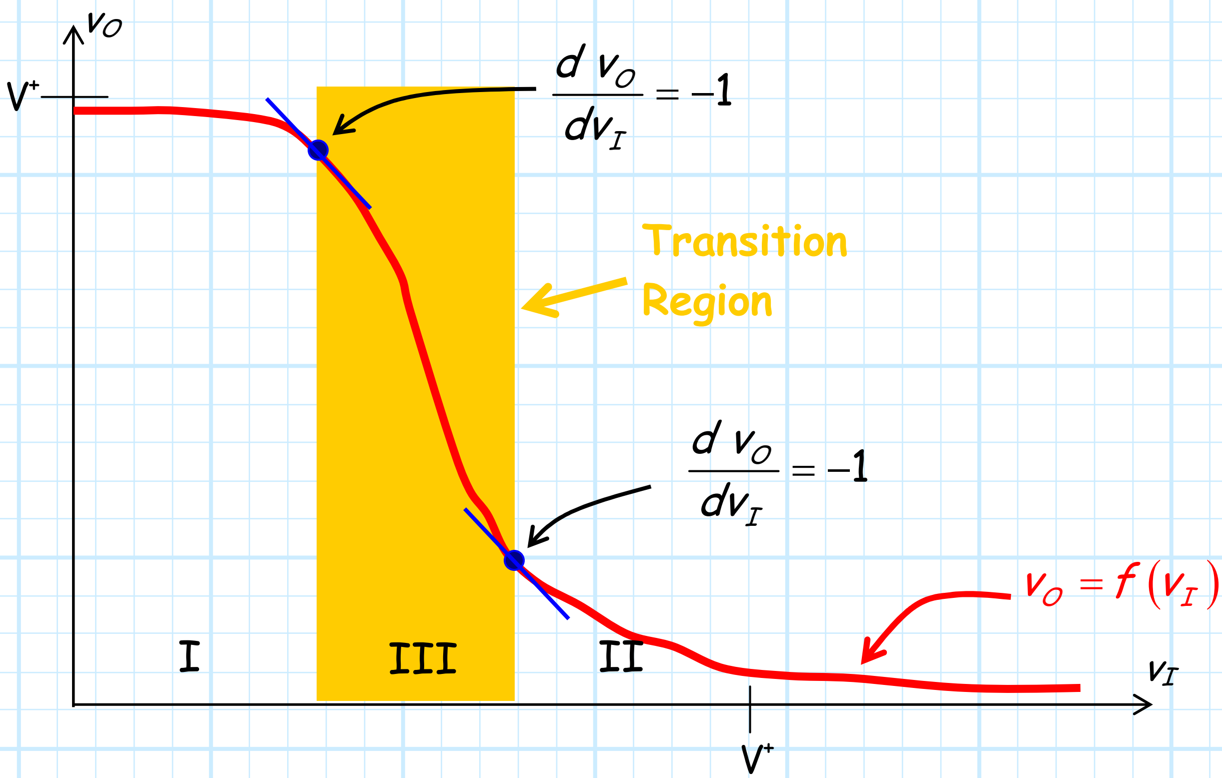
Noise Margins

The **transfer function** of a **digital inverter** will typically look something like this:



Note that there are essentially **three** regions to this curve:

I. The region where v_I is relatively **low**, so that the output voltage v_O is **high**.

II. The region where v_I is relatively **high**, so that the output voltage v_O is **low**.

III. The **transition region**, where the input/output voltage is in an **indeterminate state** (i.e, an **ambiguous** region between high and low.

Note that the **transition region** is rather **arbitrarily** defined by the points on the transfer function where the magnitude of the **slope** is **greater than one** (i.e., where $|d\,v_O/dv_I| > 1.0$).

Although this transfer function **looks** rather simple, there are actually **several parameters** that we use to **characterize** this transfer function—and thus characterize the digital inverter **as well**!

