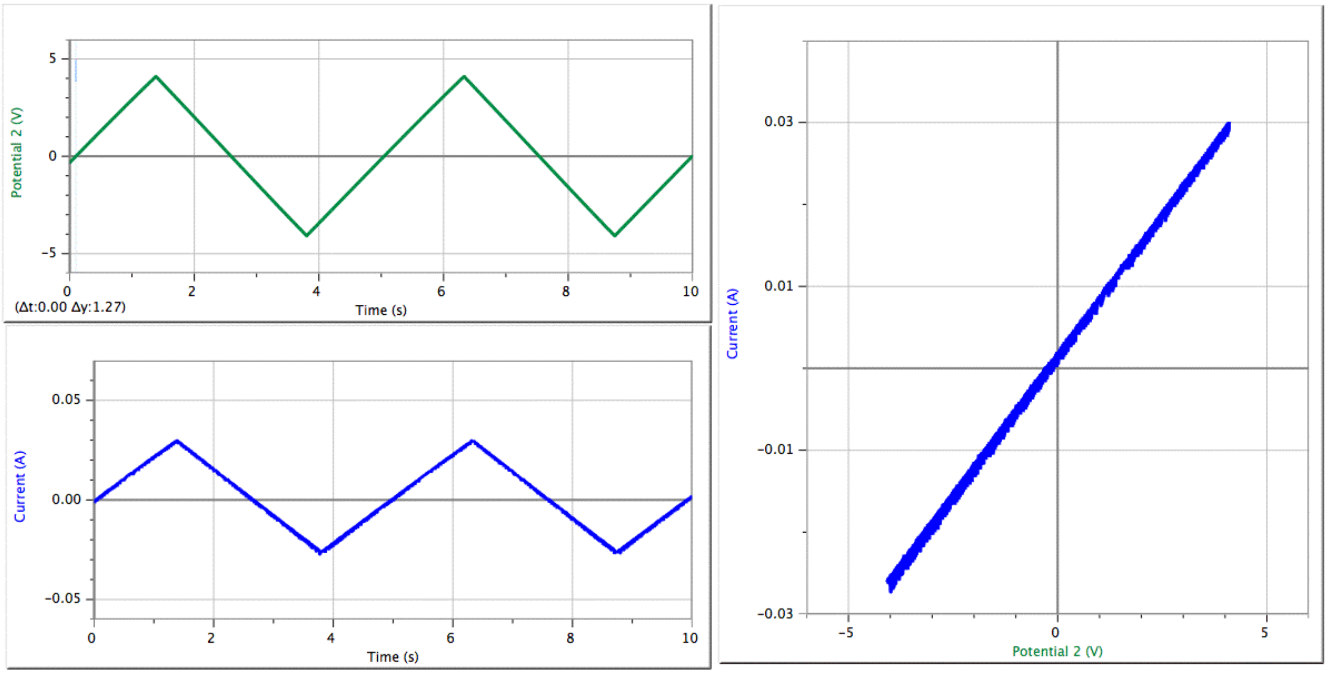
Physics 15b Lab 2: Current, Ohm's Law, Resistance, EMF

Relationships between Voltage and Current

We measure the voltage and the current as functions of time V(t) and I(t) and using this data to plot dependence I(V).. For light emitting devices power of light radiated is measured as a function of time and plotted as a function of current through the device, voltage across it and power supplied to it. Logger Pro output is provided

Resistor.



Key points: Ohm's Law

It can be clearly seen that IV curve for this element is a straight line, symmetric with respect to transformation V->-V and I->-I which corresponds to flipping the resistor.

Is it ohmic?
Yes, it is linear, hence ohmic

Calculate the effective resistance as a function of voltage. How does the measured resistance compare with the nominal resistance?

Logger Pro says 147.7 Ohm, which is quite close to the nominal value. We generally should expect **underestimation** of resistance since some extra current is detected with the ammeter — the current going to voltmeter. Other source of the discrepancy is the fact that real value is usually somewhere within +-10% of the nominal one.

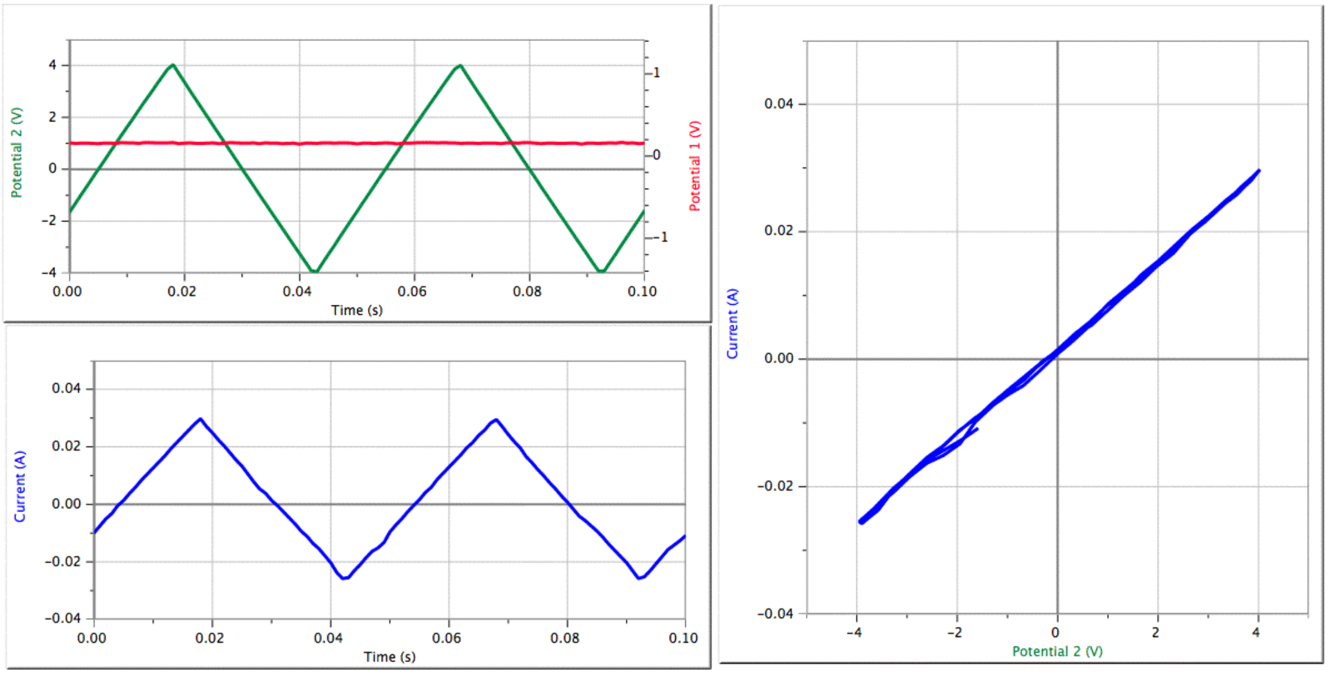
Is the device symmetric?

Yes, straight line is symmetric with respect to transformation V->-V and I->-I which corresponds to flipping the resistor.

Is it hysteretic?
No, both directions — increasing current and decreasing current are equivalent

Note: you would get the same results for a 20 Hz sine wave

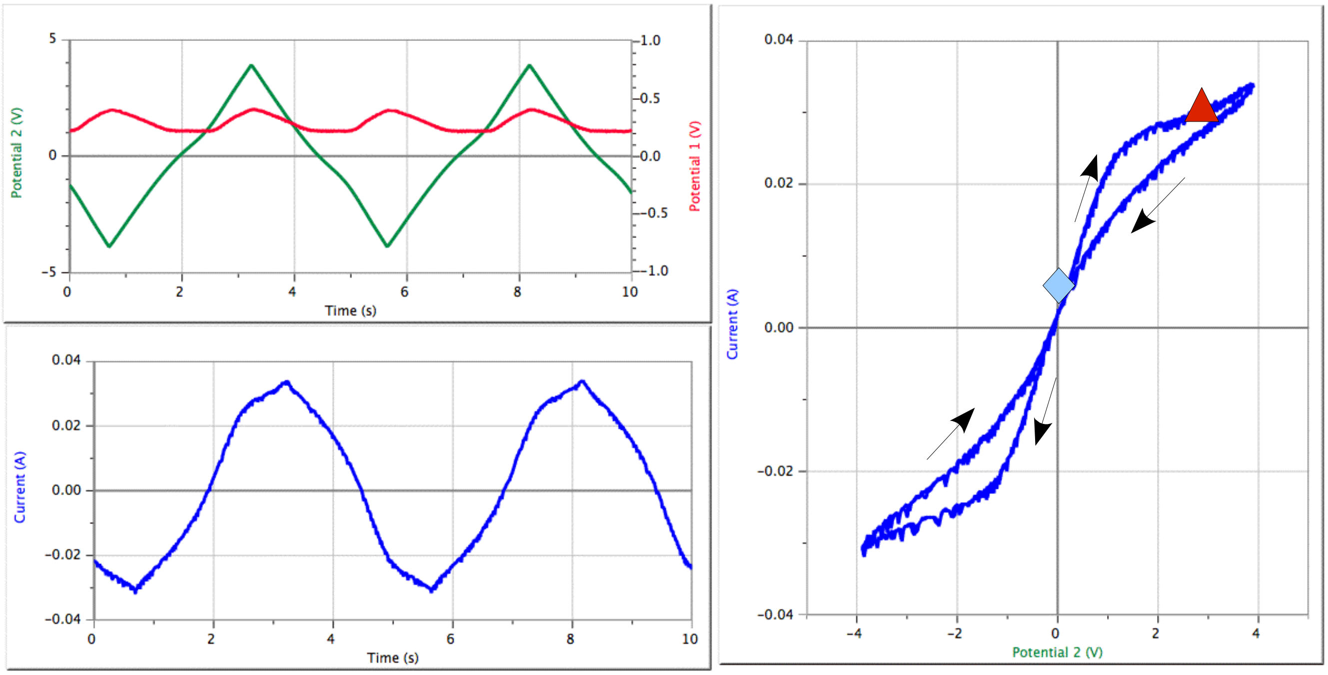
Just in case somebody does not believe so, here is the result of the measurement:



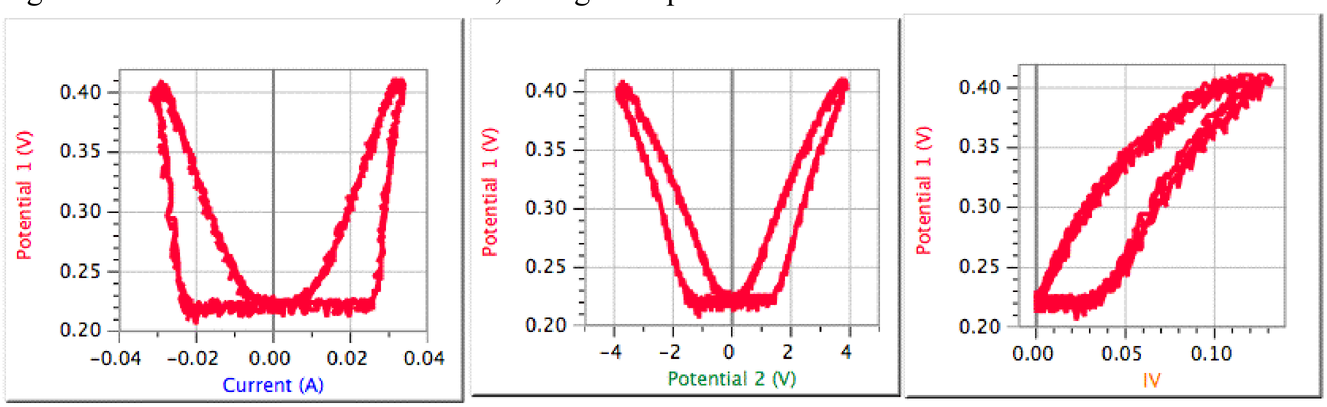
Noise became more noticeable, but this is the result of Logger Pro having a limited time resolution.

Light Bulb

IV Curves



Light emission as a function of current, voltage and power



Key points: Energy dissipation in current flow(Purcell 4.8) Temperature dependence of resistance. Black body radiation.

Calculate the effective resistance as a function of voltage. Is it ohmic? Is the device symmetric? Is it hysteretic?

The problem here is that the resistance is not anymore purely a function of the voltage: during operation of the light bulb the temperature of the filament varies over a large range, so does the resistance. Extreme values are 50ohm for the cold filament(marked with the diamond) and 350ohms for the hot one(marked with the triangle). The device is obviously not ohmic since there is no such R that for every voltage V and current I relation V=IR is true. It is symmetric — it can be observed from the IV curve. And it is hysteretic: it's properties (resistance) depend on the way, how the device was brought to the present state(how strongly was it heated before).

What is the voltage across the light bulb when it begins emitting light?

As a matter of fact light bulb emits some light(as a body with some temperature) at any given voltage, even zero. Other thing that for low temperatures this light is in the infrared region (for the room temperature wavelength is about 10 microns. compare to eye threshold of less then 1 micron) and it's intensity is very low. So the right question is «what is the voltage ... when we are able to detect with our instruments it is emitting light?» Answer is about 0.3V (or -0.3V — it works both ways)

What is the voltage across the light bulb when it stops emitting light?
Same story here... The number is 0.2V(-0.2). It is lower since the light bulb needs some extra time to cool down and to fade even after the voltage is not enough to sustain light.

What is the slope of the intensity vs current curve when the current is increasing with time?
Zero or very close to zero initially, then large: filament needs time to heat up (and high voltage) and it does not radiate unless it is hot.

Is the slope as a function of current for the case where the current is decreasing with time higher or lower than the case when the current is increasing with time? Explain your result.
There is a larger slope when the current is increasing: this is because it takes time for the light bulb to warm up to the point that it emits light; the relaxation time of cooling off to the temperature that it does not emit light is comparatively long, and it emits light during this entire cooling off process, so the slope is slower for decreasing slope.

How many light pulses does the light bulb emit during one voltage cycle?
Two — since it is symmetric it emits light both for forward and reverse voltages.

Is the intensity a linear function of electrical power?
No, neither linear nor a function.

Key points: black body radiation.
For voltages where the light bulb does emit light does the ratio of emitted intensity to electrical power increase or decrease with increasing power?
It increases first and then decreases.

Factors decreasing efficiency:

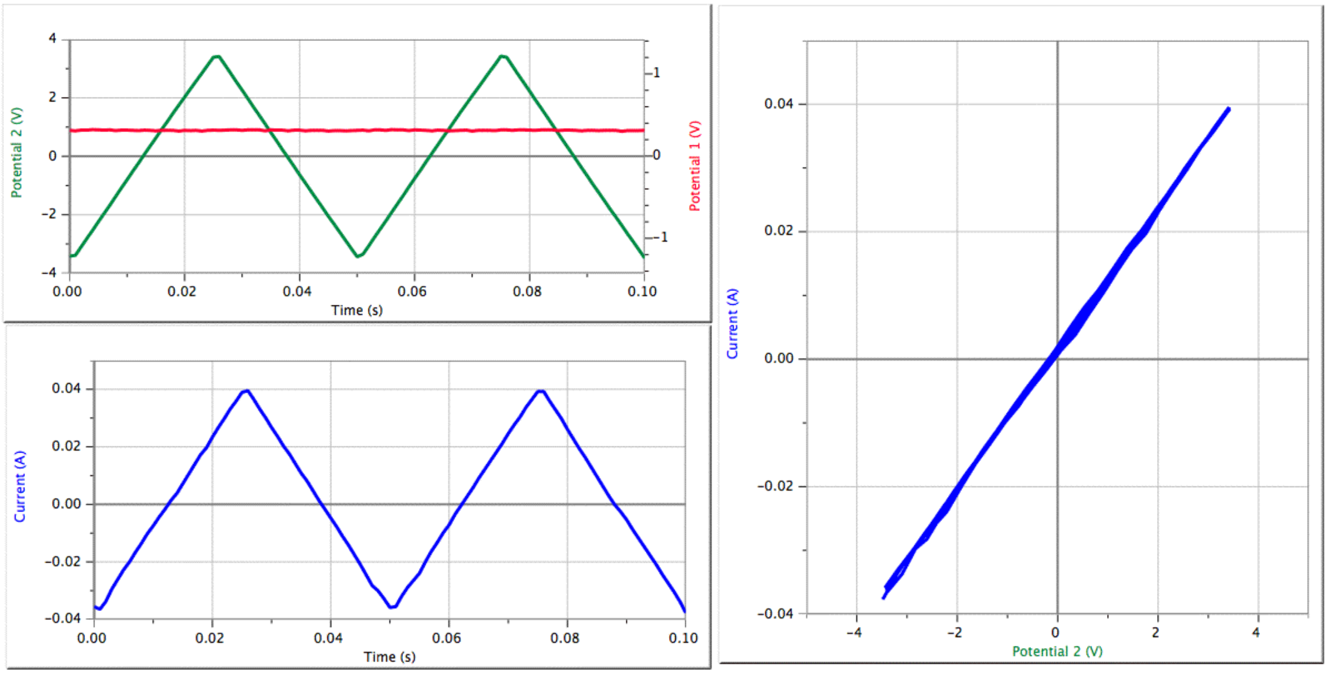
- More heat is carried away due to thermo conductivity — when light bulb is hotter, the temperature difference between it and environment is larger, which results in more heat flowing away.
- Photo diode reaches it's saturation, which makes us *measure* the decrease of efficiency.

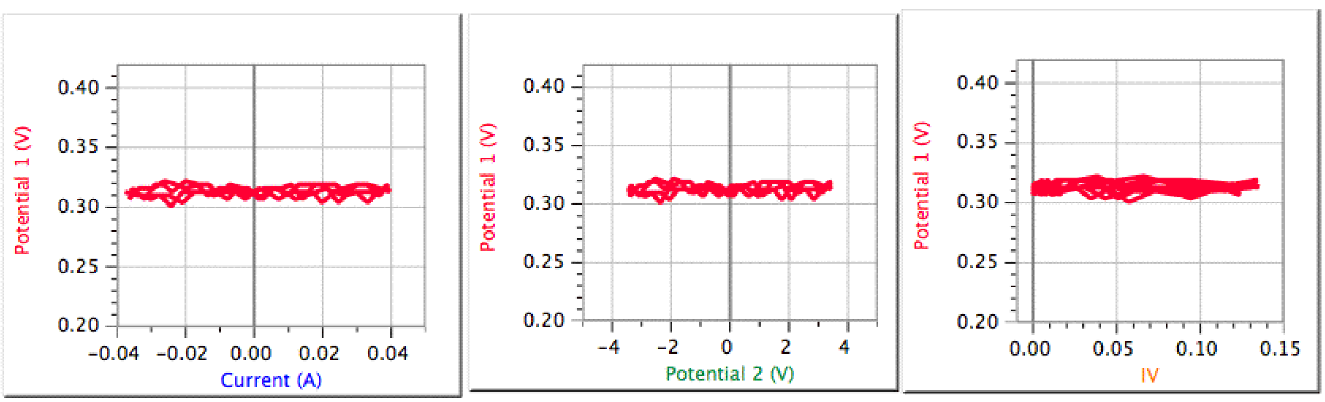
Factors increasing efficiency:

- When objects temperature is increasing, color of the light it emits moves towards blue, with temperature being proportional to the frequency at which the intercity is largest. Thus, when we heat up the filament, the light it produces is becoming less «red» and more «blue». Since our detector is only capable of measuring intensity of light in some range of wavelengths - «window», efficiency should increase, when we just enter this «window» (....and then decrease when we pass it, but is is not the case here — bulb fuses first)

Summary: bulb first heats up, it's light enters «window of detection» which results in increase of efficiency(0W...0.05W). Then, as it becomes more hot, efficiency drops due to the increasing losses associated with thermal conduction(0.05W and more).

