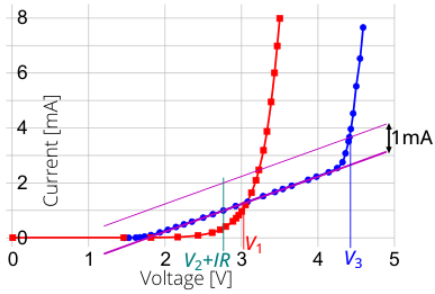
4. Black Box (12 points) — *Eero Uustalu.*

First we need to assemble a simple circuit allowing us to measure the $V-I$ curve of the black box: voltmeter in parallel to the box, and ammeter in series. The measurement results are shown in the table below, both for forward current (blue) and for reverse current (red) (the headers of the reverse current data has minus sign).



Voltage and Current Measurements

V (V)	**I (mA)**	$-V$ **(V)**	$-I$ **(mA)**
4.59	7.66	3.491	7.98
4.55	6.53	3.458	6.98
4.50	5.52	3.423	6.00
4.46	4.53	3.379	4.94
4.43	3.964	3.324	3.868
4.41	3.665	3.279	3.178
4.40	3.51	3.219	2.468
4.36	3.08	3.180	2.088
4.32	2.756	3.121	1.637
4.25	2.54	3.044	1.186
4.14	2.391	2.993	0.958
3.98	2.23	2.956	0.817
3.871	2.115	2.922	0.711
3.656	1.897	2.880	0.595
3.539	1.781	2.784	0.403
3.436	1.67	2.713	0.2931
3.282	1.519	2.607	0.1847
3.079	1.314	2.423	0.0801
2.923	1.159	2.156	0.0219
2.762	0.998	1.807	0.0037
2.625	0.862	1.451	0.0006
2.498	0.736	0	0
2.351	0.593		
2.246	0.491		
2.143	0.398		
2.036	0.2932		
1.931	0.1989		
1.815	0.1037		
1.732	0.0486		
1.670	0.021		
1.617	0.0087		
1.526	0.0016		
1.467	0.0005		

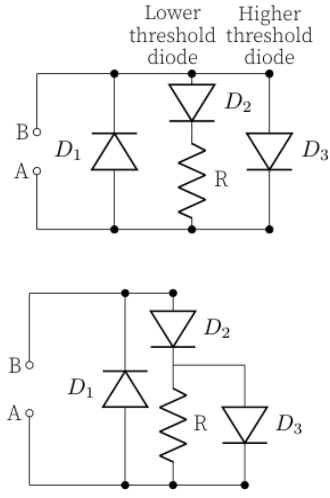
These data will be used for all the tasks.

i) *(4 points)*

Based on these data, we can determine that there is a single diode allowing negative currents to flow, with no other components in that branch, as the $V-I$ curve shows the classical exponential dependence characteristic of a diode.

The situation is more complex for positive currents: there must be two parallel branches allowing current to flow. One branch must contain a diode with a lower threshold voltage in series with a resistor, which explains why the initial exponential curve transitions into a linear relationship characteristic of resistive behaviour. The second branch must contain a diode with a higher threshold voltage (approximately 4.3 V) that only conducts when this voltage is exceeded.

This second branch could be either in parallel with just a resistor, or in parallel with the series combination of the resistor and first diode. These two configurations cannot be distinguished based solely on the $V - I$ curves, and both will be considered correct interpretations of the data. The two possible circuits are shown below.



Note that faulty measurements give no points in regard to data sufficiency (for example if the voltage was read from the power source without any corrections made).

Each plot (forward and reverse current) gives 1.2 points:

Grading: (preliminary)

- Drawing and labeling a graph's axes **0.2 pts**
- Collecting sufficient data for the graph that shows both linear and non-linear characteristics of the circuit **0.5 pts**
- Plotting the data to the graph **0.5 pts**

In total, the forward and reverse direction plots give 2.4 points. Drawing the circuit used in each the measurement gives 0.3p each for a total of 0.6p.

For drawing a possible circuit diagram (Refer to diagrams for option 1 and 2):

Grading: (preliminary)

- Placing the reverse diode D_1 correctly **0.3 pts**
- Placing the forward diodes D_2, D_3 and the resistor correctly, i.e. as described in the previous paragraphs **0.7 pts**

ii) *(2 points)* The resistor's resistance is the inverse of the slope in the linear section of the curve. To ensure accuracy, the most linear segment should be selected for this calculation. The fit line is shown in purple in the figure above, yielding a resistance of $R = 1008\,\Omega$.

Grading: (preliminary)

- Method for getting R_1 **1 pts**

- Reaching a close enough ($\pm 10\,\%$) value for the resistance **1 pts**

iii) *(6 points)* The accepted uncertainty of all subsequent results is $\pm 10\,\%$ of the values presented here. The opening voltage V_1 of diode D_1 can be found at the point where the red curve intersects the 1 mA value. For greater precision, additional measurements could be performed by gradually adjusting the voltage until exactly 1 mA current is reached. Based on our current measurements, the result is 3.004 V.

The value of V_2 can be found at the point where the blue curve reaches 1 mA, from which we must subtract the resistor's voltage drop IR. This calculation gives $V_2 = 1.757\,\mathrm{V}$.

To determine the opening voltage of diode D_3, we must first subtract the current through the resistor. This can be accomplished graphically by drawing a line parallel to the linear segment's fit line, at a 1 mA distance, as illustrated in the figure. For option 1, this procedure directly yields $V_3 = 4.47\,\mathrm{V}$. For option 2 (the actual configuration inside the box), we need to subtract voltage V_2. Consequently, $V_3 = 2.71\,\mathrm{V}$ for option 2.

Grading: (preliminary)

- Reaching a close enough value for the opening voltage V_1 **1 pts**

Getting value for V_2:

- Reading the value of $V_2 + IR$ at 1 mA **0.5 pts**
- Subtracting IR based on the inverse of the slope at the linear section **0.5 pts**
- Getting the value to within $10\,\%$ **1 pts**

Calculating the value for V_3 depends on the schematic that was used. This schema is written for option 2. Valid solution for option 1 still gives the same max points.

- Reading the total voltage where 1 mA is going through D_3 **0.5 pts**
- Subtracting V_2 from the total **1.5 pts**
- Reaching a close enough ($\pm 10\,\%$) value for $V_3 = 2.71\,\mathrm{V}$ **1 pts**