ENGG1300
Introduction to Electrical Systems
Week 8:
Frequency Response and Communications Systems

Lecturer:

Dr Philip Terrill

Mid-semester Test Feedback

- In order to provide you further feedback about the midsemester test, you should now be able to access the following information about the final exam via the 'My Grades' section of the blackboard course page:
  - The questions
  - The answer that you provided
  - The correct answer (or a sample correct answer in written responses)
- Part of the learning process is to try to understand and then to learn from your mistakes. For questions which you did not get correct, I would encourage you to do the following:
  - Attempt the question again with knowledge of the correct answer to see if you can now understand the correct approach/answer
- If you are still having difficulties working out the correct answer, in the first instance do the following to try to understand where you went wrong:
  - Please discuss with a tutor at the end of a scheduled prac class; or
  - post a question on the edstem discussion page

Audio Filter Design Activity and Report

- Details of the Audio Filter Design have been posted to: "Assessment" -> "Audio Filter Design Report
- Slightly different tasks for Flexible vs External students – please ensure you are reviewing the correct one!
- Your task is to remove a known 12.5KHz noise from an audio track by designing a filter using no more than two components.
- You must select and justify the filter type, cut-off frequency, circuit topology.
- Derive equations for transfer function and cut-off frequency for your circuit; and then select component values from a limited real-world range.
- You will then (using the setup from Lab XI):
  - Flexible students will experimentally measure their circuits, and test the ability to remove noise from the audio signal.
  - External student will simulate their circuits, estimate the impact of component tolerance on the behaviour, and simulate the ability to remove noise from the audio signal.
- The circuit you design won't work perfectly. One of your jobs is consider the trade-offs in your design decisions.

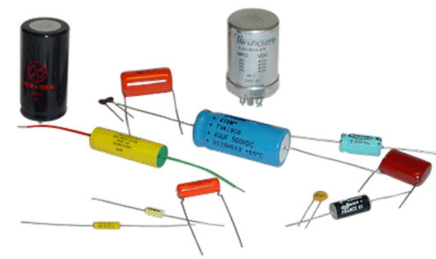
Audio Filter Design Activity and Report

- Assessment (10% to total grade):
  - Due 2pm Thursday 13th of May (week 11)
  - 2*A4 Pages maximum; 2cm margins; 11-point Times New Roman Font; Single Line spaceing. **If a longer report is submitted only the first two pages will be marked!**
  - Submitted electronically via blackboard as a single pdf (automatically screened for plagiarism)
- This is an individual task, and all design work, calculations, and report writing must be completed individually.
  - On campus students <u>are</u> permitted to complete experimental testing of their circuits with 1-2 lab partners [However you must have completed all design and theory work yourself before hand, and you must present the data for the circuit YOU designed].
  - Refer to links in the task sheet about academic integrity.
  - References: It is anticipated that the information required is contained within ENGG1300 course materials, and you do not need to reference these. If you do refer to other materials, these sources must be referenced using in-text citations in Harvard format.
- Your report will be structured under defined headings and a template is provided. This provides further guidance as to expectations.
- Still to come (next day or so):
  - Specific resistor values that will be available to use.
  - A marking rubric.

Plan For Rest of Semester:

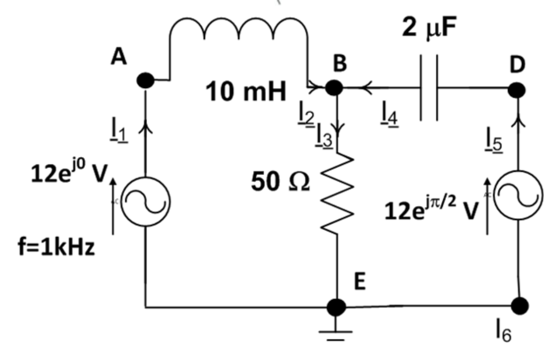
- Week 8: Filters + Communications 2
- Week 9: Monday Public Holiday
  - No lecture – Anzac day
  - No lab 9A
  - **Lab 9B: Design project work**
- Week 10: Monday Public holiday (but Monday timetable on Tuesday)
  - Lecture: Power Systems 1 (Held on Tuesday)
  - No lab 10A
  - **Lab 10B: Design project work**
- There will be **no** opportunity to use laboratory equipment for the design project outside of the designated class time.
- As such it is essential that you are prepared to make the most of this class-time (i.e. strongly recommended that you have done theory/design work before attending class).

In Week 5/6



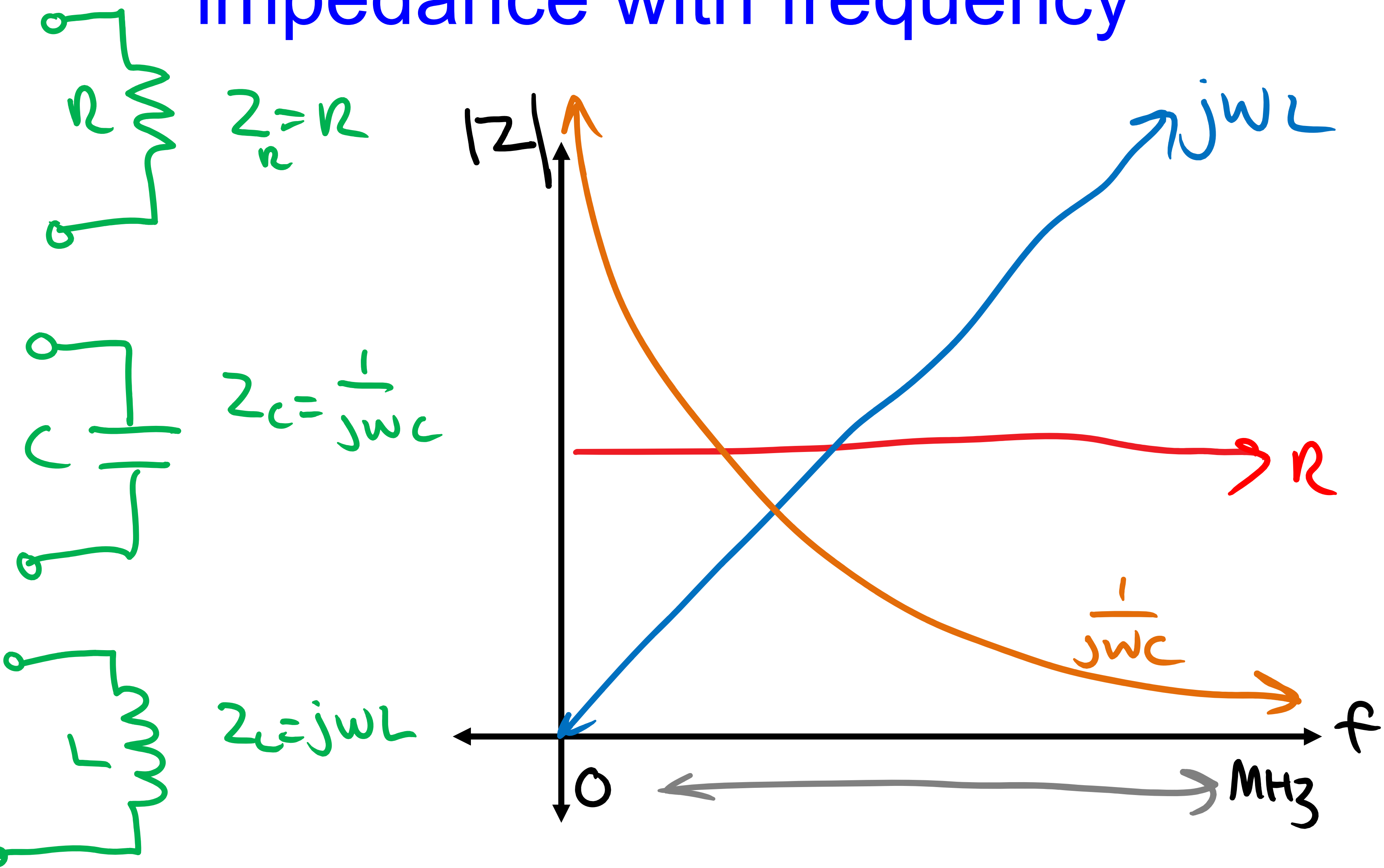
1. We have seen that we can model inductors and capacitors using frequency dependant complex impedances
2. Circuits containing inductors and capacitors thus have a frequency dependence
3. We have solved such circuits by substituting in for a particular source frequency (i.e. substituting in for f or w)
4. However, we can also make frequency the variable of interest to model how the circuit behaves at different frequencies

   i.e. model circuit as a function of frequency: $G(\omega)$ =?
5. We would like to plot this frequency response in an intuitive manner to help us understand the behaviour of the circuit.



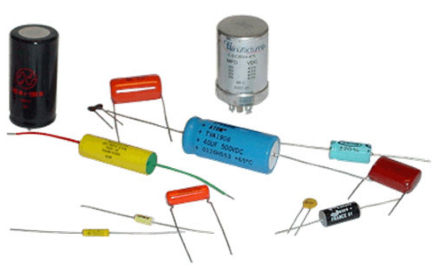
f-=1000; $\omega = 6283$;
$Z_2 = j\omega L = j\ 62.83$;
$Z_3 = 50$, $Z_4 = -j79.6$

Magnitude of Component impedance with frequency

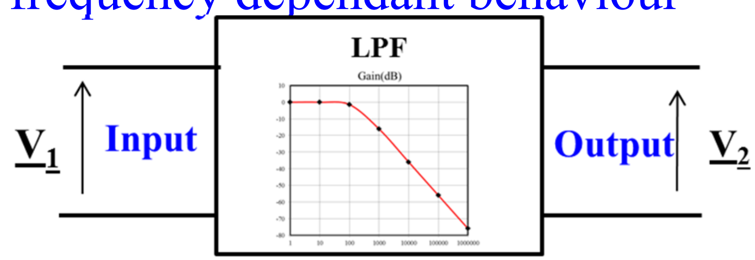


In Week 7:

- Circuits that contain inductors and capacitors have behaviour that varies with frequency. We can investigate this behaviour:
  - Two port networks
  - Transfer Functions - Describes the relationship between the input and output phasor voltages
  - Frequency Response - The frequency dependant behaviour of the transfer function
  - Bode Plots - visualising the magnitude and phase of frequency dependant behaviour
  - Filters- practical application for this frequency dependant behaviour