Repeat the measurement with a 20 Hz triangle wave





Key points: equilibrium and non equilibrium processes

Explain any differences between the 20 Hz measurement and the 0.2 Hz measurement.

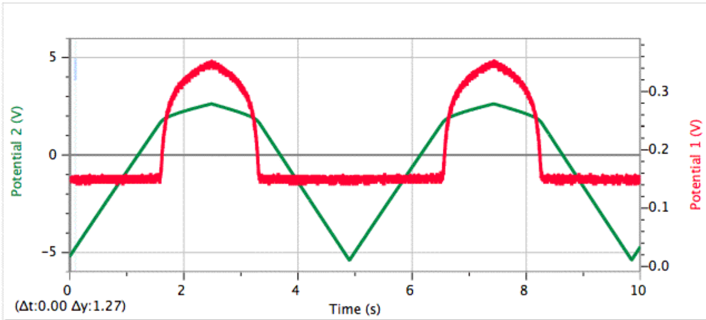
When we feed 20Hz voltage to the light bulb, it does not have enough time to cool down between pulses of the voltage — it is just too fast. This results in almost constant temperature throughout the entire cycle and, consequently constant resistance and almost constant power of light emission (which is however too small in comparison with an ambient light to be detected). All these statements are supported by the graphs above.

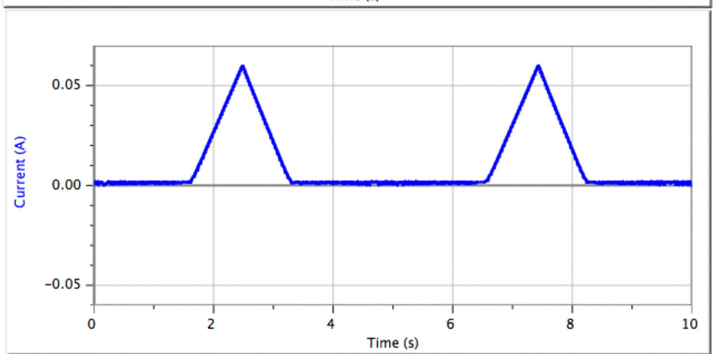
What is the implication of this result for the question in the introductory lab, where you measured the frequency at which your eye no longer saw the light bulb flashed?

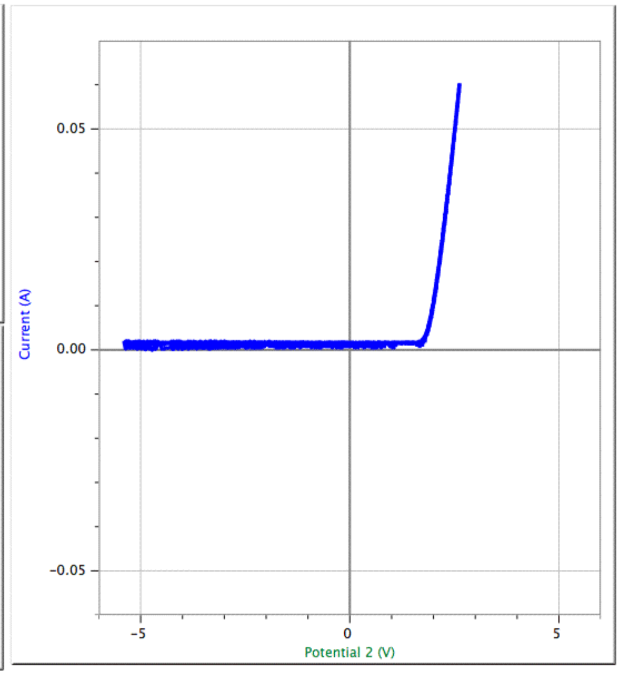
The time scale to see hysterisis and to see the light flashing is about the same.

LED

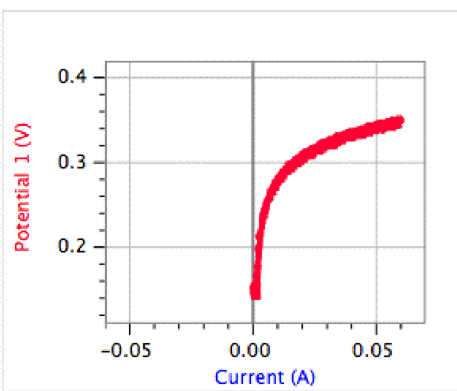
Measured data:

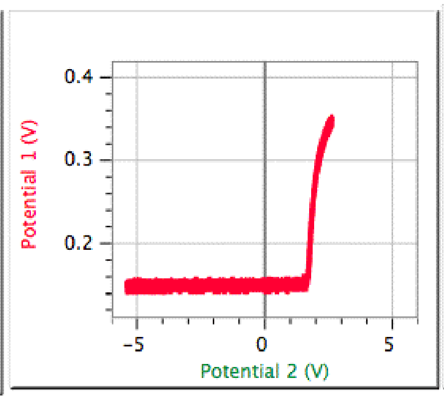


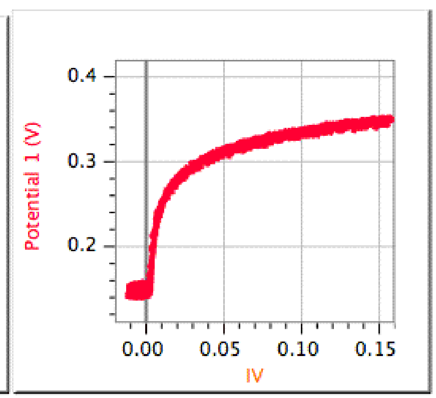




Some nice pictures at last:







Key points: diode, operation

Calculate the effective resistance as a function of voltage.

Resistance is large for voltages lover threshold value of 1.8V (can not be measured with Logger Pro equipment, since it is not able to measure so small currents and lots of noise presumably due to the lack of appropriate grounding of the probes) and about 10 ohms above.

Is it ohmic?

No, it depends on applied voltage.

Is the device symmetric?

No, it only allow current to go one way. (it can be clearly seen at the IV curve)

Is it hysteretic?

No, at least with the precision Logger Pro can provide.

What is the voltage across the LED when it begins emitting light?

1.8V

What is the current across the LED when it begins to emit light?

Something very small-- I measured 4 mA.
What is the voltage across the LED when it stops emitting light?
Same 1.8V
How many light pulses does the LED emit during one voltage cycle?
Just one — for forward voltage only.

For voltages where the LED emits light, does the ratio of the emitted intensity to the electrical power consumed increase or decrease with increasing power?

It decreases. But it seems almost linear near the zero. Possible «explanation» is that

- Voltage varies slowly — it behaves as V = 1.8volts +10ohm*I and for small I can be taken as a constant
- Number of photons emitted is proportional(equal, if we forget about losses) to number of electrons entered the device. Thus the power emitted , which is (number of photons)x(single photon energy)/(time interval) should be just proportional to the current. Lets call it P=A*I

putting these together, we have:
Eff = A*I/ (V*I)=A/V which is constant for I<<1.8V/10ohm=180mA or P<<1.8V*0.18A=0.32W which quite consistent with the experimental data.

