Imperial College London

Lecture 3

Electrical Signals and Measurement techniques

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This lecture will be mostly about electrical signals and how to measure them. The lecture is tightly coupled to the laboratory session 1 weeks 1 of the term.

Electronic Logbook

- You must keep a logbook because:
  - It is a professional practice.
  - It helps you to learn; forces you to think and reflect.
  - It is useful for future reference.
- Here are some guidelines on using the logbook:
  - Logbook should include sketches, your thoughts etc., and does not need to be tidy. It definitely should not be "beautiful".
  - Never copy someone else's logbook – it is both cheating and useless to you.
  - Stick photo's, plots, calculations, codes or anything else interesting in your logbook.
  - At the Lab Oral, you will be asked questions where answers are only found in your logbook.
- Electronic Logbook
  - MS Word or similar – simple, no learning required, sequential only
  - MS OneNote – Easy to learn, has hierarchy: book, section, pages
  - Github – Combines logbook with version control; probably more suitable for software lab than hardware lab.

As a "bonus" teaching of my module, you will learn how to keep a good electronic logbook.

The purpose of keeping a logbook is much more than having a record (or a log) of what you have done so that you can refer to it in a later date. When you conduct experiments or a project, or if we write some computer program or build some electronic hardware, there is a strong tendency for you to "hack" or try to achieve results through trial-and-error. If you develop a habit of keeping a logbook, you will find that this process forces you to slow down and THINK more, reflect on what you have done and more likely to make plan on what to do next. The over result is that you will learn more and better.

While in the past, we encourage our students to keep a paper logbook, I am encouraging you to use an electronic logbook. This means that you would need to have a laptop with you. There are various application programmes that may help you. For this module, I encourage you to try OneNote by Microsoft. This is free for Imperial College and is very easy to earn.

Please read my one-page guideline on how to keep a good electronic logbook, which you can find on the course webpage. In it I provide a link to an excellent video tutorial to OneNote.

Electrical signals (1)

- Electrical voltage or current can be constant over time (at least over a reasonably long period of time) or vary over time.
- There are various types of electrical signals (voltage or current):
  1. **Constant or dc** - For example, the output voltage of a fully charged battery is substantially constant. Connecting a resistor across the battery will also result in a constant current flowing from the battery to the resistor. We call this dc voltage or current (i.e. direct current).

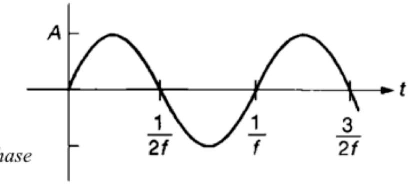
     $V = k$, where k is a constant.
  2. **Sinusoidal, sinewave or ac** - Voltage from the mains supply is changing over time, and it alternates between positive and negative value following a sinusoidal function. We call this ac voltage (i.e. alternating current).

     $V = A \sin(2\pi ft + \Phi)$

     $V = A \sin(\omega t + \Phi)$

     A = amplitude, f = frequency

     ω = angular frequency = $2\pi f$, and Φ = phase



Let us first consider a direct current or **DC signal**. This is hardly a signal because it is a constant voltage or current. It is in fact a **source**. All real sources have some **source resistance**. For a realistic voltage source such as a battery, the resistance is in series with the source. For a realistic current source (which we don't encounter often in day-to-day life), the resistance is in PARALLEL with the current source.

The second important signal is the alternating or **AC signal**. This is probably the most important signal in electronics, communications, signal processing and control. **Sine and cosine signals** are special case of AC signals. All it means is that the AC signal changes in time.

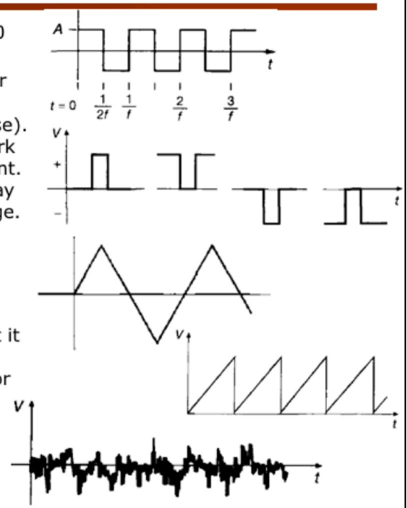
The **mains** supply to which we plug in our equipment is a power source with a sinusoidal signal at 50Hz (in the UK) and approximately 230V. We will consider what the value 230 means exactly later.

A perfect sinewave is completely characterised by only three parameters: its amplitude, its frequency and its phase. Again we will consider sinewaves in more details later.

Electrical signals (2)

3. **Squarewave** signal– symmetrical around 0 and have equal period at +A and –A.
4. **Pulse and repetitive pulse signal**– similar to squarewave, but usually going between 0 and +A (positive pulse) or –A (negative pulse). Furthermore, the duration spent on +A (mark period) and 0 (space period) may be different. The ratio mark:space (mark/space ratio) may also be expresses as duty cycle in percentage.

