Substantia
An International Journal of the History of Chemistry

Firenze University Press
www.fupress.com/substantia

Citation: E. Uskoković, T. Uskoković, V. Wu, V. Uskoković (2020) …And All the World a Dream: Memory Outlining the Mysterious Temperature-Dependency of Crystallization of Water, a.k.a. the Mpemba Effect. *Substantia* 4(2): 59-117. doi: 10.13128/Substantia-895

Received: Apr 04, 2020

Revised: May 31, 2020

Just Accepted Online: Jun 05, 2020

Published: Sep 12, 2020

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

Feature Article

…And All the World a Dream: Memory Outlining the Mysterious Temperature-Dependency of Crystallization of Water, a.k.a. the Mpemba Effect

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Abstract. *Introduction* Year 2019 marked the semi-centennial since the release of *Cool?*, a seminal paper by Mpemba and Osborne that demonstrated the counterintuitively faster crystallization of warm water than the cold one when they are both cooled under the same conditions. *Objective* This docufiction piece celebrates the "cool" of the story around the discovery of this effect by taking the form of a play during which a scientific study elucidating the mechanistic origins of this peculiar effect was performed and discussed. *Methods* This play celebrating scientific research as a literal play takes place over the period of 24 hours on an autumn day in 2019 and is divided to four acts: the noon (Act I), the afternoon (Act II), the night (Act III), and the sunrise (Act IV). It is interjected with diegetic musical lines that are sang by the muses in the alternate version and by the characters *per se* in this version, either acapella or to the tunes played by an onstage radio. The protagonists of the play are mom and dad scientists on exile from scientific institutions and their two children, an elementary school-age boy and a preschooler girl, implying the study's strong educational character, alongside the philosophical and humanistic. *Results* Through the simple kinetic analyses of the crystallization of water and the melting of ice, but also more complex light scattering, optical absorbance, infrared imaging and X-ray diffraction analyses, the study provides observations in support of the hypothesis that structural memory in the liquid state is a key factor explaining the Mpemba effect. As per this explanatory model, the increased polydispersity and delayed relaxation of cluster symmetries forming in the preheated water allow it to crystallize faster than the initially cold water. This is made possible either by the direct semblance of an unrelaxed population of high-temperature clusters to the space group of ice I_h or by preserving the dynamic conditions for cluster reorganization that shorten the stochastic search for configurations that facilitate the transition to the solid state at or around the freezing point. Air cavities in the liquid phase, including micro- and nano-bubbles, are shown not to be responsible for the Mpemba effect. However, larger temperature gradients and densities of convection streams in the preheated water get partially preserved during cooling, acting as possible factors of influence that render the occurrence of this anomalous phenomenon feasible. Parallels with hydroxyapatite, the most abundant inorganic material in our bodies after water, were made during the discussion. *Conclusions* It is concluded that structural memory allows water to exhibit the Mpemba effect and that science belongs to the province of children of all ages.

Keywords: crystallization, dialogue, DIY, indie, kinetics, memory, Mpemba effect, play, water.

ACT I

(Indian summer. High noon. Sunshine. Impressionistic colors all around.)

DAUGHTER: Yay, ice-cream!

SON: Yummy ice-cream!

MOM: Watch out guys, it will drip down the cone if you goof. It is hot out here.

SON: Mom, what would happen if an asteroid, like B612, were to hit Jupiter?

MOM: A solid rock colliding with a gaseous giant?

SON: Not just any solid rock. A rock with two active volcanoes, one extinct volcano and a baobab tree and a rose.[1]

MOM: Hard to tell. All I know is that Jupiter protects us by attracting many asteroids and comets with its huge gravity and diverting them from the Earth.

DAD: A catcher in the rye it is.

SON: What's a catcher in the rye?

DAD: It is a child - or a grownup - standing on the edge of a cliff and keeping other children playing chase in rye fields from falling down the cliff.[2] This child, however, cannot play. It is a noble sacrifice that she or he must make to allow other children to play.

MOM: "A torch for me: let wantons light of heart tickle the senseless rushes with their heels, for I am proverb'd with a grandsire phrase; I'll be a candle-holder, and look on".[3]

DAD: So said a dreamy boy when asked to dance at the ball. A minute later he'd see the girl of his dreams and all the moons would jump out of their orbits and stars spin off their axes.

SON: And what about Andromeda galaxy? When it starts colliding with the Milky Way, how will it look like?

DAUGHTER: Swoosh-bash-smash!

SON: Yoo-hoos-caboose!

DAD: Actually, stars stand at such big distances from one another that they won't even feel it.

MOM: Solitude paves way to shininess.

DAUGHTER: Look-a-me, I'm in time capsule.

DAD: Time traveler, where are you heading today? Future or past?

DAUGHTER: To history we go!

DAD: How far back in time? To say hi to Eskimo curlews? Or dire wolves?

MOM: Take a peek at the Earth forming from cosmic dust?

DAD: Climb the giant conifers that stood here and pierced the late Miocene sky?

SON: "Why do we need clocks when we never have the time? We're here now"[4] (♪♫♪).

MOM: Guys, as you dream about spaceships and stars, your ice-creams have dripped to the porch.

SON: Look, the blob is making up the heart shape.

DAUGHTER: The chocolate heart shape.

[1] A. Saint-Exupery – "The Little Prince", Reynal & Hitchcock, New York, NY (1943).

[2] J. D. Salinger – "The Catcher in the Rye", Little, Brown and Co., New York, NY (1951).

[3] W. Shakespeare – "Romeo and Juliet", Easton Press, Norwalk, CT (1597).

[4] M. Nilsson – "Clocks", In: History, Dark Skies Association, Berlin, Germany (2011).

MOM: It really looks like a heart. How splendid.

DAUGHTER: A discobery!

SON: It is just a blob, baby sister, not a discovery.

DAUGHTER: A discobery says I, the king of the jungle.

SON: I Mowgli, you Chil!

MOM: Chil? You mean, like "cool down"?

SON: No, I mean the brahminy kite[5] who flies around and chirps in unknown, aerial languages.

DAD: How cool. A gaze at the farthest, the most mysterious, both the brightest and the darkest of it all brought us here, at the doorstep of a discovery in a tiny drop of chocolate ice-cream.

MOM: All I know is that when "there's poetry in an empty Coke can"[6] (♪♫♪), life is at its most beautiful, even in this "burnt out caravan". These petite discoveries matter more than most things grownups ascribe greatness to in life.

DAD: Actually, this chocolate ice-cream blob reminds me of a story.

SON: Ah, Dad, what story now?

DAD: The story behind the discovery of an effect known today by the name of a boy named Mpemba.

DAUGHTER: 'Memba?

DAD: No, not 'Memba, but Mpemba. Though the effect known by his name and the one I will tell you about may have a lot to do with 'memba, that is, "remember". At least, so have I always deemed, but never got the courage to test.

MOM: Was Mpemba a scientist?

DAD: It is not certain how he would have classified himself. But the fate spared him from the dehumanizing, heart-mincing world of academia and made him earn for living as a gamekeeper in reserves near Kilimanjaro.

[5] R. Kipling – "The Jungle Book", Macmillan, New York, NY (1894).

[6] Guillemots – "Made-Up Love Song #43", In: Through the Windowpane, Polydor, London, UK (2006).

SON: He protected games? How cool.

DAUGHTER: A 'puter games? Like Maniac Mansion?

MOM: More like wild animals.

DAD: Isn't it what animals are here to teach us anyway? How to approach life as a game? Play as a route to the world's grandest discoveries.

MOM: That is indeed what puppies teach us: "that the more animals need to learn, the more they need to play".[7] And not just puppies, but dolphins, chimps and many other animals that are next of kin to our evolutionary lineage too.

DAD: Once I heard that they play for the sake of playing.

SON: Like we, children do.

DAD: Purposelessly, in the "blue-skied" manner, which is, by the way, how the best discoveries are made.

MOM: Animals have really taught us that playful behavior is at the root of learning.

DAD: Does this mean that to enable a child to remain a child for its entire life is the only way to promote its proper growing up, in spiritual and creatively expressive terms?

MOM: Perhaps. Remember that unlike wolves, who sooner or later surpass the phase of puppyhood in their development and become stern and serious individuals, so to speak, dogs dwell in the state of incessant puppyhood and puerility. Whether they were domesticated and inaugurated into man's best friends owing to these qualities or these qualities were the outcomes of the domestication process, it is not certain.

DAD: Except that the most probable answer, as in all cyclical causal loops, is both. Which makes me wonder what in the world we, as humanity, do wrong with the nurture and education of children if our domestications wipe out these playful impulses as children transition into adulthood. For, when wondrous, exploratory play is rooted in the emotional centerpiece of a human being and all its physical responses originate from it, then and only then can it deserve the epithet of "complete".

[7] M. Milani – "Animal Behavior, Learning, and Playfulness", retrieved from http://mmilani.com/2883/commentary-200209/ (2009).

MOM: Or divine.

DAD: By stimulating it, the tendency of the animal to exhibit stereotypies, that is, repetitive movements indicative of mental disorders, is avoided and behavior typified by incessantly introduced novelties becomes instigated. For, think of it: our ascent on the evolutionary ladder of life corresponds to leaving behind the rigidly preprogrammed repertoire of responses to environmental stimuli and entering the realms of unexpected and flexibly innovative behavior, bearing resemblance to a jazz tune in which not a single string of notes is repeated twice.

SON: Do we improvise here, Dad?

DAD: We do. We must. Everywhere and at all times we must improvise. It is a vow we have made.

DAUGHTER: Woof, woof! Tap-pat-rap-tap!

SON: Is that the beat science, the way you called it once?

DAD: Science tuned to the swing of the moment it is. So yes, we could call it the beat science.

DAUGHTER: Thump-thump-rump-trump, bash-smash!

DAD: Just as Kerouac was against editing, considering it as analogous to lying and believing that it is wrong to interfere with the streams of consciousness[8] that spontaneously, in an improvisatory manner, emerge to the surface of one's being, so have I made it a rule never to approach a new paper or a presentation in sciences with anything but a blank state of mind to be filled with ideas as they fall in run-on showers from the starry sky.

MOM: Lest you appear a cheater to thyself under this cosmic hat.

SON: "It was a long, long time ago when all we had was a hat full of stars..."[9] (♪♫♪).

DAUGHTER: 'Ake up, li'l bunnies. It's playtime.

DAD: Besides, life is ever-changing and so must an expression perfectly fitting the spirit of the moment be too.

MOM: We must never reproduce and repeat, but always reinvent ourselves and be born anew with every breath under this canopy of stars.

DAD: And yet, it seems that we must continue to search for that perfect expression, or else we risk becoming a sheer imitation of life. Only for as long as we aspire to dig this perfect movement from the bottoms of our hearts and minds can we nurture hopes of transforming into an emanation of life that magically resonates with all things around us.

MOM: Is that what many expressionist and postmodern artists and art critics meant when they said that art exists only in the process of art-making, and that when the piece of art is made, so does the art end?

DAD: Because any expression adjusted perfectly to its zeitgeist is no longer perfect with even the slightest passage of time. Only in the context of its exact time and place is it relevant.

MOM: Also, we should note that Kerouac wrote about being on the road,[10] so his improvisatory style was a natural and honest way of writing about this subject.

DAD: Which brings us to another point: namely, we should always try to be true to the semantic points that we are discussing by making them at as many levels of the logical structure that this paper is becoming as possible.

SON: What do you mean by that, Dad?

DAD: I mean that if we talk about a discovery that was fun to make and that proceeded with no blueprint in mind, then we must create this atmosphere of fun and spontaneity all around us as we compose these lines and carry out this research project.

SON: We must be fun.

MOM: And natural.

SON: Be who we are.

DAD: We must play, for the sake of play only.

SON: Hey, and think of it, one in a thousand, or even a million of blobs like this would have a sweet shape too. Of chocolate it is made.

[8] "Van Morrison: Under Review (1964–1974)", Hal Leonard, Milwaukee, WI (2008).

[9] C. Lauper – "Hat Full of Stars", In: Hat Full of Stars, Epic, Los Angeles, CA (1993).

[10] J. Kerouac – "On the Road", Penguin, New York, NY (1955).

DAD: Well, the story I was going to tell you is the one about sweet serendipity. It is also about the beauty of play and its importance for good science.

MOM: Go on.

DAD: The tale is about one Erasto Bartholomeo Mpemba, a curious 13-old boy supposedly late for the ice-cream making class in a middle school in Magamba, a tropical rainforest village nested in the foothills of the Usambara mountains in northeast Tanzania, about 50 miles west of the Indian Ocean coast. I have always imagined him rushing into the classroom, sweaty, gasping for air, causing an angry look of the stern teacher to land on him. He comes to his desk, looks around at the classmates who were already in the middle of the experiment. He may have asked them what the protocol is and then he hears that the instructions handed over to the class were to mix sugar with milk, add the flavors and heat the mixture to speed up the dissolution process, then cool it down and put it in the freezer when the mixture has sufficiently cooled at room temperature. But Erasto, realizing that there is a limited room in the freezer, which is getting rapidly filled, comes up with the idea to do a little detour and places a very warm ice-cream mixture directly into the freezer, against the instructions. Later he would admit in the opening sentence of his seminal paper that his "discovery (was) due to misusing a refrigerator", for "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".[11]

MOM: A troublemaker he was.

DAD: Like the storyteller, here and now.