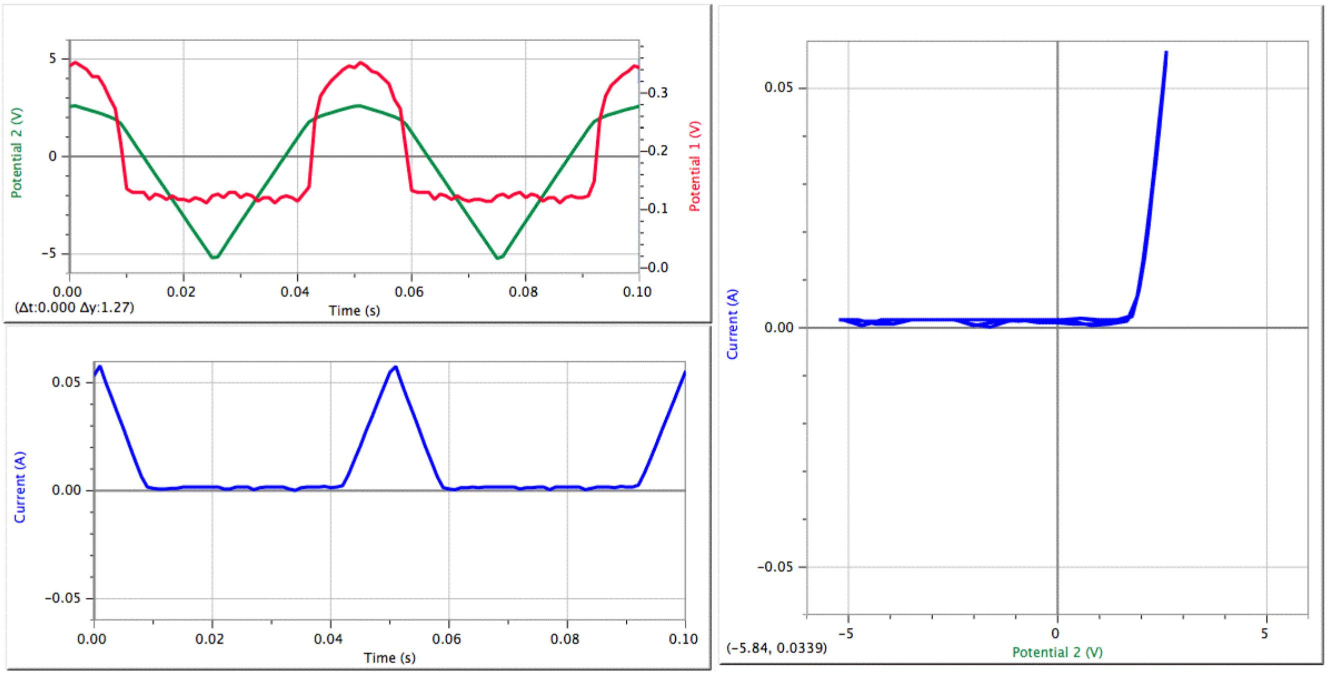
For voltages where the LED emits light, is there a range of current values for which the intensity is a linear function of current?
Yes, I<<250 mA or so.

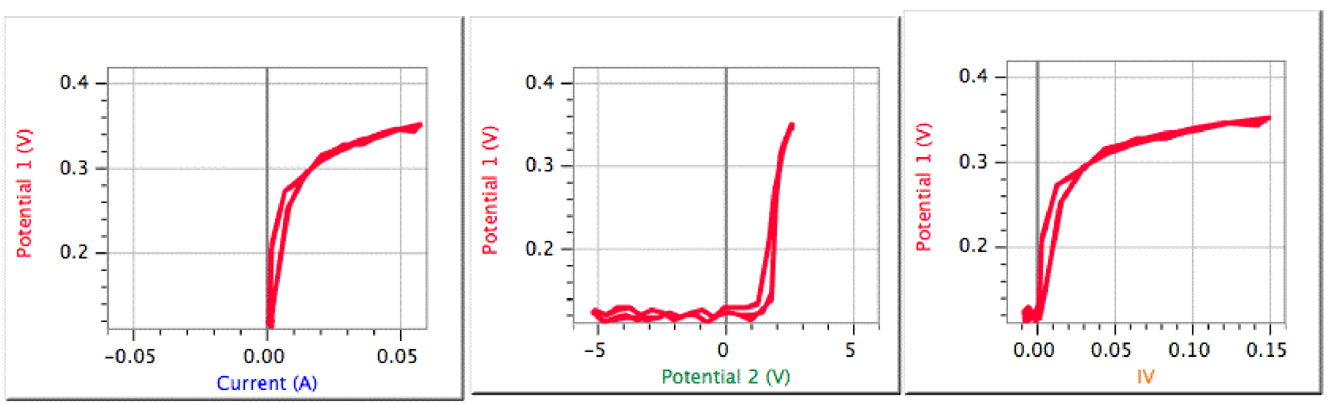
What does this imply for the electrical efficiency of LED light bulbs?
The efficiency goes down at higher voltages: you get less power per energy there. However, they are still very efficient overall: note that they consume no current when they are not shining!

Key points: non-ideal voltage source , Networks With Voltage Sources(Purcell 4.10)

Look at the signal generator output on the scope. Remove the BNC cable that is connected to the circuit from the BNC Does the signal generator output change when you disconnect the circuit? Why?
No picture here unfortunately, but if we detach the circuit from the generator, it will produce — surprise — triangular wave (otherwise it is broken)
It can be easily observed that on the plot above voltage vs time is not «truly triangular»: each positive peak is lower then it should be. The reason is in the nonzero internal resistance of the generator. Textbook result for the voltage output for a non-ideal generator is:
$V=V_{ideal} - I(R_{internal})=V_{ideal} * R_{load}/(R_{load}+R_{internal})$
supports the plot absolutely — when $R_{load}=R_{diode}$ is small (= diode is open) V drops.

Repeat the measurement with a 20 Hz triangle wave Explain any differences between the 20 Hz measurement and the 0.2 Hz measurement.





The difference is not that striking as for the light bulb, but it exists — hysteresis on the light power curves appears. It can not be seen on the IV curve due to either error or absence of hysteresis for that curve. Thus it is unclear whether it is hysteresis due to the LED or the photo diode. Possible explanation is finite capacitance of one of the diodes — if device is able to hold some considerable charge it is clearly concerned about history (of charging).

When does your eye stop seeing the flashing?
I could see it up to ~40 Hz: higher! This is because the LED only turns on half as much as the light bulb, but also because it has a much higher turn on time.

Bonus: *Diodes are often modeled as a series combination of an ideal diode (R=0 for V>0, R= Infinity for V<0), a battery with a voltage difference equal to the threshold voltage of the diode, and a series*

resistor. Find the values of the series resistance and the battery for the diode in this experiment
V= 1.8V, R_{series}= 10ohm

Assume that the frequency of the LED is approximately 430 TeraHz. Calculate Planck's constant given that the energy of the photon with frequency f is given by E = h f, where h is Planck's constant.
The photons emitted have the energy of the incoming electron which kicks them out (approximately), so E = q V = h f, and therefore h = q V / f .

q = 1.6 * 10^-19 C
V = 1.8 V
f = 430 TeraHz

h = 6.69 * 10^-34 J/s, remarkably close to the right answer! (6.63 * 10^-34 J/s)

What happens when we use a 1K resistor instead of the 150 Ohm?
There is significantly less current, so the intensity of the light coming out of the LED is significantly less.

What comes out of the wall?
Setup: just measuring voltages from the outlet

Key points: some household physics =)
What is the measured voltage difference between hot and ground?
Roughly 120V as one would expect

What is the measured voltage difference between hot and neutral?
Roughly 120V as well

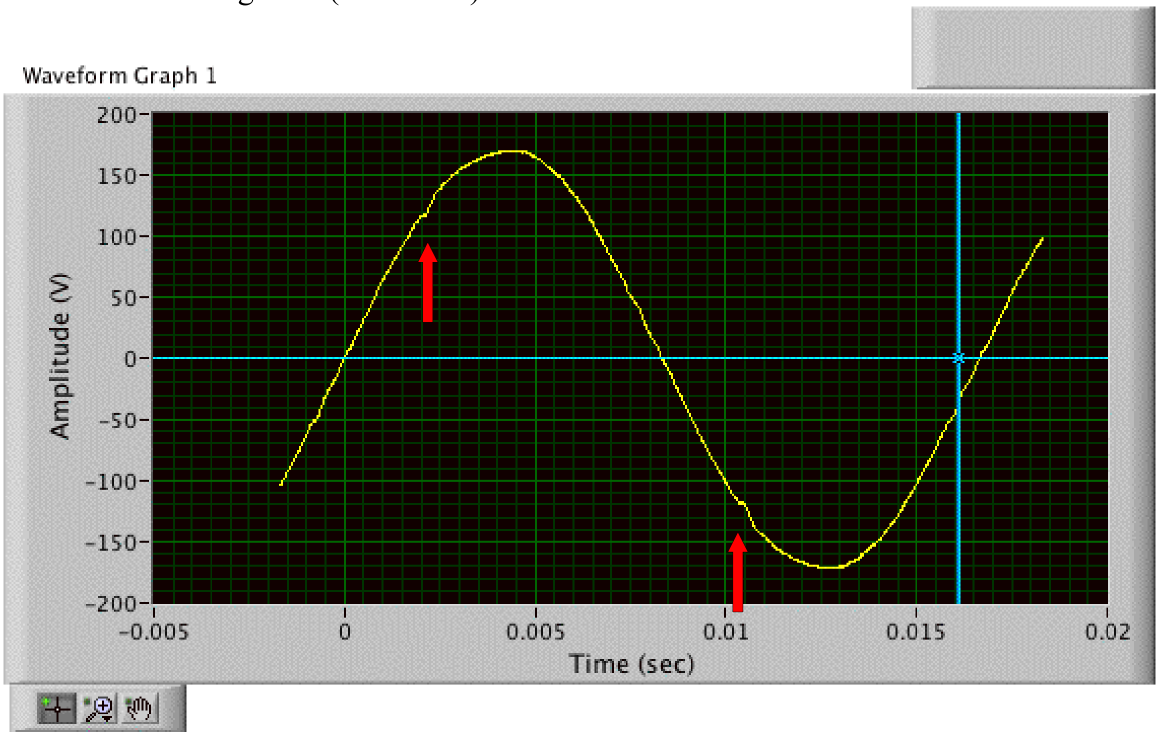
What is the measured voltage difference between neutral and ground?
About 0,5V and associated with the finite resistance of the wires of the neutral and a nonzero current flowing through the neutral because the other devises in the room.

