# PHYS2641 – Laboratory Skills and Electronics

## Electronics

**Lecture 4**

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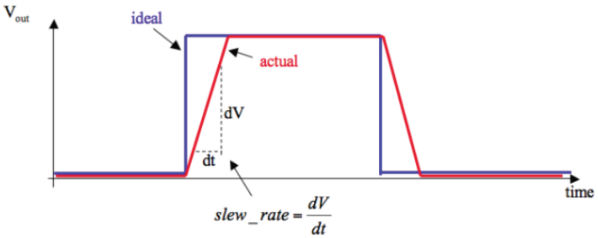
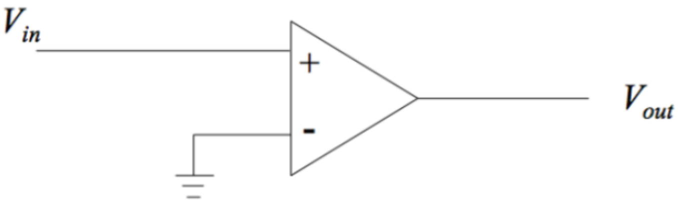
# Last lecture

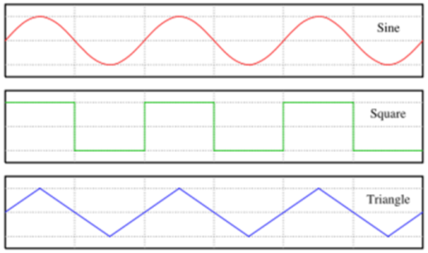
- **Limitations of real op-amps**
  - Gain-bandwidth, slew-rate & saturation




- **Comparators**
  - Simple comparator
  - Schmidt trigger




- **Positive-feedback and oscillators**
  - Barkhausen criteria
  - Square, triangular, and sinusoidal waveforms

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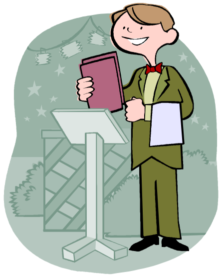
# Today’s menu



Modulation:

- What and why?
- Amplitude modulation (AM)
- [Frequency modulation (FM) – for completeness only, not used in lab classes]
- Pulse-width modulation (PWM)

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# What is ‘modulation’?

Modulation uses a *‘carrier’ signal*, which we can use to alter the properties of (or ‘modulate’) the waveform to *encode* the signal we want to transmit

There are many properties of a waveform which may be modulated – the most common are:

- Signal amplitude: Amplitude modulation
- Instantaneous frequency (or phase): Frequency (or phase) modulation
- Waveform shape – e.g. mark:space ratio: Pulse-width modulation

# Why use it?

In some cases it isn’t practical to connect a signal ‘source’ directly to a ‘target’:

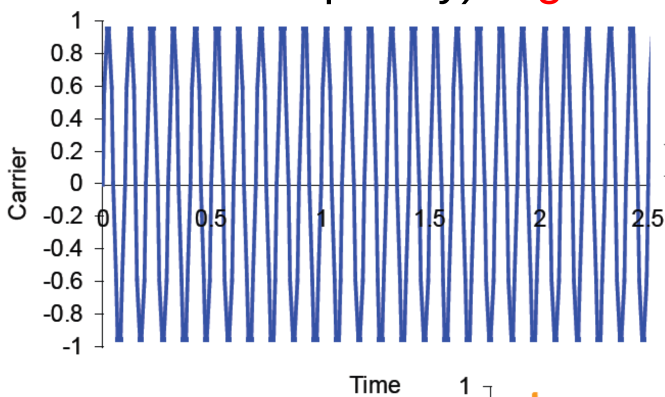
- if the target is remote
- if the source, target, or connection is in a ‘noisy’ environment
- if you have limited bandwidth (e.g. telephone line)
- if you need to have several channels of communication running in parallel (e.g. TV/radio stations)
- if you need to communicate with multiple targets in unknown locations
- if you need to transmit information through a non-linear system without losing information

Modulation allow us to transmit or broadcast data through a ‘noisy’ connection

Jupyter Demo: Example_Amplitude_modulation.ipynb

# Amplitude modulation (AM)


In an AM signal the (high frequency) ‘carrier’ amplitude is multiplied by the (much lower frequency) ‘signal’ amplitude:

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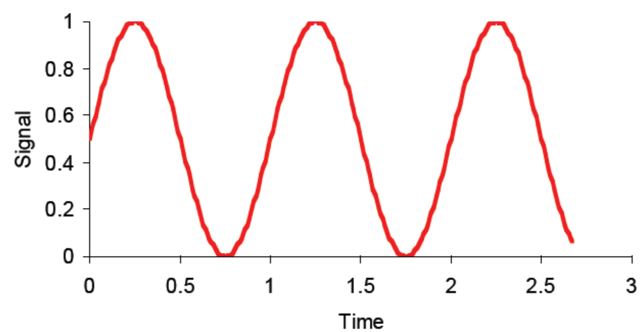


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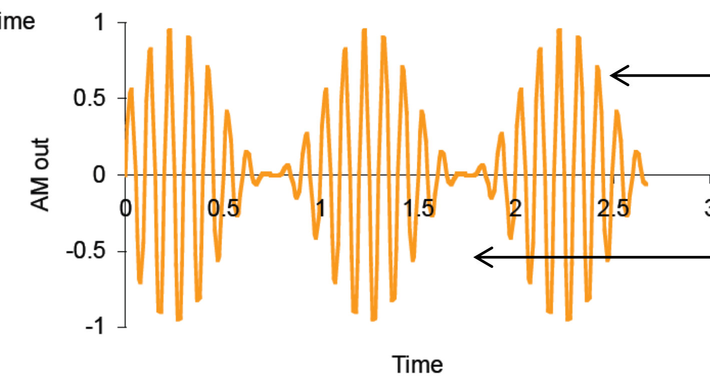


High (carrier) frequency waveform

Envelope function related to ‘signal’

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# Amplitude modulation (2)

The carrier waveform can be modelled as: $c(t) = A_c \cos(\omega_c t + \theta_c)$

Frequency Phase

and the signal waveform is: $s(t) = A_s \cos(\omega_s t + \theta_s)$

The amplitude-modulated signal is $m(t) = c(t) \cdot s(t)$

Using trig. identity $\cos(a)\cos(b) = \frac{1}{2}\left[\cos(a-b) + \cos(a+b)\right]$

