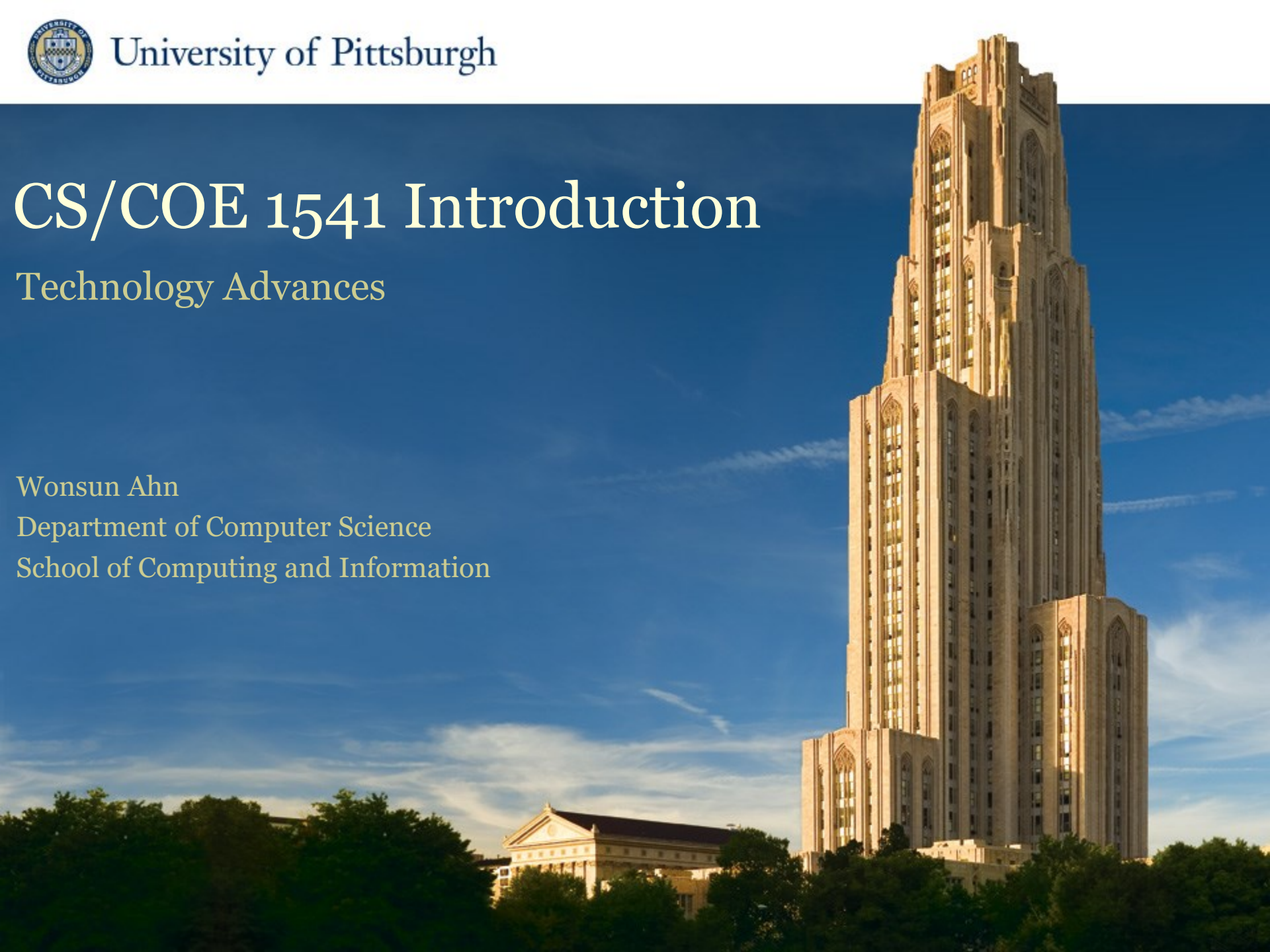

University of Pittsburgh

CS/COE 1541 Introduction

Technology Advances

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School of Computing and Information

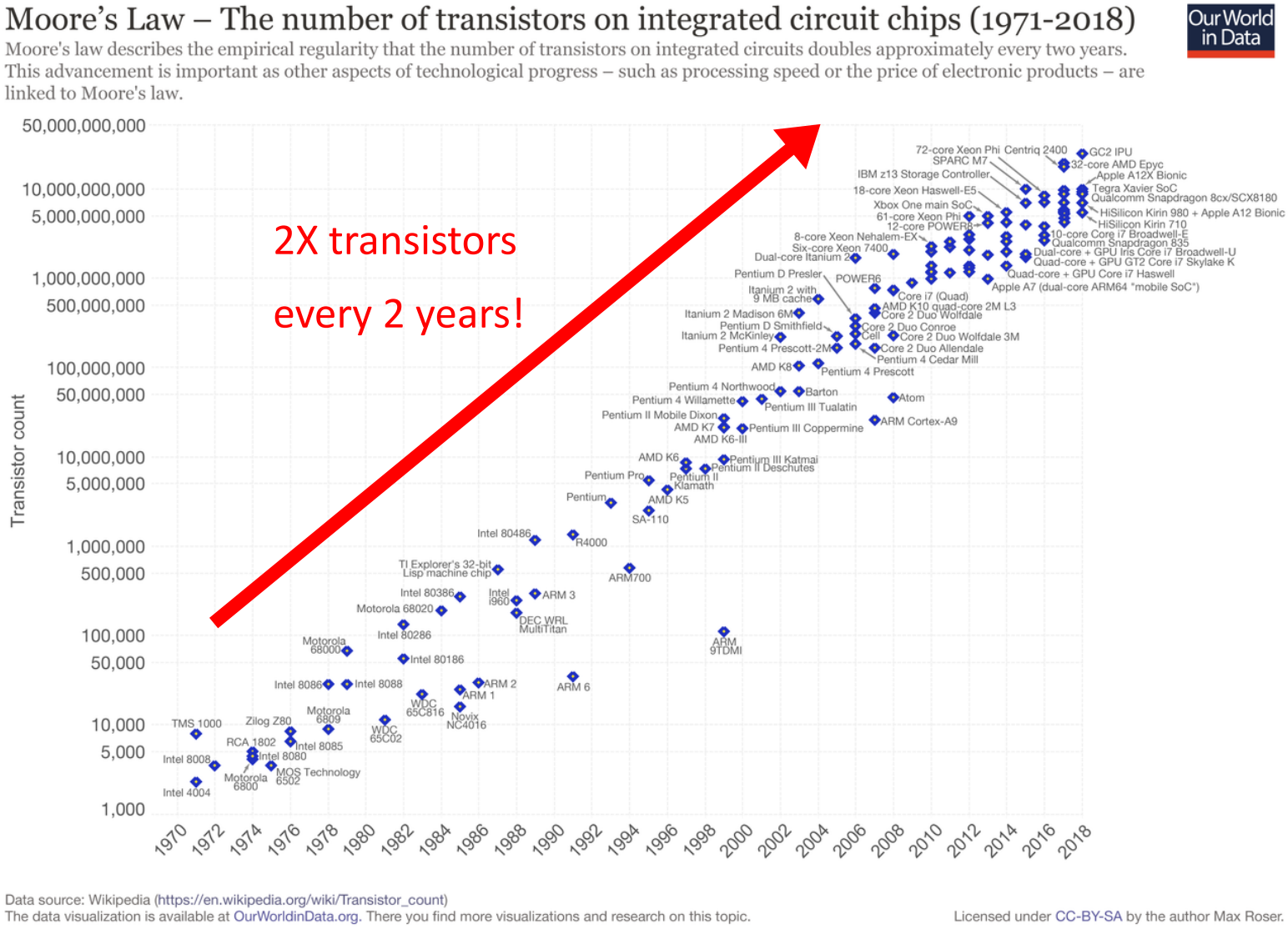
Technology Advances

Advances in Technology

- Technology has been advancing at lightning speed
- Architecture and IT as a whole were beneficiaries

