Digital Design & Computer Arch.

Lecture 2a: Tradeoffs, Metrics, Mindset

Prof. Onur Mutlu

ETH Zürich

Spring 2021

26 February 2021

Let's Start with Some Puzzles

a.k.a. Computer Architecture resembles Building Architecture

What Is This?

Source: https://www.flickr.com/photos/tambako/2286064777/in/photostream/

What About This?

Source: By Toni_V, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=4087256

What Do the Following Have in Common?

Gare do Oriente, Lisbon

Source: By Martín Gómez Tagle - Lisbon, Portugal, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=13764903

Milwaukee Art Museum

Source: By Andrew C. from Flagstaff, USA - Flickr, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=379223

Athens Olympic Stadium

Source: By Spyrosdrakopoulos - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16172519

City of Arts and Sciences, Valencia

Source: CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=172107

Florida Polytechnic University (I)

Source: http://www.architectmagazine.com/design/buildings/florida-polytechnic-university-designed-by-santiago-calatrava_o

Oculus, New York City

Source: https://www.dezeen.com/2016/08/29/santiago-calatrava-oculus-world-trade-center-transportation-hub-new-york-photographs-hufton-crow/

What do All Those Have in Common with Bahnhof Stadelhofen?

Answer: All Designed by a Famous Architect

- ETH Alumnus, PhD Civil Engineering
- "The train station has several of the features that became signatures of his work; straight lines and right angles are rare."

Santiago Calatrava Valls (born 28 July 1951) is a Spanish architect, structural engineer, sculptor and painter, particularly known for his bridges supported by single leaning pylons, and his railway stations, stadiums, and museums, whose sculptural forms often resemble living organisms.[1] His best-known works include the Milwaukee Art Museum, the Turning Torso tower in Malmo, Sweden, the Margaret Hunt Hill Bridge in Dallas, Texas, and the Museum of Tomorrow in Rio de Janeiro,

Source: By 準建築人手札網站 Forgemind ArchiMedia - Flickr: IMG_2489.JPG, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=31493356, https://en.wikipedia.org/wiki/Santiago_Calatrava

Your First Comp. Architecture Assignment

- Go and find the closest Calatrava building to this classroom
  - For those who like a challenge, find the furthest building that was designed by Calatrava to his classroom ☺
- Appreciate the beauty & out-of-the-box and creative thinking
- Think about tradeoffs in the design
  - Strengths, weaknesses, goals of design
- Derive principles on your own for good design and innovation
- Due date: **Any time during this course**
  - Later during the course is better
  - Apply what you have learned in this course
  - Think out-of-the-box

But First, Today's First Assignment

Find The Differences of This and That

This

Source: By Toni_V from Zurich, Switzerland - Stadelhofen2, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=4087256

That

Source: http://cookiemagik.deviantart.com/art/Train-station-207266944 - Göttingen, DE

Many Tradeoffs Between Two Designs

- You can list them after you complete the first assignment…

Aside: Evaluation Criteria for the Designs

- Functionality (Does it meet the specification?)
- Reliability
- Space requirement
- Cost
- Expandability
- Comfort level of users
- Happiness level of users
- Aesthetics
- Security
- …

- How to evaluate goodness of design is always a critical question → "Performance" evaluation and metrics

A Key Question

- How was Calavatra able to design especially his key buildings?
- Can have many guesses
  - (Very) hard work, perseverance, dedication (over decades)
  - Experience
  - Creativity, Out-of-the-box thinking
  - A good understanding of past designs
  - Good judgment and intuition
  - Strong skill combination (math, architecture, art, engineering, …)
  - Funding ($$$$), luck, initiative, entrepreneurialism
  - Strong understanding of and commitment to fundamentals
  - Principled design
  - …
- You will be exposed to and hopefully develop/enhance many of these skills in this course

Principled Design

- "To me, there are two overriding principles to be found in nature which are most appropriate for building:
  - one is the optimal use of material,
  - the other the capacity of organisms to change shape, to grow, and to move."
  - *Santiago Calatrava*

- "Calatrava's constructions are inspired by natural forms like plants, bird wings, and the human body."

Source: http://www.arcspace.com/exhibitions/unsorted/santiago-calatrava/

Gare do Oriente, Lisbon, Revisited

Source: By Martín Gómez Tagle - Lisbon, Portugal, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=13764903

Source: http://www.arcspace.com/exhibitions/unsorted/santiago-calatrava/

A Principled Design

Zoomorphic architecture

From Wikipedia, the free encyclopedia

Zoomorphic architecture is the practice of using animal forms as the inspirational basis and blueprint for architectural design. "While animal forms have always played a role adding some of the deepest layers of meaning in architecture, it is now becoming evident that a new strand of biomorphism is emerging where the meaning derives not from any specific representation but from a more general allusion to biological processes."[1]

Some well-known examples of Zoomorphic architecture can be found in the TWA Flight Center building in New York City, by Eero Saarinen, or the Milwaukee Art Museum by Santiago Calatrava, both inspired by the form of a bird's wings.[3]

What Does This Remind You Of?

Source: https://www.dezeen.com/2016/08/29/santiago-calatrava-oculus-world-trade-center-transportation-hub-new-york-photographs-hufton-crow/

The Architect's Answer

Design [edit]

Calatrava said that the Oculus resembles a bird being released from a child's hand. The roof was originally designed to mechanically open to increase light and ventilation to the enclosed space. Herbert Muschamp, architecture critic of *The New York Times*, compared the design to the Bethesda Terrace and Fountain in Central Park, and wrote in 2004:

Source: https://en.wikipedia.org/wiki/World_Trade_Center_station_(PATH)

Strengths and Praise

> Santiago Calatrava's design for the World Trade Center PATH station should satisfy those who believe that buildings planned for ground zero must aspire to a spiritual dimension. Over the years, many people have discerned a metaphysical element in Mr. Calatrava's work. I hope New Yorkers will detect its presence, too. With deep appreciation, I congratulate the Port Authority for commissioning Mr. Calatrava, the great Spanish architect and engineer, to design a building with the power to shape the future of New York. It is a pleasure to report, for once, that public officials are not overstating the case when they describe a design as breathtaking.[43]

Source: https://en.wikipedia.org/wiki/World_Trade_Center_station_(PATH)

Design Constraints and Criticism

However, Calatrava's original soaring spike design was scaled back because of security issues. The *New York Times* observed in 2005:

> In the name of security, Santiago Calatrava's bird has grown a beak. Its ribs have doubled in number and its wings have lost their interstices of glass.... [T]he main transit hall, between Church and Greenwich Streets, will almost certainly lose some of its delicate quality, while gaining structural expressiveness. It may now evoke a slender stegosaurus more than it does a bird.[45]

