Video:

- Seems like a natural extension from images no?
- We just have a new dimension (time)
- Each “frame” is just an image made up of pixels
- Display n frames per second (fps); called the *frame rate*
- **Exercise:** theoretically, how much data are you blowing through on your video game?
- Assume: 60fps frame rate, 1920x1080 (1080p resolution), 8-bit channel depth RGB
- 1 second of gaming = 60 frames x 2073600 pixels x 8 bits x 3 channels (rgb)
- = 60 frames x 2073600 pixels x 3 bytes = 373248000 bytes of data, or about the ~373MB
- **HOW DO THEY DO IT?!**
- Our old friend compression (both in space and time now)

Audio:

- Analog sound is just a waveform. How do we turn it into bits?
- Quantize and sample
- Sample rate (analog of frame rate in video example), quantization (how many bits?)
- Most common parameters: 44.1 kHz sample rate (44100 sps), 16-bit quantization for each channel
- **Exercise:** 4 minute uncompressed digital audio? 4min * 60 sec/min * 44100samples/sec * 16 bits/chan * 2chan/sample
- = 338,688,000 bits = 42,336,000 bytes = ~42MB
- **Exercise:** How many uncompressed albums could you fit on your 16GB iPhone, assuming 10 tracks per album?

Programs:

- We’ll find later that they also can be represented in binary.
- They are just a series of pre-determined instructions in sequence, which we can attach to a taxonomy
- (plus some metadata of course)

Boolean Logic

- Named after George Boole
- Two constants, TRUE & FALSE
- We use logical operators
- Unary: NOT (inversion)
- Binary: AND, OR, NAND, NOR,
- There are more, we’ll come back to them
We can represent the outputs of these operators using truth tables.

Why do we care? This set of functions is sufficient to implement digital arithmetic and other digital structures we'll need.

**TRANSISTORS**

- Question we seek to answer: how do we implement logical operations in silicon?
- Transistors are the answer.
- Transistors are *active* components, meaning the current flowing through them can be controlled via inputs.
- There are several types of transistors (BJTs, JFETS, etc.) Some are used for amplification. We are concerned with *switching* transistors.
- Ultimately, they are voltage controlled switches (they control a current with a voltage).
- We're going to focus on a type of transistor technology called CMOS.
- Stands for Complimentary Metal Oxide Semiconductor.

**Introduction to the Logical Transistor**

- The diagram.
- Basic logical components: source, drain, gate.
- Source connected to Vdd (voltage supply).
- Gate is connected to some input.
- Assume a logical one on the gate produces a current across the transistor.

**CMOS**

- The *complimentary* here means there are two types of transistor, with opposite behaviors.
- pMOS, nMOS. We use these to create logic networks.
- nMOS drawing -> pMOS adds the bubble.
- Why do we need two? Device limitations.
- pMOS passes a “strong one,” meaning it conducts well at positive gate inputs.
- nMOS passes a “strong zero,” meaning it conducts well at negative gate inputs.

**Logical Operations with CMOS**

- Inverter (NOT Gate).
- NAND Gate (see other notes).

**Semiconductor operation - The Diode**

- See other notes.
Basic MOSFET Device Properties

- These transistors are also called MOSFETS=Metal Oxide Semiconductor Field Effect Transistors
- The gate acts somewhat like a capacitor, the device works by having an electric field at the gate (across a dielectric)
- The “metal” is the cap of the gate, nowadays it is polycrystalline silicon (poly)
- The dielectric is the oxide, but does not have to be an oxide. Commonly SiO2 (glass!)
- When there is a strong enough field, current flows from the source to the drain
- “Strong enough” is determined by the threshold voltage of the transistor (Vt)
- Transistor size: size is determined by gate length (measured in nm)
- Oxide width is measured in angstroms (a few atoms!) one layer os SiO2 is 3Å
- We won’t go any more into their electrical properties. They are actually nonlinear devices, so their analysis requires that you take differential equations

Device Physics

- We get pMOS and nMOS from doping, or adding impurities to silicon crystal
- Pentavalent materials (Group V on periodic table) (antimony, arsenic, phosphorus) add free electrons to the silicon lattice
- Trivalent materials (Group III) (boron, aluminum, gallium) create deficiencies in valence electrons (holes)

Current MOSFET Trends

- How have we made processors faster? (increase frequency!)
- You can increase frequency by making the device smaller, making voltage swings smaller (lower Vt)
- But, Dynamic power equation: \( P = \alpha \cdot C \cdot V^2 \cdot f \)
- Is this sustainable? (no) Remember the pentium 4?
- What terms are best to tackle? (The non-linear terms!) Thus we reduce the threshold voltage and we get a quadratic decrease in power consumption
- Quantum effects come into play here: when the gate oxide is thin enough, there’s some probability of a charge appearing on the other end when its wavefunction collapses. This is called quantum tunneling.
- Device trends also cause subthreshold leakage from source to drain. Gets worse as technology shrinks

Moore’s Law

- Halve feature sizes every 18 months
- Put another way, number of transistors on a chip will double every 18 months
• THIS IS NOT HAPPENING ANYMORE! (at least not at that rate)
THE DIODE

CIRCUIT SYMBOL

P-N "JUNCTION"

ANODE

CATODE

EXTRA "HOLSE"

EXTRA ELECTRONS

ATTRACTION

ELECTRONS FROM N-type FILL "HOLSE"

DEPLETION REGION

VOLTAGE! (BARRIER VOLTAGE)

(3)
The Diode (contd.)

???

[Diagram of a diode with labels P and N, and notes: IMPER DEPLETION ZONE, NO CURRENT FLOWS, (REVERSE BIAS)]
The Diode (cont.)

???

DEPLETION ZONE DISAPPEARS

CURRENT FLOWS!

(FORWARD BIAS)
NMOS TRANSISTOR

Source
Gate
Drain
"Well"

"Metal" (Poly)

"Oxide" (SiO₂)

Channel

Bulk / Body / Substrate

Depletion Regions!

(1) \( V_{gh} \approx V_T \)

Inversion Regime (Current Flows)

Diodes Forward Biased
TRANSISTOR SIZE

(\text{\textmu}m)

GATE LENGTH

"DEVICE NODE"

"TECHNOLOGY NODE"

OXIDE WIDTH (\AA)

CHANNEL LENGTH (\text{\textmu}m)

CURRENT INTEL NODE: 14\text{\textmu}m

(7 DNA HELICES)

(CELL MEMBRANE THICKNESS)
BASIC SEMICONDUCTORS

PENTAVALENT (GROUP V)  TRIVALENT (GROUP III)

"Electrons"

"Holes"