Lab 4: Opamps in POSITIVE Feedback

Conceptual introduction

The prototype design for an opamp circuit using positive feedback is shown below in Fig 1

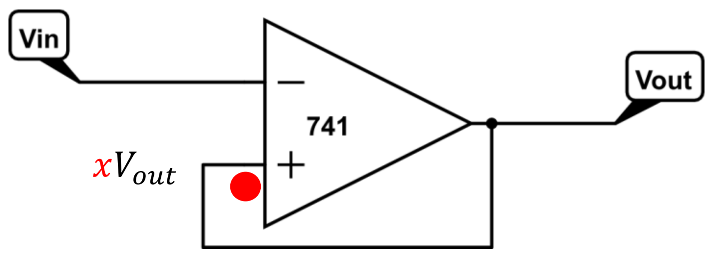


Fig 1: Prototype showing essential features of a positive feedback circuit. Fraction xV_{out} is send as feedback to the V_+ terminal

The two defining features of a positive feedback circuit are:

1) feedback signal is **always** applied to the V_+ terminal

2) V_{out} can have only two values - $+V_{sat}$ or $-V_{sat}$: these are the two states of the output – we will refer to the output 'switching' between these two states. V_{sat} is the maximum saturation voltage of the opamp output, usually a volt or so less than V_{CC}

The two Golden Rules of opamp design are obviously still applicable and all analysis is done on the basis of those two rules.

1) Circuit design

Problem statement:

What we DON'T want: Opamp running open-loop acts a comparator.

In Fig 1, consider what happens when the circuit in Fig 1 does not have the feedback loop in place. If $x = 0$ (i.e. V_+ is set to GND (and disconnected from V_{out}, breaking the feedback connection) then, V_{out} will switch states when V_{in} transitions from $V_{in} < 0$ to $V_{in} > 0$ and vice versa. However, as we know voltages are always noisy! So a small noise fluctuation in V_{in} around transition threshold will cause the output to switch multiple times.

With your kit's current battery state (maybe much less than 9V!) check the V_{sat} values you get with opamp open-loop comparator – most of the calculations below will depend on the numerical V_{sat}

WHAT WE WANT: Design a circuit that is called a **"Schmitt Trigger"**

Protect against the problem with noisy V_{in} and the desired solution for behavior of V_{out} is shown in Fig 2

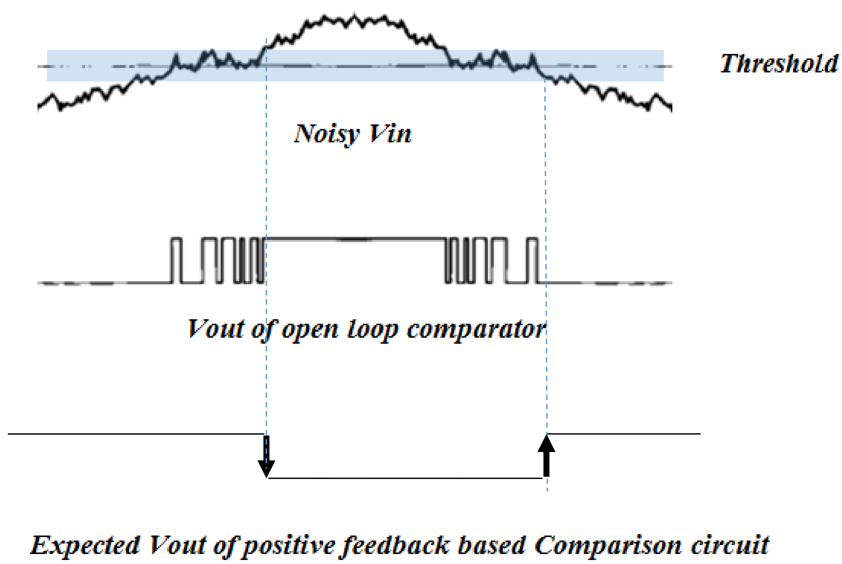


Fig 2: V_{out} of open loop comparator switches many times as noisy V_{in} crosses threshold.
OBJECTIVE: You should be able to set a specified value of threshold voltage V_T and have a specified safety 'noise' band around the threshold (marked as blue shaded box):
Required circuit: V_{out} must switch only when V_{in}exits that safety band.
Note: Timing & logic of the transitions highlighted above are caused by the intrinsic structure of our **inverting** Schmitt trigger.