SON: And then?

DAD: And then, to his surprise, he noticed that the ice-cream mixture froze faster than the mixtures of his classmates. He wrote down in his notebook this observation and began to wonder how in the world the warm ice-cream mixture could freeze faster than a cold one. It is a very counterintuitive effect, which, we know now, fits the long list of anomalous properties of water, the liquid which makes up the great majority of both our bodies and the surface of the Earth. When he shared his observations with the instructor, however, he was told that he was flat out wrong and that he must have made a mistake somewhere in the experiment. The effect he observed was plainly impossible, in the opinion of his seventh-grade teacher. But his curiosity about this observation did not wind down. Or perhaps it would had it not been for a street ice-cream seller in the seaside town of Tanga he met on a holiday a year later.

DAUGHTER: An ice-cream? Again?

DAD: Yes. Without ice-cream to guide Erasto, I doubt we would be here doing what we do, that is, talking about the strange behavior of water, the liquid of life, over the last bites of chocolate ice-cream on this hot autumn day.

MOM: I have an impression that we would not be talking about this right now either if it wasn't for that heart-shaped drop of chocolate ice-cream on this little suntrap.

DAD: So true.

SON: So what happened in Tanga?

DAD: There Erasto met a young man who, as we learned from his seminal paper, "made twenty shillings profit a day by selling ice-creams only" and who told Erasto that sticking a warm mixture of milk, sugar and fruit juices into the freezer is a trick he regularly employed to make the ice-cream freeze faster. That is when Erasto remembered his own classroom observations from a year ago.

SON: So ice-cream makers can give people key signs on the way to discovery. What if our dropping chocolate ice-cream here has given us signs too?

DAD: What if…

SON: Oh, now I remember this prank kids in very cold climates do under polar vortices.

MOM: What is it about?

SON: Well, basically, they boil water and then toss it over a friend's head. The friend gets scared, but the water actually turns into snow in the air because it is so cold. A real Arctic winter it is there. But the water has to be hot. The trick won't work if the water is cold.

DAD: That is the Mpemba effect at work too.

MOM: All these tricks children know. An inexhaustible source of sapience.

[11] E. B. Mpemba, D. G. Osborne – "Cool?", Physics Education 4 (3) 172–175 (1969).

DAD: But how they convince the adults in their veracity is a whole different story.

MOM: Given how counterintuitive the observation is, Erasto must have faced a lot of disbelieving looks.

DAD: Yes. For, to say that hot water freezes faster than the cold one is like pointing to a longer path and saying that it is faster than a shorter path.

MOM: The two paths, of course, looking equally straight.

DAD: Absolutely. No tricky bends, twists or slippery slopes in one *versus* the other. And to say that the short path is longer than the longer one is as odd as that age-old claim, "Before Abraham was, I am".[12] Proving it true is adequate to opening a whole new dimension of experiential reality. Where magic mixes with science.

MOM: As if science was not magic, the greatest of them all.

SON: Did Erasto's classmates think that he was nuts?

DAD: I am sure that a lot of people he talked to about this may have whispered "cuckoo" with a long and inflicted "oo" in their heads, but things would only get bad in his high school in the town of Iringa in central Tanzania. There, Erasto insisted during a class on Newton's law of cooling that his observation was correct, which irritated the physics teacher so much that he began to call Erasto's views some "Mpemba's physics and not the universal physics", prompting salvos of laughter by the class whenever this reference would be made. And it was made often, as the story goes. Soon after, the epithet of "Mpemba's" began to be used by his classmates to describe things that are abnormal, sloppily set or plainly wrong, in or out of classroom. Mocking continued for years and the poor boy was sidelined by his teachers and peers because of his insisting that an abnormal effect was real.

MOM: "A king's lot: to do good and be damned".[13]

DAD: Exactly. "If it had not been laughed at, it would not be the Way", Lao-Tzu said once.[14] The nature of the most beautiful signs in life is really such that the imprudent minds see in them sources of ridicule and gird. The crude seem to see in the sublime more crudeness than in the crude itself. Quite unlike the enlightened.

DAUGHTER: Whitened?

SON: Like snow?

DAD: No, no, en…light…ened. Which is not to say that all colors and perspectives at life have not been concocted into one inside their all-embracing hearts. They recognize in these sublime expressions the sources of new beginnings, of adventures that open up paths to treasures of an unthinkable significance.

MOM: And they worry not about language, about the correctness of grammar, syntax or typography. Never bite the finger, always look where the finger has pointed at.

DAD: And so the name for this curious effect was born at that very moment, despite anyone in that infamous class being aware of it.

MOM: They were too busy derogating and denigrating.

DAD: Perhaps we would not know today about this effect by Erasto's name had the boy not been intrigued by the anomalousness of his observation to such an extent that he went on asking one teacher after another about it. He refused to accept their request to comply with their commonsense thinking, and his obsession with this phenomenon did not wind down. The determination to delve deeper into its secrets made him sneak first into a high school lab when no one was around and then to the school kitchen to repeat the experiment with pure water, receiving the same result each time: the hot water, over and over again, would freeze before the cold one.

MOM: Was that the end to his struggles?

DAD: Not really because most of those intrigued by the matter continued to believe that he must have made a blunder somewhere in the experiment. This included his classmates, but also many of the professors he shared his observations with. For a few years he sought an academic advisor who would support a more elaborate study, which would either prove or disprove his observations, but, alas, one such man or woman was nowhere to be found.

SON: Should not Erasto have given up by then?

[12] "Holy Bible", John 8:58, King James Version (1611).

[13] M. Aurelius – "Meditations", Penguin, London, UK (167), pp. 89.

[14] Lao-Tzu – "Tao-Te-Xing, Song 41", In: V. Uskoković – "Tao-Te-Xing: The Book for All Ages", Amazon Kindle Direct, Scotts Valley, CA (2011).

DAD: Had he given up, we would not be here telling this story. His relentless, hardheaded search, in fact, after years of failure after failure, opened up the way. It happened on a day when Erasto dropped by the high school auditorium where the guest lecture of certain Denis Osborne was to take place. He peeked at the podium and the audience and decided to take a seat, shyly. At that time, Denis was affiliated with the University of Dar es Salaam and he came to Erasto's school to give a talk about the national strategies for the scientific development of Tanzania. Erasto attended the talk and his question during the Q&A session after it was very much out of place: why does hot water freeze faster than the cold one. It was the least appropriate, but also the most appropriate time to ask this question. Everything else is history.

MOM: So the talk was not on the properties of water?

DAD: It wasn't. In fact, the talk Denis gave was on "the importance of science and science teaching for country's development" and there was an hour-long series of "questions of personal concern about entering the university" and "questions about the remote possibility of relating parts of the school syllabus to national development"[11]. And then Erasto asked his question.

MOM: It was really out of place.

DAD: Out of context too. And that was when the mocking entered its climax. Many classmates felt that Erasto ashamed them with his alleged stupidity and, even worse, risked their chances of getting into the university. Sardonicism went out of hand and anger, thereafter, was born in young Erasto's heart.

SON: "Let fury have the hour, anger can be power"[15] (♪♫♪).

DAD: And it was. For, it open the door that might have been locked for good to a more timid and less resolute spirit. Denis agreed to ask his lab technicians to repeat Mpemba's experiment under more controlled conditions and so they did. Although he later disparaged their "unscientific enthusiasm" for initially disbelieving Erasto's observations, they did prove that he was right. Hot water froze faster than the cold. Hence, although Erasto never got the chance nor diligence to repeat his rudimentary experiments in a rigorously controlled, scientific manner, Denis and him eventually published their findings in 1969, in a physics education journal[11]. They titled the rather unusually structured paper very simply: *Cool?*

SON: Cool.

DAD: No, no, cool with the question mark.

SON: Ah, does it even make a difference?

DAD: It does. Only questions can keep the wheel of progress - intellectual, practical, spiritual, you name it – spinning. The more we know, the greater the temptation to put a full stop on our epistemic voyages, but when we do so, we close the door to this greatest adventure in our lives that science is.

MOM: And with being it is the same.

DAD: Nonbeing too, its obscurer flipside, lest Parmenides object.

MOM: Everywhere and at all times, questions have been the drivers of progressive thought and premature answers have locked it inside the shackles of stifling dogmas and codes.

DAD: Was it Rilke who advised young poets not to find solace in tenets of any sort, but to live out the questions that tear their beings apart because only thereby could they evolve into their answers? Godard was even more cryptic when he coined – or rephrased - the Heideggerian definition of philosophy as "a being, the heart of it being the question of its being insofar as this being posits a being other than itself".[16]

SON: And what does all this have to do with Mpemba?

DAD: Well, nothing, but also everything. For example, Erasto was determined to live with the questions revolving around the strange effect he experimentally observed. Had he been more inclined to settle for cheap answers and accept what the paradigm says, he might have convinced himself that the observation is erroneous or irrelevant and gone along with his teacher's call to conform to the common sense. But in reality, a deviation from our expectations is the starting point of discovery. Here I could argue that it is also the basis of perception[17] and

[15] The Clash – "Clampdown", In: London Calling, CBS, London, UK (1979).

[16] J.-L .Godard - "Goodbye to Language", Wild Bunch/Canal+/CNC, Paris (2012).

[17] V. Uskoković – "Co-Creation of Experiential Qualities", Pragmatics & Cognition 19 (3) 562–589 (2011).

learning, but since this would imply the switching of the topic of our discussion to doves[18] and take us beyond the limits of this sky, we should leave it for another occasion. It's just that this is the point at which most people subconsciously turn a blind eye on things and pretend that the divergence of the experience from the expectation is an illusion. Usually, it takes a social and intellectual outlier – an outlaw, so to speak - to start one's inquiry from outliers in one's experiments rather than from the data points that yield safe trends that conform to the expectations. This is what Mpemba meant when he said that his discovery was due to "misusing a refrigerator" in the first sentence of *Cool?*. A troublemaking error as the starting point of a colossal discovery.

MOM: Many people in life, sooner or later, on the other hand, like J. J. Gittes in Polanski's Chinatown, learn that it is "better not to act, better not to know".[19] Remember, he tried to expose the corruption behind events surrounding the building of Mulholland's aqueduct and the ensuing California water wars and the collapse of St. Francis Dam, one of the biggest civil engineering failures in American history. Silenced voices notwithstanding, thanks to these projects of a disputably ethical socioeconomic character, we do have the water running up and down these hoses and sprinklers. Thanks to them, we are here.

DAD: Ah, Mulholland Drive, that dark road that, as Lynch had it, epitomizes what the city of angels, ironically, has been mostly about. Culturally, it is not even a slightest bit about the lights and the sunshine. A world best seen from the darkness and from afar it is, as Polanski, himself, said once.

MOM: Water, the resource that is still a human right, but for how long before it becomes a privilege.

DAD: Like once science understands that there is not water, as it is commonly thought today, but that there are waters.

SON: A water good to drink and sprinkle the flowers with and a water not so good for these things.

MOM: Water in biology, for example, is very much different from the water we drink.

DAD: Very true. In the cytoplasm and in the extracellular space, water is mostly bound to the interface. As such, it behaves as a completely different liquid, almost semi-crystalline in some aspects, compared to the bulk liquid.[20,21] In fact, a number of different physical properties of water, including viscosity, diffusivity and polarity, change as a function of the droplet size.[22] For example, the proton conductivity of water confined to nanoscopic channels was six orders of magnitude higher than that of the bulk water,[23] and the biological implications relating to the intrinsic intelligence of the biological matter may be largely due to these exceptional properties of interfacial water. It is a medium on which biomolecules surf as they traverse the cell cytoplasm and the extracellular space and come into contact with each other. Logically, because it is more structured at the interface, such water acts as an excellent "information" carrier, unlike its bulk analogue. Water molecules tightly bound to protein molecules are also now known to be so crucial for their structural stabilization that they are routinely being depicted as integral components of their structure and treated as a single thermodynamic entity with a unique energy landscape.[24] Also, thanks to directional hydrogen bonding, liquid water under all condition forms clusters that are in a dynamic, dissipative-formative equilibrium with single water molecules and adjacent clusters of different geometries. However, because of the ultralow timescale of changes in these equilibria and the complexity of species involved in it, they are nearly impossible to probe and pinpoint experimentally.

MOM: But when we do succeed in this with the advent of ultralow timescale measurement techniques, the broader, practical repercussions of this knowledge will be immense.

DAD: The scope of these effects is difficult to outline with certainty, but this might help us gain a better con-

[18] V. Uskoković – "On the Light Doves and Learning on Mistakes", Axiomathes: An International Journal in Ontology and Cognitive Systems 19, 17–50 (2009).

[19] T. Andersen - "Los Angeles Plays Itself", Thom Andersen Productions, Los Angeles, CA (2004).

[20] V. M. Gunko, V. V. Turov, V. M. Bogatyrev, V. I. Zarko, R. Leboda, E. V. Goncharuk, A. A. Novza, A. V. Turov, A. A. Chuiko – "Unusual Properties of Water at Hydrophilic/Hydrophobic Interfaces", Advances in Colloid and Interface Science 118, 125–172 (2005).

[21] E. A. Vogler – "Structure and Reactivity of Water at Biomaterial Surfaces", Advances in Colloid and Interface Science 74, 69 – 117 (1998).

