E. Circulators and Isolators

Q: *You made a big deal about* ***linear*** *devices and* ***passive*** *devices and* ***reciprocal*** *devices, but we have yet to discuss even one microwave device that is* ***all*** *of those things. Are Circulators and Isolators* ***all*** *of those things?*

A: Nope. They **are** linear, and they **are** passive, but they are **not reciprocal**. It is their non-reciprocal nature that makes them **useful**!

HO: The Circulator

HO: The Isolator

Circulators

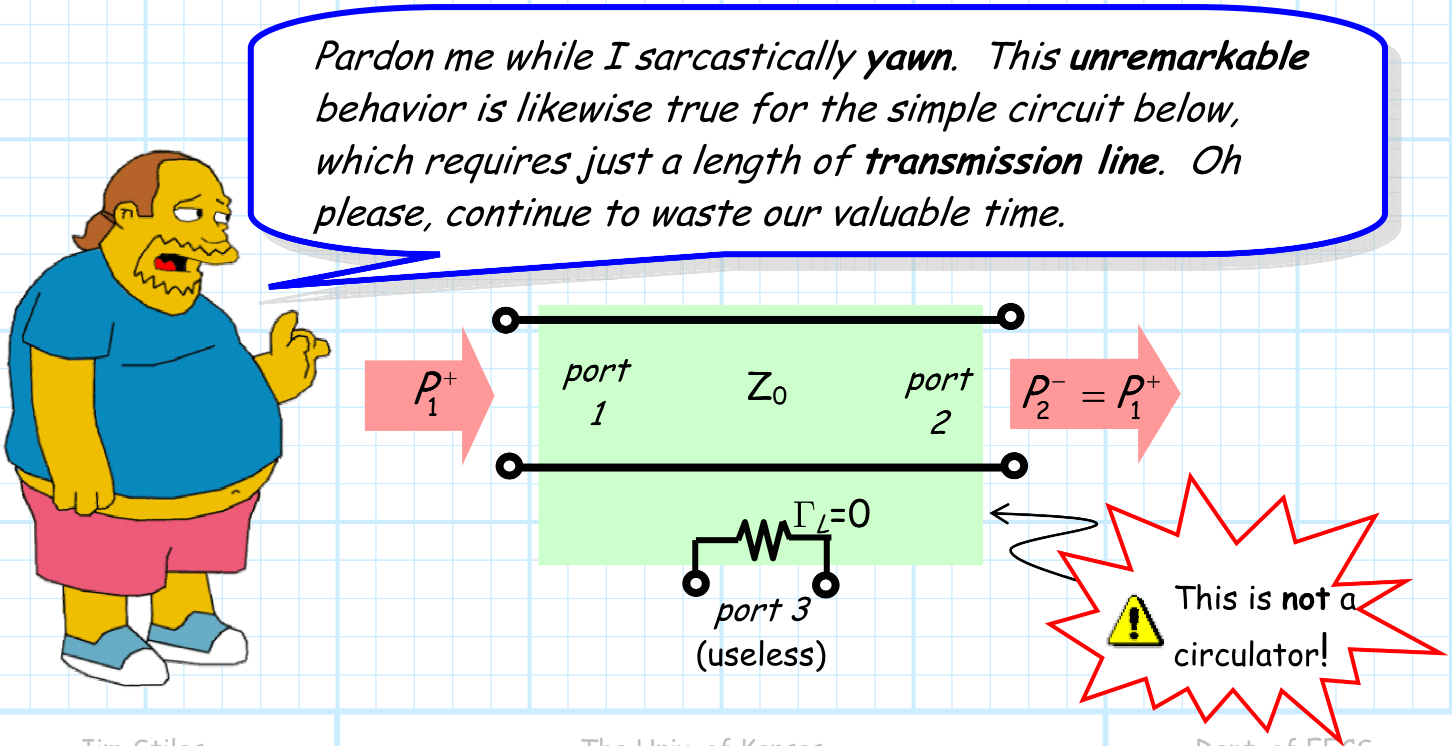
A circulator is a matched, lossless but **non-reciprocal** 3-port device, whose scattering matrix is **ideally**:

$$\mathcal{S} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

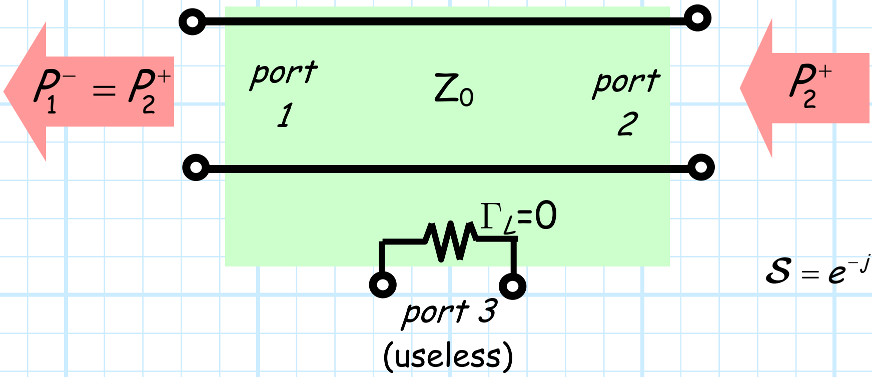
Circulators use anisotropic **ferrite** materials, which are often "biased" by a permanent magnet! → The result is a **non-reciprocal** device!

First, we note that for a circulator, the power incident on port 1 will exit **completely** from port 2:

$$P_2^- = P_1^+$$

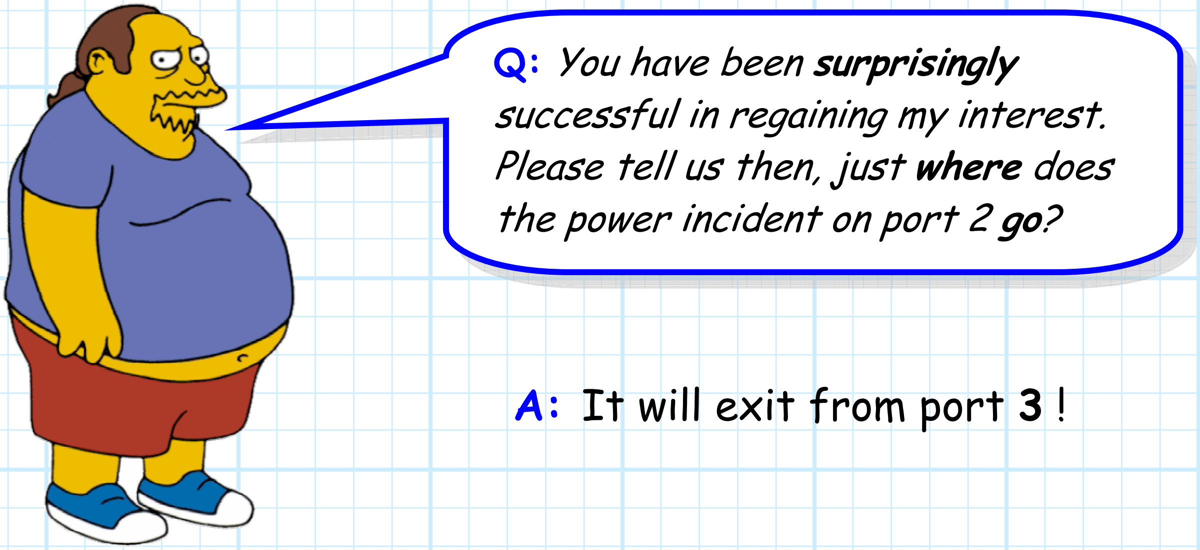


True! But a transmission line, being a **reciprocal** device, will likewise result in the power **incident** on **port 2** of your simple circuit to **exit** completely from **port 1** ($P_1^- = P_2^+$):



$$\mathcal{S} = e^{-j\beta\ell}\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