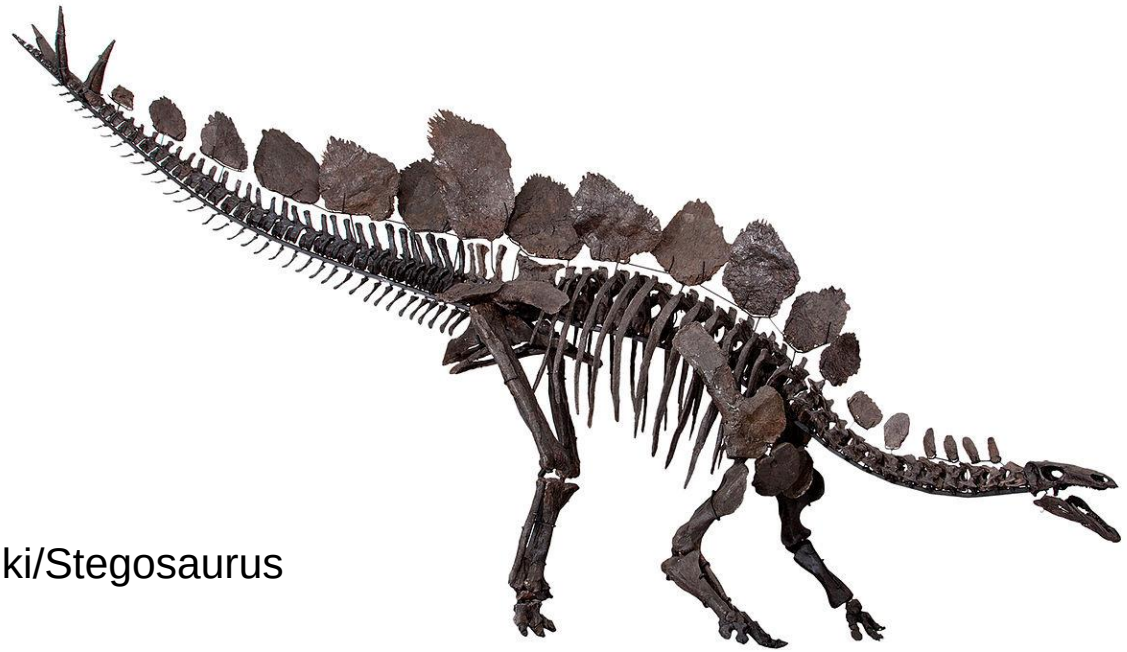
Source: https://en.wikipedia.org/wiki/World_Trade_Center_station_(PATH)

Stegosaurus

From Wikipedia, the free encyclopedia

For the pachycephalosaurid of a similar name, see Stegoceras.

Stegosaurus (/ˌstɛgəˈsɔːrəs/[1]) is a genus of armored dinosaur. Fossils of this genus date to the Late Jurassic period, where they are found in Kimmeridgian to early Tithonian aged strata, between 155 and 150 million years ago, in the western United States and Portugal. Several



Source: https://en.wikipedia.org/wiki/Stegosaurus

Susannah Maidment et al. & Natural History Museum, London - Maidment SCR, Brassey C, Barrett PM (2015) The Postcranial Skeleton of an Exceptionally Complete Individual of the Plated Dinosaur Stegosaurus stenops (Dinosauria: Thyreophora) from the Upper Jurassic Morrison Formation of Wyoming, U.S.A. PLoS ONE 10(10): e0138352. doi:10.1371/journal.pone.0138352

Design Constraints: Noone is Immune

However, Calatrava's original soaring spike design was scaled back because of security issues. The *New York Times* observed in 2005:

> In the name of security, Santiago Calatrava's bird has grown a beak. Its ribs have doubled in number and its wings have lost their interstices of glass.... [T]he main transit hall, between Church and Greenwich Streets, will almost certainly lose some of its delicate quality, while gaining structural expressiveness. It may now evoke a slender stegosaurus more than it does a bird.[45]

The design was further modified in 2008 to eliminate the opening and closing roof mechanism because of budget and space constraints.[46]

The Transportation Hub has been dubbed "the world's most expensive transportation hub" for its massive cost for reconstruction—$3.74 billion dollars.[48][58] By contrast, the proposed two-mile PATH extension

Source: https://en.wikipedia.org/wiki/World_Trade_Center_station_(PATH)

The Lecture Was Slightly Different When I Was at CMU

What Is This?

Source: https://roadtrippers.com/stories/falling-water

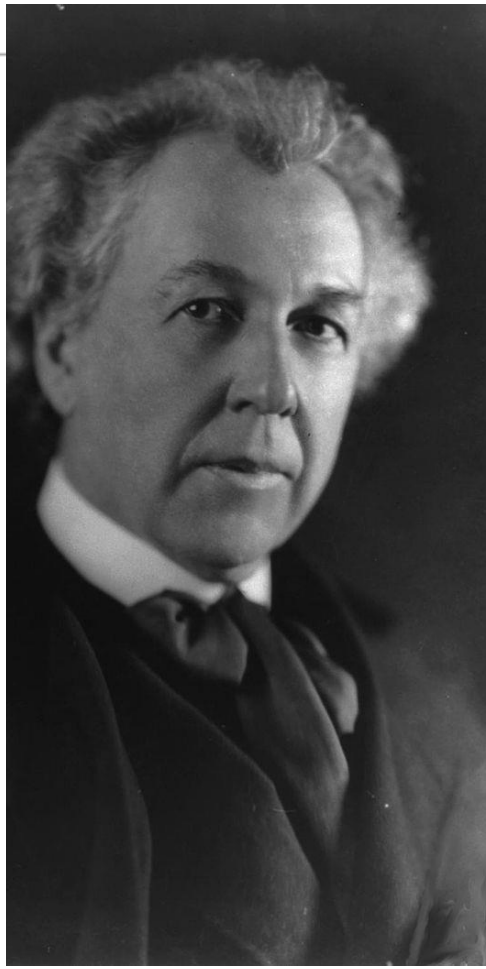
Answer: Masterpiece of A Famous Architect

Fallingwater

From Wikipedia, the free encyclopedia

Fallingwater or **Kaufmann Residence** is a house designed by architect Frank Lloyd Wright in 1935 in rural southwestern Pennsylvania, 43 miles (69 km) southeast of Pittsburgh.[4] The home was built partly over a waterfall on Bear Run in the Mill Run section of Stewart Township, Fayette County, Pennsylvania, in the Laurel Highlands of the Allegheny Mountains.

Time cited it after its completion as Wright's "most beautiful job";[5] it is listed among *Smithsonian*'s Life List of 28 places "to visit before you die."[6] It was designated a National Historic Landmark in 1966.[3] In 1991, members of the American Institute of Architects named the house the "best all-time work of American architecture" and in 2007, it was ranked twenty-ninth on the list of America's Favorite Architecture according to the AIA.