[22] V. Crupi, S. Interdonato, F. Longo, D. Majolino, P. Migliardo, V. Venuti – "A New Insight in the Hydrogen Bonding Structures of Nanoconfined Water: A Raman Study", Journal of Raman Spectroscopy 39 (2) 244–249 (2007).

[23] I. A. Ryzhkin, M. I. Ryzhkin, A. M. Kashin, E. A. Galitskaya, V. V. Sinitsyn. High proton conductivity state of water in nanoporous materials. EPL 126, 36003 (2019).

[24] A. R. Bizzarri, S. Cannistraro – "Molecular Dynamics in Water at the Protein-Solvent Interface", Journal of Physical Chemistry B 106 (26) 6617–6633 (2002).

trol of surface processes in aqueous media, which are highly dependent on wetting. This, in turn, may lead to new materials and attractive applications. On the more popular end of things, we may be able to differentiate water that is very good for consumption from the one that is less good for it. It is likely that some new water wars along the divides between the rich and the poor will be waged in the wake of these findings.

MOM: But on the scientific ends of things, we may be able to control a range of chemical processes to a finer degree than we are able today.

DAD: Yes. According to the principle of co-assembly, every physicochemical reaction can be perceived from two angles, one of which is defined by the movement of the reactants and the other one of which is defined by the movement of the medium.[25] Which of them is the prime driver of these processes is often impossible to discern. For example, when an atomic growth unit diffuses across the surface of a growing crystal, does it push out of the way the molecules of the solvent adhering to it or the solvent molecules make way for the growth unit? If we consider that the dehydration of one such growing surface is a more energetic step than the surface anchorage or diffusion, we could refute the common thinking that presumes the irrelevancy and passivity of the medium and realize that it must play a key role in defining the crystal growth process. Countless other examples could be given.

SON: So if we understand water better, we would understand chemistry better too.

DAD: Undoubtedly.

MOM: Then I wonder why water has not been explored more than it has. Could we do something about it? Should we center one of our backyard studies around it?

DAD: I have always had it in mind, but running studies on pure water is dangerous for a career in materials science and here I must apologize to the firmaments for using this word, career, which denotes all things that science and creative efforts *per se*, in any walk of life, should not be about, notwithstanding that they indisputably are in today's increasingly entrepreneurial world of science.

[25] V. Uskoković – "Isn't Self-Assembly a Misnomer? Multi-Disciplinary Arguments in Favor of Co-Assembly", Advances in Colloid and Interface Science 141 (1-2) 37–47 (2008).

MOM: Why is that so? Why do materials scientists devalue simplicity?

DAD: Because there is this implicit premise that science must be complex to be meaningful and to be viewed highly by the peers. Imagine, for example, a Janus polymeric sphere encapsulating a magnetic nanoparticle, a quantum dot, a nucleotide code, then functionalized with antibody-targeting ligands and accommodated inside a carbon nanotube. Put it side by side with water or good old bone mineral and virtually everyone in the materials science community would choose it for their subject of research.

MOM: But then no one wants to study the simplest grounds of them all. And if we don't understand them…

SON: …we won't be able to understanding the complex things either.

DAD: Exactly.

SON: So shall we do it?

DAD: Do what?

SON: Experiment and understand the Mpemba effect?

DAD: Now may be the time. When we ran an affluent lab, this would have been akin to cutting the branch on which the nest was seated to make wood for the nest to build, but now that the lab has been reduced to this backyard and the garage and we are jobless and broke and poorer than ever, it may be the right time. Poor materials must be in the hands of poor people if important discoveries on them are to be made.

MOM: Mpemba was poor too.

DAD: No doubt about that. Like us now, he did not have an accessible lab to test his observation either, but moved like a nomad from the lab he intruded when no one was around to the kitchen and back to run his experiments. We will similarly do our experiments in the kitchen and the backyard. Though we might also break into some of the labs on campus, if the need for experiments badly be.

SON: "The world is full of refugees, just like you and just like me"[26] (♪♫♪).

[26] Manic Street Preachers – "The Everlasting", In: This is My Truth Tell Me Yours, Epic, Los Angeles, CA (1998).

DAUGHTER: Excuse me.

DAD: And if *Cool?* was released in 1969, it means that now, in 2019, we could celebrate the 50th anniversary of this seminal paper. One more reason to run the study, well, now, under these Indian summer skies.

MOM: It was also the year when the man landed on the Moon.

DAUGHTER: 'Scuse me, I'm superman.

SON: "Well it's 1969, okay, war across the USA"[27] (♪♫♪).

DAD: 'twas also the year when this country fell asleep.

MOM: Yet to be woken up from that sleep of the just.

DAUGHTER: We ran out of gas, we ran out of gas!

SON: The nearest gas station is in space. We must go there and then rewind.

DAD: Would it restore all the soul it has lost by being unconscious on so many planes, from the cultural to the moral to the aesthetic, we know not, but what we try to do here contributes to its waking up and becoming the embodiment of creativity and freedom that it once stood for.

MOM: Perhaps it will undergo a phase transition, like the one that is at the spotlight of this dialogue.

DAD: And we become a part of the nucleus of this new phase.

MOM: A new dawn.

SON: "A change of speed, a change of style"[28] (♪♫♪).

DAD: And how magically instructive it is that we, in hope of becoming one such nucleus, should not shy from departing farther than anyone from this transition point. Because, in the end, we may still be the first to crystallize.

MOM: A total madness it is.

DAD: Anyway, we must move from hot to cold and be lukewarm for as short of a time as possible if our goal is to depart to heavenlier station than this one. At least so the holy books instruct us.[29]

SON: "Belladonna, belladonna, burn me out or bring me home"[30] (♪♫♪).

DAD: And if Mpemba had it right, then even Nature herself, judging from the inclination of water, does not like to spend much time in lukewarm conditions.

MOM: And there is no reason now to suspect that Mpemba had it wrong.

SON: In fact, here is the proof.

DAD: Yes. While this discussion was ongoing, Theo and I ran a couple of experiments in the kitchen by placing side by side pairs of test tubes or silicone vessels filled with equal volumes of distilled/deionized (DI) water in the freezer. One set of water samples was preheated to 80–90 °C before cooled down to 60–80 °C and then put into the freezer, and another set was placed in the freezer while still at room temperature. We measured the temperature in parallel and here are the results (Fig. 1-2). We got a couple of interesting findings.

SON: First of all, based on the plots presented here, it seems that Mpemba was correct.

DAD: However, the path to reaching this insight was no golly doll's cakewalk.

DAUGHTER: Why?

DAD: Well, our first sets of data showed no significant difference between the freezing rate of hot and cold water. However, these experiments were carried out in elongated test tubes and 10 ml of water volume. One way of explaining the lack of difference in the freezing rate is the relatively low surface exposed to air. Namely, the phase transition here, as it is often the case, proceeds from the surface and into the bulk, surface here meaning the interface between water and air. Additionally, ice tends to cream rather than precipitate.

DAUGHTER: Cream? Yum.

DAD: Cream here is just a correct colloidal term to describe segregation of the solid phase at the top, not the

[27] The Stooges – "1969", In: The Stooges, Elektra, New York, NY (1969).
[28] Joy Division – "New Dawn Fades", In: Unknown Pleasures, Factory, Manchester, UK (1979).
[29] "Holy Bible", Revelation 3:16, King James Version (1611).
[30] The Stone Roses – "This is the One", In: The Stone Roses, Silvertone, Manchester, UK (1989).

bottom of the liquid, in which case we would talk about a precipitate. Anyway, under those conditions, when this interface with the gaseous phase was very small in surface area, the temperature of water is no longer the major limiting factor defining the timescale of the transition. The same occurs when the volume of the liquid is relatively small, even when the liquid is spread well and the contact area with the air is large. But when both of these conditions are satisfied, that is, when neither the volume nor the contact area with air are too small, the effect of the initial temperature could be observed. We settled at 30 ml of DI water poured in silicone cupcake liners with round bottoms measuring 45 mm in diameter of the base. Under those conditions, the effect is clearly observable (Fig. 2). Even then, though, it is most intense for the DI water (Fig. 2a) and it gradually gets diminished as the salinity of water increases (Fig. 2b-d). Note that the salinity of the seawater we sampled from the Pacific coast is around 37 mg/ml, as opposed to only around 0.3 mg/ml for our tap water and nil for the DI one.

SON: And we developed a possibly new method for measuring the freezing rate too.

DAD: Necessity, that is, want, that is, hardship is the source of invention. Here we really could not afford leaving the thermocouple in solidifying water and so we found a way to go around this apparent obstacle. We measured the amount of the solid phase at different time points by gently breaking the surface ice and pipetting out the liquid, before normalizing the volume of the remaining ice to the total volume of water in the vessel and expressing it in percentages. These data invariably show that water freezes faster when it is preheated, but with a large effect of salinity. Specifically, while the Mpemba effect is obvious for the DI water (Fig. 2a) and hardly discernible for the tap water (Fig. 2b), it does not exist for the seawater, in which case the initially cold water freezes significantly faster than the preheated one (Fig. 2c).

SON: We also tried different heating regimens. We used heating in the microwave oven and also heating on a convection plate, but no difference was observed.

DAD: We thought that the heating method may affect the collective energy states and distribution of water cluster symmetries and thereby the solidification process too, but this did not happen to be the case.

MOM: Though from what we see here, cold water reaches the freezing point before the hot water does. As per the results shown in Fig.1b, the time it takes for water to reach 0 °C is linearly dependent on its temperature upon entering the freezer.

DAD: It is correct and it dispels the idea that hot water freezes faster because of the faster cooling. Many literature reports erroneously claims this to be at the heart of Mpemba effect, but it is now. Preheated water freezes faster because it is structured differently than the water that started off as cold. Cold water took some time to start forming crystals of ice after it reached 0 °C.

SON: How boring. We just had to wait, without anything changing.

DAD: As a matter of fact, this nucleation period is one of the liveliest and most fascinating phenomena in the whole of physics, even though nothing is seen by the naked eye, nor by our probes. The archetypal analogy of the phase transition *per se* aside, this is a period when crystals are born. As their unstable embryos form from the water clusters and swiftly dissipate, a very small percentage of them will become nuclei that stably grow to crystalline (or amorphous) particles.[31] And it takes time for this process to occur. But this is not to say that this period is "dead";[32] it is, in fact, far livelier and more physically versatile than the cooling phase that preceded it.

MOM: And this nucleation period was, it seems, longer in water that started off as cold than in the one that was preheated.

DAD: Exactly. It appears that the initially warm water did not waste much time when it hit the freezing point to form ice. It already knew what configurations were energetically favorable and pursued them, without having to go through the lengthy process of search that I just explained. It is almost as if it still had a fresh memory of how water clusters should organize and crystallize.

SON: As our temperature measurements show, water that was initially warm began to freeze at temperatures higher than 0 °C.

DAD: It is correct. The temperatures measured in the liquid phase were around 2 °C when relatively large masses

[31] V. Uskoković – "Revisiting the Fundamentals in the Design and Control of Nanoparticulate Colloids in the Frame of Soft Chemistry", Review Journal of Chemistry 3 (4) 271–303 (2013).

[32] V. Uskoković – "Visualizing Different Crystalline States during the Infrared Imaging of Calcium Phosphates", Vibrational Spectroscopy 107, 103045 (2020).

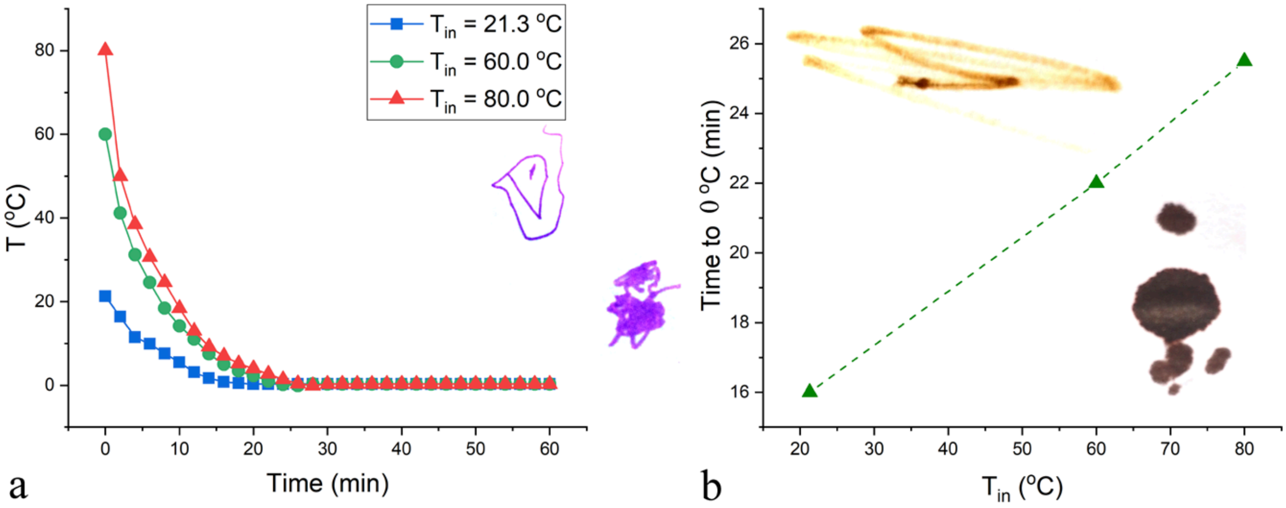

Figure 1. Temperature change over time for DI water with different starting temperatures, including 25 and 60 and 80 °C, when incubated at -18 °C (a). Time it takes for the liquid phase to reach 0 °C depending on the initial temperature of DI water incubated at -18 °C (b).

of ice were seen forming. That is why by the time point at which the freezing point is hit (Fig. 1b), finite amounts of ice were already present in the preheated samples (Fig. 2a). This, it should be noted, does not speak about the formation of ice at temperatures exceeding the freezing point. Rather, it speaks about the inhomogeneity in the distribution of the heat content throughout the water samples that started off as warm. Intense convection streams and temperature gradients on the microscale allow this peculiar phenomenon to happen.

