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ABSTRACT

A discrepant event is a happening contrary to our current beliefs. Discrepant events are said to be useful in clarifying concepts. This is one of the interesting features of current theories of constructivism. The story of Mpemba's ice cream is quite well known, but it is the educational aspects of the experiment that are of interest in this story. Mpemba was a Tanzanian school boy, who was passionate about knowing the reason for his unexpected observations. His teacher made fun of him rather than carrying out the experiment and eventually a university lecturer listened to him and carried out the experiments. The paper focuses on the educational aspects of this experiment.

The positive message is that although discrepant events are contrary to our current beliefs, they are useful in enabling learners to reconstruct concepts that have been imperfectly understood. The experimental observation is that if approximately equal amounts of a hot and a cold liquid are placed adjacent to each other in a fridge, then the hot liquid freezes first. This is a prime example of what science educators call a discrepant event (cognitive dissonance or cognitive conflict).

DOES HOT WATER FREEZE FASTER THAN COLD? OR WHY MPEMBA'S ICE CREAM IS A DISCREPANT EVENT

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INTRODUCTION

Firstly I will relate three stories about a surprising experiment. The experiment is based on an observation made on a number of occasions that appears to go against common sense. It is straightforward enough to be done at home by students subject to their parents' agreement. The observation is that if approximately equal amounts of a hot and a cold liquid are placed together in a fridge, then the hot liquid freezes first. This seems to me to be a prime example of what science educators call a discrepant event (cognitive dissonance/ cognitive conflict). A discrepant event is a happening contrary to our current beliefs. Discrepant events are said to be useful in enabling learners to reconstruct concepts that have been imperfectly understood. The literature on discrepant events is comparatively small with the following being the main easily accessible references (Fensham & Kass, 1988; Hand,1988; Thompson, 1989).

I am going to quote several long passages verbatim, because they are all first hand experiences of individuals coming to new understandings through this experiment. In addition to which the references quoted are not always easy to find. The reader may take these simply as interesting human stories or as examples of increasing understanding through discrepant events.

EXAMPLE 1

I am quoting at length with some brief annotations from Mpemba and Osborne (1969) as it is the style as much as the story that makes this particular example interesting.

> *My name is Erasto B Mpemba. and I am going to tell you about my discovery, which was due to misusing a refrigerator. All of you know that it is advisable not to put hot things in a refrigerator, for you somehow shock it; and it will not last long.*
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> *In 1963, when I was in form 3 in Magamba Secondary School, Tanzania, I used to make ice-cream. The boys at the school do this by boiling milk, mixing it with sugar and putting it into the freezing chamber in the refrigerator, after it has first cooled nearly to room temperature. A lot of boys make it and there is a rush to get space in the refrigerator.*
>
> *One day after buying milk from the local women, I started boiling it. Another boy, who had bought some milk for making ice-cream, ran to the refrigerator when he saw me boiling up milk and quickly mixed his milk with sugar and poured it into the ice-tray without boiling it; so that he may not miss his chance. Knowing that if I waited for the boiled milk to cool before placing it in the refrigerator I would lose the last available ice-tray, I decided to risk ruin to the refrigerator on that day by putting hot milk into it. The other boy and I went back an hour and a half later and found that my tray of milk had frozen into ice-cream while his was still only a thick liquid, not yet frozen. I asked my physics teacher why it happened like that, with the milk that was hot freezing first, and the answer he gave me was that*

"You were confused, that cannot happen". Then I believed his answer. In my next holidays...................

Here Mpemba relates a number of experiences of other ice-cream sellers who are familiar with the fact that ice-cream when put into a fridge when hot cools more quickly than if it is left to cool.

After passing my O level examination, I was chosen to go to Mkwawa High School in Iringa. The first topics we dealt with were on heat. One day as our teacher taught us about Newton's law of cooling, I asked him the question, ''Please, sir, why is it that when you put both hot milk and cold milk into a refrigerator at the same time, the hot milk freezes first ?" The teacher replied: "I do not think so, Mpemba." I continued: "It is true, sir, I have done it myself" and he said: "The answer I can give is that you were confused." I kept on arguing, and the final answer he gave me was that: "Well, all I can say is that that is Mpemba's physics and not the universal physics." From then onwards if I failed in a problem by making a mistake in looking up the logarithms this teacher used to say: "That is Mpemba's mathematics."And the whole class adopted this, and any time I did something wrong they used to say to me "That is Mpemba's . . .", whatever the thing was. Then one afternoon I found the biology laboratory open.............