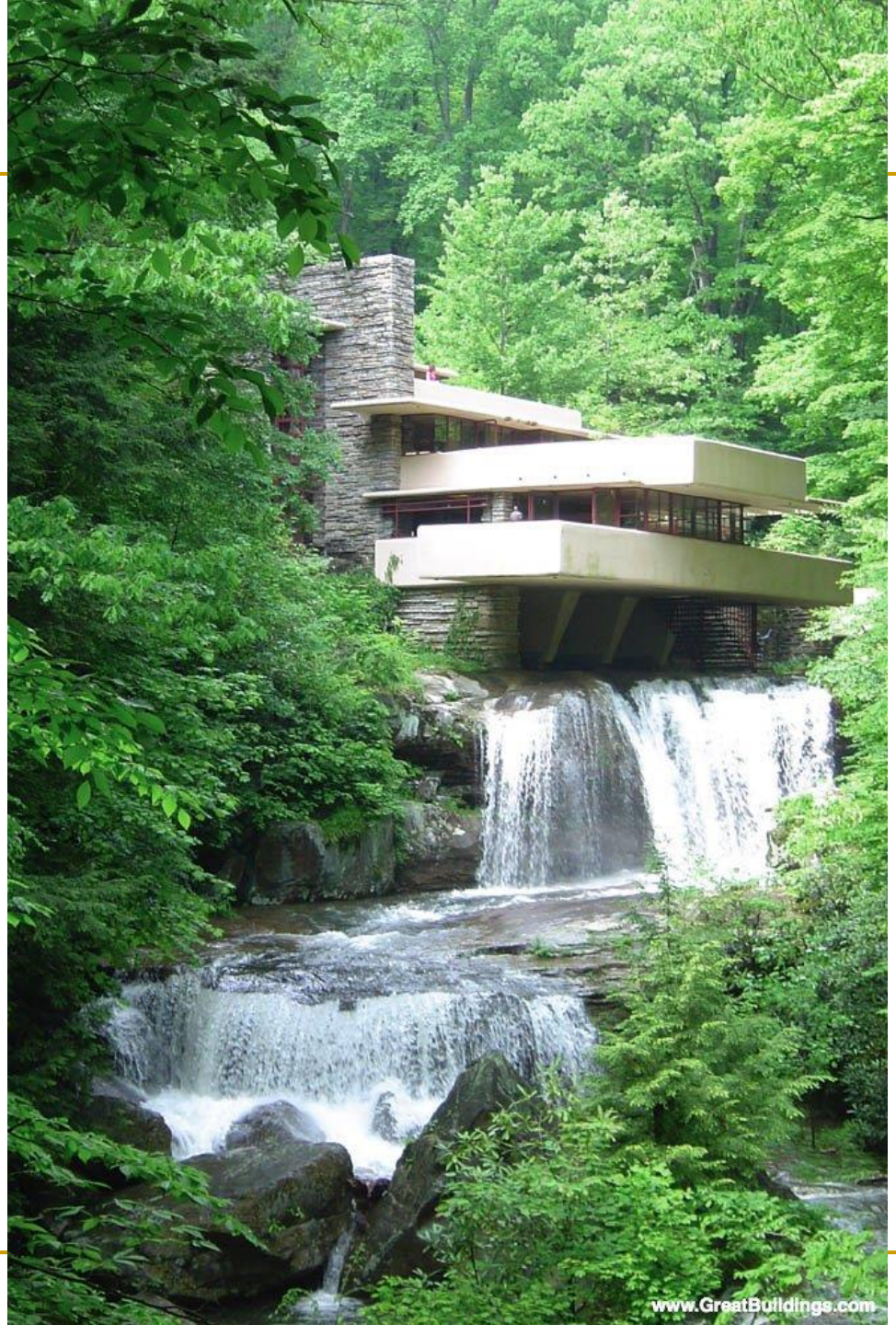
Source: https://en.wikipedia.org/wiki/Fallingwater

Find The Differences of This and That

This

Source: http://www.fallingwater.org/

This



That

A Key Question

- How was Wright able to design his masterpiece?
- Can have many guesses
  - (Very) hard work, perseverance, dedication (over decades)
  - Experience
  - Creativity, Out-of-the-box thinking
  - A good understanding of past designs
  - Good judgment and intuition
  - Strong skill combination (math, architecture, art, engineering, …)
  - Funding ($$$$), luck, initiative, entrepreneurialism
  - Strong understanding of and commitment to fundamentals
  - Principled design
  - …
- You will be exposed to and hopefully develop/enhance many of these skills in this course

A Quote from The Architect Himself

- "architecture [...] based upon principle, and not upon precedent"

Source: http://www.fallingwater.org/

A Principled Design

Organic architecture

From Wikipedia, the free encyclopedia

Organic architecture is a philosophy of architecture which promotes harmony between human habitation and the natural world through design approaches so sympathetic and well integrated with its site, that buildings, furnishings, and surroundings become part of a unified, interrelated composition.

A well-known example of organic architecture is Fallingwater, the residence Frank Lloyd Wright designed for the Kaufmann family in rural Pennsylvania. Wright had many choices to locate a home on this large site, but chose to place the home directly over the waterfall and creek creating a close, yet noisy dialog with the rushing water and the steep site. The horizontal striations of stone masonry with daring cantilevers of colored beige concrete blend with native rock outcroppings and the wooded environment.

A Key Question

- How was Wright able to design his masterpiece?
- Can have many guesses
  - (Very) hard work, perseverance, dedication (over decades)
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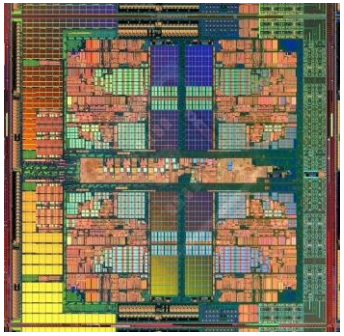
Takeaways

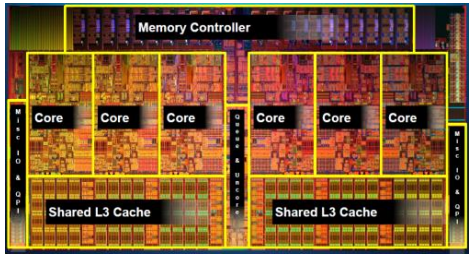
- It all starts from the basic building blocks and design principles
- And, knowledge of how to use, apply, enhance them
- Underlying technology might change (e.g., steel vs. wood)
  - but methods of taking advantage of technology bear resemblance
  - methods used for design depend on the principles employed

The Same Applies to Processor Chips

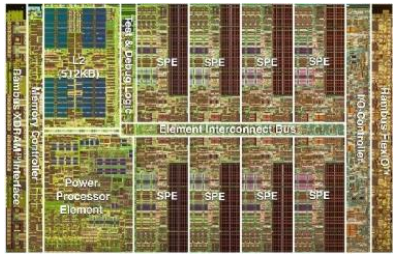
- There are basic building blocks and and design principles