Design specification:

As per Figures 1 and 2, design a positive feedback circuit using the LM741 such that:

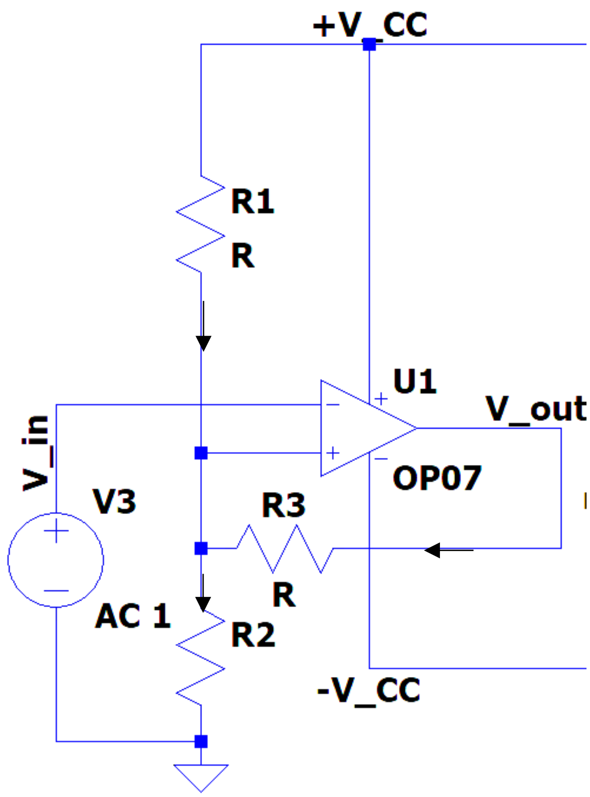
1) Threshold Voltage $V_T = 2V$
2) Noise band allowed around V_T $is \pm 0.3V$
3) Use regular opamp power supply setup as earlier $\pm V_{CC} \sim \pm 8V$ don't forget the power supply bypass caps!

Hints for design:

a) As in negative feedback the fraction xV_{out} is set by a resistor divider. However, now our analysis is constrained by V_{out} being stuck to $\pm V_{sat}$ and having to set **two** bounds on the comparison :
both $2V + 0.3V$ and $2V - 0.3V$
For simplicity we have asked for a symmetrical noise band around V_T. In principle it is possible to set different lower and upper bounds around V_T
b) You will find THREE resistors are required instead of two as used in the negative feedback case.
c) Generally, such a circuit is called a 'Schmitt Trigger'

Solution to Question 1) **5**

Put a sketch of your Schmitt Trigger design here labelling the resistors and the design calculation equations that fulfill the required specifications. Equations must be properly formatted



The notation used for the components has been shown in the diagram on the left.
We want to set:

1) $V_{T|u} = V_T + 0.3V = 2.3V$ (upper threshold)
2) $V_{T|l} = V_T - 0.3V = 1.7V$ (lower threshold)
3) $V_{ref} = V_{CC} \simeq 8V$
4) $V_{out|u} = 8V$ and $V_{out|l} = -8V$

$V_{in} = V_-$ and $i_{in} = i_- = -i_+$

$i_1 = \frac{V_{ref}-V_+}{R_1}$, $i_2 = \frac{V_+}{R_2}$ and $i_3 = \frac{V_{out}-V_+}{R_3}$

The sign convention for the direction of currents is shown in figure.

i_{in} temporarily goes to zero when $(V_- = V_+)$ the V_{out} switches sign.
Since we have an inverting Schmitt trigger, this occurs when V_{in} just crosses $V_{T|u}$ and V_{out} is driven to -8V (assuming it was previously 8V).
Or, it occurs when V_{in} just goes below $V_{T|l}$ and V_{out} is driven to 8V (assuming it was previously -8V).
When, $i_{in} = 0 \Rightarrow i_1 + i_3 = i_2$

$$\frac{V_{out}-V_+}{R_3} + \frac{V_{ref}-V_+}{R_1} = \frac{V_+}{R_2}$$

Case1: $V_{out} = 8V \Rightarrow V_+\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}\right) = 8\left(\frac{1}{R_3}+\frac{1}{R_1}\right) = V_{T|u}\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}\right)$

Case2: $V_{out} = -8V \Rightarrow V_+\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}\right) = 8\left(\frac{-1}{R_3}+\frac{1}{R_1}\right) = V_{T|l}\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}\right)$