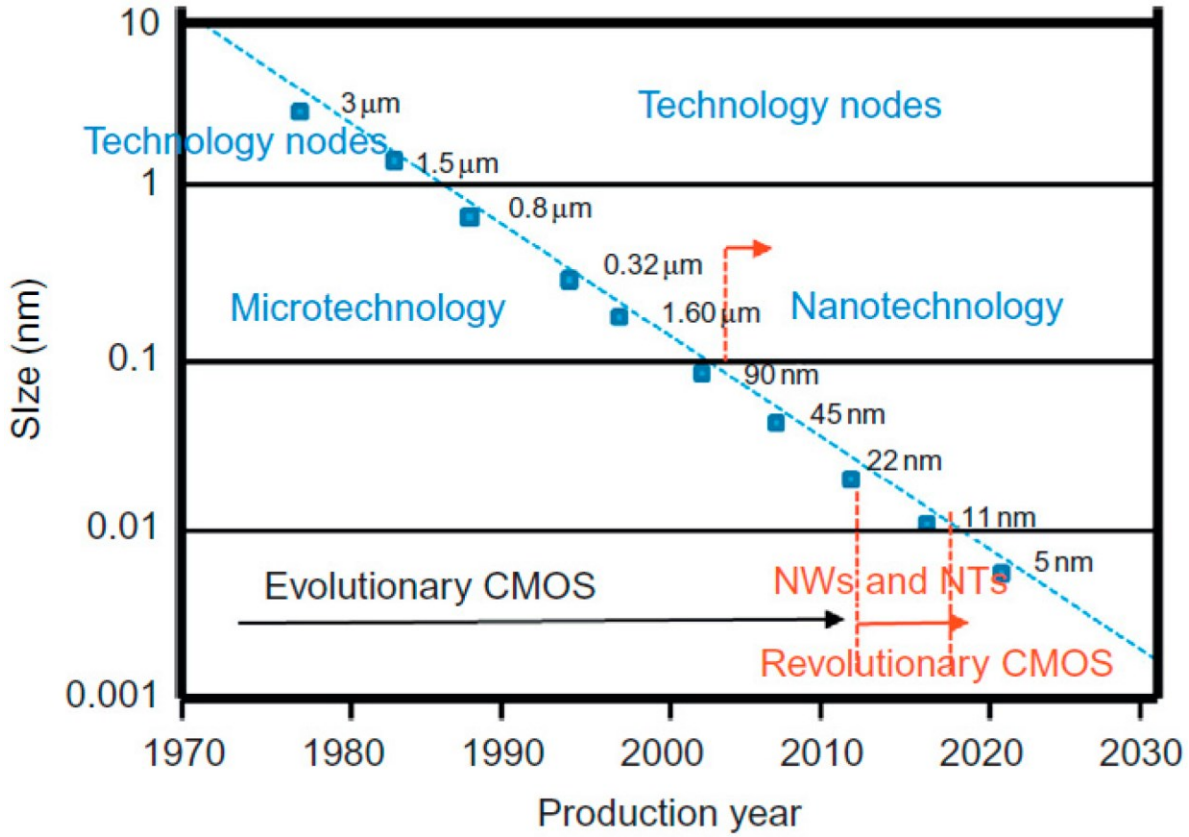
- Technology advance is summarized by *Moore's Law*
  - You probably heard of it at some point. Something about …
  - "X doubles every 18-24 months at constant cost"
- Is X:
  - CPU performance?
  - CPU clock frequency?
  - Transistors per CPU chip?
  - Area of CPU chip?

Moore's Law



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

Miniaturization of Transistors



Data source: Radamson, H.H.; He, X.; Zhang, Q.; Liu, J.; Cui, H.; Xiang, J.; Kong, Z.; Xiong, W.; Li, J.; Gao, J.; Yang, H.; Gu, S.; Zhao, X.; Du, Y.; Yu, J.; Wang, G. Miniaturization of CMOS. *Micromachines* **2019**, *10*, 293.

- Moore's Law has been driven by transistor miniaturization
  - CPU chip area hasn't changed much

Future of Moore's Law

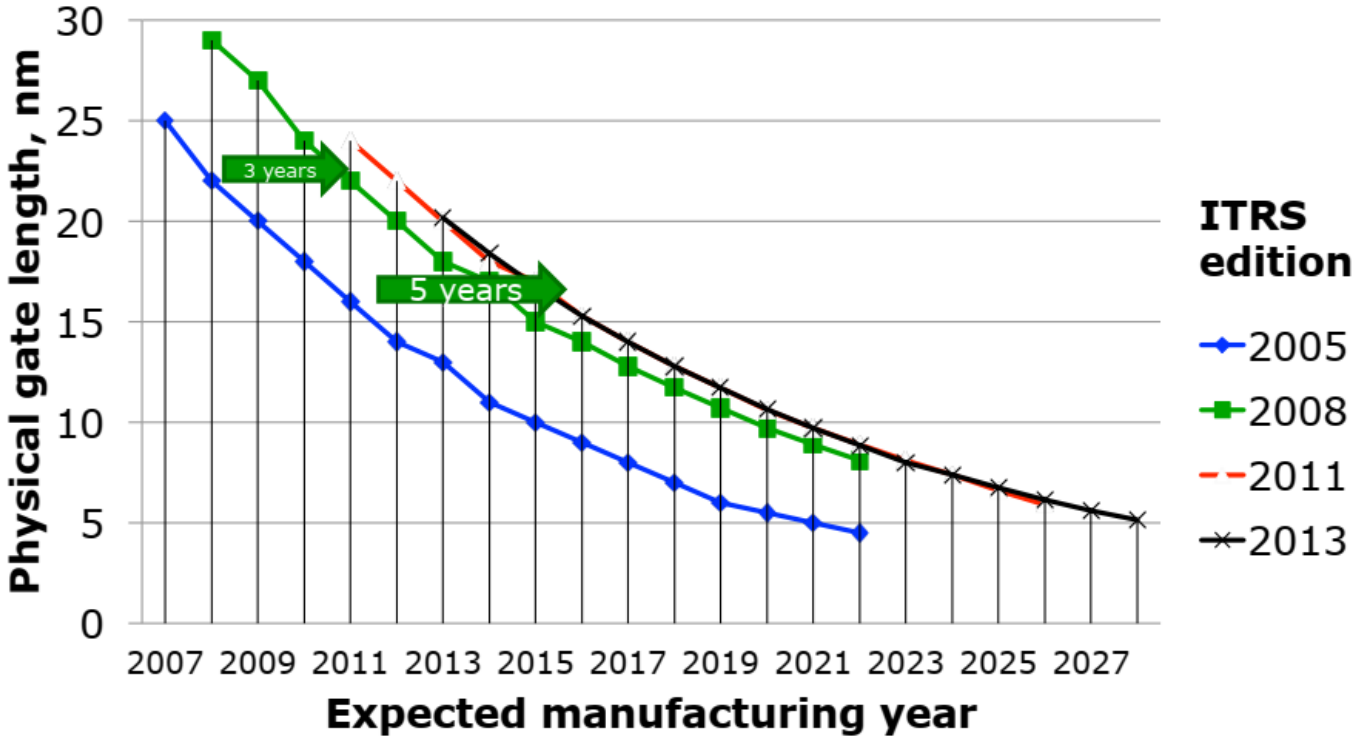
- The semiconductor industry has produced roadmaps
  - Semiconductor Industry Association (SIA): 1977~1997
  - International Technology Roadmap for Semiconductors (ITRS): 1998~2016
  - International Roadmap for Devices and Systems (IRDS): 2017~Present
- IRDS Lithography Projection (2020)

