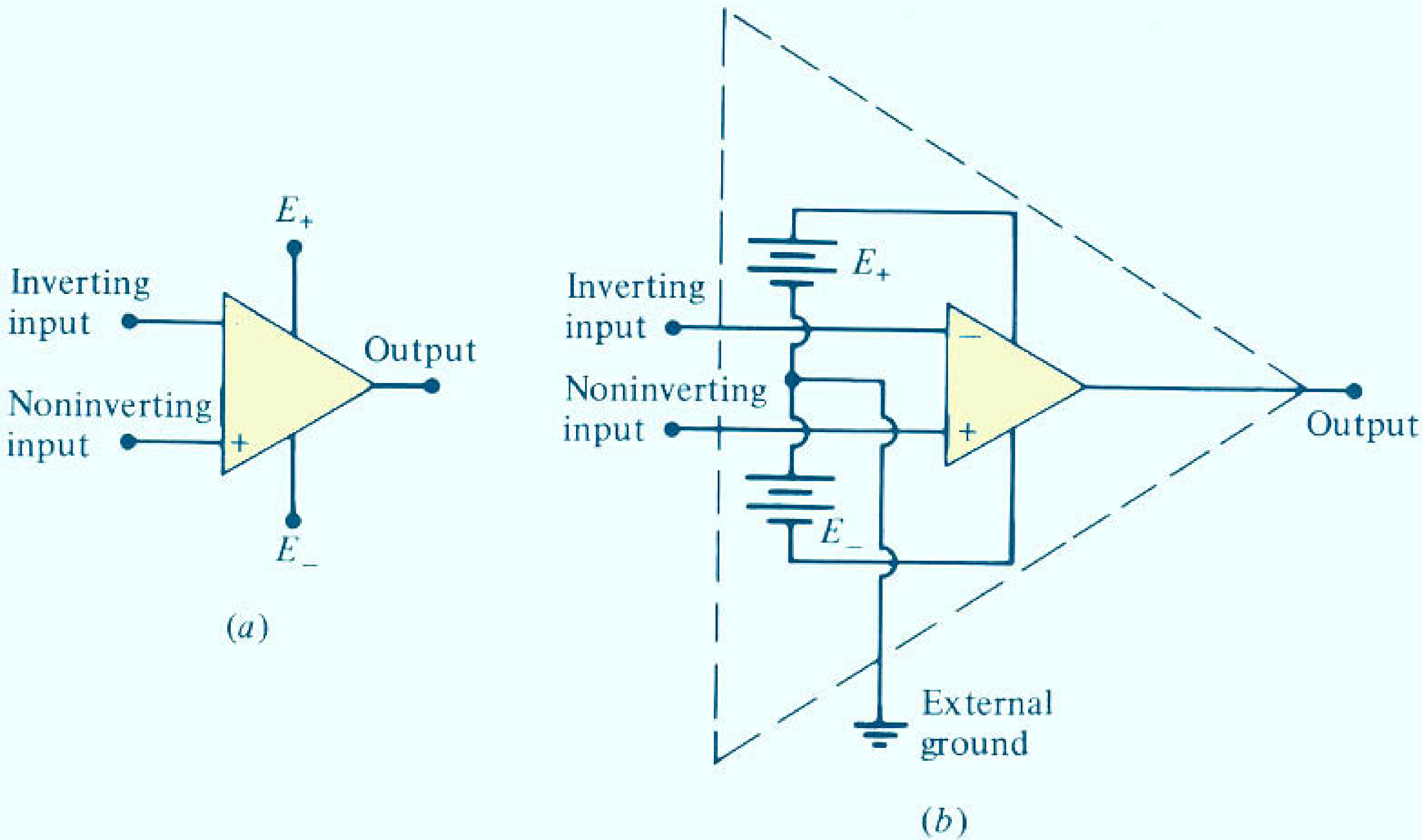
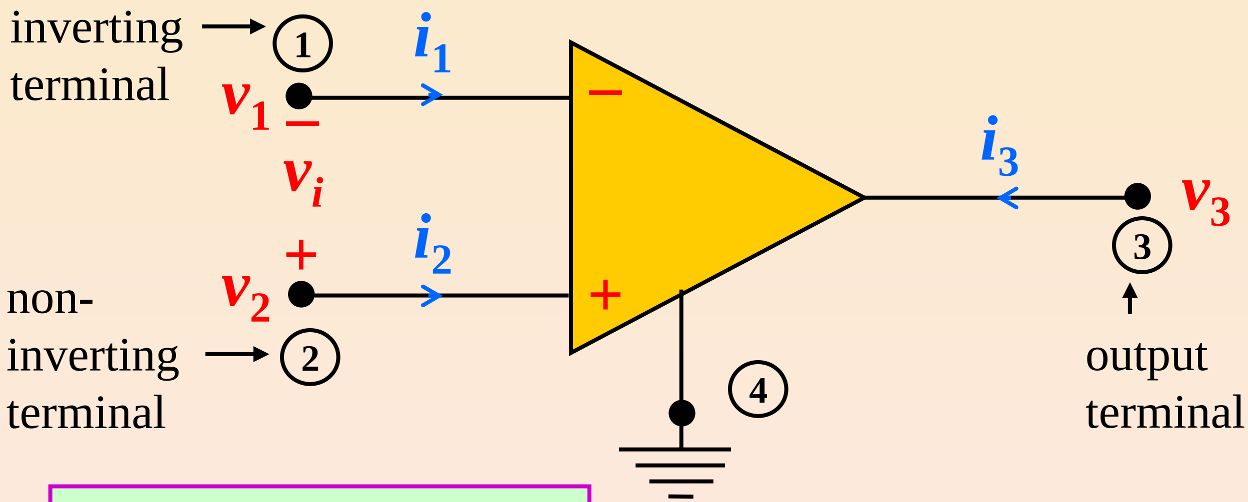

