Objectives

1. To understand the historical developments behind
   • Computing systems;
   • Processors;
   • Memory systems;
   • Integrated circuits.

2. To catch a glimpse of the future of computing.
Early Bluetooth

Computer History Timeline
Early Computers: 1942 - 1958

- Mark I - 1944
- ENIAC - 1946
- EDSAC - 1949
- EDVAC - 1949
- LEO - 1951
- UNIVAC - 1951

Mark I

- An early electromechanical computer developed at Harvard.
- The name was later adopted by Manchester for its machine, a small prototype known for being the first operational stored-program machine.
ENIAC (Electronic Numerical Integrator and Calculator)

- World's first operational electronic, general-purpose computer.
- Used for computing artillery-firing tables.
- 80’ long x 8.5’ tall x several feet wide.
- 18,000 vacuum tubes.
- 1900 additions per second.
- Reprogrammed by plugging cables and setting switches.
- Data entered on punched cards.

EDVAC (Electronic Discrete Variable Automatic Computer)

- Proposed in a memo written by John von Neumann, who stole credit from Eckert and Mauchly.
- A binary serial computer with automatic addition, subtraction, multiplication, programmed division, and automatic checking with an ultrasonic serial memory capacity of 1,000 44-bit words.
EDSAC (Electronic Delay Storage Automatic Calculator)

- Designed by Maurice Wilkes of Cambridge University who was inspired to build a stored-program computer.
- World’s first full-scale, operational, stored-program computer.

LEO (Lyons Electronic Office)

- The food and catering company J. Lyons & Co. wanted a method to quickly perform business related calculations and crunch large amounts of numbers. Thus, it helped fund the development of the EDSAC in exchange for being allowed to copy portions of it to create a business computer.
UNIVAC (Universal Automatic Computer)

- Designed to be sold as a general-purpose computer.
- Cost $1 million.
- The first successful commercial computer – 48 were built.
- It correctly predicted the outcome of the 1952 presidential election.

New Technologies - Vacuum Tubes

- A vacuum tube is about the size of a human thumb.
Transistors

- A fraction of the size of vacuum tubes.
- Used no power while not under operation.
- Extremely reliable.
- Won the inventors the 1956 Nobel Prize in Physics.

Integrated Circuits

- Reduced the need to hand wire or solder every single transistor together in a computer.
- Saved on space as better IC's were developed.
- Sped up computers due to shorter distances for electrons to travel.
Mainframes: 1960s

- IBM dominated the computing market during the 60's.
- Their computers were used in mostly industrial, military, and scientific areas.
- These computers were expensive, hard to maintain, and not user friendly.

The Advent of the Personal Computer: 1970's – 1990's

- In 1974 Intel came out with the 8080 microprocessor which many computer hobbyists used to build home computers around.
- Steve Wozniak and Steve Jobs went into business together and launched the Apple II in 1977 which was the first home computer that was easy to use, reliable, and relatively affordable.
The Advent of the Personal Computer: 1970's – 1990's

- In 1981 IBM released the IBM Personal Computer (PC) based on the Intel 8080 microprocessor and was powered by Microsoft's DOS operating system.
- Base system had 16K on-board RAM, audio cassette to load data, and only capable of running the built-in Microsoft BASIC language.
- The success of IBM's PC launched Intel and Microsoft to the forefront of their respective markets.
- Window's and Intel's new found success led to a market dominated by Intel processing chips and Window's operating systems through the present day.

The Modern Era: 2000's - Present

- Microprocessors are used in almost everything today from cars and smartphones to refrigerators and smart lights.
- For many years computers could be made faster and better by simply increasing clock speeds and shrinking transistor sizes. This process, known as Moore's law, will no longer hold true in the future due to inability to further shrink transistors, as well as the "power wall".
- The power wall is the inability to dissipate enough heat in the extremely small form factors that today's CPU's inhabit.
The Future

- To see continued advancements in computing new advancements will need to be made in three key areas: Software, Cloud processing, New computing architectures
  - Software advances will rely on the development of new algorithms and ways of processing data faster and more efficiently.
  - Cloud processing can be used to help reduce the load on any one computer allowing that CPU to spend its resources on other tasks.
  - New computer architectures such as quantum computers and other specially made processors will help to keep pushing the bounds of what is possible in computing.