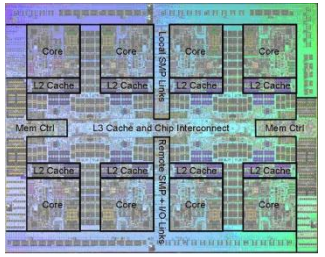
AMD Barcelona
4 cores



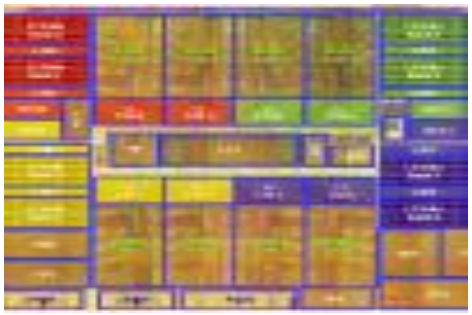
Intel Core i7
8 cores



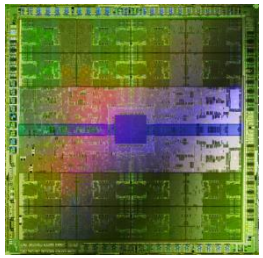
IBM Cell BE
8+1 cores



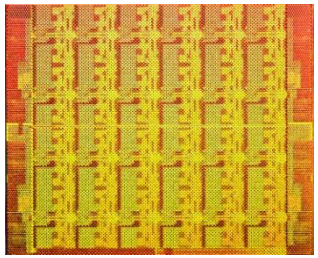
IBM POWER7
8 cores



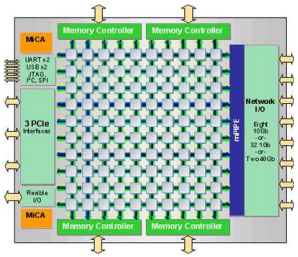
Sun Niagara II
8 cores



Nvidia Fermi
448 “cores”



Intel SCC
48 cores, networked



Tilera TILE Gx
100 cores, networked

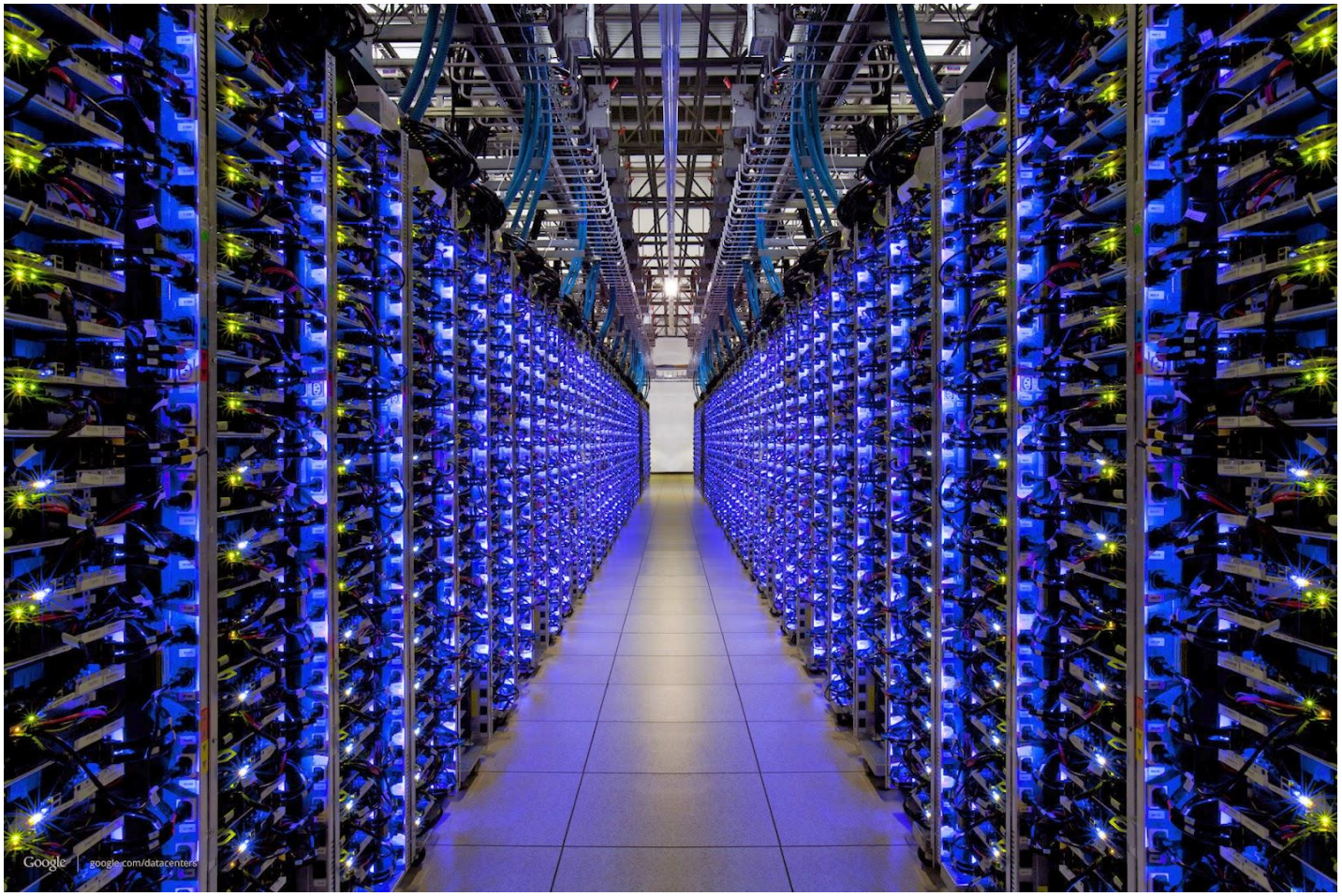
The Same Applies to Computing Systems

- There are basic building blocks and and design principles

source: http://www.sia-online.org (semiconductor industry association)

The Same Applies to Computing Systems

- There are basic building blocks and and design principles



Source: http://datacentervoice.com/wp-content/uploads/2015/10/data-center.jpg

Different Platforms, Different Goals

Source: https://iq.intel.com/5-awesome-uses-for-drone-technology/

Different Platforms, Different Goals

Source: https://taxistartup.com/wp-content/uploads/2015/03/UK-Self-Driving-Cars.jpg

Different Platforms, Different Goals

Source: http://sm.pcmag.com/pcmag_uk/photo/g/google-self-driving-car-the-guts/google-self-driving-car-the-guts_dwx8.jpg

Different Platforms, Different Goals

Source: https://fossbytes.com/wp-content/uploads/2015/06/Supercomputer-TIANHE2-china.jpg

Different Platforms, Different Goals

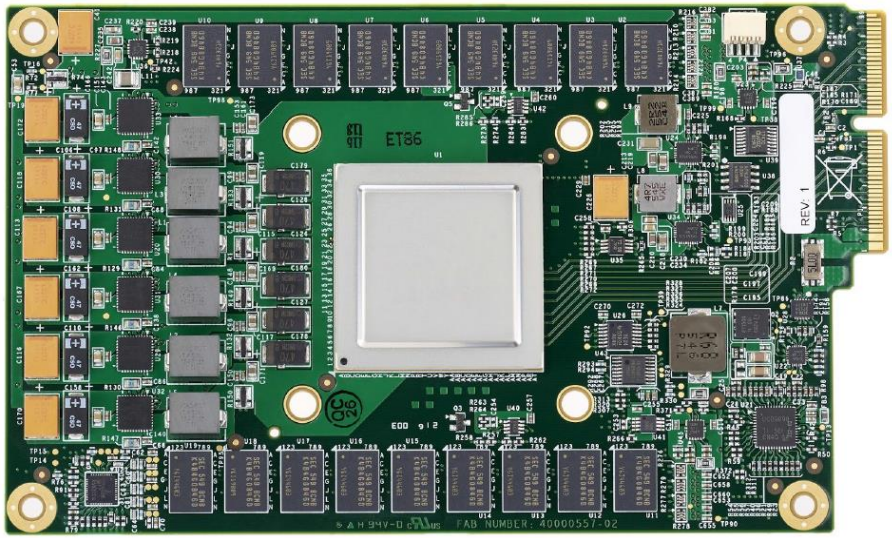


Figure 3. TPU Printed Circuit Board. It can be inserted in the slot for an SATA disk in a server, but the card uses PCIe Gen3 x16.