Year of Production	2018	2020	2022	2025	2028	2031	2034
Technology Node (nm)	7	5	3	2.1	1.5	1.0	0.7

  - Looks like Moore's Law will continue into foreseeable future
  - IRDS does not project significant increase in CPU chip size
  - Increases in transistors will come from *transistor density*

IRDS isn't Perfect

- ITRS (predecessor of IRDS) has made corrections before



  - After all, you are trying to predict the future
  - But architects rely on the roadmap to design future processors

Moore's Law and Performance

- Million-dollar question:
  Did Moore's Law result in higher performance CPUs?

- Please go to your respective Teams chat groups
  - But stay in the Zoom room and use only chat on Teams
  - To have chat content accessible to asynchronous students

1. Get to know each other
2. And then try to answer the following questions:
   - What do you think? Are CPUs getting faster?
   - If not, why do you think so? If yes, again why do you think so?
3. After 10 minutes, we will share discussions with class

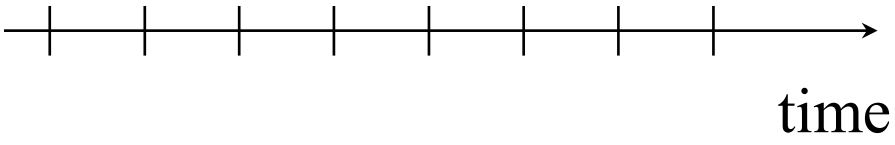
Are CPUs getting Faster?

- Yes!
- Clock speeds are increasing, power draw is decreasing – Andrew
- More cores – Jason
- Visual Studio compilation is actually faster - Nick

- No!
- Clock speeds are plateauing recently – Jason
- Seems stagnant from user's perspective e.g. Visual Studio - Josh

Components of Execution Time

- Processor activity happens on clock “ticks” or cycles



  - On each tick, bits flow through logic gates and are latched

- Execution time = $\frac{\text{seconds}}{\text{program}}$

$$\frac{\text{seconds}}{\text{program}} = \frac{\text{cycles}}{\text{program}} \times \frac{\text{seconds}}{\text{cycle}}$$

$$= \frac{\text{instructions}}{\text{program}} \times \frac{\text{cycles}}{\text{instructions}} \times \frac{\text{seconds}}{\text{cycle}}$$

Improving Execution Time

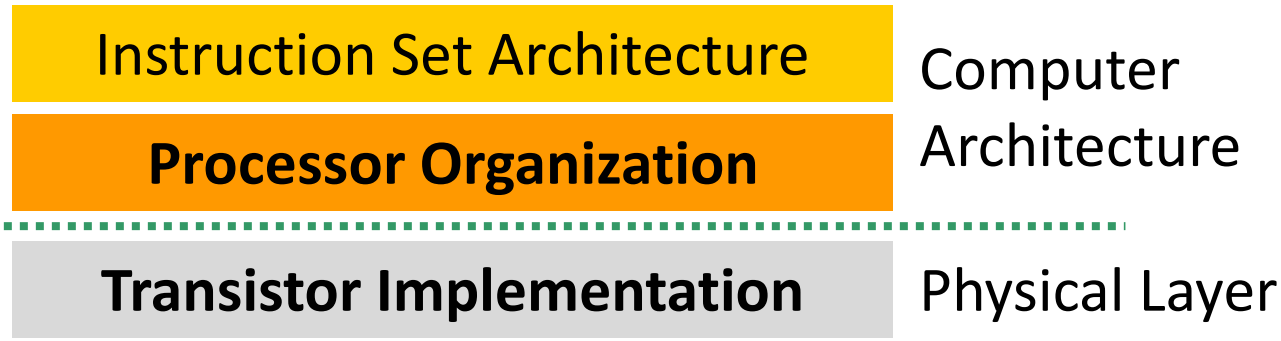
$$\frac{\text{instructions}}{\text{program}} \times \frac{\text{cycles}}{\text{instructions}} \times \frac{\text{seconds}}{\text{cycle}}$$

- Improving $\frac{\text{seconds}}{\text{cycle}}$:
  - Clock frequency = $\frac{\text{cycles}}{\text{second}}$ = reverse of $\frac{\text{seconds}}{\text{cycle}}$
  - Higher clock frequency (GHz) leads to shorter exec time
- Improving $\frac{\text{cycles}}{\text{instructions}}$:
  - Also known as CPI (Cycles Per Instruction)
  - IPC (Instructions Per Cycle) = $\frac{\text{instructions}}{\text{cycles}}$ = reverse of $\frac{\text{cycles}}{\text{instructions}}$
  - Higher IPC leads to shorter execution time
- Improving $\frac{\text{instructions}}{\text{program}}$:
  - Less instructions leads to shorter execution time
  - ISAs that do a lot of work with one instruction shortens time

Moore's Law and Performance

- Million-dollar question:
  Did Moore's Law result in higher performance CPUs?

- Law impacts both architecture and physical layers



  - Processor Organization: many more transistors to use in design
  - Transistor Implementation: smaller, more efficient transistors

Moore's Law Impact on Architecture

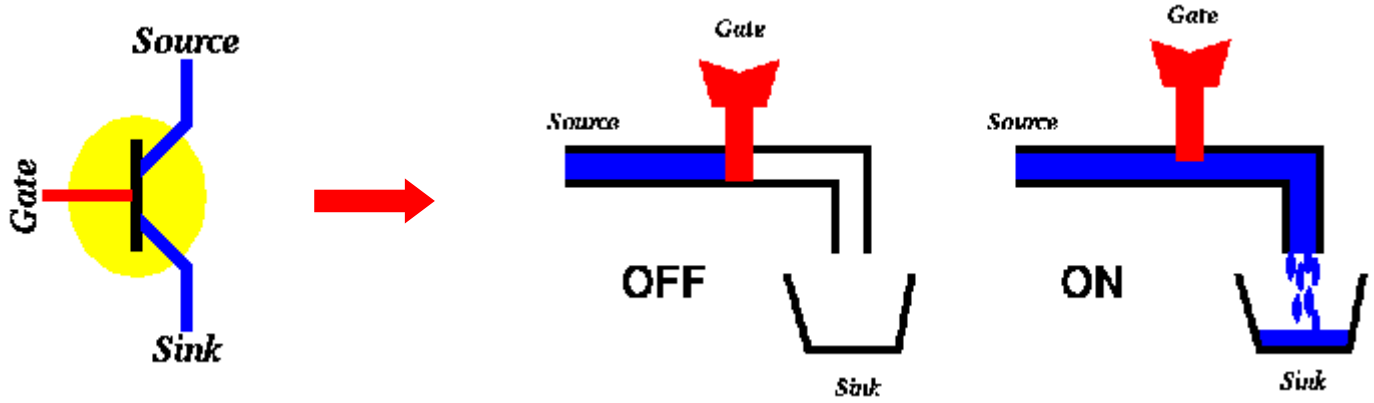
- So where did architects use all those transistors?
- Well, we will learn this throughout the semester ☺
  - Pipelining
  - Parallel execution
  - Prediction of values
  - Speculative execution
  - Memory caching
  - In short, they were used to improve frequency or IPC
- Let's go on to impact on the physical layer for now