E+
Inverting input
Noninverting input
Output
E−
(a)
E+
Inverting input
Noninverting input
E−
Output
External ground
(b)

Ideal Operational Amplifier (Op Amp)



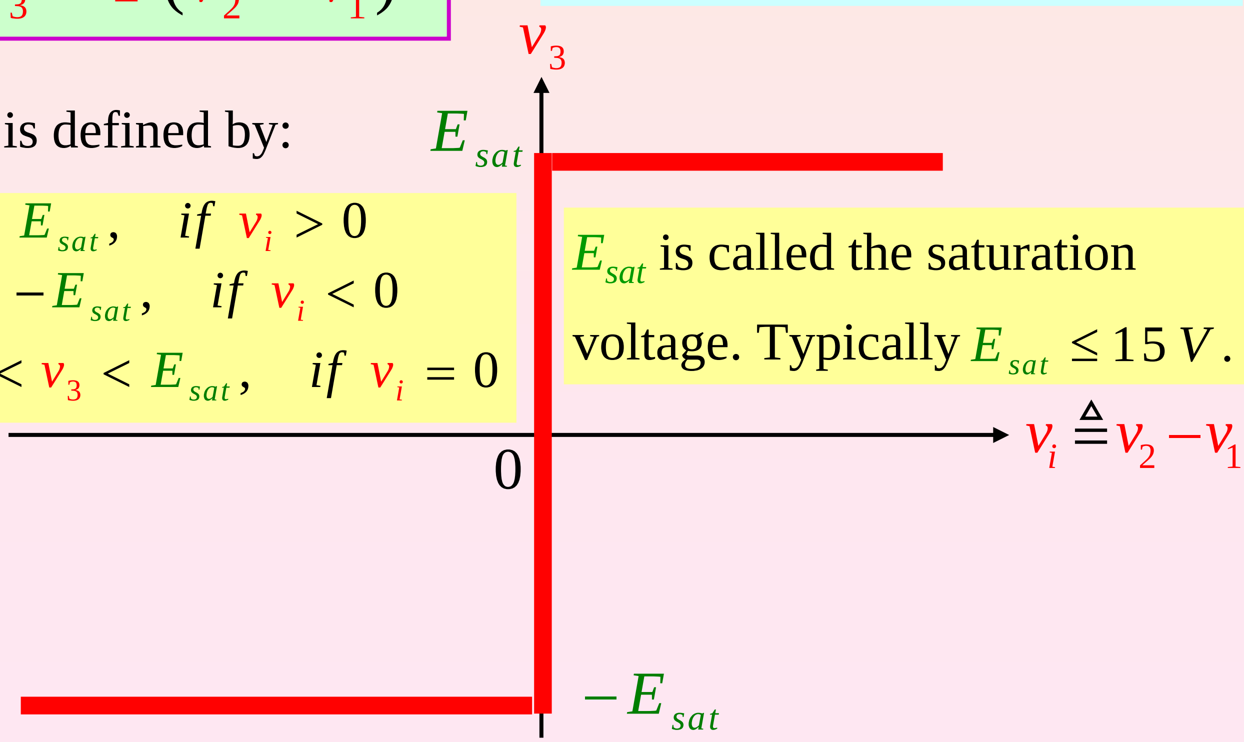
$$i_1 = 0$$
$$i_2 = 0$$
$$v_3 = \mathbf{F}(v_2 - v_1)$$