MOM: So there is a lesser degree of supercooling occurring in water when it is preheated?

DAD: Yes. The unheated water exhibited the typical drop in temperature down to below 0 °C, followed by the increase to 0 °C when the crystal formation began.[33] According to the classical model of crystallization, the temperature of water and ice during the freezing reaction stays at 0 °C until the last pocket of the liquid phase transitions to ice. Only at this point does the temperature of the system begin to drop and equilibrate to the temperature inside the freezer. But this is not what was observed for the preheated sample, in which case the degree of supercooling was much lesser and the liquid began to form ice even before it made a touchdown at the freezing point. Some pockets in the liquid afterwards did exhibit supercooling, but this early formation of ice facilitated the crystallization process even for these water molecules that had to undergo supercooling to solidify. Again, it is as if the system brought with itself from the higher temperature range something that helped it crystallize. The identity of this mysterious "something" we will try to unravel.

SON: You mentioned that these kinetic data in Fig. 3 corroborate these points.

DAD: It is correct. They represent the crystallization kinetics using the Johnson-Mehl-Avrami-Kolmogorov model and show that the fit is better for the crystallization of water that started off as cold than for the crystallization of water that started off as warm, that is, $r^2 = 0.993$ *versus* $r^2 = 0.944$, respectively (Fig. 3a). This is a testimony to the more spatially variable crystallization in the preheated water, being presumably the result of more erratic convection currents and greater temperature gradients in it than in the cold water. This is the primary insight we could derive from this kinetic modeling. The secondary insight would refer to the absolute values of the Avrami exponent, n, and the kinetic rate constant, k, derivable from the model for the two types of water. They suggest that preheating makes nucleation more distant from $n = 3$ and the ideal 3D growth of heterogeneously preformed nuclei, implying a greater contribution of interfacial and, essentially, kinetic effects in the preheated water, which is in agreement with its faster rate of crystallization inferable from the absolute values of the kinetic constants (Table 1). As the salinity of water increases, this influence of the surface effects

[33] B. M. Adhikari, V. P. Tung, T. Truong, N. Bansal, B. Bhandari. Water crystallization of model sugar solutions with nanobubbles produced from dissolved carbon dioxide. Food Biophysics 14, 403–414 (2019).

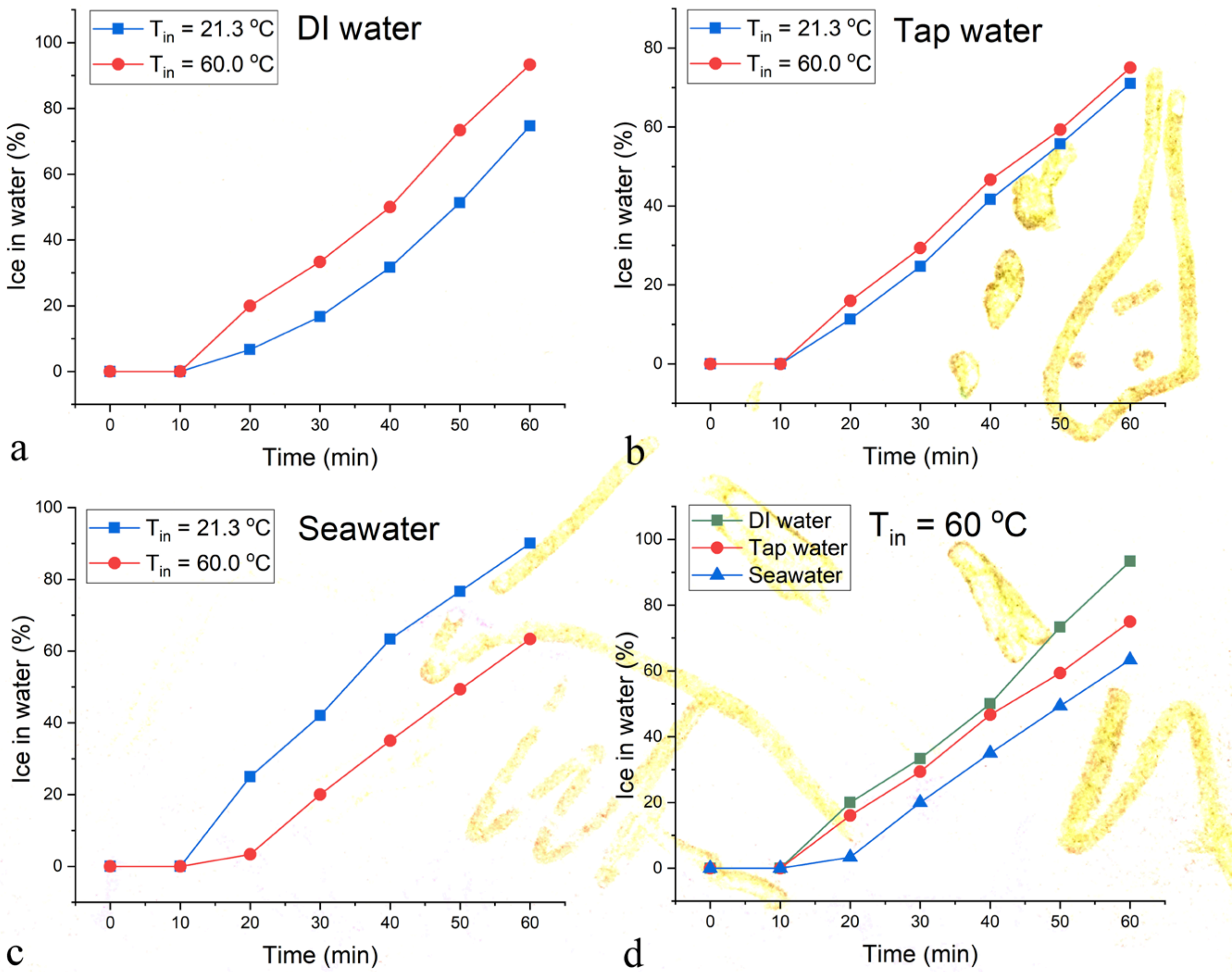

Figure 2. Percentage of the total volume of ice in the 30 ml water samples as a function of the time of incubation at -18 °C for different starting temperatures, including 25 and 60 °C, for DI water (a), tap water (b) and seawater (c), along with the comparison between the percentage of the solid phase for the three different waters starting at 60 °C as a function of time (d).

becomes more prominent, as it can be inferred from the reduction of the Avrami exponent, n, in direct proportion with the water salinity (Fig. 3b).

MOM: At the same time, the kinetic constant, k, increases with salinity.

DAD: Yes, but only for water starting off as cold (Fig. 3b). Preheated water apparently does not keep up with the steadiness of this increase and, hence, the rate of crystallization of the initially cold water becomes higher than that of its preheated counterpart beyond a certain salt concentration.

MOM: What were the other interesting observations?

SON: Well, for example, the top layer of ice forming on the initially cold water was way smoother.

DAD: It was more even and covered the entire surface of the liquid by the 20th minute. This agrees with this higher concentration of convection streams and temperature gradients in the warm water, which prevents the formation of very even crystals. Rather, the solid phase appears to be more polycrystalline and randomly distributed throughout the whole volume of the liquid compared to that forming an even cap over the surface of water that entered the freezer as cold.

MOM: Could this be an effect favoring faster crystallization of the initially warm water, given that an ice cap

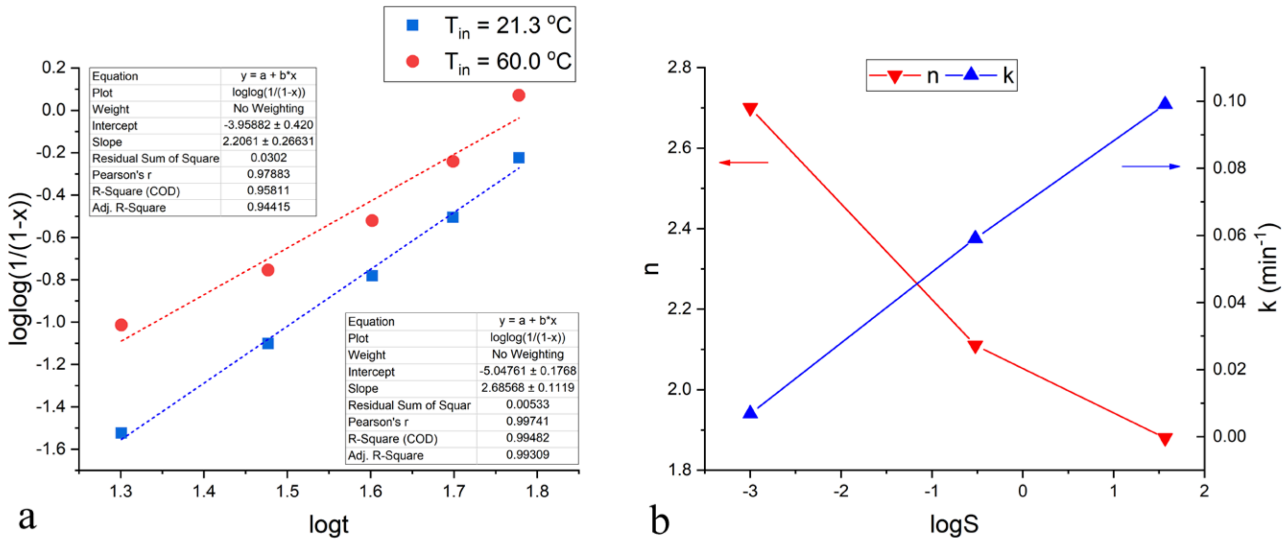

Figure 3. Linear fits of kinetic data for the crystallization of DI water depending on the initial temperature of its exposure to the at -18 °C environment using the Johnson-Mehl-Avrami-Kolmogorov method (a). Dependence of the Avrami exponent, *n*, and the kinetic constant, *k*, on the salt concentration in water for the water samples introduced to the -18 °C environment with the initial temperature of 21.3 °C (b). The salinity of DI water was arbitrarily set to 0.001 mg/ml so that it can fit the logarithmic graph.

uniformly covering the surface of the liquid would act as a thermally protective layer?

DAD: It is likely that this is a contributing factor to the Mpemba effect, but it cannot be the major, let alone the sole one. Our temperature measurements showing that preheated water begins to crystallize sooner than the cool water, at the time points when no ice cap has formed, speak in favor of more internal, bulk factors that are independent of effects involving thermal conduction at the surface.

SON: Also, we would break the ice cap every time we took the temperature measurements…

DAD: …so these surface effects are likely to be marginal at best.

SON: There is also the question of how high the temperature of warm water has to be for the Mpemba effect to take place.

DAD: It appears that heating to 60 °C and then putting the water into the freezer is not enough to produce a difference. Rather, heating to 80–90 °C is needed before the water is slightly cooled to 60 °C and put into the freezer. This is in agreement with Mpemba's original observation, given that the story goes that he brought his water and ice-cream mixtures to boil before putting them into the freezer.

MOM: Another counterintuitive detail.

DAD: And a very important one. Whatever water brings with itself from this high temperature down to the freezing point is more abundant at these higher temperatures. It could simply be a specific cluster symmetry that resembles ice and that does not get relaxed fully by the time water reaches the freezing point, at which point it facilitates the crystallization process by shortening the time needed for diffusive water molecules to stochastically recognize the right configurations and organize into long-range symmetries that we call ice.

MOM: Atop all of this, somebody decorated these graphs, I see, with a heart-shaped kite and other fancy curves.

DAUGHTER: Hearts, hearts!

Table 1. Kinetic parameters derived from the fit with the Johnson-Mehl-Avrami-Kolmogorov model, including the Avrami exponent, *n*, the Avrami rate constant, *k*, and Pearson's adjusted correlation coefficient, r^2, for DI water with different initial temperatures, T_{in}.

T_{in} (°C)	n	k (min^{-1})	r^2
21.3	2.7	0.0069	0.993
60.0	2.2	0.0105	0.944

MOM: And chocolate smears in Fig. 1b. And orange smudges in Fig. 2.

DAD: "The caravan continues on its way, the gypsies do not stop",[34] Jean Cocteau said to shrug off the criticism over the accidentally shaky images in the final scenes of *Les Parents terribles*, the film he regarded as his greatest technical accomplishment.[35]

MOM: We should also never underestimate the subliminal message of technical imperfections. It is the assertion of love for the amateur, for the child in us, ignorant of the strivings for perfection and immune to the sterility that perfectionist strivings in the world create.

DAD: Also, when is the time for abstract art to be painted if not now? When realism knocks on the door, this sweet idealism, abstract and arcane, will fly out the window. And only come quietly, once in a while, through the rain gutters and chimneys.

MOM: *Summa summarum*, warm water freezes before the ambient one when they are cooled under the same conditions.

SON: How cool is that?

