Should we use colours as symbolic representations of hot and cold?

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Should we use colours as symbolic representations of hot and cold?

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Abstract

People usually talk about 'hot and cold' colours without really thinking of the impact these definitions may have on scientific understanding. These colours are associated with the human sensations of hot and cold, and this idea is consistent with commonsense and daily experience. Interacting with students, we detect conceptual conflicts when they have to interpret phenomena whose origin is the emission of radiation. The contradiction between the scientific explanation for blackbody radiation and their understanding of 'hot and cold' colours, reinforced by the coloured images in textbooks, leads frequently to misconceptions and to the remembering of facts and interpretations that are based on context and not on scientific knowledge. In this article we show the difficulties experienced by students with these concepts and make some suggestions of strategies that teachers should use when dealing with them.

Introduction

The idea of using different colours to symbolize the temperature of objects is not new. From ancient times, red and other colours classified by artists as 'hot' have been used in painting to represent objects at higher temperatures while blue and other colours classified as 'cold' have traditionally been associated with objects at lower temperatures. This idea is apparently consistent with our everyday perception: for instance, fire is red and ice has a bluish colour. Moreover we are surrounded by examples that confirm and reinforce this perception: the blue colour of swimming pools, the coloured symbols on hot and cold water taps and even the warm red coat of Santa Claus (who would like a cold blue Santa?).

When students take their first steps in learning physics, they come across many coloured images in textbooks that are intended to represent objects at different temperatures or simply to explain heat transfer in water pipes, air flow or heat engines (Serway and Beichner 2000, Halliday *et al* 2001, Young and Freedman 1996, among many others, including almost every school textbook).

Therefore it is not surprising that most students will associate red and blue colours with the human sensations of hot and cold. This interpretation is typical of concrete thought: it comes mostly from their perception of the real world, it is anthropomorphic and it is essentially egocentric. They consider themselves as receivers of radiation and therefore the concepts of 'hot and cold' colours are determined by this point of view.

Conceptual conflicts only arise when students are confronted with phenomena where the point of view of the emitter has to be considered such as, for example, the colours of the stars (or other incandescent sources) and their corresponding temperatures. They reluctantly accept that blue stars are hotter than red stars when they are taught so in the classroom, since this contradicts the old established idea of 'hot and cold' colours.

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Most of the misconceptions concerning colour are related to the incapacity of students to differentiate the physical and the physiological aspects of colour (Jung 1982, Andersson and Kärrqvist 1983, La Rosa *et al* 1984). On the other hand, students come into contact with colour firstly through visual education, where it is associated with matter, then later in physics education, where it is associated with light. Perceptual mechanisms are almost never discussed (Chauvet 1993).

What can be done by teachers and authors to clarify this imbroglio and avoid misconceptions? In the following we suggest some teaching strategies to clarify the apparent contradiction concerning colour and temperature and to achieve a better conceptual understanding.

Theory and discussion

In the first place, students must understand properly the meaning of colour (Zajonc 1976). It all starts with a light source. Matter interacts with light by absorbing radiation in a selective way: for instance, a red body reflects red and absorbs all other colours (higher frequency radiations) while a blue body reflects blue and absorbs all other colours (lower frequency radiations). Reflected and source radiations are then both detected by the eye, sending information to the brain, which generates a subjective sensation of colour (figure 1). The aim of this discussion is to allow students to make predictions and analyse situations, using the idea of a *network* in the processing of information about colour.

Students must develop a non-Aristotelian concept of colour, beyond a simple property of matter. They must also see the role of light in the objective view of colour and the role of perception in the subjective one. This discussion can be useful to clarify some physical concepts involving addition and subtraction of radiation (Heilemann 1935, 1936, Holtsmark 1969) such as those of primary and secondary colours (Edge and Howard 1979).

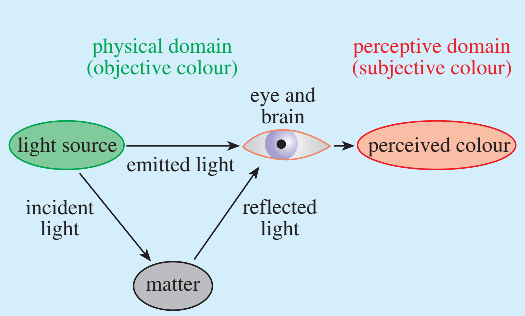

Figure 1. Functional diagram: colour (adapted from Chauvet 1993).

To help students understand the consequence of different colours in radiation absorption, we should now recall Planck's relation, which relates the elementary quantum of energy of an electromagnetic wave with the frequency of the radiation:

$$E = h\nu$$

where E is the energy and ν the frequency of the radiation, and h is Planck's constant.

Now we may lead students to conclude that a red body absorbs higher energy than a blue body. This is why red clothes are generally warmer than blue ones (of course, when made of the same material). Students can apply this idea in a more extreme situation, comparing white bodies (ideally, all colours reflected) with black bodies (ideally, all colours absorbed), concluding that from the point of view of the receiver, the temperature of a body is related to the frequencies (colours) absorbed and not to the frequencies reflected. This is the immediate perspective we have in our daily life, which can explain the use of 'hot and cold' colours to represent bodies at different temperatures.