The higher of the two is $V_{T|u} = 2.3V$ and the lower is $V_{T|l} = 1.7V$
Dividing the two expressions:

$$\frac{R_3 - R_1}{R_3 + R_1} = \frac{1.7}{2.3} \Rightarrow 4R_1 = 0.6R_3 \Rightarrow \boldsymbol{\frac{R_3}{R_1} = \frac{20}{3} = 6.667}$$

$$2.3\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{3}{20R_1}\right)=8\left(\frac{1}{R_1}+\frac{3}{20R_1}\right)$$

$$\Rightarrow \frac{R_1}{R_2}=\frac{57}{20}\Rightarrow \boldsymbol{\frac{R_2}{R_1}=\frac{20}{57}=0.35}$$

Thus, we have worked out the ratios, but the exact resistor values depend on the amount of current one wants to allow through the circuit. For $i_{in} \sim 500\mu A$ the optimal resistor value $R_1 \sim 10xk\Omega$

The values chosen are: $R_1 = 20k\Omega,\ R_2 = 6.8k\Omega,\ R_3 = 133k\Omega\ (100k\Omega\ series\ 33k\Omega)$

2) Simulation 5

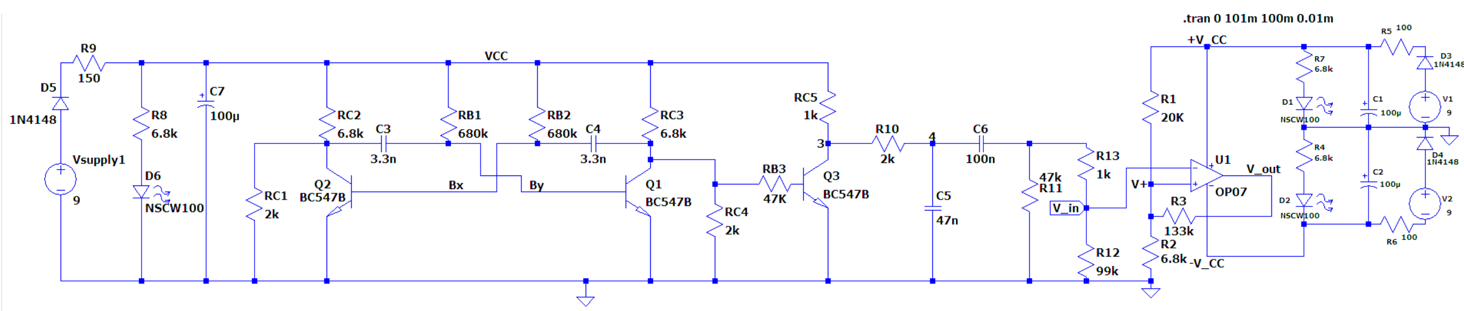
Simulate the circuit in LTSpice. For V_{in} Use the full-scale sawtooth output waveform from your regularly used FG.

Circuit diagram **2 marks**

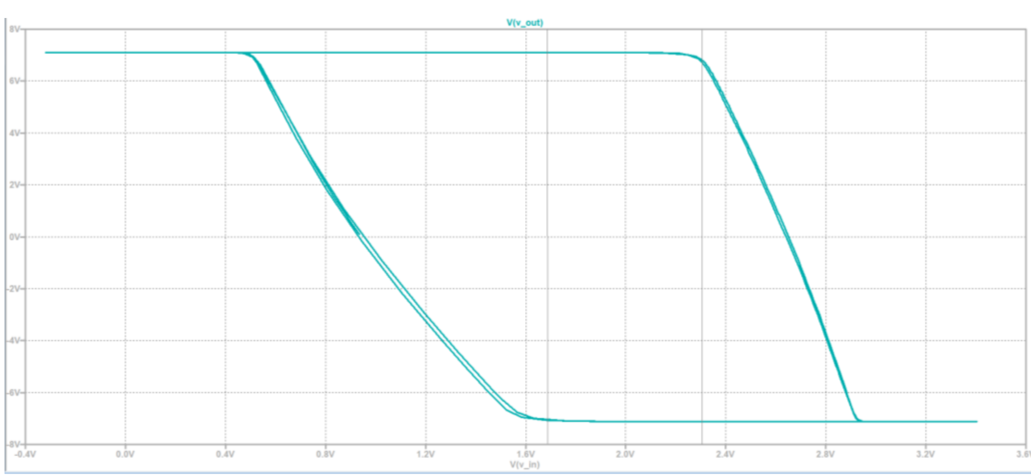
Plot of V_{out} & V_+ (time domain) **1 mark**

