Lessons From Five Years of Making Michigan Micro Motes (M^3)

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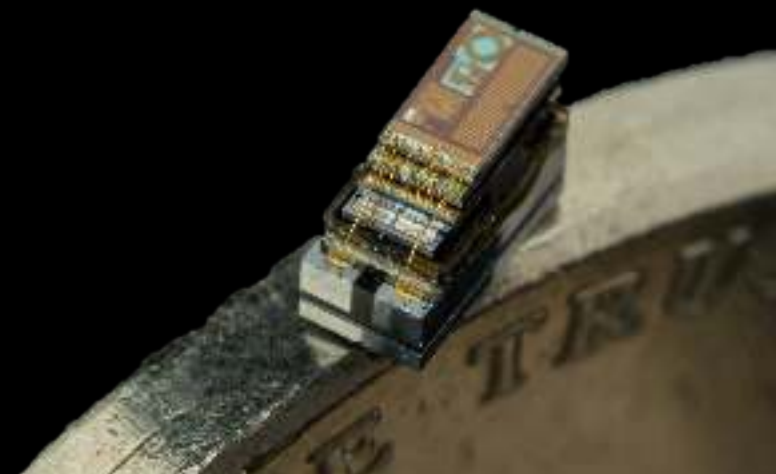
University of Michigan

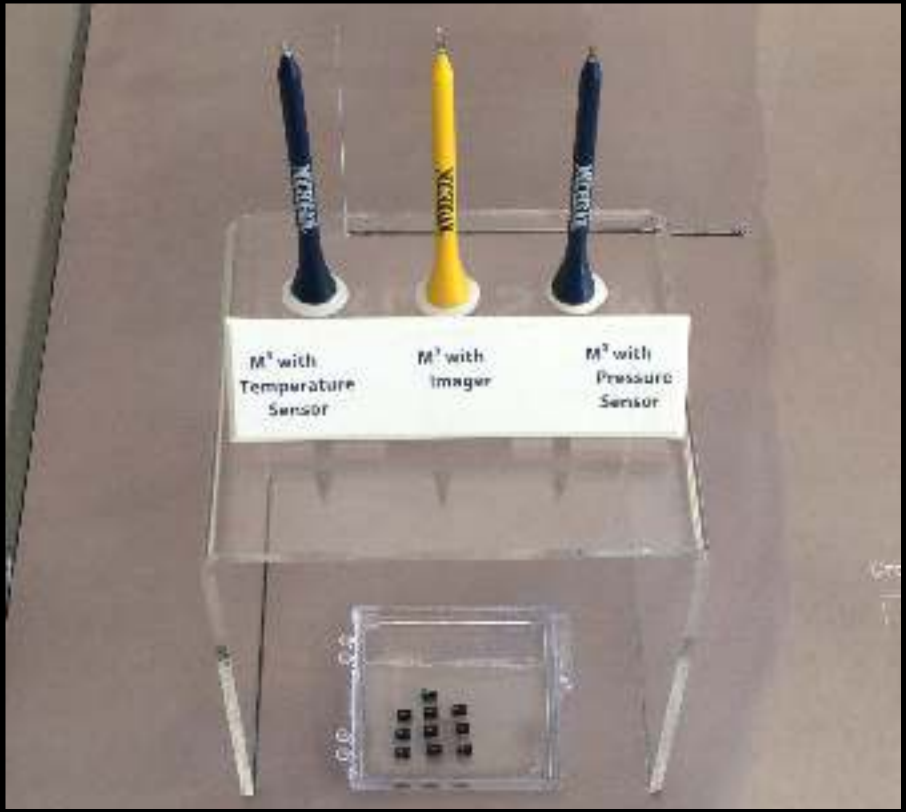
6th Workshop on Architectural Research Prototyping (WARP '15)

June 14, Portland, Oregon, USA



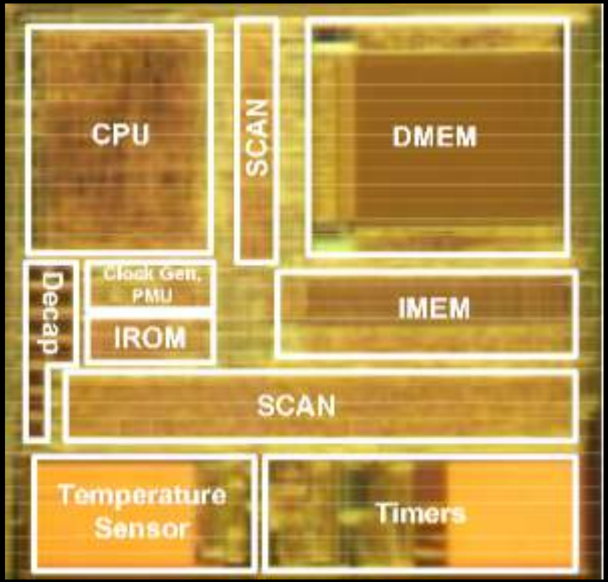
Behind the scenes on what was required to realize an ecosystem of mm-scale computers

On display now at the computer history museum



2008: The Phoenix Processor

- World's lowest power computer
  - Set records for **volume** and **energy**
  - And could be used by at best the grad students that built it




Mingoo Seok


Scott Hanson


Yu-Shiang Lin


ZhiYoong Foo


Daeyeon Kim


Yoonmyung Lee


Nurrachman Liu

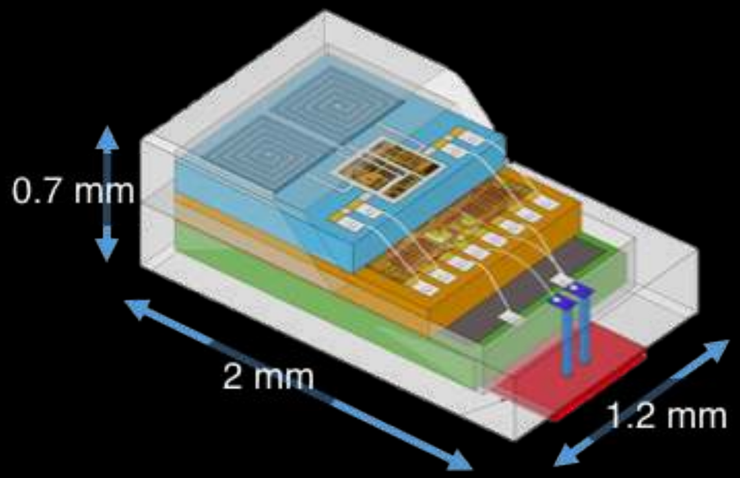

Dennis Sylvester

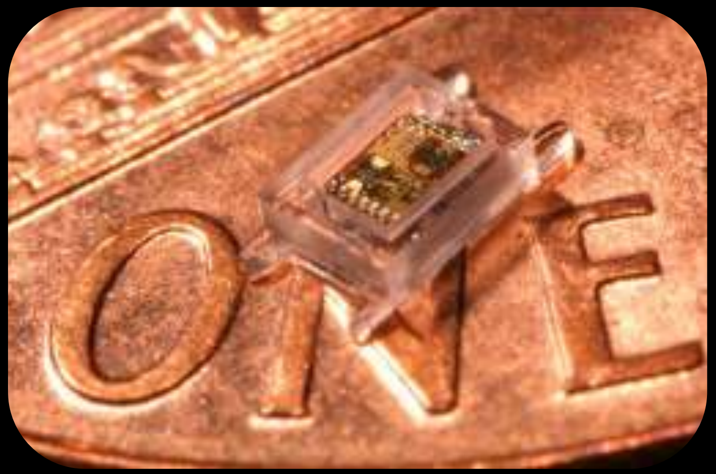

David Blaauw

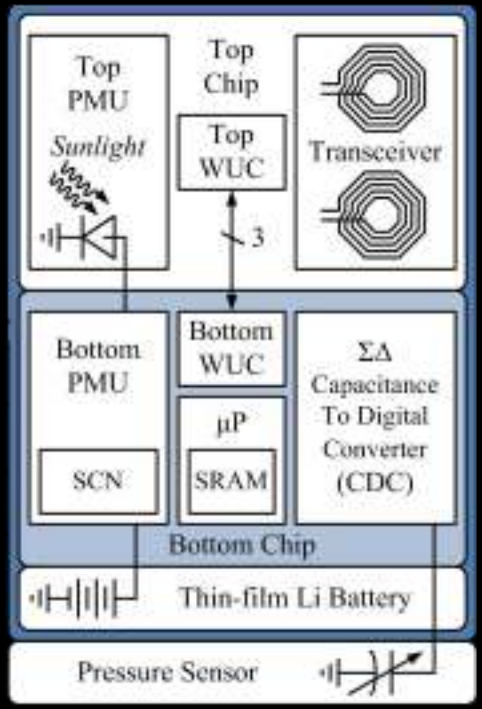
The Phoenix Processor: A 30pW Platform for Sensor Applications, M. Seok, VLSI '08

