ESE 566A
Modern System-on-Chip Design

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What is a System-on-Chip?
A **system on a chip** or **system on chip** (SoC or SOC) is an integrated circuit (IC) that integrates all components of a computer or other electronic **system** into a single **chip**. It may contain digital, analog, mixed-signal, and often radio-frequency functions—all on a single **chip** substrate.

**System on a chip - Wikipedia, the free encyclopedia**
A system in package (SiP) or system-in-a-package is a number of integrated circuits enclosed in a single module (package). The SiP performs all or most of the functions of an electronic system, and is typically used inside a mobile phone, digital music player, etc.

System in package - Wikipedia, the free encyclopedia

System In Package
This cross section of a SiP shows a microprocessor (μP), SRAM and flash memory chips packaged together in the same housing. The LRC stands for inductor, resistor, capacitor. (Image courtesy of Amkor Technology, Inc.)
Package on Package (PoP)

Lower density I/O BGA ball count (0.65mm pitch and more) connects memory die to landing pads on the top of the bottom package. Memory die typically require less I/O than logic die.

Stacked memory die

Gold or copper wirebonds

High density I/O BGA ball count (0.5mm pitch or less) connects ASIC logic die to motherboard.

Single or multiple ASIC logic die

Laminate substrate (essentially a mini PCB)

source: "ASIC + Memory PoP Schematic" by Moody751 at English Wikipedia.
- Contain general-purpose processor
  - but also other computing units
- Designed for specific application
- Small, low power, portable
- Unique architecture
  - core, memory, accelerators, peripherals
- Combine digital, analog, mixed-signal
- Power management circuits
- Timing source
- Cost constrained
Intelligence, everywhere
Why call it “Modern”? 
Table 10 System Functional Requirements for the PDA SOC-LP Driver

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</thead>
<tbody>
<tr>
<td>Process Technology (nm)</td>
<td>130</td>
<td>90</td>
<td>65</td>
<td>45</td>
<td>32</td>
<td>22</td>
</tr>
<tr>
<td>Supply Voltage (V)</td>
<td>1.2</td>
<td>1</td>
<td>0.8</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Clock Frequency (MHz)</td>
<td>150</td>
<td>300</td>
<td>450</td>
<td>600</td>
<td>900</td>
<td>1200</td>
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<tr>
<td>Application (maximum required performance)</td>
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<tr>
<td>Still Image Processing</td>
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<tr>
<td>Web Browser</td>
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<tr>
<td>Electric Mailer</td>
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<tr>
<td>Scheduler</td>
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<tr>
<td>Application (other)</td>
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<tr>
<td>Real Time Video Codec (MPEG4/CIF)</td>
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<tr>
<td>TV Telephone (1:1)</td>
<td></td>
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<tr>
<td>Voice Recognition (Input)</td>
<td></td>
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<tr>
<td>Authentication (Crypto Engine)</td>
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<tr>
<td>Real Time Interpretation</td>
<td></td>
<td></td>
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<tr>
<td>TV Telephone (&gt;3:1) Voice Recognition (Operation)</td>
<td></td>
<td></td>
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<tr>
<td>Processing Performance (GOPS)</td>
<td>0.3</td>
<td>2</td>
<td>15</td>
<td>103</td>
<td>720</td>
<td>5042</td>
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<tr>
<td>Required Average Power (W)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Required Standby Power (mW)</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
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<tr>
<td>Battery Capacity (Wh/Kg)</td>
<td>120</td>
<td>200</td>
<td>400</td>
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Bell’s Law of Computer Classes: A new computing class roughly every decade

"Roughly every decade a new, lower priced computer class forms based on a new programming platform, network, and interface resulting in new usage and the establishment of a new industry."

- Adapted from D. Culler
• Technology advances
  - fabrication process
  - electronic design automation (EDA)
  - system integration

