E: Physics of illumination

An incandescent light bulb produces light by heating a tungsten filament to a high enough temperature to emit black body radiation in the visible part of the spectrum, but a lot of energy is still wasted in the infrared part.

To quantify light as perceived by human vision, we use photometric units, which take into account sensitivity of the human eye to light of different wavelengths. The total amount of visible light *emitted* by a source into all directions is called **luminous flux**, measured in lumens [lm]. The amount of visible light *received* by a surface per unit of its area is called **illuminance**, in lux [$\mathrm{lx} = \mathrm{lm/m^2}$], and can be measured by a light meter.

When measuring quantities of light based solely on the energy it carries, we use radiometric units, which are expressed with conventional units of power. Radiometric counterpart of the luminous flux is **radiant flux**, measured in watts [W], and **irradiance** [$\mathrm{W/m^2}$] is the counterpart of the illuminance.

Today you will study thermal and illumination properties of light sources. The three tasks are mostly independent from each other. Sketch your setup for each task. No error analysis is required for Tasks 1 & 2.

Equipment (see also Fig. 1)

A Black and white plastic plate $3\,\mathrm{mm}$ thick with a stand. Both plates are good absorbers of infrared light.

B Light meter with a stand. The light meter turns off automatically after 6 minutes – turn it back on with a long press on the on/off button. Pay attention to the units (lx, not fc). You may use the `HOLD` button to freeze the displayed value.

C A light mounting stand with a round base, a weight for stability, and two interchangeable light modules: incandescent light bulb (**maximum voltage** $12\,\mathrm{V}$) and LED (**maximum voltage** $3.0\,\mathrm{V}$, **do not exceed** $400\,\mathrm{mA}$ **current**). You may use toothpicks to wedge the modules in place. Black paper is provided to shield your eyes while reading the instruments.

D Infrared thermometer. The measurement reading is held after a short delay when the trigger is *released*. The measurements may have a substantial but constant systematic error.

E Paper work mat with angular and distance grid.

F Protractor.

G Red, green and blue light filters in an envelope. If you have trouble telling the colours apart, raise the help card for assistance.

> **The filters are sensitive to heat. Keep them away from the light source.**

H Power supply. Press the voltage/current knob *multiple times* to select which digit to adjust (indicated by the blinking light below the digit), and turn the knob to change the digit. After a few seconds, the light stops blinking and the display starts showing the actual voltage/current. Vary the current to control the light source. If the requested current cannot be reached without exceeding the maximum voltage, the power source will switch into the constant voltage mode and limit the current. Plug the wires into the matching negative (black) and positive (red) sockets of the power supply. Do not use the green socket.

> **To avoid damaging the light sources, set the voltage to allowed maximum and set the current to zero before you plug in the wires!**
> **If your light source burns out, you can ask for a replacement. Note that only a limited number of spare light sources are available.**

Task 1 - Colour and temperature (4 pts)

The colour of the black body radiation depends on its temperature. In astronomy, the temperature of stars is determined from their colour index, the ratio of illuminances measured through two different colour filters.

(a) Table 1 contains the illuminances measured through the red, green and blue filter for a standard incandescent light source at known temperatures. Choose suitable light filters and construct a calibration curve that relates the chosen colour index to the temperature.

(b) Measure the relationship between the electrical input power and the tungsten filament temperature. Plot the result over a relevant range.

Task 2 - Luminous efficacy (8 pts)

The performance of light sources is quantified by their **luminous efficacy**, measured in lumens per watt, as the ratio between the luminous flux and the consumed power. As a point of reference, the sun has luminous efficacy of $93\,\mathrm{lm/W}$.

Measure the dependence of luminous efficacy on the electrical input power for both light sources across the range with detectable light output. Plot the results, one plot per light source. State all steps of the calculation procedure and present all the measured data.

Task 3 - Radiative heating (8 pts)

> **The following task may be time consuming, plan your work accordingly.**

When light hits an object, some of it is absorbed. At moderate temperature differences between the object and the environment, we can model heat dissipation into the surroundings with the **heat transfer coefficient** h, in the form $P/A = h(T - T_0)$, where T is the temperature of the surface, T_0 the temperature of the surroundings, and P/A denotes the power lost to the environment due to dissipation, per unit area.