Moore's Law Impact on Physical Layer

- CPU frequency is also impacted by transistor speed
  - As well as how many transistors are in between clock ticks (which is determined by processor organization)
- So did Moore's Law result in faster transistors?
  - In other words, are smaller transistors faster?

Speed of Transistors

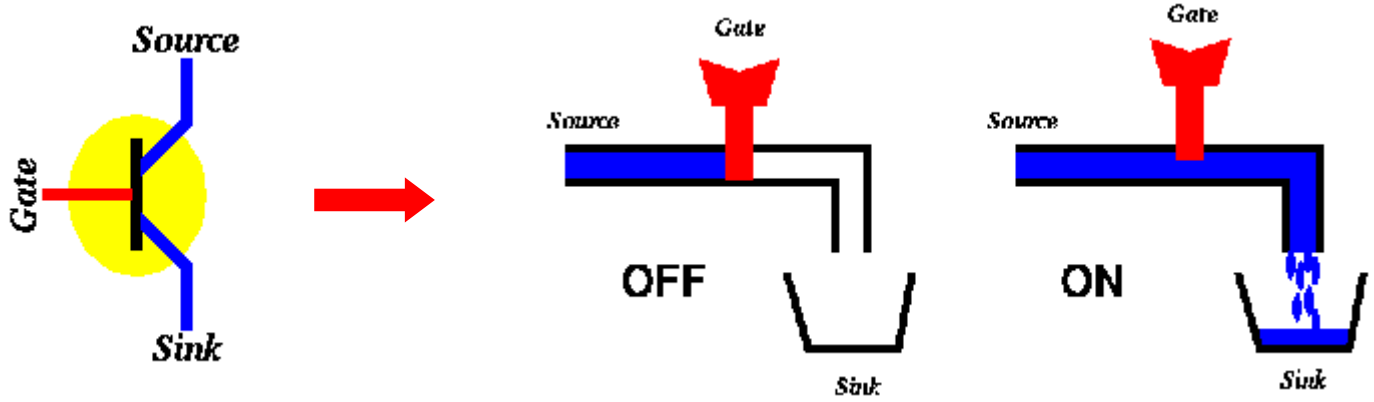
- Transistor 101: Transistors are like faucets!



- To make a transistor go fast, do one of the following:
  - Reduce distance from source to sink (*channel length*) ⇩
  - Reduce bucket size (*capacitance*) ⇩
  - Increase water pressure (*supply voltage*) ⇧

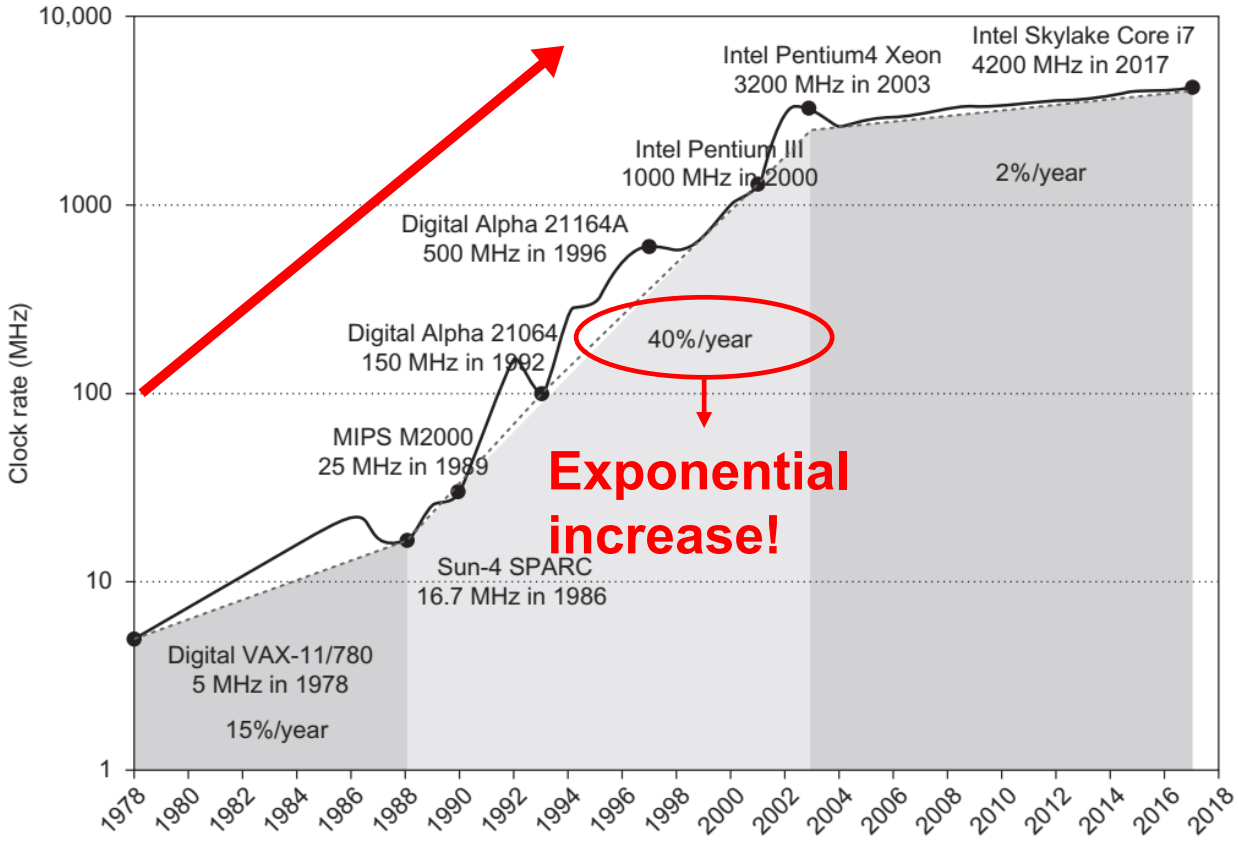
Smaller Transistors are Faster!

- Transistor 101: Transistors are like faucets!



- When a transistor gets smaller:
  - *Channel length* (channel resistance) is reduced ⇩
  - *Capacitance* is reduced ⇩
- So, given the same *supply voltage*, smaller is faster!
- So, did Moore's Law enjoy faster and faster frequencies?