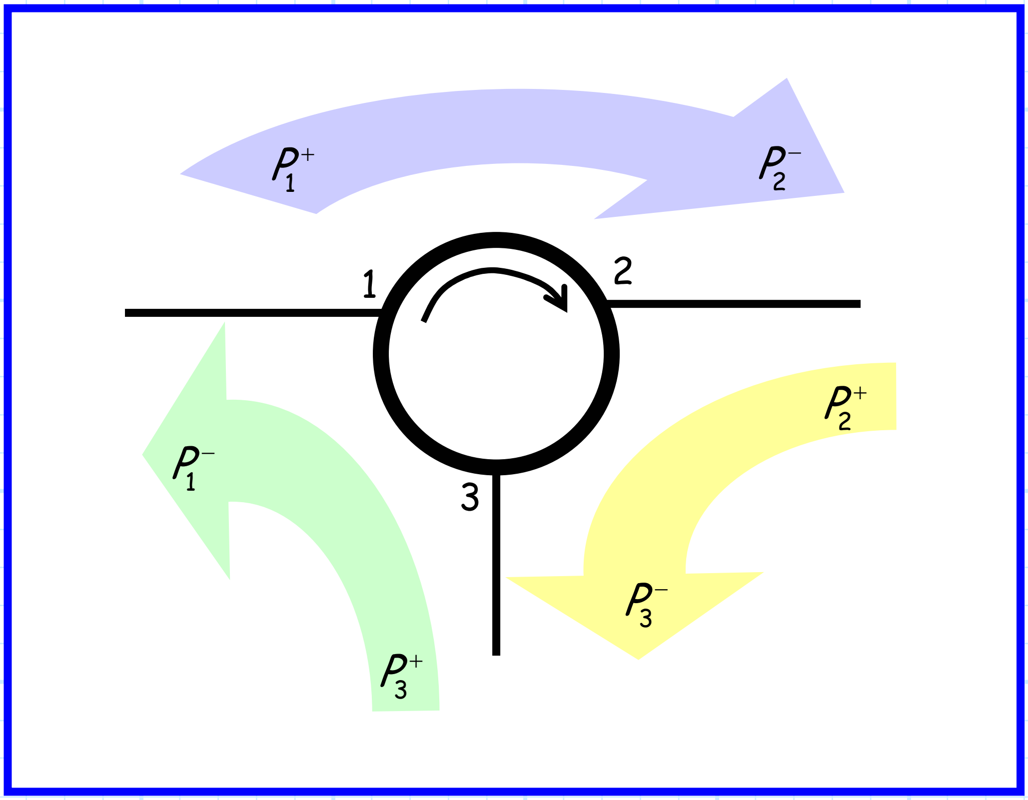
But, this is **not** true for a circulator! If power is incident on port 2, then **no power** will exit port 1 !



A: It will exit from port **3** !

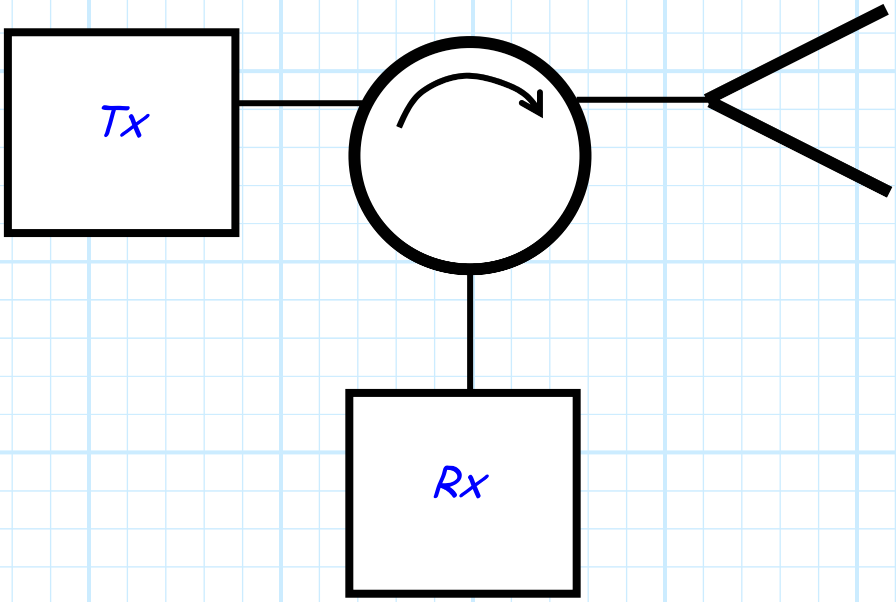
Likewise, power flowing into **port 3** will exit—**port 1**!