History of the Processor

1903: Tesla invents logic gates.
1904: Vacuum tubes invented.
1947: Bardeen, Brattain, and Shockley invent the transistor.
1958: First IC produced and demonstrated.
Early Microprocessors

- Intel 4004 - 1971
  - 2300 transistors
  - 60,000 op’s per second (60 kHz)
  - 640 bytes of memory
- Intel 8008 - 1972
  - 500 or 800 kHz
  - 8-bit architecture
  - 16 kB

Early Microprocessors

- Intel 8080 - 1974
  - 6000 transistors
  - 2 MHz
  - 64 kB
- Intel 8086 - 1976
  - 29,000 transistors
  - 5 – 10 MHz
  - 1 MB
  - 16-bit architecture
Early Microprocessors

- Intel 80286 - 1982
  - 134,000 transistors
  - 4 – 12 MHz
- Intel 80386 - 1985
  - 275,000 transistors
  - 12 – 40 MHz
  - 32-bit processor
- Intel 80486 - 1991
  - 1.2 mil transistors
  - 20 – 33 MHz (variants multiplied to get up to 100 MHz)

The Pentium

- Intel Pentium - 1993
  - 3.1 million transistors
  - 60 – 300 MHz
  - 32-bit processing
  - 64-bit databus
**The L2 cache**

- On-chip data.
- Faster than other forms of memory.
- Slower than L1, less expensive.
- First Celeron (1998) didn't include one.

**64-bit Architecture**

- AMD Opteron (2003)
  - First widely accepted.
  - Runs 32-bit with no slowdown.
- Intel Xeon (2004)
Processing on a Budget

- AMD – Advanced Micro Devices
  - AM386
  - K5
  - K6
  - Athalon
- Intel's Celeron series

Like Your Processor – Add More!

- Enter Dual-core processing
- AMD
  - Athalon 64 X2 3800+ (2005)
- Intel
  - Core 2 Duo (2006)
  - Core 2 Quad (2006)
Processing Efficiency

• Multithreading
  – MIPS MT

• Pipelining
  – First used in Supercomputing (1970s)
  – Adopted to RISC

Desks Aren't Portable

• IBM PC Convertible (1986)
• IBM ThinkPad 775CD (1994)
• Intel Pentium M (2003)
Processors Today

- **i7-7700k** - $340
  - Processing cores: 4
  - Processing threads: 8
  - Base Frequency: 4.2 GHz
  - Transistor size: 14 nm
  - Intel Turbo Boost

- **FX-9590** - $190
  - Processing cores: 8
  - Processing threads: 8
  - Base Frequency: 4.7 GHz
  - Transistor size: 32 nm
  - Requires liquid cooling

Advanced Graphics (1980s)

- Raycasting

Graphics User Interface
Graphics Processing Units

Super FX Chip
- Developed in the early 1990s
- 16-bit RISC based processor
- Renders 2d special effects and 3d polygons
- First version ran at 10.7 MHz
  Later versions ran at 21 MHz

High Quality Graphics Games

Star Fox
Stunt Race FX
Yoshi's Island
A Titan Emerges...

Geoforce 256
- World's "first" GPU.
- Memory Core: 256-bits
- Memory Interface: 128-bit
- Triangles Per Second: 15 Million
- Pixels Per Second: 480 Million
- Handles Transform and Lighting
- Cube Environment Mapping

RAGE!!!

ATI releases competitor to Nvidia's graphics card.
3dfx Wins!

Voodoo 1 is Released

3dfx is Voodooed

3dfx went bankrupt in 2002 and canceled the Voodoo 5.