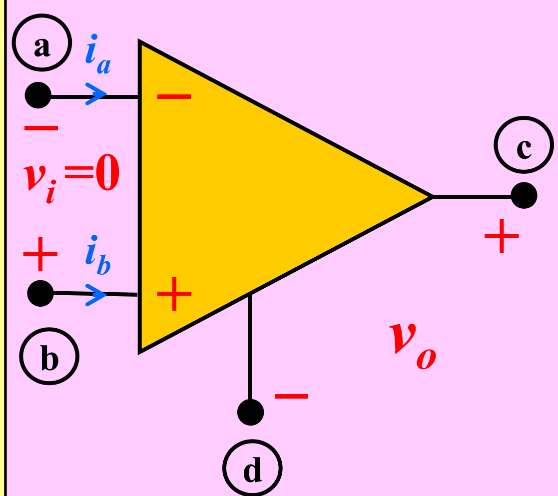
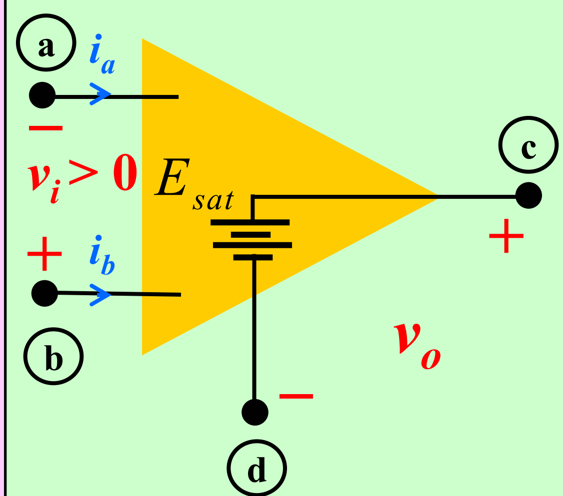
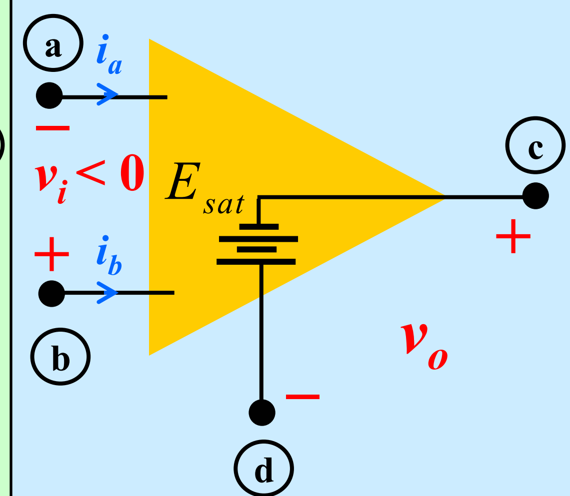
The nonlinear relationship **F** depends only on $v_i \triangleq v_2 - v_1$

F (v_i) is defined by:

$$v_3 = E_{sat}, \quad if \ v_i > 0$$
$$v_3 = -E_{sat}, \quad if \ v_i < 0$$
$$-E_{sat} < v_3 < E_{sat}, \quad if \ v_i = 0$$