We find $m(t) = \frac{A_c A_s}{2}\left[\cos\left([\omega_c - \omega_s]t + [\theta_c - \theta_s]\right) + \cos\left([\omega_c + \omega_s]t + [\theta_c + \theta_s]\right)\right]$

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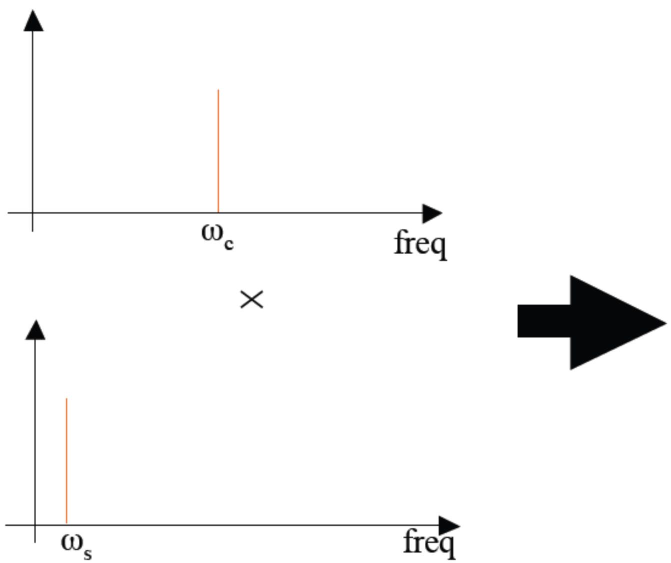
# Amplitude modulation (3)

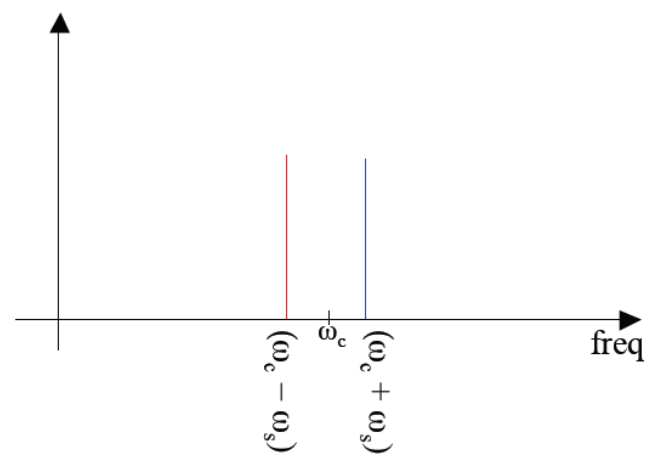
We can set the system so that the phase terms vanish; the amplitude-modulated signal becomes

$$m(t) = \frac{A_c A_s}{2}\left[\cos\left(\left[\omega_c - \omega_s\right]t\right) + \cos\left(\left[\omega_c + \omega_s\right]t\right)\right]$$

Frequency components have **sum** and **difference** terms!




These terms, or freq. components are known as upper and lower *sidebands*



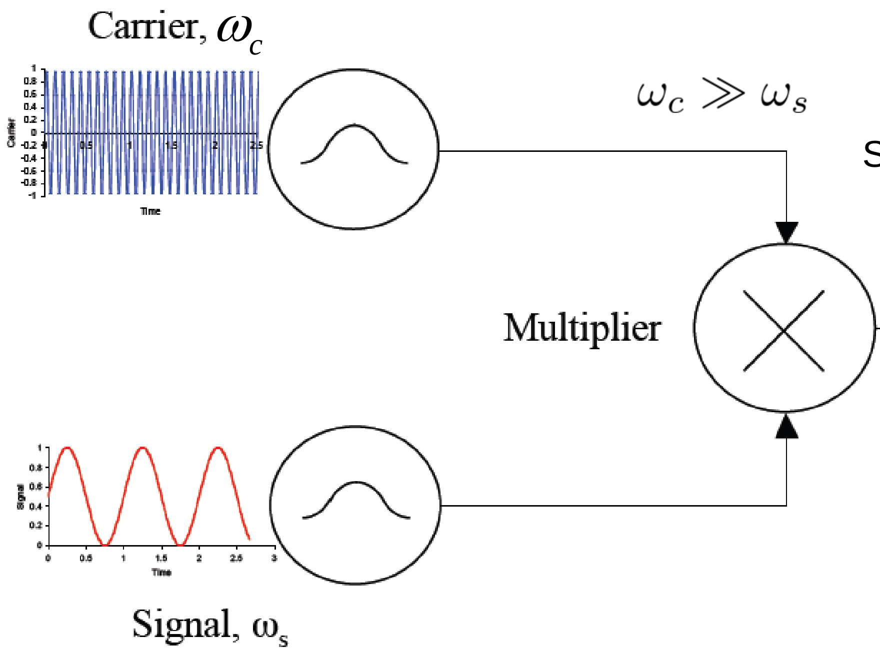

This type of AM signal is called 'dual-sideband suppressed carrier' (DSBSC).
There are many other types...e.g. upper sideband can be removed by a low-pass filter

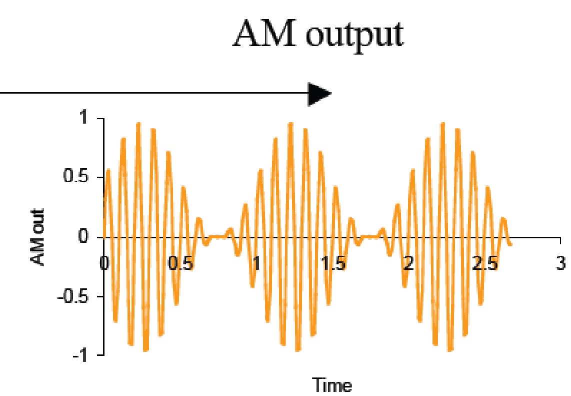
# AM implementation

Amplitude modulation is the simplest form of modulation to implement, only requiring a ‘multiplier’ circuit:

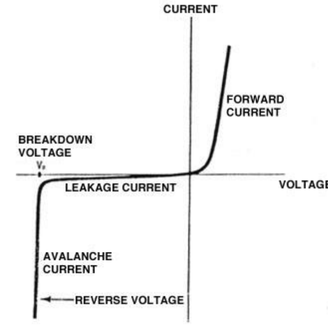
Carrier: ‘Long-wave’ – 153-279 kHz
‘Medium-wave – 531-1611 kHz
‘Short-wave’ – 2.3-26.1 MHz