Plot of V_{out} v/s V_{in} **2 marks**

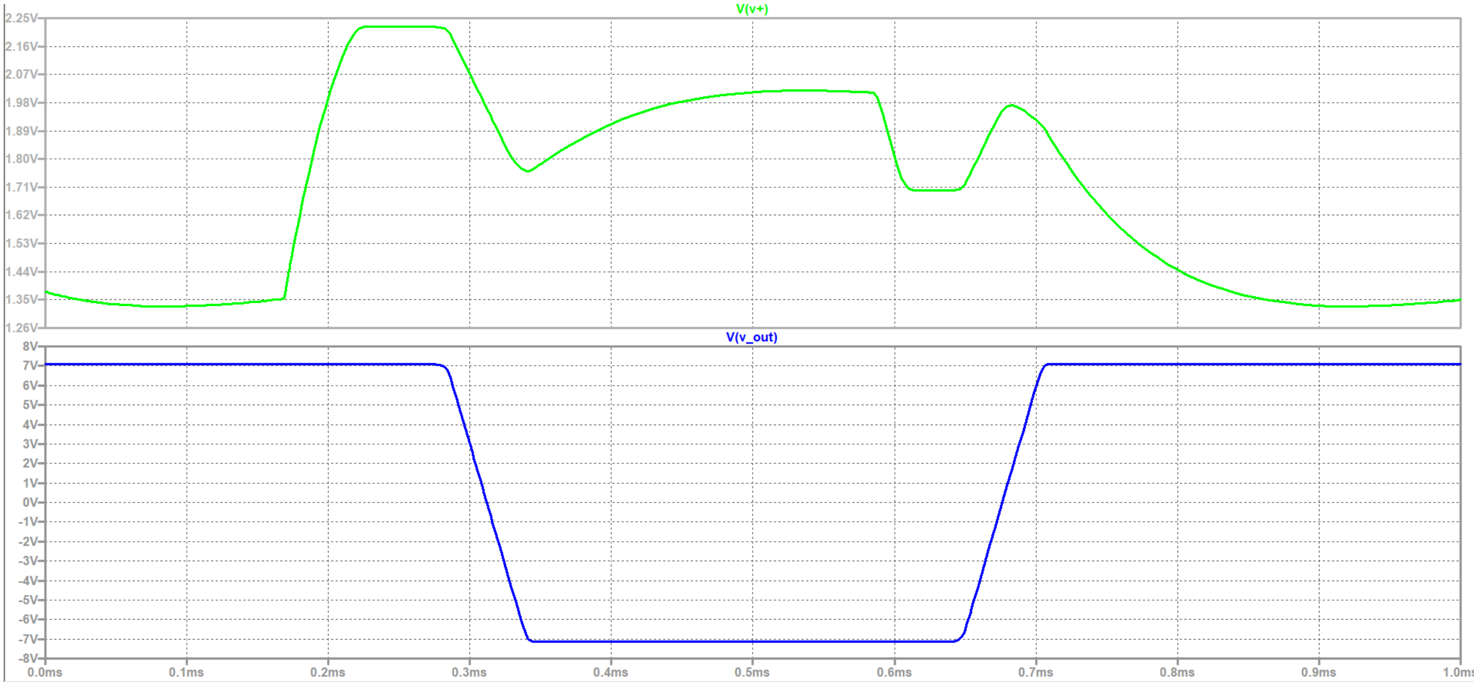
Circuit Diagram:



$V_{out}\ v/s\ V_{in}$:



$V_{out}(blue)\ and\ V_+(green)$:



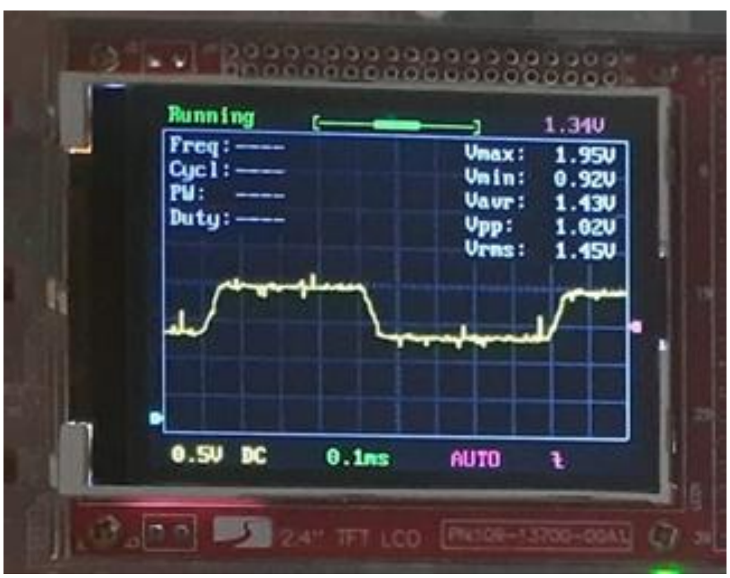
3) Circuit test – electrical voltages 5

Build the Schmitt trigger circuit designed and simulated on your breadboard.