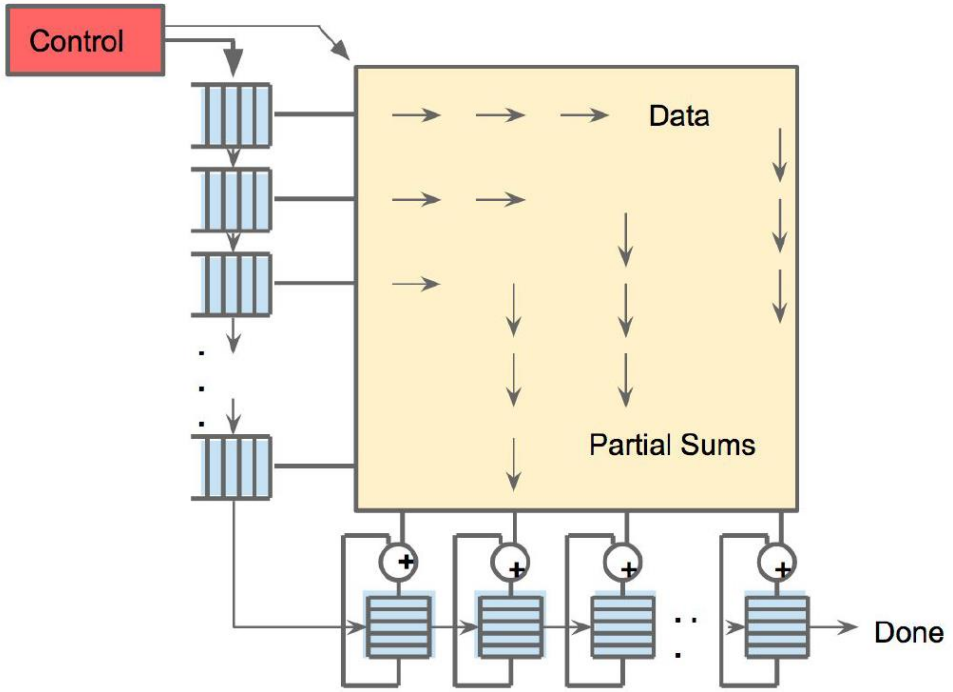
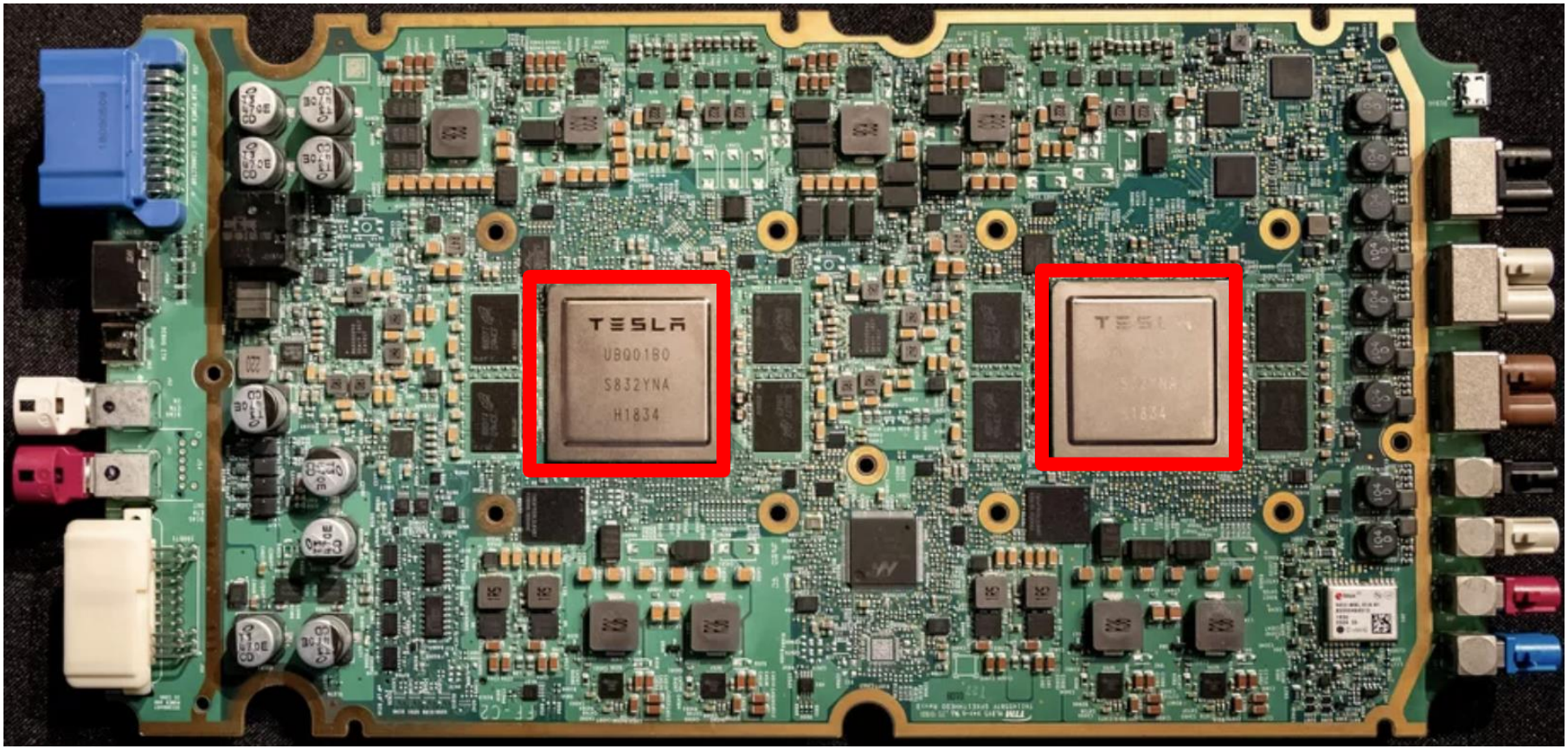


Figure 4. Systolic data flow of the Matrix Multiply Unit. Software has the illusion that each 256B input is read at once, and they instantly update one location of each of 256 accumulator RAMs.

