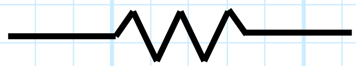
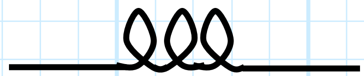
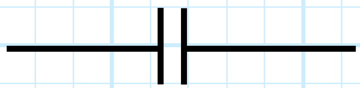
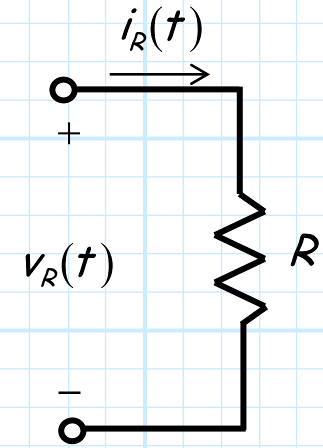
# Linear Circuit Elements

Most microwave devices can be described or modeled in terms of the **three** standard circuit elements:

1. RESISTANCE (R) 
2. INDUCTANCE (L) 
3. CAPACITANCE (C) 

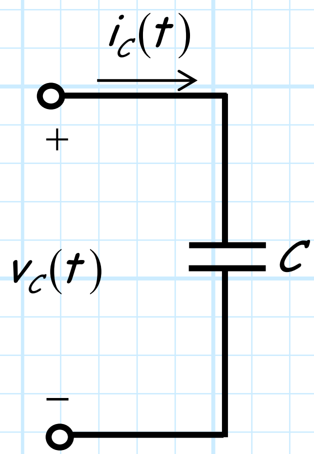
For the purposes of circuit analysis, each of these three elements are **defined** in terms of the **mathematical** relationship between the difference in electric potential $v(t)$ between the two terminals of the device (i.e., the **voltage** across the device), and the **current** $i(t)$ flowing through the device.

We find that for these three circuit elements, the relationship between $v(t)$ and $i(t)$ can be expressed as a linear operator!



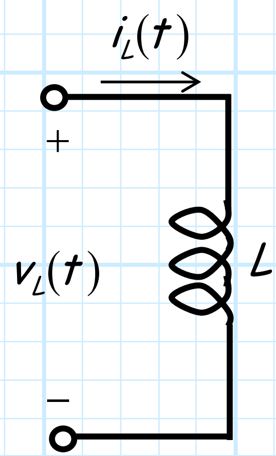

$$\mathcal{L}_{\mathcal{Y}}^{R}\left[v_R(t)\right] = i_R(t) = \frac{v_R(t)}{R}$$

$$\mathcal{L}_{\mathcal{Z}}^{R}\left[i_R(t)\right] = v_R(t) = R\, i_R(t)$$




$$\mathcal{L}_{\mathcal{Y}}^{C}\left[v_C(t)\right] = i_C(t) = C\,\frac{d\,v_C(t)}{d\,t}$$

$$\mathcal{L}_{\mathcal{Z}}^{C}\left[i_C(t)\right] = v_C(t) = \frac{1}{C}\int_{-\infty}^{t} i_C(t')\,dt'$$




$$\mathcal{L}_{\mathcal{Y}}^{L}\left[v_L(t)\right] = i_L(t) = \frac{1}{L}\int_{-\infty}^{t} v_L(t')\,dt'$$

$$\mathcal{L}_{\mathcal{Z}}^{L}\left[i_L(t)\right] = v_L(t) = L\,\frac{d\,i_L(t)}{d\,t}$$

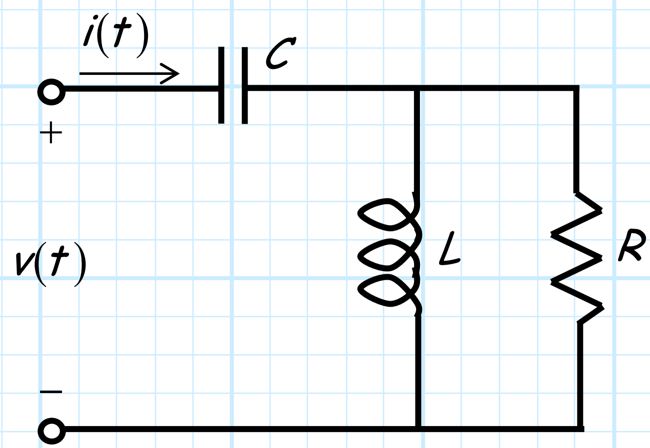
Since the circuit behavior of these devices can be expressed with **linear** operators, these devices are referred to as **linear circuit elements**.

# A linear operator describes any relationship

**Q:** *Well, that's simple enough, but what about an element formed from a **composite** of these fundamental elements?*

*For **example**, for example, how are $v(t)$ and $i(t)$ related in the circuit below??*

$$\mathcal{L}_z\left[i(t)\right] = v(t) = ???$$




**A:** It turns out that **any** circuit constructed **entirely** with linear circuit elements is **likewise** a linear system (i.e., a linear circuit).