MOM: Very cool. Both literally and metaphorically.

DAD: Now that we have verified this anomalous effect experimentally, it may be time to recall that it has been known for much longer than Mpemba's times.

SON: Wait, does it mean that Mpemba wasn't the one who discovered this strange effect?

DAD: Not really. The ancient Greeks, as it can be judged from Aristotle's writings on aerology, knew about this effect.[36] The Greek philosopher in his writings made a casual reference to people's habit of leaving water in the sun when they wanted it to freeze quickly. As far as the holey records of history tell us, the medieval Italian physicist, philosopher and astrologist, Giovanni Marliani became the first to empirically prove that hot water freezes faster than the cold one. His records state that he placed two containers, each holding 100 ml of water, one regular and one boiled, outside, on a cold winter day of 1461, somewhere near Milan. The effect was later discussed by Francis Bacon[37] and Descartes[38] and also closely hinted at by Joseph Black in 1775.[39] However, the tale about Mpemba holds a legendary status in the physical chemistry community because of this fascinating story surrounding it. As a result, this curious effect is colloquially tied to its origin in a classroom in Africa, even though it had been known long before then. It, of course, is a true tale, instructive to young scientists from a plethora of angles.

SON: Like what?

DAD: For one, it teaches us that obedience to petty rules, such as punctuality, is usually a hindrance to a creative mind. It also instructs us about the dangers of unquestionably conforming to the authority. Further, it shows us that fundamental discoveries lurk in the most trivial of experiments, which are among the cheapest to run, and in the least sophisticated of samples, which, likewise, we need not spend even a dime to procure.

SON: So they say that the best things in life are the cheapest too.

MOM: And because an infinitely beautiful object or experience would be infinitely cheap too, no price tags can be put on them. They are free. To take, turn, twist, and toss. Like us.

DAD: Another very instructive thing about the Mpemba effect is that it exemplifies an effect that is extraordinarily difficult to explain despite its equally extraordinary simplicity. Even when the empirical focus is reduced down to pure solvent, water, that most basic of all liquids, its properties continue to elude any attempts to capture them inside a tight and secure web of scientific theories and other conceptualizations.

MOM: Water is such an anomalous liquid.

DAD: Utterly anomalous. Here is what Kurt said about it: "Water is the exception to almost every rule and its interactions with other forms of matter are extremely complex. If it were not of such paramount importance to our world and life itself, we might never study water and

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[34] J. Marais. Histoires de ma vie, Albin Michel, Paris, France (1975), pp. 308.

[35] J. Cocteau, Entretiens sur le cinématographe: édition établie par André Bernard et Claude Gauteur, Belfond, Paris, France (1973), pp. 55.

[36] Aristotle – "Meteorologica" (350 BC), Translated by E. W. Webster, Clarendon Press, Oxford, UK.

[37] F. Bacon – "The New Organon" (1620), Lib. II, L, Cambridge University Press, Cambridge, MA.

[38] R. Descartes – "Les Météores" (1637), Fayard, Paris, France.

[39] J. Black – "The supposed effect of boiling upon water, in disposing it to freeze more readily, ascertained by experiments", Phil. Trans. 65, 124–128 (1775).

simply write it off as pathological".[40] All my life I have spent in wonder whether it is because water is so strange that life built itself around it. Is this a sign in favor of quirkiness as the starting point of discovery in science and creative achievements in all other avenues of life, just like in the one that marks the story we discuss here?

MOM: And the one that will be ascribed to this piece too.

DAD: Undoubtedly. Strange we are to the point of strangeness, even to ourselves. Maybe that predisposes us to penetrate deep into the secrets of water. Just as we do not belong to the academic categories where most people fit just fine, so does water not fit the family to which most liquids with their more predictable properties belong.

SON: Is water alone in this "pathological" strangeness?

DAD: No. This strangeness is paralleled by hydroxyapatite, the major component of our bones and teeth and the most abundant inorganic compound in our bodies beside water.

MOM: It makes sense that hydroxyapatite is an inorganic material, but is water too?

DAD: It contains no carbon, so yes, it is classifiable as an inorganic substance. In fact, I could not think of any inorganic molecules that are parts of our bodies other than water and hydroxyapatite.

MOM: Maybe that tiny amount of calcium carbonate forming the otoconia of our inner ears[41] and being embedded in our pineal glands?[42]

DAD: Calcite is inorganic, but note that it does contain carbon. Just like calcium oxalate, one of those inorganic materials that occasionally pop up in our bodies, but can be written off as strictly pathological. Hydroxyapatite does contain carbon in the form of carbonate ions, but they comprise impurities rather than constitutive ions in it. And so we are left with hydroxyapatite and water as the two inorganic materials in our bodies without which life would not be possible.

MOM: Just think of their abundance. Sixty weight percent or so of our bodies is water.

DAD: Meanwhile, bones comprise roughly 15 wt.%. And with hydroxyapatite occupying about 70 % of the composition of bone and teeth by weight, the amount of it in our bodies can be estimated at around 10 wt.%.

SON: They may indeed be like a brother and a sister. Like us here now.

DAD: Once I did crown water as the princess of peculiarities and hydroxyapatite as the prince, but the editor of a Royal Society of Chemistry journal where the paper was accepted for publication deemed the terminology inappropriate and insisted that these epithets be changed into something blander. Eventually, I used the words "epitome" and "paradigm" and, saddened, left princes and princesses behind.

MOM: Only temporarily.

DAD: Well, now we can use those terms and say them out loudly. These yucca pincushions and hooded orioles will be fond of them, I reckon.

SON: And hydroxyapatite and water, do they marry by the end of this fairytale?

DAD: They might. But I always fancied to see their relationship as akin to that between Michael Fury and Gretta Conroy.[43] Because hydroxyapatite gets burned by the fire of life and its passions, while water solemnly traverses that vertical road from the rivers and oceans to our veins to clouds and back, without changing its chemical state as much. However, it will be years before the Dubliners will be on the list of your reading assignments at school.

MOM: And Ulysses, when will it be?

DAD: The sooner the better, to unwind the rigid ties to language, that silent killer of creativity, and unleash the ways of being unthinkable to us now. Just think how strange and beautiful they will be in all their bedazzling anarchy when they first appear before us.

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[40] K. W. Kolasinski. Surface Science: Foundations of Nanoscience and Catalysis, 3rd Edition, Wiley, New York, NY (2012), pp. 230.
[41] L. E. Walther, A. Blodow, M. B. Bloching, J. Buder, W. Carrillo-Cabrera, E. Roseeva, H. Borrmann, P. Simon, R. Kniep. The Inner Structure of Human Otoconia. Otology & Neurotology 35, 686–694 (2014).
[42] S. Baconnier, S. B. Lang, M. Polomska, B. Holczer, G. Berkovic, G. Meshulam. Calcite microcrystals in the pineal gland of the human brain: First physical and chemical studies. Bioelectromagnetics 23, 488–495 (2002).
[43] J. Joyce – "The Dead", In: Dubliners, Penguin, London, UK (1914).

MOM: Even if our speech becomes akin to Molly Bloom's soliloquy or lines from Godard's *Film Socialisme*?

SON: "The beach ball's set to fly, the starfish butterfly, the coffee clash career, she talks to strangers"[44] (♪♫♪).

DAD: In a crowded kingdom on warm summer nights, a little princess with lazuline looks gliding down magnolia moonbeams past yellowy roses and potpourris of cosmic grief grown in ginormous vases on balconies adorned with slumbering peahens and withering chrysanthemums and the bells that toll for thee, they all fly by me.

SON: Breese moves islands f snlight the waves go out come in again remember: your present is you.[45]

DAUGHTER: Goo-goo gaga, choo-choo da-choo!

DAD: Chirp-chirp-cheap, pipery-peep, in the darkness of the deep.

DAUGHTER: Cheeky little Dada.

SON: Dad, you're so strange.

DAD: Not as strange as water though. Just think if the same percentage that water occupies in our bodies - 60 % or so - could be made, in our mental spheres and our behavior alike, just like water: strange, unpredictable, transparent, cohesive, but also capable of reacting with anything in one way or the other. A universal solvent as it is, water is reactive, but also different from any chemical under the sun, displaying a curious combination of philicity and phobicity that would make its human epitomizers tiptoe around the thin line between sympathy and antipathy, one moment being lauded and another moment being dissed. Hence, were to really be like water, it is not clear whether our life-bearing propensities would be recognized or we would end up being harassed and pilloried, like that holy traveler that this blue planet pays homage to day in, day out, given that his unfortunate story occurs with every blink of the eye somewhere on it. Besides, when we create for the sake of creativity, for diviner reasons that moneymakers can ever understand, the dark fate of his lurks right beside us and it is only a question of time when it will swallow us in its chasms.

DAUGHTER: In belly of the whale.

MOM: And *Cool?* can be considered, first and foremost, a story about the rejection and mocking that all those heralds of progressive values throughout the history have had to go through.

DAD: Of views that are blessed with the ability to glimpse that celestial wonder that makes the world go 'round. Or, conversely, it is a story that provides a beacon of hope for all those who are different, who are strange and who, therefore, feel drowning in a finger-pointing, accusatory world that demands uniformity and shoves anyone who opposes its paradigms into its deepest gutters, forgetting that without differing from the mainstream, nothing innovative, in life and science alike, could evolve.

MOM: Marching helmets stomping over that lonely, worn-out straw hat rolling in the dust.

DAD: Aye.

SON: So what are some of these peculiarities of water and hydroxyapatite?

DAD: There are many. Where should we start? Water, for example, exhibits the highest surface tension among all liquids except mercury.

SON: Is that why ice floats over water?

DAD: If we went deep enough in search of the heart of causality, we would come face to face with the effect that explains both of these phenomena, namely hydrogen bonding. But in more simplistic terms, ice floats over water because its specific gravity is higher in the liquid state than in the solid state, contrary to most other materials.

SON: But not all.

DAD: No, not all. Many metals, such as gallium, germanium and antimony, share this counterintuitive property with water. In fact, a number of anomalous properties of water are tied to temperature effects, resonating with the Mpemba effect. Unlike most other liquids, which exhibit monotonous changes in physical properties with temperature, water exhibits strange temperature maxima/minima, including the minimal isothermal compressibility

[44] R.E.M. – "Beachball", In: Reveal, Warner Bros, Los Angeles, CA (2001).

[45] Radiohead Theme Park, a web page retrieved from archive.radiohead.com/Site4/getin01.html (1999).

near 46 °C,[46] the maximal refractive index near 0 °C,[47] the light scattering minimum at around 22 °C[48,49] and maximum at around 15 °C,[50] and so on. Thus, whereas the isothermal compressibility, heat capacity and thermal expansion coefficient almost universally decrease with temperature in simple liquids, in water they start to increase at temperatures lower than 46 °C, 35 °C and 4 °C, respectively.[51]

MOM: The fact that the density of water peaks at 4 °C at the atmospheric pressure, as most every schoolboy knows, helps the aquatic life by facilitating the vertical circulation of water, alongside allowing for the formation of the thermally insulating layer of ice on the surface.

DAD: But what not every schoolboy knows is that for each effect that benefits life, there is at least one that threatens it and so it is with this peculiar density maximum at 4 °C too. Namely, it happens often that water infiltrates rocks and then undergoes the unexpected expansion between 4 °C and the freezing point, causing the cracking of the rocks and the erosion of the land.[52]

MOM: But molecules of water, as the Lehninger textbook says,[53] engage in four hydrogen bonds per molecule in the solid state and only 3.4 on average in the liquid state. So how does this higher density of intermolecular bonds translate to lower bulk density?

SON: It does not make sense.

DAD: It does not, but the key to explaining this complex effect lies in the orientation of hydrogen bonds. In ice, they are very rigid and stable, creating an open, honeycomb-like framework where the separation of water molecules is greater than when these bonds partially collapse and become more dynamic and fluid, which is what we see in liquid water. Amorphous phases, because of the stretched, deformed bonds and structural voids, are typically less dense than their more densely packed crystalline counterparts, but this is not so with water. Not only does water have a higher density than ice, which is extremely unusual in itself, but at 0.94 g/cm^3 amorphous ice is also denser than regular, hexagonal ice (I_h), whose density is around 0.92 g/cm^3. Hydrogen bonding, of course, causes most of these peculiarities. This low-density amorphous ice, which has been found in the cosmic dust, is also more viscous than water.

SON: That is already a lot of peculiarities. Any other effects?

DAD: Water has an extremely low vapor pressure, again thanks to strong intermolecular forces, implying, on the other hand, unusually high heat of vaporization and a very high boiling point compared to the adjacent hydrides in the Periodic Table. In fact, judging from the molecular weight of water only, we would expect its boiling point to be 200 °C lower than it is. In other words, water, without hydrogen bonds, would be a vapor at room temperature and the pressure of 1 bar. This contributes to its being one of the rare carbonless liquids under ambient conditions. Also, off the top of my head, there is the strange and counterintuitive reduction of viscosity with pressure at temperatures lower than 30 °C.[54]

MOM: In fact, Martin Chaplin, a water chemistry enthusiast, has created a long list of 74 anomalous properties of water,[55] one of which was the ability to undergo the Mpemba effect, so we can survey them one by one on another day.

SON: And as for hydroxyapatite?

