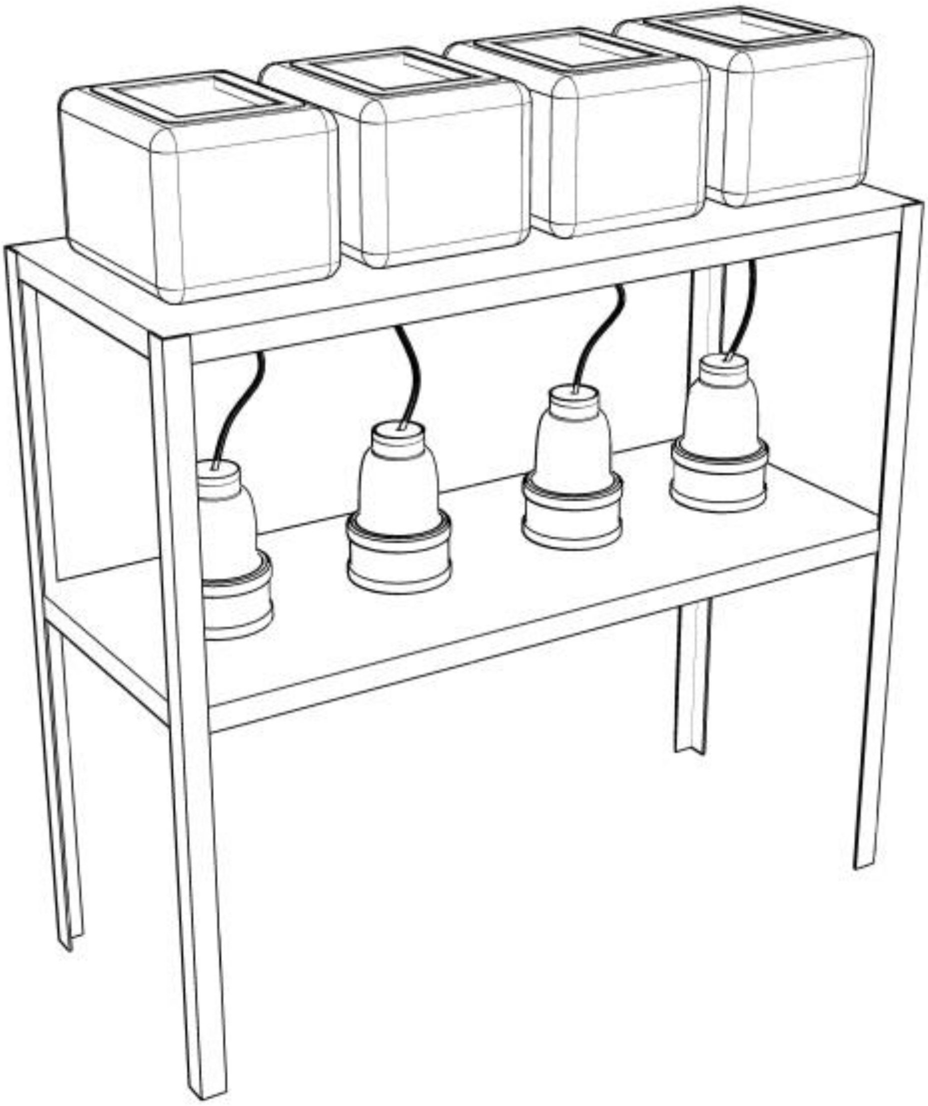
Why do surfaces have different temperatures and what does that mean for the city?

An experiment with the Cool City Lab



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PULCHRA

1. What can be explored with the Cool City Lab

You have certainly walked through the city in summer, through narrow streets, through parks and perhaps past a fountain or pond.

Maybe you can remember it, or, if it is hot outside right now, you can just do it again!

You will see that it is hottest on the street or in a parking lot. When you walk through a park, it feels a lot more pleasant. However, the coolest is, when you stop at a fountain. Here you can often feel a real cool breeze in summer. This raises the research question "Why does it feel warmer or colder in some places in the city than in others?”.

One idea to explain this is that it might be caused by different surfaces of the ground like sand, stones, lawn, or tar. In science, we call the idea to answer a research question a hypothesis. Therefore, our hypothesis is "The different surfaces in the city make it feel warmer or colder in some places than in others". With the Cool City Lab, we want to find out if our hypothesis could be correct. It exposes different surfaces to the weather to imitate the different places.