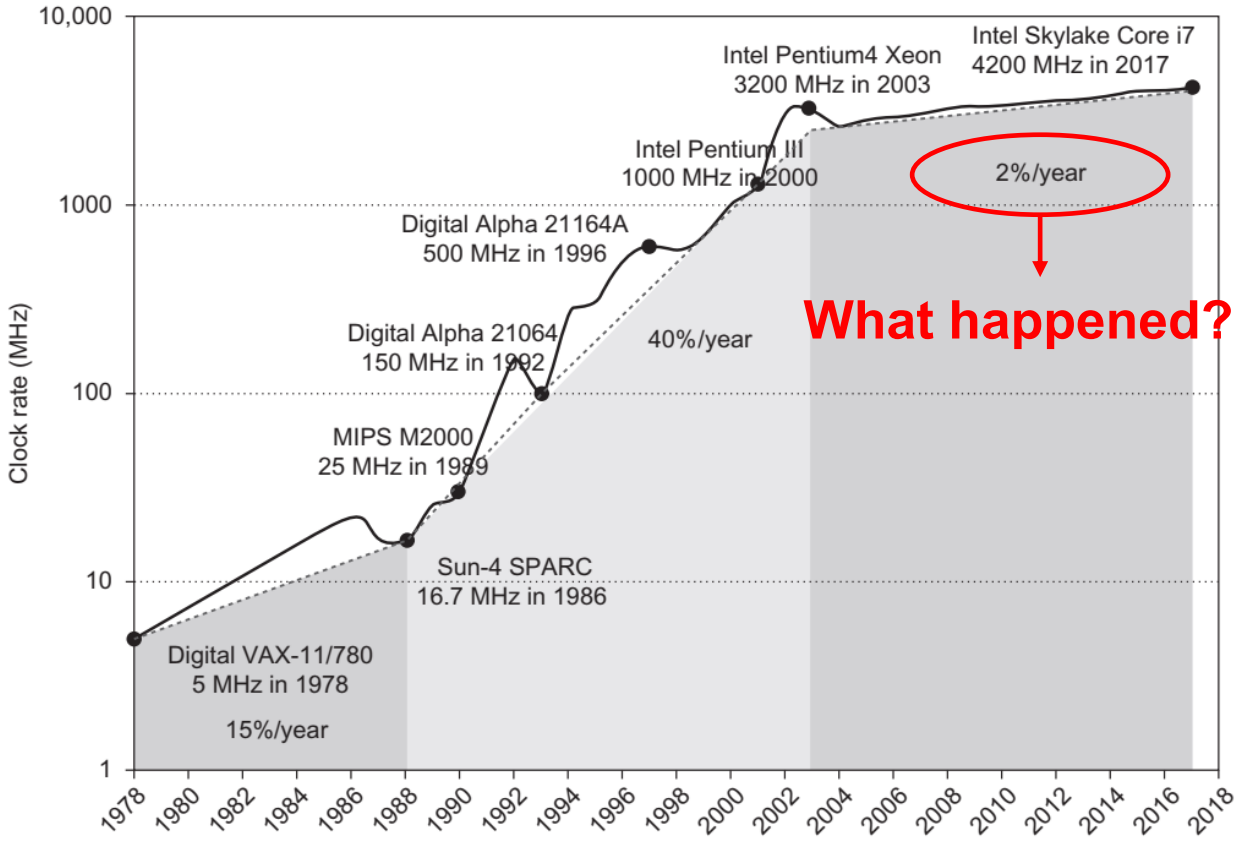
Yes, for a while …



Source: Computer Architecture, A Quantitative Approach (6th ed.) by John Hennessy and David Patterson, 2017

- Improvements in large part due to transistors
  - Processor design also contributed but we'll discuss later

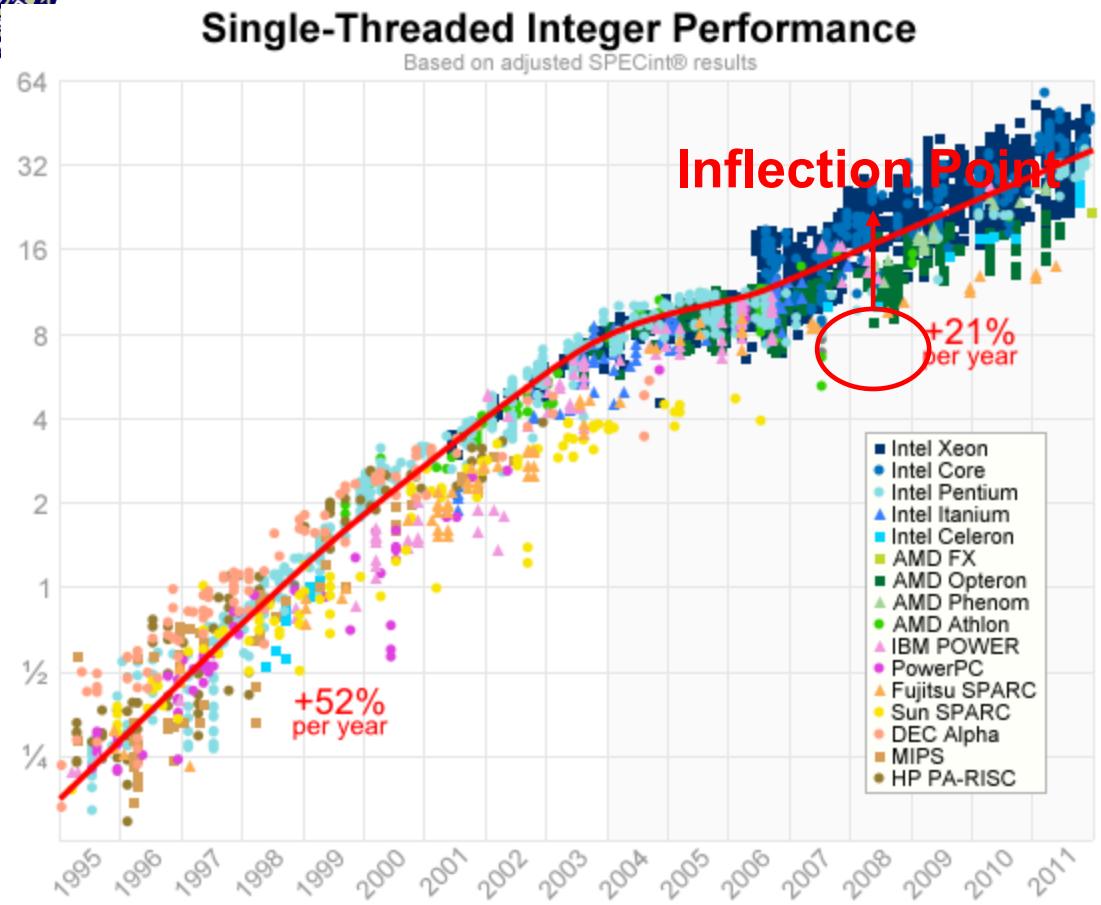
But not so much lately



Source: Computer Architecture, A Quantitative Approach (6th ed.) by John Hennessy and David Patterson, 2017

- Suddenly around 2003, frequency scaling stops

Dent in CPU Performance



Source: https://preshing.com/20120208/a-look-back-at-single-threaded-cpu-performance/

- This caused a big dent in CPU performance at 2003
- Improvements henceforth only came from architecture
  - From improvements to IPC (instructions per cycle)

So What Happened? TDP.