1. **First** of all, let's consider the case when v_I**=0**. The **output** of the digital inverter in this condition is **defined** as V_{OH} (i.e., OH → "output high"), i.e.:

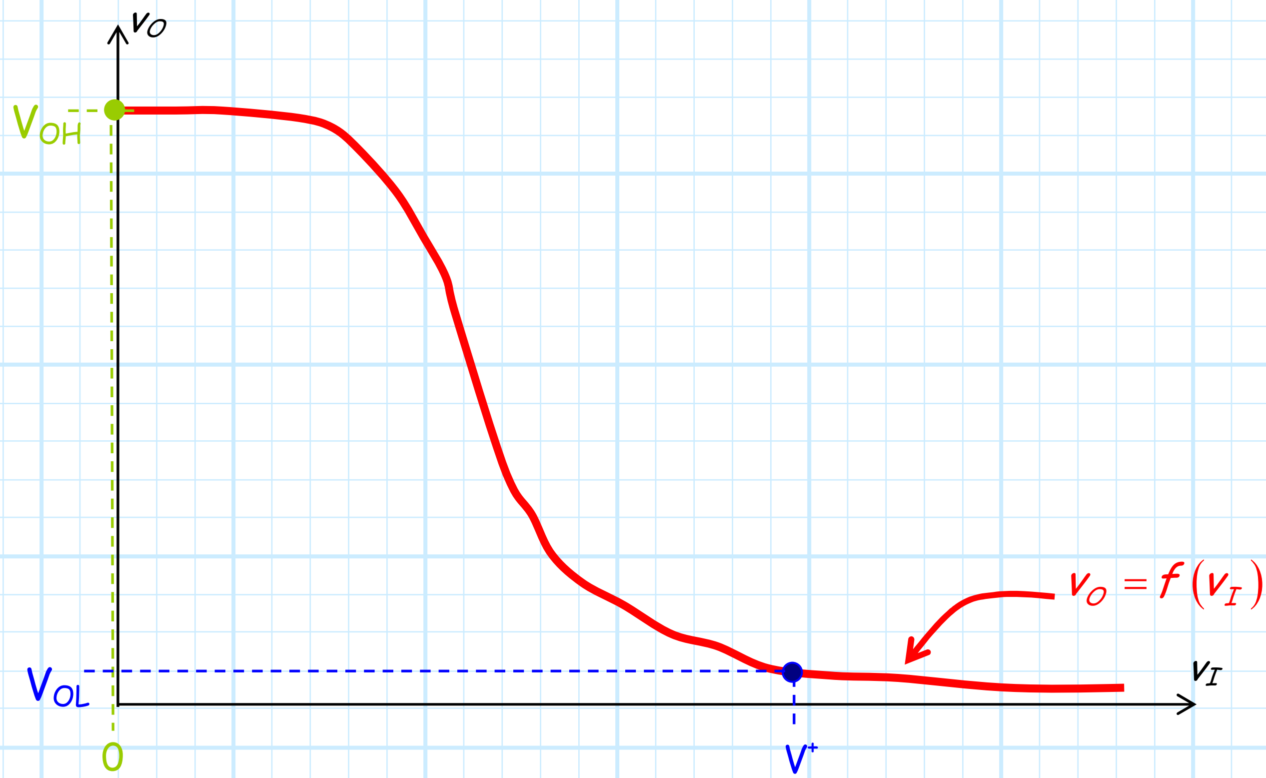
$$\boxed{V_{OH} \doteq v_O \text{ when } v_I = 0}$$

Thus, V_{OH} is essentially the "**ideal**" inverter **high** output, as it is the output voltage when the inverter input is at its ideal low input value v_I=0. Typically, V_{OH} is a value just **slightly** less than supply voltage V^+.

2. Now, let's consider the case when $v_I = V^+$. The output of the digital inverter in this condition is **defined** as V_{OL} (i.e., OL → "output low"), i.e.:

$$\boxed{V_{OL} \doteq v_O \text{ when } v_I = V^+}$$

Thus, V_{OL} is essentially the "**ideal**" inverter **low** output, as it is the output voltage when the inverter input is at its ideal high input value $v_I = V^+$. Typically, V_{OL} is a value just **slightly** greater than 0.



3. The "**boundary**" between region I and the transition region of the transfer function is denoted as $\mathbf{V_{IL}}$ (i.e., IL → "input low"). Specifically, this is the value of the **input** voltage that corresponds to the **first** point on the transfer function where the **slope** is equal to -1.0 (i.e., where $d\,v_O / dv_I = -1.0$).