Mpemba tries out the experiment in a more scientific way but due to the lack of time the results are inconclusive.

When Dr Osborne visited our school we were allowed to ask him some questions, mainly in physics. I asked: "If you take two similar containers with equal volumes of water, one at 35 °C and the other at 100 °C, and put them into a refrigerator, the one that started at 100 °C freezes first. Why?" He first smiled and asked me to repeat the question. After I repeated it he said: "Is it true, have you done it?" I said: "Yes.'' Then he said: "I do not know, but I promise to try this experiment when I am back in Dar es Salaam." Next day my classmates in form six were saying to me that I had shamed them by asking that question and that my aim was to ask a question which Dr Osborne would not be able to answer. Some said to me: "But Mpemba did you understand your chapter on Newton's law of cooling?" I told them: "Theory differs from practical." Some said: "We do not wonder, for that was Mpemba's physics."

Now Mpemba tries out the experiment again in the school kitchen and the results are conclusive, when he tries them on his own, when his friends witness the experiment and finally when his physics observes the experiment. Now the same story is told by the visiting lecturer (Dr Osborne) from his point of view.

One student raised a laugh from his colleagues with a question I remember as: "If you take two beakers with equal volumes of water, one at 35 °C and the other at 100 °C, and put them into a refrigerator, the one that started at 100 °C freezes first. Why? "It seemed an unlikely happening, but the student insisted that he was sure of the facts. I confess that I thought he was mistaken but fortunately remembered the need to encourage students to develop questioning and critical attitudes. No question should be ridiculed.

Later on Dr Osborne instructs firstly his technician and later his students to carry out the experiment carefully.

At the University College in Dar es Salaam I asked a young technician to test the facts. The technician reported that the water that started hot did indeed freeze first and added in a moment of unscientific enthusiasm: "But we'll keep on repeating the experiment until we get the right result." Further tests have vindicated the student's claim and we think they point the way to an explanation.

The explanation of the experiment will be discussed later in the light of the other information received. It is interesting to note however that explanations that are discredited in terms of scientific evidence in one era are used later as correct explanations by those unfamiliar with the earlier studies.

EXAMPLE 2

This is a description received on AARNET (E-Mail) from Franklin Antonio in the USA in a discussion about this experiment over the physics network. Much of the previous discussion had been mistaken or just abusive. I thought this to be an interesting contribution (Some corrections of spelling and grammar have been made).

I've been following this thread with interest, because I seem to be one of the few people who have actually TRIED this experiment. It was a LONG LONG time ago. I was in the 6th grade at the time. One of my female teachers mentioned that you should always make ice cubes from hot water, because it freezes faster. She asked how many people knew that. Just a few girls raised their hands. Said their mothers had taught 'em this. I was outraged!! I knew enough physics to see (I thought) that this was impossible. Teacher said I should try it, and report back. Well I did just that! Boy I was gonna show them non-scientific ninkompoops.

In those days, before frost-free refrigerators were universal, my parents had the old kind that you had to defrost. For those of you who don't remember... the walls of the freezer section were metal, and they were cooled by conduction. The freon pipes were bonded directly to these walls. There was no blower, as with today's freezers. Of course, a thin layer of ice formed on these metal walls. If you were lazy, it was a thick layer of ice. It was my job to defrost the freezer, so it was often a thick layer. As many of you know, ice is not a very good conductor of heat. That's why you can stay warm in an igloo, and also why you needed to defrost your refrigerator often.

I filled two ice cube trays with water. One from the cold tap, and one from the hot tap at the kitchen sink. In those days ice cube trays were metal too. I put them both in the freezer. To my utter amazement, the HOT WATER FROZE FIRST.

Here's what happened. Metal trays sat on the omnipresent layer of ice which was on top of the metal bottom wall of the freezer which was bonded directly to freon lines (the freon evaporator coils). The tray of hot water proceeded to melt the ice layer, and put itself in direct contact with the cold metal freezer wall below, thus providing excellent thermal conduction to the freon evaporator coils. The tray of cold water sat on top of the layer of ice, and had a much poorer thermal conduction path. It's not hard to understand why, in this environment, the tray of hot water freezes first.