Jouppi et al., "In-Datacenter Performance Analysis of a Tensor Processing Unit", ISCA 2017.

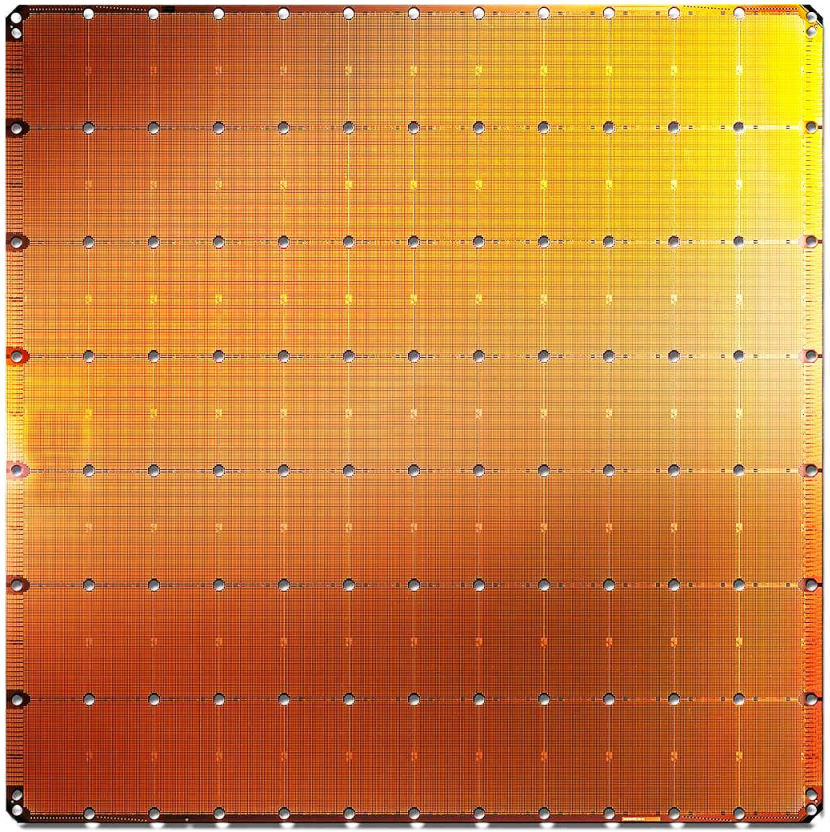
Different Platforms, Different Goals

- ML accelerator: 260 mm^2, 6 billion transistors, 600 GFLOPS GPU, 12 ARM 2.2 GHz CPUs.
- Two redundant chips for better safety.



https://youtu.be/Ucp0TTmvqOE?t=4236

Different Platforms, Different Goals



- The largest ML accelerator chip
- 400,000 cores

Cerebras WSE
1.2 Trillion transistors
46,225 mm^2

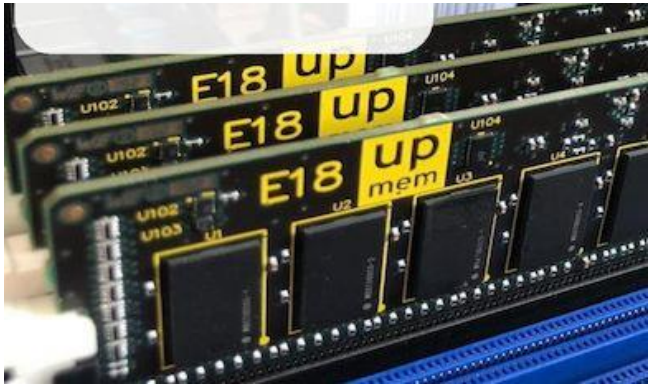
Largest GPU
21.1 Billion transistors
815 mm^2
NVIDIA TITAN V

https://www.anandtech.com/show/14758/hot-chips-31-live-blogs-cerebras-wafer-scale-deep-learning

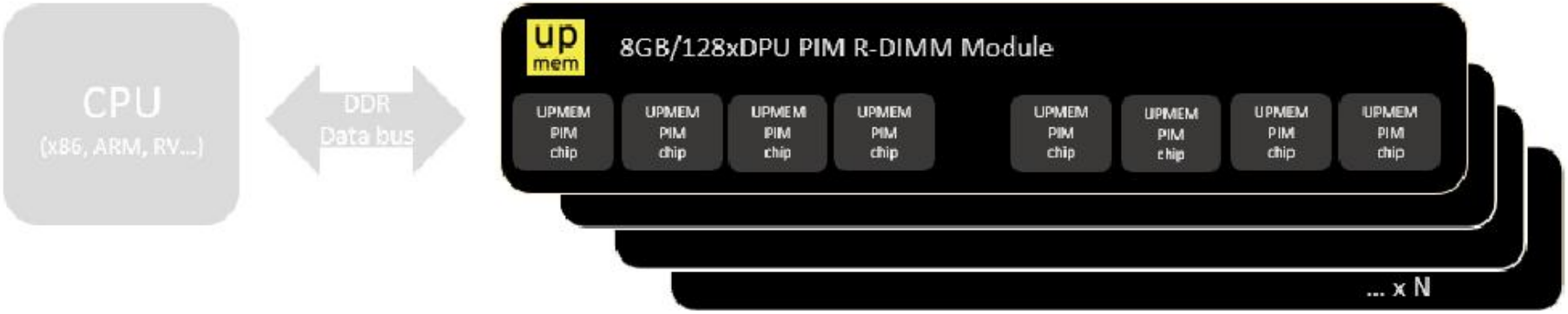
https://www.cerebras.net/cerebras-wafer-scale-engine-why-we-need-big-chips-for-deep-learning/

UPMEM Processing-in-DRAM Engine (2019)

- Processing in DRAM Engine
- Includes **standard DIMM modules**, with a **large number of DPU processors** combined with DRAM chips.



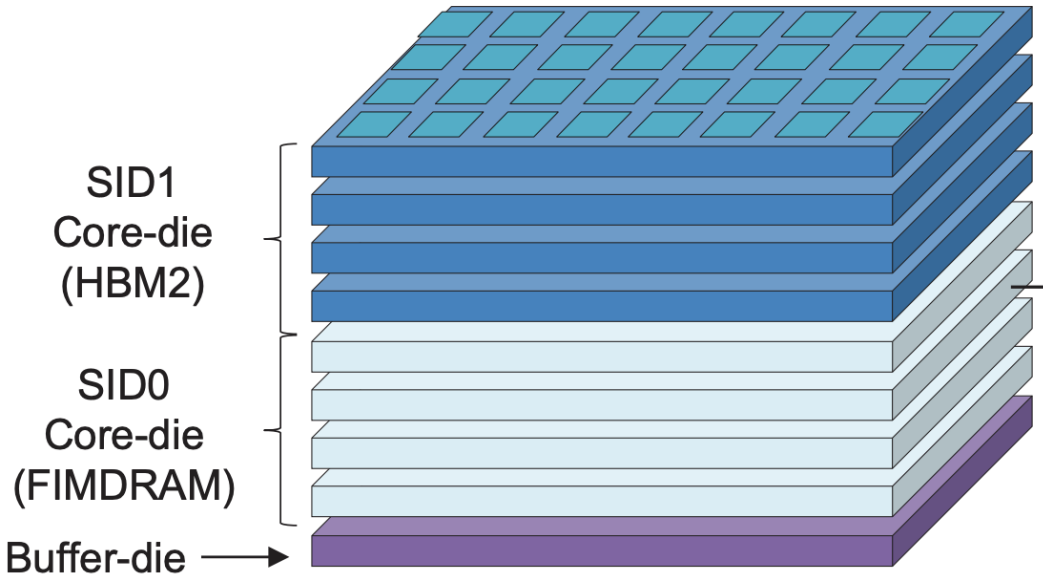
- Replaces **standard** DIMMs
  - DDR4 R-DIMM modules
    - 8GB+128 DPUs (16 PIM chips)
    - Standard 2x-nm DRAM process
  - **Large amounts of** compute & memory bandwidth