- *TDP* (*Thermal Design Power*):
  - Maximum heat (power) that cooling system can handle
  - Cooling system hasn't improved much over generations (Typically a CPU cooling fan attached with thermal paste)

- CPU Power = A * N * CFV^2 must be < TDP
  - A = Activity factor (% of transistors with activity)
  - N = Number of transistors
  - C = Capacitance ($\propto$ transistor size)
  - F = Frequency
  - V = Supply Voltage

- What happens to each factor with Moore's Law?

TDP and Moore's Law

- CPU Power $\propto$ A * N * CFV^2 with Moore's Law
  - A = Activity factor
  - N = Number of transistors ⇧ ⇧
  - C = Capacitance ($\propto$ transistor size) ⇩
  - F = CPU frequency ⇧ (thanks to reductions in transistor size)
  - V = CPU Supply Voltage

- Reductions in C cannot offset increases in N and F

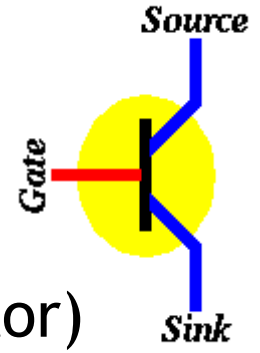
  Q) How did CPU frequency keep increasing up to 2003?

  A) By maintaining power through reductions in Voltage ⇩

  Q) Wait! Voltage reduction reduces frequency! (Transistor 101)

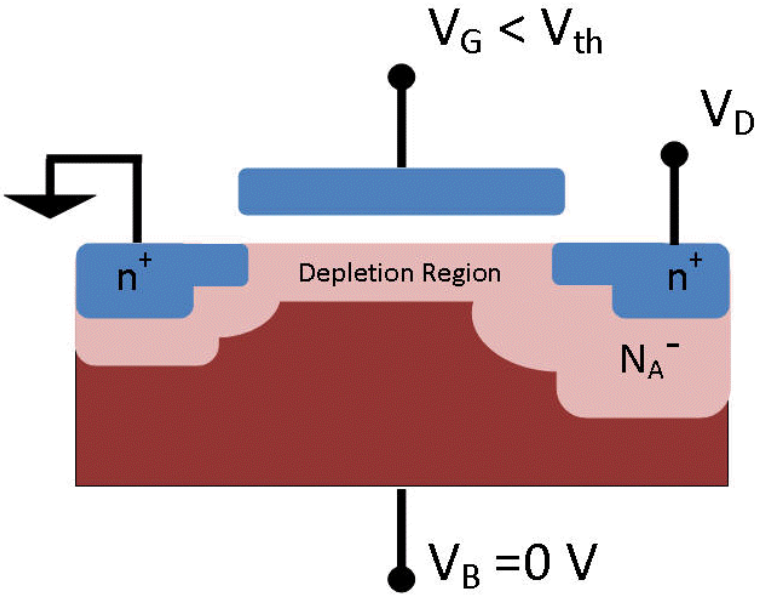
  A) Alright, time to do MOSFET 101

MOSFET 101

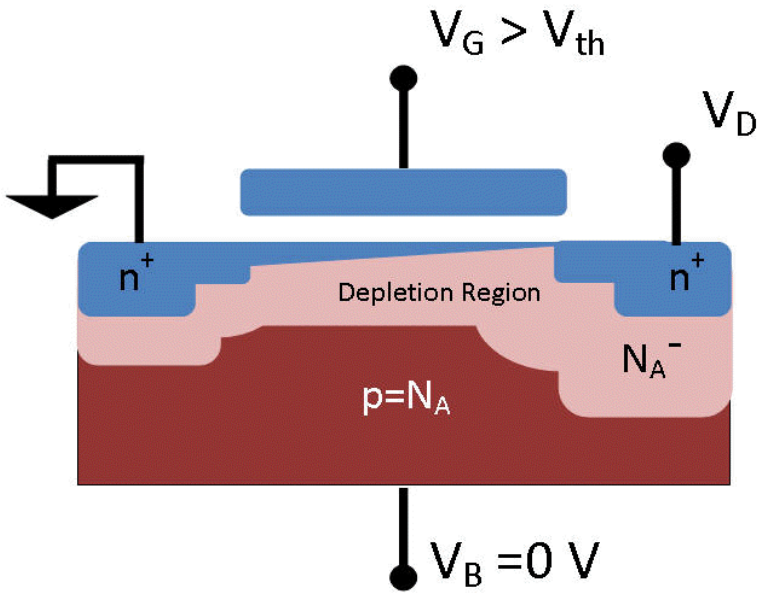


- MOSFET (Metal Oxide Silicon Field Effect Transistor)

[A MOSFET transistor switched off]



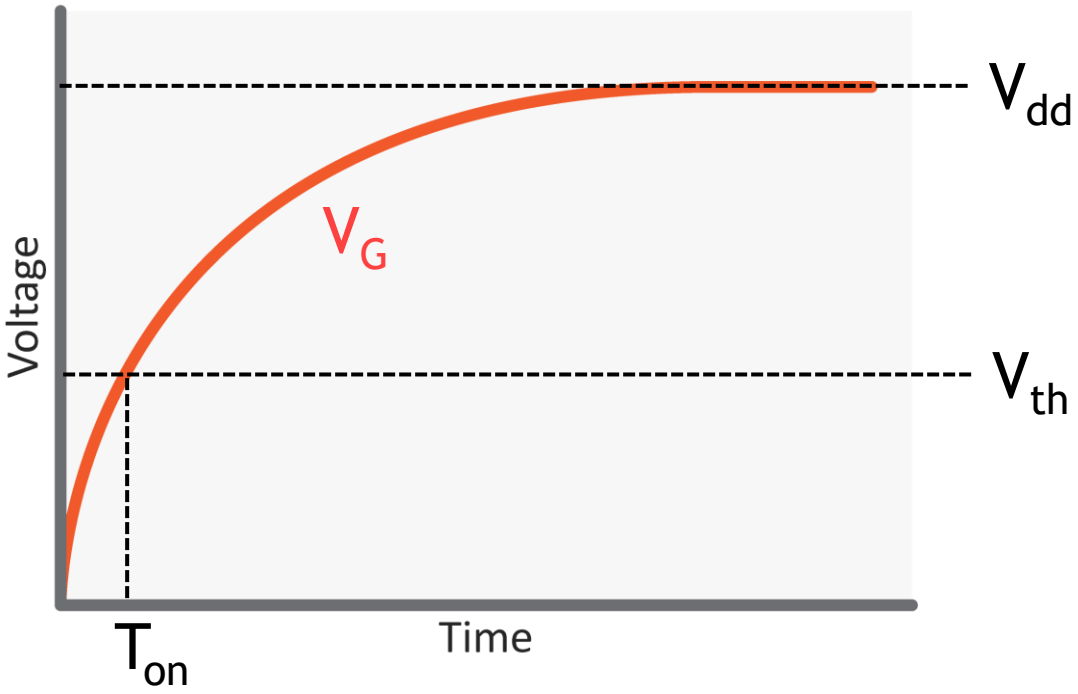
[A MOSFET transistor switched on]



