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There is more about light than our eyes can see

(TEACHERS' GUIDE)

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Main goals of the activity:

- To engage students in scientific reasoning through the real problem in radiation.
- To deepen students' conceptual knowledge about radiation. In particularly, to develop awareness that optical properties of objects (such as albedo or "colour") may be very different in different wavelength regions.
- To let students learn about devices and procedures for obtaining images in different wavelength regions.

Expected students' knowledge: Students should be familiar with the 1st law of thermodynamics, energy transfer through the process of heating and through the process of radiation.

Theoretical background of this activity: The steps in this activity were developed following the *Investigative Science Learning Environment (ISLE)* approach [1]. ISLE engages students in scientific practice and reasoning by unpacking and "slowing down" steps that would typically be taken by scientists.

About the equipment: Images 1a, 1b were obtained with a conventional digital camera. Images 2a, 2b were obtained with the same digital camera but with its objective covered with a filter that passes only near infrared light (Kodak Wratten gelatine filter, No 87C). Note that semiconductor-based light detectors in most of the digital cameras are sensitive to visible and NIR light up to 1000 nm (sensitivity of digital cameras to UV light is negligible or very small due to large absorption of UV in lenses and other reasons). The time of exposure for images 2a, 2b was about 10 s, which is reasonable knowing that these cameras are designed to take images in visible light. Images 3a, 3b were obtained with thermal camera FLIR B335. In all cases cameras were fixed on a tripod. Objects were illuminated with a studio flood light using 1 kW tungsten bulb. Two squares were cut from 5 mm kappa board

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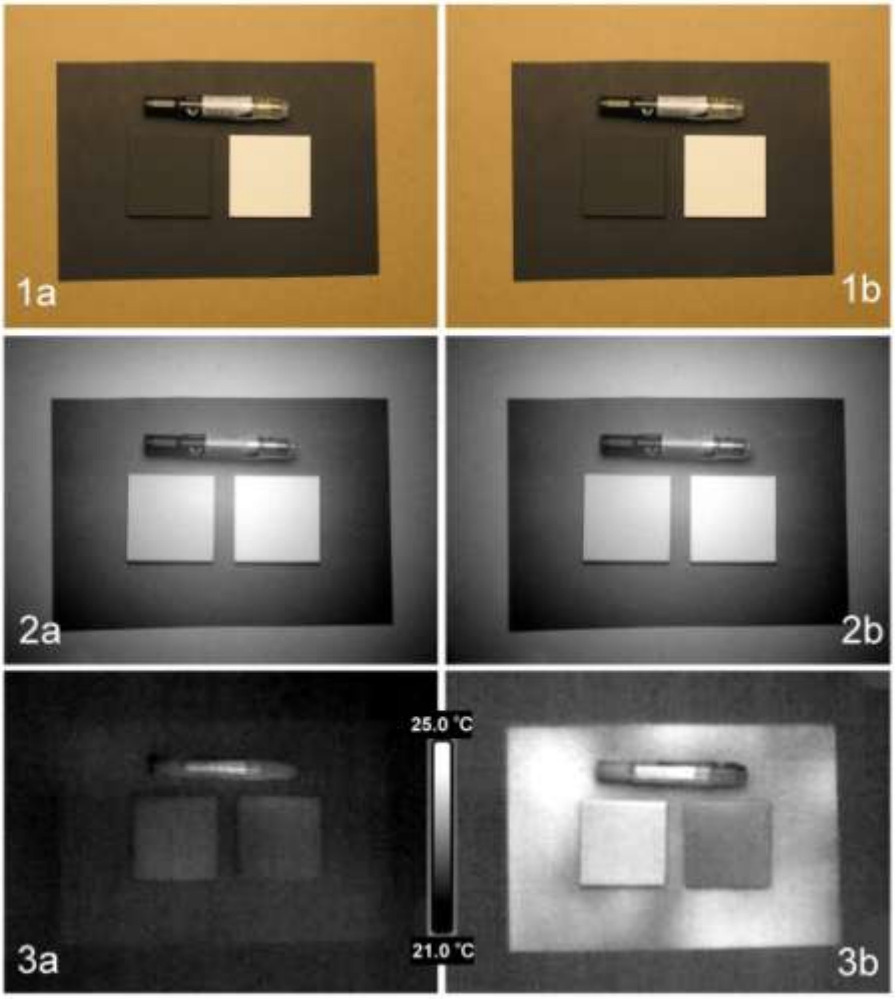
(sandwich of two papers with Styrofoam layer in between) and the large sheet of paper was cut from usual masking paper (slightly harder than conventional printing paper).