The hot water tray was also difficult to remove when the experiment was over. It was frozen hard to the bottom of the freezer. I had to eat crow the next day when I explained my results to the class. I tried to explain that the physics I had explained to them the previous day was still right, but there was this interesting mechanism I had discovered that made the answer come out different. I was excited about my discovery that the problem was not as simple as I had thought the previous day. I could find no one to share my excitement. The teacher had been right, and I had been wrong. Her opinion seemed to be that I should learn, and not question.

The girls who raised their hands the day before gave me a smug "I told you so" look. They had no interest in why the hot water froze first. It was, to them, a simple fact of home economics, like how to get a crayon stain off of sweat socks. It was true because mom said so.

Of course, today's freezers cool their contents by a different mechanism, (ie blowing cold air on 'em), and today's ice cube trays are mostly plastic. I imagine that I might get a different result if I did the experiment again today. I don't know the result, because I haven't done the experiment in a modern refrigerator.

(Franklin Antonio, E-Mail, sci.physics 5985, June 24, 1991)

EXAMPLE 3

The same question was raised again recently in the correspondence columns of the New Scientist (Channon, 1992). It is a perennial question (FAQ: a frequently asked question) that keeps cropping up.

> *On a recent edition of the BBC World Service's programme"Pop Science" it was claimed that a beaker of warm water freezes more quickly than a beaker of cold water when both are placed in a fridge. I have tried it myself (several times) and have found that it is true. Can anyone explain it for me?*

There are however no shortage of answers, but it is not possible for all the explanations to be true, though there may be several effects each contributing in part to the final result. Four explanations follow.

> *Mark Channon (Letters, 25 July) asks why warm water freezes more quickly than cold in a domestic fridge (and reports that it really does). Attempts to repeat this experiment in laboratories usually show that the cold water freezes faster. The difference? The surfaces of domestic fridges are usually covered with a layer of frost. The warm water melts the frost, so that the surrounding vessel makes better contact with the cold metal below. The cold water remains partially insulated by the frost layer. (The same mechanism explains why something very similar occurs for buckets of water left out in the snow) Mr Channon should thoroughly defrost his freezer compartment and try again.*

(Stewart, 1992)

> *Other things being equal, Channon should realise that warm water is significantly less dense than cold water. The warm water will also evaporate far faster from an open beaker. If he starts with equal volumes, the mass of ice in the "warm" beaker will be less than that in the "cold" beaker at the end of his experiment! There is simply less water there to freeze!*

(Reynolds, 1992)

> *This is often called the Mpemba effect, after Erasto Mpemba from Tanzania, who observed it while making ice cream. A good account of his discovery and subsequent experiments and a discussion of possible causes can be found in Physics Education, vol 14, p 410 (1979). The effect had been noticed as early as the 17th century by Bacon and Descartes, neither of whom could explain this apparent anomaly.*

(Gordon, 1992)

> *Cold water reaches maximum density at 4°C, and stratifies. It can only lose heat by conduction internally, which is slow. Most of the heat loss is from the top surface by evaporation and by air convection. Hot water acquires vigorous internal convection currents during early cooling and the momentum continues to bring water to the surface when cool, thus preventing stratification. The hot water reaches O°C throughout first, and even then currents may persist allowing overall supercooling and increasing the rate of conduction through the surface ice. The shape and material of the container must not impede circulation or conduct too much heat. Now, why are peas green? What use is chlorophyll inside the pod?*

(Wood, 1992)

THE EXPLANATION

Hot water in a refrigerator freezes faster than cold water. Osborne carefully investigated the problem.

> *Because of the element of surprise in this simple observation we based a project for second year university students upon it. In a series of experiments, test systems of 10 cm^3 of water in 100 cm^3 pyrex beakers of approximately 4.5 cm diameter were frozen in the icebox of a domestic refrigerator. The beakers were supported on a sheet of polystyrene foam, providing thermal insulation. It was observed that:*
>
> *(i) If two systems are cooled, the water that starts hotter may freeze first.*
>
> *(ii) The graph of 'time to start freezing' against initial temperature, has the shape of an inverted U with water at an initial temperature of 30°C taking longest to cool and water hotter or cooler than that, cooling more quickly.*
>
> *(iii) An oil film on the water surface delayed freezing for several hours, showing that without this film most of the heat lost escapes from the top surface.*
>
> *(iv) Only small changes in volume occur due to evaporation; the latent heat of vaporization cannot account for more than 30% of the cooling and cannot alone be responsible for the rapid freezing of systems with high initial temperatures.*
>
> *(v) A temperature gradient is established in the liquid.*