   Duty cycle = (mark period/total period) x 100%
5. **Triangular wave and sawtooth signal** – obvious!
6. **Noise signal** – general this is the signal voltage or current that you DON'T want, but it is there anyway. The noise signal can be random (such as noise signal from space), or predictable (e.g. noise caused by picking up the electrical mains at 50Hz).



A **square wave** is obvious. Normally a square wave is assumed to be symmetrical in amplitude (going between ±A) and spend equal time in +A and –A.

More common is the pulse signal or repetitive pulse signal. A pulse signal or sequence of pulses are used in many situation – such as an ultrasound distance sensor would use a burst of pulses to measure distance through echo location.

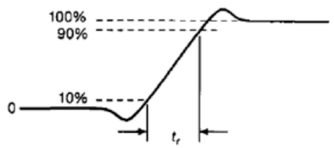
Even more common is the use of repetitive pulse signal as a **clock reference** in digital circuits. Pulse signals normally go between 0 and A.

Then there are **triangular** signal and **sawtooth** signal which are similar and obvious.

Finally, there is the **noise signal**. Noise is a general term, referring to the component of a signal that you do not want, but it is there! If you are measuring the mains supply voltage signal, you will see the 50 Hz sinewave. This signal is NOT noise – it is the one that you want to measure. However, if you are measuring your cardiac signal (ECG) you may find superimposed on your wanted signal a 50 Hz "hum" that you don't want. The 50 Hz component is now regarded as noise. In other words, what is noise and what is signal depends entirely on the context.

Electrical signals (3)

7. **Step signal** – this is a theoretical signal where a signal goes from P to Q instantaneously. The step can be positive (Q>P) or negative (P>Q). In practice, the signal will take finite time to transit. Rise (fall) time t_r is defined as the time when a step signal rises (falls) from 10% to 90% of the final level.

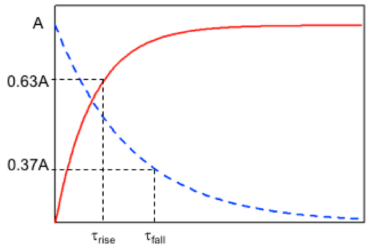


8. **Exponential signal** – This is often the output signal of a circuit driven by a step signal at the input. The mathematical representation of this signal is:

$V = A\,(1 - e^{-t/\tau})$ for rising exponential

$V = A\; e^{-t/\tau}$ for falling exponential

τ is often called time constant, and it is the time for the signal to reach 63% of the final value for a rising exponential and 37% for a falling exponential.



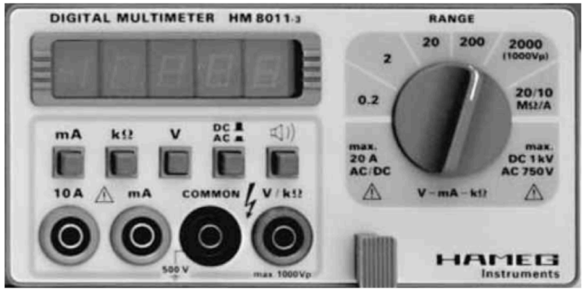
In Lecture 2, we briefly looked at **digital signals**, and suggested that when a digital signal goes from 0 to 1, or zero volt to supply voltage (say 5V for TTL), it takes finite time for the signal to reach its final value. This is a **step signal** and associated with it is the **rise time**, which is defined by the time it takes to go from 10% to 90% for a rising edge (and 90% down to 10% on a falling edge for the **fall time**).

A step signal are often used and produced in the physical analogue world. For example, if you move a robot arm from A to B and monitor the signal from a sensor (transducer) that measures the ARM position, the ideal case is see a perfect step signal with zero rise time. In reality, you are likely going to see a waveform similar to the one shown at top of this slide. There is not only a finite rise time, there could be an overshoot, or even oscillation that eventual dies down.

Finally, we have the **exponential** rise and fall **signals**. This Is found everywhere, particularly in digital circuits. The rising exponential signal is characterised by its final voltage value A, and the time it takes to reach 63% of A. This time is known as the **TIME CONSTANT**.

A Digital Multimeter (DMM)

- DMM is a basic electrical measurement equipment.
- We use a DMM to measure a DC or AC voltages.
- You can also use the DMM to measure resistance of a component.
- DMM cannot tell you much about a time-varying signal.
- For that you need to use an oscilloscope, or scope for short.