From temperature sensor to pressure sensor: **3 Years.**

- Motivating application for mm-scale sensor: Intraocular pressure
  - Critical diagnostic tool for glaucoma







A Cubic-Millimeter Energy-Autonomous Wireless Intraocular Pressure Monitor, G. Chen, ISSCC '11

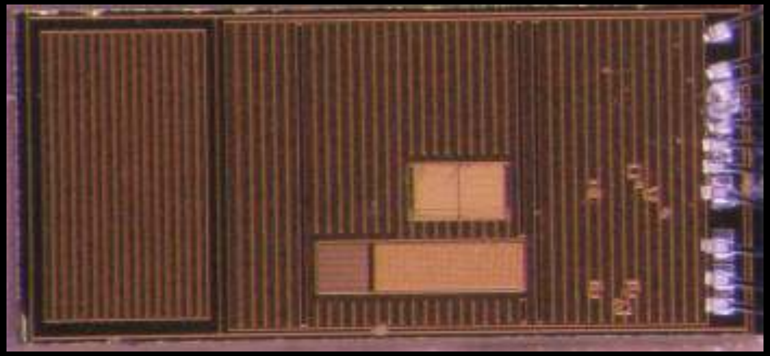
What's wrong with this picture:
"How to build a wireless temperature sensor?"

cm-scale

- Step 1: Buy a low-power temperature sensor

mm-scale

- Step 1: Design a low-power temperature sensor



~10 pW standby, < 1 μW active

What's wrong with this picture:
"How to build a wireless temperature sensor?"

cm-scale

- Step 1: Buy a low-power temperature sensor
- Step 2: Buy a low-power microcontroller

mm-scale

- Step 1: Design a mm-scale temperature sensor
- Step 2: Design a mm-scale CPU

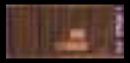
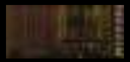
~10 pW standby, < 1 μW active

What’s wrong with this picture:
“How to build a wireless temperature sensor?”

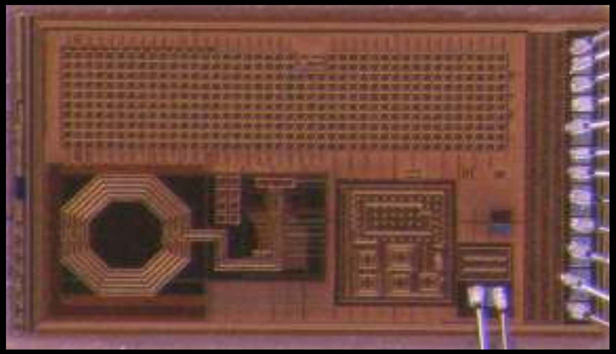
cm-scale


- Step 1: Buy a low-power temperature sensor
- Step 2: Buy a low-power microcontroller
- Step 3: Add low-power communications

mm-scale

- Step 1: Design a mm-scale temperature sensor
- Step 2: Design a mm-scale CPU
- Step 3: Design a mm-scale radio



~10 pW standby, ~5 μW active

What's wrong with this picture:

"How to build a wireless temperature sensor?"

cm-scale

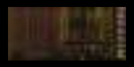
- Step 1: Buy a low-power temperature sensor

- Step 2: Buy a low-power microcontroller

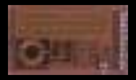
- Step 3: Add low-power communications
- Step 4: Add a power supply

mm-scale

- Step 1: Design a mm-scale temperature sensor



- Step 2: Design a mm-scale CPU



- Step 3: Design a mm-scale radio
- Step 4: Add power supply and storage

Energy Harvesting

Energy Storage

What’s wrong with this picture:
“How to build a wireless temperature sensor?”

cm-scale

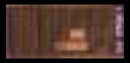
- Step 1: Buy a low-power temperature sensor

- Step 2: Buy a low-power microcontroller

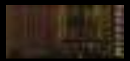
- Step 3: Add low-power communications

- Step 4: Add a power supply
- Step 5: Integrate the **chips**

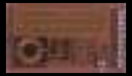
mm-scale



- Step 1: Design a mm-scale temperature sensor

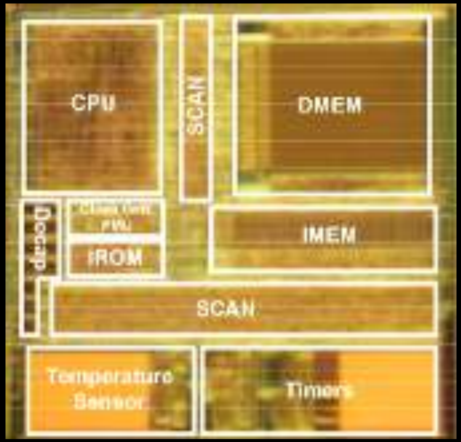


- Step 2: Design a mm-scale CPU



- Step 3: Design a mm-scale radio

- Step 4: Add power supply and storage
- Step 5: Integrate the **modules**



What’s wrong with this picture:

“How to build a wireless temperature sensor?”

cm-scale – Modular System

- Step 1: Buy a low-power temperature sensor

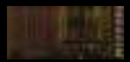
- Step 2: Buy a low-power microcontroller

- Step 3: Add low-power communications

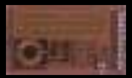
- Step 4: Add a power supply
- Step 5: Integrate the **chips**

mm-scale – Monolithic System

- Step 1: Design a mm-scale temperature sensor

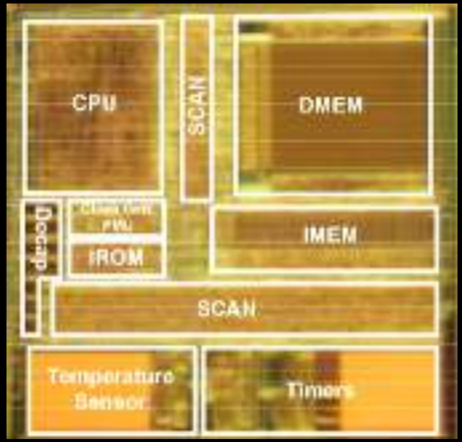


- Step 2: Design a mm-scale CPU



- Step 3: Design a mm-scale radio

- Step 4: Add power supply and storage
- Step 5: Integrate the **modules**



What’s wrong with this picture:
“How to build a wireless temperature sensor?”

cm-scale – Modular System

- Integrate components using well-defined, standard interfaces
  - **SPI**
  - **UART**
  - **I²C**

mm-scale – Monolithic System

- Integrate components using Verilog
  - **temp_sense t1 (**
    ...
    .sample_valid_out (to_proc_t1_sample_valid),
    .sample_out (to_proc_t1_sample),
    );
  - **processor p1 (**
    ...
    .temp_valid_in (to_proc_t1_sample_valid),
    .temp_in (to_proc_t1_sample),

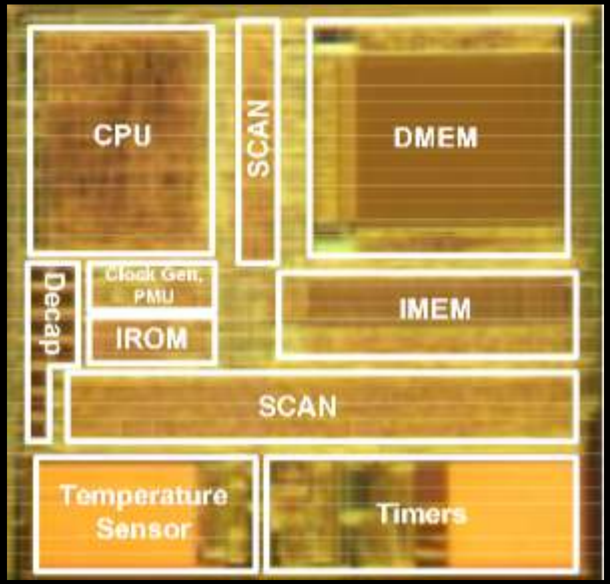
What’s different?