Signal: AM audio bandwidth – 10.2 kHz



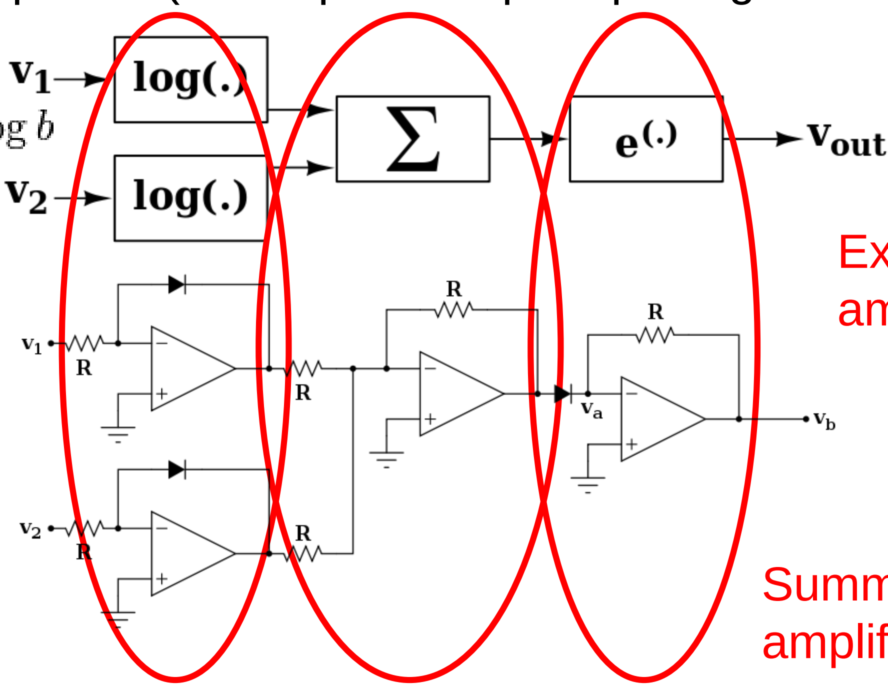
# Aside: Multiplier




Diode: forward-biased current increases exponentially with increasing voltage

Combination of a diode and op-amp can be used to make exponential and logarithmic amplifiers (*c.f.* Capacitor/op-amp integrators & differentiators)

$$\log(a \cdot b) = \log a + \log b$$




Logarithmic amplifiers

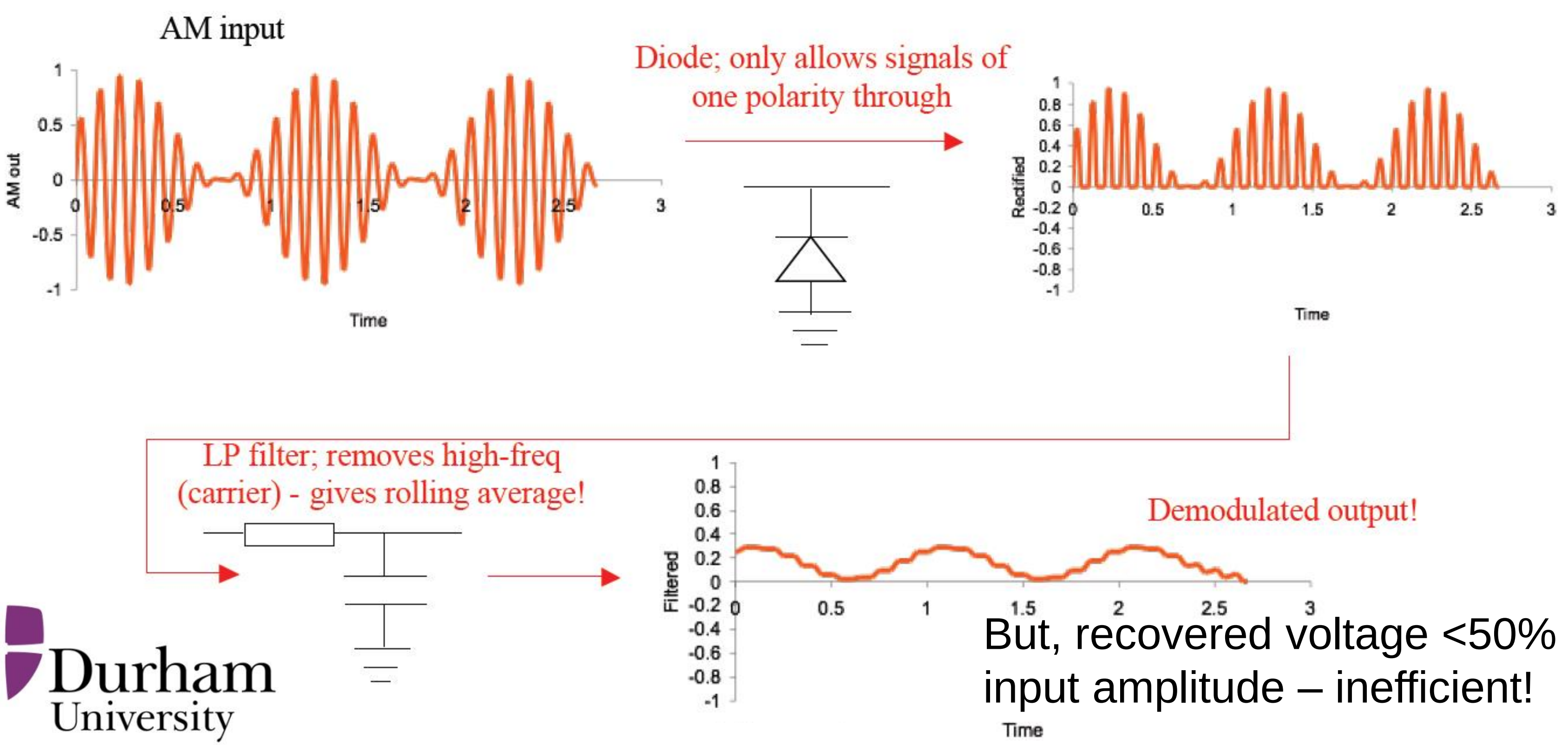
Exponential amplifier

Summing amplifier

A 'simple' (positive quadrant) multiplier

# AM de-modulation

Demodulation is the process of extracting the encoded signal from a modulated signal. The simplest amplitude demodulator circuit uses a diode and a low-pass filter – ‘envelope detector’:




But, recovered voltage <50% of input amplitude – inefficient!