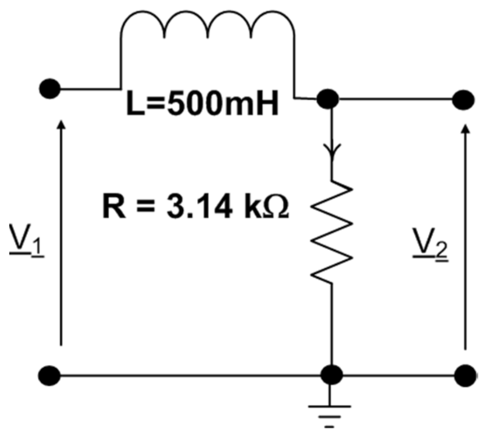


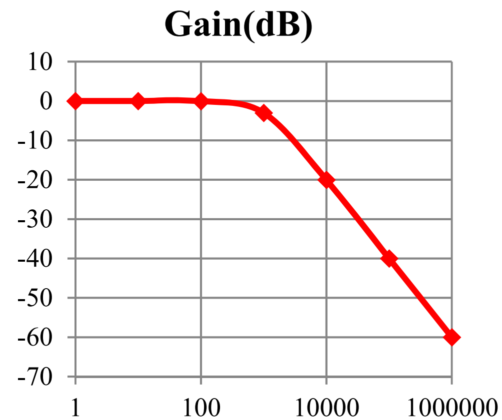
$$G(\omega) = ?$$



Recap:
Low Pass Filter – Frequency Response

- Simple RL filter

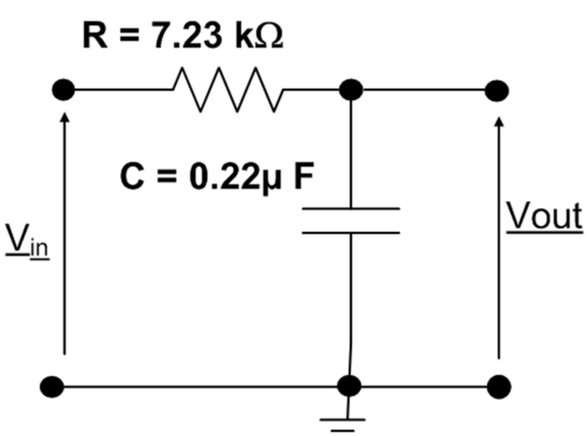


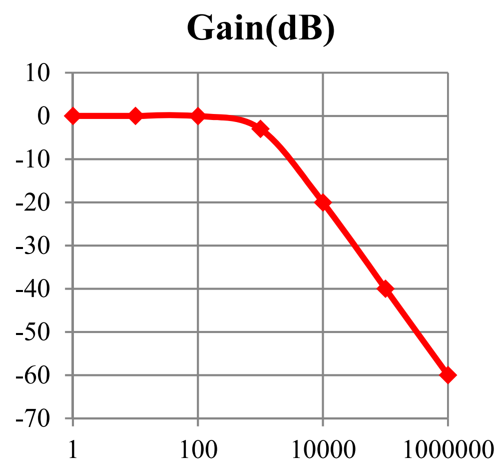


- $|G(\omega)| = \frac{1}{\sqrt{1+\frac{\omega^2 L^2}{R^2}}}$
- Cut-off frequency:

$$Fc = \frac{R}{2\pi L} = 1KHz$$

- Simple RC filter



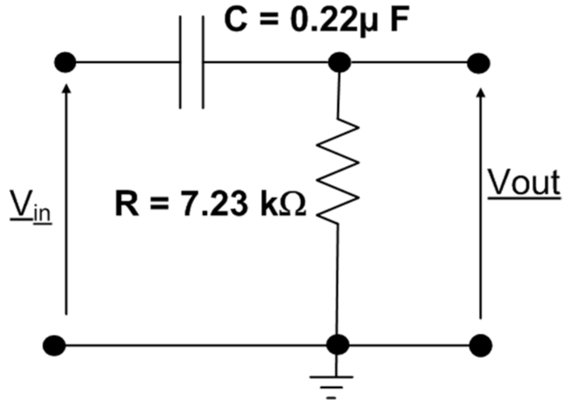


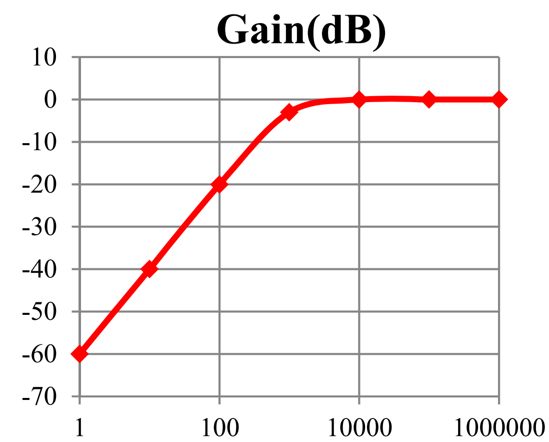
- $|G(\omega)| = \frac{1}{\sqrt{1+\omega^2 C^2 R^2}}$
- Cut-off frequency:

$$Fc = \frac{1}{2\pi RC} = 1KHz$$

High Pass Filter – Frequency Response

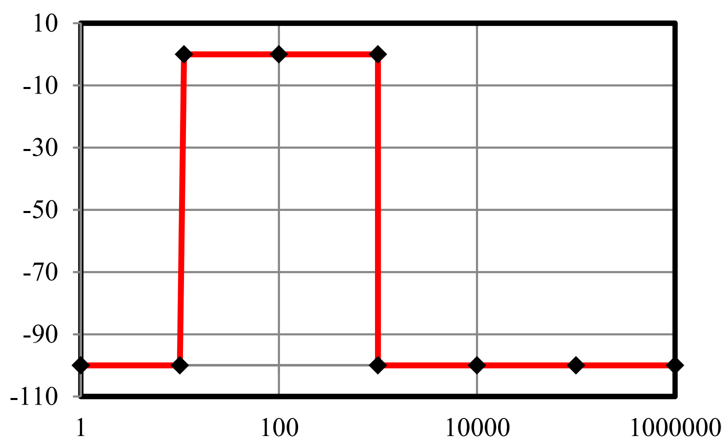
- Simple RC filter:



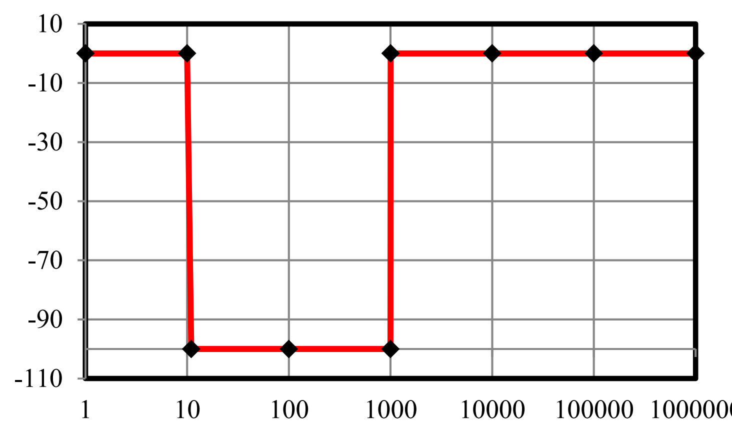


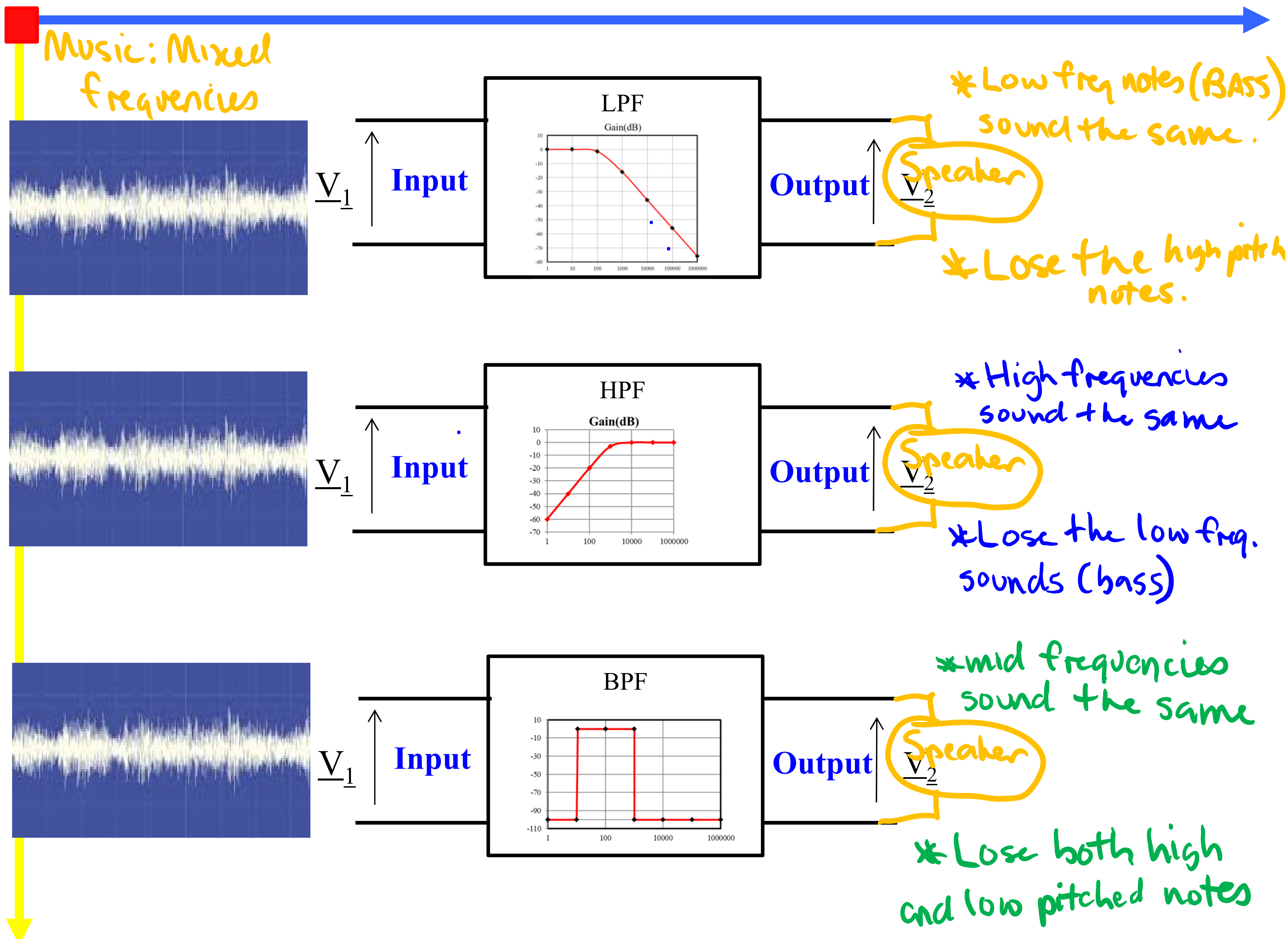
In your laboratories this week you'll investigate:

Band Pass Filters:



Band Stop Filters:




Music: Mixed frequencies
V1
Input
LPF
Gain(dB)
Output
V2
Speaker
*Low freq notes (BASS) sound the same.
*Lose the high pitch notes.
V1
Input
HPF
Gain(dB)
Output
V2
Speaker
*High frequencies sound the same
*Lose the low freq. sounds (bass)
V1
Input
BPF
Output
V2
Speaker
*mid frequencies sound the same
*Lose both high and low pitched notes

This week ahead

- We can exploit the frequency response of circuits and filters in practical communications applications?
  - Session 8A - Laboratory (XIII) – Band-pass and Band-stop filters
  - Session 8B:
    - Laboratory (XIV) – Circuit Simulators (Flexible Students Only)
    - Laboratory (XVIII) Activity 1 – Discussion activity: communication systems in practice

- On-line Quiz 8 due Monday 26th April 4pm.

Frequency Spectrum: Describing information in the frequency "Domain"

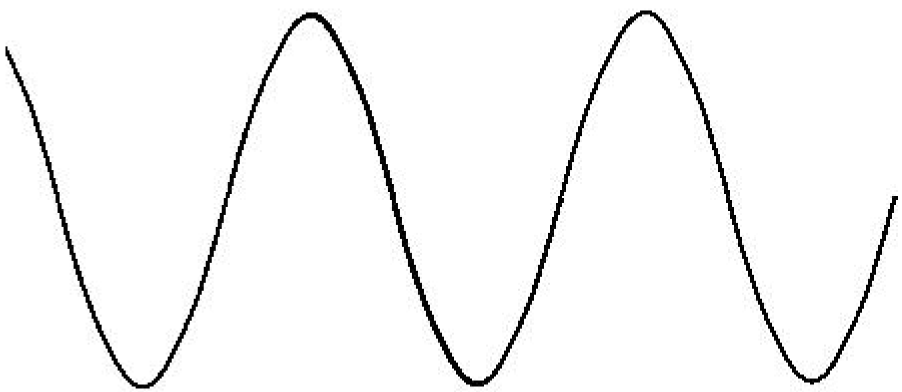
- In practice, most signals (like voice or music) are a mixture of frequencies.
- **Fourier's theorem** says that any periodic signal can be decomposed into a set of sinusoids
- So for any time-varying signal, we can decompose the signal into its "components" at various frequencies – this is called its **spectrum**.

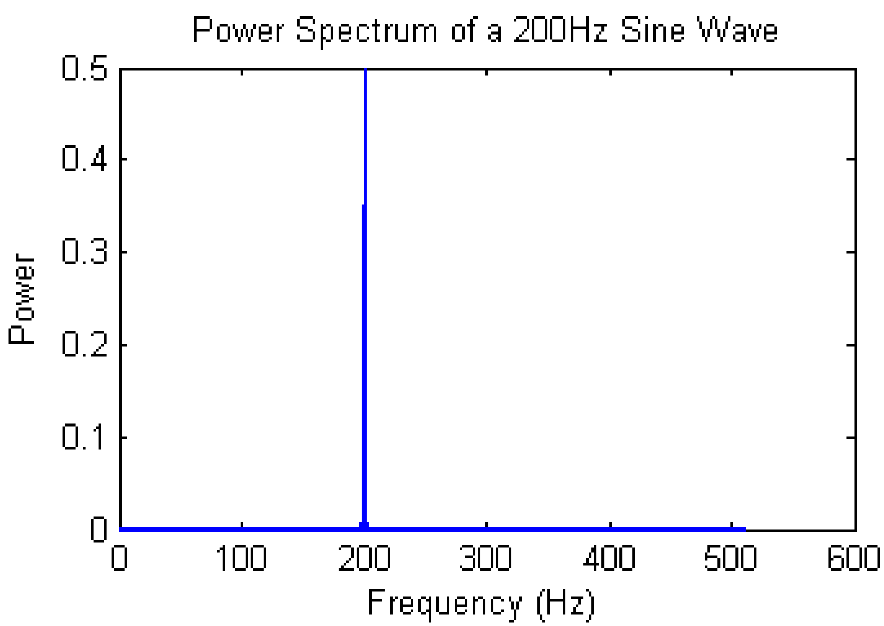
We can plot a signal vs. time

or

We can plot a signal vs. frequency (spectrum plot)

Spectrum of a Sine Wave





http://www.mathworks.com.au/support/tech-notes/1700/1702.html

Spectrum of a Musical Note

- An audio signal, such as a musical note, that we think of as having a particular pitch is made up of many frequency components:

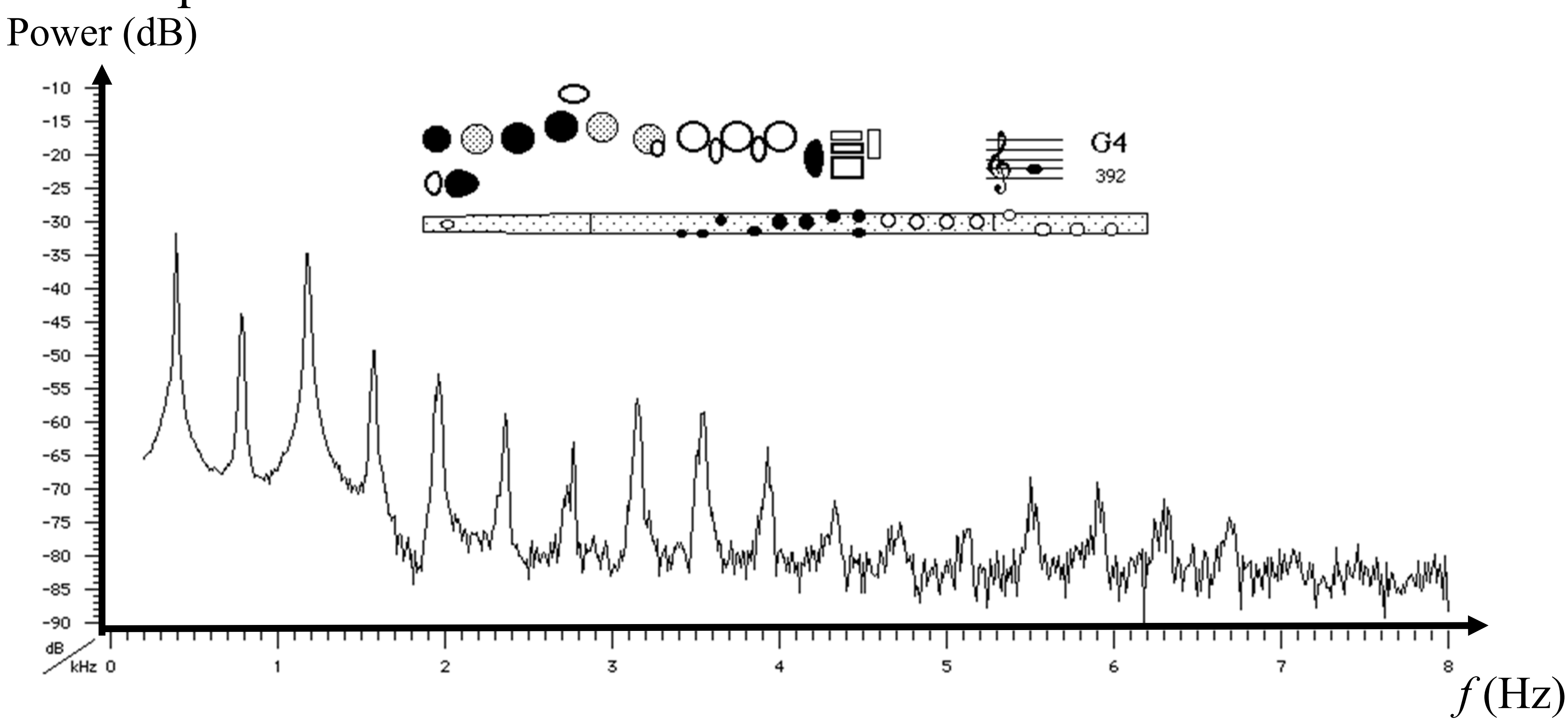


Image source: UNSW

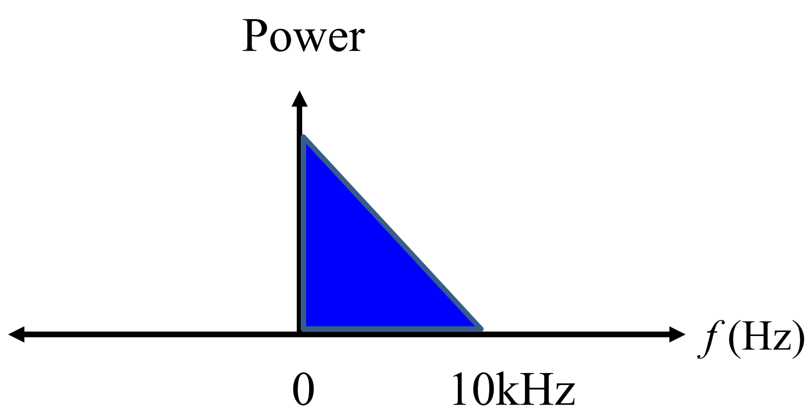
Spectrum of "Sound"