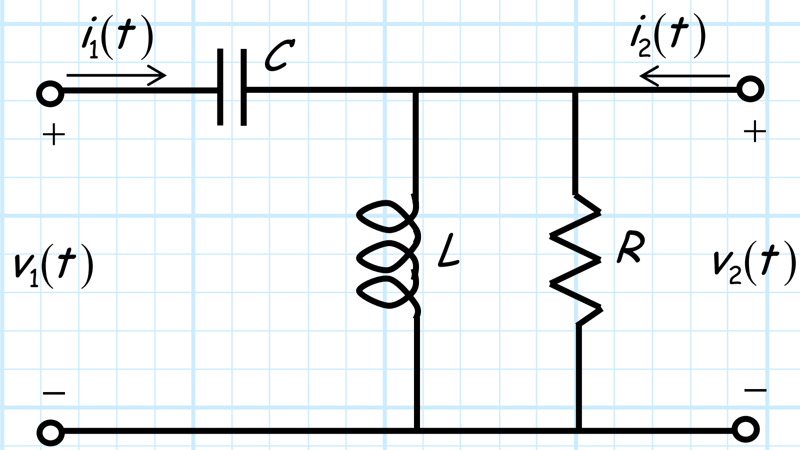
As a result, we know that that there **must** be some linear operator that relates $v(t)$ and $i(t)$ in your example!

$$\mathcal{L}_z\left[i(t)\right] = v(t)$$

# This is very useful for multi-port networks

The circuit above provides a good example of a **single-port** (a.k.a. **one-port**) network.

We can of course construct networks with **two or more** ports; an example of a **two-port network** is shown below:




Since this circuit is **linear**, the relationship between **all** voltages and currents can likewise be expressed as **linear operators, e.g.**:

$$\mathcal{L}_{21}\left[v_1(t)\right] = v_2(t) \qquad \mathcal{L}_{Z21}\left[i_1(t)\right] = v_2(t) \qquad \mathcal{L}_{Z22}\left[i_2(t)\right] = v_2(t)$$

# The linear operator is a convolution integral

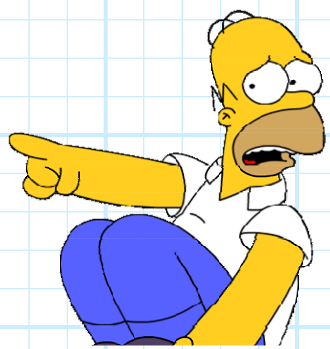
**Q:** *Yikes! What would these linear operators for this circuit **be**? How can we **determine** them?*

**A:** It turns out that linear operators for **all** linear circuits can all be expressed in precisely the **same** form!

For example, the linear operators of a single-port network are:

$$v(t) = \mathcal{L}_{\mathcal{Z}}\left[i(t)\right] = \int_{-\infty}^{t} g_{\mathcal{Z}}(t-t')\; i(t')\,dt'$$

$$i(t) = \mathcal{L}_{\mathcal{Y}}\left[v(t)\right] = \int_{-\infty}^{t} g_{\mathcal{Y}}(t-t')\; v(t')\,dt'$$



In other words, the linear operator of linear circuits can always be expressed as a **convolution** integral—a convolution with a **circuit impulse function** $g(t)$.

# The impulse response

**Q:** *But just what **is** this "circuit impulse response"??*

**A:** An impulse response is simply the **response** of one circuit function (i.e., $i(t)$ or $v(t)$) due to a **specific** stimulus by another.

→ That specific stimulus is the **impulse function** $\delta(t)$.

The impulse function **can** be defined as:

$$\delta(t) = \lim_{\tau \to 0} \frac{1}{\tau} \frac{\sin\left(\frac{\pi t}{\tau}\right)}{\left(\frac{\pi t}{\tau}\right)}$$

Such that is has the following two **properties**:

**1.** $\delta(t) = 0 \quad \text{for} \quad t \neq 0$

**2.** $\int_{-\infty}^{\infty} \delta(t)\, dt = 1.0$

# We can define all sorts of impulse responses

The impulse responses of the **one-port example** are therefore defined as:

$$g_z(t) \doteq v(t)\big|_{i(t)=\delta(t)}$$

and:

$$g_y(t) \doteq i(t)\big|_{v(t)=\delta(t)}$$

Meaning simply that $g_z(t)$ is equal to the **voltage** function $v(t)$ when the circuit is "thumped" with a **impulse current** (i.e., $i(t)=\delta(t)$), and $g_y(t)$ is equal to the **current** $i(t)$ when the circuit is "thumped" with a **impulse voltage** (i.e., $v(t)=\delta(t)$).

# We can make convolution integrals simple!

Similarly, the relationship between the **input** and the **output** of a **two-port** network can be expressed as:

$$v_2(t) = \mathcal{L}_{21}\left[v_1(t)\right] = \int_{-\infty}^{t} g(t-t')\, v_1(t')\, dt'$$

where:

$$g(t) \doteq v_2(t)\Big|_{v_1(t)=\delta(t)}$$

Note that the circuit impulse response must be **causal** (nothing can occur at the output **until** something occurs at the input), so that:

$$g(t) = 0 \quad \text{for} \quad t < 0$$

**Q:** *Yikes! I recall evaluating convolution integrals to be messy, difficult and* ***stressful****. Surely there is an* ***easier*** *way to describe linear circuits!?!*

**A:** Nope! The convolution integral is **all** there is.

**However,** we can use our linear systems theory toolbox to greatly **simplify the evaluation** of a convolution integral!