(a) Determine the heat transfer coefficient h and the thermal conductivity λ for the black plastic, and perform error analysis. Assume the material absorbs all received light and the incandescent light bulb emits all power in the form of electromagnetic radiation.

(b) Estimate the albedo (the fraction of the irradiance that is reflected instead of absorbed) of the white plastic and perform error analysis.

Useful relations: An area of a segment of a sphere with radius r between polar angles θ_1 and θ_2 with $0 \leq \theta_1 \leq \theta_2 \leq \pi$ is $\Delta A = 2\pi r^2(\cos\theta_1 - \cos\theta_2)$.

Picture of equipment

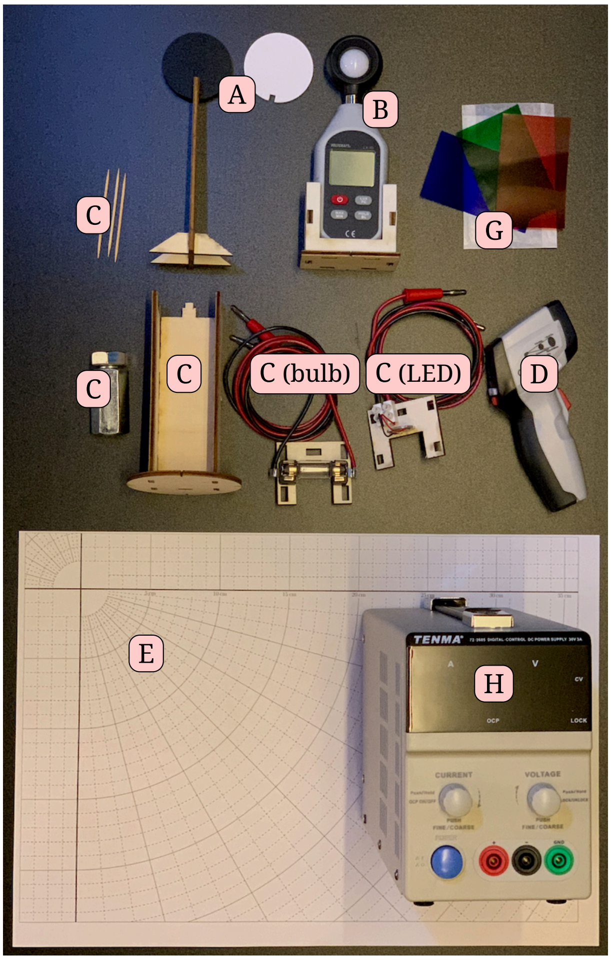


Figure 1: Picture of equipment for experimental problems (protractor and black paper shield not shown).

Illuminance table

T [K]	Red [lx]	Green [lx]	Blue [lx]
1570	2	0	0
1600	4	0	0
1610	5	1	0
1620	6	2	0
1630	8	3	0
1640	10	4	0
1660	12	5	0
1670	14	6	0
1700	18	9	1
1730	24	14	3
1780	37	23	7
1820	51	34	11
1880	80	57	21
1940	120	91	36
2000	165	130	53
2060	230	194	80
2120	310	274	118
2160	379	348	155
2220	484	460	210
2260	586	570	264
2310	753	748	348
2350	888	929	440
2390	1032	1107	527
2460	1292	1452	697
2500	1577	1826	879
2540	1811	2198	1078

Table 1: Illuminances by an incandescent light source of a known temperature, measured through three colour filters at a fixed position of the light source and the light meter. The accuracy of the measurements is $\pm 2\,\mathrm{lx}$.

Power supply instructions

The benchtop power supply outputs the maximum amount of electricity allowed by the set current limit and voltage limit. If the current limit is reached first, it operates as a constant current source, and if the voltage limit is reached first, it operates as a constant voltage source, indicated by CC and CV indicator lights.