Bonus: Measure the resistance across your body by holding the Ohmmeter leads in your hands. Compare to the resistance across one hand. Compare with the resistance across your body when your hands are wet. Compare with the resistance when your hands are wet with salt water. How much current would flow through those three resistive paths if a 110V AC potential was connected to those points on your body. How does this compare with 5 mA, the "safe current?"

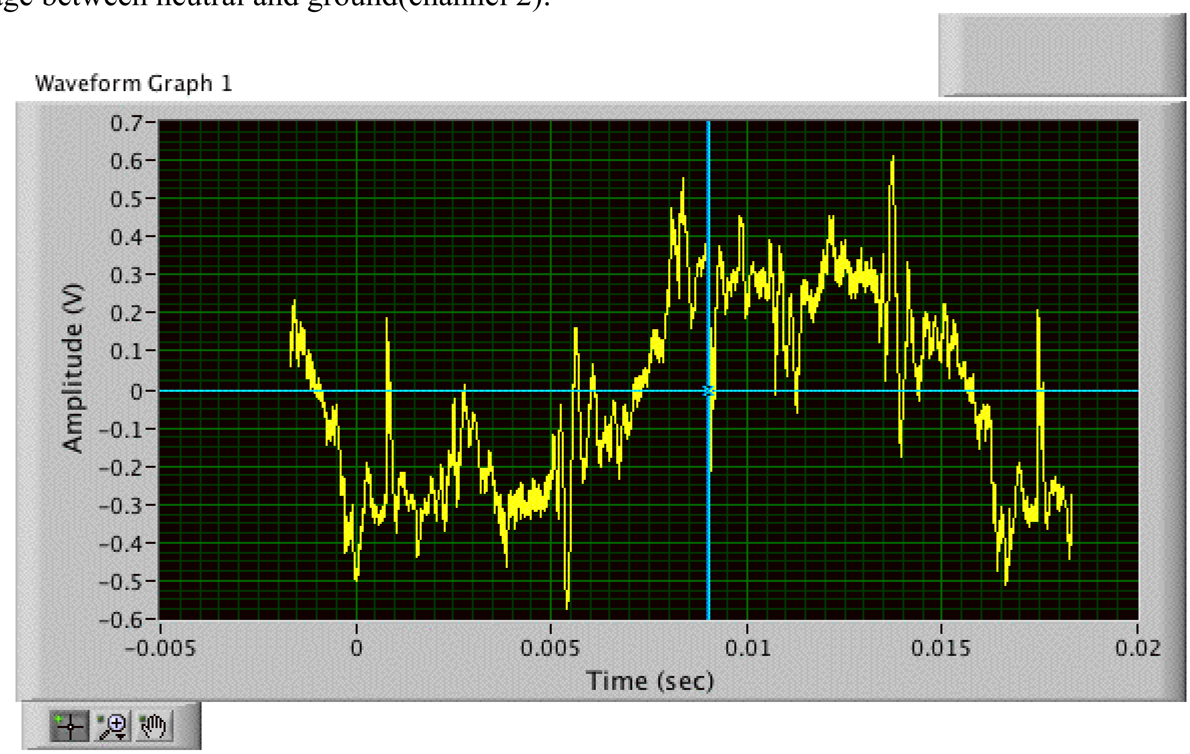
All the resistances are of the order of 10MOhm which is well described by the model where the skin has large resistance and body internals are good conductive. The current produced by 120V is about 10mkA which seems like a low and safe current, but please do not take this as a guide for action — skin resistance varies from person to person and because of many other reasons, so it *can* kill you if you are lucky.

b Oscilloscope measurements

Voltage between hot and ground(Channel 1):



Voltage between neutral and ground(channel 2):



Channel 2 shows the voltage difference between neutral and ground. Is it zero? How can there be a voltage difference between neutral and ground if the two are connected at the breaker box?

As it was noted above the reason is that wires of neutral have nonzero resistance and carry some current because of other devices connected to the outlets in the room. It is noisy but dominative feature is still a 60Hz sine signal, which supports statement above.

Channel 1 shows the difference between hot and ground. How well is CH1 described by V = 170 Sin (2 p 60 t)?
It is described very well, measured values are 170+-1V and 60Hz, but there is one more thing — signal is not a pure sine wave — it has some noise and some of the higher harmonics. One regular (not noise) feature with frequency 120Hz is marked with the arrows.

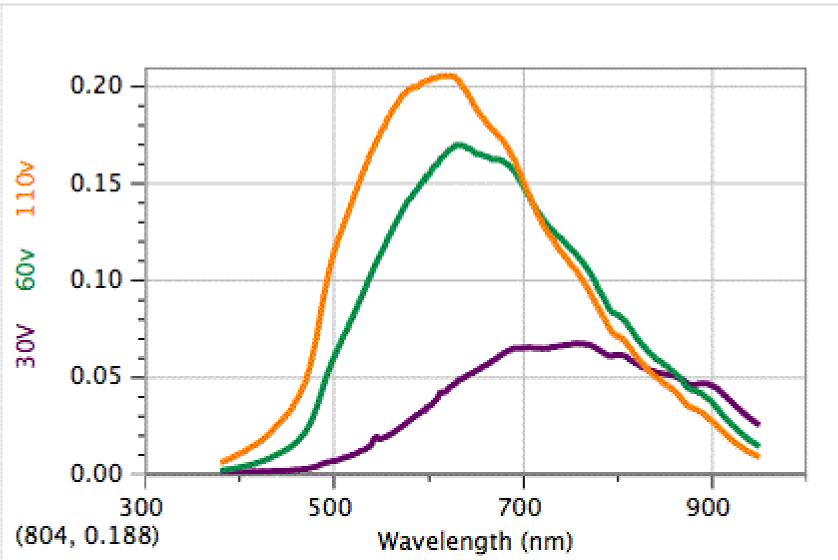
Key Points: RMS values for voltage and current.
How do the measured peak to peak values compare with voltage reading on the AC voltmeter when it was connected between hot and ground?
Voltmeter shows RMS values which for the harmonic wave are different by a factor of square root of two. $170/2^{0.5}=120.2$

Spectra of the light sources.

Spectra of three different light souses was measured.

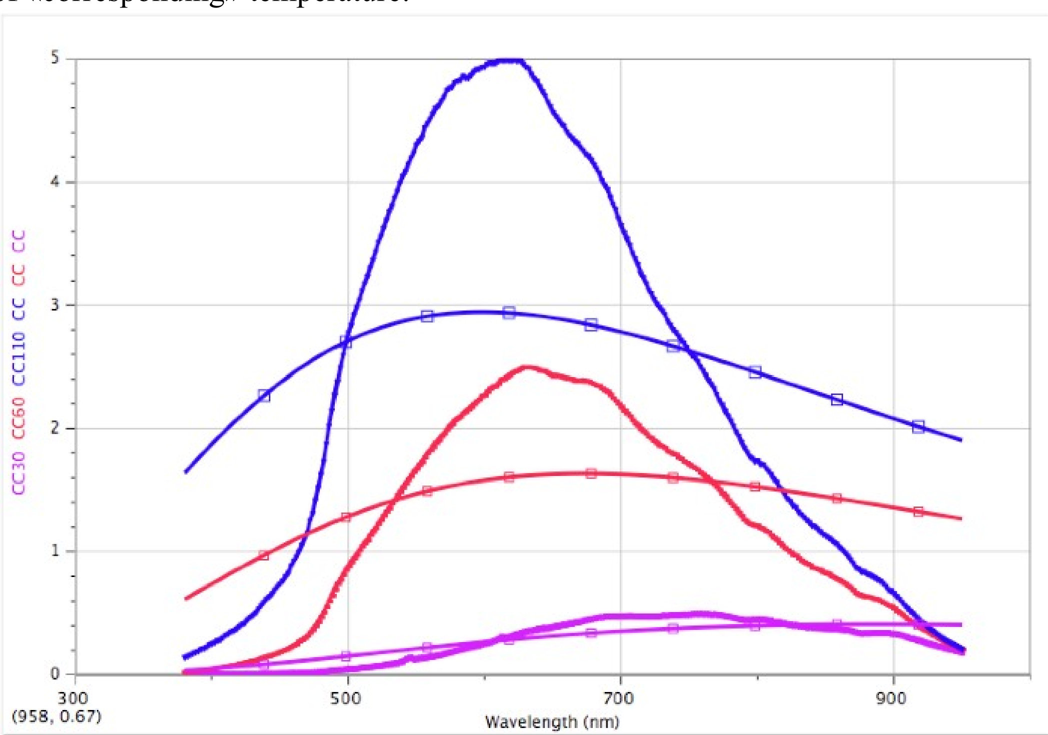
1 Incandescent Lamp.

Spectra for three different voltages are presented below.



Since lamp brightness changes significantly, at this plot spectra presented are not to scale.

Other plot depicts the same three spectra, but brought to the same scale and compared to black body spectrum of «corresponding» temperature:



Legend: curves with square marks - fits , without marks - measured spectra.
purple - spectrum for 30V and black body 3.3KK fit, red - 60V and 4.3KK, blue — 110V and 4.9KK

Word «corresponding» is quoted, because fit was made to match wavelengths of maximum intensity for both measured and theoretical curve.

Lab Questions:

Does the spectrum of your source change with voltage?
Yes, for larger applied voltage spectrum moves towards short wavelengths because temperature of the filament in the lump raises.

How does your measured spectrum the solar spectrum shown above?
It resembles solar spectrum, but it is «colder» even for the voltage 110V - maximum intensity in the solar spectrum is at the shorter wavelength.