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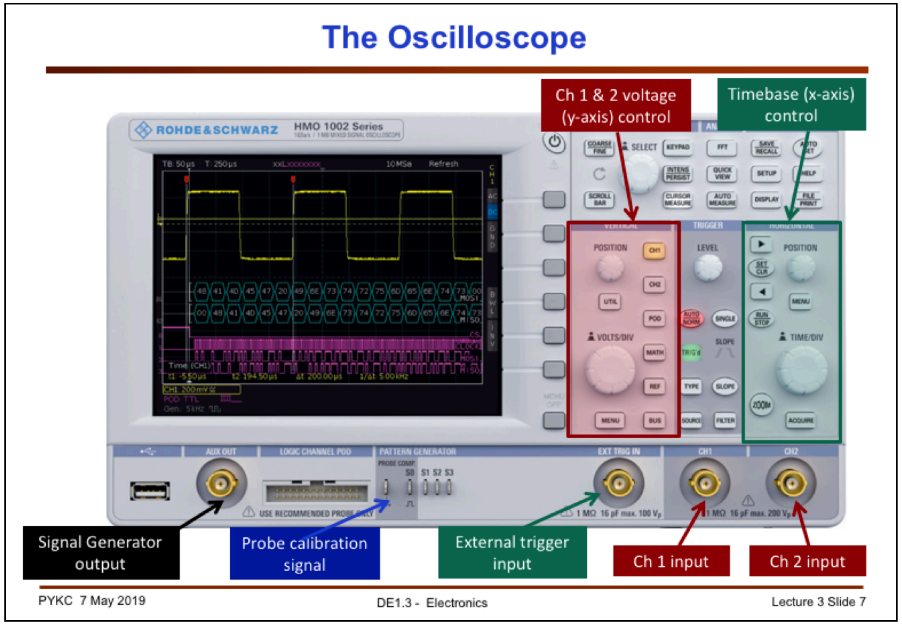
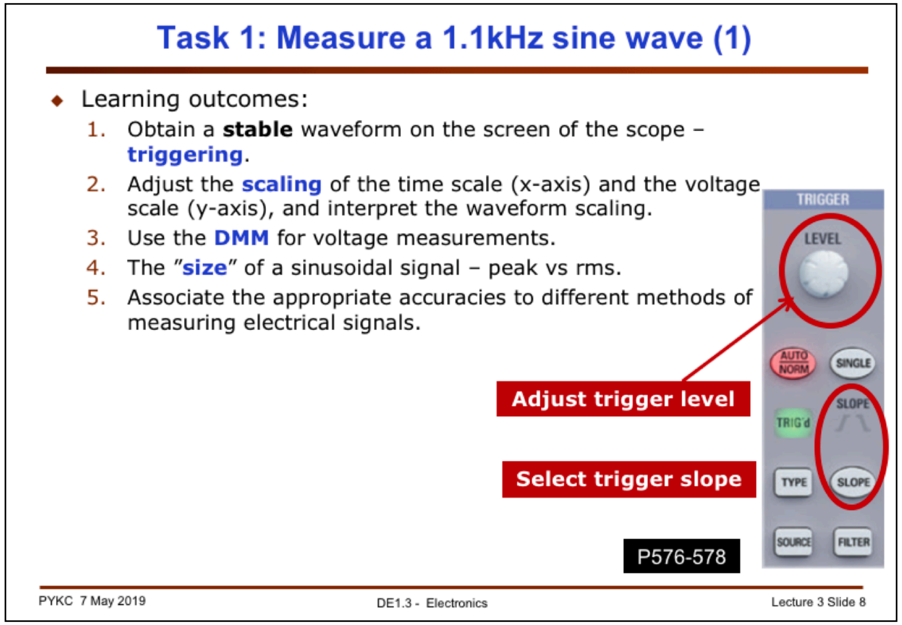
DMM is generally used to measure DC and AC voltages, resistance value, current etc. Its display has four digits resolution. In general a DMM has an accuracy of 1% or better.





Digital Multimeter (DMM) is useful to measure DC or AC voltage or current values of an electrical signal. It is cannot give you information about the a signal that changes over time quickly. For that you need to use a scope.

We use a scope to check whether a signal is changing, to see if the signal is repetitive. If it is repetitive, we can measure the signal frequency and peak-to-peak voltage. If the signal is not repetitive but changing over time, we can also measure the time between two events such as the time between consecutive heartbeats.

We also use the scope to measure the unwanted noise signal on top of the wanted signal.

Although the scope is generally used to measure analogue signals, we can also use it to observe and measure digital signals.

There are different types of scopes. They can be analogue or digital scopes. Modern scopes are generally digital. For this module, we use a modern digital oscilloscope.

Shown in this diagram are the different groups of control knobs and connectors. They are used to control:

1. X-axis or timebase, i.e. time per division.
2. Y-axis or signal voltage, i.e. volts per division.
3. Trigger control – see later.
4. Signal connnectors inputs and signal output.

Task 1 : You have to generate a 1.1kHz sine wave signal with 1v amplitude and centred at zero volt. That is the dc offset is 0. You do this with the bench-top function generator.

One of the key learning of this task is to appreciate exactly the meaning of "triggering" a scope using the level knob in the trigger panel. You also need to understand the significance of selecting the slope of the signal to trigger on.

Another important learning outcome is the use the time base control to adjust the X-axis of the waveform; and to use the voltage scale knob to adjust the verticle sensitivity.