We can use the Cool City Lab to investigate what causes the temperature differences. We study different surfaces as we find them in the city: Tar, stones, sand and grass (lawn). To find out differences, we put these surfaces on polystyrene boxes and put the experiment outside where it is exposed to the weather. Depending on the air temperature and radiation, the surfaces either get warmer or cool down. The sun, whose radiation can be felt on the skin as warmth, shines on the surfaces. Furthermore, there is the rain, which makes the surfaces wet and then seeps in or runs off at the surface. In the Cool City Lab, we measure how warm it is inside the boxes with the different surfaces. We also measure how much water seeps through the surfaces. In the end, we compare the temperatures and amounts of seepage water of the different surfaces and try to find out why it feels differently warm in different places in the city.

How one can work with the Cool City Lab:

1. If it has not been done yet, build the Cool City Lab (building instructions are in material P30 of the PULCHRA Collection of Educational Materials). If you have an already finished Cool City Lab, have a close look at how it is build and how it works.
2. Carry out the experiment as described in chapter 2. This takes at least one week.
3. While the experiment is running, read the information on what is going on at the surfaces in chapter 3 and work on the tasks. This includes making your own hypotheses.
4. Once the experiment is finished, the analysis of the measurements begins. How this can be done is explained in chapter 4. This includes thinking about what the results mean for the hypotheses.

5. Due to climate change, the temperatures are changing and it is getting warmer and warmer, in summer it is more and more often really hot. Now that you know more about why it is warmer in one place than another, you can end up by thinking about what the results of the experiment could mean for your school, city, or home. To do that, you will find suggestions and questions in chapter 5.

2. Carrying out the experiment

Procedure

To find out how different surfaces act on temperatures, the Cool City Lab must be set up outdoors, where the effects of real weather can be seen. It should be set up in the open air, without a roof above it and with as little shade as possible in order to record the real environmental influences. The experiment should be set up outside for at least a week to have enough data for the analysis. If possible, the experiment should run longer, up to four weeks. It is best to do the experiment on hot summer days, as the effects are strongest then. However, you can do the experiment in all seasons.

Before starting the experiment, the temperature sensors must be set up to do regular measurements. Some types of sensors have to be programmed. Others require programming a control unit, which is connected to the sensors. That depends on the type of sensor used.

During the measuring period, nothing should be changes inside and on the boxes, in order not to confound the measurements. The lids should stay closed and the Cool City Lab has to stay at the same place. Therefore, it makes sense to carry out the experiment in a backyard or fenced area.

It is important that the four boxes are always treated exactly the same. Otherwise, any differences you find in the measurements could be because you handled the boxes differently. In that case, we do not know whether a difference is caused by the surface of the box or by the fact that we did something different with one box than with another.

The only permitted intervention is watering of the surfaces if the grass tends to dry out. In this case, however, the same amount of water (e.g. about 200 ml per day in hot weather) should be poured on all boxes. The water has to be poured in such a way that the whole surface is evenly wetted and the water can seep or evaporate. This is important in order to be able to correctly assess the amount of water in the seepage water collection bottles afterwards.

Measurement data

Usually the temperature measurements will be carried out automatically and the data will be saved. If there is a way to access the measured data while the experiment is running, a copy should be saved in a different location every now and then. If something goes wrong later, you still have the saved data. If the data is saved on the temperature sensors inside the boxes, this unfortunately is not possible, because the boxes should not be opened during the experiment.

The amount of water in the seepage water collection bottles should also be read off regularly, preferably every day. You should enter this data carefully in a table. Do not forget to also note date and time. If the scale on the bottle is imprecise, another way is to weigh the bottles. The weight of the empty bottle must also be known. It is best to write this on the bottle with a waterproof pen.

The experiment can be evaluated particularly well if, in addition to the data measured in the Cool City Lab, you also have measurement data about the weather. If you measure the air temperature outside the boxes, you know whether it is warmer or colder inside the boxes than outside. If you measure the amount of rain, you know how much water has fallen on the surfaces and this can be compared with the amount of water in the seepage water collection bottles. It can be also of interest how much solar radiation has reached the experiment or how cloudy it was.