What's wrong with this picture:
"How to build a wireless temperature sensor?"

cm-scale – Modular System

- Integrate components using well-defined, standard interfaces
  - ~~SPI~~
  - ~~UART~~
  - I^2C

mm-scale – Monolithic System



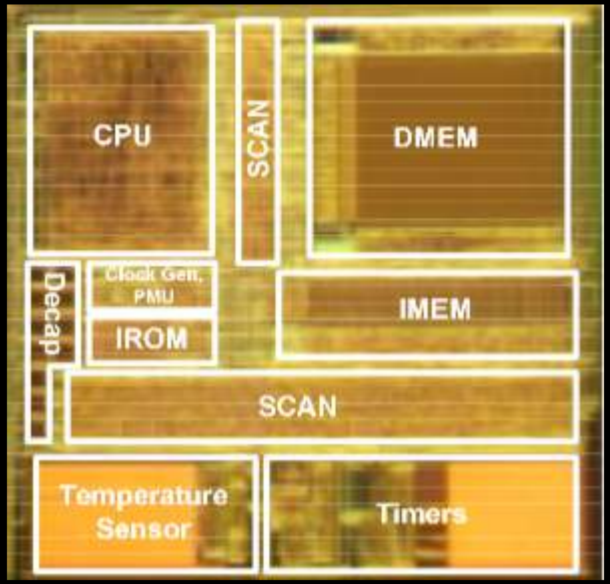
Previously unseen constraints on volume

What's wrong with this picture:
"How to build a wireless temperature sensor?"

<u>cm-scale</u> – Modular System

- Integrate components using well-defined, standard interfaces
  - ~~SPI~~
  - ~~UART~~
  - ~~I^2C~~

<u>mm-scale</u> – Monolithic System



Previously unseen constraints on volume and energy

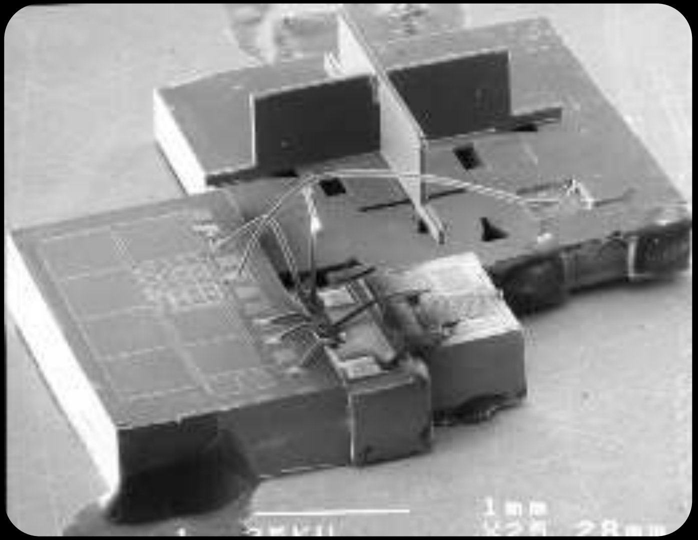
What's wrong with this picture:

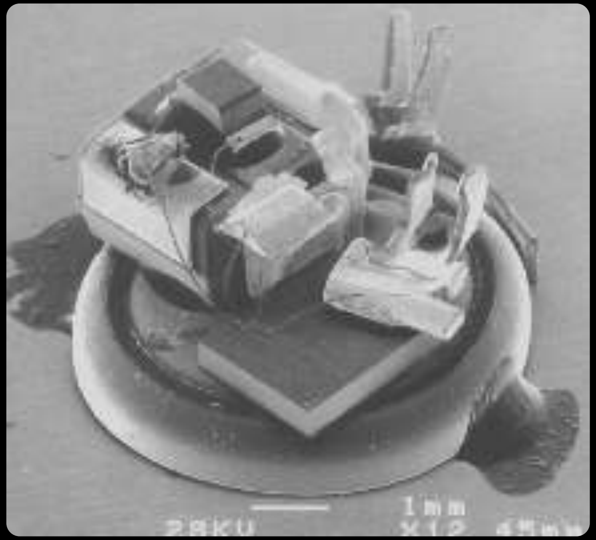
"How to build a wireless temperature sensor?"

cm-scale – Modular System

- Integrate components using well-defined, standard interfaces
  - ~~SPI~~
  - ~~UART~~
  - ~~I^2C~~

mm-scale – "Modular" Systems





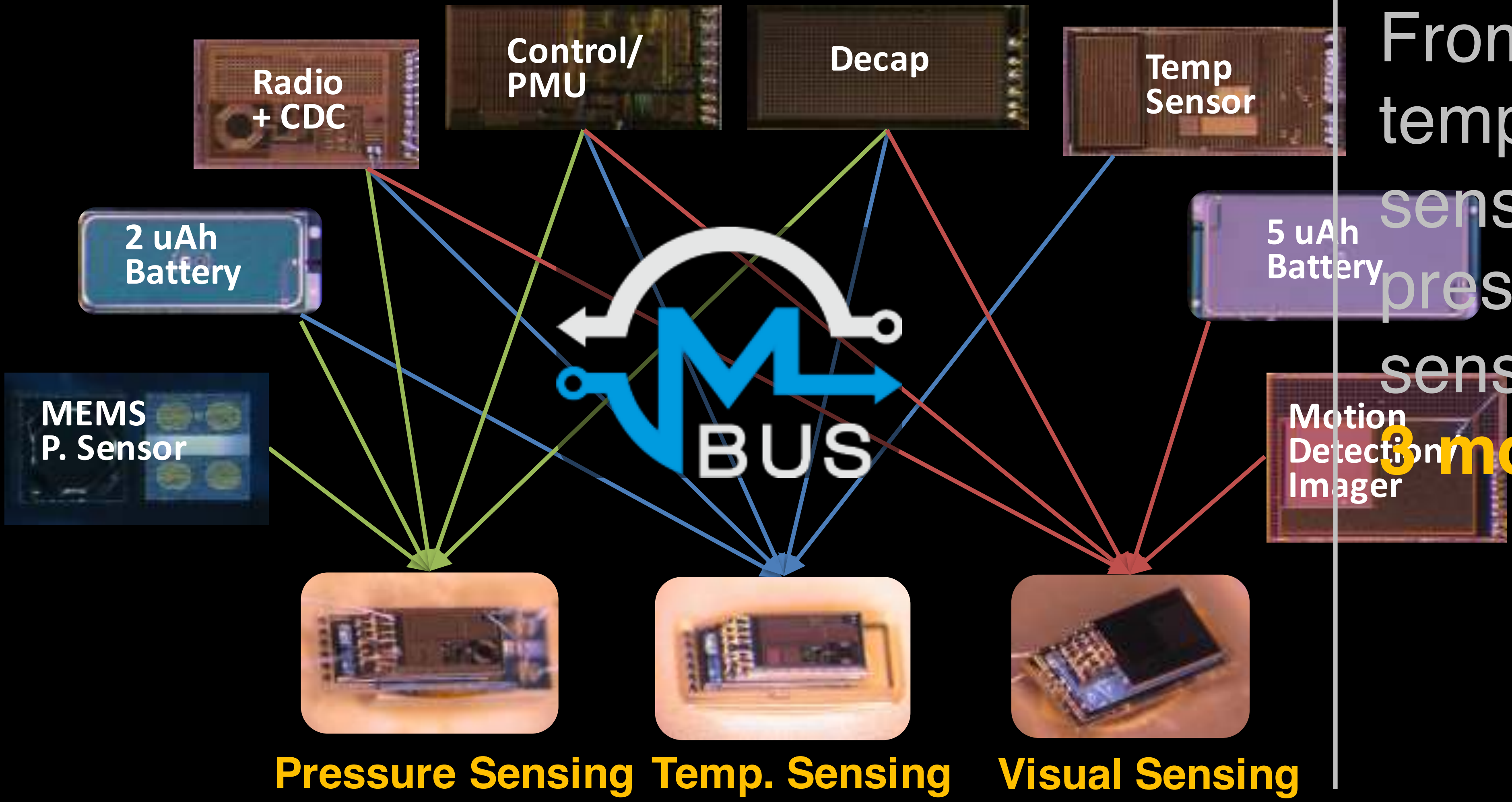
Ad-hoc composition results in poor use of volumetric space