https://www.anandtech.com/show/14750/hot-chips-31-analysis-inmemory-processing-by-upmem
https://www.upmem.com/video-upmem-presenting-its-true-processing-in-memory-solution-hot-chips-2019/

Samsung Function-in-Memory DRAM (2021)

- FIMDRAM based on HBM2



[3D Chip Structure of HBM with FIMDRAM]

Chip Specification
128DQ / 8CH / 16 banks / BL4
32 PCU blocks (1 FIM block/2 banks)
1.2 TFLOPS (4H)
FP16 ADD / Multiply (MUL) / Multiply-Accumulate (MAC) / Multiply-and- Add (MAD)

ISSCC 2021 / SESSION 25 / DRAM / 25.4

25.4 A 20nm 6GB Function-In-Memory DRAM, Based on HBM2 with a 1.2TFLOPS Programmable Computing Unit Using Bank-Level Parallelism, for Machine Learning Applications

Young-Cheon Kwon[1], Suk Han Lee[1], Jaehoon Lee[1], Sang-Hyuk Kwon[1], Je Min Ryu[1], Jong-Pil Son[1], Seongil O[1], Hak-Soo Yu[1], Haesuk Lee[1], Soo Young Kim[1], Youngmin Cho[1], Jin Guk Kim[1], Jongyoon Choi[1], Hyun-Sung Shin[1], Jin Kim[1], BengSeng Phuah[1], HyoungMin Kim[1], Myeong Jun Song[1], Ahn Choi[1], Daeho Kim[1], SooYoung Kim[1], Eun-Bong Kim[1], David Wang[2], Shinhaeng Kang[1], Yuhwan Ro[3], Seungwoo Seo[3], JoonHo Song[3], Jaeyoun Youn[1], Kyomin Sohn[1], Nam Sung Kim[1]

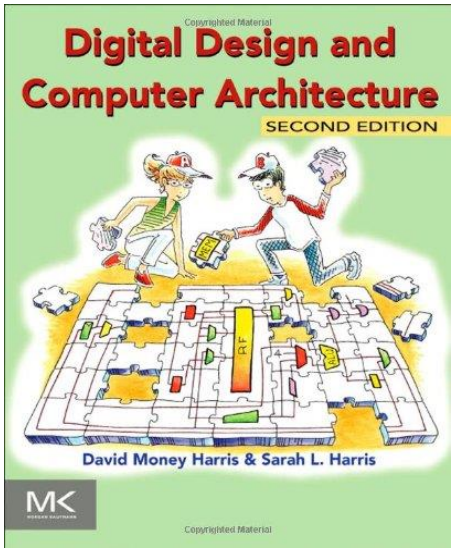
[1]Samsung Electronics, Hwaseong, Korea
[2]Samsung Electronics, San Jose, CA
[3]Samsung Electronics, Suwon, Korea

Basic Building Blocks

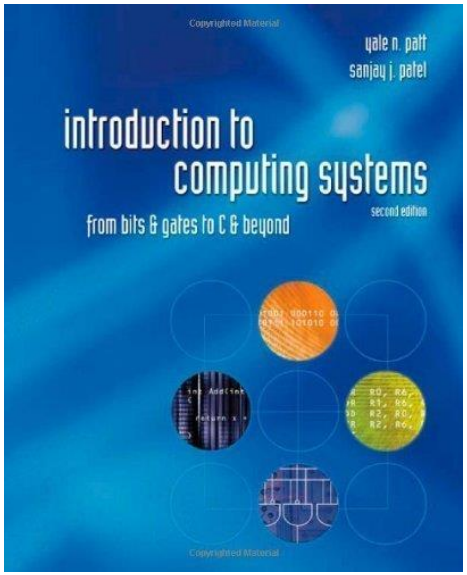
- Electrons
- Transistors
- Logic Gates
- Combinational Logic Circuits
- Sequential Logic Circuits
  - Storage Elements and Memory
- …
- Cores
- Caches
- Interconnect
- Memories
- …

Reading Assignments for This Week

- Chapter 1 in Harris & Harris



- Chapters 1-2 in Patt and Patel



- Supplementary Lecture Slides on Binary Numbers

Major High-Level Goals of This Course

- In Digital Circuits & Computer Architecture

- Understand the basics
- Understand the principles (of design)
- Understand the precedents

- Based on such understanding:
  - learn how a modern computer works underneath
  - evaluate tradeoffs of different designs and ideas
  - implement a principled design (a simple microprocessor)
  - learn to systematically debug increasingly complex systems
  - Hopefully enable you to develop novel, out-of-the-box designs

- The focus is on basics, principles, precedents, and how to use them to create/implement good designs

Why These Goals?

- Because you are here for a Computer Science degree

- Regardless of your future direction, learning the principles of digital design & computer architecture will be useful to
  - design better hardware
  - design better software
  - design better systems
  - make better tradeoffs in design
  - understand why computers behave the way they do
  - solve problems better
  - think "in parallel"
  - think critically
  - …

Course Info and Logistics

Course Info: Instructor

- Onur Mutlu
  - Full Professor @ ETH Zurich ITET (INFK), since September 2015
  - Strecker Professor @ Carnegie Mellon University ECE/CS, 2009-2016, 2016-…
  - PhD from UT-Austin, worked at Google, VMware, Microsoft Research, Intel, AMD
  - https://people.inf.ethz.ch/omutlu/
  - omutlu@gmail.com (Best way to reach me)
  - https://people.inf.ethz.ch/omutlu/projects.htm
- Research and Teaching in:
  - Computer architecture, computer systems, hardware security, bioinformatics
  - Memory and storage systems
  - Hardware security, safety, predictability
  - Fault tolerance, robust systems
  - Hardware/software cooperation
  - Architectures for bioinformatics, health, medicine, intelligent decision making
  - …

Course Info: Lecturer & PhD Assistants

- Head Assistant
  - Dr. Juan Gómez Luna
- Vice-Head Assistant
  - Hasan Hassan
- Lecturer
  - Dr. Frank Gurkaynak
- (Other) Key Assistants and Guest Lecturers
  - Dr. Jisung Park
  - Dr. Mohammed Alser
  - Dr. Lois Orosa
  - Minesh Patel