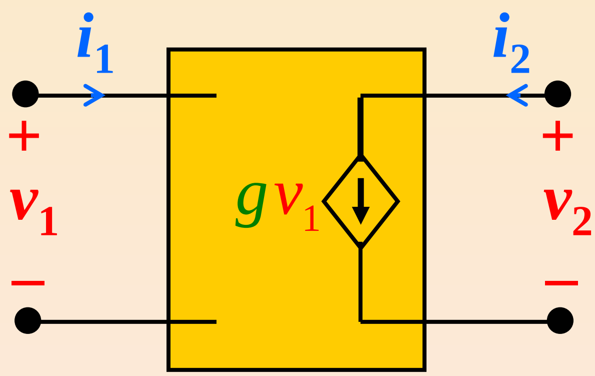
E_{sat} is called the saturation voltage. Typically $E_{sat} \le 15\,V$.



Operating Region	**Linear Region**	**+ Saturation Region**	**- Saturation Region**
op amp Circuit Model			
op amp Equation	$i_a = 0$ $i_b = 0$ $v_i = 0$	$i_a = 0$ $i_b = 0$ $v_o = E_{sat}$	$i_a = 0$ $i_b = 0$ $v_o = -E_{sat}$
Validating Inequality	$-E_{sat} < v_o < E_{sat}$	$v_i > 0$	$v_i < 0$