MBus, the missing interconnect that enables the mm-scale computing class

- 22.6 pJ / bit / chip, < 10 pW standby / chip
- Single-ended (push-pull) logic
- Low, fixed wire count (4)
- Multi-master
- **Power-aware**

- Implemented in over a dozen (and growing) mm-scale **chips**
  - CPU, Radio
  - Flash Memory
  - Temperature, Pressure, Imager
- To make half a dozen (and growing) mm-scale **systems**

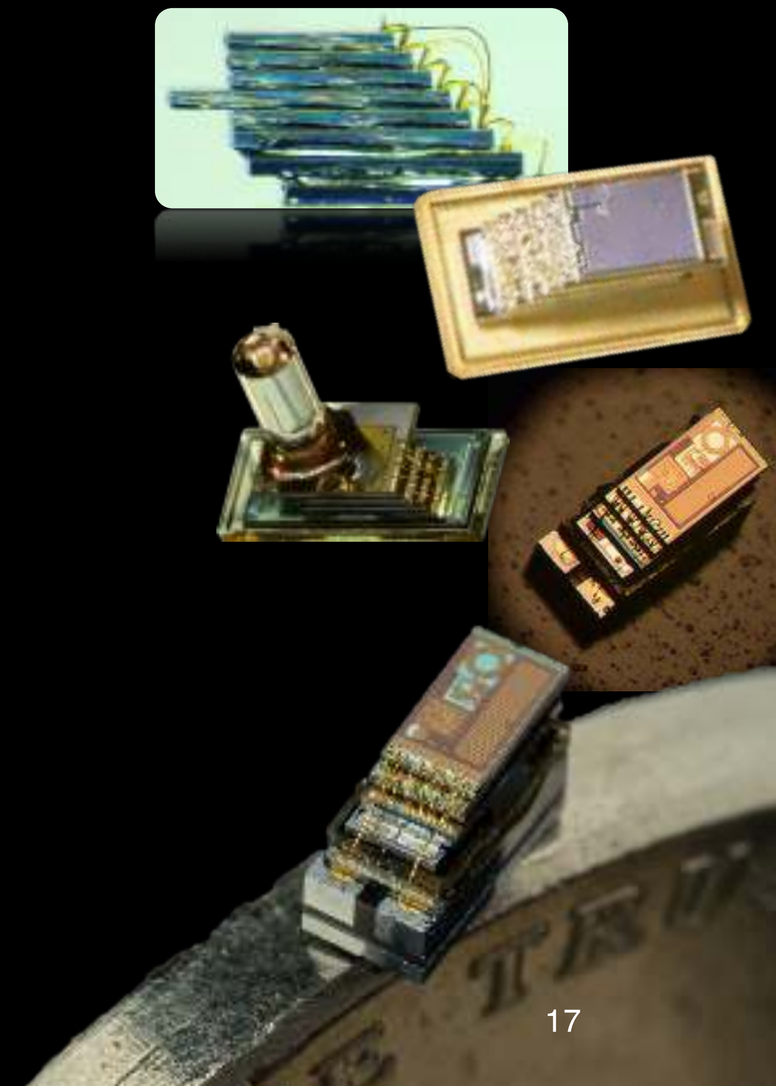
MBus enabled modular components, key to the rapid development cycle we now enjoy



From temperature sensor to pressure sensor: **3 months.**

Learn more about MBus at ISCA

- Session 10B
  - MBus: An Ultra-Low Power Interconnect Bus for Next Generation Nanopower Systems
- Wednesday, 13:50 in Oregon 204

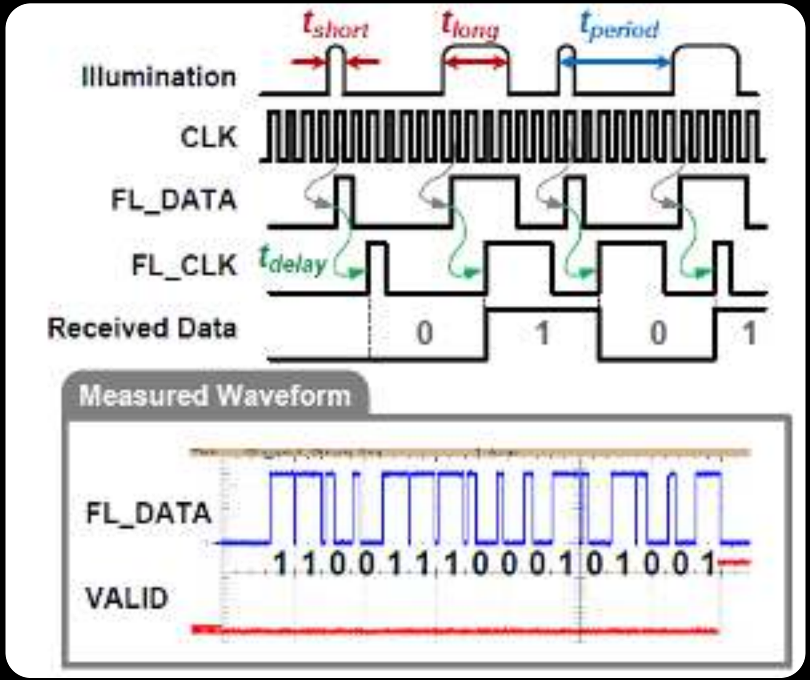


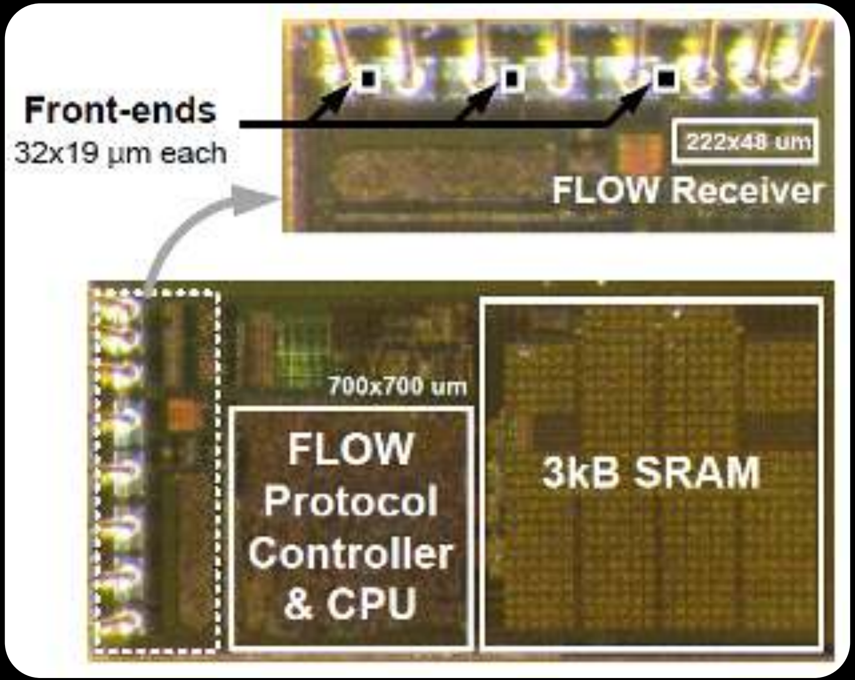
Digging into what a mm-scale system looks like and why that really matters

- Flashy pictures from a good camera can be misleading.
- In practice, several nodes fit on a period

How do you bootstrap (program) a node that’s too small to attach wires to?