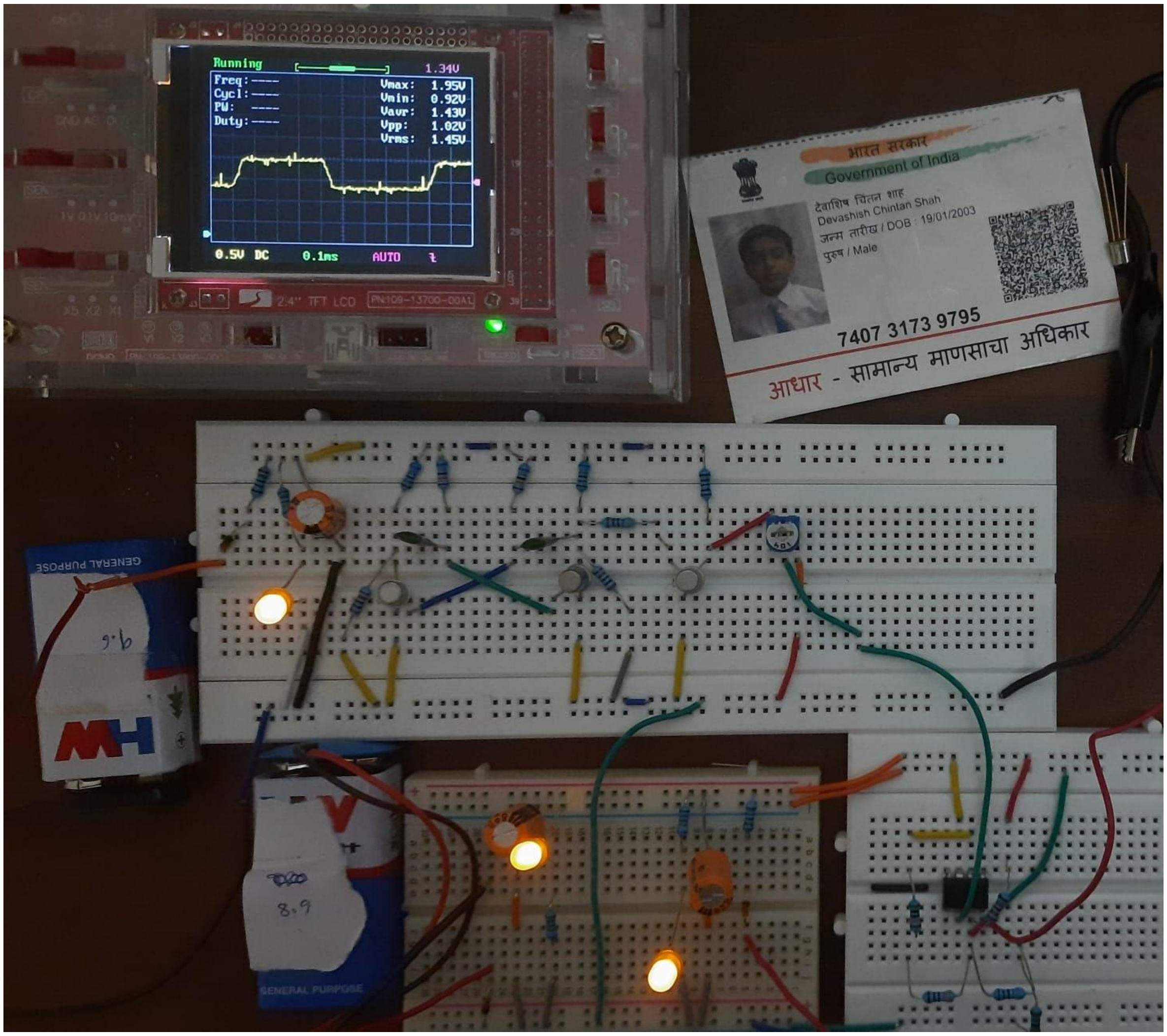
Do a photogenic demo of your V_+ and the V_{out} of your Schmitt trigger. Label each photo to distinguish which is which.