- Sound is a pressure wave
- Any sound we hear can be described as a combination of sounds of different frequencies.
  - High pitched notes: High Frequency information content
  - Low pitched notes: Low Frequency information content

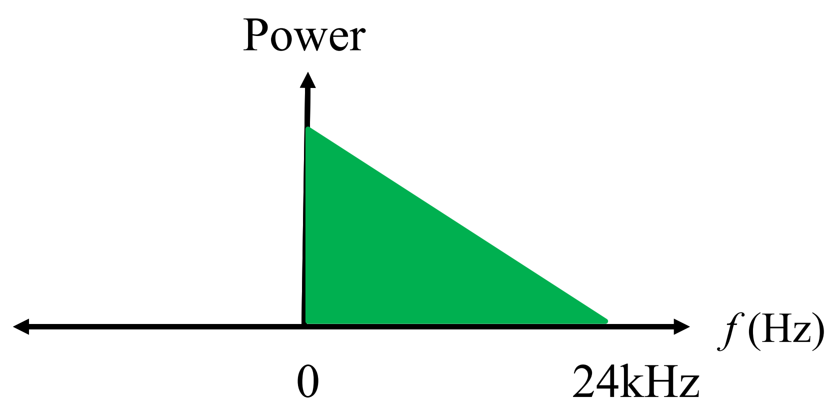
- We can think about the **band-width** (i.e. the range of frequencies) a sound (or other signal) occupies:
  - Speech is about 10 Hz-4000 Hz
  - FM Quality music – about 10Hz -10 kHz
  - CD Quality music 10 Hz – 24 kHz
  - Human Hearing 12 Hz – 20 KHz

“Bandwidths” of Analogue signals

- Any time-varying signal requires a certain range of frequencies (i.e. 0-10 kHz).
  - We can represent FM quality audio of as a “bandwidth” of 10 kHz from 0 to 10 kHz on a frequency spectrum
  - And, CD quality audio as a “bandwidth” of 24 kHz from 0 to 24 kHz on a frequency spectrum



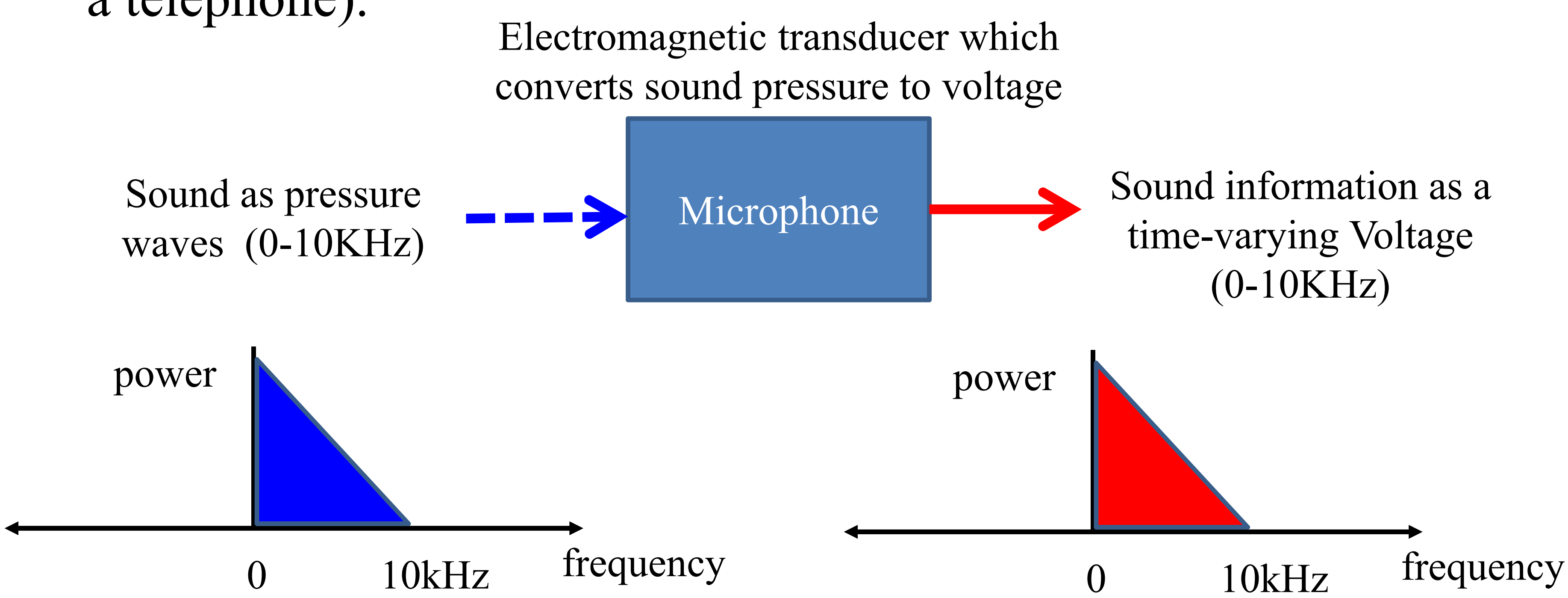
FM Quality Audio



CD Quality Audio

Analogue Representation of Audio as Electronic Information

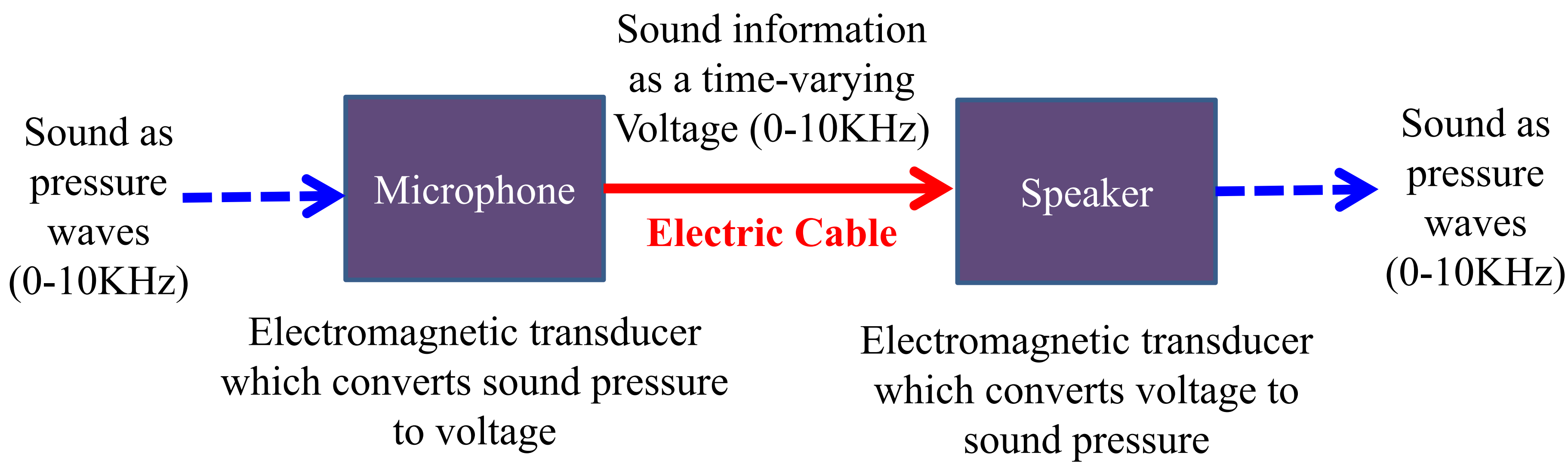
- Audio signals are sound pressure waves, and a microphone converts these to analogue voltages, (e.g. for transmission via a telephone).



The bandwidth of the sound pressure wave and the electrical signal are the same!

Electronic Communications

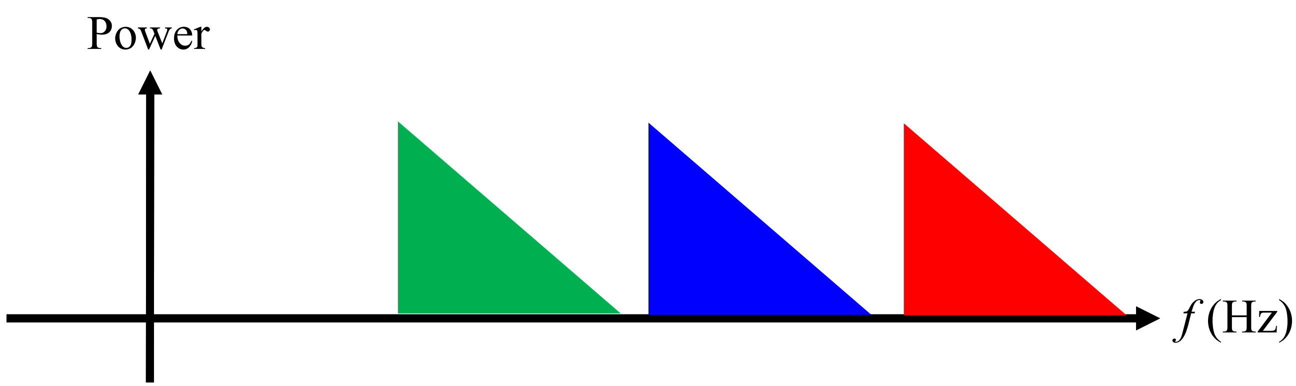
- Fundamentally, we are interested in transmitting information from one location to another: The simplest case – electronic "intercom"



More generally, we are interested in transmitting many different streams of information down a minimum number of communications mediums

Multiple Channels

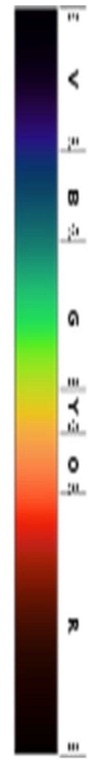
- If the information in each signal occupies a different frequency range, we can transmit multiple streams (channels) down a single cable (or "band")



- Provided these signals don't overlap (i.e. don't have information at the same frequencies), we can recover the information from each channel with a band pass filter
- A lot of communications engineering is about how we:
  - Take a **"baseband"** signal, such as 0-10 kHz audio, and then transfer this up to a higher radio frequency (called **modulation**),
  - Transmit it
  - Receive it
  - Then convert the received signal back to baseband (**demodulation**).