Is the emitted spectrum well described by a black body at some temperature T?
As it can be seen from the fits, it is not very well described. Black body spectrum is derived for a *black* body which is *in equilibrium with its radiation*. None of this conditions is fulfilled. Tungsten is not black, as a conductor it is very reflective and there is obviously no equilibrium here.

If so, what temperature?
Temperatures are 3.3kK, 4.3kK and 4.9kK

If not, what is the origin of the light and what determines its color?

Are there any narrow features in the emission spectrum. If so, what is their origin.
No narrow features except for two small peaks from fluorescent lamps at the 30V spectrum,which are irrelevant.

2. **LED array**:

Three spectra for increasing voltages are shown below.
Lab Questions:

Does the spectrum of your source change with voltage?
Yes, apparently, threshold voltages for LED of different colors are slightly different and as a result greens and blues light up first with green being most intensive right at the threshold, then for the most part range of the voltage color is dominated by green and red which have the same intensity, and for the highest voltages red diodes become most bright. Other thing is that with the increase of the voltage emission lines gradually move towards blue end of spectrum and become broader. The latter effect can be explained by the fact that diodes heat up more at larger currents and since electrons and holes before annihilation have spread of energy of the order of kT, this energy is given to photons.

How does your measured spectrum the solar spectrum shown above?
They are completely different.

Is the emitted spectrum well described by a black body at some temperature T? If so, what temperature?
No

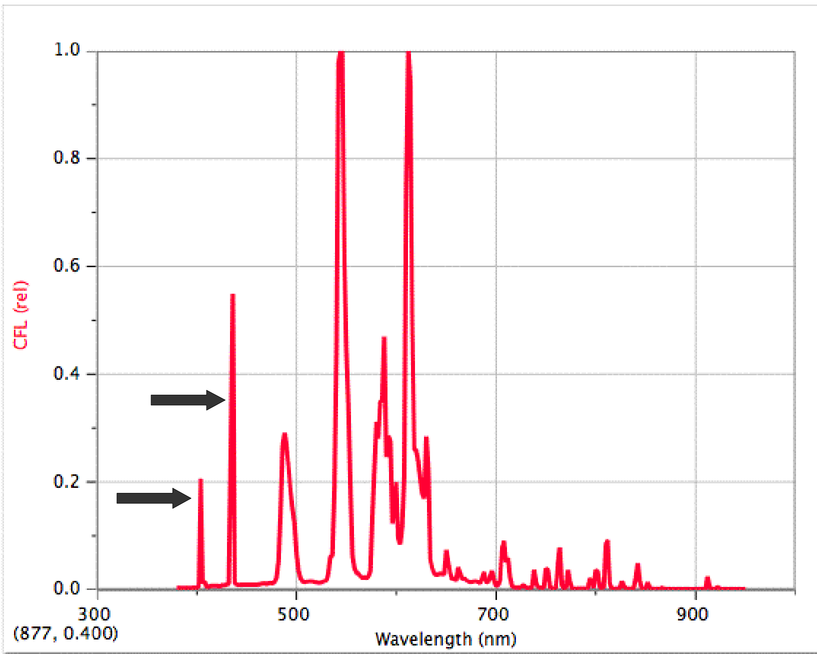
If not, what is the origin of the light and what determines its color?

There are 4 different types of colored LEDs — blue, green, orange and red. They mix to create illusion of white light.

Are there any narrow features in the emission spectrum. If so, what is their origin.
Four quite narrow features — each type of diode emits light of a certain wavelength(with some spread)

3 CFL

one of the spectra looks like:



It features two narrow mercury emission lines(marked) and whole set of not-so-narrow lines of lower energy(=higher wavelength) which are produced by phosphor mix — it absorbs high energy (and harmful for the living organisms) mercury radiation and re-emits it within the borders of visible spectrum.

Lab Questions:

Does the spectrum of your source change with voltage?
It does not change significantly after the lamp ignites. One small but noticeable change is that one of the mercury emission lines (left one at the plot) becomes more intensive compared with second one. (*Note: please read answer to the questions below first*) To explain this one need to recall that the shorter wavelength of the light corresponds to the more energetic photons (energy of a single photon is proportional to the frequency and frequency is inversely proportional to the wavelength). So, what we observe is that for higher voltages mercury will more likely emit photon with higher energy(out of two possible) which I reasonable, since high voltage accelerates electron faster and electrons have more energy an average when hitting mercury atoms.

How does your measured spectrum the solar spectrum shown above?
It has nothing to do with the solar spectrum.

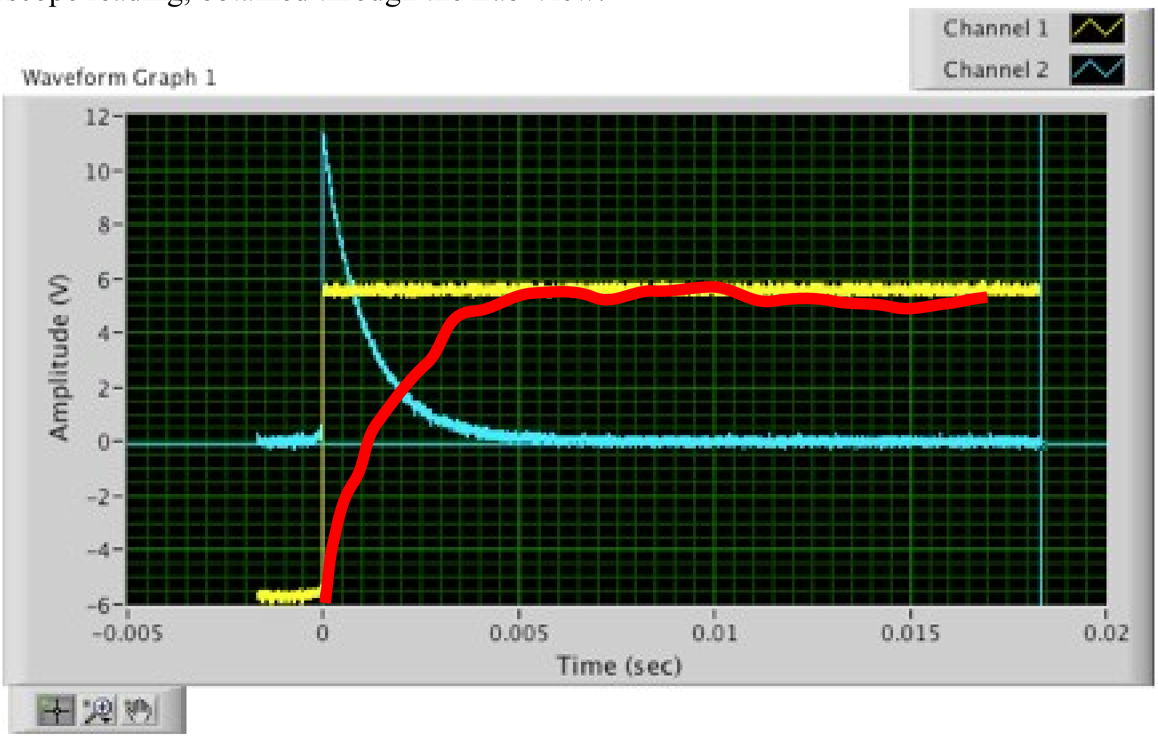
Is the emitted spectrum well described by a black body at some temperature T? If so, what temperature?
No

If not, what is the origin of the light and what determines its color?
Origin of light is the following: the gas mix in the lamp is ionized and subject to strong electric field. Free electrons flowing inside the tube are accelerating by the electric field. When accelerated enough hits a mercury atom, it can can give part of its kinetic energy to the atom - «excite» mercury atoms. Atoms can only store fixed amounts of energy, corresponding to two wavelengths marked on the plot. After some time mercury atoms radiate this energy in form of UV photons(two marked lines on the plot), which is turn are adsorbed by phosphor and re-emitted in the visible spectrum.

Are there any narrow features in the emission spectrum. If so, what is their origin.
See above

Bonus: RC circuit
Setup: the resistor R=10kohm is connected in series with the capacitor C=10e-7F. They both are powered with rectangular pulses V(t)= 5volt* sign(Sin(20Hz*t*2Pi)). Voltage across the resistor and generator are measured with the oscilloscope.

Oscilloscope reading, obtained through the Lab View:



Color code is: blue - voltage across the resistor, yellow — generator output, red roughly represents voltage across the capacitor, which is difference between two formers.

Key points: Ohm's law
How is this(voltage across the resistor) *related to the current flowing through the resistor?*

Since the resistor is an ohmic device, current through it is just a ratio of the voltage drop to it's resistance.

Key points: simple circuits, connection in series, charge conservation
How is this(voltage across the resistor) *related to the current flowing through the capacitor?*
Since the resistor and the capacitor are connected in series, the current flowing through them is the same.

Key points: Kirchhoff's laws
Why is Ch1-Ch2 equal to the voltage across the capacitor?
Because the voltage drop across any closed loop should be zero: $V_{gen}=V_{batt}+V_{cap}$

Key points: Non equilibrium processes in RC circuit (Purcell 4.11)
Do the voltages across the resistor and capacitor approach equilibrium during one half cycle of the square wave?
Yes, they do: it can be seen from the plot, that voltage across the resistor, and, consequently, the current

through the circuit go to zero faster then even quarter of one cycle.