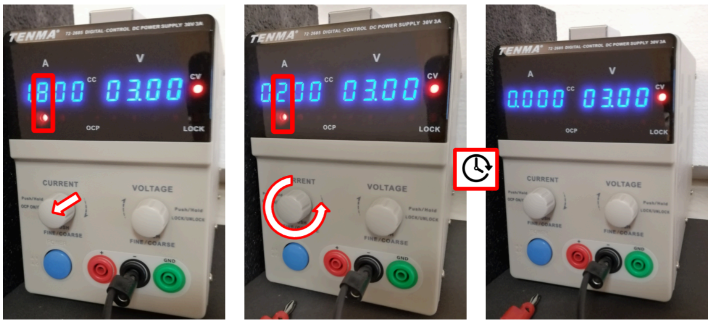
Do not plug in the light source before setting up the power supply! Notice the red wire in the image not connected, so the circuit is interrupted.

You will see two displays: current display on the left and voltage display on the right. They show the actual current and voltage at the moment, so the current will be zero, and the voltage will equal the chosen voltage limit. The CV indicator next to the voltage display will glow, indicating that the voltage limit is reached.

Press the voltage knob to set the voltage limit. The display will now show the voltage limit instead of the actual voltage, and the light below one of the voltage digits will glow. Turning the knob sets the chosen digit, and pressing it will cycle through all the digits. Use this to set the voltage to the maximum allowed voltage of the light source, e.g. 3.00 V for the LED.

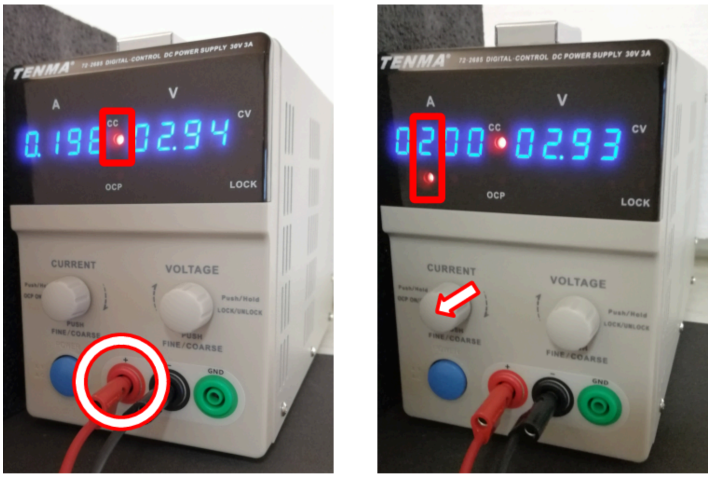
After 4 seconds, the display goes back to showing the actual voltage and the light below the voltage digits turns off.

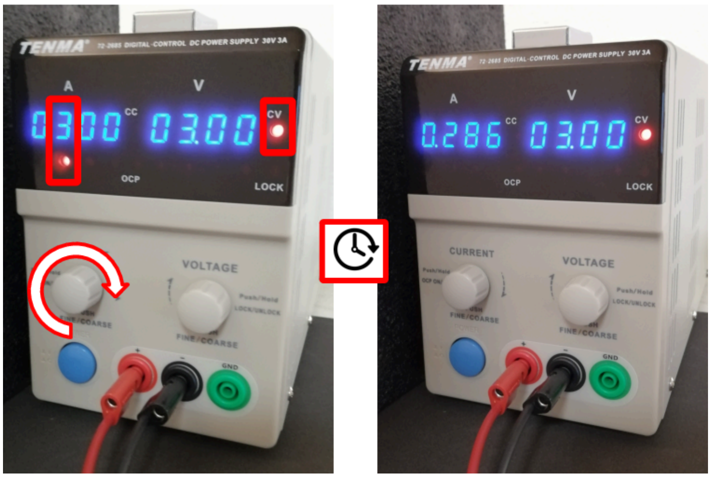
Repeat the procedure with the current knob (left), to set the current limit.



The example shows the limit 0.200 A. After 4 seconds, the display reverts to showing the actual current (still zero), and the digit selector light will turn off.

Now that both limits are set correctly, plug in the light source. Now the current limit is reached, indicated by the CC (constant current) light. Actual voltage is now lower than the setting. The light source in this example is not the same as in your experiment, so your values will be different. Try increasing the current limit with the left knob.





When the current is increased too much, the voltage limit is reached (CV indicator), which protects the light source. Use the current setting to control the light sources.