Former employees later got revenge working for Nvidia.
The War Today

Nvidia GeForce 1080
- 8 GB of Dedicated Memory GDDR5
- Core Clock: 1.6 GHz
- DirectX 12 and OpenGL 4.5
- VR support
- Memory Speed: 10 Gbps
- Memory Bandwidth: 320 Gbps
- Memory Interface-Width: 256-bits
- Maximum Resolution: 7680x4320 @ 60Hz

$560

AMD Radeon R9 Fury X
- 4GB of Dedicated Memory HBM
- 8.5 billion transistors
- DirectX 12 and OpenGL 4.5
- LiquidVR support
- Memory Speed: 1 Gbps
- Memory Bandwidth: 512 Gbps
- Memory Interface-Width: 4K
- Maximum Resolution: 4K @ 60Hz

$380

History of Memory

- Vacuum tube memory
- Mercury delay line
- Magnetic drum memory
- Magnetic core memory
- Notable mentions
**ENIAC (1946)**

- The first computer with memory
- 20 registers for storage
- Used vacuum tube memory
- Issues: very expensive, very slow, and tubes were easily broken

**EDSAC (1949)**

- First stored-program computer
- Used Mercury Delay Lines
- 1024 Memory Locations
- 32 memory tanks
- Each holds 32 17-bit words
- 100 times more cost effective than vacuum tubes
Drum Memory

– Coated with ferromagnetic material.
– Read/write heads fixed positions.
– Invented in the 30s, used in the 50s.

Magnetic Core Memory

– Predominant from 1955-1975 (20 years).
– Small magnetic rings that are magnetized to store information.
– Wires running down the core to access/change each core.
– Each core represents 1 bit of information.
– Destructive readout: reading a bit clears value.
– Nonvolatile: maintains last value w/o power.
MIT Whirlwind (1955)

– First digital computer with magnetic core RAM.
– Enabled 3D storage of information; first core memory of 32 x 32 x 16 bits installed; 32 Kbits.
– Reduced maintenance time; better reliability.
– 9 microsecond access time (64% increase in speed over mercury delay lines).

Notable Mentions

• Twister memory (early 1970s)
  – Wrapping magnetic tape around a wire that conducts electrical current
• Bubble memory (1970s)
  – Thin film storing one bit of data in small areas that looked like bubbles; data not lost after being turned off.
  – Harder to make, more expensive, power hungry, slow.
  – Obsolete by flash memory, continued to be used by the military until late 80s due to its reliability.
IBM Reigns in Disk Storage

- 1956 IBM develops first disk storage system (RAMAC 305)
  - It could store 5 MB of data on 50 disks
- 1962: IBM 1311 removable disk storage
  - Each pack weighed 10 lbs, had 6 disks, and could store 2MB
  - Disks rotated at 1,500 RPM
- 1970: IBM “Minnow” floppy disk drive
  - Read-only, 8-inch, 80 KB disk drive
  - 3 years later IBM launched a read/write drive
- 1973: IBM 3340 data module
  - Winchester technology put read/write heads in a sealed removable unit
- IBM disk industry ended in 2002 selling the disk storage division to Hitachi; they would go on making the first 1 TB hard disk drive in 2007.

IBM cont.

- 1970: IBM “Minnow” floppy disk drive
  - Read-only, 8-inch, 80 KB disk drive
  - 3 years later IBM launched a read/write drive
- 1973: IBM 3340 data module
  - Winchester technology put read/write heads in a sealed removable unit
- IBM disk industry ended in 2002 selling the disk storage division to Hitachi; they would go on making the first 1 TB hard disk drive in 2007.
Modern Memory

- SRAM
- DRAM
- Flash
- SDRAM
- DDR SDRAM

SRAM

- Integrated circuits that are memory arrays.
- Needs constant power.
- Usually have a single access port for either a read or write.
- No need to refresh, access time $\approx$ cycle time.
- 6-8 transistor per bit to prevent information from being disturbed when read.
- Uses minimal power to retain charge in standby.
SRAM cont.