Why does this approximate a measurement where the RC is charged and discharged using a switch and a battery?
Because both the battery and the generator provide constant voltage, and when generator quickly changes the sign of the voltage, one can think of the battery is being quickly unplugged, flipped and plugged back. The key point here is that the time during which generator switches voltage is much smaller then time constant of the circuit.

Key points: Ohm's law
Is the current a linear function of the voltage across the resistor?
As it was mentioned above it it. V=I*R

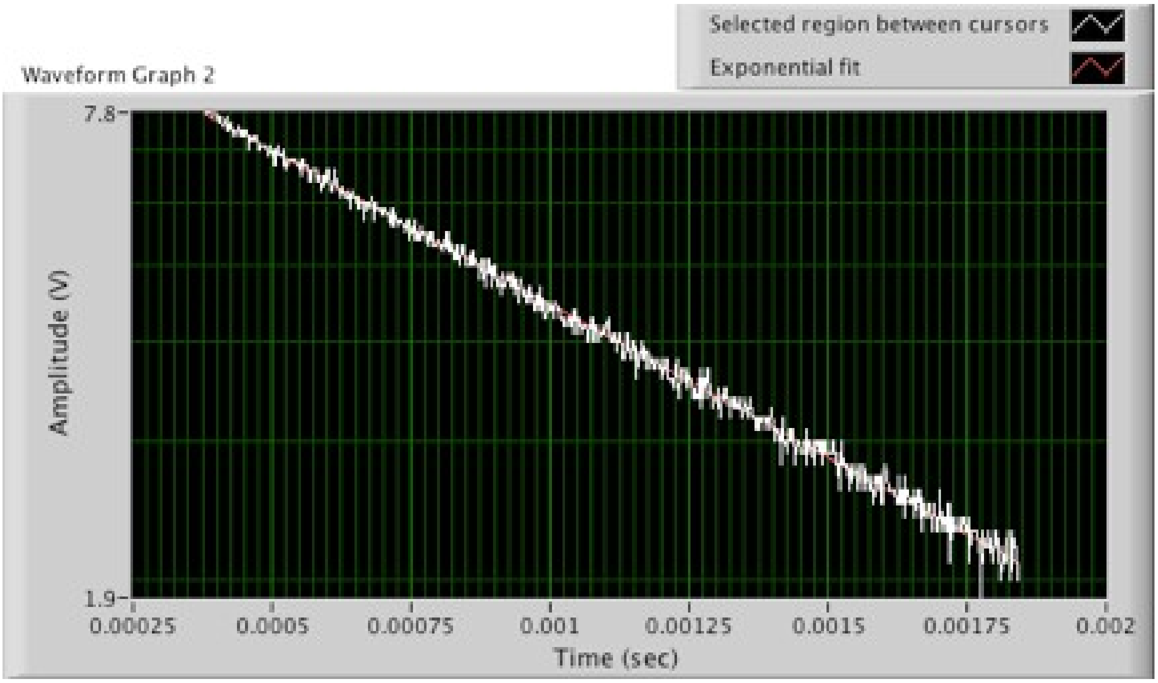
Key points: Kirchhoff's laws
Is the current a linear function of the voltage across the capacitor?
Usually it is no the case, but for the constant voltage and a series combination of the capacitor and the resistor it is: $V_{cap} = V_{bat} - V_{resistor} = V_{bat} - IR$ which is linear in some sense.

Immediately before the square wave voltage changes from +5 V to -5 V, what is the current flowing in the circuit, and what are the voltages across the resistor and the capacitor?
Immediately before there is no current in the circuit -> there is no voltage across the resistance -> voltage across the capacitor is the same as battery voltage and equals to +5V.

Immediately after the square wave switches, what is the current flowing in the circuit, and what are the voltages across the resistor and the capacitor?
Since voltage across the capacitor is governed by the charge it holds and charge does not go away immediately, for the times after switching such as t<< RC=1ms voltage across the capacitor will be still +5V. Since sum of the voltages across the cap and the resistor equals -5V now, the voltage across the resistor should be -10V now. So, the current is 10V/10kohm = 1mA

Is the absolute magnitude of either of the voltages larger than 5V?
10>5. Questions?

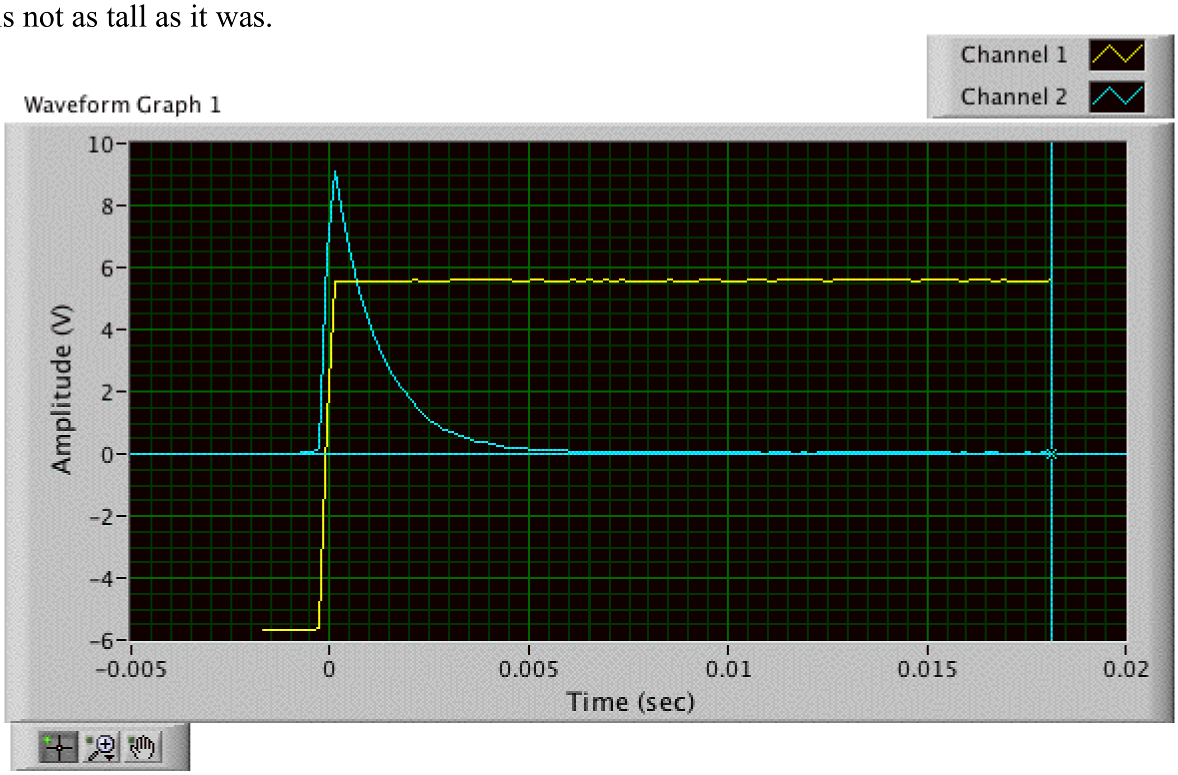
Key points: non equilibrium processes in RC circuit(Purcell 4.11)
Is the voltage linear on a semi-log scale?
It is. Here is the plot:



What is the decay rate for the resistor voltage, and is it consistent with what you would expect?
The decay rate is 1.08ms which is quite consistent with RC=1ms from nominal values.

Key Points: Noise in real systems.
The white box at the right of the window shows the time points that are averaged to make the plot. Choose 1 and take data. Choose 10 and take data again. Did the signal change? If so, how?
It did. Averaging suppresses random noise and makes steep slopes less steep. Illustrations are below

N=100(for N=10 effects are the same but less pronounced): less noise, steep slopes changed, sharp peak is not as tall as it was.



The signal to noise improves if the averaging number increased, but if you make it too large the data becomes distorted. Why?
Because averaging does not respect anything but constant -> if you average long enough every function becomes constant. Which is only fixed point of most averaging procedures(that wouldn't be a big lie to say «all» instead of «most»). Naturally, function with large derivative are changed more rapidly, then those close to a constant.

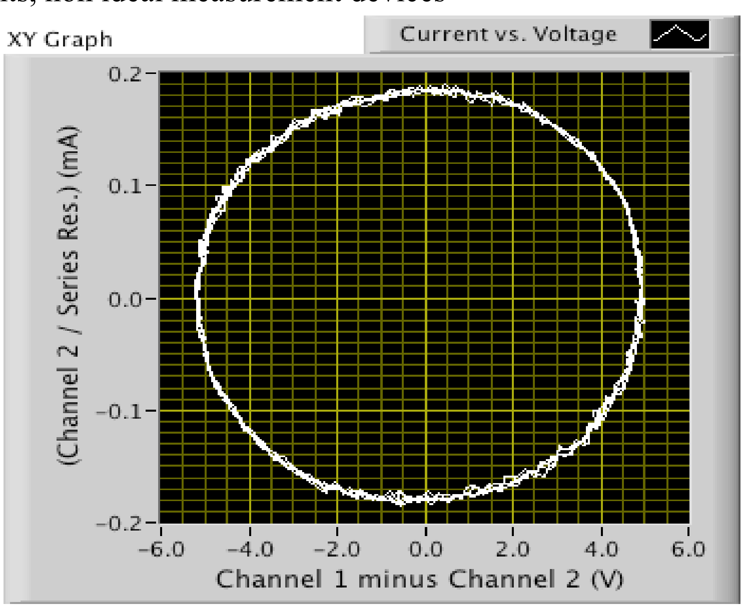
Key points: equivalent circuits
Bonus: *Add the second 0.1 micro Farad capacitor in parallel with the original 0.1 micro Farad capacitor. Draw a schematic of this circuit. Repeat the voltage vs time measurement. Is the new RC time constant what you would predict? Explain. Look at the time dependence of the resistor voltage when the resistor is in series with a series combination of the two 0.1 micro Farad capacitors. Draw a schematic of this circuit. Repeat the voltage vs time measurement. Is the new RC time constant what you would predict? Explain.*

Adding one parallel capacitor will provide the effective capacitance of 2C, since capacitances are added when one connects capacitors in parallel. Change in circuit: change 0.1mkF by 0.2mkF, Expected time constant — $T_{parallel}$ = R*2C = 2ms. Measured time constant 2.18ms agrees with the prediction.