It is evident, then how the circulator gets its **name**: power appears to **circulate** around the device, a behavior that is emphasized by its device **symbol**:



We can see that, for example, a **source** at port **2** "thinks" it is attached to a **load** at port **3**, while a **load** at port **2** "thinks" it is attached to a **source** at port **1**!

This behavior is useful when we want to use **one** antenna as **both** the transmitter and receiver antenna. The transmit antenna (i.e., the load) at port 2 **gets** its power from the transmitter at **port 1**. However, the receive antenna (i.e., the source) at port 2 **delivers** its power to the receiver at **port 3**!



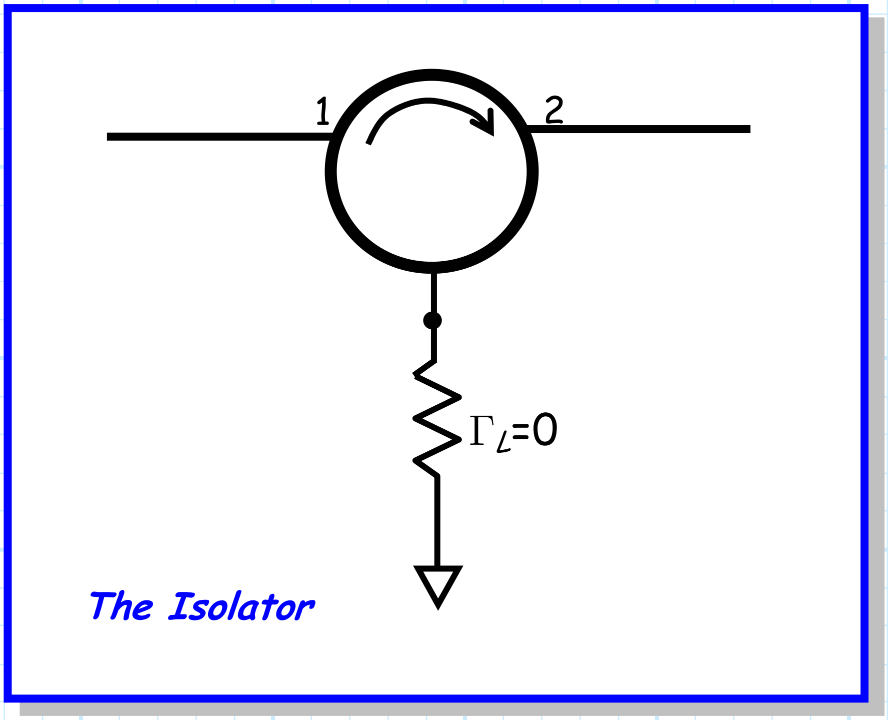
It is **particularly** important to keep the transmitter power from getting to the receiver. To accomplish this, the **antenna** must be **matched** to the transmission line. Do **you** see why?

Finally, we should note some major **drawbacks** with a circulator:

1. They're **expensive**.
2. They're **heavy**.
3. The generally produce a large, static **magnetic field**.
4. They typically exhibit a large **insertion loss** (e.g., $|S_{21}|^2 = |S_{32}|^2 = |S_{13}|^2 \approx 0.75$).

Isolators

An **isolator** is simply a **circulator**, with port 3 terminated in a **matched** load!



