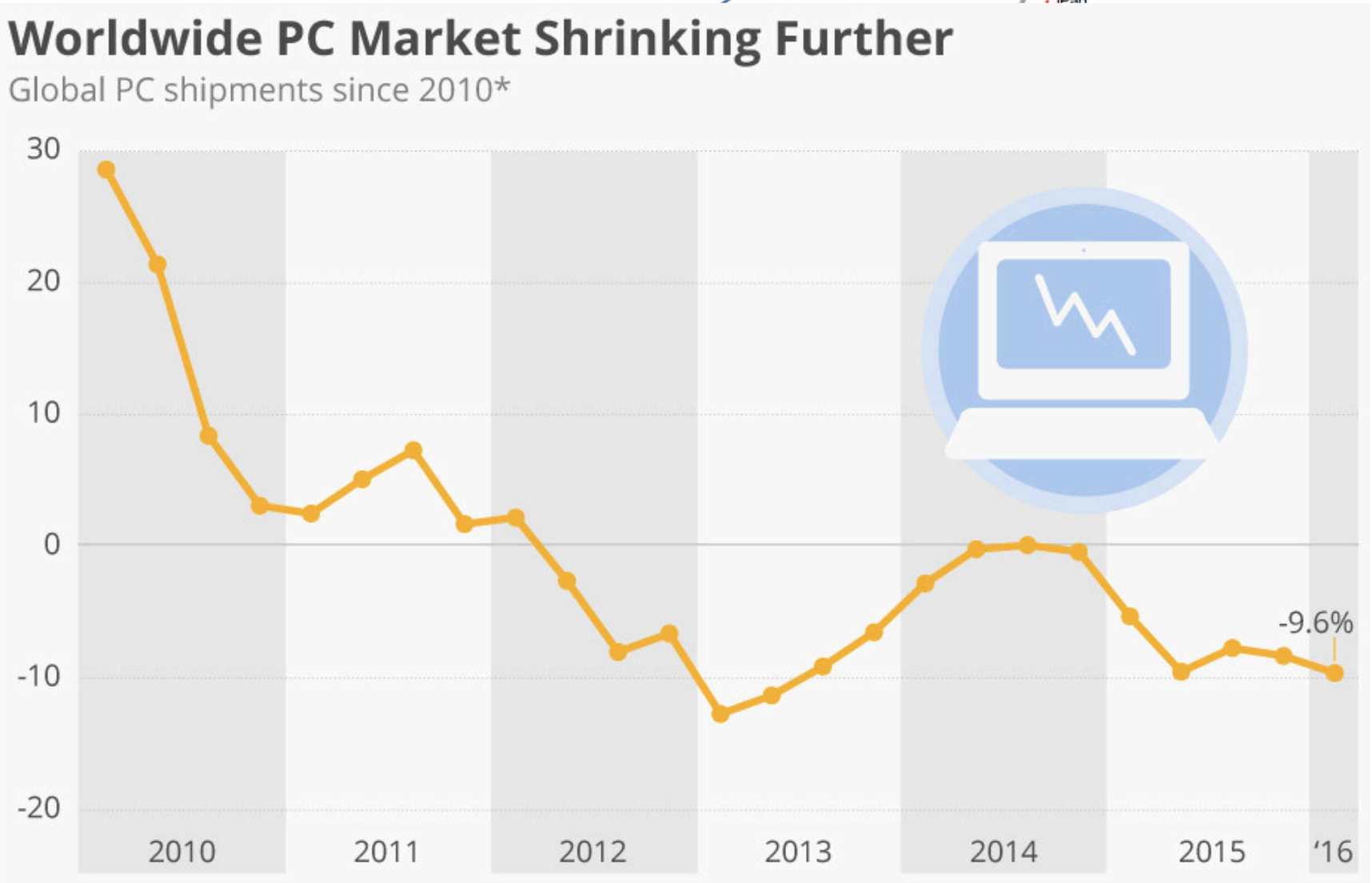
So What's Next?

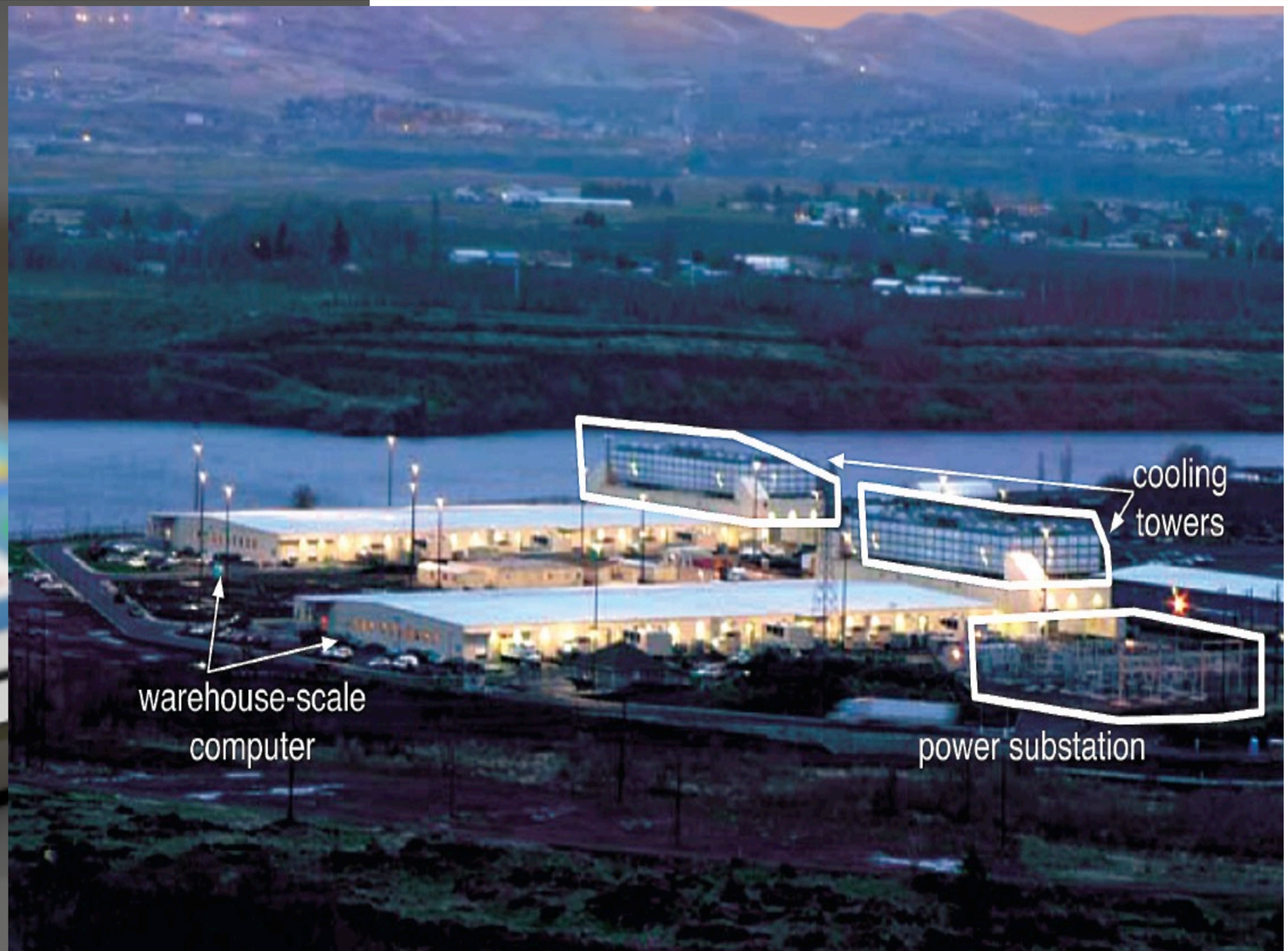
Where Do We Go From Here?