Adding one capacitor in series will provide the effective capacitance of C/2, since inverse capacitances are added when one connects capacitors in series . Change in circuit: change 0.1mkF by 0.05mkF, Expected time constant — $T_{parallel}$ = R*C/2 = 0.5ms. Measured time constant 0.53ms agrees with the prediction.

Double Bonus: *Look at the IV relationship for the capacitor when the circuit is driven by a sine wave.*
IV curve should be a circle for the capacitor driven by sine wave since it introduces phase shift of Pi/2. Experiment supports theory:

*note — one more hysteretic device.
Key points: measurements, non ideal measurement devices

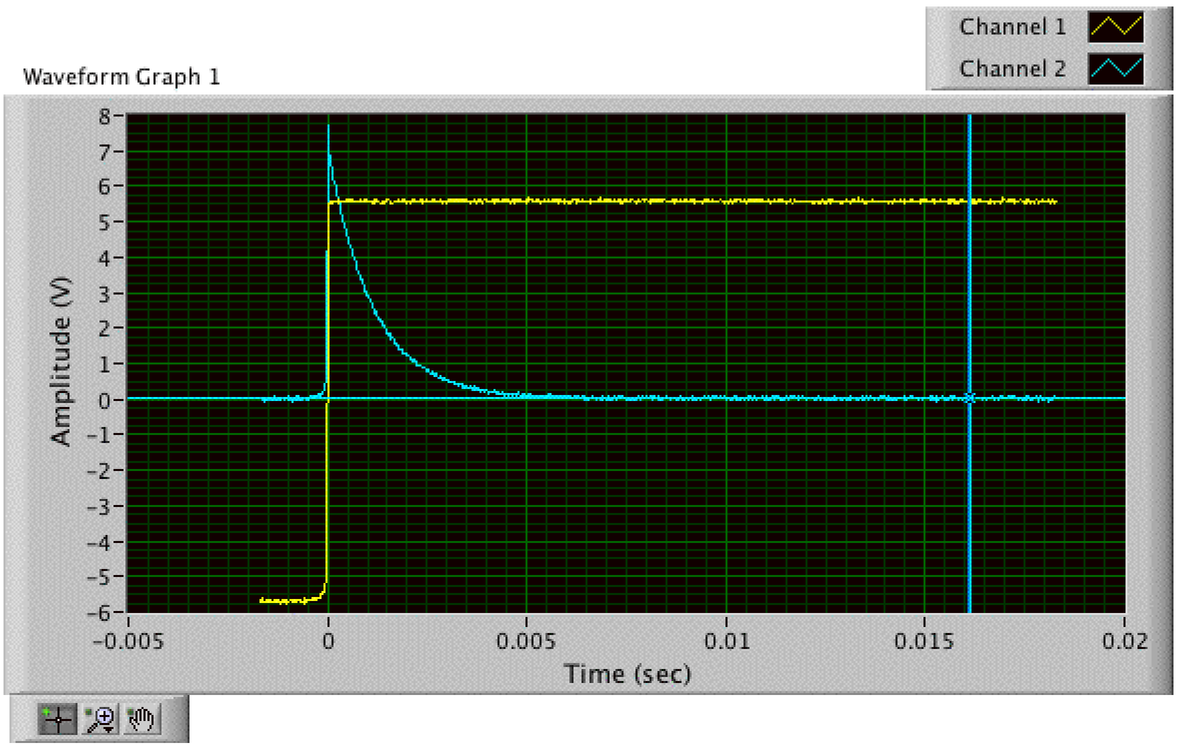


Key points: real life measuring devices, influence of measurement to to measured quntity

Triple Bonus: Measure the IV using Logger pro and explain why it produces the wrong voltage responses.

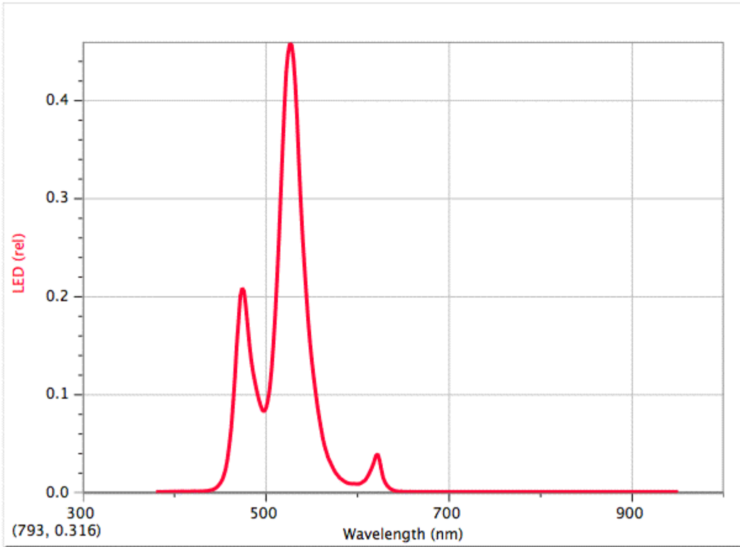
Logger Pro fails in two ways: it's voltage probe has capacitance comparable to that of capacitor, thus altering the voltages and currents in the circuit. Voltages with Logger Pro probe attached:

It is clearly seen that peak voltage on the resistor is not 10V anymore. Time constant changes as well

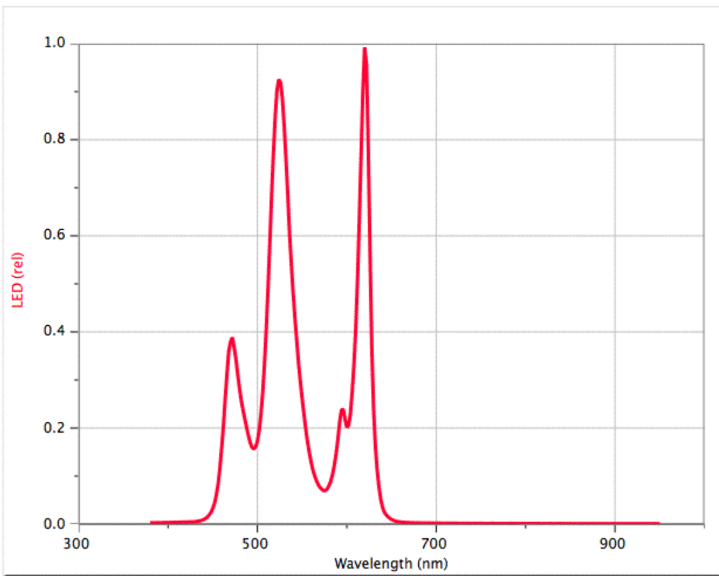


1.04ms becomes 1.14ms

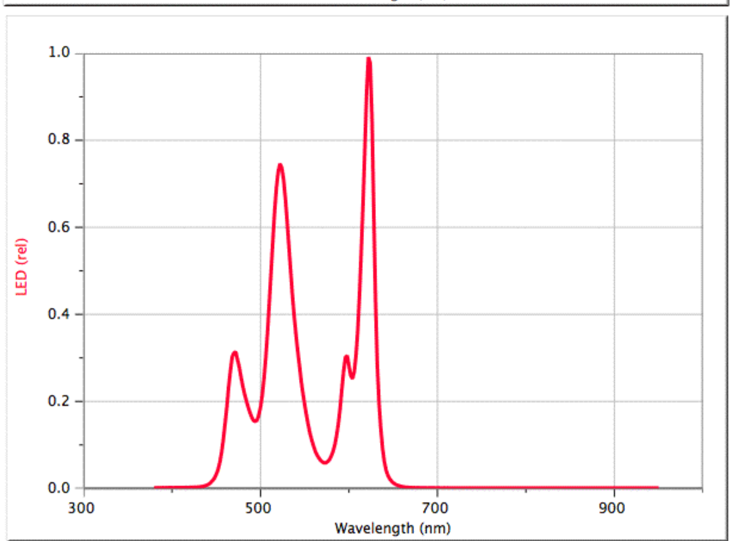
Other problem with Logger Pro is the current probe — it does not interfere with circuit that much, but it is not able to measure currents less then 1mA — it provides just a noise.(To be fair, one does not necessary need current probe to measure IV curve, but the point is that the direct and simplest way does not work at all)



0.4
0.3
0.2
0.1
0.0
LED (rel)
300
500
700
900
(793, 0.316)
Wavelength (nm)



1.0
0.8
0.6
0.4
0.2
0.0
LED (rel)
300
500
700
900
Wavelength (nm)



1.0
0.8
0.6
0.4
0.2
0.0
LED (rel)
300
500
700
900
Wavelength (nm)