Use the full-scale square wave output from FG as V_{in}

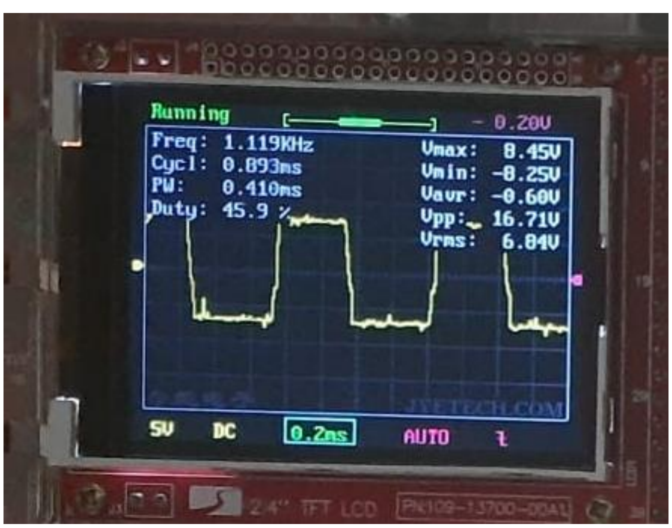
$V_+(zoomed\ in\ DSO)$:



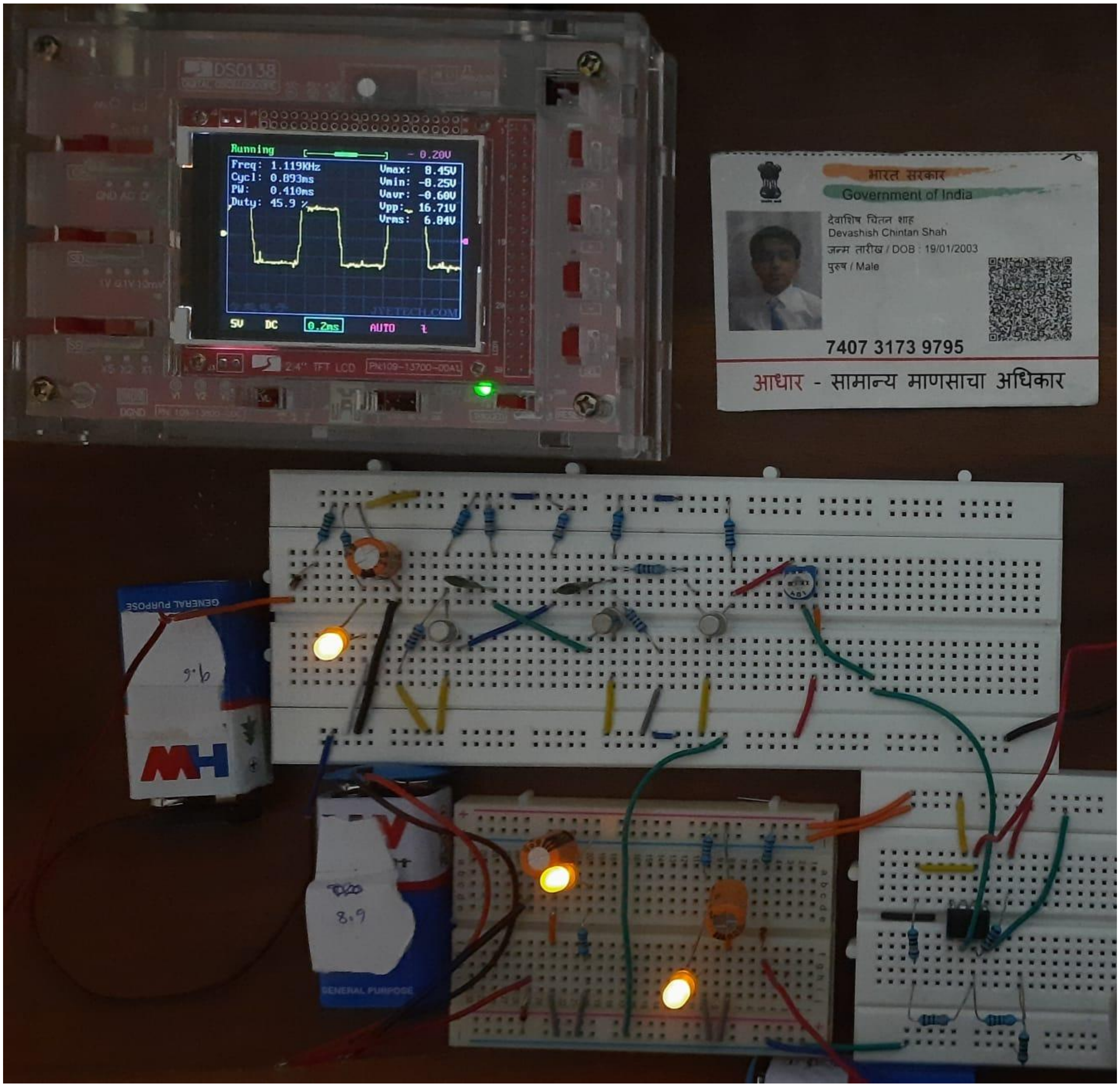
V_+:



$V_{out}(zoomed\ in\ DSO)$: $\pm 7V$ $(checking\ grid\ marking)$



V_{out}:

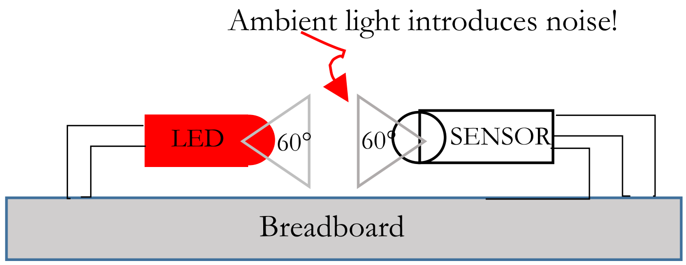


4) Circuit test – noisy light intensity measurement 10

Now we would like to test the Schmitt trigger with a realistic, noisy sensor voltage input.

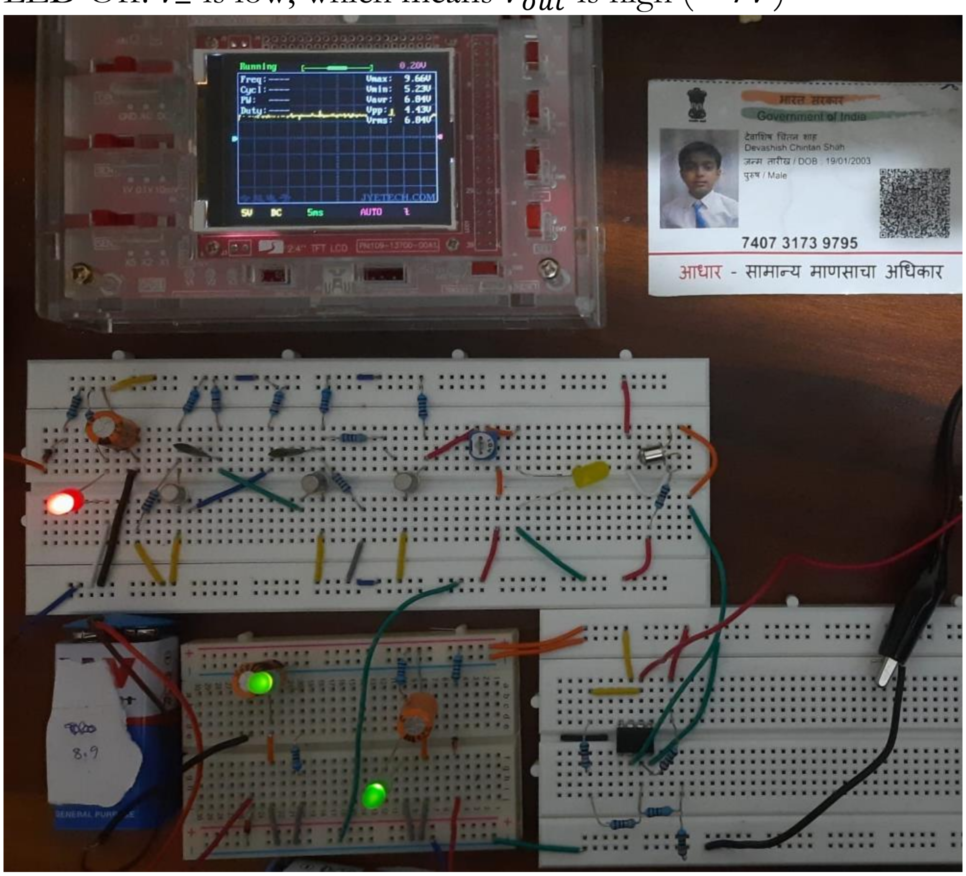
Sensor: Setup the photo-transistor in your kit as a light detector. With the base left unconnected, the voltage obtained at the emitter is proportional to the light incident on the device

Light source: Use an LED connected to the FG output with a suitable series resistor to provide a variable light intensity to your sensor photo-transistor. Note that the LED and photo-transistor must be mounted facing each other on the breadboard as close to each other as possible. The LED has ≈ 60° cone of light emission and the phototransistor also has maximum sensitivity within a 60° cone as shown below.