Note that the scope shows the scaling on the top left and bottom left of the screen.

Task 1: How to trigger a scope (2)

The layout of the scope is divided into different regions (or panels). The two main panels are: 1) VERTICAL control for Channel 1 and channel 2; 2) HORIZONTAL control of time or x-axis. The vertical control determines the voltage scale in volts/division and the position of the zero voltage reference. The horizontal control determines the the time scale in sec/division relative to a time reference determined by something called the "**trigger**".

The middle groups of knobs and buttons are the trigger controls. Trigger is the mechanism that determines when the scope should start a display plotting from left to right (i.e. the time origin of the waveform). Since this is a digital scope, we can display what happens BEFORE time zero (or the trigger point.

There are various trigger modes. Two are most common:

Auto – means the scope will do its best to automatically trigger the display scan, no matter if the trigger condition is met or not. It is the most useful and common setting. This may result in a "moving" display.

Normal – means the scope will only start a display scan if the trigger condition is satisfied. Under this mode, the display is usually stationary or blank.

There are also various trigger sources: CH 1, CH 2 and EXT are the most commonly used.

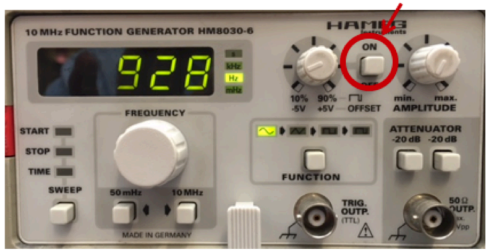
Here is an excellent video on triggering control on a scope:

https://www.youtube.com/watch?v=H0Czb2zBzsQ

Task 1: DMM measurements- Peak vs RMS value

- You should also learn to use the DMM to measure the signal size.
- Remember that the DMM on AC signal setting will report RMS value of the signal, NOT amplitude value!
- Also remember that the DMM would give you an accuracy of 1% or better.
- On the scope, and by counting number of divisions, you may get an accuracy of 5% or even less.

OFF for zero offset



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In Task 1 of Lab 1, you are asked to use the DMM to measure the 1.1kHz sinewave, which has been set to have an amplitude value of 1V (i.e. peak-to-peak of 0V).

Most of you have a reading on the DMM (set to measure AC) of around 0.69V. Why? This is because the DMM reports the AC signal value as its root-mean-square (RMS) value, NOT peak amplitdue. The reason is simple. The DMM has no way to know that the signal is a perfect sinewave. What happen when you set the signal generator to produce a square wave? Giving you the peak AC signal value is misleading and not very useful.

On the other hand RMS value of a signal x(t) is defined as:

$$x_{RMS} = \sqrt{\frac{1}{T}\int_0^T x^2(t)dt}$$

For a sinusoidal signal $x(t) = Asin(\omega t)$,

$$x_{RMS} = \sqrt{\frac{1}{T}\int_0^T \text{Asin}(\omega t)^2\, dt} = A\sqrt{\frac{1}{T}\int_0^T \frac{1-\cos(2\omega t)}{2}dt}$$

$$x_{RMS} = A\sqrt{\frac{1}{T}\left\{\frac{T}{2} - \int_0^T \frac{\cos(2\omega t)}{2}dt\right\}} = \frac{A}{\sqrt{2}}$$

0

Remember that this equation only applies to sinewaves.

Task 2: Using the Scope's signal generator

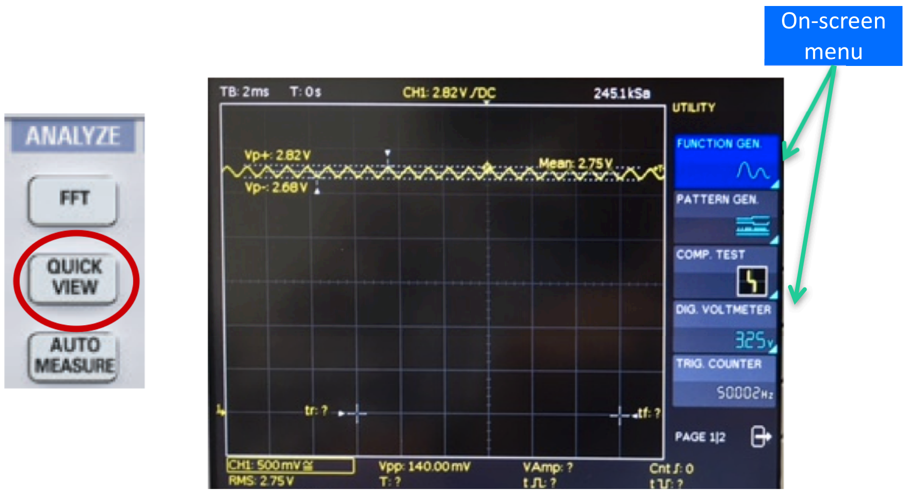
- We will now use the **built-in function generator** of the scope to produce the 1V amplitude sine wave. Connect the AUX OUT signal on the left of the scope to the input of CH1 using the BNC cable.
- Press the 

button on the VERTICAL panel, and select FUNCTION GEN on the on-screen menu.
- You can now set the desired signal type (sine), frequency (1.1kHz) and amplitude (1V). Measure this on the scope.
- Next, generate a 100mV **pk-to-pk** sinewave on a 2.8V offset at 1.1kHz using the scope's function generator.
- Measure this using the scope as before.
- Produce a **hardcopy** of the screen by plugging in a USB drive to the scope (far left) and press the button. This allows you to stick the screenshot in your logbook.