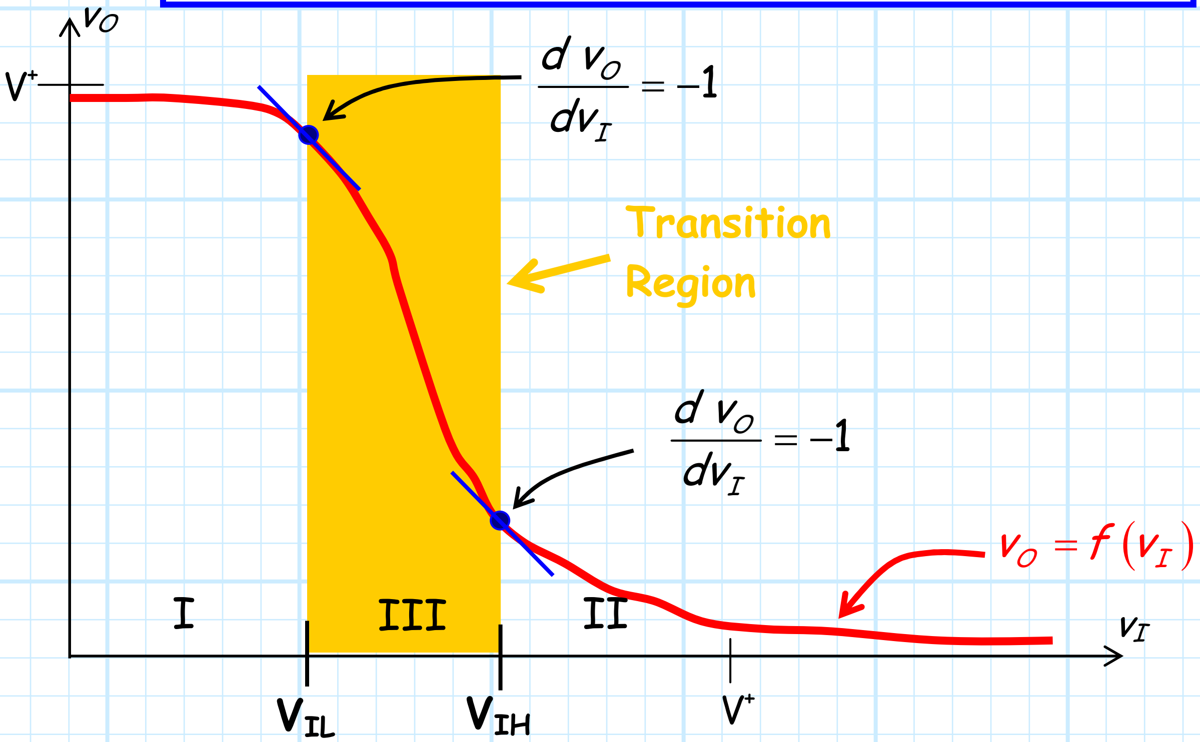
Effectively, the value V_{IL} places an **upper bound** on an acceptably "**low**" value of input v_I—any v_I **greater** than V_{IL} is **not** considered to be a "low" input value. I.E.:

$$v_I \text{ considered "low" only if } v_I < V_{IL}$$

4. Likewise, the "**boundary**" between region II and the transition region of the transfer function is denoted as $\mathbf{V_{IH}}$ (i.e., IH → "input high"). Specifically, this is the value of the **input** voltage that corresponds to the **second** point on the transfer function where the **slope** is equal to -1.0 (i.e., where $dv_O/dv_I = -1.0$).

Effectively, the value V_{IH} places a **lower bound** on an acceptably "**high**" value of input v_I—any v_I **lower** than V_{IH} is **not** considered to be a "high" input value. I.E.:

$$v_I \text{ considered "high" only if } v_I > V_{IH}$$

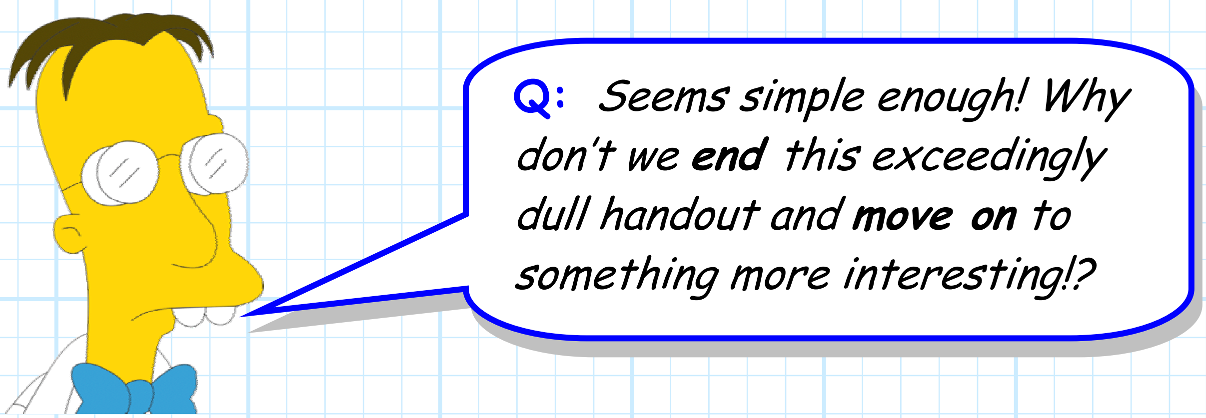


Note then that the **input** voltages of the **transition region** (i.e., $V_{IL} < v_I < V_{IH}$) are **ambiguous** values—we **cannot** classify them as either a digital "low" value or a digital "high" value.

Accordingly, the **output** voltages in the transition region are both significantly less that V_{OH} and significantly larger then V_{OL}. Thus, the **output** voltages that occur in the transition region are **likewise ambiguous** (cannot be assigned a logical state).

Lesson learned → Stay away from the **transition region**!

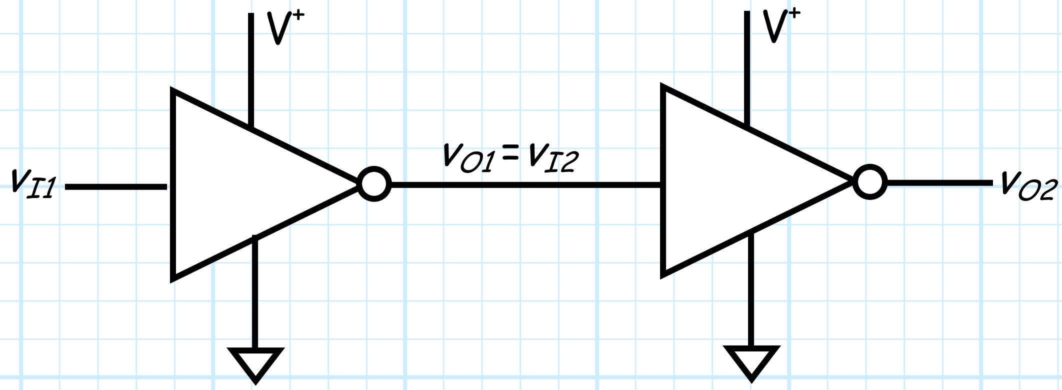
In other words, we must ensure that an **input** voltage representing a logical "**low**" value is **significantly lower** than V_{IL}, and an **input** voltage representing a logical "**high**" value is **significantly higher** than V_{IH}.



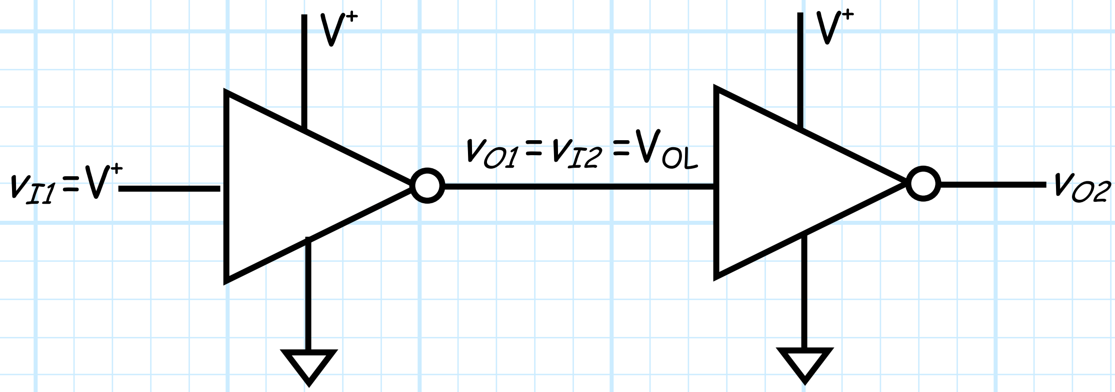
A: Actually, staying **out** of the transition region is sometimes **more difficult** than you might first imagine!