- A Review of the Class
- A Map of the Future
- Future Classes at Berkeley

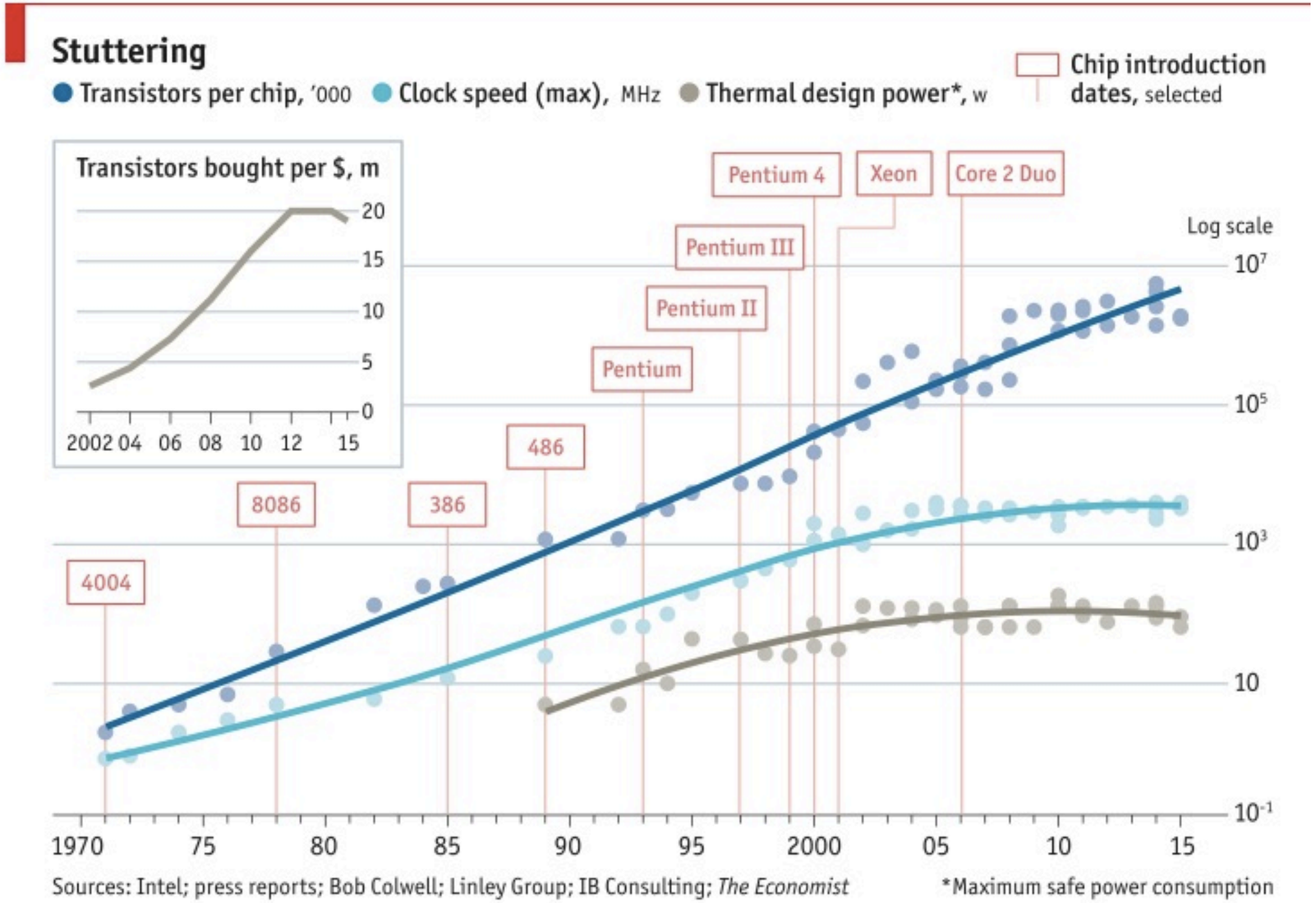

Units Shipped Per Year
1000000
100000
© asymco.com
PC
Android
iPhone
iPad


Worldwide PC Market Shrinking Further
Global PC shipments since 2010*
30
20
10
0
-10
-20
-9.6%
2010
2011
2012
2013
2014
2015
'16

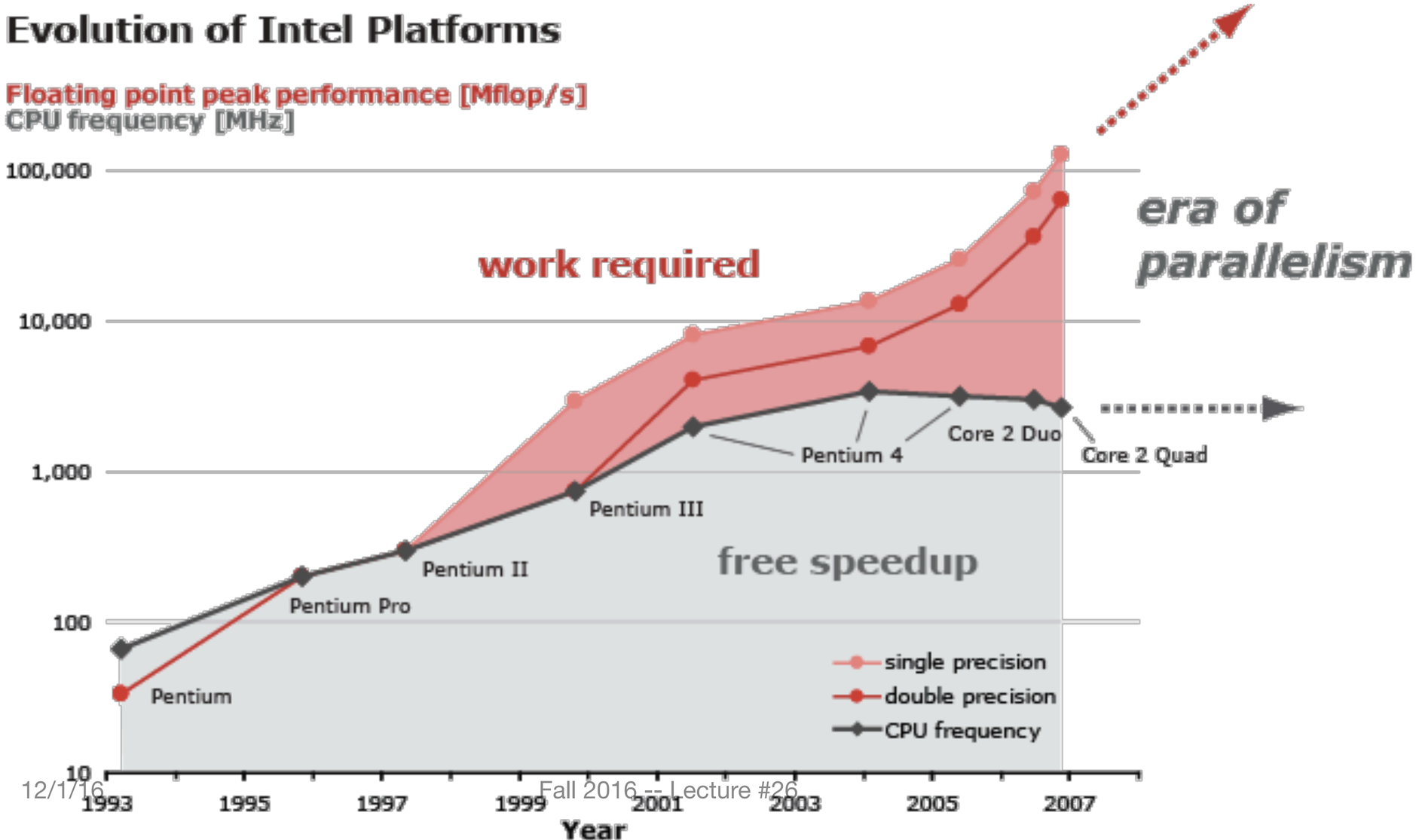
Current 61C:
The Same Concepts Over a Mass Scale



