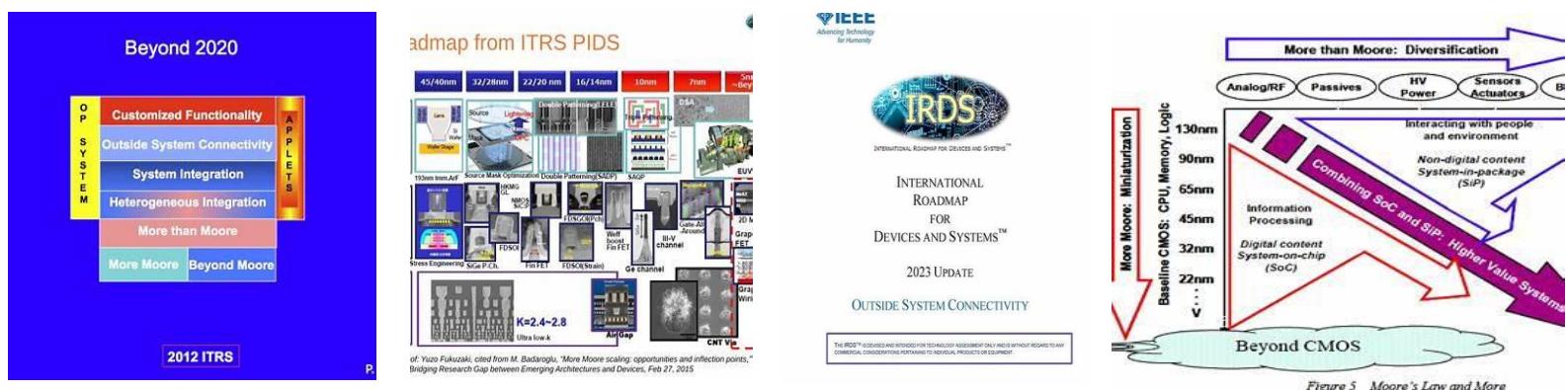


Week 1 Challenges ECE 410/510 Spring 2025

Challenge #1

Go to the IEEE International Roadmap for Devices and Systems (IRDS) website (<https://irds.ieee.org>) and browse through the “Beyond CMOS” 2023 update roadmap to get a sense of the variety of devices that are being considered for beyond Moore technologies:
https://irds.ieee.org/images/files/pdf/2023/2023IRDS_BC.pdf
 Read as long as your interest lasts



The IEEE International Roadmap for Devices and Systems (IRDS) 2023 "Beyond CMOS" update explores a diverse array of emerging devices poised to transcend the limitations of traditional CMOS technology. These innovations aim to address challenges in power efficiency, computational performance, and novel functionalities essential for future computing paradigms'

Key Categories of Beyond CMOS Devices

1. Emerging Memory Technologies

These devices seek to overcome the "memory wall" by offering high-speed, high-density, and low-power alternatives to conventional SRAM and FLASH. Notable candidates include: [IEEE IRDS](#)

- **Spin-Transfer Torque Magnetic RAM (STT-MRAM)**
- **Resistive RAM (RRAM)**
- **Ferroelectric RAM (FeRAM)**
- **Phase-Change Memory (PCM)**
- **Magnetoelectric RAM (MeRAM)**

- **Carbon Nanotube RAM (CNT-RAM)**

Some of these technologies also support analog in-memory computing, which is advantageous for AI and neuromorphic applications. [IEEE IRDS](#)

2. Emerging Logic Devices

Beyond CMOS logic devices aim to reduce power consumption and enable new computational paradigms. Key technologies include:[IEEE IRDS](#)

- **Tunnel Field-Effect Transistors (TFETs)**
- **Negative Capacitance FETs (NC-FETs)**
- **Spintronic Devices:** such as Spin-FETs and Magnetoelectric Spin-Orbit Logic (MESO)
- **Carbon Nanotube FETs (CNT-FETs)**
- **Graphene Nanoribbon FETs**
- **Molecular Electronics**
- **Superconducting Logic:** including Rapid Single-Flux Quantum (RSFQ) circuits[IEEE IRDS+5](#)[Wikipedia+5](#)[IEEE IRDS+5](#)

These devices often utilize state variables beyond charge, such as spin or magnetic flux, to achieve ultra-low power operation. [IEEE IRDS](#)

3. Device-Architecture Co-Design

The roadmap emphasizes the importance of co-designing devices and architectures to optimize performance. This includes integrating emerging devices into architectures like neuromorphic computing, in-memory processing, and reconfigurable logic systems. [IEEE IRDS](#)

4. More-than-Moore Applications

Beyond CMOS technologies also cater to applications beyond traditional computing, such as:

- **Hardware Security:** utilizing physically unclonable functions (PUFs)
- **Flexible and Wearable Electronics**
- **Energy Harvesting Devices**
- **Bioelectronics and Sensors**[IEEE IRDS+1](#)[IEEE IRDS+1](#)

These applications benefit from the unique properties of emerging devices, including flexibility, biocompatibility, and low-power operation. [IEEE IRDS+1](#)[IEEE IRDS+1](#)

5. Emerging Materials Integration

Advancements in materials science are crucial for the development of beyond CMOS devices. Key areas of focus include:

- **2D Materials**: such as graphene and transition metal dichalcogenides (TMDs)
- **Topological Insulators**
- **Ferroelectric and Multiferroic Materials**
- **Phase-Change Materials**
- **Carbon-Based Nanomaterials**: including carbon nanotubes

Integrating these materials presents challenges in synthesis, scalability, and compatibility with existing fabrication processes.

For a comprehensive understanding of these technologies, including detailed assessments and benchmarking data, you can access the full 2023 IRDS Beyond CMOS report here:

[2023 IRDS Beyond CMOS PDF](#)

This document provides in-depth insights into the future landscape of semiconductor devices and systems beyond traditional CMOS technology.

ChatGPT said:

Here is a **summary of the 2023 IEEE IRDS "Beyond CMOS" roadmap** ([source PDF](#)):

Overview of Beyond CMOS Technologies

The IRDS 2023 “Beyond CMOS” report evaluates next-generation electronic devices that aim to overcome the limitations of traditional CMOS (complementary metal-oxide-semiconductor) technology in terms of **scaling, energy efficiency, and functionality**.

Key Focus Areas

1. Emerging Memory Technologies

Designed to address the *memory bottleneck* in conventional systems:

- **STT-MRAM**: Non-volatile, fast, low power.
- **RRAM (ReRAM)**: Uses resistive switching, scalable.
- **FeRAM**: Low power, fast read/write.
- **PCM**: Based on phase transition, promising for AI workloads.
- **MeRAM**: Uses magnetoelectric effects.

- **CNT-RAM**: Carbon nanotube-based, high performance.

2. Emerging Logic Devices

Targeting **low-power, high-performance** computation:

- **Tunnel FETs (TFETs)**: Operate with lower voltages.
- **Negative Capacitance FETs (NC-FETs)**: Improve switching energy.
- **Spintronics / MESO Logic**: Use spin rather than charge.
- **Carbon Nanotube FETs (CNT-FETs)**: High mobility, nanoscale.
- **Graphene Nanoribbon FETs**: Narrow bandgap materials.
- **Molecular Electronics**: Ultimate device miniaturization.
- **Superconducting Logic**: Zero resistance paths (RSFQ).

These go beyond traditional charge-based computing

3. Device-Architecture Co-Design

The roadmap promotes **co-optimization of devices and system architectures**:

- *Neuromorphic computing*
- *Reconfigurable logic*
- *In-memory computing*

Focus is shifting from device-only metrics to **system-level integration**.

4. More-than-Moore Applications

Beyond-CMOS devices support non-traditional computing and electronics:

- **PUFs for hardware security**
- **Flexible electronics and wearables**
- **Bioelectronics**
- **Energy harvesting devices**

Low power, unconventional form factors, and niche applications.

5. Emerging Materials Integration

New materials enable novel functionality and device scaling:

- **2D Materials:** Graphene, MoS₂, TMDs.
- **Topological Insulators:** Edge states for energy-efficient transport.
- **Ferroelectric & Multiferroic Materials:** Store state without power.
- **Carbon-based materials:** For logic and interconnects.
- **Phase-change materials:** For memory and logic.

Challenges: fabrication compatibility, stability, integration. Roadmap Themes & Metrics

- **Benchmarking:** Energy-delay product (EDP), switching speed, area.
- **Device Maturity Levels:** From exploration to manufacturable.
- **Transition Pathways:** From lab to fab (TRLs 1–9).

Conclusion

The 2023 IRDS “Beyond CMOS” roadmap outlines **a diverse ecosystem of novel devices**—from **spintronics to carbon-based FETs, in-memory computing, and bioelectronics**—aimed at extending **Moore's Law** through **functional diversification, performance scaling, and architectural innovation**.

Challenge #2

Read the following paper:

James P. Crutchfield, William L. Ditto, Sudeshna Sinha; Introduction to Focus Issue: Intrinsic and

Designed Computation: Information Processing in Dynamical Systems—Beyond the Digital Hegemony. Chaos 1 September 2010; 20 (3): 037101. <https://doi.org/10.1063/1.3492712>



The paper titled "*Introduction to Focus Issue: Intrinsic and Designed Computation: Information Processing in Dynamical Systems—Beyond the Digital Hegemony*" by James P. Crutchfield, William L. Ditto, and Sudeshna Sinha, published in *Chaos* (2010), serves as an editorial preface to a collection of articles exploring computation beyond traditional digital paradigms.