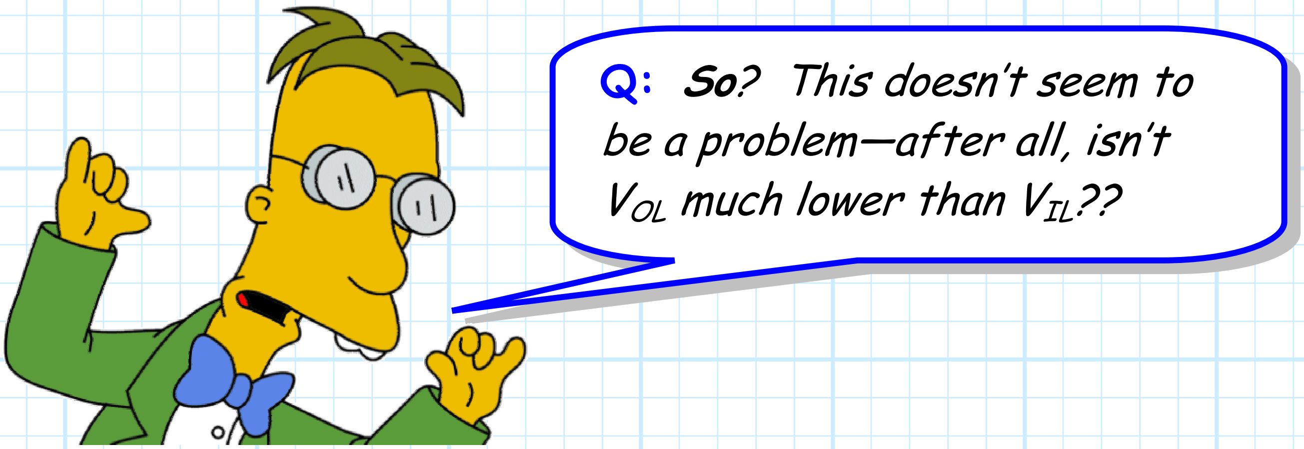
The reason for this is that in a **digital system**, the devices are **connected** together—the input of one device is the output of the other, and vice versa.

For **example**:



Say that the **input** to the **first** digital inverter is $v_{I1} = V^+$. The **output** of that inverter is therefore $v_{O1} = V_{OL}$. Thus, the **input** to the **second** inverter is **likewise** equal to V_{OL} (i.e., $v_{I2} = v_{O2} = V_{OL}$).