All Have Hit the Single-Thread Brick Wall



Leaving Parallelism the ***only*** way to improve throughput



Well, with an * of course...

- "If you put enough rockets on it, a pig will fly...
  And Intel has strapped that pig to a Saturn V"
  - Truly heroic efforts have gone into performance for an ISA that, even in 64b mode, is crippled by legacy as there are only a few general registers and a lot of complex operations
- The big deals:
  - Translate x86 to a RISC-like internal representation (micro-OPs)
    - Adds a couple of pipeline stages
  - Heroically out-of-order, superscalar, and register renaming
    - ~150 actual registers although x86 has remarkably few general purpose integer registers
  - Heroic efforts at branch prediction
    - But really hit diminishing returns:
      A mispredicted branch ***kills*** performance and you can only predict so well

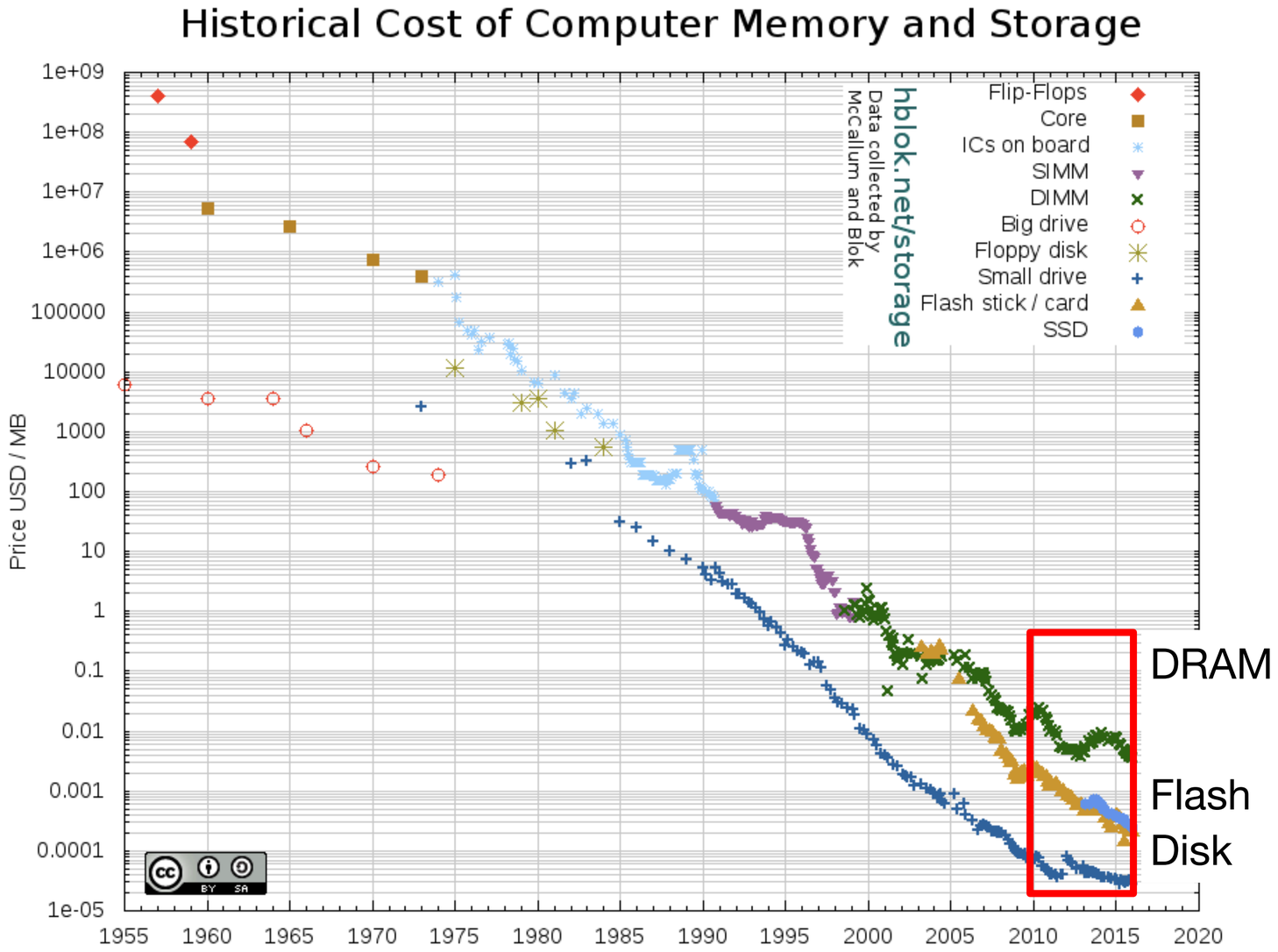
Apple is far less wedded to ISA...
And Has More Money Than God...

- So the Apple M1: A ***high performance*** Arm v8.5
  - 64b Arm mostly competed in the power space:
    Having 2-3 less pipeline stages needed for translation saves a lot...
    and phones were never wedded to x86
    - Arm isn't quite a RISC: its only semi-RISC as there are a lot of instructions even just restricted to 64b...
      - Example of the not-really-RISC nature:
        FJCVTZS: Floating-point Javascript Convert to Signed fixed-point, rounding toward Zero
    - But it ***does*** have a RISC-sized register file: 32 registers.
- So the M1 says...
  - Hey, lets strap Arm to the ***same Saturn-V rocket***!
    - Yes, its horribly expensive development costs, but we have billions of $ in cash doing nothing, so we might as well
    - And we were already getting close on our latest phones!
      Our limit was power consumption...

Results are stunningly good

- It isn't just process
  - Intel is still mostly at a 14nm process, although latest at "Intel 7"
  - AMD uses TSMC's 7nm process
  - M1 is TSMC's 5nm process
- It isn't just implementation architecture
  - 4 high performance cores use all the tricks x86 does, 4 low power cores
- It probably comes down to an observation:
  All the renaming in the world can't make up for not having enough registers for the compiler
- Of course, this is a ***one time*** boost in sequential performance
  - It is ***not repeatable*** so hey...

And Other Things Are Still Getting Cheaper & Better (until the Crypto-Bros strike...)