DAD: The peculiar properties of hydroxyapatite are not a far cry from those of water. Take sintering behavior, for example: hydroxyapatite densifies more at higher heating rates,[56] which is highly unusual. In fact, so abnormal it is

[46] Vedamuthu, M.; Singh, S.; Robinson, G.W. Properties of Liquid Water. 4. The Isothermal Compressibility Minimum near 50 °C. J. Phys. Chem. 99, 9263–9267 (1995).
[47] Cho, C.H.; Urquidi, J.; Gellene, G.I.; Robinson, G.W. Mixture model description of the T-, P dependence of the refractive index of water. J. Chem. Phys. 114, 3157–3162 (2001).
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[49] X. Zhang, L. Hu. Anomalous light scattering by pure seawater. Appl. Sci. 8, 2679 (2018).
[50] Buiteveld, H.; Hakvoort, J.H.M.; Donze, M. The optical properties of pure water. SPIE 2258, 174–183 (1994).
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[52] L. Labrador-Paez, C. Mingoes, F. Jaque, P. Haro-Gonzalez, H. Bazin, J. M. Zwier, D. Jaque, N. Hildebrandt. pH dependence of water anomaly temperature investigated by Eu(III)cryptate luminescence. Anal. Bioanal. Chem. 412, 73–80 (2020).
[53] D. L. Nelson, M. M. Cox. Lehninger Principles of Biochemistry, W. H. Freeman and Company, New York, NY (2005), pp. 49.
[54] P. W. Bridgman, The viscosity of liquids under pressure. Proceedings of the National Academy of Sciences 11, 603–606 (1925).
[55] M. Chaplin – "Anomalous properties of water", In: Water Structure and Science, retrieved from http://www1.lsbu.ac.uk/water/water_anomalies.html (2019).
[56] M. J. Lukić, L. Veselinović, Z. Stojanović, M. Maček-Kržmanc, I. Bračko, S. D. Škapin, S. Marković, D. Uskoković. Peculiarities in sintering behavior of Ca-deficient hydroxyapatite nanopowders. Materials Letters 68, 331–335 (2012).

that it defies some of the basic postulates of the science of sintering. Hydroxyapatite also exhibits a well-known heat capacity anomaly at the temperature of transition from the monoclinic to the hexagonal phase.[57,58] The extremely fluid and volatile phase composition of the hydroxyapatite surface, which can respond with swift changes in composition and structure to the changing conditions of the microenvironment presents another one of its unique characteristics. This surface fluidity can be largely traced to the effects of the intrinsic hydroxyl groups, which form an approximate continuum with the aqueous layers wetting the surface. However, when these hydroxyl groups get to be fully or partially removed by creation of vacancies or substitution with halogens, a number of exotic properties in hydroxyapatite get augmented, ranging from piezoelectricity[59] to pyroelectricity[60] to dielectric polarizability[61] to conductivity to protons[62] or ions.[63] Hydroxyapatite is also typified by a high nucleation rate even at extremely low supersaturations, but also a fairly low crystal growth rate even at ultrahigh supersaturations.[64] While the former of the two effects facilitates the precipitation of ultrafine particles from aqueous solutions, the latter one favors the formation of versatile microarchitectures. This protean nature of hydroxyapatite is best described by the diametrically opposite properties it can be made to adopt by controlling its microstructure. For example, it can be made transparent[65] or opaque,[66] conductive[67] or insulating,[68] diamagnetic[69] or ferromagnetic,[70] superhydrophobic[71] or wettable,[72] and so on. Hydroxyapatite is also weakly luminescent,[73] like water,[74] and exhibits very peculiar oscillatory behavior, specifically dynamic instabilities in crystallinity and viscosity during the hardening of its pastes.[75] There is many more, of course, but we have a lot more things to do today than merely recycle the old findings.

MOM: I wonder if it is because Nature finds utility in peculiarity that both of these compounds, water and hydroxyapatite, have been handed the major role in supporting the higher forms of life?

DAD: Naturally, a lot of commonalities can be found between these two materials. For example, both

[57] H. Suda, M. Yashima, M. Kakihana, and M. Yoshimura, J. Phys. Chem.99, 6752 (1995).

[58] A. Slepko, A. A. Demkov. Hydroxyapatite: Vibrational spectra and monoclinic to hexagonal phase transition. J. Appl. Phys. 117, 074701 (2015).

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[62] N. Horiuchi, K. Madokoro, K. Nozaki, M. Nakamura, K. Katayama, A. Nagai, K. Yamashita. Electrical conductivity of polycrystalline hydroxyapatite and its application to electret formation. Solid State Ionics 315, 19–25 (2018).

[63] S. Kasamatsu, O. Sugino. First-principles investigation of polarization and ion conduction mechanisms in hydroxyapatite. Phys. Chem. Chem. Phys. 20, 8744–8752 (2018).

[64] V. Uskoković – "The Role of Hydroxyl Channel in Defining Selected Physicochemical Peculiarities Exhibited by Hydroxyapatite", RSC Advances 5, 36614–36633 (2015).

[65] Li Z, Thompson BC, Dong Z, Khor KA. Optical and biological properties of transparent nanocrystalline hydroxyapatite obtained through spark plasma sintering. Mater Sci Eng C Mater Biol Appl. 69, 956–966 (2016).

[66] V. Uskoković, T. A. Desai – "Phase Composition Control of Calcium Phosphate Nanoparticles for Tunable Drug Delivery Kinetics and Treatment of Osteomyelitis. II. Antibacterial and Osteoblastic Response", Journal of Biomedical Materials Research Part A 101 (5) 1427–1436 (2013).

[67] M. Horiuchi, K. Madokoro, K. Nozaki, M. Nakamura, K. Katayama, A. Nagai, K. Yamashita. Electrical conductivity of polycrystalline hydroxyapatite and its application to electret formation. Solid State Ionics 315, 19–25 (2018).

[68] Li, H.; Wu, J.; Dong, L.-Y.; Zhu, Y.-J.; Wu, D.; Hu, X. Flexible, High-Wettability and Fire-Resistant Separators Based on Hydroxyapatite Nanowires for Advanced Lithium-Ion Batteries. Advanced Materials 2017, 29 (2017).

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[70] Mondal S, Manivasagan P, Bharathiraja S, Santha Moorthy M, Kim HH, Seo H, Lee KD, Oh J. Magnetic hydroxyapatite: a promising multifunctional platform for nanomedicine application. Int J Nanomedicine. 12, 8389-8410 (2017).

[71] Chen, F.-F.; Zhu, Y.-J.; Xiong, Z.-C.; Dong, L.-Y.; Chen, F.; Lu, B.-Q.; Yang, R.-L. Hydroxyapatite Nanowire-Based All-Weather Flexible Electrically Conductive Paper with Superhydrophobic and Flame-Retardant Properties. ACS Applied Materials and Interfaces 9, 39534–39548 (2017).

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[73] J. Roman-Lopez, V. Correcher, J. Garcia-Guinea, T. Rivera, I. B. Lozano. Thermal and electron stimulated luminescence of natural bones, commercial hydroxyapatite and collagen. Spectrochimica Acta A 120, 610–615 (2014).

[74] V. I. Lobyshev, R. E. Shikhlinskaya and B. D.Ryzhikov, Experimental evidence for intrinsic luminescence of water, Journal of Molecular Liquids, 82, 73–81 (1999).

[75] V. Uskoković, J. V. Rau – "Nonlinear Oscillatory Dynamics of the Hardening of Calcium Phosphate Cements", RSC Advances 7, 40517–40532 (2017).

hydroxyapatite[76] and water[77] undergo crystallization by following a non-classical pathway involving aggregation and reordering of primary particles into larger, secondary units. They also both obey Ostwald's law of stages, according to which an amorphous phase is the first one to precipitate from a supersaturated solution, before it rearranges into a crystalline phase. This mechanism of formation applies to both hydroxyapatite[78,79] and water.[80,81] Consequently, there is an exceptional tolerance to metastabilities exhibited by both. The variety of crystal or amorphous structures of ice that are metastable or stable under very specific conditions is unusually high, including both open- and close-packed structures and ranging from the white ice that you know of to black ice, a.k.a. ice XVIII, which is stable only at temperatures as high as those reigning on the surface of the Sun. Moreover, supercooled water has been regularly detected by satellites in all kinds of clouds, including cirri,[82] orographic wave clouds[83] and deep convective clouds,[84] where the concentration of impurities that would act as nucleation surfaces is so low that water exists in the -35 – -40 °C temperature range – in which it should promptly freeze according to its phase diagram – for prolonged periods of time. Hydroxyapatite, in turn, is very fond of crystal structure defects of all kinds. In the body, it coexists well at the equilibrium between the amorphous and the poorly crystalline states.

MOM: Right at that fine boundary between metastable existence and disintegration where the sensitivity to environmental stimuli is the highest?

DAD: Indeed. It is this walk on the edge of bare metastabilities that we ought to thank for making our bones what they are: a material that is alive, constantly remodeled through the antagonistic processes of osteoblastic mineralization and osteoclastic resorption.[85] Invariably poorly crystalline and practically always adopting the intrinsically disordered hexagonal symmetry while pushing its more native and more ordered monoclinic symmetry into the gutters of experimental rarity, hydroxyapatite is also unusually open to impurities. Impurities accommodated in it increase the number of defects, which provides more room for the impurities to feel like at home, without the structure dissipating under the influence of this positive feedback. Such is its love for the embracement of impurities as it (re)crystallizes, as if wanting to leave no soul behind.

MOM: A good soul it is, embracing all those foreign bodies.

SON: Water is good too, it makes us full when thirsty.

DAD: Hydroxyapatite is known for its exceptional ability to turn its crystal lattice into a home for an incredible number of foreign monoatomic and polyatomic species. Only in our bones has hydroxyapatite often been found to have over 10 wt.% of foreign ionic inclusions,[86] making it a key mineral reservoir for our metabolism.

SON: And crystal structure?

DAD: There is a level of commonality there too. Namely, both hydroxyapatite and water adopt hexagonal crystal structures. Technically, as I mentioned a heartbeat ago, hydroxyapatite can also be monoclinic, but only under extremely rare conditions, in which case the view down the c-axis, from which these characteristic hexagons are visible (Fig. 4a), would not change. The reason is that what differs the monoclinic structure of hydroxyapatite from its hexagonal one lies solely in the order and orientation of the hydroxyl groups running down in channels

[76] V. Uskoković - "Disordering the Disorder as the Route to a Higher Order: Incoherent Crystallization of Calcium Phosphate through Amorphous Precursors", Crystal Growth and Design 19 (8) 4340–4357 (2019).

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[86] V. Uskoković, D. P. Uskoković – "Nanosized Hydroxyapatite and Other Calcium Phosphates: Chemistry of Formation and Application as Drug and Gene Delivery Agents", Journal of Biomedical Materials Research B: Applied Biomaterials 96B (1) 152–191 (2011).

through the centers of these hexagons: in the hexagonal structure, they are randomly oriented, whereas in the monoclinic structure, the OH^- groups in each channel point in the same direction, which is the opposite from that of the OH^- groups in the nearest channels.

MOM: Wait, both water and hydroxyapatite are hydroxylated materials. There goes another commonality. Huh.

DAD: They do both contain intrinsic OH^- groups. This helps hydroxyapatite form a distinct surface layer that is unlike that in most ionic oxides: highly diffusive and fluctuant, difficult to delineate from the aqueous medium with which it engages in constant ionic exchange.

MOM: This is why one often hears of the surface of water being called ice-like and the surface of ice water-like.

DAD: As for the ice-like surface of water, this effect ties back to the aforementioned structuration of water under spatial confinement. The water-like surface of the crystals of ice is, on the other hand, where a similarity with the highly mobile and fluid surface of hydroxyapatite on the atomic scale lies.

SON: And the crystal structure of water? You drifted away.

MOM: When the discourse is on water, what else to expect but a constant drift?

DAD: As for crystal structures, water, that is, ice can adopt a dozen or so of them, just like calcium phosphates.[87]

SON: A dozen?

DAD: To be precise, the list of crystal structures adoptable by water and by calcium phosphate are far from being finalized, as new entries continue to be occasionally reported. For example, just recently, a new form of ice, so-called superionic ice, where hydrogen protons form a conductive, superliquid state around oxygen atoms locked in a close-packed, face-centered cubic lattice, was created at pressures exceeding 100 GPa and temperatures over 2000 K.[88] At around the same time, a new, albeit transient calcium phosphate phase was crystallized from amorphous hydrogen calcium phosphate. The two regular forms of dicalcium phosphate, $CaHPO_4$, are monetite, the anhydrous form of it, and brushite, the dihydrate form of it, but this new form of $CaHPO_4$, interestingly, was a monohydrate.[89]

MOM: But what is exactly the similarity between the crystal structure of ice in the ice-cream we ate and hydroxyapatite of the enamel of our teeth around which the ice melted? That is what the urchins want to know.

DAD: The key similarity, as I mentioned a minute ago, is that the most commonly found crystalline forms of both calcium phosphate and water are hexagonal. As for water, that is, ice, the only crystal structure observed under the atmospheric conditions is the hexagonal I_h, while the most common form of calcium phosphate found in Nature, including our bones and teeth, is hydroxyapatite, which in real-life conditions universally crystallizes in the hexagonal form. But here is a picture to make things clearer.

SON: "There's more to the picture than meets the eye"[90] (♪♫♪).