Core Themes and Objectives

1. Intrinsic vs. Designed Computation

- **Intrinsic Computation:** Refers to the natural information processing occurring within dynamical systems, such as biological, chemical, or physical processes. These systems inherently process information through their dynamics without external programming.
- **Designed Computation:** Pertains to human-engineered systems, primarily digital computers, where computation is explicitly programmed and controlled.

The paper emphasizes the importance of understanding and leveraging intrinsic computation to develop novel computing paradigms that transcend the limitations of traditional digital systems.

2. Limitations of Digital Hegemony

The authors critique the dominance of digital computation, highlighting its constraints in scalability, energy efficiency, and adaptability. They argue that as Moore's Law approaches its limits, alternative computing models inspired by natural systems become increasingly vital.

3. Interdisciplinary Approach

The focus issue brings together research from various disciplines, including physics, biology, computer science, and engineering, to explore how dynamical systems can perform computation. This interdisciplinary perspective aims to foster innovative approaches to information processing.

Highlights from the Focus Issue

The collection includes studies on:

- **Biological Computation:** Investigations into how living organisms process information, offering insights into energy-efficient and adaptive computing. [Academia](#)
- **Chaos Computing:** Exploring the use of chaotic systems to perform logical operations, potentially leading to reconfigurable and robust computing architectures. [Wikipedia](#)
- **Quantum Information Processing:** Examining how quantum systems can be harnessed for computation, promising significant advancements in processing power and speed.

- **Neuromorphic Engineering:** Designing hardware that mimics neural structures, aiming for systems that can learn and adapt in real-time.

Conclusion

The editorial underscores the necessity of moving beyond conventional digital computing by embracing the computational capabilities inherent in natural dynamical systems. By doing so, it sets the stage for a new era of computing that is more integrated with the physical world, energy-efficient, and capable of handling complex, real-time information processing tasks.

For a deeper exploration of these themes, you can access the full article here: [DOI: 10.1063/1.3492712](https://doi.org/10.1063/1.3492712).

Challenge #3

Use the power of the internet and of LLMs to identify a physical system that solves differential equations Inherently, through its physical properties, it executes instructions without executing instructions as a traditional processor does for basic DC-to-DC converter topologies. - Buck, boost, buck-boost, C1

Identify **physical systems** that inherently **solve differential equations — not through traditional digital computation** (e.g., CPUs or software), but through their **natural dynamics**.

Now apply this concept to **basic DC-to-DC converter circuits** like:

- Buck Converter
- Boost Converter
- Buck-Boost Converter
- Ćuk Converter (with capacitor C1)

⚡ Physical Systems as Differential Equation Solvers:

DC-to-DC converters are **nonlinear dynamical systems**. When you observe how **voltage and current change over time** in these circuits, you're witnessing a **real-time solution** to differential equations.

⌚ How Do They “Solve” Equations?

Each converter topology obeys specific **differential equations** based on **Kirchhoff's laws** and the **physics of L (inductors) and C (capacitors)**. Their time-domain behavior is governed by:

- **Inductor law:** $VL = L \frac{di}{dt}$
- **Capacitor law:** $IC = C \frac{dv}{dt}$

These equations describe **how energy is transferred and stored — and the converter passively solves them** via its components.

DC-to-DC Converter Differential Equations

Buck Converter

1. $L \frac{di_L(t)}{dt} = Vin - Vo(t)$
2. $C \frac{dVo(t)}{dt} = iL(t) - \frac{Vo(t)}{R}$

Boost Converter

1. $L \frac{di_{L_{boost}}(t)}{dt} = Vin_{boost}$
2. $C \frac{dVo_{boost}(t)}{dt} = iL_{boost}(t) - \frac{Vo_{boost}(t)}{R}$

Buck-Boost Converter

1. $L \frac{di_{L_{bb}}(t)}{dt} = Vin_{bb}$
2. $C \frac{dVo_{bb}(t)}{dt} = iL_{bb}(t) - \frac{Vo_{bb}(t)}{R}$

Cuk Converter

1. $L_1 \frac{d}{dt} i_1(t) = Vin_{cuk} - vC_1(t)$
2. $C_1 \frac{d}{dt} vC_1(t) = i_1(t) - i_2(t)$
3. $L_2 \frac{d}{dt} i_2(t) = -Vo_{cuk}(t) + vC_1(t)$
4. $C_2 \frac{d}{dt} Vo_{cuk}(t) = i_2(t) - \frac{Vo_{cuk}(t)}{R}$