- John Schmidt designed the first 64-bit MOS p-channel SRAM at Fairchild. (1964)
- New company Intel releases its first product the 3101 Schottky TTL bipolar 64-bit SRAM. (1969)

DRAM

- Value kept in a cell is stored as a charge in a capacitor.
- Uses a single transistor per cell used to read or write charge.
- Is much denser and cheaper than SRAM.
- Because charge is held in capacitor it must be periodically refreshed hence the term dynamic.
DRAM cont.

- Robert H. Dennard invented DRAM cells. (1966)
- William Regitz and colleagues at Honeywell invent a three-transistor DRAM cell. (1969)
- Intel 1103 (1970)
  - First commercially available DRAM IC
    Made possible with the use of integrated circuits
  - 1-kbit used in HP second-generation desktop computers

---

Flash Memory

- Flash memory is electronic (solid-state) non-volatile computer storage medium that can be electrically erased and reprogrammed.

  - NAND-type
    - Can be written or stored in blocks
  
  - NOR-type
    - Allows a single machine word (byte) to written to a single erased location or read from it
Flash Memory cont.

• Lead-up to Flash memory
  – Intel released the 3301 Schottky bipolar 1024-bit read-only memory ROM. (1969)
  – While at Intel, Dov Frohman invents and patents (#3,660,819) the EPROM. (1971)
  – George Perlegos with Intel develops the Intel 2816, the first EEPROM. (1978)
• First Flash Memory
  – Toshiba develops first flash memory from EEPROM. Both NOR and NAND types of flash memory were invented by Dr. Fujio Masuoka from Toshiba. (1980s)

SDRAM

• Before SDRAM
  – We had DRAM which is asynchronous. Input signals had direct affect on internal functions.
• After SDRAM
  – Synchronous. Input signals are recognized at the rising edge of the clock can now control things in steps.
  – Memory is now stored in “banks”.
  – Interleaved memory.
  – Introduces ability to pipeline.
• Samsung introduces the KM48SL2000 synchronous DRAM (SDRAM). (1993)
**DDR SDRAM**

- Double data rate synchronous dynamic random-access memory
- Double pumping: transfer data on both rising and falling edges of a clock signal
- Lower voltage
- DDR2 SDRAM: doubles min read/write to 4 consecutive words (1.8V)
- DDR3 SDRAM: doubles read/write to 8 words (1.5V)
- DDR4 SDRAM: 1.2 V or less

**History of Integrated Circuit Development**

- Evolution of Intel Microprocessors
  - Scaling from 4004 to Core i7
  - Courtesy of Intel Museum
4004

- First microprocessor (1971)
  - For Busicom calculator
- Characteristics
  - 10 mm process
  - 2300 transistors
  - 400 – 800 kHz
  - 4-bit word size
  - 16-pin DIP package
- Masks hand cut from Rubylith
  - Drawn with color pencils
  - 1 metal, 1 poly (jumpers)
  - Diagonal lines (!)

8008

- 8-bit follow-on (1972)
  - Dumb terminals
- Characteristics
  - 10 mm process
  - 3500 transistors
  - 500 – 800 kHz
  - 8-bit word size
  - 18-pin DIP package
- Note 8-bit datapaths
  - Individual transistors visible
8080

- 16-bit address bus (1974)
  - Used in Altair computer
    - (early hobbyist PC)
- Characteristics
  - 6 mm process
  - 4500 transistors
  - 2 MHz
  - 8-bit word size
  - 40-pin DIP package

8086 / 8088

- 16-bit processor (1978-9)
  - IBM PC and PC XT
  - Revolutionary products
  - Introduced x86 ISA
- Characteristics
  - 3 mm process
  - 29k transistors
  - 5-10 MHz
  - 16-bit word size
  - 40-pin DIP package
- Microcode ROM
**80286**

