Example:
Consider the circuit shown in Figure 1. Find the value of the voltage measured by the voltmeter.

![Figure 1](image)

**Figure 1** The circuit considered in this example.

**Solution:** Figure 2 shows the circuit from Figure 1 after replacing the voltmeter by an equivalent open circuit and labeling the voltage measured by the voltmeter. We will analyze this circuit by writing and solving node equations. The nodes of the circuit are numbered in Figure 2. Let $v_1$, $v_2$, $v_3$, $v_4$, $v_5$ and $v_6$ denote the node voltages at nodes 1, 2, 3, 4, 5 and 6 respectively.

The inputs to this circuit are the voltages of the voltage sources. These inputs are related to the node voltages at the nodes of the voltage sources by

1. $110 \quad 0.15 \quad 0.15 \ \text{V} \quad v_1 \quad -0.15 \ \text{V}$
2. $22 \quad 0 \quad 3.5 \quad 3.5 \ \text{V} \quad v_2 \quad = \quad 3.5 \ \text{V}$

The output of this circuit is the voltage measured by the voltmeter. The output voltage is related to the node voltages by

$$v_m = v_3 - v_6$$

The noninverting input of the top op amp is connected to node 1. The node voltage at the inverting input of an ideal op amp is equal to the node voltage at the noninverting input. The inverting input of the op amp is connected to node 4. Consequently,

$$v_4 = v_1 = -0.15 \ \text{V}$$
The noninverting input of the bottom op amp is connected to node 2. The node voltage at the inverting input of an ideal op amp is equal to the node voltage at the noninverting input. The inverting input of the op amp is connected to node 5. Consequently,

\[ v_5 = v_2 = 0.35 \text{ V} \]

Apply KCL to node 4 to get

\[ \frac{v_3 - v_4}{40000} = 0 + \frac{v_4 - v_5}{40000} \Rightarrow v_3 = \frac{9}{2} v_4 - \frac{5}{2} v_5 \]

Apply KCL to node 4 to get

\[ \frac{v_4 - v_5}{40000} = 0 + \frac{v_5 - v_6}{100000} \Rightarrow v_6 = -\frac{5}{2} v_4 + \frac{7}{2} v_5 \]

Using \( v_m = v_3 - v_6 \) shows that the output voltage is related to the input voltages by

\[ v_m = \left( \frac{9}{2} v_4 - \frac{7}{2} v_5 \right) - \left( -\frac{5}{2} v_1 + \frac{7}{2} v_2 \right) = 7 (v_1 - v_2) \]

Using \( v_1 = -0.15 \text{ V} \), and \( v_2 = 0.35 \text{ V} \) gives the value of the voltage measured by the voltmeter to be

\[ v_m = 7 \left( (-0.15) - (0.35) \right) = 7 (-0.5) = -3.5 \text{ V} \]