Electromagnetic Spectrum

- If we convert signals to voltages, then we can transmit these as radio waves, also called Electromagnetic or EM waves.
- Travel at the speed of light, approx 300,000 km/s in vacuum or air!
  - Infrared: 10^{12} to 4 x 10^{14} Hz
  - Visible Light: 4-8 x 10^{14} Hz
  - UV Light: 10^{15} to 10^{16} Hz
  - Xray: around 10^{17} to 10^{19} Hz
  - Gamma Rays: around 10^{20} Hz

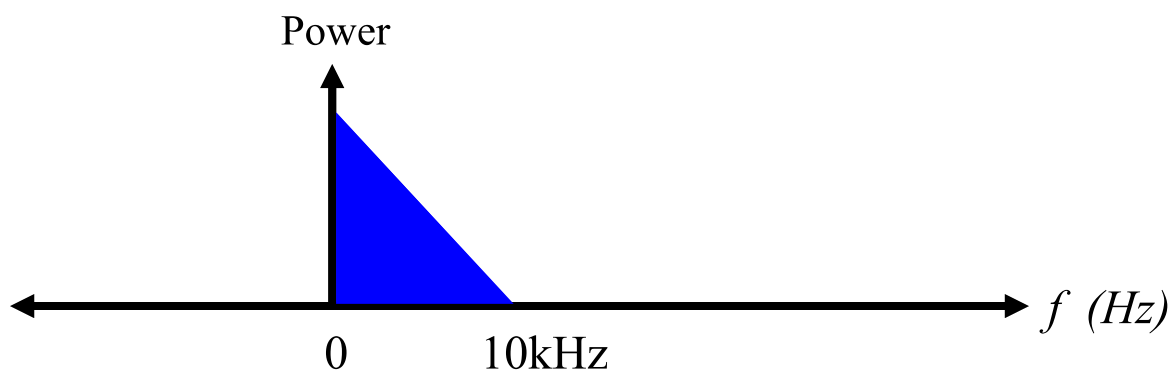


Color	Frequency
violet	668–789 THz
blue	631–668 THz
cyan	606–630 THz
green	526–606 THz
yellow	508–526 THz
orange	484–508 THz
red	400–484 THz

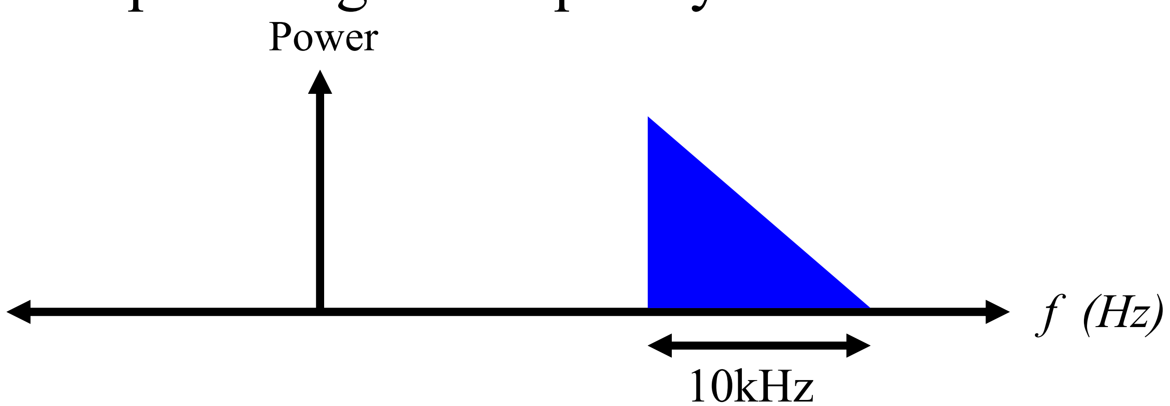
- Some important communication frequencies:
  - AM Radio – about 1MHz
  - FM Radio – about 100 MHz
  - Mobile phone: 1800, 1900 MHz
  - Microwave oven: 2.4 GHz
  - WiFi: 2.4 GHz, 5 GHz
  - Satellite: 1 GHz – 30 GHz

Modulation

- Take our baseband signal:



- And Modulate it up to a higher frequency:



The signal still occupies the bandwidth at this higher frequency!

Modulators

- A cosine wave at a radio transmission (or carrier) frequency (e.g. 612 kHz) is represented as:

  $$C(t) = A\cos(2\pi f t + \phi)$$

- We can "modulate" this with our baseband signal to cause one of three things to change:
  - **A** (amplitude) - "Amplitude Modulation"
  - **f** (frequency) - "Frequency Modulation"
  - ϕ (phase) - "Phase Modulation"

Amplitude Modulation (AM)

- We modify our baseband signal, *v(t)* by adding a DC constant to give $v_p\,(t)$ that is always positive:

$$v_p(t) = V_{DC} + v(t)$$

- Then we can vary amplitude of our "carrier" signal by multiplying with $v_p(t)$:

$$R(t) = (v_p\,(t)) \times A\cos(2\pi f_C t)$$

- Consider one frequency of our baseband signal:

$$v_B(t) = B\cos(2\pi f_B t)$$

- Then when we multiply this by amplitude modulation we get:

$$R(t) = [B\cos(2\pi f_B t)]\, A\cos(2\pi f_C t)$$

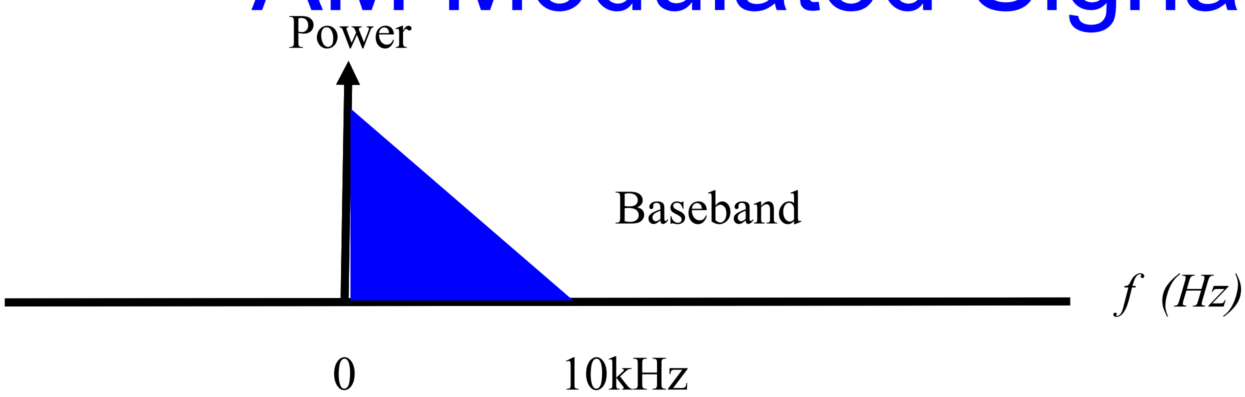
Double angle rule: $\cos(X)\cos(Y) = ½\,[\cos(X+Y) + \cos(X-Y)]$

$$R(t) = ½AB[\cos 2\,\pi(f_C + fB)t \; + \cos 2\,\pi(f_C - fB)t]$$

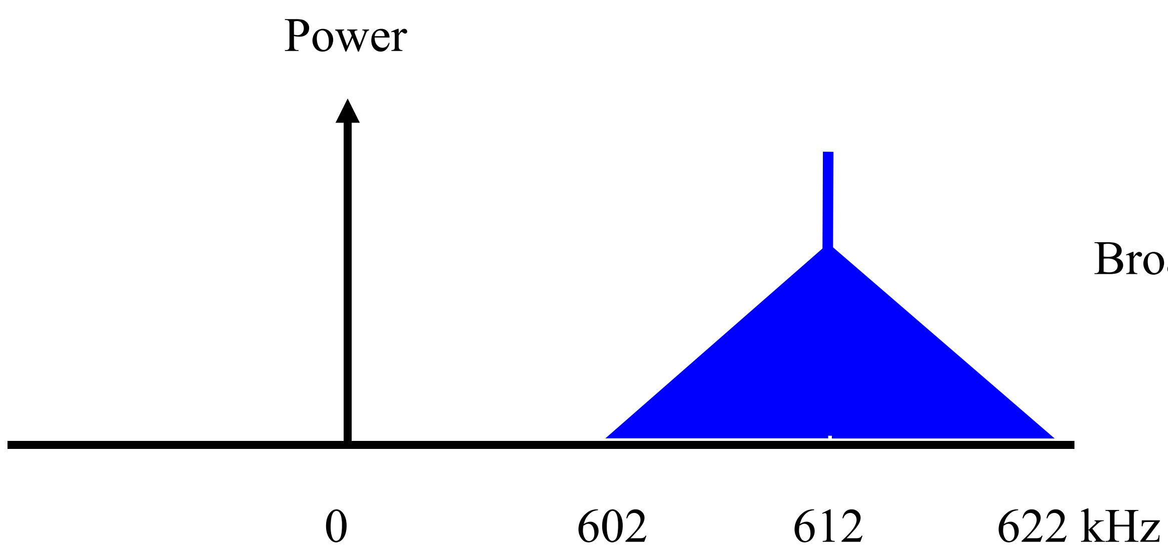
Modulation of baseband frequency f_B gives two sinusoids:

- **At f_C+f_B and**
- **At f_C- f_B**

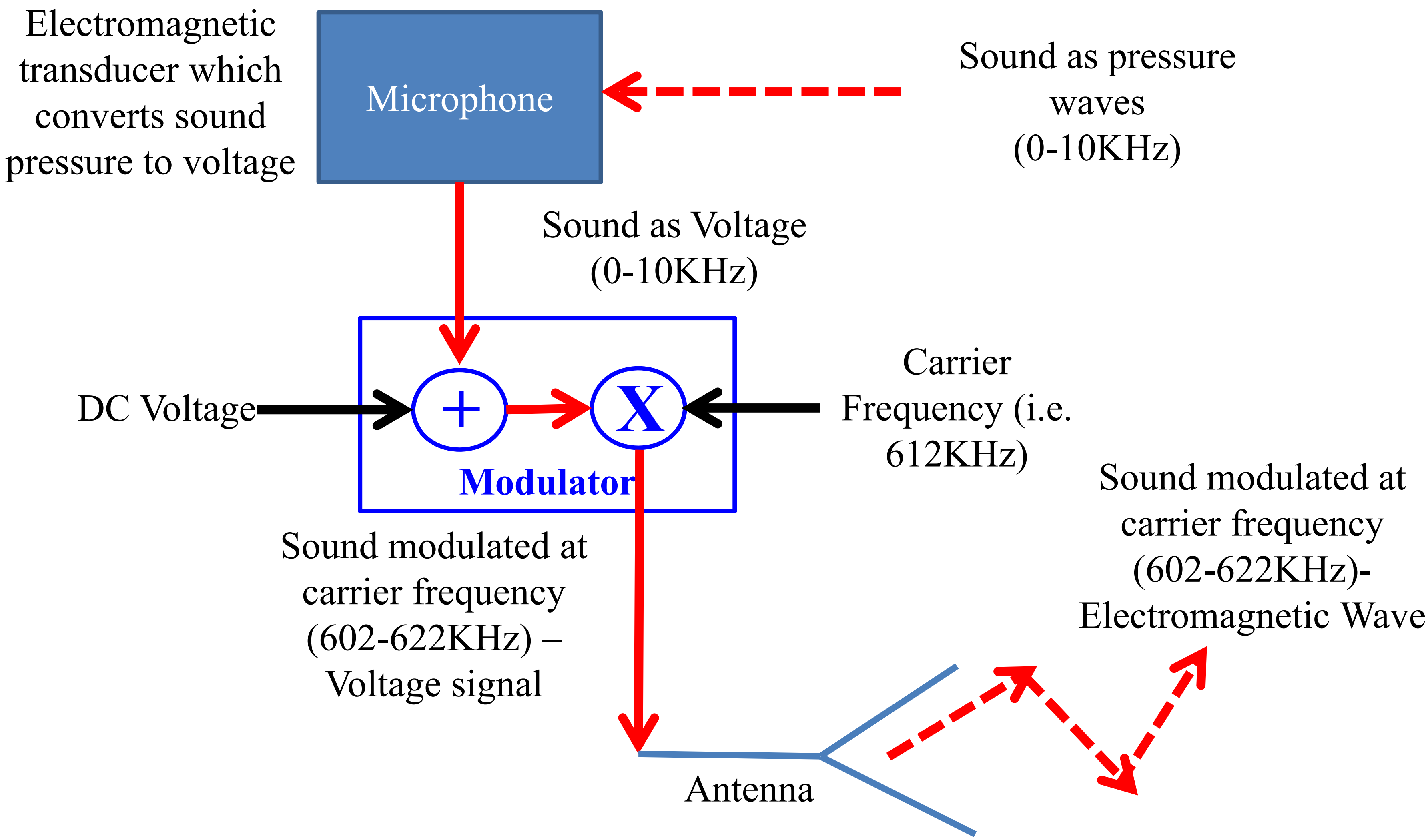
AM Modulated Signal:

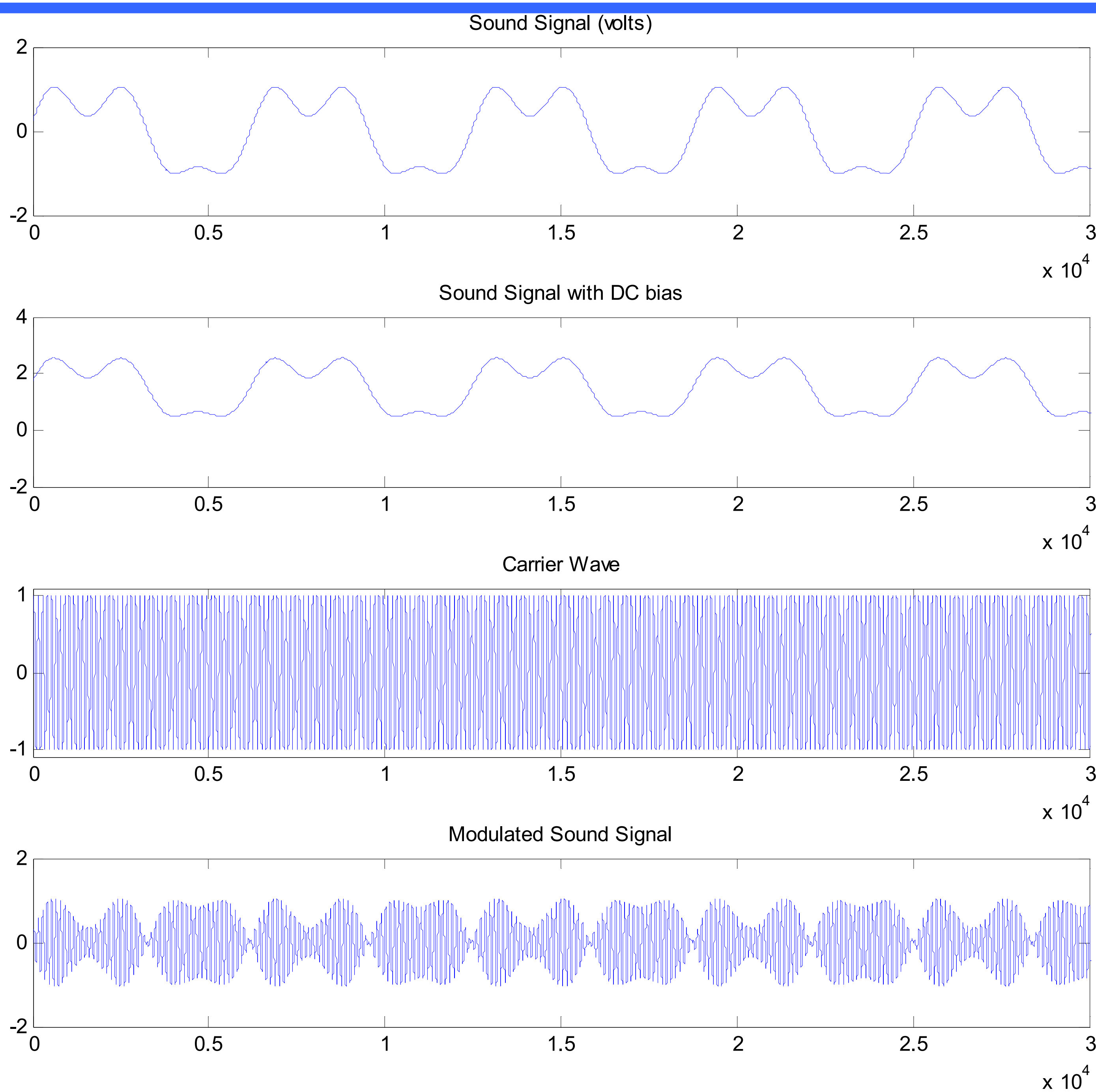


- Simple Amplitude Modulation gives:
  - Two copies of the original baseband spectrum either side of the carrier frequency,
  - A large signal at the carrier frequency due to the DC offset added to the baseband signal.



AM Transmitter – Put it all together

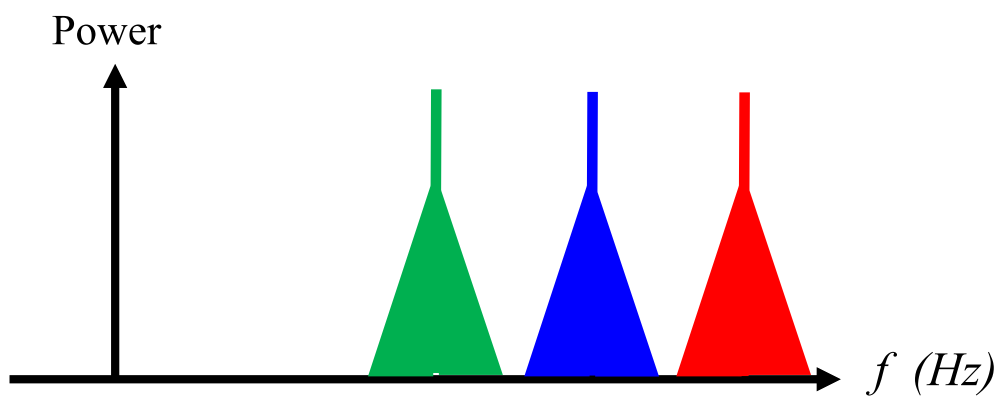



Sound Signal (volts)
2
0
-2
0
0.5
1
1.5
2
2.5
3
x 10^4
Sound Signal with DC bias
4
2
0
-2
0
0.5
1
1.5
2
2.5
3
x 10^4
Carrier Wave
1
0
-1
0
0.5
1
1.5
2
2.5
3
x 10^4
Modulated Sound Signal
2
0
-2
0
0.5
1
1.5
2
2.5
3
x 10^4

AM Demodulator: “Product Detector

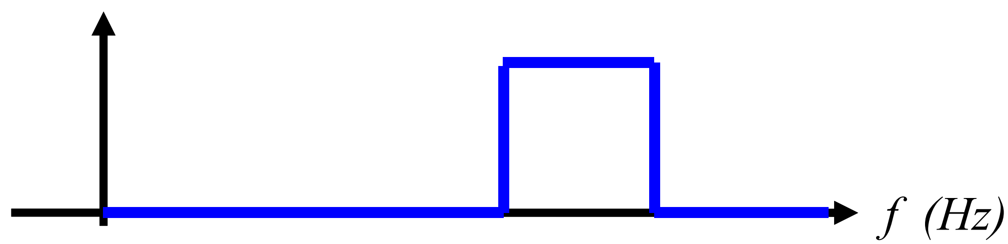
- In any geographical area, there will be a number of different AM stations broadcasting.