• Market force shifts
  - mobile dominate

• Industry business model evolves
  - foundry vs integrated device manufacturers (IDM)
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<tr>
<td>1</td>
<td>NEC</td>
<td>4.8</td>
<td>Intel</td>
<td>Intel</td>
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<tr>
<td>2</td>
<td>Toshiba</td>
<td>4.8</td>
<td>NEC</td>
<td>Toshiba</td>
<td>Samsung</td>
<td>37.8</td>
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<td>3</td>
<td>Hitachi</td>
<td>3.9</td>
<td>Toshiba</td>
<td>NEC</td>
<td>TI</td>
<td>Qualcomm**</td>
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<td>4</td>
<td>Intel</td>
<td>3.7</td>
<td>Hitachi</td>
<td>Samsung</td>
<td>10.6</td>
<td>10.0</td>
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<tr>
<td>5</td>
<td>Motorola</td>
<td>3.0</td>
<td>Motorola</td>
<td>TI</td>
<td>ST</td>
<td>SK Hynix</td>
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<td>6</td>
<td>Fujitsu</td>
<td>2.8</td>
<td>Samsung</td>
<td>Motorola</td>
<td>7.9</td>
<td>TI</td>
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<tr>
<td>7</td>
<td>Mitsubishi</td>
<td>2.6</td>
<td>TI</td>
<td>ST</td>
<td>Hynix</td>
<td>Toshiba</td>
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<tr>
<td>8</td>
<td>TI</td>
<td>2.5</td>
<td>IBM</td>
<td>Hitachi</td>
<td>Freescale</td>
<td>Broadcom**</td>
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<tr>
<td>9</td>
<td>Philips</td>
<td>1.9</td>
<td>Mitsubishi</td>
<td>Infineon</td>
<td>NXP</td>
<td>Toshiba</td>
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<tr>
<td>10</td>
<td>Matsushita</td>
<td>1.8</td>
<td>Hyundai</td>
<td>Philips</td>
<td>NEC</td>
<td>Renesas</td>
</tr>
</tbody>
</table>

| Semi Market ($B) | 54.3 | 154  | 218.6 | 265.5 | 354.8 |
| Top 10 % of Total Semi | 59% | 56%  | 49%   | 45%   | 53%   |

Source: IC Insights

*Not including foundries  **Fabless

source: www.icinsights.com
Outline

Technology Trends

Design Opportunities

Course Administrivia
Moore’s Law:

Transistor count doubles every two years.
source: Intel, U. Michigan

Intel® 4004 processor
Introduced 1971
Initial clock speed
108 KHz
Number of transistors
2,300
Manufacturing technology
10μ

15x size decrease
40x transistors
55x smaller λ

UMich Phoenix Processor
Introduced 2008
Initial clock speed
106 kHz @ 0.5V Vdd
Number of transistors
92,499
Manufacturing technology
0.18 μ

Quad-Core Intel® Xeon® processor
Quad-Core Intel® Core™-2 Extreme processor
Introduced 2006
Intel® Core™2 Quad processors
Introduced 2007
Initial clock speed
2.66 GHz
Number of transistors
582,000,000
Manufacturing technology
65nm
Flash memory scaling:
Rise of density & volumes; Fall (and rise) of prices

Graphs illustrating the increase in bit volume and decrease in cost over time for NAND Flash memory.
Hendy’s “Law”:
Pixels per dollar doubles annually

source: Barry Hendy/Wikipedia
MEMS Accelerometers: Rapidly falling price and power

ADXL345
[Analog Devices, 2009]

10 µA @ 10 Hz @ 6 bits
source: ST Microelectronics, annn. 2009
Energy harvesting and storage: Small doesn’t mean powerless...

- Thin-film batteries
- RF [Intel]
- Clare Solar Cell
- Shock Energy Harvesting
  CEDRAT Technologies
- Electrostatic Energy Harvester [ICL]
- Piezoelectric
  [Holst/IMEC]
- Thermoelectric Ambient
  Energy Harvester [PNNL]
Outline

Technology Trends

Design Opportunities

Course Administrivia
Inside an iPad Air 2

Physical world interaction:
- camera
- speakers

Communication:
- Antenna

Energy:
- Battery

Display / touch screen

“Brains”: the main board

User interface device:
- home button
iPad Main Board

Maxim: Amplifier
Micron RAM: The “Operating Memory”
NXP NFC Chip for ApplePay.
Apple A8X: The “Brains” of the iPad Air 2
Texas Instruments Touch Screen Controller
Cirrus Logic: Audio chip
Bosch: Accelerometer
Hynix Flash Memory: The “Storage”
Interface to the Physical World:
The camera

Focus/Exposure Control
- Pre-processing
  - White-balancing
  - Demosaic
  - Color Transform
  - Post-processing
  - Compression
Apple iPhone: The quintessential smart system