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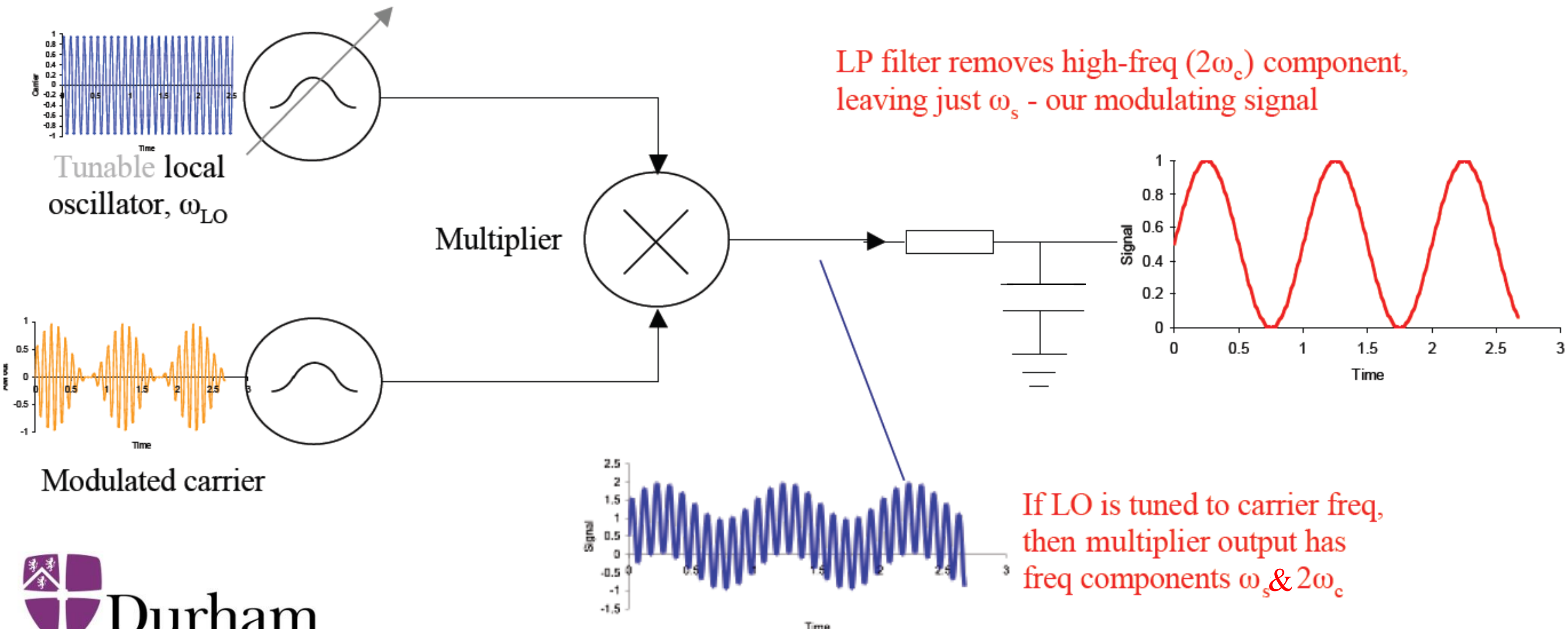
# AM de-modulation (2)

Envelope detection 'throws-away' >75% of the AM signal power (output is <50% of voltage and $P=V^2/R$)

***Heterodyne detection*** is a better system: uses multiplication of the AM signal with a reference signal from a *local oscillator* tuned to the carrier frequency

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# AM summary

Amplitude modulation:

- **is simple to implement** – just needs carrier source, signal source and a multiplier
- **is simple to demodulate**
- **is useful if we want to have multiple simultaneous channels of communication**; each channel can be modulated onto a unique carrier frequency and operate independently. (This is exactly what happens with AM radio stations; each operates on a different frequency – problems only occur when there is overlap between the sidebands of adjacent stations. )

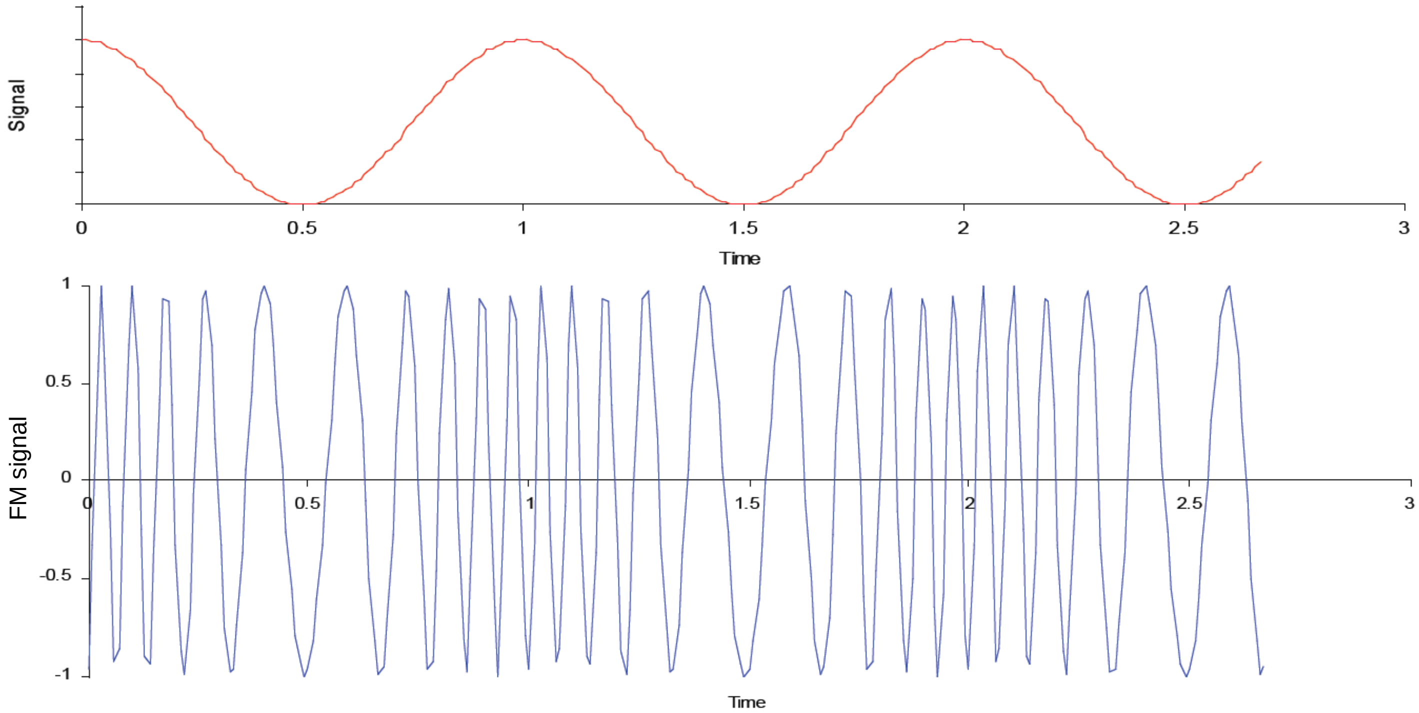
But it is also:

- **prone to interference** – because information is encoded in the amplitude of the modulated signal, any environmental noise which falls within the bandwidth of interest will change the signal level and thus our encoded signal
- **wasteful of bandwidth** – has an upper and a lower sideband, each containing the same information, thus using twice the bandwidth of the original signal and reducing the number of channels we can fit into a given band (and reducing the power efficiency!)*

* note: it is possible to suppress one of the side-bands to improve power and bandwidth efficiency, but at the cost of making the demodulation more complex

# Frequency modulation (FM)

In an FM signal the (high) carrier frequency is modulated around its base value by the instantaneous value of the 'signal' waveform:



# Frequency modulation (2)

The carrier waveform can again be modelled as: $$c(t) = A_c \cos(2\pi f_c t)$$

and the signal waveform is: $$s(t) = A_s \cos(2\pi f_s t)$$

Frequency deviation – 'modulation index'

The frequency-modulated signal is $$m(t) = A_c \cos\left(2\pi \int_0^t \left[ f_c + \beta \cdot s(t') \right] dt' \right)$$

So, for the sinusoidal signal waveform above, $$m(t) = A_c \cos\left(2\pi \left[ f_c + \Delta f A_s \sin(2\pi f_s t) \right]\right)$$

Integral representation used to distinguish FM from 'phase modulation' (PM), where

$$m(t) = A_c \cos(2\pi f_c t + \beta \cdot s(t))$$

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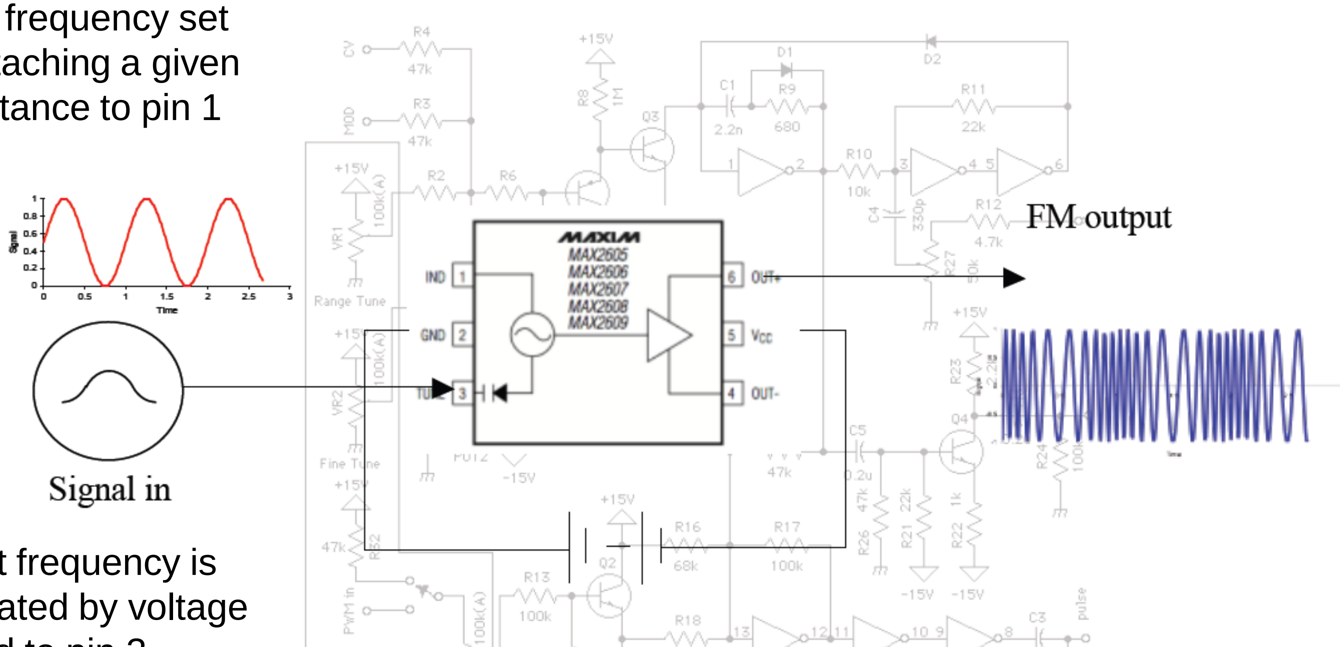
# FM implementation

To produce FM output signal we need a ***voltage-controlled oscillator*** (VCO): the ‘VCF’ (voltage controlled frequency) input on a signal generators can do this.