Input signal:

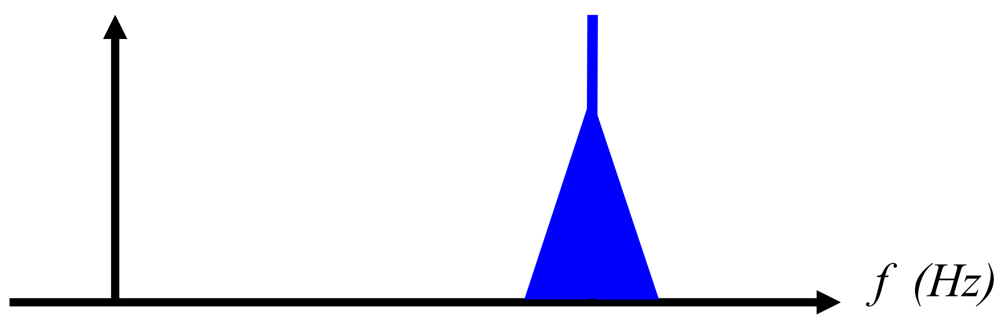


- We select our particular radio station from others of the AM band, using a band-pass filter:

Transfer Function of Bandpass Filter:

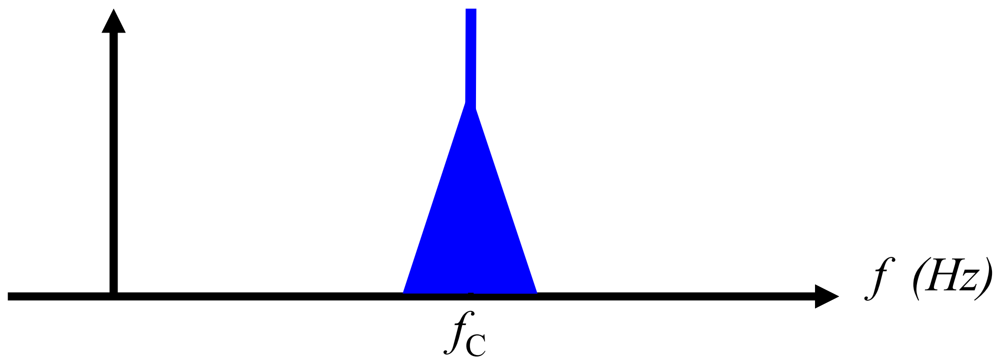


Output of Filter:

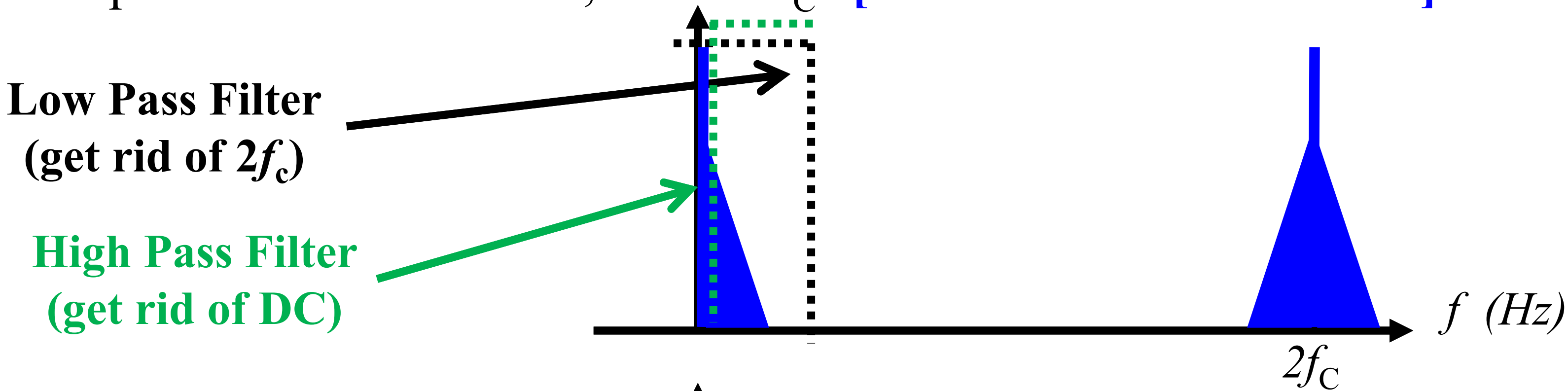


AM Demodulator

Output of Filter:



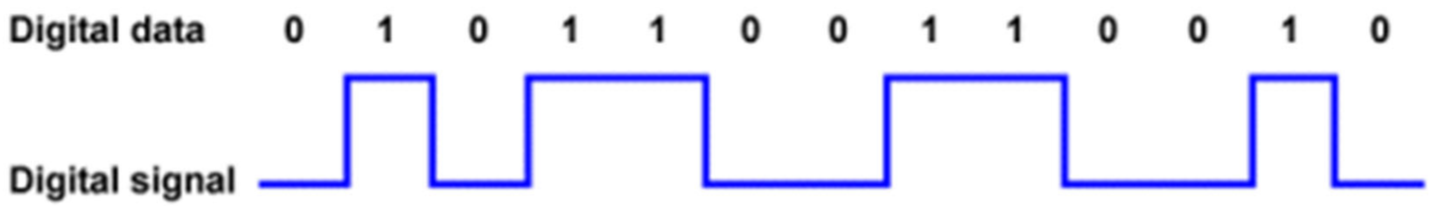
- Now we multiply by the original carrier frequency cos $(2\pi f_C t)$ which gives two copies – one around 0Hz, one at $2f_C$ **[check the math at home!]**



Our original signal back!

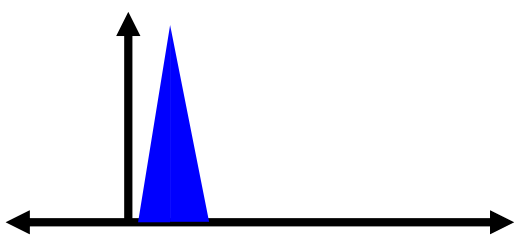
Digital Signals and Communications

- Much of modern information transmission is **digital** (internet protocols; GSM and 3G communications; digital TV, digital radio etc.):



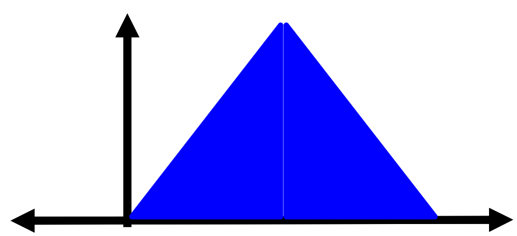
http://www.technologyuk.net/telecommunications/telecom_principles/digital_signals.shtml

- The **bandwidth** of a digital signal depends on rate which bits are transmitted (i.e. 1Mbps, 10 Mbps, 100Mbs etc). The higher the rate, the more information that can be sent (**i.e. The faster the download speed**)



1MHz

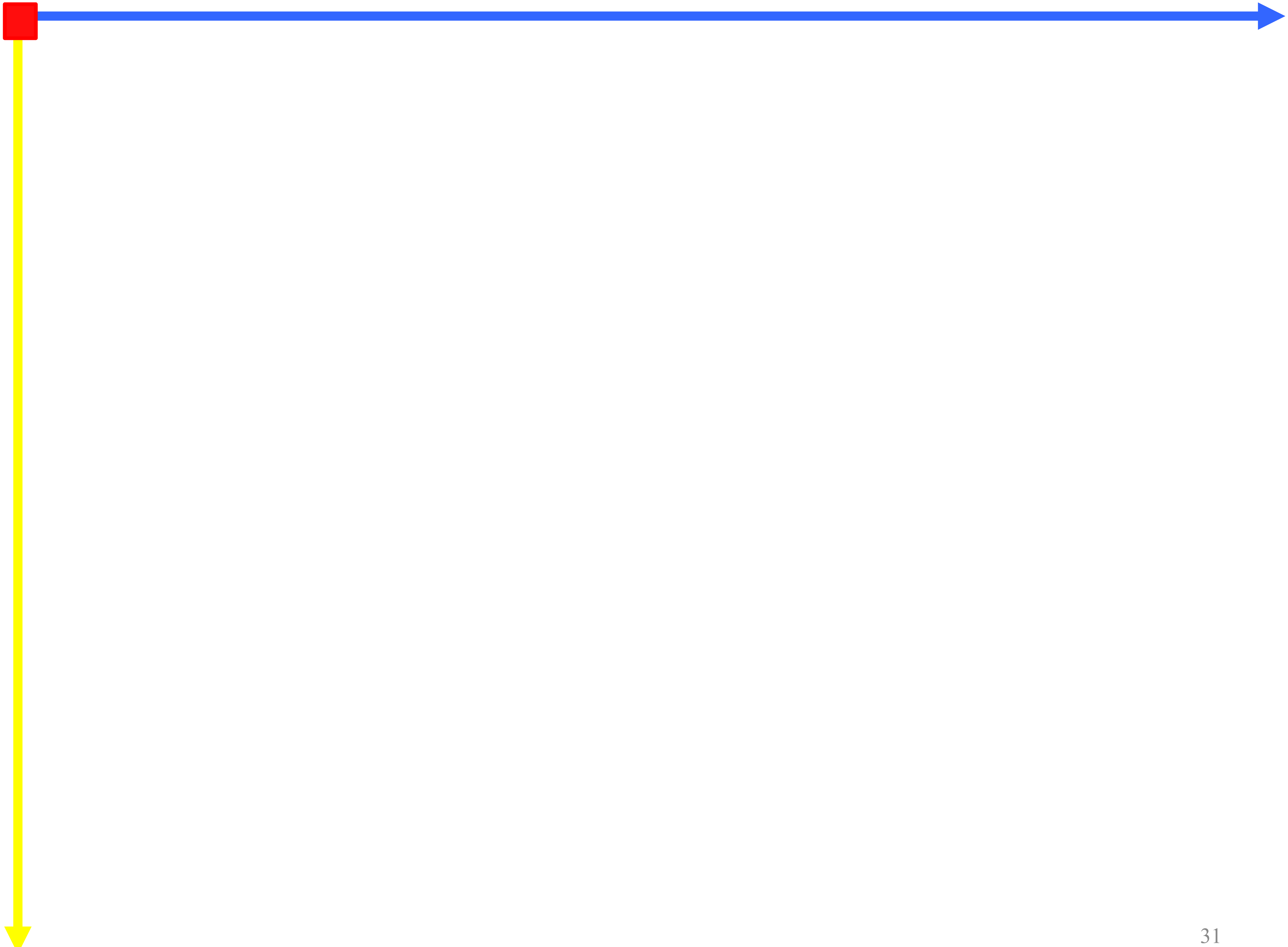
i.e. 1Mbps



100MHz

i.e. 100 Mbps

However, the higher the rate, the less channels that can fit in a finite frequency range

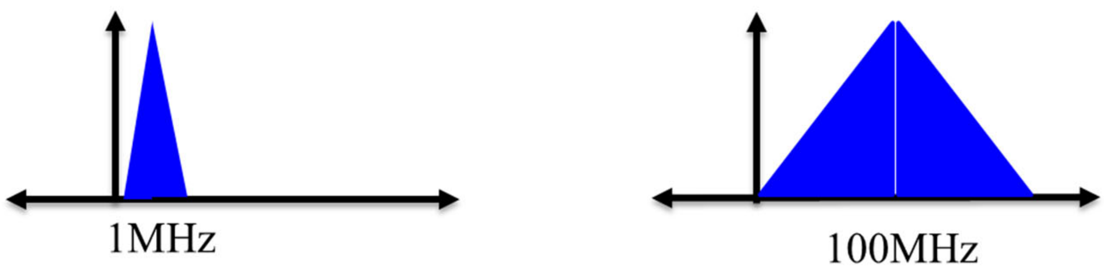


Why use “Fibre Optic” rather than “copper” for internet?