To measure the air temperature outside the boxes with a small temperature sensor like the ones used in the Cool City Lab, you need a radiation shield, which you can build yourself as shown in material P35 of the PULCHRA Collection of Educational Materials.

3. What happens at the surfaces?

To evaluate and understand your measured data, you need to understand what happens at the surfaces. In science, we call the things happening processes.

<u>Reflection</u>

Reflection takes place, when a part of the radiation that arrives at a surface is radiated back. This is comparable to a mirror. The measure for the fraction of radiation that is reflected by a surface is called albedo. If you shine your flashlight against a bright wall in the dark, the light comes back, it is reflected and the whole room is illuminated. That means the wall has a high albedo. However, if you shine against a black wall, there is much less reflection of the light. It seems like the wall swallows the light. That means the wall has a low albedo.

Light is the visible fraction of the shortwave radiation from the sun that arrives at the surface coming from the sun. However, where does the energy / light go if it is not reflected?

It is converted into heat. That is why it becomes hot in a black car in summer, while it stays much cooler in a white one.

Evaporation

If you leave a glass of water, the water will become less and less over time. It evaporates. What is the force that causes the water to evaporate?

When it is warm, water evaporates faster than when it is cold, as anyone who has ever lain in the sun with wet swimwear knows. It usually feels quite cold! So what do you do instead when you come out of the water after swimming? You towel yourself off first! Because, if you stand outside the water with a wet body, it suddenly gets quite cold, despite the sun.

The sun's radiation itself is not warm, when it reaches the earth. First of all, it brings energy to the earth. This energy can be used for different processes such as heating up the surface, evaporating water, or simply reflecting it back into the atmosphere. When water evaporates, it changes from liquid to the gaseous state. This change of state requires energy. Energy can never be destroyed it can only change form. Thus, the energy taken up to evaporate water is hidden in the gaseous state of the water. This energy is called latent energy or latent heat. It is released again when the water condenses.

The process of taking up solar energy and converting it to a different form is called absorption. When the sun hits a dry surface, this surface gets warm. On a sunny day, you may feel this on your skin. Thus, this energy flux is call sensible heat flux. The radiation is converted into thermal energy on your skin.

However, if your skin is wet, the sunrays first hit the water on your skin, where energy is used to evaporate this water. The process of evaporation even takes heat out of your skin and you get cold. Thus, both sensible heat and latent heat fluxes typically happen at the same time.

So we now know that evaporation cools because the process converts energy into latent heat that we do not feel as sensible heat.

A process in which water evaporates also occurs in plants. Evaporation cools the surface and therefore a plant from overheating in the sun. As water evaporates from the surface, the plants draw water through its roots from the soil. This is comparable to a straw where evaporation is sucking on the upper end and water is taken up at the lower end. Since it can be controlled by the plant via opening and closing of small openings in the leaves (stomata), evaporation from leaves has a different name. It is called transpiration. Transpiration generates a flow of water from the soil trough the plant into the atmosphere. This flow –or often called flux– also transports nutrients from the soil into the plant. Plants can take up water from considerable depth, as deep as their roots reach. Evaporation can take water only from the surface.

Other ways of the water

After the rain, the water does not simply remain on a surface. It disappears over time even when it does not evaporate. Using material P19 of the PULCHRA Collection of Educational Materials, you can think about where the water goes and what happens to it. If you want to do this, only read on afterwards.

So where does the water go that reaches a surface when it rains? During rain, it cannot evaporate since the air already contains all the water it can possibly hold. It is said to be saturated with water. Either the rain seeps through the surface, which is called infiltration, or if it rains very hard or the soil is completely filled with water, it flows at the surface, which is called surface runoff.

If water can infiltrate therefore depends on how many pores (or holes) are in the soil and how these pores transport the water downwards. It also depends on how much water is already contained in the pores and how much more water fits into the soil. Some surfaces hardly have any pores or the pores are not connected so water cannot flow through. Here water cannot infiltrate. We call these sealed soils or sealed surfaces.

A sealed surface dries off quickly after a rain and gets hot when the sun shines, because there is no cooling effect of evaporating water anymore. Thus, going barefoot on a sunny day is much more enjoyable on a lawn than on a tarred surface. The lawn lets water infiltrate which can later evaporate the tarred surface does not.

<u>Tasks</u>

Get together in groups of two or three people. Half of the groups will work on task 1, the other half on task 2.