Base frequency set by attaching a given inductance to pin 1



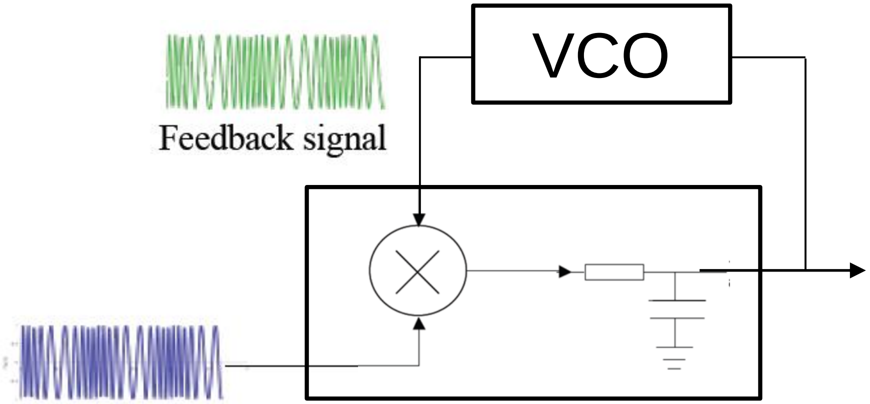

Output frequency is modulated by voltage applied to pin 3

| | |
|---|---|
| Carrier: | Base freq. 87.5-108 MHz |
| Signal: | FM audio bandwidth ~15 kHz |
| Channel separation: | 100 kHz – defines ‘modulation index’ |

# FM de-modulation

Demodulation of an FM signal is usually achieved using a ***phase-locked loop*** (PLL)

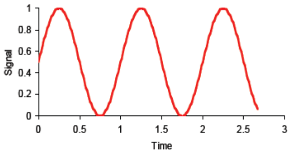
A PLL consists of a local VCO and a phase-detector – which consists of a multiplier and filter (similar to the AM heterodyne demodulator) – in a negative-feedback loop




FM input

Phase detector

**Negative feedback** – the output of the phase detector drives to reduce the error signal – i.e. Such that the *feedback* and *input* signals are ***identical***




Tuning by adjusting base-frequency of VCO with inductance

In this case the ***output*** is then the ***demodulated signal*** – the feedback voltage causes the VCO to produce a signal identical to the FM input; it is identical to the original modulating input!

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# FM summary

Frequency modulation:

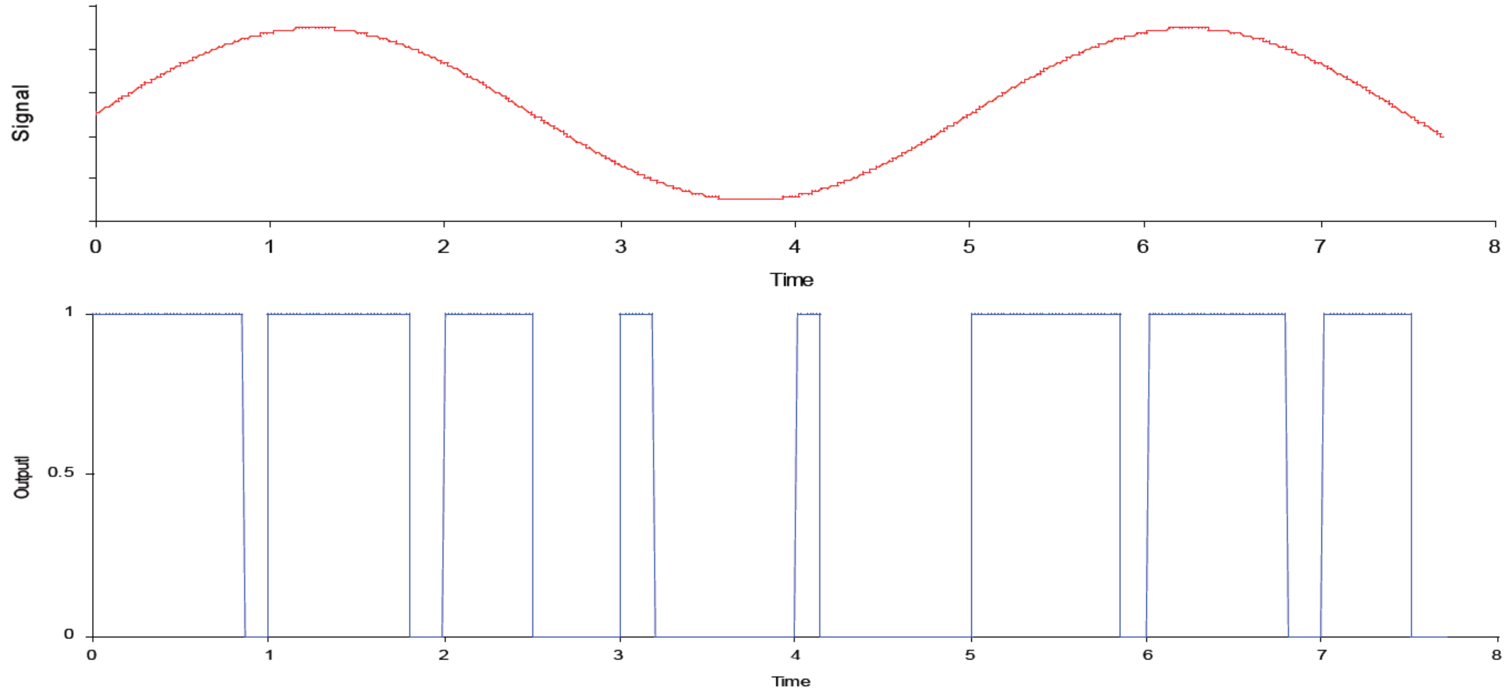
- **is largely immune to interference** – the addition of in-band noise doesn't change the *frequency* of the modulated signal. Noise can make weak signals difficult to demodulate
- **allows multiple simultaneous channels** to be broadcast within a given band by modulating different carrier frequencies (e.g. FM radio stations).

