MOSFETs are similar to JFETs, except:

- $V_p$ (JFETs) → $V_T$ (MOSFETs)
- $V_T$ is positive for N-MOSFETs
- MOSFETs require a positive voltage on the Gate -- also no self-biasing.
- Input impedance is $\sim 10^{14}\Omega$.
- Power MOSFETs can handle 100’s of Amps.
- Generally, you must have $I_{DS}>0$ and $V_{DS}>0$ (for N-MOSFETs).
- MOSFETs are used in most low power digital electronics chips.
- MOSFETs are very susceptible to ElectroStatic Discharge (ESD).

[Figure from Horowitz & Hill p. 120]
ElectroStatic Discharge (ESD)

Common everyday actions generate large VOLTAGES (ESD) -- high impedance sources luckily !!!

ESD is very bad for MOSFETs

Most semiconductor components have some ESD susceptibility !

**TYPICAL ELECTROSTATIC VOLTAGES**

<table>
<thead>
<tr>
<th>Action</th>
<th>10%-20% humidity (V)</th>
<th>65%-90% humidity (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>walk on carpet</td>
<td>35,000</td>
<td>1,500</td>
</tr>
<tr>
<td>walk on vinyl floor</td>
<td>12,000</td>
<td>250</td>
</tr>
<tr>
<td>work at bench</td>
<td>6,000</td>
<td>100</td>
</tr>
<tr>
<td>handle vinyl envelope</td>
<td>7,000</td>
<td>600</td>
</tr>
<tr>
<td>pick up poly bag</td>
<td>20,000</td>
<td>1,200</td>
</tr>
<tr>
<td>shift position on foam chair</td>
<td>18,000</td>
<td>1,500</td>
</tr>
</tbody>
</table>

[Table from Horowitz & Hill p. 170]

Figure 3.76. Scanning electron micrograph of a 6 amp MOSFET destroyed by 1kV charge on “human body equivalent” (1.5k in series with 100pF) applied to its gate. (Courtesy of Motorola, Inc.)

[Figure from Horowitz & Hill p. 170]
Introduction to Op-Amps
Operational amplifiers (op-amps) are nearly ideal amplifiers:

- Nearly **infinite input impedance** … typically 1 MΩ - 10^{14}Ω.
- Nearly **infinite gain** … typically 10^5-10^6 at DC.
- **Small output impedance** … typically 10 Ω – 0.1 Ω or less.

→ Op-amp can drive currents of ~10 mA.

- \( V_{out} = Gain \times (V_+ - V_-) \).
- It’s EASY to design circuits with op-amps !!!
If op-amps are perfect, why would you anything else?

Op-amp drawbacks:

- They usually require **two power supplies** (i.e. +15 V and -15 V).
- They **cannot** provide a lot of power (i.e. Amps and Watts).
- **Emitter-follower** and the **common-emitter** amplifier are simple and work well.

→ **One frequently combines transistors and op-amps for power circuits.**
Integrated Circuits (ICs)

An op-amps is an integrated circuit:
- It has many discrete components (resistors, capacitors, and transistors)
- All made at the same time on the same piece of silicon.
- Put into a standardized package (DIP-8).

Most of the circuit design is already done:
- Makes them easy to use.
- Fits directly into a breadboard.
What's inside an op-amp?

LM741 schematic
What’s inside an op-amp?

LM741 schematic

V+  positive supply
V-  negative supply
Vout

Q1, Q3, Q5, Q7, Q9, Q11, Q13, Q15, Q17, Q20
Q2, Q4, Q6, Q8, Q10, Q12, Q14, Q16, Q18, Q21
What’s inside an op-amp?

LM741 schematic

- **Differential Amplifier**
- **High-Gain Amplifier**
- **Push-Pull Amplifier**
Op-amps are hardly ever used as straight super-high gain amplifiers:

- Gain is so large that the amplifier **output saturates** (i.e. go to the supply rails) for most reasonable signals.
- Susceptible to **manufacturing spread** of parameters.
- Gain has a **non-linearities** (i.e. can depend on voltage and frequency).

### Feedback

Op-amps are almost always operated with negative feedback from the output to the $V_-$ input.

- Feedback **stabilizes the performance** of the op-amp.
  - Feedback eliminates any dependence of the circuit on the op-amp's open-loop specs.
- Feedback produces **very linear gain**.
- The price of feedback is reduced gain.
- We will discuss feedback in detail in two weeks.
When using **negative feedback**, you can understand and design most op-amp circuits using the 2 following rules:

1. **The op-amp inputs do not draw any current.**

2. **The op-amp will adjust its output so that the voltage difference between the 2 inputs is zero.**