Task 2 : The point about this task is that you should learn to use the built-in function generator of this scope.

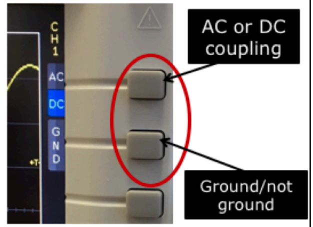
I also want you to learn the QUICK VIEW function to help measurement of signals. Beware that YOU MUST ALREADY MASTER the way to do manual (instead of automatic) measurements by counting divisions and using the VOLTS/DIV setting. I don't want you to completely rely on the automatic measurement feature of the scope.

Another important point to note is that the accuracy of the scope's automatic measurement is limited. You will find that the function generator setting and the measured pk-pk voltage and DC offset may not completely agree with each other.



Task 3: DC and AC coupling

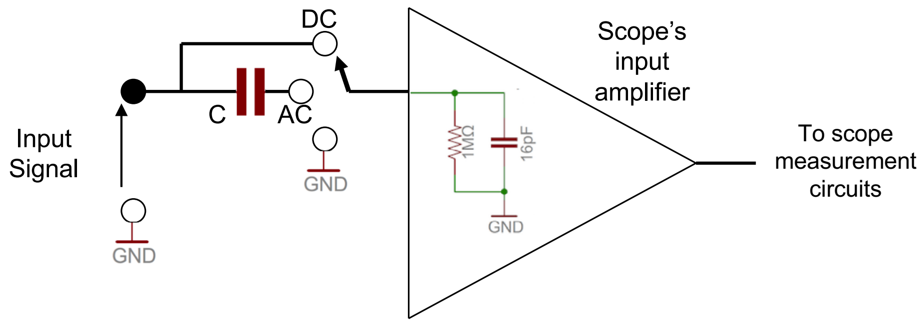
- In task 2, we measured a small time varying (AC) signal on a large DC offset. The scope was in DC coupling setting. It showed both the DC offset and the AC signal on the same screen. The AC measurement was inaccurate.
- To measure the AC component of the signal accurately, we need to use AC coupling.
- Select CH1, and then press the AC-DC on-screen menu button to select AC coupling.



- Enlarge the tiny sine signal to fill the entire screen.
- So, measuring a small time-varying signal sitting on a large DC requires two steps:
  1. Use DC coupling to measure the offset level.
  2. Use AC coupling to measure the amplitude.

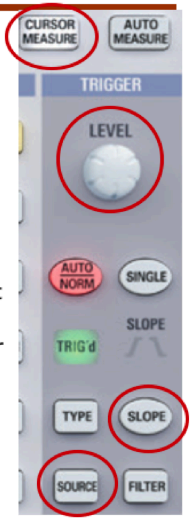
Task 3: When measuring a small sinewave sitting on top of a large DC offset, you will find that even establishing trigger with the scope is difficult. This forces you to learn to use the DC coupling and AC coupling setting on CH1.

I have not taught you about capacitor and its ability to block DC signals. Don't worry – you will learn that later. For now, you only need to know that you need to measure the DC component and AC component of the signal separately. Detail about how the capacitor can block the DC is not that important for now.