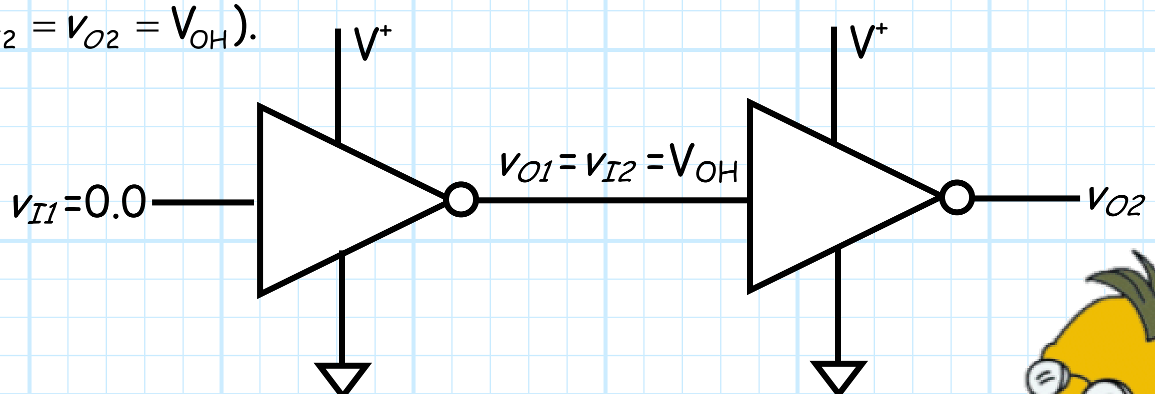


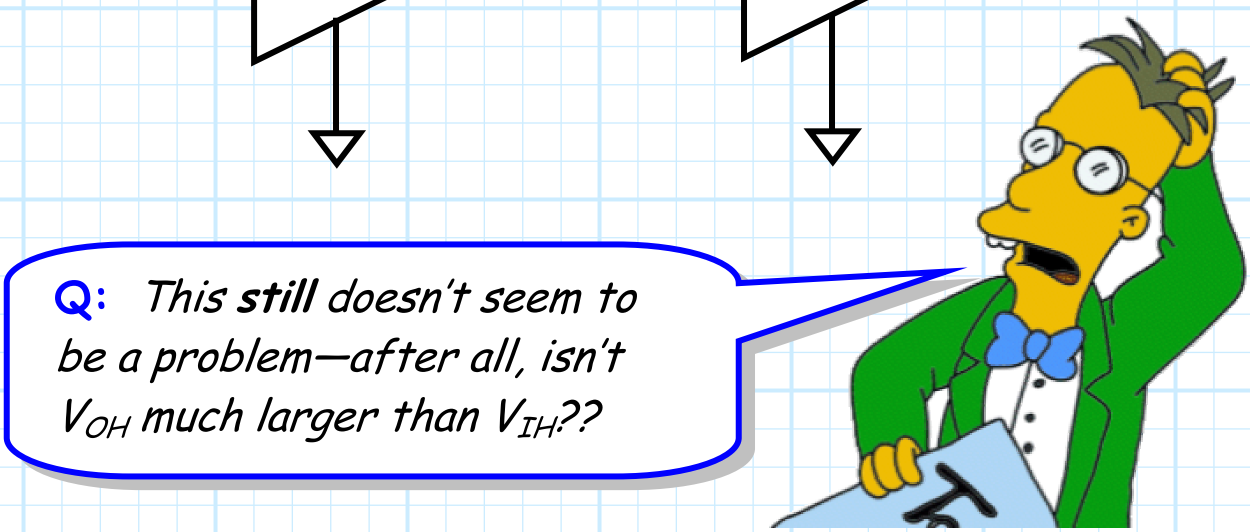
A: True enough! The input $v_{I2}=V_{OL}$ is typically **well below** the maximum acceptable value V_{IL}. In fact, we have a specific name for the **difference** between V_{IL} and V_{OL}—we call this value **Noise Margin** (NM):

$$\boxed{NM_L = V_{IL} - V_{OL} \qquad [Volts]}$$

The noise margin essentially tells us **how close** we are to the **ambiguous** transition region for a typical case where $v_I = V_{OL}$. Of course, we do **not** wish to be close to this transition region at all, so **ideally** this noise margin is **very large**!

Now, consider the **alternate** case where v_{I1}=0.0 V. The **output** of the **first** inverter is therefore $v_{O1} = V_{OH}$. Thus, the **input** to the **second** inverter is **likewise** equal to V_{OH} (i.e., $v_{I2} = v_{O2} = V_{OH}$).



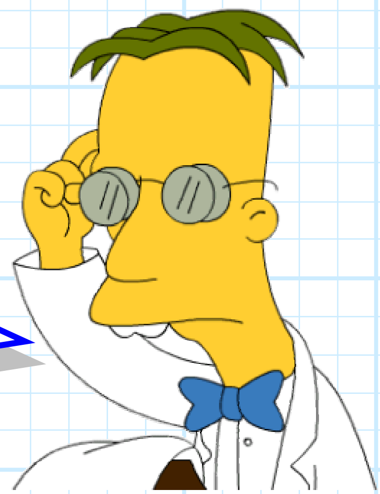


A: Again, this is **true** enough! The input $v_{I2}=V_{OH}$ is typically **well** above the minimum acceptable value V_{IH}. We can **again** specify the **difference** between V_{IH} and V_{OH} as a **noise margin** (NM):

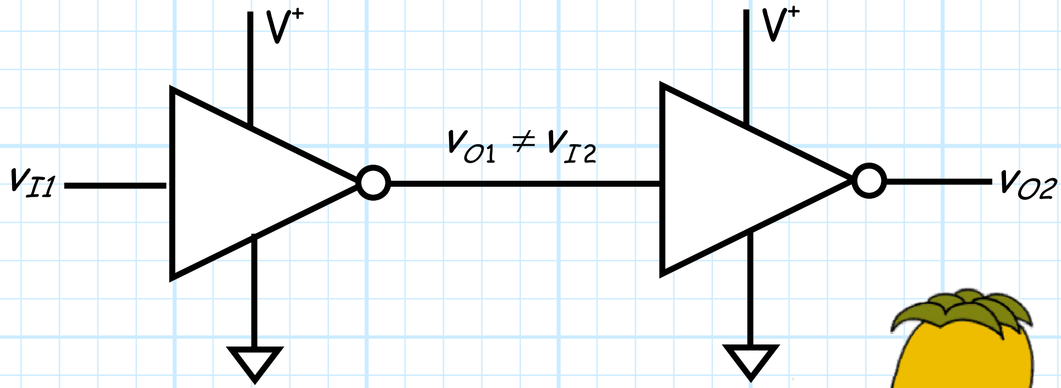
$$NM_H = V_{OH} - V_{IH} \qquad [Volts]$$