Table 1. Short descriptions of the experiments and their outcomes.

	Right after the incandescent lamp was switched on.	**Five minutes later (the lamp was switched on all the time).**
Images in visible light. Visible light covers wavelengths from about 400 nm to 750 nm.		
Images in near infrared light. Photos have been done with a digital camera and a filter that passes EM waves with wavelengths from about 850 nm to 1000 nm = 1 µm.		
Images obtained with a thermal camera. Camera detects EM waves with wavelengths from about 7 µm to 14µm. Based on these measurements the camera determines a temperature of the particular spot on the object.		

Short explanation:

Three ideas are important to explain images (in addition to conservation of energy): 1 – objects can be detected either because they emit or because they reflect electromagnetic (EM) waves (or both), 2 – albedo (reflection coefficient) of objects depends on the wavelength and 3 – all objects at non-zero absolute temperature emit EM waves; the higher the temperature, the shorter the peak wavelength in emission spectrum of a given body. Therefore, objects can absorb radiation in one wavelength region and radiate the corresponding energy in a different wavelength region.

The fact that images 1a, 1b and 2a, 2b look the same shows that change in temperature in these experiments did not visibly affect the EM waves emitted in visible and NIR wavelength regions. Consequently one can assume that images 1-2 show mainly reflected light. Differences between images 1 and 2 can be explained by dependence of the albedo on wavelength. In visible light the left square is black (albedo close to 1) and the right square is white (albedo close to 0). However, in NIR the albedo of both squares is close to 1. Combining this information with the spectrum (see students' handout) of the light bulb one can conclude that the left square absorbs more energy than the right square from the visible light emitted by the light bulb. Absorption of the NIR light emitted by the light bulb is similar for both squares. As a result, left square temperature should increase more than the right square temperature, what is consistent with the information obtained from images 3a, 3b. Note that the temperature of the right square also increased after illumination, but the increase is smaller than for the left square. Note also that the large sheet of paper has albedo close to 1 both in visible and NIR region. Consequently we can expect that it absorbs even more radiation emitted by the light bulb than the left square. Image 3b shows that the temperature of some parts of the paper is indeed slightly larger than the temperature of the left square (note that temperature of the object depends also on other parameters such as heat capacity; for example – although the albedo of the table is also relatively large in visible and NIR region, its temperature does not change much because of its large heat capacity). Possible explanation why temperature of the paper is not uniform is that the paper is touching the table. The only object that does not seem to fit into this explanation is the marker. It seems that the smooth plastic cover of the marker produce specular reflection of the light and forming the image of the light bulb, which appears as a brightest part in the image 3a.

Now we can look back and indentify assumptions that we made in our explanation. We assumed that all objects (except the small part of marker) produce diffuse reflection and we assumed that albedo in the wavelength region from 7 μm to 14 μm is near 1 for all objects (so we can trust that the temperatures measured by the thermal camera are correct). It is important to note that even small changes in wavelength region can result in significant changes in albedo (going from images 1 to 2, the albedo of the left square changed from about 1 to nearly 0).

University students' responses:

The activity was given to 11 university level physics students in their 3rd year of study as voluntary activity. All of them wrote extensive solutions. The results of a qualitative analysis of their work are summarized below.

1. Describe everything you notice on the images in Table 1. At this stage do not make any explanations – focus only on description of your observations.

All students noticed that images 1a, 1b are colour images and the rest are black and white images. All students also noticed that there are no differences between images 1a and 1b as well as there are no differences between images 2a and 2b. Most students wrote that the left cardboard square, which appears black on 1a, 1b appears almost white on images 2a, 2b. Many of them noticed that on images 2a, 2b the left square looks slightly darker than the right square. Some students noticed that on images 2a, 2b the overall brightness is largest in the middle of the images and decrease towards the edges. Several students also noticed that on images 2a, 2b the large sheet of paper looks dark (compared to cardboard squares) and the table looks bright. Some students also noted that the marker looks similar on all images from the first two sets.