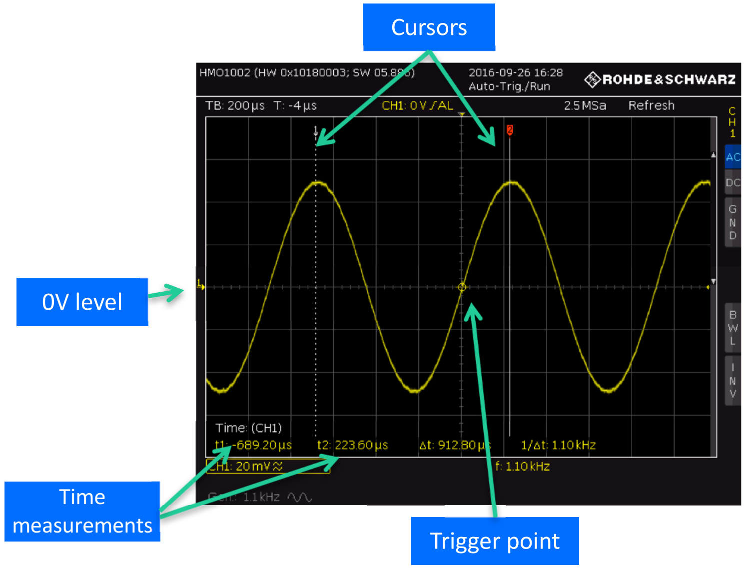
Task 4: Trigger and cursor measurements

- In this task, you will learn more about the trigger mechanism and the use of cursors for measurements.
- Use the signal in Task 3 and set the scope to: AC coupling, CH1. Adjust the TRIGGER LEVEL knob until the cross-hair symbol is right at the centre of the screen.
- The cross-hair shows the time and voltage when trigger occurs. Now change the slope of trigger between rising, falling and both. Explain what you see.
- So far we have not used CH2. Connect CH2 to the HAMEG signal generator. Set the HAMEG to produce a sine wave at around 10kHz of some amplitude. Turn CH2 ON.
- Press the SOURCE button and change the source to CH1 or CH2. Explain what you see.
- Finally, press the CURSOR MEASURE button, and explore how to adjust the cursor position to measure both time and voltage values on the waveform.



Task 4: This task is intended to get you to really understand what is establishing TRIGGER on a scope. The key points are: trigger source selection, trigger level and trigger slop. For example, why when trigger on both rising and falling edges, we get two waveforms superimposed on each other?

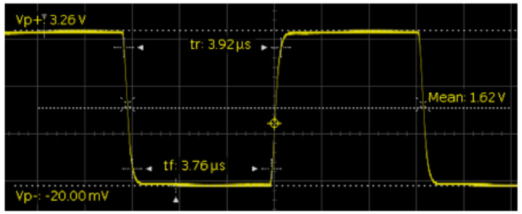
I also want them to learn how to use cursors to make more accurate measurements, particularly on the time axis.



Task 5: Measuring digital signals

- Use the pulse option of the scope's function generator to produce a 3.3V symmetrical clock signal at 8kHz. (That is, '0' at 0v and '1' at 3.3V with equal high and low periods.)
- You can accomplish this by: 1) select PULSE signal, 2) set amplitude to 3.3V, 3) set offset voltage to 1.65V, 4) set duty cycle to 50%.
- Measure the signal with CH 1 of the scope to confirm the high and low logic voltage level, the frequency and the duty cycle.
- In addition to voltage levels and signal frequency, the scope also shows rise and fall time (as t_r and t_f). This is the time it takes for the signal to go from 10% to 90% of full scale (and vice versa).

> Adjust the signal so that the duty cycle is 25%. Explain the mean voltage value.



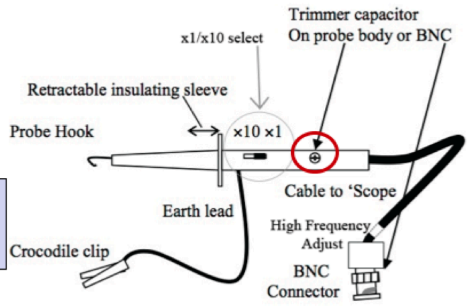
Task 5: The learning outcomes are:

1. Signals can be digital in nature. Here there are only logic 0 voltage level and logic 1 voltage level.
2. With 3.3V logic, 1 level is around 3.3V and 0 level is around 0V.
3. The definition of duty cycle and the relationship between duty cycle and mean voltage for a digital signal. (Mean voltage = 3.3V x duty cycle for 3.3V logic.)

$$\text{duty cycle} = \frac{\text{time when signal is high } (t_H)}{\text{period of the signal } (t_C)} \times 100\%$$

Task 6: Using the x10 probes (1)

- Using BNC cable to do measurement on signals at high frequencies will result in signal attenuation and/or signal distortion.
- We almost ALWAYS use a scope with its dedicated measurement probes, known as the **high impedance** or **x10 probe**.
- There is a x1 or x10 selector. x1 setting is equivalent to what we have done so far, and is only good for low frequency measurements.
- **Always** use x10 setting to measure high frequency signals or signals with high source impedance.
- When you use x10 setting, all readings will be **reduced** by a factor of 10.



- You must also tell the scope that you are on the x10 setting.

Task 6: This is a long task. I want you to learn to use the high impedance x10 probe.

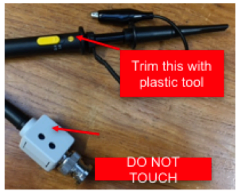
The main message is NOT that the high impedance probe has higher impedance and therefore less loading on the signal. Even 1M ohm (x1 impedance) is already pretty high for most application.

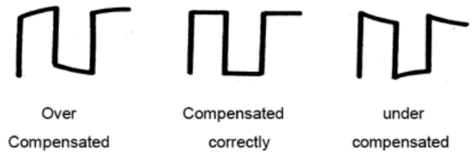
The main message is that you need a x10 probe to measure fast changing signal (i.e. fast edge). They will not know what is bandwidth and frequency response by this stage. Therefore the main idea is limited to:

1. We use x10 probe for most measurements.
2. We need to set up the scope to use the x10 probe because the signals are attenuated by a factor of 10.
3. We need to compensate the probe first before using it.