- Gate is switched on when V_G reaches a threshold V_{th}
  - By creating a channel in depletion region through field effect
  - V_{th}: threshold voltage (minimum voltage to create channel)

MOSFET 101

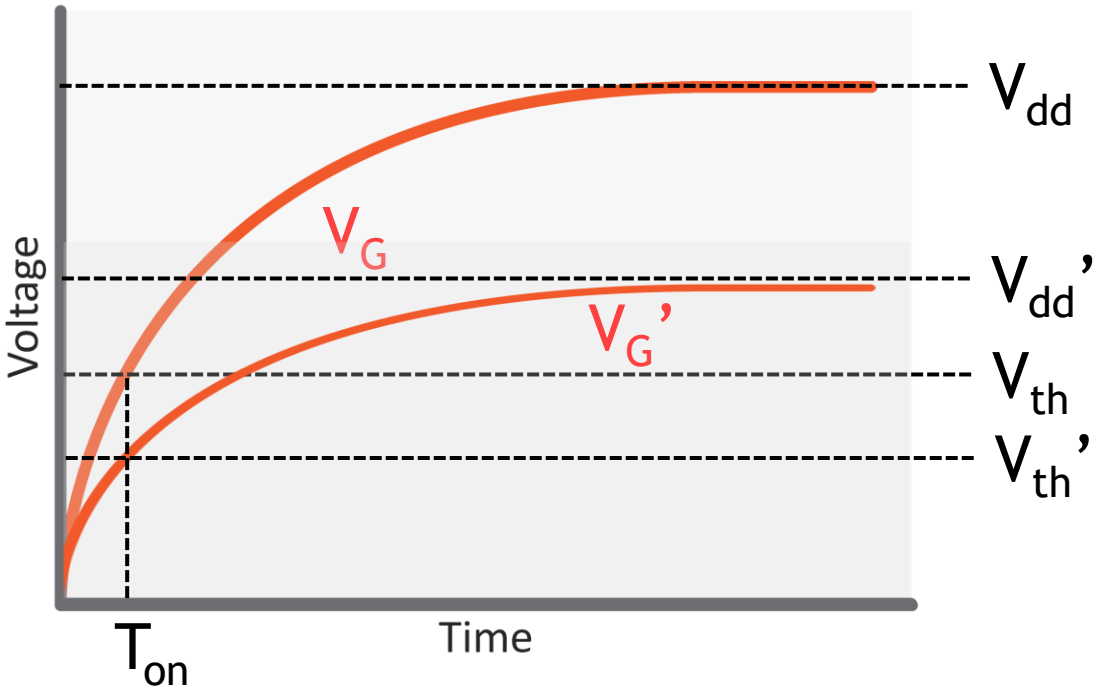
- RC charging curve of V_G



- Speed (T_{on}) is determined by V_{dd} if V_{th} is fixed
  - V_{dd} is the CPU supply voltage (the water pressure)
  - If V_{dd} is lower, V_G will reach V_{th} more slowly (low pressure)

MOSFET 101

- RC Charging Curve of V_G



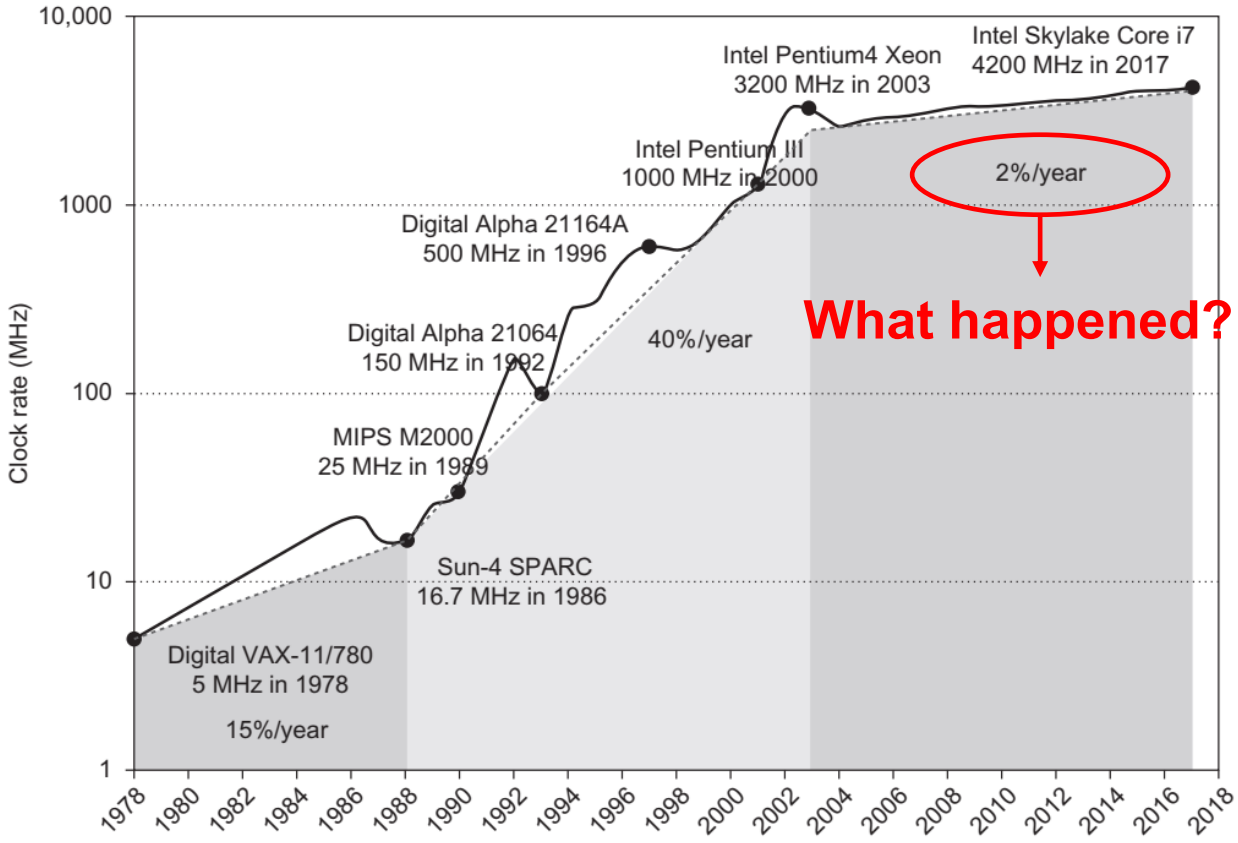
- Speed (T_{on}) is maintained while reducing V_{dd} to V_{dd}', if V_{th} is also reduced to V_{th}'

Dennard Scaling

- So in the end, this is what happens …
- CPU Power $\propto$ A * N * CFV^2 with Moore's Law
  - A = Activity factor
  - N = Number of transistors ⇧ ⇧
  - C = Capacitance ($\propto$ transistor size) ⇩
  - F = CPU frequency ⇧ (thanks to reductions in transistor size)
  - V = CPU Supply Voltage ⇩ (to reduce power)
  - V_{th} = CPU Threshold Voltage ⇩ (to maintain frequency)
- Factors balance each other out to make power constant

- This recipe for scaling frequency while keeping power constant is called Dennard Scaling