Once we have clarified this, we must discuss with students the completely different phenomenon that occurs in the emission of radiation. For this purpose we must appeal (at least in a qualitative way) to the Stefan–Boltzmann law; in recent curricular changes, it has been introduced in several countries such as Portugal, at secondary level. Students should grasp the idea that all bodies emit radiation simply because they have internal energy (which is proportional to their temperature). However, this emission is not the same for all wavelengths: for a certain absolute temperature T, the maximal emission of radiation is obtained for a certain wavelength $\lambda_{\max}$ given by Wien's displacement law:

$$\lambda_{\max} = \frac{2.9 \times 10^{-3}}{T} \quad \text{(SI)}.$$

This means that the body's temperature determines the frequency at which the radiating body emits most radiation. If the body is not being illuminated, its colour is mostly determined by this frequency of maximal irradiation.

There are some fine examples that we can explore with students, in different scientific contexts:

(1) White cans and black cans absorb different quantities of radiation when illuminated by light (as explained above). As a result, a black can becomes hotter than a white can. This can be tested experimentally, by putting a thermometer inside two identical cans, coloured respectively with white and black matt paint, and illuminating both for about ten minutes. However, by heating them to the same temperature and then scanning the cooling process, they will both show the same decrease in temperature because they have maximal emission of radiation at the same wavelength (Bartels 1990, Baierlein 2003). This is a direct consequence of Wien's law. And since they emit in the infrared region, the amount of energy irradiated is the same for both cans; therefore the concept of colour has no meaning at all!

(2) The flame of a Bunsen burner has different coloured zones. It can be easily verified with an appropriate probe that the higher temperature is found in the blue zone!

(3) Stars with temperatures below 3500 K (like Betelgeuse or Antares) are *red*, while stars with temperatures between 8000 K and 11 000 K (like Sirius) are *blue*; yellow and white stars have intermediate surface temperatures, like for example our Sun, with a surface temperature of about 5800 K that gives it a pale yellow colour. Why there are no green stars? The reason is rather simple: a green star should have a surface temperature of about 6000 K and emit most radiation at 'green'; however, such a star also emits great quantities of 'blue' and 'red' radiation, and the sum of these results in a white or pale yellow colour. Those we call white stars are in fact mostly 'green stars' (Overduin 2003). There are some good internet sites where students can find plentiful astronomical information related to this subject. Some of these are listed at the end of this article.

(4) It is known from biology that the skin colour of animals or other living organisms is a reflective property associated only with visible radiation and *not* with infrared radiation that all animals emit spontaneously. So, there is no relation between the colour of animals' skin and their blood temperature, as frequently stated: for instance, we can find in nature different 'cold blooded' reptiles that have all kinds of colours from white to dark tones (Nussear *et al* 2000).

After the discussion of these topics, students should also conclude that reflection and emission of radiation are quite different phenomena. Illuminated bodies present a colour resulting from the radiation(s) they reflect. However, they also emit radiation, and the radiation emitted by a body is related to its temperature: blue radiation is emitted by objects at higher temperature and red radiation is emitted by objects at lower temperature; those at the same temperature emit radiation of the same colour. This means that bodies emit radiation even when they are not illuminated. Therefore, colours *should not* be used to represent human sensations such as hot or cold.

Conclusions

Usually, students fail to understand the relation between the concepts of temperature and colour, associating them both with the points of view of emitter and receiver, which is not possible because the reflection and emission of radiation from a body have quite different physical explanations. That's why teachers should discuss these phenomena very carefully and provide the opportunity for students to put forward their ideas in the classroom. Some simple insights that should come out from discussion are:

1. Illuminated objects are coloured because they absorb and reflect radiation.
2. Objects absorbing high frequency radiation become hotter than those absorbing low frequency radiation.
3. Reflection and emission of radiation are quite different phenomena: objects emit radiation even when they are not being illuminated.
4. The radiation emitted by objects depends on their temperature.
5. High temperature objects emit high frequency radiation, and vice versa.

Teachers should also avoid any representations that can induce or reinforce students' misconceptions. One of these is to use colours to distinguish hot entities from cold ones (water, air flow, bodies, reservoirs…); it is preferable to give this indication by words or simply to write down their temperature, when appropriate. They should also alert students to this situation when it is illustrated in textbooks, helping them to conclude that 'things' do not emit any visible radiation spontaneously unless they exceed temperatures of about 500 K (there are some good java applets to explore in this subject; one of them can be found at www.shodor.org/refdesk/Resources/Models/BlackbodyRadiation).

We also believe publishers and authors should reflect on this point very carefully. Sometimes colour is added to figures just to highlight an idea or simply to make the presentation more pleasant, but in the subject of 'hot and cold' colours, this can inhibit understanding and even lead to misconceptions. In this case, it is better *not to colour figures at all*.

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