The Isolator

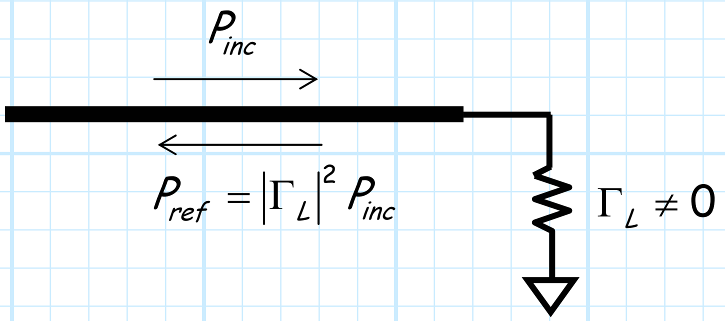
The matched load at port 3 insures that $P_3^+ = 0$ **always**. As a result we know that $P_1^- = P_3^+ = 0$ —**always**!

An ideal isolator is thus a **two-port** device with an **odd** looking scattering matrix:

$$\mathcal{S} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$$

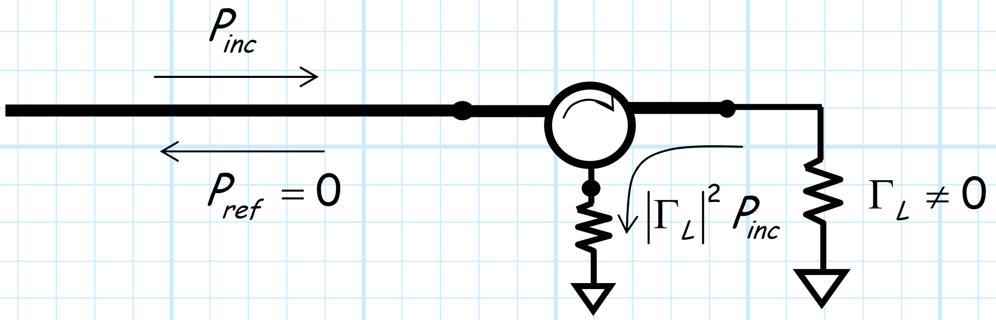
Therefore, $P_2^- = P_1^+$, but $P_1^- = 0$ regardless of P_2^+--an ideal isolator **is** matched, but is also non-reciprocal and **lossy**!

An isolator is useful for **isolating** a load from a source. For example, consider an **unmatched** load at the end of a transmission line:



Plenty of power is reflected back toward the source!

Now, let's **insert** an isolator between the source and load:



There is **no power** reflected back to the source! Instead, power reflected by the load is **absorbed** by the isolator.

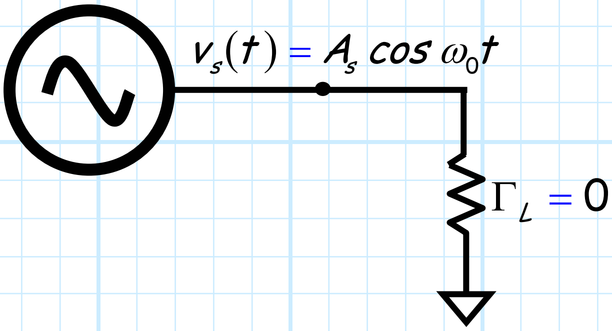
To the source, the circuit appears **matched**—but its **not**!

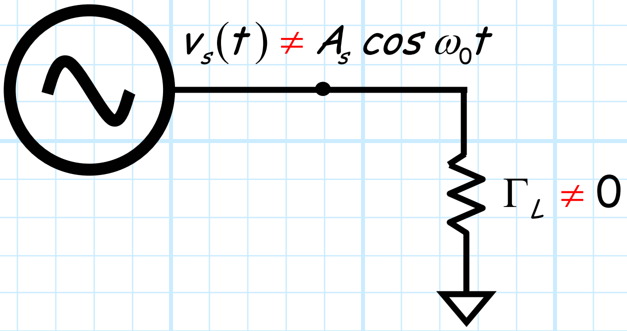
If the isolator was truly a matching network, then the **absence** of reflected power would indicate that **all** the incident power was absorbed by the **load**. Instead, there is no reflected power because this power is instead absorbed by the **isolator**—the isolator is **lossy**!