- Virtual memory (1982)
  - IBM PC AT
- Characteristics
  - 1.5 mm process
  - 134k transistors
  - 6-12 MHz
  - 16-bit word size
  - 68-pin PGA
- Regular datapaths and ROMs
  Bitslices clearly visible

**80386**

- 32-bit processor (1985)
  - Modern x86 ISA
- Characteristics
  - 1.5-1 mm process
  - 275k transistors
  - 16-33 MHz
  - 32-bit word size
  - 100-pin PGA
- 32-bit datapath, microcode ROM, synthesized control
80486

- Pipelining (1989)
  - Floating point unit
  - 8 KB cache
- Characteristics
  - 1-0.6 mm process
  - 1.2M transistors
  - 25-100 MHz
  - 32-bit word size
  - 168-pin PGA
- Cache, Integer datapath, FPU, microcode, synthesized control

Pentium

- Superscalar (1993)
  - 2 instructions per cycle
  - Separate 8KB IS & DS
- Characteristics
  - 0.8-0.35 mm process
  - 3.2M transistors
  - 60-300 MHz
  - 32-bit word size
  - 296-pin PGA
- Caches, datapath, FPU, control
Pentium Pro / II / III

• Dynamic execution (1995-9)
  – 3 micro-ops / cycle
  – Out of order execution
  – 16-32 KB IS & DS
  – Multimedia instructions
  – PIII adds 256+ KB L2S
• Characteristics
  – 0.6-0.18 mm process
  – 5.5M-28M transistors
  – 166-1000 MHz
  – 32-bit word size
  – MCM / SECC

Pentium 4

• Deep pipeline (2001)
  – Very fast clock
  – 256-1024 KB L2S
• Characteristics
  – 180 – 65 nm process
  – 42-125M transistors
  – 1.4-3.4 GHz
  – Up to 160 W
  – 32/64-bit word size
  – 478-pin PGA
• Units start to become invisible on this scale
Pentium M

- Pentium III derivative
  - Better power efficiency
  - 1-2 MB L2$

- Characteristics
  - 130 – 90 nm process
  - 140M transistors
  - 0.9-2.3 GHz
  - 6-25 W
  - 32-bit word size
  - 478-pin PGA

- Cache dominates chip area

Core2 Duo

- Dual core (2006)
  - 1-2 MB L2$ / core

- Characteristics
  - 65-45 nm process
  - 291M transistors
  - 1.6-3+ GHz
  - 65 W
  - 32/64 bit word size
  - 775 pin LGA

- Much better performance/power efficiency
Core i7

- Quad core (& more)
  - Refinement of Core architecture
  - 2 MB L3 core
- Characteristics
  - 45-32 nm process
  - 731M transistors
  - 2.66-3.33+ GHz
  - Up to 130 W
  - 32/64 bit word size
  - 1366-pin LGA
  - Multithreading
- On-die memory controller

Atom

- Low power CPU for netbooks
  - Pentium-style architecture
  - 512KB+ L2
- Characteristics
  - 45-32 nm process
  - 47M transistors
  - 0.8-1.8+ GHz
  - 1.4-13 W
  - 32/64-bit word size
  - 441-pin FCBGA
- Low voltage (0.7 – 1.1 V) operation
  - Excellent performance/power
Summary

- $10^4$ increase in transistor count, clock frequency over 3 decades!