Course Info: PhD Assistants

- (Other) Key Assistants and Guest Lecturers (cont.)
  - Dr. Jawad Haj-Yahya
  - Dr. Haiyu Mao
  - Dr. Behzad Salami
  - Jeremie Kim
  - Giray Yaglikci
  - Can Firtina
  - Geraldo De Oliveira Junior
  - Rahul Bera
  - Konstantinos Kanellopoulos
  - Nika Mansouri Ghiasi
  - Gagandeep Singh

Course Info: Student Assistants

- Roknoddin Azizibarzoki
- Anaïs Berkes
- François Costa
- Haocong Luo
- Lukas Gygi
- Lara Lazier
- Chris Mnuk
- Daniel Nezamabadi
- Bernard Pranjic
- Nina Richter
- João Dinis Sanches Ferreira
- Diego de los Santos
- Roberto Starc
- Kosta Stojiljkovic

Course Info: Lab Assistants (I)

- Tuesday 16-18
  - TBD
- Wednesday 16-18
  - TBD

Course Info: Lab Assistants (II)

- Friday 8-10
  - TBD
- Friday 10-12
  - TBD

If You Need Help

- Post your question on Piazza Q&A Forum
  - https://piazza.com/class/klgb5v5se8d4y7
  - **Preferred** for **technical** questions
- Write an e-mail to:
  - digitaltechnik@lists.inf.ethz.ch
  - The instructor and all assistants will receive this e-mail
- Come to office hours
  - We will provide Zoom links
  - TBD

Where to Get Up-to-date Course Info?

- Website:
  - https://safari.ethz.ch/digitaltechnik/
  - Lecture slides and videos
  - Readings
  - Lab information
  - Course schedule, handouts, FAQs
  - Software
  - Plus other useful information for the course
  - Check frequently for announcements and due dates
  - This is your single point of access to all resources
- Your ETH Email
- Lecturers and Teaching Assistants

Lecture and Lab Times and Policies

- Lectures:
  - Thursday and Fridays, 14:00-16:00
  - YouTube livestream playlist: https://www.youtube.com/watch?v=LbC0EZY8yw4&list=PL5Q2soXY2Zi_uej3aY39YB5pfW4SJ7LlN
  - Zoom link provided via Moodle
  - Attendance is for your benefit and is therefore important
  - Some days, we may have guest lectures and exercise sessions
- Lab sessions:
  - See online
  - You should definitely attend the lab sessions
    - In-class evaluation (70%) and mandatory lab reports (30%)
  - Labs will start on March 9th
  - Lab information and handouts are here:
    - https://safari.ethz.ch/digitaltechnik/spring2021/doku.php?id=labs

Lab Organization

- Groups
  - Choose your preferred group in Moodle
    - https://moodle-app2.let.ethz.ch/mod/choicegroup/view.php?id=563589
    - Due 03.03.2021 at 11:59pm
  - Choose your partner
    - https://moodle-app2.let.ethz.ch/mod/feedback/view.php?id=563590
    - Due 03.03.2021 at 11:59pm

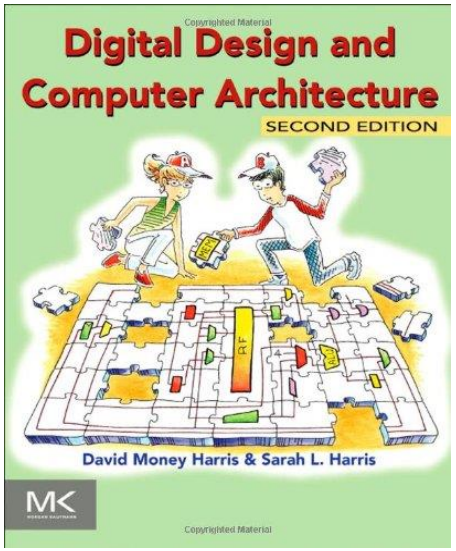
- Lab grades from previous years
  - https://moodle-app2.let.ethz.ch/mod/choice/view.php?id=563167
  - Choose among (due 26.02.2021 at 11:59pm):
    - 1) I will use my lab grades from previous years, and I won't do the labs this year
    - 2) I will use my lab grades from previous years, but I will do the labs this year
    - 3) I won't use my lab grades from previous years. I will do the labs this year

Final Exam

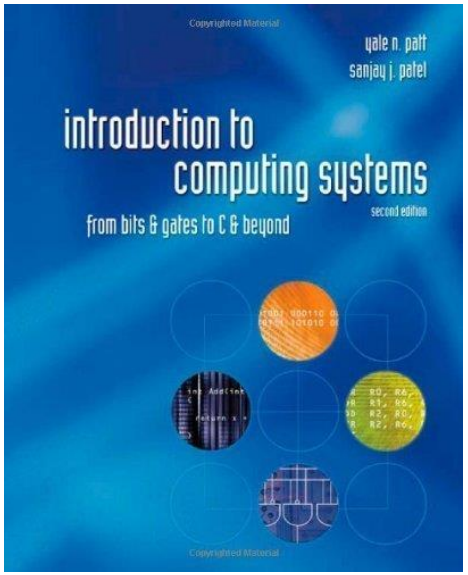
- 180-minute written exam
  - Find examination rules in Course Catalogue
    - http://www.vvz.ethz.ch/Vorlesungsverzeichnis/lerneinheit.view?semkez=2021S&ansicht=LEISTUNGSKONTROLLE&lerneinheitId=151053&lang=en
  - Also in the first page of previous exams
    - https://safari.ethz.ch/digitaltechnik/spring2021/doku.php?id=exams
  - Some exam questions are similar to questions in Optional HWs and Past Exams
    - Optional HWs are optional, but highly recommended
    - Solving past exams could also be useful

Reading Assignments for This Week

- Chapter 1 in Harris & Harris



- Chapters 1-2 in Patt and Patel



- Supplementary Lecture Slides on Binary Numbers

Reading Assignments for Next Week

- Combinational Logic chapters from both books
  - Patt and Patel, Chapter 3
  - Harris and Harris, Chapter 2

- Check course website for all future readings
  - Required
  - Recommended
  - Mentioned

Future Lectures and Assignments

- You can also anticipate (and study) future lectures and assignments based on Spring 2020 schedule:
  - https://safari.ethz.ch/digitaltechnik/spring2020/doku.php?id=schedule
  - https://www.youtube.com/watch?list=PL5Q2soXY2Zi_FRrloMa2fUYWPGiZUBQo2&v=AJBmIaUneB0&feature=emb_logo

- An example of "Last Time Prediction"
  - Speculative Execution
    - The concept of doing something before knowing it is needed
  - A key concept we will cover in the design of microprocessors

Digital Design & Computer Arch.

Lecture 2a: Tradeoffs, Metrics, Mindset

Prof. Onur Mutlu

ETH Zürich

Spring 2021

26 February 2021