Task 6: Calibrating the Probe (2)

- Connect both probes to the PROBE COMP hooks as shown below.
- You will see an on-screen instruction displayed. Use the special trimmer tool to adjust the trimmer capacitor on the probe until clean edges on the square wave is obtained. Now the probe is properly compensated.



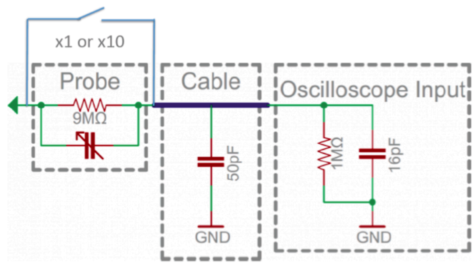


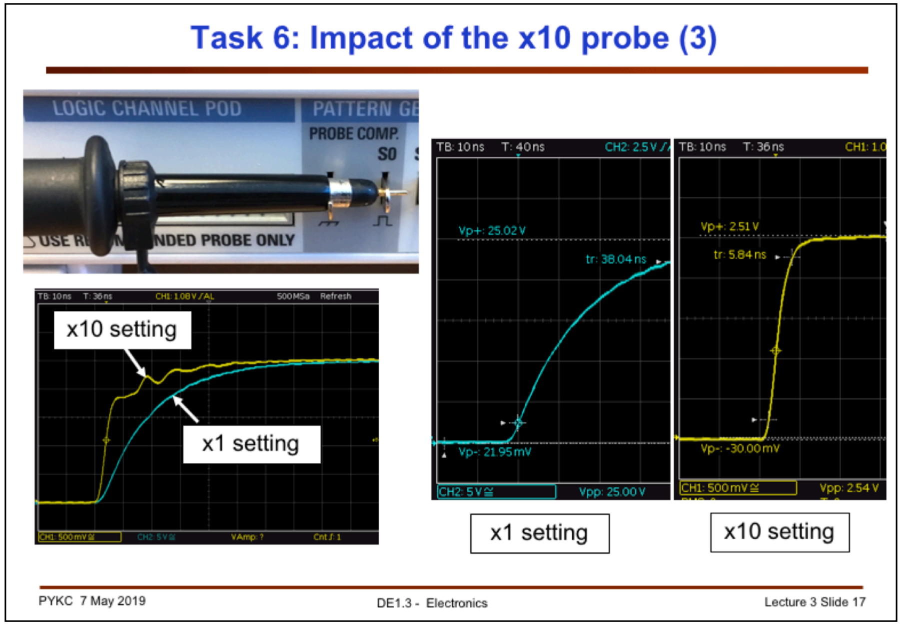
Task 6 (continue): Make sure that you have tried this yourself.

The probe we use here is high performance probe with a bandwidth of 300MHz. There are two more compensation capacitors on the BNC end of the probe, as well as ONE capacitor on the probe end.

You should ONLY adjust the capacitor at the probe end. You must use a plastic adjustor, and not a metallic screw driver. Otherwise, the screw driver will affects the adjustment.

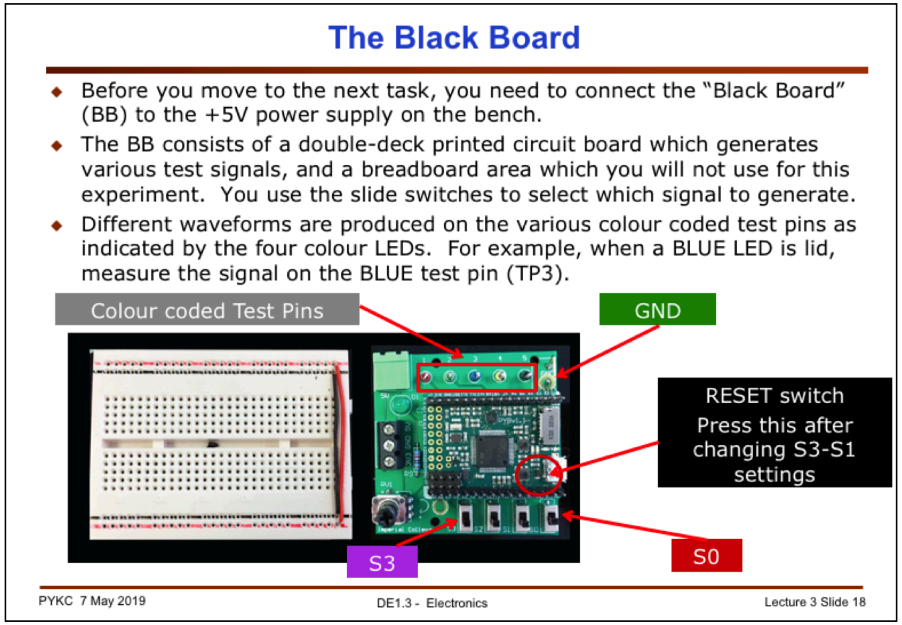
The circuit of the probe is shown here. Don't worry about this for now. You don't need to understand at the moment how this probe works. Only know this: you must use a x10 probe to measure signals that is over 1MHz in frequency.