New-School Machine Structures

Software *Hardware*

- Parallel Requests
  Assigned to computer
  e.g., Search “@ncweaver”
- Parallel Threads
  Assigned to core
  e.g., Lookup, Ads
- Parallel Instructions
  >1 instruction @ one time
  e.g., 5 pipelined instructions
- Parallel Data
  >1 data item @ one time
  e.g., Add of 4 pairs of words
- Hardware descriptions
  All gates functioning in parallel at same time
- Programming Languages

Leverage Parallelism & Achieve High Performance

Six Great Ideas in Computer Architecture

- Design for Moore's Law:
  - Multicore & Thread-Level Parallelism (Multicore, Parallelism, OpenMP, Project #4)
- Abstraction to Simplify Design
  - And when in doubt, add another layer of abstraction
- Make the Common Case Fast
  - The design philosophy behind RISC
- Dependability via Redundancy
  - ECC, RAID, and clusters of systems
- Memory Hierarchy
  - Caches, Caches, and More Caches…
- Performance via Parallelism/Pipelining/Prediction

The Five Kinds of Parallelism

- Instruction Level Parallelism
  - Pipelining & 152/252 topics: Superscalar, out-of-order execution, branch prediction
- (Fine Grain) Data Level Parallelism:
  - SIMD instructions, graphics cards
- (Course Grain) Data/Task Level Parallelism:
  - Map/Reduce: Hadoop and Spark
  - Or Nick pegging the CPU on The Beast
- Thread Level Parallelism:
  - Multicore systems, OpenMP, Go
- Request Level Parallelism
  - Google & warehouse scale computers

Nick's First Computer: 1980, Apple][+

- MOS 6502 processor:
  - 8b processor with a 16b address bus
- 16kB of RAM
  - Extended it to 32kB with a memory card
- Floppy drive: 140kB disks
- 280x192, 6 color graphics in "Hi Resolution" Mode
- ~$4000 in today's money!
- Languages supported included BASIC and Logo
  - Logo is remarkably subtle and cool, its remarkably similar to scheme under the hood

Nick's Freshman Year Computer: 1991

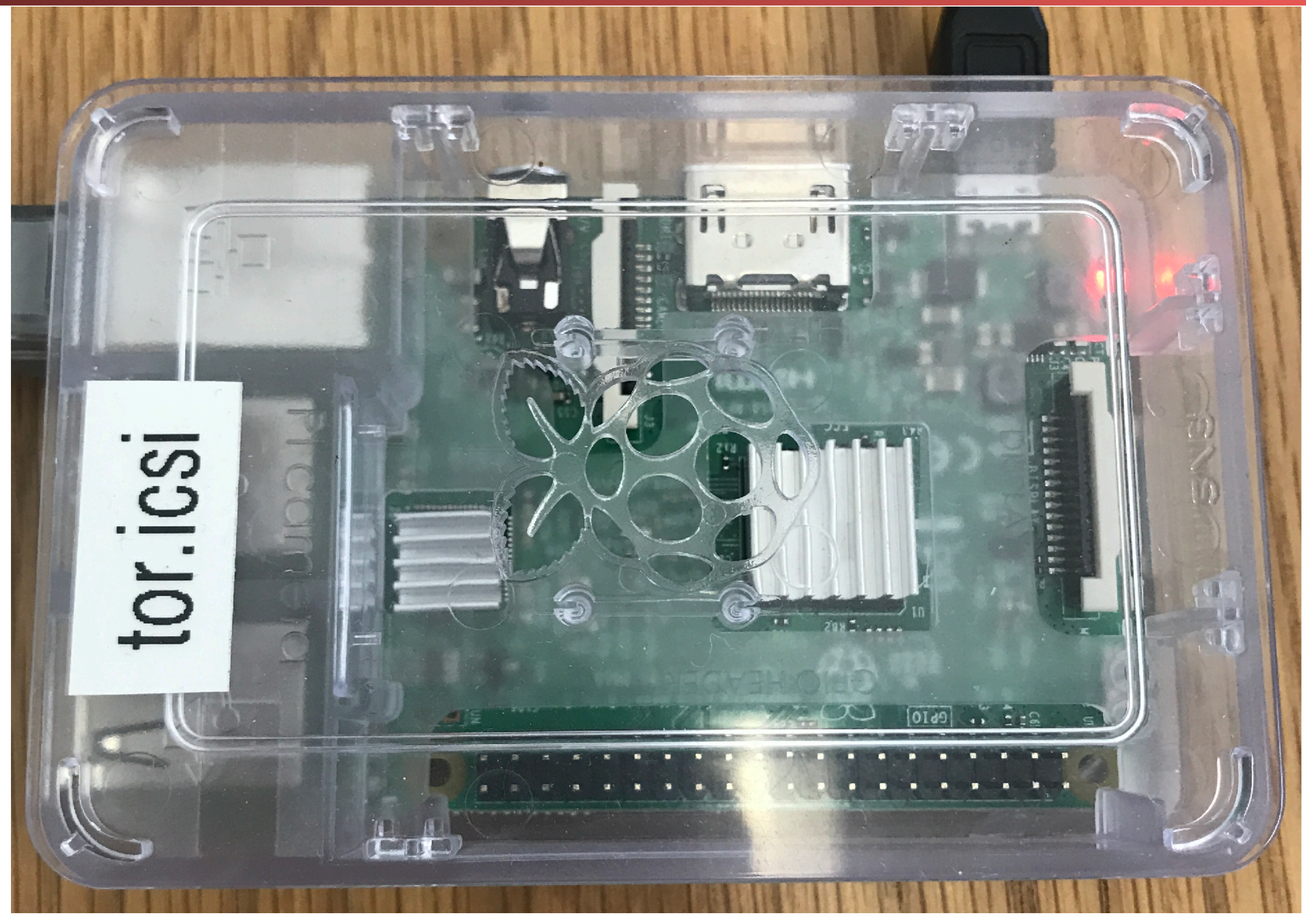
- 25MHz 68040, 32b CISC processor, 6 stage pipeline ***with floating point!***
  - Whopping 4kB I$ and 4kB D$
- 20 MB of memory
  - I expanded it from the original 8 MB, it cost me a ***fortune!***
- 1120x832 2-bit grayscale display
  - But I'd rather have a sharp grayscale display than an ugly color display at the time
- ~100 MB hard drive, 2.88MB floppy drive
  - About $9k in today's dollars...
    Other kids got cars for HS graduation, I got a computer

But That Was Sufficient For 60B…

- The predecessor to current 61C
  - Added more learning of C
  - Didn’t include parallel programming, data-center stuff, RAID, etc…
- But otherwise, the contents looked rather familiar
  - Basically include caches, I/O, virtual memory, assembly (MIPS not RISC-V but well, same diff), C
    - "All RISCs are the same except for one or two 'seemed like a good idea at the time' decisions"
      - RISC-V is just so new we don't know what those are (apart from not building in PAC from the start)
      - MIPS has a software-managed TLB (more and more expensive page faults) and a "branch delay slot"
  - But with a bit more handholding on learning C and assembly because it was the second semester class