1. Create a drawing that shows what happens to solar radiation when it reaches a surface. Also, think about what happens to the surface. Do not forget to label the drawing.
2. Create a drawing that shows all three explained ways of the water and do not forget to label the drawing.

Now find a partner group that worked on the other task. Mutually explain your drawing to the other group.

Next, look at the four boxes of the Cool City Lab and …

3. … put your heads together with your partner group on how the ways of the water differ between the boxes. Which fraction of the water goes which way? Consider what you learned about radiation and reflection.
4. … put your heads together with your partner group on how radiation and reflection differs between the boxes. Consider what you found out about the ways of the water.
5. … set up hypotheses for the following questions:
   a) In which box will be the highest temperatures?
   b) At which box, the most seepage water will accumulate in the seepage water collection bottle?

   It may help to first consider what the situation would be like if there was only radiation or only water. Then try to combine the two.

Make sure to write down the results of your work.

4. Analysis of the measurements

Preparation of the measurement data

Before the actual analysis can begin, the measurement data must be prepared. It is often helpful to have a graphical representation of the data in diagram, a visualization. The easiest way to do both is to use a spreadsheet software on a computer such as Open Office Calc, Microsoft Excel or others. **Remember to always write down what you have done with the data.**

When using a digital thermometer to measure the temperature inside the boxes, the data are often already provided in a computer-readable form, i.e. in a digital file.

1. At first, import the temperature data into a spreadsheet software. Make sure, that the numbers and the timestamp (date and time) are displayed correctly in the spreadsheet.
2. Organize the data so that one column shows the timestamp of the measurements and the four columns next to it show the measured temperatures of the four boxes. You can color the columns in the colors of the boxes.
3. Display the data as curves in a diagram. On the x-axis of the diagram (horizontal axis, at the bottom) you have the time and on the y-axis (vertical axis, left hand side) there is the measured temperature. It is best to display the temperatures of all four boxes in a single diagram, to make it easy to compare them.

Now, the data on the seepage water has to be prepared. Presumably, these data were read from the seepage water collection bottles or the bottles have been weighed at several points of time and have been written into a table.

4. Transfer the data in an empty sheet in your spreadsheet file. Let another person check the transferred data by comparing it to the written table. When typing from a paper table, mistakes can easily happen. Pay special attention to transposed digits, i.e. numbers that are mixed up in their order.
5. Display the seepage water data as a diagram like you did with the temperature data.

Maybe it was possible to measure additional weather data like air temperature, precipitation or radiation. If not, you can skip the next points.

6. Import the weather data into the spreadsheet file, at best on a new sheet.
7. Display the weather data as diagrams as explained above.
8. Add the measured air temperature to the diagram from point 3. Doing this, you can easily see how the temperature in the boxes compared to the air temperature.
9. Add the measured precipitation to the diagram from point 5. Doing this, you can see how the amount of seepage water developed compared to the precipitation. Probably the measurements of the seepage water and the precipitation have different units. You probably measured the water in the bottle as a volume in milliliters. The precipitation is usually given in millimeters. This refers to the height

to which the water would stand if it neither infiltrated nor evaporated. To convert this into a volume, the value must be multiplied by the base area. Be sure to calculate the area in square millimeters. First, consider the origin area of the seepage water originates.

Data can always be incorrect. Errors do not only occur when reading the amount of seepage water. Even electronic measurements can be wrong. Therefore, the next step is to check the data and to make sure that only good data is included in the analysis.

10. First, you check the temperature data if they are reasonable or if they exceed the expected range. Think about what range of temperatures can reasonably occur and discuss that with others. Delete wrong data from the table and make a note of which data you deleted and why.

11. For the seepage water, it is best to check the course of the curve. Since water can only go into the bottle but cannot leave it, the amount of water can only increase or stay the same. If that is not the case anywhere in the curve, the measurement needs to be checked again. If the value in the spreadsheet is the same as in the written table, it has to be deleted.

The preparation of the data is finished now and you can proceed with the analysis.