- Visible light communications



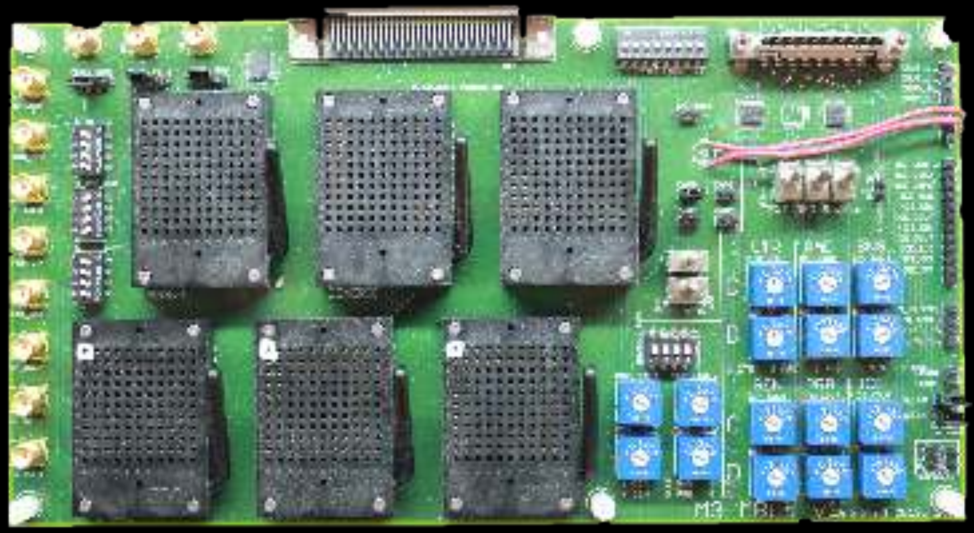


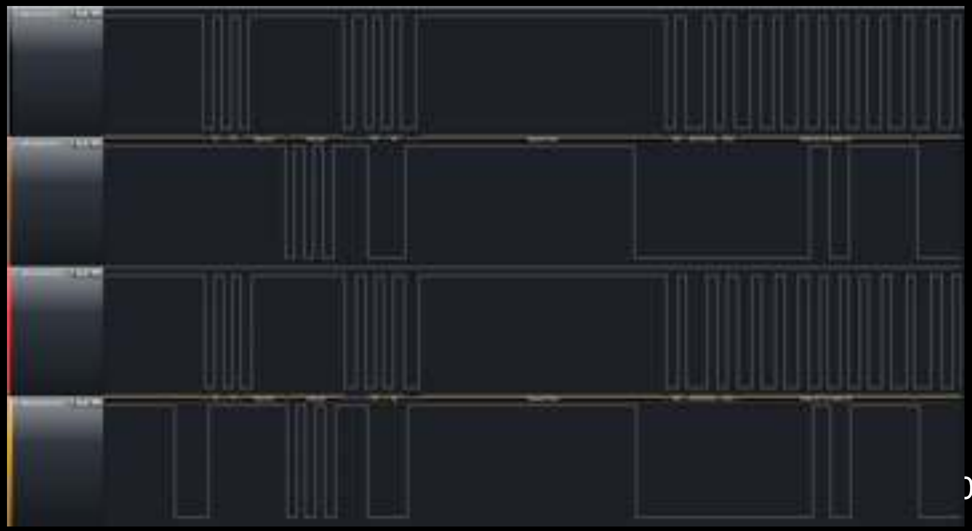
Gyouho Kim, Yoonmyung Lee, Suyoung Bang, Inhee Lee, Yejonng Kim, Dennis Sylvester, David Blaauw, “A 695 pW Standby Power Optical Wake-up Receiver for Wireless Sensor Nodes,” IEEE Custom Integrated Circuits Conference (CICC), September 2012

Open Q: How do you debug a node that's too small to attach wires to?

- Partial answers
  - Breakout system
  - Visible light debugging
    - Inject arbitrary messages
  - Power trace debugging
    - Each state has a power signature
  - Bus snooping
    - Plug-in for Saleae logic analyzer

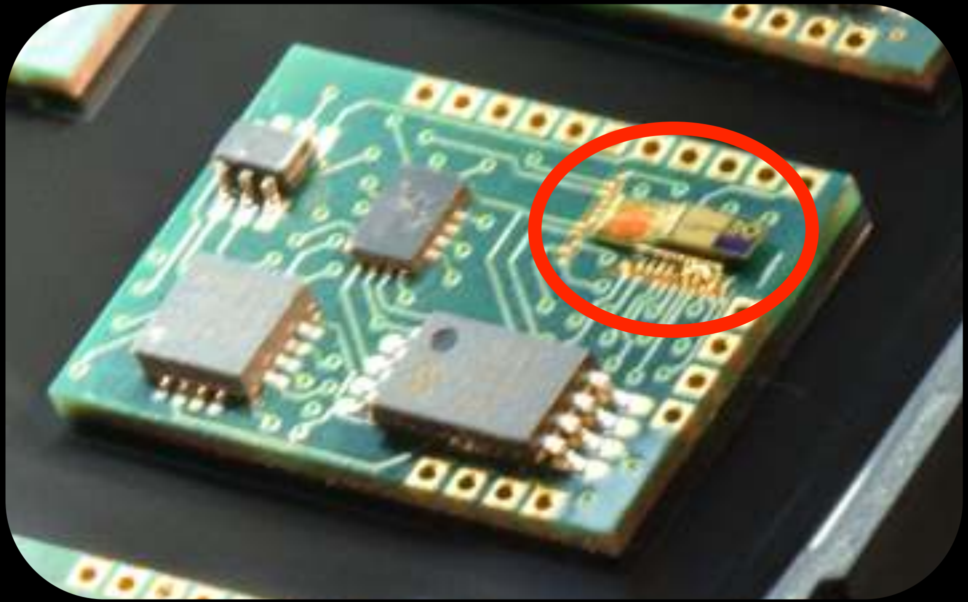
- **Big Open Q: Postmortem**

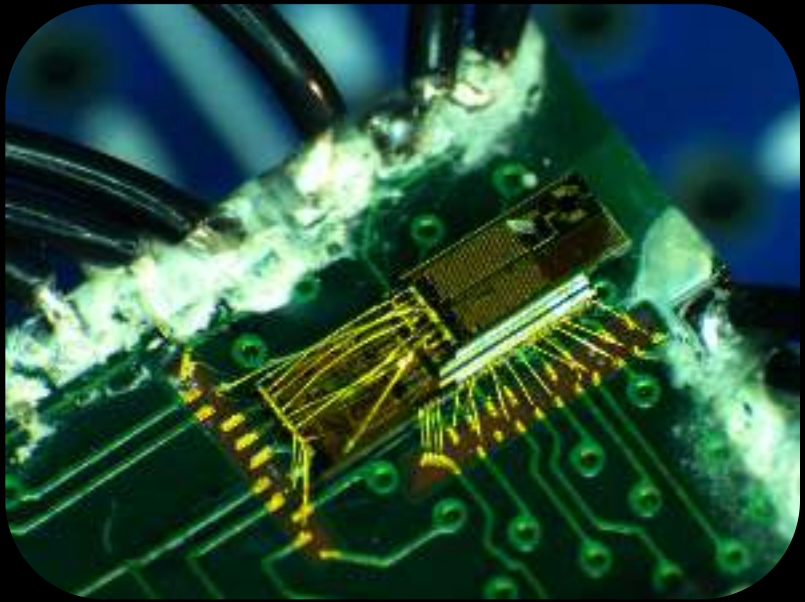




[Recent efforts] How do you solder a node that's too small to attach wires to?

- Integrating mm-scale chips with COTS chips



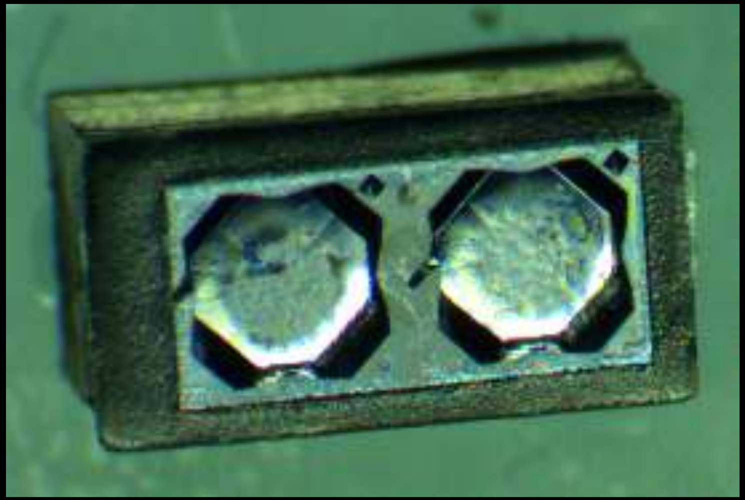


- Recent issues: Metals for **both** soldering and wirebonding

(to 50 µm pads)