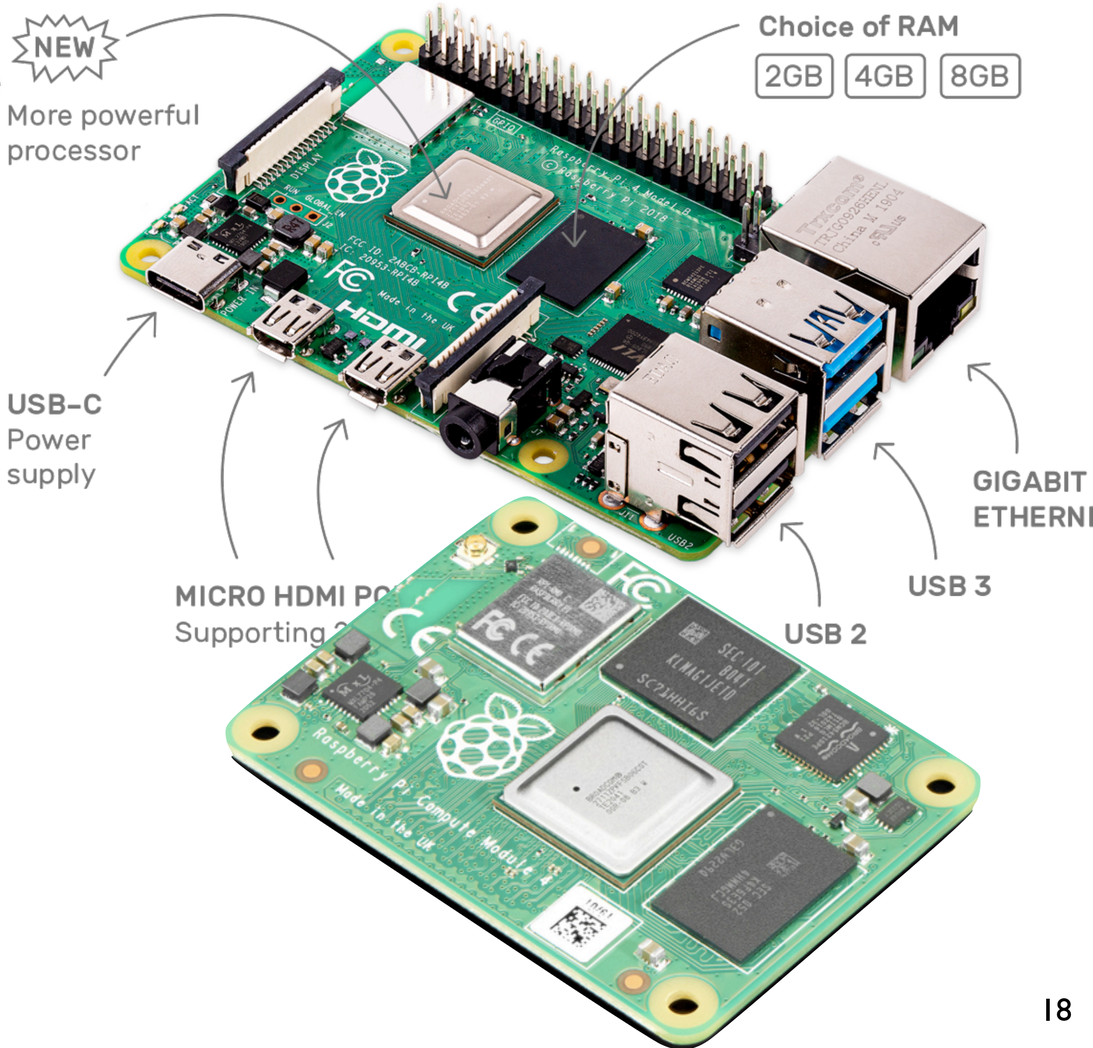
One of Nick's Research Computers…

- Yeup, an RPi3
  - ~50x single-thread performance
  - ~200x multi-threaded performance
  - 50x the RAM
- Only difference from what you might have:
  - I stuck in a 128GB SDCARD: 1000x the storage!



And now I'm loving the RPi 4...

- Take the RPi3 and turn it up to 11+
  - ~2x the single threaded & multithreaded performance
  - More RAM options: up to 8 GB RAM
  - Faster I/O with 2x USB3 ports,
    Gigabit Ethernet
- And the compute module...
  - Remove the physical connectors:
    Instead provide 2x 100 pin connectors on the other side
  - Get the raw PCIe x1 rather than USB3
  - And put it on a card to stick in larger systems
  - $50 for a version with 2GB RAM, 16 GB storage, and WiFi/Bluetooth



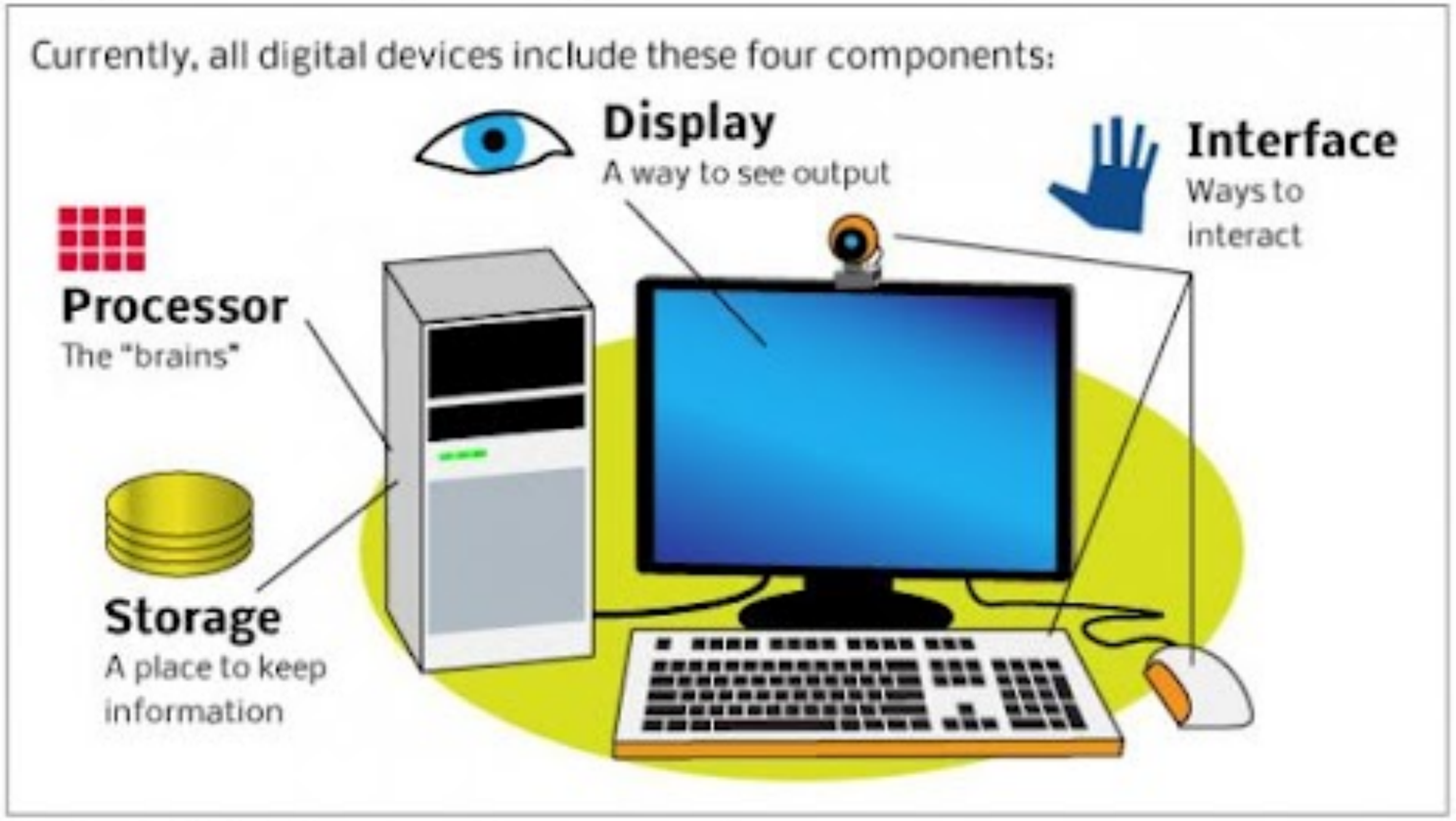
And Nick's Beast!!!