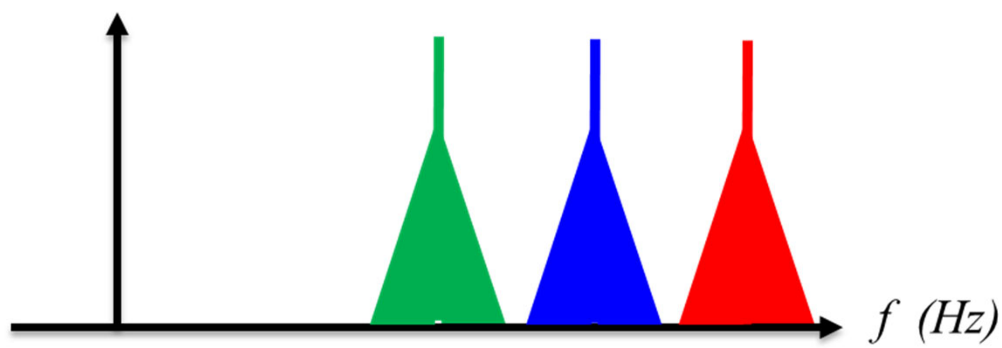
- You may have heard statements like:
  - “Fibre optic cable has higher bandwidth than copper”
  - “up to 1000Mbps with fibre vs. 10Mbps with copper”
- What is the technical basis for this?

Topical Question – Why "Fibre Optic" rather than "copper" for internet?

- What is the technical basis for this?
- So we have seen: faster download = faster data rate = larger bandwidth of signal



- And that we can modulate signals to higher frequencies, but the bandwidths are the same:

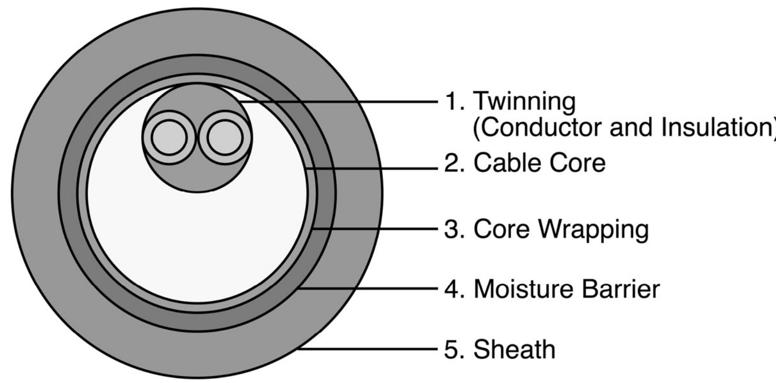


- So, if we have a fixed frequency band, the wider the bandwidth of each channel, the less channels we can fit in the band

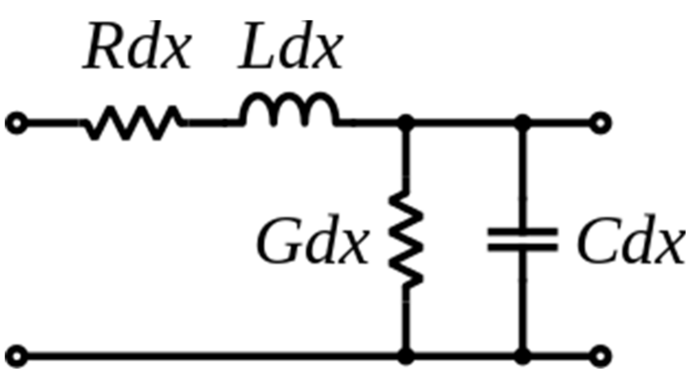
Even important in short cables—check out *[The Checkout](#)* [on HDMI cables](#). It's all about the frequency response.

▲ Image source: [sortius-is-a-geek.com](#)

▼ Image source: *[Leader Cable](#)*



- A typical connection from the exchange consists of two copper wires ('twin') to form a circuit
- The two wires are not perfect conductors, nor perfectly insulated, and each small length of cable, *dx*, is modelled as:



Low Pass Filter!!

- Attenuation is measured in dB/km—increases with frequency [i.e. low pass filter effect!].
- i.e. We can't modulate signals to very high frequencies – they just become filtered out across cable length.

So… Why "Fibre Optic" rather than "copper" for internet?

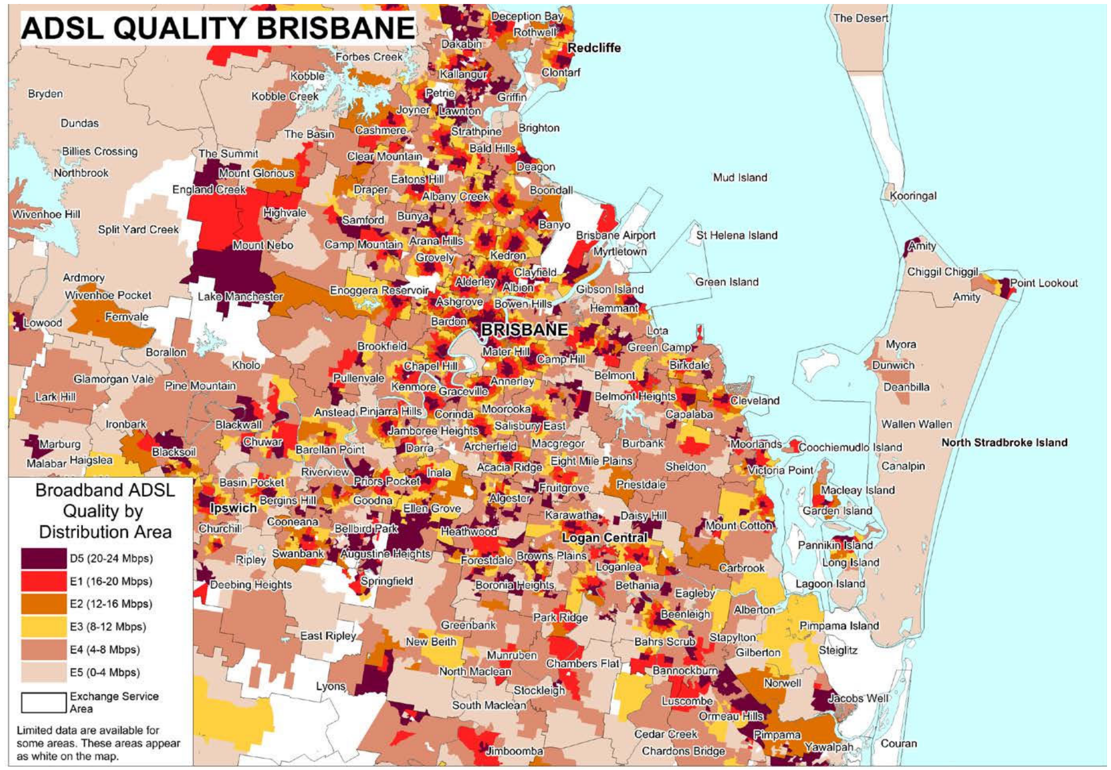
- The wider our frequency band, the more channels we can fit.
  - But, "Copper" has a natural low-pass filter effect: Limited in the frequencies that we can modulate up to.
- In contrast:
  - Optical frequencies are very high; and,
  - Fibre optic cable does not have the same low-pass filter effect

Color	Frequency
violet	668–789 THz
blue	631–668 THz
cyan	606–630 THz
green	526–606 THz
yellow	508–526 THz
orange	484–508 THz
red	400–484 THz

- At these very high optical frequencies (10^{14} Hz):
  - Modulated carrier can be very large relative to bandwidth of signal
  - Much greater capacity to fit in more channels (or the same number of channels, each with a wider bandwidth)
  - Fibre optic cable therefore allows a greater number of wider (i.e. higher data-rate) channels relative to copper; and therefore per user, faster data transmission speeds.

Fibre To The… Node or Home? (FTTx)

- Map of copper DSL speed shows hotspots (dark colour) near exchanges
- On the other hand, optical fibre provides *terahertz* of bandwidth over very long distances
- *Fibre to the home* (FTTH) brings it to your house
- *Fibre to the node* (FTTN) brings it to within a short distance of your home then DSL over remaining copper with short loop length



▲ Source: *Australian Government Department of Communications*

- FTTN or FTTH has been of political contention since 2004!
- Current NBN is somewhat of a compromise
- Key cost contention in FTTH *vs.* FTTN is digging up your front yard!

Summary

- A fundamental property of information is it’s band-width
- Information can be modulated to different frequencies, but still occupies the same bandwidth (or some multiplier of)
- Modulating multiple channels at different frequencies allows multiple streams of information to be transmitted over a single “line” – however, frequencies must not overlap!
- Thus fundamental limitation to the amount of information that “fits” in a communication band.
- This week’s lecture has covered some of the applications of circuits like filters that we have been building and analysing.
- This is intended to explain and motivate why we study such circuits, and give you an idea of where theoretical concepts such as phasors are useful in practice.