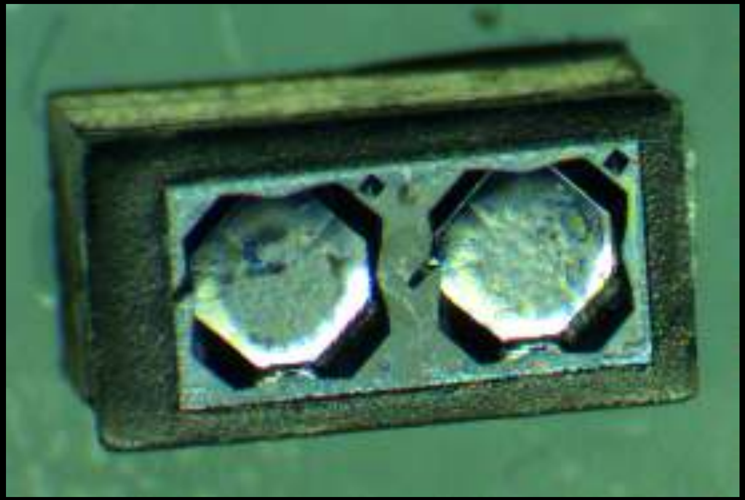
Re-discovering packaging problems from the MEMS community

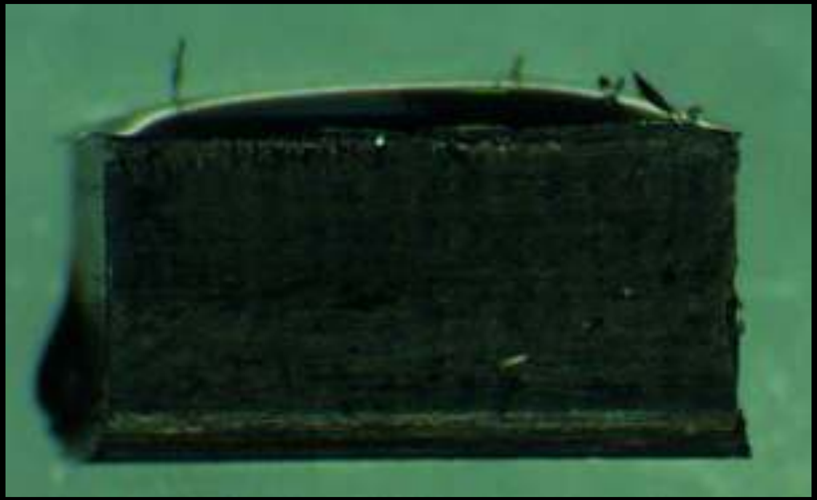
- Bio-compatible pressure sensor
  - Can seal electronics in bio-compatible epoxy
  - *How to expose the pressure sensor?*



And adding some new packaging problems of our own

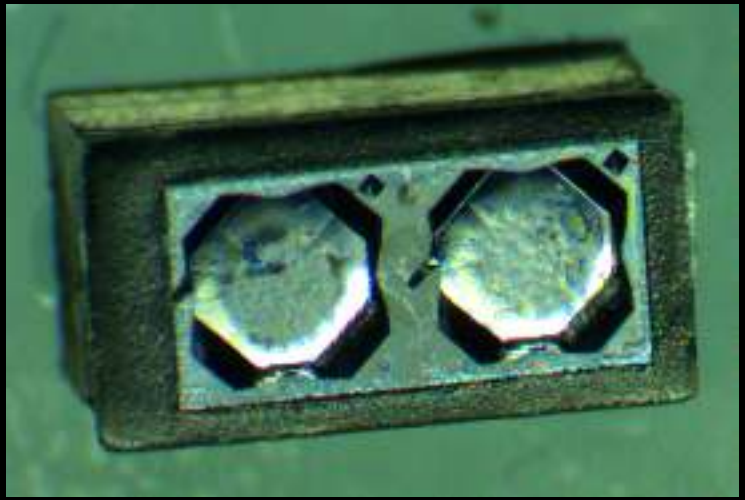
- Bio-compatible pressure sensor
  - Can seal electronics in bio-compatible epoxy
  - How to expose the pressure sensor?
  - *Some of the electronics are light sensitive*

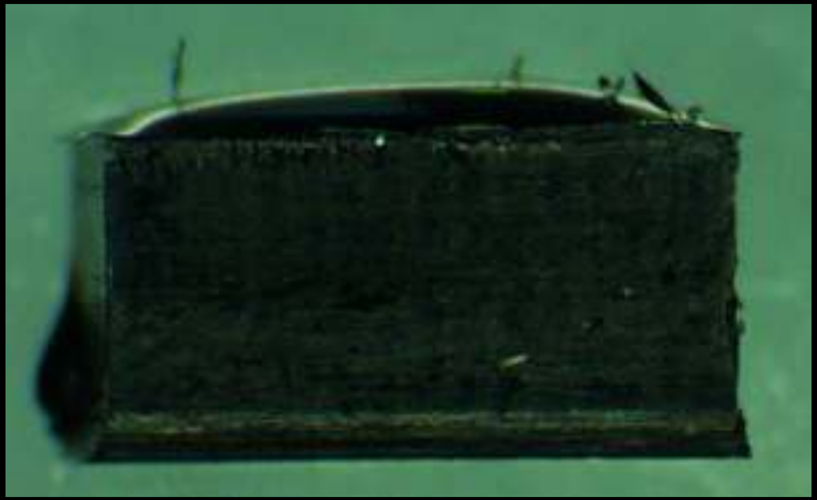


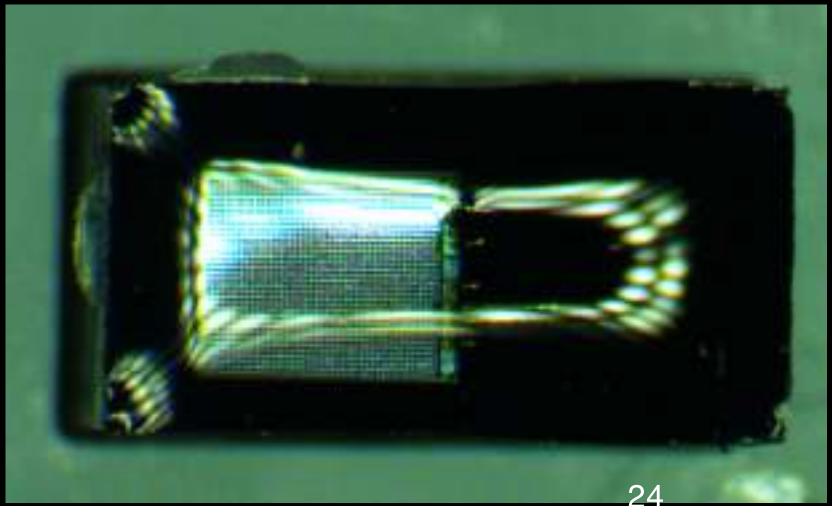


Systems considerations fit into the packaging puzzle too

- Bio-compatible pressure sensor
  - Can seal electronics in bio-compatible epoxy
  - How to expose the pressure sensor?
  - Some of the electronics are light sensitive
  - *The node relies on solar (or IR) harvesting to charge [and program…]*

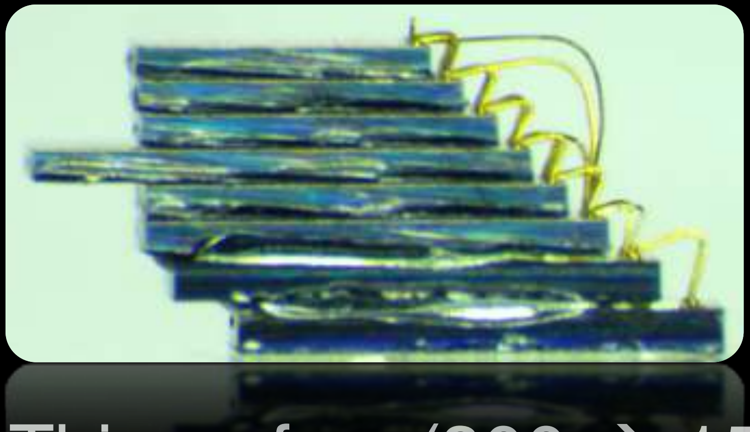




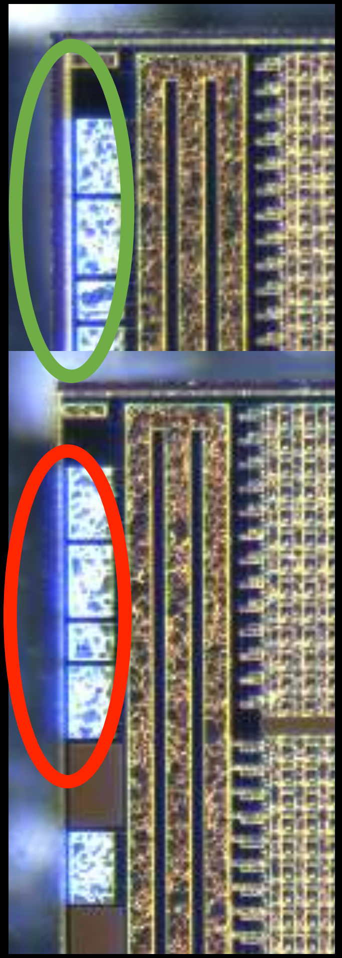


How do you reliably manufacture a mm-scale system?