- 12 core Ryzen-9 processor
  - 3.8 GHz, 2 threads/core
  - 32KiB I$, 32KiB D$, 512KiB L2$/core
  - 64 MB shared L3 cache
  - 32 GB RAM, 1 TB SSD
  - 10 TFLOP single precision GPU
  - Driving a 3840 x 2160 pixel, 43" 'monitor'
- A close to spare-no-expense desktop...
  - And ***still*** costs significantly less than my Apple][+ I had as a kid!

TechNewsDaily www.technewsdaily.com

Your Computer is Going Away

Soon, your smartphone, TiVo, laptop, television -- all of your current gadgets -- will be obsolete. The future is "ubiquitous computing." Think Google Docs, but on every screen you use, running every program you use -- every device drawing from the same pool of data and processing power. Here's how we got to this point.



2010 In the emerging **ubiquitous computing era**, every device accesses all its data and processing power from the Internet **"cloud."** This means the devices themselves need not have any on-board processing or data storage, reducing their price and increasing their deployment. Additionally, the interface will move beyond the mouse and keyboard into task specific form-factors. Computers will be everywhere, but you won't even notice them.

But A Dissent From The Cloudy Future…

- The “Cloud” is really just a name for someone else’s computer…
- And you are therefore trusting them to do right by your data…
- It could be because you pay them
  - Amazon EC2
- It could be because you bought “ohh shiny”
  - Apple
- It could be because they are ~~selling your soul~~ using your data for their own profit
  - Google
- And its not like the "cloud" is cheaper! The computer in your hand is obscene by the standards of a decade ago
  - And wireless communication is ***not getting better!***
    4G is already at the "Shannon's Limit" for all practical purposes

Shannon's Limit & Wireless Networks...

- Don't believe the 5G hype...
  - So compute at the wireless edge, not in the cloud, if you need to communicate a lot of data for the computation
- There are physical limits to how much information you can transmit given frequency, power, etc...
  - The "Shannon's Limit": 4G is already at the Shannon's Limit
- So the only way for more bandwidth...
  - Better antennas at the towers (but that works for 4G as well)
  - More frequencies... (That get blocked by the rain!)
  - More smaller towers (but that works for 4G as well)
- Also why Starlink won't eat the world...
  - Think of it as a cell tower serving a huge area.
    Great in rural areas but even for a small town it is better to string a wire

Nick's Happy Prediction: The Fabrication Revolution…

- We've seen incredibly powerful and cheap compute modules with built-in networking
  - RPi 4: $35-75
  - RPi CM4: $30-95 depending on capacity
    - 1, 2, 4, 8 GB RAM
    - 0, 8, 16, 32 GB Solid state storage
    - WiFi/Bluetooth optional
  - Raspberry Pi Zero 2 W: $15, 1 GHz quad core 64b CPU, 512 MB RAM, Mini HDMI, WiFi/Bluetooth, I/O, SD-card slot & camera interface
- Amdahl's Law applies to cost optimization…
  - If you have a $15 RPi Zero 2 W + SD Card to drive your product…
    - Oh, which runs on 5V and is even kind and gives you a 3.3V/1A power output
  - The rest of the cost has to be pretty damn low before its worth replacing with something cheaper
- So the compute & communication to make a device is effectively ***free***:
  - When in doubt, you can ***throw a computer at the problem***

But It's Not Just The Compute & Control…

- 3D printers, laser cutters, C&C Machines all make prototyping stuff cheap
  - And direct paths to go from 1 to 10 to 1000 to 100,000 thingies
- And logistics
  - Time from manufacturer to me doesn't actually care where I am in the US:
    I could run a design business from a shack in the woods
  - And the pandemic has turned a lot of business trips into "couldn't this just be a Zoom call?"
- And direct to consumer marketing

FedEx®

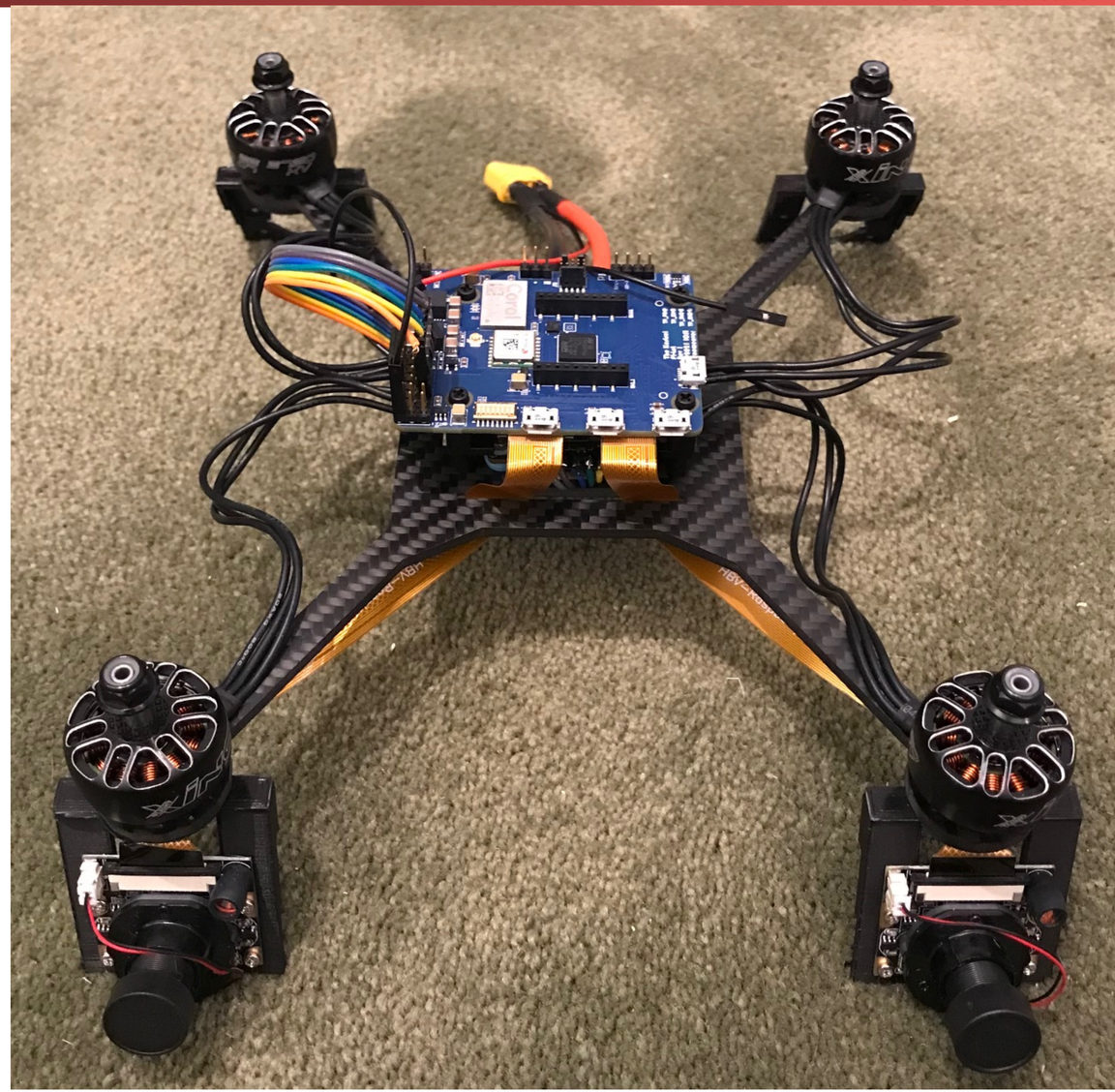
KICKSTARTER

You Can Even Do Custom ***Compute Platforms***...