DAD: Out of the borders of the frame indeed our gazes ought to roam. But look here for now. As it can be seen from Fig. 4 that I have just plotted on the fly, one could recognize hexagons, the ancient symbols of the reconciliation between the material and the spiritual,[91] in both structures. They are a bit harder to spot in the hydroxyapatite structure and I marked them in green to make them more visible. You could see that the center of each hexagon lies at the corner of a primitive cell. In contrast, in water, these hexagons are packed together more tightly and, as a result, the symmetry level of water is higher than that of hydroxyapatite. It is $P6_{3/m}$ for hydroxyapatite and $P6_{3/mmc}$ for water. Each of these letters or numbers denotes a particular symmetry operation. Clearly, there are more of them for water than for hydroxyapatite.

SON: Like what?

[87] V. Usković – "Nanostructured Platforms for the Sustained and Local Delivery of Antibiotics in the Treatment of Osteomyelitis", Critical Reviews in Therapeutic Drug Carrier Systems 32 (1), 1–59 (2015).

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[90] N. Young – "My My, Hey Hey (Out of the Blue)", In: Rust Never Sleeps, Reprise, Los Angeles, CA (1979).

[91] R. P. Welsh – "Sacred Geometry: French Symbolism and Early Abstraction", In: The Spiritual in Art: Abstract Painting, 1890–1985, edited by Edward Weisberger, Abbeville Press (1986), pp. 72.

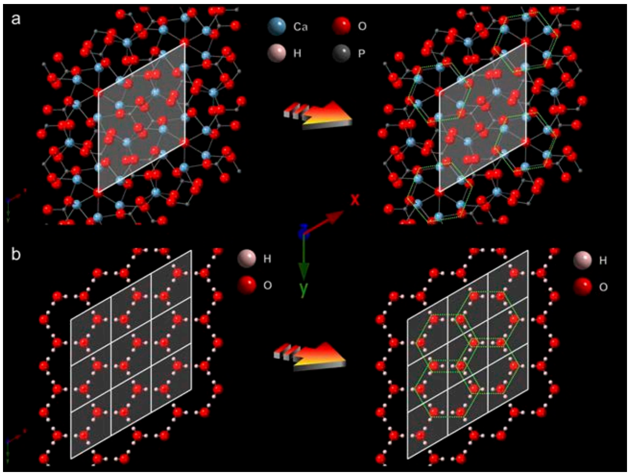

Figure 4. Crystal structures of hydroxyapatite (a) and water (b) when viewed down the c-axis. Shaded parallelograms denote the unit cells, while the four nearest hexagons to the unit cell are marked with dashed green lines for each structure.

DAD: Number 6, for example, stands for the hexagonal symmetry, which contains 6 mirror planes perpendicular to the basal, hexagonal plane; number 3 stands for rotational symmetry, which makes the structure repeat itself 3 times during a full, 360° rotation around the c-axis; then, the first *m* represents the mirror plane perpendicular to the basal plane; the second *m* stands for the mirror plane parallel to the c-axis, and *c* stands for the glide planes. This higher level of symmetry in water guarantees that each water molecule in the crystal experiences an identical molecular environment, in contrast to atoms comprising hydroxyapatite crystals whose degree of symmetry is lower.

MOM: Does this similarity in crystal structure symmetry mean that both hydroxyapatite and water grow into similarly shaped crystals?

DAD: There is a similarity in the preferential crystal growth direction too, that is correct. In the case of hydroxyapatite, we know that the crystals grow far faster along the c-axis, that is, in the direction perpendicular to the basal plane of the hexagons. Such is the case with plate-shaped hydroxyapatite crystals in bone and dentin and especially with the extremely elongated, fibrous hydroxyapatite crystals in enamel.[92] How this crystallographic tendency gets reconciled with the non-classical, aggregative mechanism of growth is not entirely clear. One model states that the shape similarity between Posner's clusters, the basic building blocks of amorphous and crystalline hydroxyapatite, and these crystallographic hexagons allows them to bind to the (001) plane, which is perpendicular to the c-axis, with the least amount of effort.[93] Another model takes into account the lower interfacial energy between (001) planes and water compared to that between (100) and (010) planes and water, which amounts to 0.08 J/m^2 *versus* 0.21 J/m^2, respectively, based on some theoretical estimates.[94] As for water, a classical study that looked at the crystal growth of water on different surfaces came to conclusion that the completely uninterrupted growth occurs when the c-axis of the crystals is perpendicular to the substrate surface.[95] The evidence of the most intense growth when the ice hexagons are parallel to the substrate and most exposed to the attachment of water molecules from liquid or vapor phases has implied that the c-axis is the preferential direction of growth of water crystals too. Another classical study demonstrated that the rate of formation of new crystalline layers is more immune to inhibition by dissolved salts along the c-axis than along the basal plane directions.[96] Similarly, as in the case of hydroxyapatite, the enthalpy of the basal, (0001) face lying perpendicular to the c-axis is lower than the enthalpy of prismatic faces parallel to the c-axis: 5.57 J/cm^2 *versus* 6.42 J/cm^2, respectively.[97] These values are concordant with another estimation of the ice/water interfacial energies for the (0001) basal face and the (1010) prismatic face – 121 mJ/m^2 *versus* 128 mJ/m^2, respectively[98] – explaining why ice crystals tend to form distinct hexagonal plates and columns, just like hydroxyapatite.

SON: Dad, I know you say that you are children and that you grow young, not old, but you also say that a parent that only watches children with love can be a best parent of them all. So I wonder about the shape of these crys-

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[92] V. Uskoković, M.-K. Kim, W. Li, S. Habelitz – "Enzymatic Processing of Amelogenin during Continuous Crystallization of Apatite", Journal of Materials Research 32, 3184–3195 (2008).

[93] Onuma, K.; Ito, A. Cluster Growth Model for Hydroxyapatite. Chem. Mater. 10, 3346–3351 (1998).

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[95] C. A. Knight. Curved growth of ice surfaces. Journal of Applied Physics 33, 1808–1815 (1962).

[96] H. R. Pruppacher. Growth modes of ice crystals in supercooled water and aqueous solutions. Journal of Glaciology 6, 651 – 662 (1967).

[97] M. J. Shultz, A. Brumberg, P. J. Bisson and R. Shultz, Producing desired ice faces, Proceedings of the National Academy of Sciences, 112, E6096–E6100 (2015).

[98] Kuroda, T. and R. Lacmann. Growth kinetics of ice from the vapor phase and its growth forms. Journal of Crystal Growth, 56: 189–205 (1982).

tals of water; do they really get prettier if we think pretty next to the water or if we play beautiful music to it?[99]

MOM: It is a dream. Even if it were true, it would be impossible to verify. What is beautiful and what is ugly lies solely in the eye of beholder.

DAD: This dream of molding matter with mellifluent music and thoughts brings us over to the commonality between hydroxyapatite and water with respect to the memory effect. Our former seminal studies on memory effects in hydroxyapatite showed that this material is capable of memorizing past structural states and responding to future stimuli accordingly. Specifically, the material was sensitive to the route it would take toward a particular structural state. Two hydroxyapatite samples made to traverse a different path toward an indistinct final state were thus shown to respond thoroughly differently in both physicochemical and biological contexts.[100] And to say that a material has memory is just a different way of saying that the history of its formation and restructuring affects its properties.

MOM: And for water, prior research has hinted at the memory effects intrinsic to it,[101] albeit occasionally blowing the spiritualistic significance of these finding beyond the proportion.[102] But if these are sidelined and memory is associated with the exhibition of properties that depend on the history of the treatment of the material, then water must have memory too.

DAD: According to the work by Sun *et al.*, this memory has been found to be stored in the delayed relaxation of O:H-O bonds in the order of minutes following particular temperature and pressure water treatments.[103] They showed that the nonbonding lone pairs and the strong coupling between intermolecular and intramolecular interactions play a key role in enabling this memory to occur.[104] Also, microwave irradiation can imprint memory onto water in terms of modifying its surface tension for similarly long timescales after the treatment is over.[105] Oscillatory restructuring of water at the molecular level on much longer timescales, extending into hours, days or weeks has also been reported after the treatments with infrared radiation,[106] magnetic fields[107] and electrical resonance,[108] respectively.

SON: So water can remember?

DAD: It is one of many materials that have the capacity to remember their previous states. Nitinol (NiTi) is a textbook example of a memory shaped alloy,[109] but other alloys, such as CuZn,[110] CuAlBe[111] and various steels,[112] as well as pure metals, such as bismuth,[113] polymers, such as urethanes,[114] acrylates,[115] styrenes,[116] lactides[117]

[99] M. Emoto. The Miracle of Water, Atria, New York, NY (2007).

[100] V. Uskoković, S. Tang, V. M. Wu – "On Grounds of the Memory Effect in Amorphous and Crystalline Apatite: Kinetics of Crystallization and Biological Response", ACS Applied Materials and Interfaces 10 (17), 14491–14508 (2018).

[101] Chaplin, M. F. – "The Memory of Water: an overview", Homeopathy 96, 143–150 (2007).

[102] Beauvais, Francis. Ghosts of Molecules - The case of the "memory of water", Lulu Publishing, Morrisville, NC (2016).

[103] Y. Huang, X. Zhang, Z. Ma, Y. Zhou, W. Zheng, J. Zhou, C. Q. Sun, Hydrogen-bond relaxation dynamics: Resolving mysteries of water ice, Coordination Chemical Reviews 285, 109–165 (2015).

[104] C. Q. Sun. Solvation Dynamics: A Notion of Charge Injection, Springer, New York, NY (2019).

[105] H. Parmar, M. Asada, Y. Kanazaw, Y. Asakuma, C.M. Phan, V. Pareek and G. M. Evans, Influence of microwaves on the water surface tension, Langmuir 30, 9875–9879 (2014).

[106] T. Yokono, S. Shimokawa, T. Mizuno, M. Yokono and T. Yokokawa, Clathrate-like ordering in liquid water induced by infrared irradiation, Japanese Journal of Applied Physics 43, L1436–L1438 (2004).

[107] E. Bormashenko, Moses effect: physics and applications, Advances in Colloid and Interface Science 269, 1–6 (2019).

[108] C. Cardella, L. De Magistris, E. Florio and C. W. Smith, Permanent changes in the physico-chemical properties of water following exposure to resonant circuits, J. Scientific Exploration 15, 501–518 (2001).

[109] Lester, B. T.; Baxevanis, T.; Chemisky, Y.; Lagoudas, D. C. – "Review and perspectives: shape memory alloy composite systems", Acta Mechanica 226, 3907–3960 (2015).

[110] Y. C. Miao, R. Villareal, A. Talapatra, R. Arroyave, J. J. Vlassak. Nanocalorimetry and ab initio study of ternary elements in CuZr-based shape memory alloy. Acta Materialia 182, 29–38 (2020).

[111] V. Fuster, J. F. Gomez-Cortes, M. L. No, J. M. San Juan. Universal Scaling Law for the Size Effect on Superelasticity at the Nanoscale Promotes the Use of Shape-Memory Alloys in Stretchable Devices. Advanced Electronic Materials 2019, 1900741 (2019).

[112] R. Silva, C. Arana, A. M. D. Malafaia, A. A. Mendes, C. Pascal, J. Otubo, V. L. Sordi, C. A. D. Rovere. Microstructure and surface oxidation behavior of an austenitic Fe-Mn-Si-Cr-Ni-Co shape memory stainless steel at 800 degrees C in air. Corrosion Science 158, 108103 (2019).

[113] Shu, Y.; Yu, D.; Hu, W.; Wang, Y.; Shen, G.; Kono, Y.; Xu, B.; He, J.; Liu, Z.; Tian, Y. – "Deep melting reveals liquid structural memory and anomalous ferromagnetism in bismuth", PNAS 114, 3375–3380 (2017).

[114] Yu, J.; Xia, H.; Teramoto, A.; Ni, Q. Q. – "The effect of hydroxyapatite nanoparticles on mechanical behavior and biological performance of porous shape memory polyurethane scaffolds", J Biomed. Mater. Res A 106, 244–254 (2018).

[115] R. X. Liang, H. J. Yu, L. Wang, L. Lin, N. Wang, K. U. R. Naveed. Highly tough hydrogels with the body temperature-responsive shape memory effect. ACS Applied Materials & Interfaces 11, 43563–43572 (2019).

[116] Bai, J; Shi, Z. – "Dynamically Cross-linked Elastomer Hybrids with Light-Induced Rapid and Efficient Self-Healing Ability and Reprogrammable Shape Memory Behavior", ACS Applied Mater. Interfaces 9, 27213–27222 (2017).

[117] Balk, M.; Behl, M.; Wischke, C.; Zotzmann, J.; Lendlein, A. – "Recent advances in degradable lactide-based shape-memory polymers", Adv. Drug. Deliv. Rev. 107, 136–152 (2016).

and chitins,[118] and graphene/polymer composites[119] can display memory effects too. Then there is hydroxyapatite, of course.

MOM: Sliding down the hallways of memory, causing the voile curtains to flutter and make way for the inflow of the dazzle of here and now.

SON: "Last day in May, the afternoon, remember?"[120] (♪♫♪).

DAD: Do I remember?

SON: Do you remember?

DAUGHTER: 'Memba?

DAD: My last hour in the Castle? The late afternoon of May 31? When the unjust judges' axes slashed for one last time and got the wolfish dreamer excommunicated from their dragonish lair?

MOM: From the fiendish flock blind to the fact that nonconformity and creativity are but two sides of the same coin.