The last set of images was perceived as most interesting for majority of students. Many students noticed that all objects on the image 3a are of approximately the same shade but in 3b several changes appear. The brightness of the two squares is inverted with respect to the images from the first two sets: the right square appears darker than the left square. The large sheet of paper becomes very bright with non-uniform patterns on it. Some students also noticed that the table and the right square on the image 3b are slightly brighter than on the image 3a and that the middle part of the marker is brighter on the image 3b.

2. Propose explanations for the observed patterns. If possible, try to find several different explanations for each pattern.

Students' work in units 2 and 3 showed that most students assumed (subconsciously, probably based on their experiences with incandescent lamps) that the temperature of the objects in images 1b, 2b, 3b increase or stay the same compared to temperature of the objects in images 1a, 2a, 3a.
Most students explained the same appearance of images 1a, 1b by referring to everyday experience that the appearance of objects such as those used in these experiments normally does not change if temperature of the objects changes for a few degrees.

To explain the same appearance of images 2a, 2b, several students used the following reasoning. Images 2a, 2b show only (near) infrared light that have been emitted by the lamp and reflected from the objects. They support this idea by noting that the peak of the spectrum of the lamp falls in the detected range of wavelengths. Some students speculated that the fact that images 2a and 2b are equal may indicate that the light emitted by the objects due to the changes in temperature does not contribute visibly to these images.
Several students explained changes in contrasts between 1st and 2nd set of images (black/white square in set 1 turns to bright/bright square in set 2; large black sheet of paper remain black on both sets of images) referring to differences in properties of the materials but only two students explicitly said that this is so because the reflectance (albedo) of the objects depends on the wavelength of incident EM waves.

Students' proposed the following explanations for patterns in images 3a, 3b.

All objects on the image 3a appear to have about the same (dark) colour. Most of the students wrote that this is because all objects are of approximately the same (room) temperature right after the lamp was switched on. One student suggested that all objects on the image 3a appear dark because the wavelengths of the IR light emitted by the objects are too large to be detected by the thermal camera.

After illumination the left square becomes much brighter than the right square. Most of the students explained that after illumination the temperature of the left square increased more than the temperature of the right square "because black objects warm more than white objects". Some students explicitly wrote that the left square absorbs larger fraction of the light emitted by the lamp than the right square and therefore its temperature increased more. One student suggested alternative explanations: (1) the left square has smaller heat capacity than the right square and objects did not reach yet the equilibrium temperatures; (2) the temperature of both squares is equal but their albedos in IR region are different. (Note that both explanations are plausible although not valid for this particular case).

After illumination the large sheet of paper becomes much brighter and shows non-uniform shades. Only one student attempted to explain this observation. He explained the increase in brightness with increase in temperature (in the same way as in previous case) and the non-uniform brightness of the large sheet of paper as the result of non-uniformity in the material.

The middle part of the marker is the brightest part in image 3a. After illumination the middle part of the marker becomes even brighter. Some students explained the first pattern by suggesting that the experimenter was holding the marker before the first image was taken. For the second pattern most students suggested that it is the result of different material, which was warming faster than the rest of the marker.

3. Suggest testing experiments for your explanations. For each testing experiment make predictions based on explanations under test. Describe also any assumptions that you made in your reasoning.

Students suggested several testing experiments. In some cases their experimental ideas were unrealistic and their predictions were not consistently based on their explanations but the main value of these descriptions for teacher is additional and deeper insight of students' ideas that in many cases would remain hidden if students completed only the unit 2. Let me describe one example.

One of the students suggested covering the thermal camera with a filter that blocks EM radiation and take pictures such as in cases 3a, 3b. Her reasoning was that if the EM radiation is related to temperature of the objects the images should be the same as image 3a. The suggested experiment and prediction revealed that this student thought that the thermal camera separately acquires "temperature image" and "real image". It may also indicate that this student does not see the connection between the body temperature and the EM radiation associated with it, but to check this more data would be needed.

Interested readers can find more about student difficulties in understanding thermal radiation in two papers by Ugo Besson *et al* [2,3] and more about infrared imaging in the paper by Michael Vollmer *et al* [4].

High-school students' responses:

The same activity was also given to high-school students (age 18-19) in their final (fourth) year. In Slovenia physics is compulsory subject in the first three years of high-school and elective subject in the fourth year. Black body radiation is part of the curriculum, but usually only a short time is devoted to this topic.