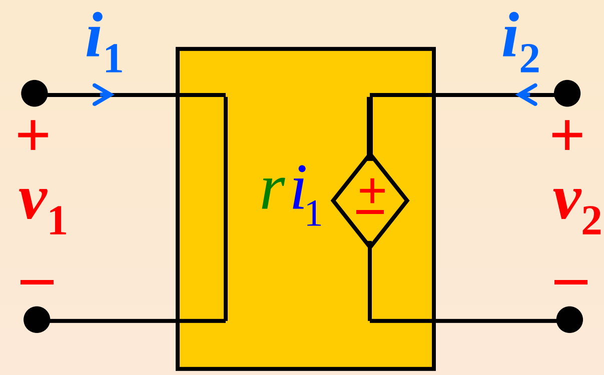
Controlled Sources

1. Voltage-Controlled Current Source (VCCS)



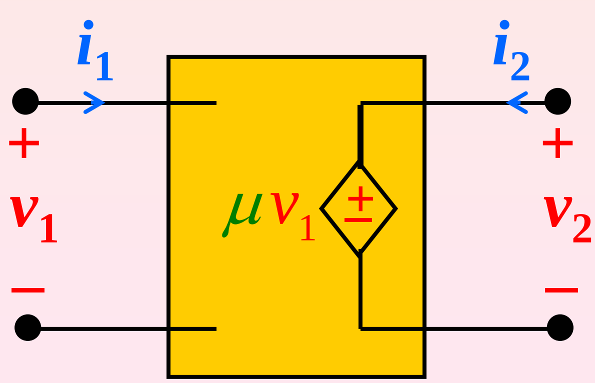
$$i_1 = 0$$
$$i_2 = g v_1$$

2. Current-Controlled Voltage Source (CCVS)



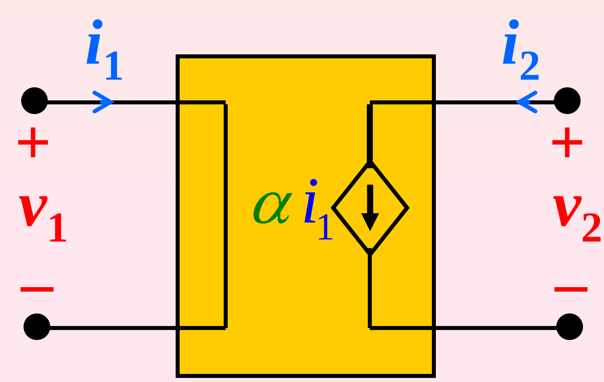
$$v_1 = 0$$
$$v_2 = r i_1$$

3. Voltage-Controlled Voltage Source (VCVS)



$$i_1 = 0$$
$$v_2 = \mu v_1$$

4. Current-Controlled Current Source (CCCS)



$$v_1 = 0$$
$$i_2 = \alpha i_1$$

Op amp circuit realization of linear controlled sources

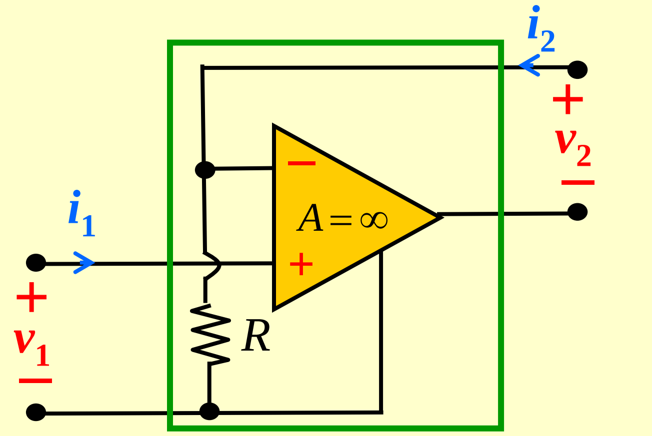
VCCS

$$i_1 = 0$$
$$i_2 = g\, v_1$$

$$g \triangleq \frac{1}{R}$$

dynamic range:

$$v_2 - E_{sat} < v_1 < v_2 + E_{sat}$$



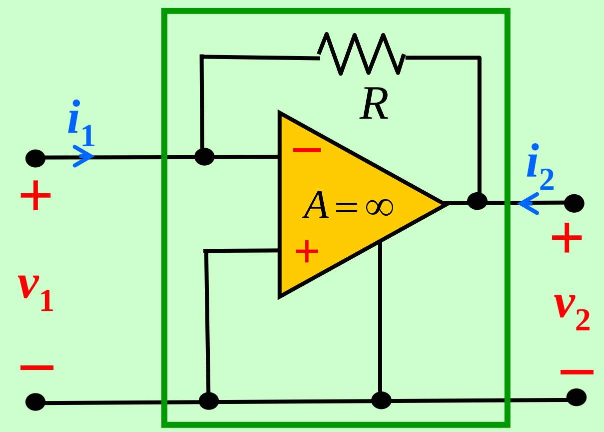
CCVS

$$v_1 = 0$$
$$v_2 = r\, i_1$$

$$r \triangleq -R$$

dynamic range:

$$-\frac{E_{sat}}{R} < i_1 < \frac{E_{sat}}{R}$$



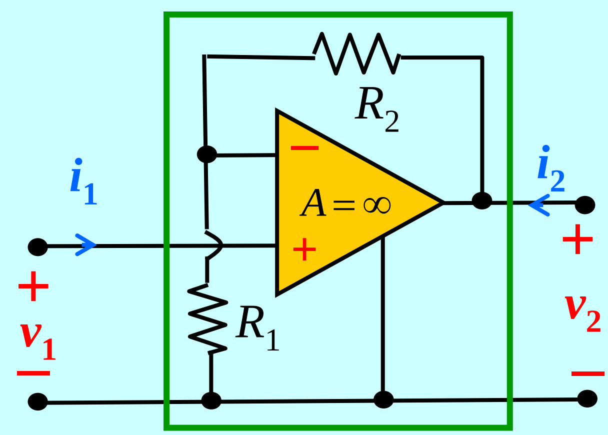
VCVS

$$i_1 = 0$$
$$v_2 = \mu\, v_1$$

$$\mu \triangleq 1 + \frac{R_2}{R_1}$$

dynamic range:

$$-\left(\frac{R_1}{R_1 + R_2}\right) E_{sat} < v_1 < \left(\frac{R_1}{R_1 + R_2}\right) E_{sat}$$



CCCS

$$v_1 = 0$$
$$i_2 = \alpha\, i_1$$

$$\alpha \triangleq 1 + \frac{R_1}{R_2}$$

dynamic range:

$$\left(\frac{v_2 - E_{sat}}{R_1}\right) < i_1 < \left(\frac{v_2 + E_{sat}}{R_1}\right)$$