Q: *So what **good** is this device? Why would we care if the device "looks" like a matched load if in fact the power is **not** efficiently delivered to it?*

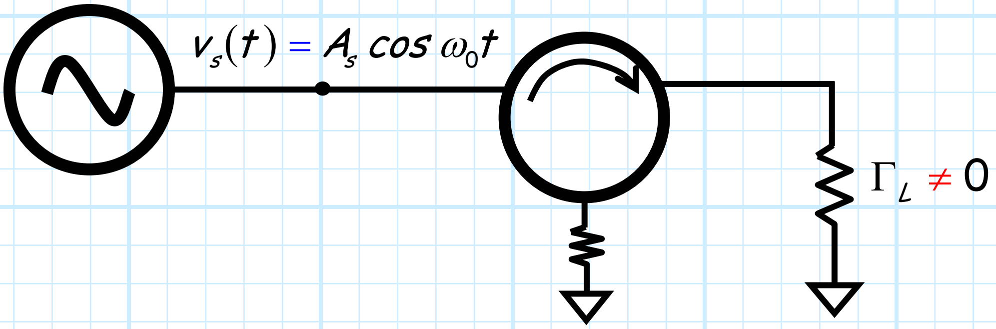
A: There are many devices whose **"behavior"** is dependent on the impedance of the devices attached to it. Devises are designed (typically) to provide optimal performance when they are attached to **other** matched devices. If they not, then (in **addition** to inefficient power transfer) the performance of the device may be degraded.

For example, consider the problem of **frequency pulling** with regard to a microwave oscillator. Recall that a **mismatched** load will cause the **frequency** of the signal to **shift** from its ideal value ω_0.





If we place an **isolator** between the source and the load, we can **fix this problem**!



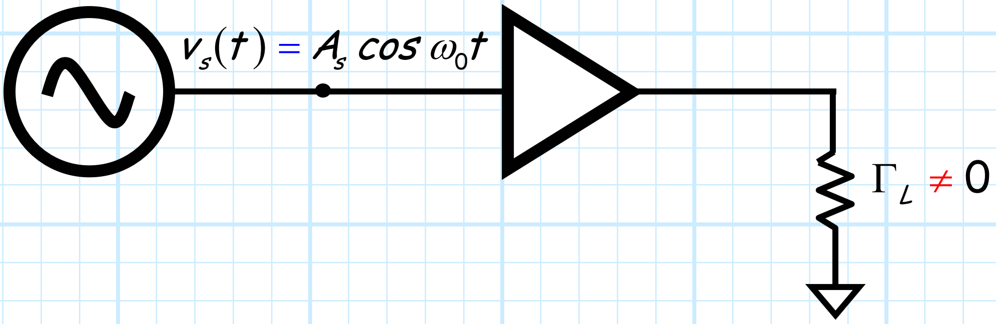
But remember, the power delivered to this mismatched load is **less** than that available at the source!

Q: *So why wouldn't we use a lossless **matching network** instead of an isolator? With a matching network we eliminate frequency pulling **and** provide maximum power transfer to the load.*

A: Making a good wideband matching network is more **difficult** than you might imagine, particularly when the load you're matching to is **badly** mismatched and **changes** significantly as a function of frequency (i.e., the **LO port** of a mixer).

It turns out that an **isolator** will almost certainly provide a better "match" over a **wider** frequency bandwidth.

Q: *In an earlier handout you said that we could isolate an oscillator with an **amplifier**. How does that work?*



A: Remember the scattering matrix for an **ideal amplifier**:

$$\mathcal{S}_{amp} = \begin{bmatrix} 0 & 0 \\ S_{21} & 0 \end{bmatrix} \qquad where \qquad |S_{21}| \gg 1$$

Compare this to the scattering matrix for an **isolator**:

$$\mathcal{S}_{iso} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$$

Note the amplifier has essentially the **same form** ($\mathcal{S}_{12} = 0$) as an isolator, and so it can perform the **same isolation function**!

"Back in the day", microwave amplifiers were **large and expensive**, and so they **rarely** would be used **simply** for providing isolation.

But, with the advent of **MMIC** (monolithic microwave integrated circuits) technology, the price and size of microwave amplifiers have **dramatically** been reduced, such that they now are **commonly** used to provide isolation—particularly around the poorly matched ports of a microwave **mixer**!