<table>
<thead>
<tr>
<th>Processor</th>
<th>Year</th>
<th>Feature Size (μm)</th>
<th>Transistors</th>
<th>Frequency (MHz)</th>
<th>Word Size</th>
<th>Power (W)</th>
<th>Cache (L1/L2/L3)</th>
<th>Package</th>
</tr>
</thead>
<tbody>
<tr>
<td>4004</td>
<td>1971</td>
<td>10</td>
<td>2.3k</td>
<td>0.75</td>
<td>4</td>
<td>0.5</td>
<td>none</td>
<td>16-pin DIP</td>
</tr>
<tr>
<td>8008</td>
<td>1972</td>
<td>10</td>
<td>3.5k</td>
<td>0.5-0.8</td>
<td>8</td>
<td>0.5</td>
<td>none</td>
<td>18-pin DIP</td>
</tr>
<tr>
<td>8080</td>
<td>1974</td>
<td>6</td>
<td>6k</td>
<td>2</td>
<td>8</td>
<td>0.5</td>
<td>none</td>
<td>40-pin DIP</td>
</tr>
<tr>
<td>8086</td>
<td>1978</td>
<td>3</td>
<td>29k</td>
<td>5-10</td>
<td>16</td>
<td>2</td>
<td>none</td>
<td>40-pin DIP</td>
</tr>
<tr>
<td>80286</td>
<td>1982</td>
<td>1.5</td>
<td>134k</td>
<td>6-12</td>
<td>16</td>
<td>3</td>
<td>none</td>
<td>68-pin PGA</td>
</tr>
<tr>
<td>Intel 386</td>
<td>1985</td>
<td>1.5-1.0</td>
<td>273k</td>
<td>16-25</td>
<td>32</td>
<td>1-1.5</td>
<td>none</td>
<td>100-pin PGA</td>
</tr>
<tr>
<td>Intel 486</td>
<td>1989</td>
<td>1-0.6</td>
<td>1.2M</td>
<td>25-100</td>
<td>32</td>
<td>0.3-2.5</td>
<td>8K</td>
<td>168-pin PGA</td>
</tr>
<tr>
<td>Pentium</td>
<td>1993</td>
<td>0.8-0.35</td>
<td>3.2-4.5M</td>
<td>60-300</td>
<td>32</td>
<td>8-17</td>
<td>16K</td>
<td>296-pin PGA</td>
</tr>
<tr>
<td>Pentium Pro</td>
<td>1995</td>
<td>0.6-0.35</td>
<td>5.5M</td>
<td>166-200</td>
<td>32</td>
<td>29-47</td>
<td>16K / 256K+</td>
<td>387-pin MCM PGA</td>
</tr>
<tr>
<td>Pentium II</td>
<td>1997</td>
<td>0.35-0.25</td>
<td>7.3M</td>
<td>233-450</td>
<td>32</td>
<td>17-43</td>
<td>32K / 256K+</td>
<td>242-pin SECC</td>
</tr>
<tr>
<td>Pentium III</td>
<td>1999</td>
<td>0.25-0.18</td>
<td>9.5-28M</td>
<td>450-1000</td>
<td>32</td>
<td>14-44</td>
<td>32K / 512K</td>
<td>330-pin SECC2</td>
</tr>
<tr>
<td>Pentium 4</td>
<td>2000</td>
<td>180-65 nm</td>
<td>42-178M</td>
<td>1400-3800</td>
<td>32/64</td>
<td>21-115</td>
<td>20K+ / 256K+</td>
<td>478-pin PGA</td>
</tr>
<tr>
<td>Pentium M</td>
<td>2003</td>
<td>130-90 nm</td>
<td>77-140M</td>
<td>1300-2130</td>
<td>32</td>
<td>5-27</td>
<td>64K / 1M</td>
<td>479-pin FCGBA</td>
</tr>
<tr>
<td>Core 65</td>
<td>2006</td>
<td>65 nm</td>
<td>152M</td>
<td>1000-1860</td>
<td>32</td>
<td>6-31</td>
<td>64K / 2M</td>
<td>479-pin FCGBA</td>
</tr>
<tr>
<td>Core 2 Duo</td>
<td>2006</td>
<td>65-45 nm</td>
<td>167-410M</td>
<td>1060-3160</td>
<td>32/64</td>
<td>10-65</td>
<td>64K / 4M</td>
<td>775-pin LGA</td>
</tr>
<tr>
<td>Core i7</td>
<td>2008</td>
<td>45 nm</td>
<td>731M</td>
<td>2660-3350</td>
<td>32/64</td>
<td>45-130</td>
<td>64K / 256K / 8M</td>
<td>1366-pin LGA</td>
</tr>
<tr>
<td>Anm</td>
<td>2008</td>
<td>45 nm</td>
<td>47M</td>
<td>800-1680</td>
<td>32/64</td>
<td>1.4-13</td>
<td>56K / 512K+</td>
<td>441-pin FCGBA</td>
</tr>
</tbody>
</table>