- Nick's drone control board: Cost: ~$4000 for the first 5
  - Should be <$100/each for 500 fully assembled, tested, & delivered...
    Once the electronic supply chain un-fsks itself.
- Specifications:
  - ST H7 embedded CPU for flight control duties and to drive 8 PWM/servo outputs
    - Keeping a quad-copter drone in the air is a hard realtime problem:
      Standard OSs are great unless you need a <10ms update loop
  - GPS, accelerometer, compass, barometer
  - Backside slot for CM4
    - 2 1080p camera inputs
  - Coral AI accelerator
  - Frontside slot for cellphone/modem
  - Power distribution accepting unregulated 7-36V input:
    provides both 5V/4A and 3.3V/4A
- This is incredibly powerful
  - For slightly more than "hobby" money!
    Certainly pocket lint for a trivially funded startup

And More...

- I'm leaving Berkeley to become Chief Mad Scientist (+CEO, +Janitor) at Skerry Technologies
  - Focused on developing very cheap, fully autonomous vision-based drones for multiple applications
- Camera mounts?
  - Designed myself, 3D printer next to my desk
- Cameras?
  - Raspberry Pi 2-pack cameras from Amazon
- Frame?
  - Designed myself and prototyped with 3D printer
  - Outsourced fabrication for $40!
- Drone motors & speed controller?
  - Purchased and mail-ordered
  - 3D printed a custom jig to assemble/solder connections



Getting This To Work:
61C will be needed all throughout the stack!

- Dedicated coprocessor to run the autopilot itself
  - Why? 10 ms control loop is fundamentally incompatible with a normal OS's timer interrupt model
- Board design itself
  - Schematics like project 3!
- And the vision software I'll have to write...
  - The problem: Stereo vision & optical flow for 3D scene reconstruction...
  - Students using OpenCV could get ~8 FPS at ~480p B/W resolution
- But I want 30 FPS in color at 1080p resolution! How do I hope to get this?

Making the Optical Flow flow...

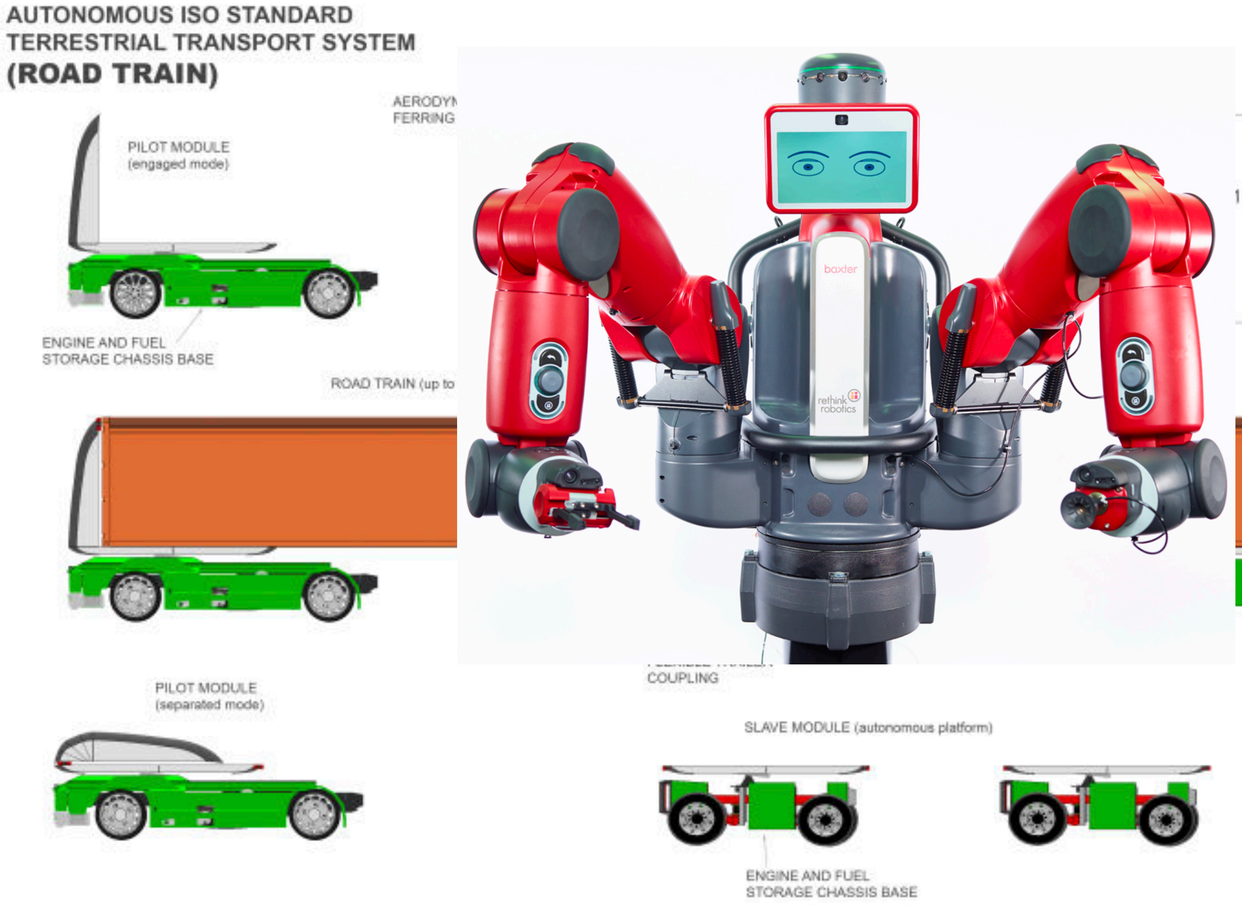
- For each camera:
  - Adjust the color
  - De-distort the image
  - Detect corners and edges
- Combine multiple frames:
  - Use detected corners/edges and basic trigonometry to estimate distance
- How to do this ***fast?***
  - Option 1: Use a GPU
    - Which I can't afford: A GPU SOM is bigger and way more expensive
  - Option 2: Parallelism and cache aware software design

Both Parallelism and Pipelining

- The CM4's 4 cores have small*ish* caches
  - 32 kB, 2-way set associative data cache, 1 MB shared L2 cache
  - A single raw 1080p image: 1920 x 1080 = 2M pixels
- Coarse grained parallelism:
  - Each camera handled by a different core
  - Do optical flow on one core, stereo on another
- Fine grained parallelism:
  - ARM has some SIMD intrinsics
  - Use a small amount of loop unrolling
- Scan-Line Prefetch & Pipeline For Stereo Vision
  - On scan-line X: De-distort and color correct with prefetching
  - On scan-line X-2: Corner/Edge detection
  - On scan-line X-4: Stereo computation with prefetching
    - Because another core has the other image
  - Result ***should*** be that everything hits in L1!