- Most systems are “stair-step” stack of chips



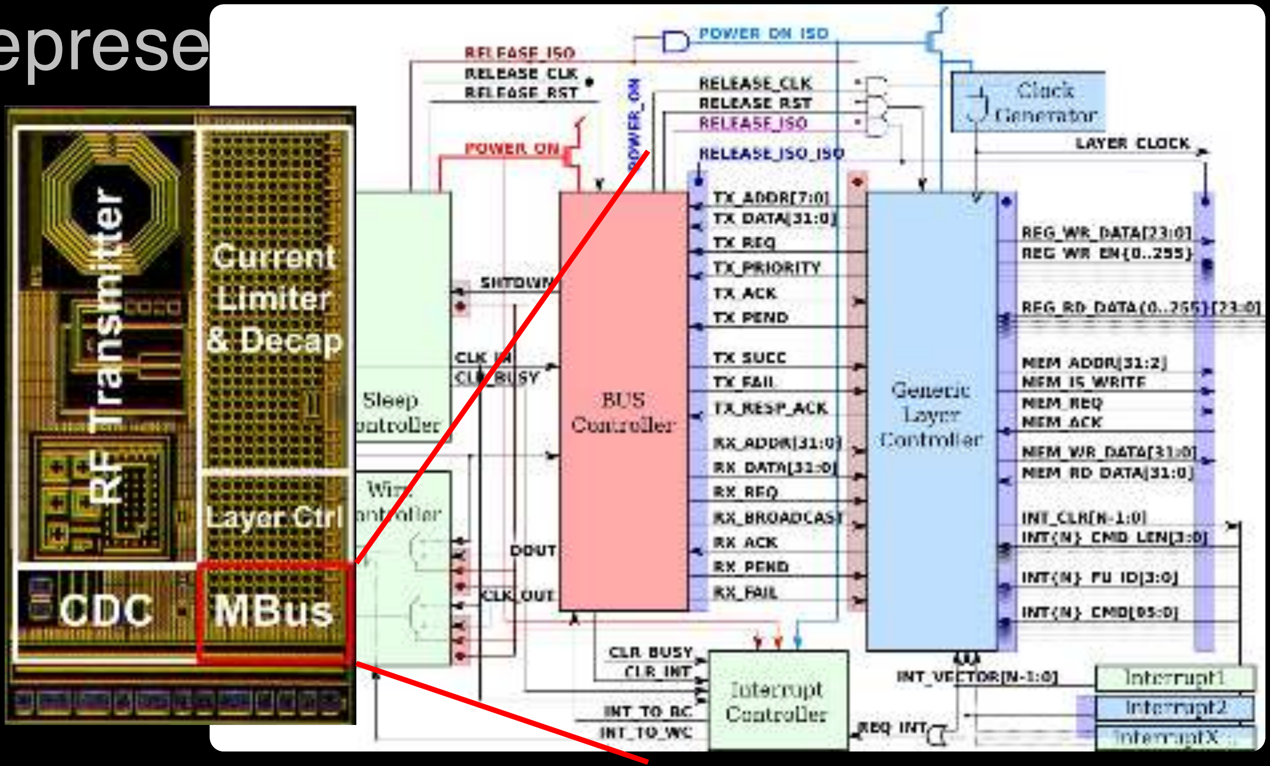
- Thin wafers (300 → 150 microns) [now brittle]
- Then dice on die-attach film
- Then flip onto stack and wirebond



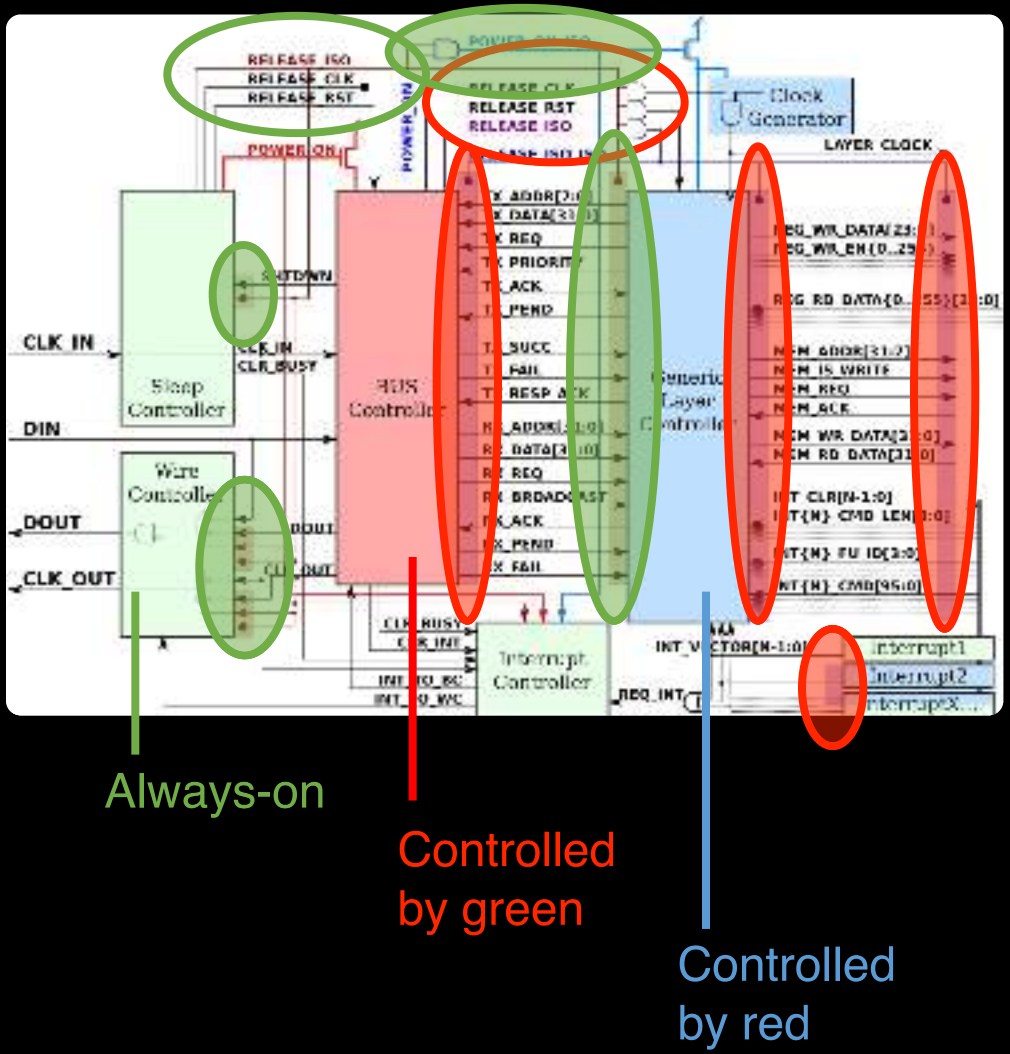
Each step requires some learning…

How do you reliably design a mm-scale system?