Future of Computing

- Cloud Computing
  - Enterprise
  - Personal
- Cutting Edge
  - Molecular Computing
  - Biological Computing
  - Quantum Computing
What is Cloud Computing?

- Cloud computing is the on-demand delivery of …
  - compute power
  - database storage
  - applications
  - other IT resources
- … through a cloud services platform via the internet with pay-as-you-go pricing

Advantages

- Variable expense \(\text{(Capital Expense)}\)
- Massive economies of scale
- Scalable Capacity \(\text{(Guessing)}\)
- Increase speed and agility
- Stop spending money on running and maintaining data centers
- Go global in minutes
Cloud Computing Types

- Infrastructure as a Service (IaaS)
- Platform as a Service (PaaS)
- Software as a Service (SaaS)


Infrastructure as a Service (IaaS)

Platform as a Service (Paas)


Software as a Service (saas)

The End of Silicon

- The two basic limitations of silicon are heat and leakage.
- Transistors smaller than 7 nm will experience quantum tunneling through their logic gates (leakage).

(22 nm is about 50 silicon atoms wide)

Biological/Molecular Computing

- Uses molecules such as DNA and proteins to perform computational calculations
- Uses less than 1% of energy used by current electronic transistors
- 3 types
  - Biochemical computers
  - Biomechanical computers
  - Bioelectronic computers
Biological/Molecular Computing

- Molecules, much like a valve, can either restrict or allow the flow of electricity, such as with a transistor

Quantum Computing

- Uses laws of quantum mechanics such as superposition and entanglement to process information.
- Uses quantum bits, or qubits, instead of the commonly known classical bit.
- The way a quantum computer works is that quantum gates are applied to the qubits making up the quantum computer.
Quantum Computing

• A single electron, or even atomic nucleus, can be considered a quantum bit
• The size of a silicon nucleus is of the order of 0.117 nanometers.
• The spin of this electron/nucleus represents its current state
  – Spin down = 0
  – Spin up = 1
  – Any quantum superposition of both states =

Quantum Computing

• Because qubits can be both states at the same time, they can hold exponentially more information than the classical bit.
• Example:
  – With 2 classical bits, only 1 out of the 4 possible combinations can be represented at the same time.
  – With 2 quantum bits, all possible combinations of 2 classical bits can be represented at the same time.
• Simply put, describing n qubits requires $2^n$ numbers
• When $n = 300$, $2^n$ is larger than the number of atoms in the Universe.
Quantum Computing

What’s the hold up?
• Qubits are notoriously tricky to manipulate.
• Current quantum computers aren’t very practical given the current technology.
• Incredibly complex and expensive.

3D Chips
5D Memory

Advanced Ergonomic Interfaces
Molecular Computers (the smallest computers can get?)

O(N!)

AATGTTCA
AAGTCAAT
GTTACGGA

GCCTATCT

Optical Computing
Nanotube Transistors

AI Technology

- IBM Watson
- Google DQN (Deep Neural Network + Machine Learning)
- Google AlphaGo

- Real World Applications
  - Weather
  - Medicine
  - Finance
Flexible Electronics

- QUICK on/off times (10 ps)
- Transparent
- Low Power

Direct Brain-to-Computer Interfaces

- Resistance is Futile
Summary

1. To understand the historical developments behind:
   - Computing systems;
   - Processors;
   - Memory systems;
   - Integrated circuits.
2. To catch a glimpse of the future of computing.