Nick's Gloomy Prediction: Automation and Its Discontents…

- We are getting damn close to the autonomous long-haul truck
  - If it costs $100K to automate a semi-truck it will pay for itself in <2 years!
- And a lot of jobs with robots
  - EG, the $20k Baxter human-safe robot:
    One robot only needs to replace .2 humans to pay for itself in 2 years
    - This particular one failed because it was too early...
      But look at Boston Dynamics or Amazon's warehouse-worker bots
- Plus all the AI-related dislocation
  - Automate out the "paper pushing" jobs
- Scary Prediction:
  20 years from now we will have >20% unemployment
  - Yes, baseline unemployment 20 years out == COVID crisis today!



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And Now:
Your Future Classes...

- CS61C is a prerequisite to most/all "system" classes here at Berkeley
  - And some thoughts about them...

CS 161:
Computer Security

- CS161 is the only other ***full stack*** course after 61C
  - Security touches basically everything in computer science:
    So welcome to another speedrun class
- We covered some of the critical ***mechanisms*** needed for security
  - Paging/Virtual memory enforces ***isolation***:
    Prevents processes from interfering with each other
  - Attacks exploit the ***call frame***:
    Buffer overflow attacks not just crashing programs but overwriting the return address or other such information
- Security and hardware also have interesting interactions
  - One example: ***Rowhammer***

Should You Take CS161 First Or Last?

- If we switch to a 5-required class format, something like CS161 will have to be in it
  - Security and robustness is a pervasive problem
  - We've also scaled the class to handle hundreds of students a semester
- But this class is the one other speed-run class
  - EG, we lightly cover a good half of 168 in just two weeks!
- So if you liked the 61C speedrun, take 161 first
  - Especially if you like my teaching style, I'm teaching it next semester...
- But if you hated the speed run aspects of 61C, take 161 LAST!

CS 162:
Operating Systems

- Operating Systems is all about several big ideas:
  - Managing concurrency/multiprocessors
    - This enables parallelism
  - Isolation through Virtual Memory
  - I/O & Interrupts
- Builds very strongly on what you've already learned
  - Just far more advanced that what you've already done:
    Focuses on concurrency, virtual memory & isolation, filesystems, and I/O
  - Class successfully scaled so far...

A 162 Project: Caches in the Filesystem

- In 162 you improve the Pintos filesystem
- One of the big aspect is adding caching
  - The default system doesn't cache reads or writes, so this ***hurts***
- This touches on I/O (you're writing to disk) caching strategies (how you allocate blocks, write-back implementation, and other areas), etc
- 162 projects are a ***beast***
  - Large, group of 4 C programming projects
    - Use Project 4 as a test. Project 4, especially the non-speedup parts, is really 162 prep: If you liked project 4 you'll do fine on 162's projects. If you didn't, avoid 162
    - And ***only take the class if you already have a good group***!
  - But it is a ***good pain***: real feeling of satisfaction when you are done!

CS 164: Compilers...

- In 61C we introduced the CALL flow:
  Compiler
  Assembler
  Linker
  Loader
- We saw how to do the assembler/linker/loader
  - They are fairly simple
- We defined a calling convention
  - So how we can make sure functions can call each other on the assembly level
- 164 completes that flow...

164 Project: Building a compiler

- The compiler itself is broken up into pieces
  - Lexer: Converts text into ***tokens***
  - Parser: Determines the ***structure*** of the program
  - Semantic Analyzer: What does the program ***mean?***
  - Optimizer: Make the program ***better***
  - Code Generator: Output the assembly code (or C, depending, because C is portable assembly language anyway)
- The last part is very much a followup to 61C:
  Rather than writing assembly, you are writing the program that writes the assembly version of the program

CS 168: Networking

- How do we turn the network I/O into something usable
  - We have a unreliable, "best effort" system
  - Lets make something useful
  - And build on top of that...
- Also the foundation for the warehouse scale computer
  - The ability to tie together multiple systems into a cohesive whole
- Unfortunately rarely taught... But it is going to be offered next fall!

CS 169: Software Engineering

- How to build bigger systems
  - Once you get >4 people working on a project, things get complicated
  - This class is about addressing those problems
- Very project centric
  - Large team project for a real world system
- Projects can often be rather web centric:
  - Real web applications are distributed client/server beasts of complexity.
    So how do you tame that complexity?
- Probably the most immediately transferrable job-skill class
  - So much modern software development is in the client/server/database web space

CS 184: Graphics

- How do we go from some notion of geometry to bits on the screen...
  - And other related issues
- Lots of programming in C++
- Modern graphics is enabled by GPUs
  - Ability to do massive amounts of parallelism
  - Ability to efficiently use massive memory bandwidth by thread-switching

CS 186: Databases

- How to actually manage the data on theses systems?
- We've got amazing computers
  - Quad CPU, gazillion core beasts
  - A ton of memory
  - Huge amounts of disk
- How can we get the most out of them?
  - Databases are an incredibly powerful primitive
  - And built well, they need to understand the hardware they are running on

More on 186...

- Databases are ***insanely*** powerful tools...
  - I've only done one paper where I needed to use Hadoop for massive map/reduce parallelism
    - A billion+ records that needed significant computational analysis
  - I've done ***dozens*** of papers where "throw everything in the big A)(#@*)(# Postgres database" was step 1...
    - Our research group even custom ordered a beefy server we called ***mammoth***, just to process millions of records for a paper
- I've heard that it can be somewhat boring...
  - But ***damn*** it is useful. I wish I took it as an undergrad
  - "If my data is structured and anywhere between 1 MB and a few TB, its going into postgres. And if it is unstructured, there is always **`grep`**"

CS188 and CS189: AI & Machine Learning

- I personally like dunking on AI/Machine Learning at times...
  - Mostly because I don't understand how it works
    - But then again, nobody does!
  - But it really has become an incredibly powerful tool
- The new driver is not the algorithms, but the computers!
  - Many ML algorithms ***vectorize*** extremely well (for every element do X style parallelism):
    Acts as a classic SIMD parallel computation
  - The graphics cards now have an ***obscene*** amount of SIMD computation: ***trillions*** of operations per second
    - In the end, it is dense matrix multiply
      - As opposed to the classic supercomputer problems which are sparse matrix multiply

EECS 151:
Introduction to Digital Design & Integrated Circuits

- Just call it "Project 3 on Steroids!"
  - Building systems from the gates up
- Two versions of the lab
  - ASIC: Build a RISC-V processor core for fabrication as a custom chip... and only test it in simulation
  - FPGA: Build a RISC-V processor core, and have it ***run on a real FPGA!***
  - Choose to take one lab or both!
- Also instantly employable skills:
  - Apple is throwing a ton of $ around at good digital designers:
    If you want to work for Apple, take 151 with FPGAs and then the 151 lab-only for ASICs

CS 152: Computer Architecture

- And how modern CPUs actually work and are designed …
  - Want to understand how you can actually make 100-deep out of order reorder buffers on 14 stage pipelines with vector coprocessors?
  - Or how graphics cards are able to compute 100x more than a CPU?
  - This class is for you!