<u>Analysis of the measurements</u>

Do you still remember the beginning? It was about different temperatures in different parts of the city. The hypothesis was that due to different surfaces different places have different temperatures. That is why the Cool City Lab consists of four boxes with different surfaces. The next step is now to learn something about temperatures and surfaces from the measurements. **Again, always remember to write down what you have found out.**

We start with the temperature data. Have a look at the curves in the diagram and try to answer the following questions:

- What is the course of the curves over time? Is there something that happens repeatedly for all boxes? If yes, how may this regular course be explained?
- How do the curves of the individual boxes compare to each other? Where is it warmer, where colder? Are always the same boxes warmer or colder, or does that change over time?
- At what time are differences between the boxes the largest, at what time the smallest?
- If applicable, how does the course of the temperature of the boxes compare to the course of the air temperatures?

The same questions arise for the seepage water:

- What is the course of the curves over time? Is there something that happens repeatedly for all boxes? If yes, how may this regular course be explained?

- How do the curves of the individual boxes compare to each other? Where is more seepage water, where less? Is that always the same, or does it change over time?
- At what time are differences between the boxes the largest, at what time the smallest?
- If applicable, how does the course of the seepage water compare to the course of the precipitation?

The next step is to combine what you have learned for the temperature and seepage water measurements and what you have learned about the processes.

- Read again in chapter 3 what you have learned about the processes.
- Can you see a connection between the temperatures and the seepage water?
- Can you explain why it is warmer in one box than in another?
- Can you explain why there is more seepage water at one box than at another?

Finally, remember that this is about testing hypotheses using the measurements.

- First, recall the hypotheses you wrote down when working on chapter 3.
- Do the measurements confirm your hypothesis on the highest temperatures?
- Do the measurements confirm your hypothesis on the largest amount of seepage water?
- What about the general hypothesis that "the different surfaces in the city make it feel warmer or colder in some places than in others"? Can you confirm this hypothesis based on your data and insight? Can you explain now, why that is?

5. Using the results

Temperatures have become an important issue in recent years. In the context of climate change temperatures on earth rise. Of course, this also affects the temperatures in buildings. Possibly, it also has become hot in your school building in summer more frequently.

In addition, it is warmer in cities than in the countryside anyway. You can find clues as to why this is the case in what you have learned. Climate change, thus, has a strong effect in the cities. This can be a problem for people living there, because health problems can arise if it is too hot.

Therefore, the question arises, what can be done to prevent buildings or the whole city from heating up so much. Think about the results of the experiment with the Cool City Lab. What could be used to reduce the warming of the city in summer?

Here are some questions that might give you some ideas:

What can be the role of green spaces and fresh air corridors?

What can be the role of roofs, their color, and their material?

How can the albedo of the city be changed?

What can be the role of water?

Many considerations on these questions and on the ideas for solving the heat problem raise new questions. It is often difficult to answer these questions by yourself. Think about who might have knowledge about it. Approach others who might be good advisors. Contact these people to present your ideas and get answers to your questions.

If you have a good idea and you learned a lot about the topic from your consultants' answers, you can continue to think about how you could make your idea a reality. Again, many questions arise:

Is it possible to simply do what I propose with my idea?

Do I perhaps need permission to do so?

What would it cost to implement my idea and who would pay for it?

Again, it is good to ask those, who are experts in the issues. This could be the local administration, a politician, or someone from an organization that is concerned with the future development of cities. Architects and urban planners are also familiar with these topics.

Write down everything you found out about the temperatures in the city and about ideas on how to keep them down in summer. You can also create one or more posters on your results. In the end, we want to present the results in school. We will invite parents and guests from outside the school to the presentation. Maybe even the mayor will be there.

Teacher information: Experiment with the Cool City Lab (for beginners)

1. Temperature measurement

   Temperature sensors must be placed inside the box to investigate the effect inside. Additional sensors such as an IR-thermometer may be help to investigate the effect of energy fluxes at the surface. We recommend using inexpensive iButtons to measure the temperature inside. These can be programmed and there is no need to open the box during the experiment. Alternatively, Arduino or Raspberry Pie microcontrollers are a good alternative to measure inside of the box.

2. Importing temperature data into a spreadsheet

   Importing the data into a spreadsheet software from a text-file generated by the digital thermometer may be challenging to some students. The format of the file and the data often differs from the standards expected by the spreadsheet software. It can save time having the teacher do this.

3. Checking the temperature data

   In addition to checking the reasonable temperature range, the course of the curve should also be checked. Sudden changes of temperatures or spikes in the curve hint at erroneous measurements.