Task 6 (continue): .

This slide shows the difference in using the probe in x1 setting and x10 setting. Both settings will measure the signal and show it on the screen. However, using a x10 setting result a much faster rise time because under x10 setting, the internal circuit inside the probe allows fast signal change to be measured. With x1 setting, this internal circuit is by-passed. Actual detail of this circuit and how it works does not matter.



Although you don't need to know how this board works, it is important that you know how to use it.

The colour LEDs on the board is useful as a reassurance that everything is working. Different LEDs will be lid on different switch settings.

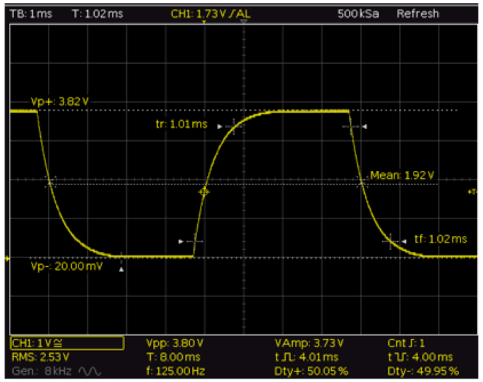
Also, when SW3-SW0 is set to zero, the LED indicates the variant number as a binary code (RED-GREEN-YELLOW-BLUE from MSB to LSB).

The variant number will be between 1 and 8. From this variant number, we can find out what signals are being generated by the Pyboard (the board on top of the base PCB).

Task 7: Exponential signals

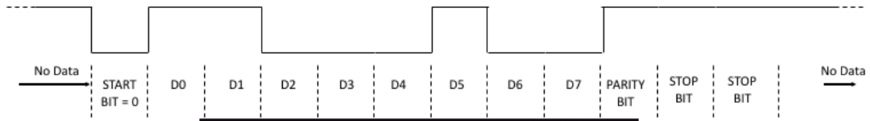
- The low to high transition of the waveform can be described by the equation: $Vout = Vamp \times (1 - e^{-t/\tau})$
- The high to low portion of the waveform can be described by the equation:

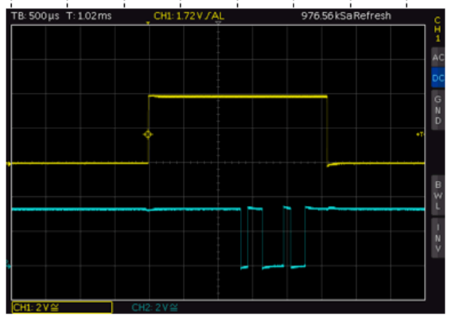
$$Vout = Vamp \times (-e^{-t/\tau})$$



Task 8: Measuring complex digital signal

- The idea is to measure a real digital UART signal that convey an 8-bit binary number representing an ASCII coded character:

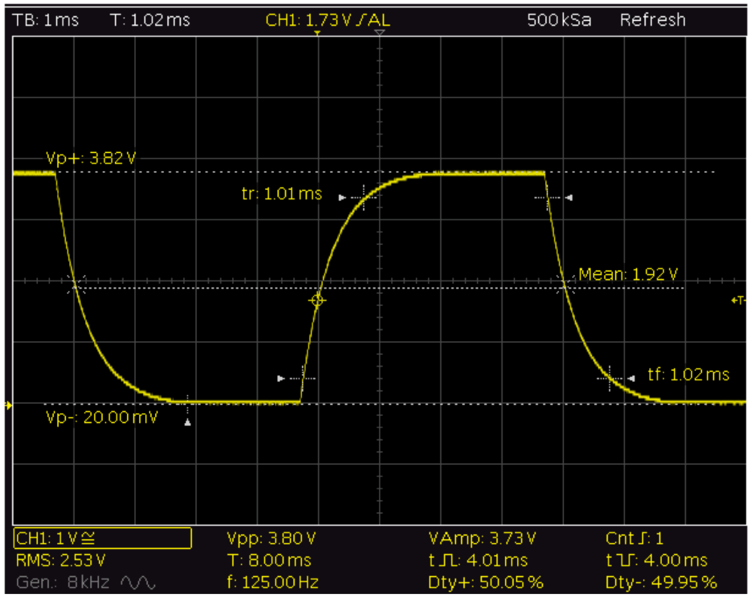




Task 7: I want you to be familiar with exponential rise and fall signals. You need to understand the difference between time constant and rise time.

The time constant value τ must be measured using the division counting method on the scope. Automatic measurement on the scope will not give you this reading.

This is the waveform students will see:



Task 8: UART signals are not covered in lecture 2. I will go through it again here.

The waveform is exactly as shown above. You need to understand how to decode the digital waveform into 1's and 0's.