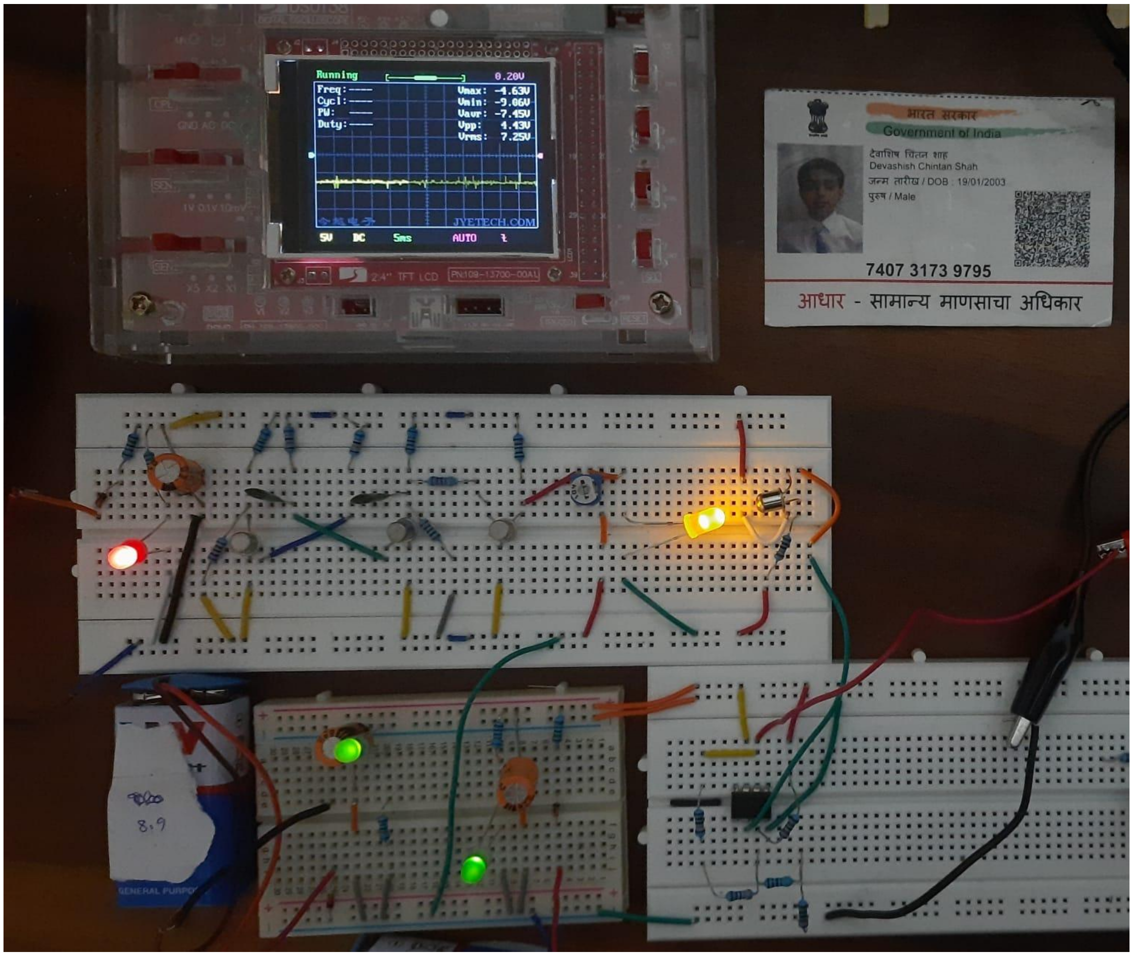


Demonstrate your Schmitt trigger circuit behavior using the above experimental setup: Introduce ambient light explicitly by shining a cellphone flashlight (there are various 'strobe' light apps available) – the. Put in a photo here of your measured Schmitt trigger V_{out} in the presence of such ambient noisy light. Shoot a video, post it on a shared google drive and put a link to your demo video here.

LED Off: V_- is low, which means V_{out} is high ($\sim 7V$)



LED On: V_{-} is high, which means V_{out} is low ($\sim -7V$)



Link to video with oscillating Light source:

https://drive.google.com/file/d/17xMmWah-6fszotyiRQESuMXHJn3h5cuf/view?usp=sharing