But it also:

- **requires more complex circuitry for modulation**, although off-the-shelf components make it very easy to implement
- **requires much more bandwidth** than an AM signal, and therefore tends to be used at higher carrier frequencies to allow multiple channels (which in the case of radio broadcast means that transmission is much more line-of sight)
- **requires a relatively complex demodulation system**

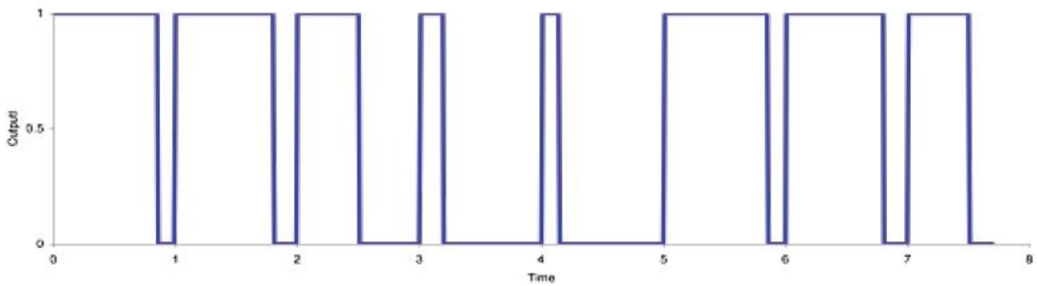
# Pulse-width modulation (PWM)

In a PWM signal the carrier '*mark:space ratio*' (duty-cycle) is modulated by the amplitude of the 'signal' waveform:



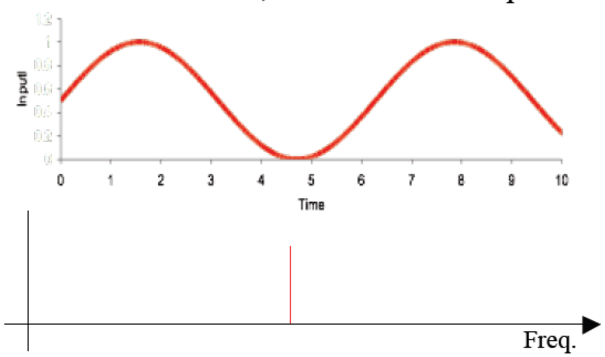
# PWM (2)

A PWM waveform is binary in so much as it is either ‘*high*’ or ‘*low*’; however, the information encoded is truly *analog* – it has *not* been digitised

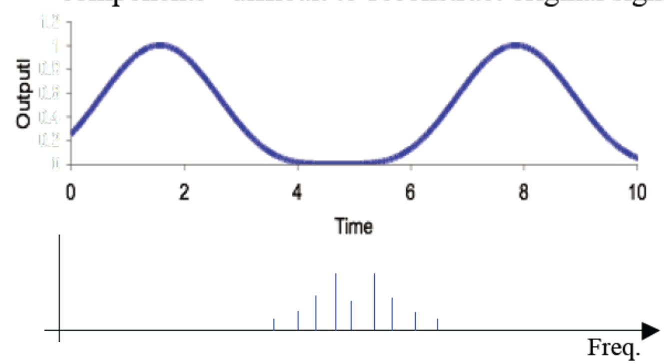



Due to the binary nature of the signal, PWM can transmit a signal through a non-linear system without distortion

e.g. using LED to transmit data to photodiode; LED is non-linear, so for sinusoidal input:




Output is not sinusoidal, and therefore has other frequency components - difficult to reconstruct original signal



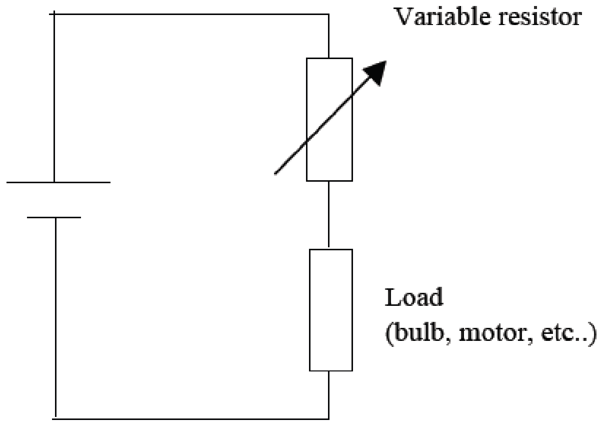

‘Class-D’ audio amplifiers output PWM signal to speakers for this reason

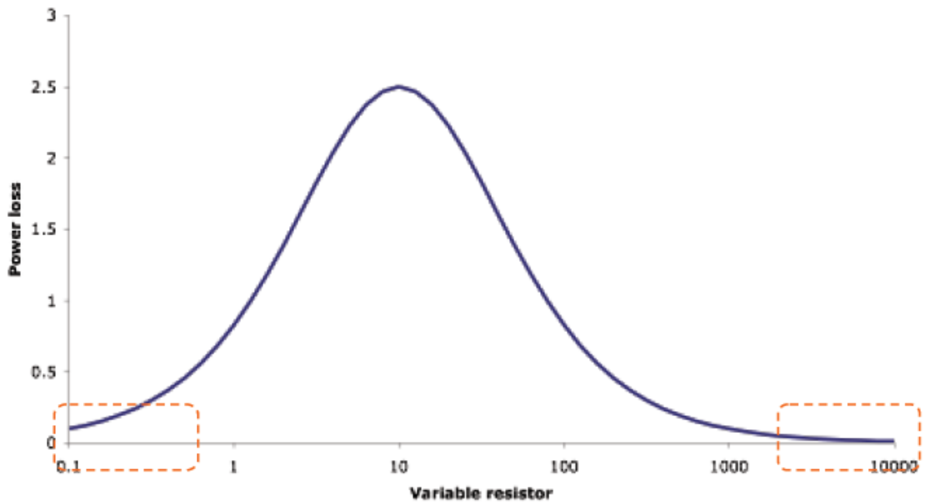
# PWM (3)

## PWM is useful for *efficient power modulation*

We could use a variable resistance in a potential divider to change voltage across a load in order to control power:

However, this is not very efficient; at peak power 50% is dissipated in the variable resistor – wastes energy, heat dissipation may be a problem etc.




Note that when VR is very low or very high, power loss is minimal

# PWM (4)

A very low or very high series resistance is equivalent to turning the power-supply ***on*** or ***off***

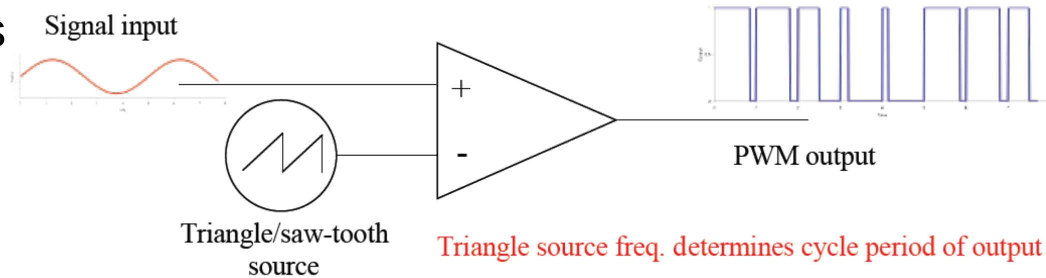
PWM lets us turn the drive power on or off, but also lets us set the ***ratio*** of on:off to control the *average power that is dissipated*

It is far more efficient because very little power is dissipated in the control electronics in either the ‘on’ or ‘off’ state – *c.f.* the variable resistor!