> *(vi) Dissolved air was eliminated as a factor by using recently boiled water for the trials starting at all temperatures.*
>
> (Mpemba & Osborne, 1969)

Osborne found that cooling near the surface and near the bottom of the liquid are different, with the majority of heat being lost from the surface, though the temperature of the surface is kept high through convection.

> *In practice the relatively rapid cooling of a system that starts hot may be accelerated if it establishes better thermal contact with the case of the freezer cabinet through melting the layer of ice and frost on which it rests. This factor was eliminated from our tests by resting the cooling beakers on a good thermal insulator. Cooling occurs mainly from the top surface. The rate of cooling depends on the surface temperature of the liquid and not its mean body temperature. Convection within the liquid maintains a 'hot top' (presumably while above 4°C) and the rate of loss of heat for an initially hot system can be greater than for an initially cooler system even when they have cooled to the same mean body temperature. A trained physicist may be surprised by the reported quicker freezing of the hotter liquid because it has to pass through intermediate temperatures before freezing. However, the systems are not described adequately by a single temperature for they have temperature gradients that depend upon their previous history. The suggested explanation in terms of convection establishing a temperature gradient and maintaining rapid heat loss from the top surface must be considered a tentative one. The experiments attempted were relatively crude and several factors could influence cooling rates.*
>
> (Mpemba & Osborne, 1969)

(Note - Graphs provided by Osborne have been omitted and the text has been altered slightly to clarify the meaning)

The explanation given by Osborne shows that what appears to be a simple phenomenon is in fact quite complex. To obtain some reasonable theory, a large number of experiments need to be carried out. Even then the results are far from conclusive, but the method is clear. Osborne and his students looked at just two variables at a time keeping other conditions constant. They chose points that could be clearly observed, such the time taken for the water to start to freeze, rather than the time taken for it to be completely frozen. In other words, they approached the matter scientifically.

It is interesting to note that reasons that Osborne says were eliminated as factors from their experiments, such as thermal conduction between the container and the surface of the freezer, are used as a complete explanation in Stewart's letter

(1992), for example. That is, we sometimes fail to learn from what is already known. From the AARNET letter quoted and in fact several other E-mail letters not reproduced, it was felt that modern refrigerators will produce a different result. However Osborne did look at the effect of evaporation so one must predict that the type of refrigerator would not make a difference, but perhaps it is time to repeat Osborne's experiments, or the work may already exist elsewhere. Any suggestions!!

THE DISCREPANT EVENT

Mpemba had a scientific understanding based on his text book definition of cooling from Newton's law of cooling which states that "for cooling under conditions of forced convection the rate of loss of heat from a body is proportional to the difference in temperature between the body and its surroundings" (Whelan and Hodgson, 1978, p.175). It is also pointed out that the law should strictly be a five over four power law. Both these laws really only apply over small temperature ranges and for bodies at high temperatures radiating heat, Stefan's law applies.

Writing on this topic Taylor (1941) writes - "Within its province Newton's Law of Cooling is a useful approximation, applying to small differences of temperature, but it is nothing more". Poor Mpemba would have had to learn Newton's law by rote, probably without understanding that it is only an approximate law. For him and his fellow students Newton's law would have been practically 'Holy Writ'. A discrepant event is a happening contrary to one's current belief. For Mpemba, it was a major discrepant event triggering cognitive conflict. There is little doubt that he would have become a better physicist as a result. However it is probable that the cognitive conflict would have done little to improve his examination results. There may be some 'food for thought' here!

For the reader and for current Australian students, Newton's law is no longer taught or is of little importance in present -day physics courses, so there may be no similar certainty on theoretical grounds that the cold water will freeze before the hot water. It might appear that for us it is not a discrepant event. Yet I believe that it is the case that for everyone cold water freezing more quickly than hot water offends common sense. It is a circumstance that begs to be investigated and explained. When the individual has done this, they will indeed be better physicists!

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