- Conceptually simple: Turn off what you aren’t using
- In practice, lots of diagrams that look like this:
- Which represe



Clock-gating != Power-gating. Need to eliminate static leakage as well

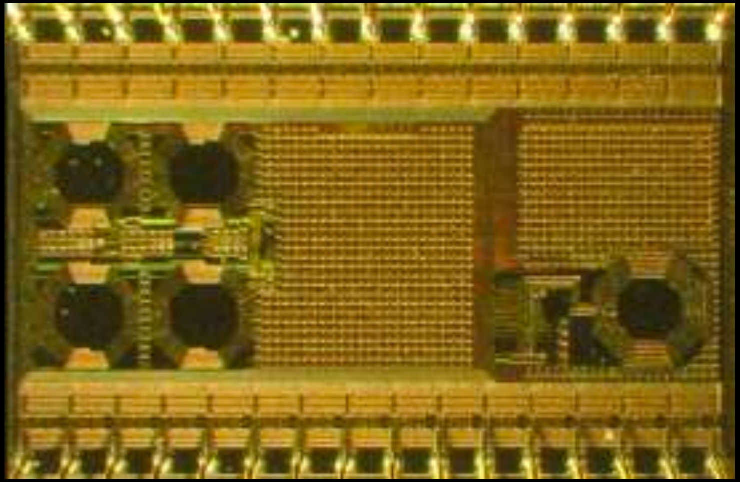


- What is this diagram actually showing?
  - Three hierarchical power domains
  - Power control signals between domains
  - Isolation gates between domains
- Absence of tool support is biggest challenge
  - Isolation correctness validated by hand
  - Effects of isolation simulated “by hand”
    - Often not at all

How to bring a new chip into M^3 ecosystem?

R1: Dedicated test chip

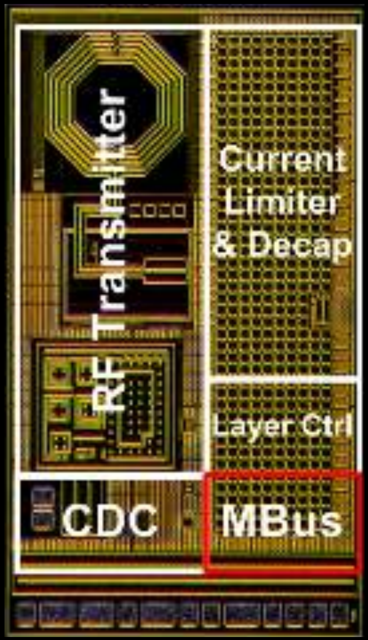
- Lots of I/O, scan, etc



Mohammad Hassan Ghaed, Skylar Skrzyniarz, David Blaauw, Dennis Sylvester, "A 1.6nJ/bit, 19.9µA Peak Current Fully Integrated 2.5mm2 Inductive Transceiver for Volume-Constraned Microsystems," IEEE Custom Integrated Circuits Conference (CICC), September 2014

R2: Integrate

- Add MBus frontend
- Remove most debug pins, expose via registers



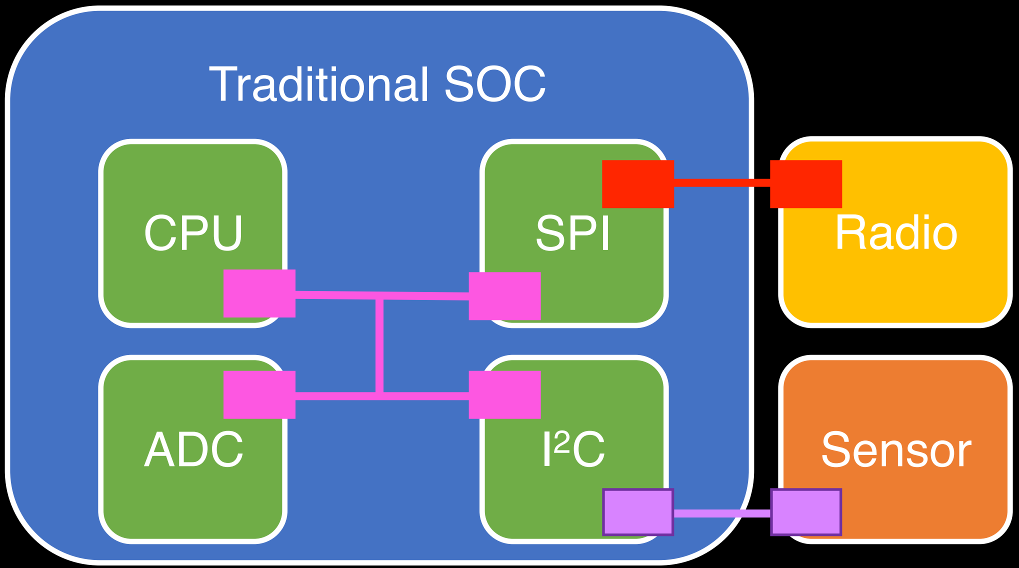
R3+: Bugs!

THERE IS A NATURAL TENSION BETWEEN BUILDING WORKING SYSTEMS AND WORKING CHIPS

Need to avoid designing **“modular” chips** that only work in **one system**

MPQ: A protocol standard for register and memory access brings SOC efficiency to multi-chip systems

- Architectural shift: Remove CPU from steady-state operation
  - Pre-programmed commands:
    - ADC: “Every 128 samples, send DMA to radio”
    - RF: “On DMA CH1 event, send buffer as payload of PKT_TEMPLATE_1”
  - Atmel’s “sleepwalking”, TI’s µDMA controller



SOCs:

Efficiency demands pushing designs back to a monolithic architecture

But the extensible parts aren’t efficient!

- CPU can’t program sensor to send packet

MPQ: A protocol standard for register and memory access brings SOC efficiency to multi-chip systems

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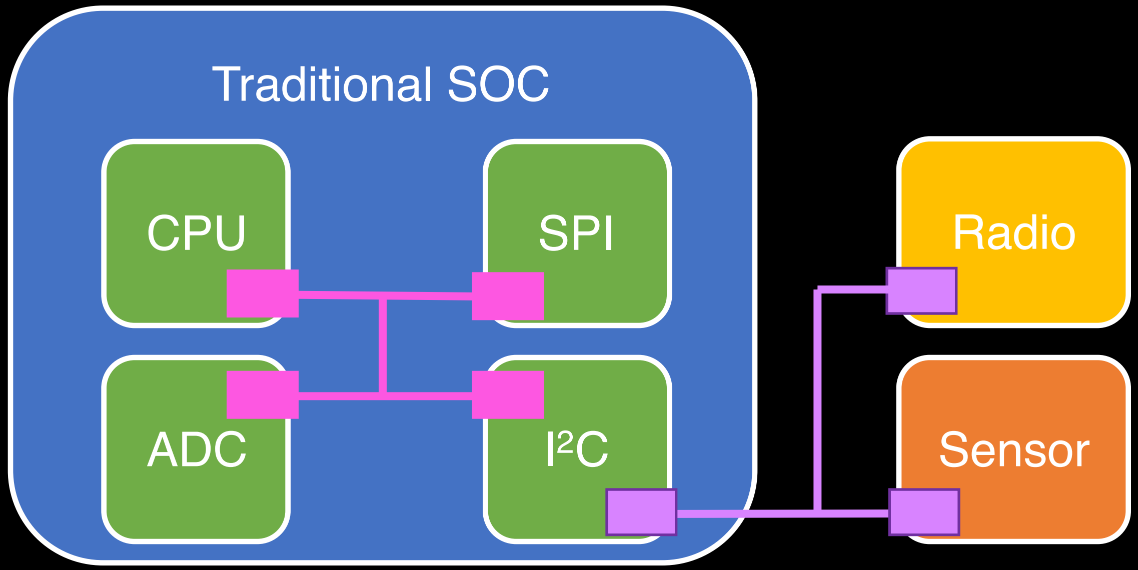

The issue isn’t the physical layer

The clean break of a new bus is an opportunity to standardize basic constructs

- MPQ – “For those who mind their P’s & Q’s on MBus”
  - Does not specify device behavior, command interface, etc
  - Only specifies
    - What a “register” looks like
    - What “memory” looks like
    - And how to read and write registers and memory
- *This is enough to enable powerful system synthesis constructs*

And aligns with how systems are already designed today

MBus and MPQ are available today: mbus.io

- “MBus Compatible”
  - Logo certification
- Specification and Verilog available (free forever)

MBus + MPQ: Standard interface for mm-scale components

It takes a village...


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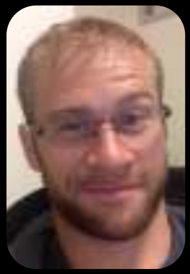
Suyoung Bang


Ryan Rogel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David Blaauw


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