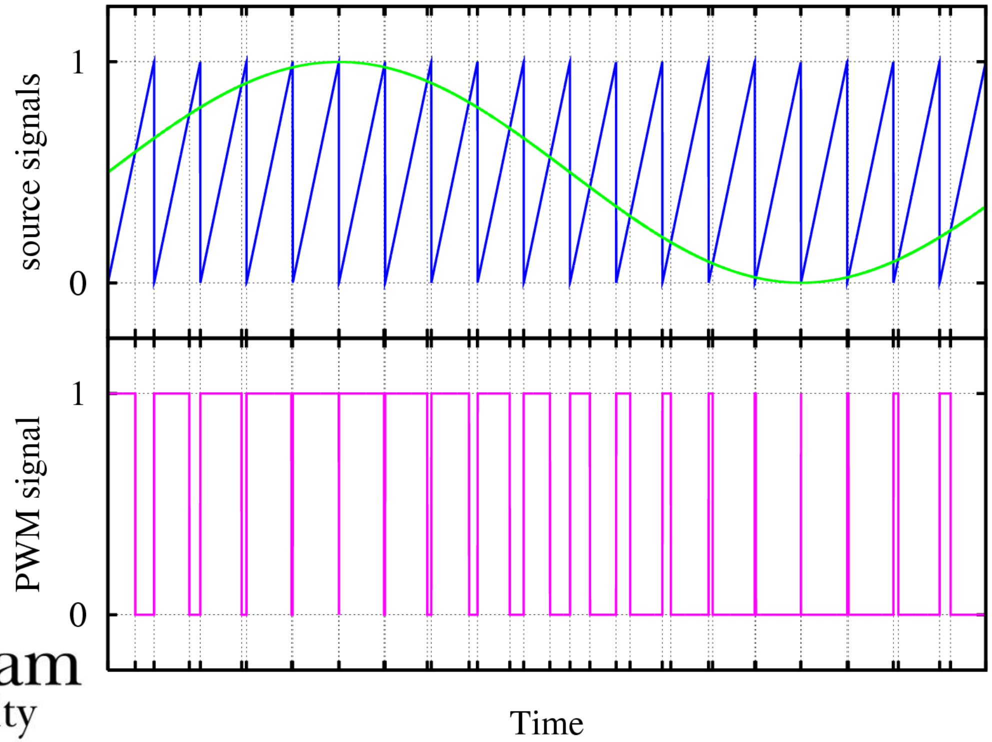
This is very commonly used in switch-mode power supplies for laptop & phone chargers, to control LED brightness in LED car running-lights, dimmer-switches for room lighting, heater output from a temperature controller, etc...

# PWM implementation

Generating a PWM signal is very simple: analog signal is fed into a comparator with a triangle (saw-tooth / linear ramp) waveform:




Triangle source freq. determines cycle period of output (i.e. of carrier)




$V_{sig} < V_{ref} \rightarrow 0$

$V_{sig} > V_{ref} \rightarrow 1$

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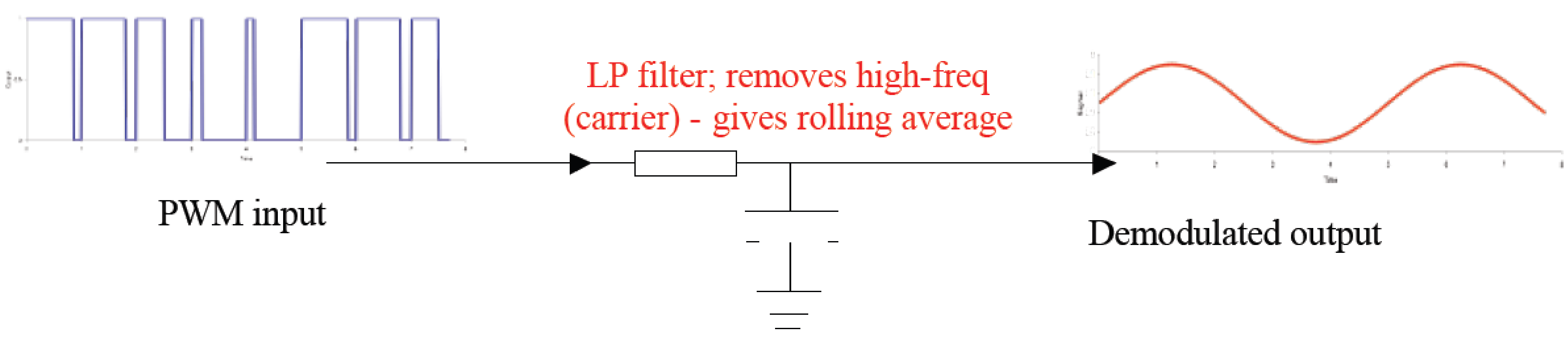
# PWM de-modulation

Demodulation of a PWM signal requires that we extract the ***local average;*** this must be on a time-scale short in comparison with the input signal period, and long in comparison with the carrier period

We can do this with a low-pass filter:

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# PWM summary

PWM:

- **allows an analogue signal to be transmitted through a non-linear system** without distortion
- **is largely immune to interference** – in-band noise is largely filtered out during demodulation
- **has a binary nature** which is well suited to communication via digital logic circuitry
- **allows very efficient power control**

But it also:

- **does not allow multiple simultaneous broadcast** of separate channels through the same system
- **has a complex spectrum**, much wider than bandwidth of modulating signal (can cause interference)
- **requires fast components** (e.g. high slew-rate op-amp) to avoid distortion and non-linearity

# Summary – modulation

**Amplitude modulation:**

- Simple to implement, supports multiple channels
- Prone to interference, generally inefficient

**Frequency modulation:**

- Immune to interference, supports multiple channels
- Large bandwidth requirements, complex to implement

**Pulse-width modulation:**

- Efficient, immune to distortion, simple to implement
- Doesn’t allow multiple channels

# Next lecture:

- Noise in analog systems
- Phase-sensitive (lock-in) detection

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