- Apple A8 APL1011 SoC + SK Hynix RAM as denoted by the markings H9CKNNN8KTMRWR-NTH (we presume it is 1 GB LPDDR3 RAM, the same as in the iPhone 6 Plus)
- Qualcomm MDM9625M LTE Modem
- Skyworks 77802-23 Low Band LTE PAD
- Avago A8020 High Band PAD
- Avago A8010 Ultra High Band PA + FBARs
- SkyWorks 77803-20 Mid Band LTE PAD
- InvenSense MP67B 6-axis Gyroscope and Accelerometer Combo

source: ifixit.com
### Apple A8 vs A7 SoCs

<table>
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<tbody>
<tr>
<td>Manufacturing Process</td>
<td>TSMC 20nm HKMG</td>
<td>Samsung 28nm HKMG</td>
</tr>
<tr>
<td>Die Size</td>
<td>89mm$^2$</td>
<td>104mm$^2$</td>
</tr>
<tr>
<td>Transistor Count</td>
<td>~2B</td>
<td>&quot;Over 1B&quot;</td>
</tr>
<tr>
<td>CPU</td>
<td>2 x Apple Enhanced Cyclone ARMv8 64-bit cores</td>
<td>2 x Apple Cyclone ARMv6 64-bit cores</td>
</tr>
<tr>
<td>GPU</td>
<td>IMG PowerVR GX6450</td>
<td>IMG PowerVR G6430</td>
</tr>
</tbody>
</table>

source: anandtech.com
Outline

Technology Trends

Design Opportunities

Course Administrivia
Instructional Staff
(see homepage for contact info, office hours)

Xuan Zhang
Sri Harsha Kondapalli
Srinath Nizampatnam
Prerequisites

- ESE 232: Introduction to Electronic Circuits
  - analysis and design of amplifiers
  - semiconductor memory devices

- ESE 260: Introduction to Digital Logic and Computer Design
  - EDA tools for circuit synthesis and simulation
  - logic minimization, propagation delays, timing
  - simple processor design trade-offs

- RTL design and HDL (verilog or VHDL)
- Basic computer architecture
- C programming, Linux
Course Syllabus (tentative)

• Course homepage:
  - http://www.ese.wustl.edu/~xuan.zhang/ese566

• Distribution
  - 40%: reading and learning
  - 60%: project-centric

• Workload
  - no exams
  - 1-page briefs
  - in-class quizzes
  - labs
  - one group project
  - one final essay
Open-ended Project

• **Goal:** learn by doing  
  - Work in teams of 4 - 5  
  - Pick a problem of your own interest or one we suggest  
  - Meet with instructors to discuss ideas

• Scope of project must be compatible to team size

• **Evaluation:**  
  - Novelty  
  - Prior art survey  
  - Coverage of topics  
  - Methodology  
  - Problem solving
Essay

- The Big Picture
- The Future
- The Killer Technology
  - How it relates to SoC design?
- Your Insights
Grading

- Assignments, Quizzes, Labs 25%
- Project Proposal 20%
- Project Presentation 15%
- Group Report 25%
- Individual Essay 15%
- Bonus 10%
Policies

- **Submission**
  - quizzes, labs, assignments due in class
  - 3-day grace period, then 50% penalty
  - no credits after 1 week, no exception

- **Discussion & Collaboration**
  - learning through discussion
  - help classmates to understand concepts
  - sharing code or schematics not-allowed

- **Plagiarism**
  - zero tolerance
  - specify sources to avoid confusion
Make and Hack

- Open Source Resources

- Community

- Explore and Have Fun
Questions?

Comments?

Discussion?
Assignment #1

- 1-Page Summary
  - compare iPhone 6 and Galaxy S6 tear-down
  - list choice of chips (manufacturer and process technology)
  - highlight and comment

- 1-Page Summary
  - tear-down of a smart device of your interest
  - smart watch, fitbit, misfit bracelet, oculus VR, ...
  - compare different spec to smart phone

- Due 09/01 (Tuesday), before class
Skandalaris Center for Interdisciplinary Innovation and Entrepreneurship

Boeing Challenge

*WUSTL faculty may participate in challenge in advisory capacity only, and do not qualify for any awards

PhantomWorks Ventures and the Skandalaris Center have teamed up to mentor a patent translation/commercialization challenge based on Boeing intellectual property – 50 categories of patents have been selected for highest commercialization potential by WUSTL undergraduate, graduate & professional students, and faculty*!

Think Big, start small. START
Acknowledgement

U. Michigan EECS373
Berkeley EE16
What happened elsewhere now happens on the phone.

**Preferred Cell Phone Services**

- Music Downloading: 37%
- AM/FM Receiver: 15%
- TV Viewing: 11%
- News/Sports: 28%
- Concierge Services: 23%
- Internet Browsing: 12%
- Audio Streaming: 8%
- Music Playback: 14%
- Text Messaging: 57%
- Weather Reports: 17%
- Traffic Reports: 39%

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