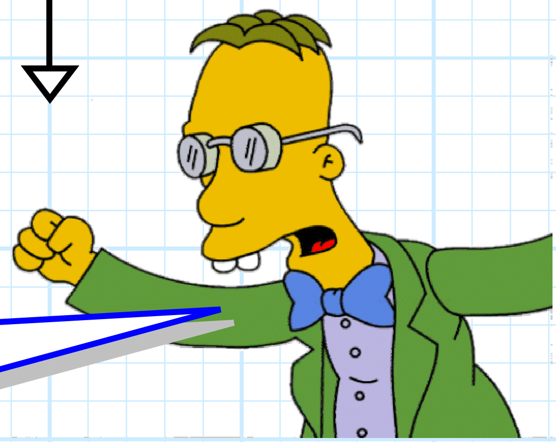
This **noise margin** essentially tells us how **close** we are to the ambiguous **transition region** for a typical case where $v_I = 0.0$ V. Of course, we do **not** wish to be close to this transition region at all, so ideally this noise margin is **very large**!

Q: *I don't see **why** we care about the values of these "noise margins". Isn't the simple fact that $V_{OL}<V_{IL}$ and $V_{OH}>V_{IH}$ **sufficient**?*



A: **Ideally** yes. However, in our example we have made one important **assumption** that in fact may **not** be true! It turns out that in a **real** digital circuit, v_{I2} may **not** be equal to v_{O1} !!





Q: *What! How can this be possible? It appears to **me** that v_{I2} **must** be equal to v_{O1} !?*

A: It turns out that for a **real** digital circuit, a lot can happen **between** the output of one device and the input to another. The voltage at the input of a device might be affected by **many** sources—**only one** of which is the output device connected to it!

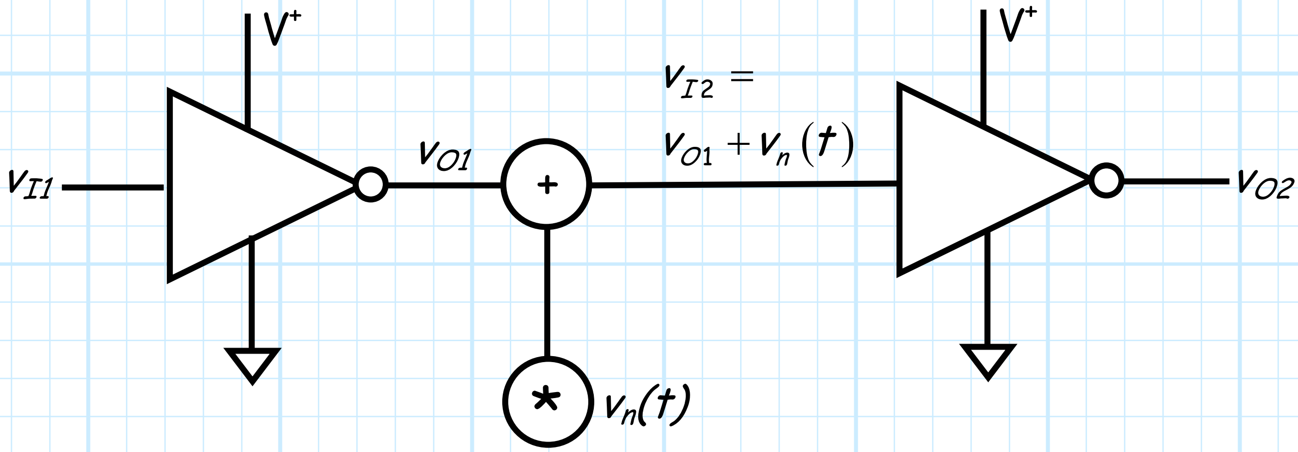
Examples of these "**extra**" sources include:

1. Thermal **noise**

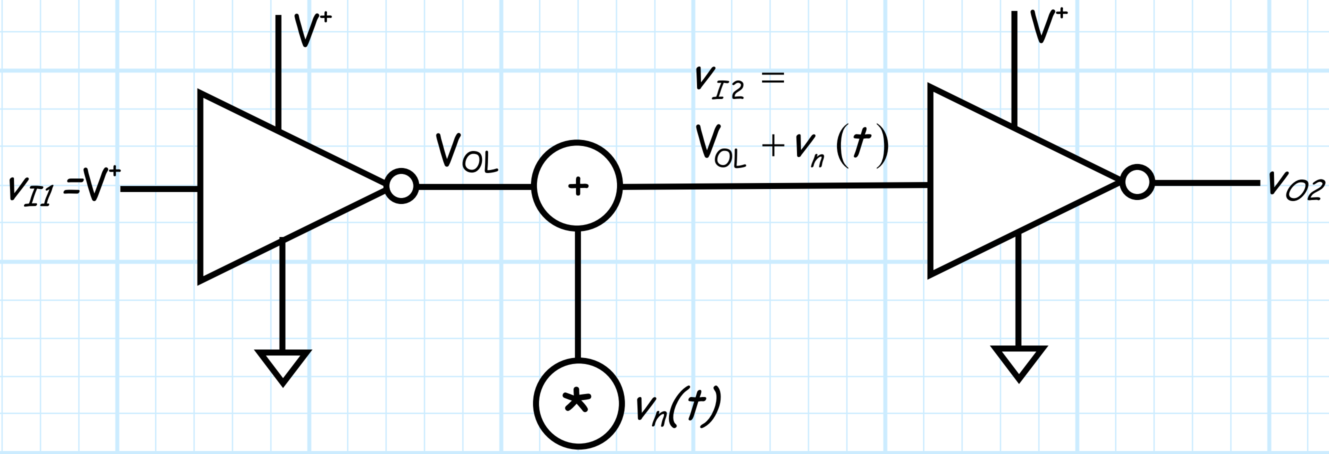
2. Coupled signals

3. Power supply **transients**

We will **combine** the effect of **all** of these sources together into one "**noise**" source $v_n(t)$. Thus, a **better model** for our digital circuit example is:



Now, let's **reconsider** the case where $v_{I1} = V^+$. We find that the **input** to the **second** digital inverter is then $v_{I2} = V_{OL} + v_n(t)$:



Now we see the **problem**! If the **noise** voltage is **too large**, then the **input** to the second inverter will **exceed** the maximum low input level of V_{IL}—we will have entered the dreaded **transition region**!!!!

To **avoid** the transition region, we find that the **input** to the **second** inverter must be less than V_{IL}:

$$\begin{aligned} V_{OL} + v_n(t) &< V_{IL} \\ v_n(t) &< V_{IL} - V_{OL} \\ v_n(t) &< NM_L \end{aligned}$$

Look at what this means! It says to avoid the transition region (i.e., for the input voltage to have an unambiguously "low" digital level), the **noise** must be **less** than **noise margin** NM_L for **all time** t!

Thus, if the **noise margin** NM_L is **large**, the noise $v_n(t)$ can be large **without** causing any deleterious effect (deleterious effect→transition region). Conversely, if the noise margin NM_L is **small**, then the noise **must** be small to avoid **ambiguous** voltage levels.

Lesson learned → **Large noise margins are very desirable**!

Considering **again** the example circuit, only this time with v_I=0.0 V, we find that to **avoid** the transition region (verify this for yourself!):

$$\begin{aligned} V_{OH} + v_n(t) &> V_{IH} \\ v_n(t) &> V_{IH} - V_{OH} \\ v_n(t) &> -NM_H \\ -v_n(t) &< NM_H \end{aligned}$$

Note that the noise $v_n(t)$ is **as likely** to be positive as negative—it is in fact **negative** valued noise that will send v_{I2} to a value **less** than V_{IH}!

Thus, we can make the statement that the **magnitude** of the **noise** $v_n(t)$ must be **less** than the **noise margins** to avoid the ambiguous values of the disturbing **transition region**! I.E., make sure that:

$$|v_n(t)| < NM \qquad \text{for all time } t$$