So far we received only the results from one high-school student. We decided to include analysis of his work for two reasons. First, the work shows a coherent (although incorrect) understanding of the phenomena and second, it shows how high-school physics problem can be used to stimulate students to think like scientists. Updates of this document will follow, when we will receive more high-school student reports.

1. Describe everything you notice on the images in Table 1. At this stage do not make any explanations – focus only on description of your observations.

Student noticed that there are no differences between images 1a, 1b as well as between images 2a, 2b. He also noticed that difference in contrast between the left and the right square on images 2a, 2b are much smaller but he did not explicitly say which square looks brighter. As regard to images 3a, 3b student started describing the images but then soon moved to interpreting them. He wrote that images show that objects were slowly and non-uniformly warming up and that the black square warmed up more than the white square. He also noted that part of the marker is very bright.

2. Propose explanations for the observed patterns. If possible, try to find several different explanations for each pattern.

Student explained lack of changes between images 1a, 1b and between 2a, 2b as the result of immediate refection of visible and NIR light from the objects. He explained similar brightness of the squares in images 2a, 2b as the result of "larger intensity of the light source in NIR region" (note, that this is consistent with the given spectrum). Student explained differences in brightness in images 3a, 3b in the following way: "...in this case the (EM) waves do not reflect immediately but objects first absorb the waves and consequently warm up because of the law of conservation of energy." He offered two explanations for non-uniform patterns on the black sheet of paper: because of air currents or because the paper was not perfectly flat and some parts of it did not touch the table. He explained that the marker was bright already on the first image (3a) because "it reflected these waves immediately after the light bulb was switched on".

3. Suggest testing experiments for your explanations. For each testing experiment make predictions based on explanations under test. Describe also any assumptions that you made in your reasoning.

Students' response to this part (using his own words) is summarised in the table below:

Explanation suggested by the student	**Testing experiment suggested by the student**	**Students' reasoning**
E1: Squares in 2a, 2b are of similar brightness because the intensity of the emitted light is high in NIR region.	TE1: Repeat the experiment with different intensities of NIR light.	If the brightness of the squares remains similar then E1 can be rejected.
E2: Non-uniformity in the brightness of the large sheet of paper is the result of air currents.	TE2: Build little walls around the paper to block/decrease the air currents.	If the non-uniformity still remains then E2 can be rejected.
E3: Non-uniformity in the brightness of the large sheet is result of the fact that the paper was not perfectly flat and some parts of it did not touch the table.	TE3: Obtain several equal sheets of paper and bend them differently before putting on the table.	If the non-uniform pattern does not change then E3 can be rejected.
E4: Marker looks bright on image 3a because it reflects waves with wavelengths between 7 μm and 14 μm	TE4: Take an image with thermal camera in darkness (no light bulb)	If the image of the marker looks the same as in 3a then E4 can be rejected.

Comments:

Reasoning

Although high-school student's ideas were more naive than ideas suggested by university students, his ability for hypothetico-deductive reasoning was much more developed. This kind of reasoning is characteristic for scientists. Hypothetico-deductive reasoning typically follows the pattern: *if my hypothesis is correct and I do ... then ... should happen; but since ...did not happen I can reject my hypotheses*. Note that if the predicted outcome did happen, no judgement can be done about the hypotheses. Note also that student did not suggest testing experiments to "prove" explanations but to reject them.

Student responses clearly show that he understands difference between a hypotheses and a prediction. He was able to make predictions based on hypotheses and judgements based on comparisons between predictions and (hypothetical) outcomes of the experiment. In our case none of the University students was able to follow this type of reasoning!

Physics

Student answers show that he is aware that different materials respond differently to EM waves of different wavelengths, which is correct, but it seems he sees these responses as independent and fixed (the central idea in students' explanations is that some wavelengths are reflected immediately while some are absorbed first and emitted with a delay). The idea that object can absorb energy in one wavelength region and emit it in a different wavelength region does not seem to occur to this student. Another interesting idea suggested by the student is that object's appearance may depend on the light intensity (see E1). Although this idea is not relevant in our case it is plausible and in agreement with several everyday experiences. In fact, this idea can be crucial for understanding some everyday phenomena (see for example L Viennot [5])

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