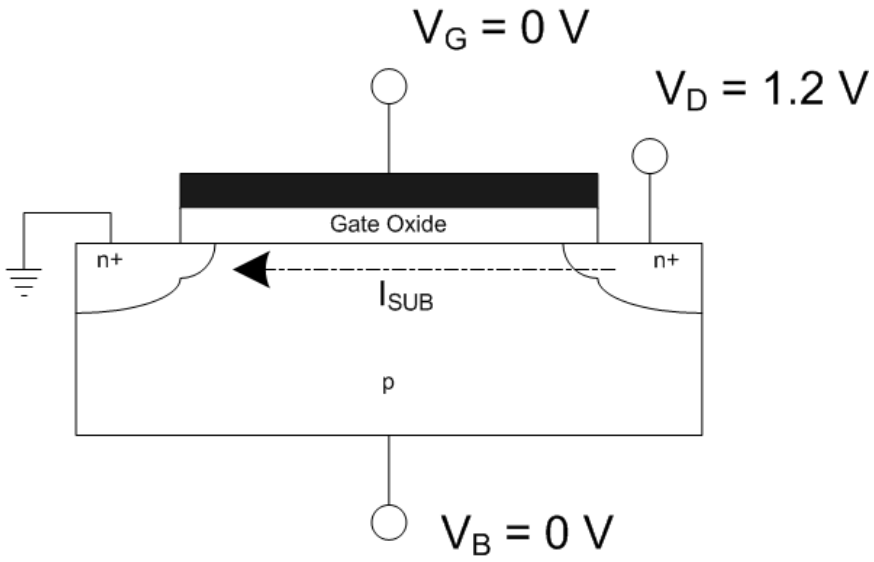
End of Dennard Scaling



- And around 2003 is when Dennard Scaling ended

Limits to Dropping V_{th}

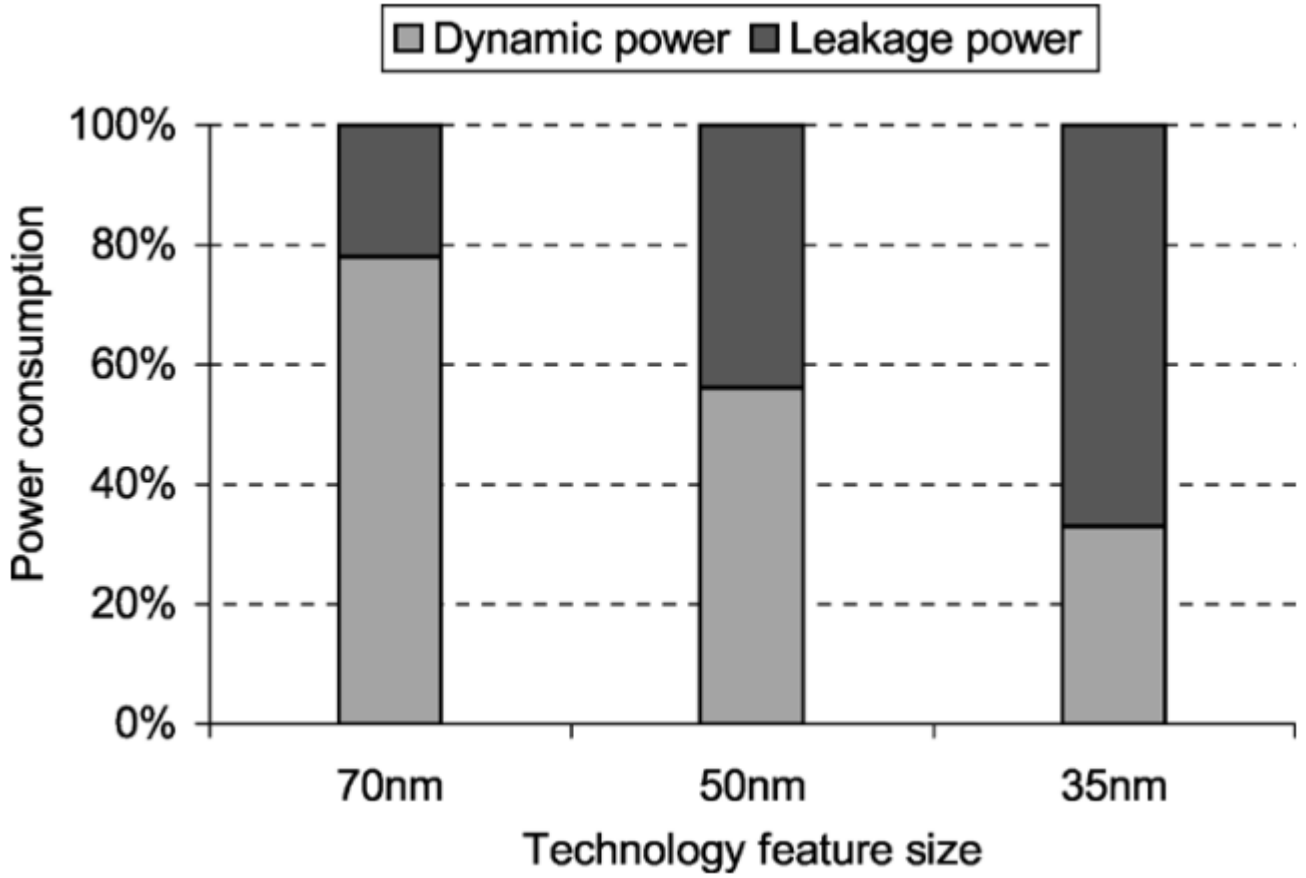
- Subthreshold leakage
  - Transistor leaks current even when gate is off ($V_G = 0$)



  - This leakage current translates to leakage power
  - Leakage worsens when V_{th} is dropped (related to oxide thickness)

Leakage Power across Generations

- Leakage power has increased across technology nodes



Source: L. Yan, Jiong Luo and N. K. Jha, "Joint dynamic voltage scaling and adaptive body biasing for heterogeneous distributed real-time embedded systems," in *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 24, no. 7, pp. 1030-1041, July 2005

End of Dennard Scaling

- $Power_{CPU} \propto Power_{dynamic} + Power_{leakage}$
  - $Power_{dynamic} \propto A * N * CFV^2$
  - $Power_{leakage} \propto f(N, V, V_{th}) \propto N * V * e^{-Vth}$
  - Leakage worsens *exponentially* when V_{th} is dropped
  - Catch-22: when dropping V_{th}, $Power_{dynamic}$ ⇩ but $Power_{leakage}$ ⇧⇧
  - That means V_{th} can't be reduced and V can't be reduced
- $Power_{dynamic}$ ($\propto A * N * CFV^2$) + $Power_{leakage}$ ($\propto N * V * e^{-Vth}$)
  - A = Activity factor
  - N = Number of transistors ⇧ ⇧
  - C = Capacitance ($\propto$ transistor size) ⇩
  - F = CPU frequency ⇔ (Can't increase without violating TDP)
  - V = CPU Supply Voltage ⇔ (Due to fixed V_{th})
  - V_{th} = CPU Threshold Voltage ⇔ (Due to leakage power)

Free Ride is Over

- "Free" speed improvements from transistors is over
- Now it's up to architects to improve performance
  - Moore's Law is still alive and well (although slowing down)
  - Architects are flooded with extra transistors each generation
- Now is a good time to discuss technology constraints
  - Since we already mentioned a big one: TDP