DAD: From the pharisaic polity that I have invested my whole life to revolutionize by fertilizing the dry logic on which it is founded with a touch of poetry, of lyricism that melts the stoniness of the scientists' hearts and turns them into open flowers, gentle and beautiful, wherefrom bedazzling bursts of creativity and spiritedness can emanate once again. But life that wants to live and bounce and play and bring the dead back to life will always be sentenced to death of the spirit by these dead that it wishes to resurrect.

MOM: Or 13, the number of death, and 6, the number of karma, and 88, the lucky number of infinity, that is, 13,688 days since Chapman terminated John Lennon, that monumental reflection of the inner figure that a star in the making may decide to look up to and listen while disregarding the demoralizing voices of the obtuse souls comprising the majority of the humankind?

DAD: Or maybe the date *Titanic* was launched, that timeless reminder that the finest human sciences and technologies can crumble into dust any day before the powerful will on Nature?

MOM: Or a decennial since the clock tower housing Big Ben started keeping time?

DAD: Time, that physical quality in which all the cosmic grief seems condensed.

DAUGHTER: The clock tower we must save?

DAD: Or the date of the first airing of a film on the American television, which happened to be the one about Scarlet Pimpernel, the escape artist whose secret name was that of a wildflower, like the one we made one of our backyard and garage studies revolve around earlier and the one I have, sadly, despite my mother's will, never got to wear on my white shirt?

MOM: Someday you will.

DAD: Or the bicentennial of the birth of the poet who looked at a golden autumn leaf and wondered "Is it a dream? Nay but the lack of it the dream, and failing it life's lore and wealth a dream, and all the world a dream".[121]

SON: Dad, I meant the date of our first nightswimming. Do you remember?

DAD: Do I remember?

MOM: Does water remember?

DAD: Ah, yes. This long elegy brings the memory back. Let me slide down its lane. Hold my hand or else this heart will be crushed by these jigsaw puzzle pieces of broken memories falling all over me now.

SON: "Time, all the long red lines, that take control, of all the smoke like streams, that flow into your dreams… (♪♫♪)

MOM: … that big blue open sea, that can't be crossed, that can't be climbed, just born between the two white lines, distant gods… (♪♫♪)

[118] K. Zhu, J. Hu, L. Zhang. Editable and bidirectional shape memory chitin hydrogels based on physical/chemical crosslinking. Cellulose 26, 9085–9094 (2019).
[119] W. N. Du, Y. Jin, S. W. Lai, L. J. Shi, Y. C. Shen, H. Yang. Multifunctional light-responsive graphene-based polyurethane composites with shape memory, self-healing, and flame retardancy properties. Composites Part A 128, 105686 (2020).
[120] The Fiery Furnaces – "Here Comes the Summer", In: EP, Rough Trade, London, UK (2005).
[121] W. Whitman – "Pioneers! O Pioneers!", In: Leaves of Grass, Walter Scott, London, UK (1886), pp. 101.

DAD: … And faded signs, of all those blinking lights, you hadn't picked the one tonight"[122] (♪♫♪).

MOM: Put your head on my lap now and dream on.

DAD: This head, a mosaic of naïve, children's brushstrokes and splashes of paint. As muddled as on a Hofmann's or Hodgkin's expressionist painting. Abstract. Post-verbal. Cryptic. With all these objects jumping out of the playrooms of my memory and flying through this dim and shadowy space within. These playdough penguins with chipped beaks, abandoned canted birdhouses, standalone princess chariot wheels, twisted sewing needles, wizen straw hats, whirligigs, sundials and fallen seahorses, all swaying on the waves of the ocean of eternal melancholy.

MOM: Our goal, indeed, is to "go back beyond the horses of the Parthenon to the rocking-horse of the childhood",[123] as a fellow primitivist, Paul Gauguin, formulated it once.

DAD: Hence, there is no memory like childhood memory, even when it is scuffled and scrambled like the one reigning in my head.

SON: I read once that those who remember a lot have an ego that is strong a lot.

MOM: You mean, a strong ego holds onto its memories strongly?

DAD: Well, the more memories color the perception of the present, where, *en passant*, the infinity resides, the more subjective the world would appear to one. And because memories are always unique, the greater the weight they provide to the gravity of the soul, the more distinct and separate their bearer will be compared to the rest of the world.

MOM: More akin to a star suspended alone in the darkness of the night sky she will be.

DAD: All the while filling our eyes with her shine.

SON: "Hang on to your ego, hang on…"[124] (♪♫♪).

[122] Mercury Rev – "Holes", In: Deserter's Songs, V2 Records (1998).
[123] E. H. Gombrich – "The Story of Art", Fifteenth Edition, Phaidon Press, London, UK (1989), pp. 601.
[124] The Beach Boys – "Hang on to Your Ego", In: Pet Sounds Reissue, Capitol, Los Angeles, CA (1990).

DAD: And yet, all these connections between ego and memory aside, I have always thought that the attachment to memory, deep down, must be about an intense empathy with physical objects and creatures, feeding secretly on the sorrow evoked in one at the thought of parting with them, let alone at the sight of their disintegration and passing.

MOM: And yet, *Panta Rei*. All changes, all flows. Even this Hobbiton will turn into dust and dust into resplendent empires.

SON: And if memory is empathy, does it mean that there is love in it? And that there is love in water too?

DAD: If there is memory, there must be an empathic connection, so yes, love in a very subliminal or primordial form must be in it.

MOM: Like that which bled from the heart of another nonconformist seagull expelled from the flock, I think named Jonathan, when he asked his friend who had "overcome time", dolefully, if they might still see each other between Here and Now, which, you know, an amnesiac mind immerses into in search of that absolute freedom. That absolute freedom that is far, far away from the absolute love.

DAD: Meaning that memory and love are twined like the briar and the rose.

SON: By the bye, was it you who were running after your daddy all night and day, saying "remember, remember" when you were little?

MOM: And forcing him to memorize all the daily impressions that you found astonishing?

DAD: *Tata, zapamti. Tata, zapamti*. That is what I was saying. Like a broken record. God only knows there were many of these impressions, popping up every minute or so in my little curious head. The thought of letting any one of these millions of impressions that struck me as a child vanish was frightening. So they had to be backed up somewhere.

MOM: And they still do. No thought is allowed to evaporate into the infinity. It must be captured and pressed into a paper. But like a bird squeezed into a flat paper, it may die.

DAD: That is what Meša Selimović wondered in *Dervish and the Death:*[125] do we give life to thoughts when we transcribe them to words, of we kill them?

SON: "The sodden leaves stuck to your feet: remember?" (♩♫♪).

DAD: Well, at wintery and grim autumn days are the best summer stories being told.

SON: Dad, is this why you are writing everything we say, even now?

DAD: Yes, it stifles the joy of the moment, but someone must be that catcher in the rye. In the bigger picture, I also wish to present this scientific study as a dialogue.

SON: Is it because you want to make it more interesting?

DAD: You are right, but only partly. It will be indeed more fun and captivating to read, bringing the subject closer to the heart of the reader.

DAUGHTER: adghnvdtfh yo:&3 yhhgvfrhbcb loyghm kirbm rgkmmbvcdgk.

MOM: Here, take this old tablet to type this slaphappy, asyntactic poetry on.

DAD: "Any invented speech is real", a Jacques Rivette's character said once.[126]

MOM: Ezra Pound and e. e. cummings would approve of it too, as well as Jack Kerouac.

SON: And Doris?[127]

DAD: She would too, as well as the Cocteaus in all their glossolalic ecstasy.[128] And all the travelers toward expressional novelties, away from deadening communicational clichés and habits.

SON: Dad, stay on the track. What about the other part?

DAD: Well, conceptual innovativeness aside, the other part is because dialogues more veritably reflect the creative thought process. If you were to magnify voices in your head during rumination over a matter, you would always here two or more mutually contradicting voices throwing theses and antitheses at one another, wherefrom meaningful syntheses are made and solidified as illuminative inferences.

MOM: Is that how water solidifies too? Through constant antagonisms.

DAD: Well, some of the newer theories of water structure do explain its relaxation and other cluster dynamics phenomena by invoking the supposed display of liquid polymorphism.[129] It takes the form of two overlapping and mutually interacting water structures: high-density liquid (HDL), which is less Arrhenius-like in behavior, and low-density liquid (LDL), which can be more Arrhenius-like.[130] A very recent derivation of the coordination number distribution from the experimentally measured X-ray scattering factor was in agreement with this model, showing the coexistence of two types of local structures in liquid water.[131]

MOM: Besides, Mpemba's paper was a dialogue too.

DAD: A rather rough one. It was divided to two parts, the first of which, titled Question, came from the pen of Erasto Mpemba, and the second of which, titled Answer, albeit somewhat presumptuously, came from the pen of Denis Osborne. Therefore, notwithstanding that we could foresee critics ascribe neocolonial connotations to this segregation of racially distinct voices, it makes sense to pay homage to *Cool?* in a dialogical form, which we do craft here on the go.

MOM: With more characters and interactive voices than in the original paper.

DAD: And with a richer play character. It is almost as if what comes out of my pen now could be performed in a theater one day.

MOM: Would this be a precedent in the history of modern science? Back in ancient Greece, natural phi-

[125] M. Selimović – "Derviš i smrt", Nolit, Belgrade, Yugoslavia (1966).

[126] J. Rivette - "Out 1 : Noli Me Tangere", Sunshine Productions, Paris, France (1971).

[127] C. Crabb – "The Encyclopedia of Doris", Doris Press, Athens, OH (2011).

[128] Cocteau Twins – "Heaven or Las Vegas", 4AD, London, UK (1990).

[129] H. E. Stanley, P. Debenedetti, S. A. Rice, A. R. Dinner (eds.) – "Liquid Polymorphism", Advances in Chemical Physics Series, Wiley, New York, NY (2013).

[130] H E Stanley, P Kumar, S Han, M G Mazza, K Stokely, S V Buldyrev, G Franzese, F Mallamace and L Xu. Heterogeneities in confined water and protein hydration water. Journal of Physics: Condensed Matter 21, 504105 (2009).

[131] R. Shi, H. Tanaka. Direct Evidence in the Scattering Function for the Coexistence of Two Types of Local Structures in Liquid Water. JACS 142, 2868–2875 (2020).

losophy, the predecessor of scientific thought, was often, as in the works by Plato, discussed in the format of a drama. "Under a plane-tree, by the banks of the Ilissus…".[132]

DAD: "…all ye other gods who haunt this place, give me beauty in the inward soul". Then there was Petrarch and his Secret Book written in the form of a meditative, confessional dialogue between the poet and St. Augustine of Hippo.

MOM: "Your words make me tremble".[133]

DAD: Like all deep and emotional ventures into the past. In Secrets, Petrarch used a triad of dialogues to evoke the spirit of antiquity, when such dialogues were the dominant literary form, and thus suggest that those classical times long gone conceal the key to profounder living for his own times, the message that marked the dawn of Renaissance. It is the same message that we, a renaissance bunch, try to invoke with these lines.

MOM: That going back, to the times when philosophy, religion and art all comingled with the scientific thought would be the way to revitalize this dry, linear and coldly machinelike form that science has taken on in the last century.

DAD: But when I think of this fusion of science with dramaturgical plays, I first think of our SF neighbor who lived a couple of blocks up north from us, on Green and Leavenworth.

MOM: And whom you two would often greet during your sprightly walks at the Coolbrith park?

SON: Cool birth?

DAD: Cool-brith. The park is named by Ina, a poetess who dreamed of a poet that "makes answer as a little child".[134]

MOM: Who "would walk, a child, through nature's wild".[135]

SON: And the neighbor? What were his views?

DAD: Unlike many other proponents of bringing science to theater who have held certain levels of reservation with respect to this quirky wedlock,[136] he was unreservedly positive about it.[137] But being preceded by the likes of Brecht,[138] Dürrenmatt[139] and Stoppard,[140] he was neither the first nor the last to write plays on science. In fact, there have been dozens of popular playwrights who brought scientific topics, particularly of historical nature, to theatre.[141] But attempts to integrate a real scientific study into a technical paper format, which is what we do here, with the goal of ennobling its dry and dull nature with a spirit that is by all means Romantic, have been none to the best of my knowledge. For, our goal, remember, is not to educate general public about science, but to instill life and light of poetry into the hearts and minds of scientists, which have been deadened by the stubborn reliance on logic and logic alone. To soften the stone, as it were. That is the mission we are on.

SON: "Don't these times fill your eyes?.. Are you all alone, are you made of stone?"[142] (♪♫♪).

DAD: But here comes another aspect where what we craft here pays homage to *Cool?* – namely, paper as a narrative. *Cool?* was exactly that – a very readable and catchy narrative. And so I thought, we cannot write about Mpemba except in a similar fashion, that is, by writing something that has a sweet flow of narration to it.

MOM: This is where the goal of writing science in an inspirational, almost belletristic manner, so as to popularize it, falls.

DAD: It is a utopian idea, but utopian visions of a world working on divine principles may be necessary to have before our minds as we set out to ennoble the desert,

[132] Plato – "Phaedrus" (370 BC), Translated by Benjamin Jowett, Echo Library, Teddington, UK.
[133] Petrarch – "Secret", Translated by William H. Draper, Chatto & Windus, London, UK (1911).
[134] I. D. Coolbrith – "The Poet", In: Poems of Today: A Collection of the Contemporary Verse of America and Great Britain, edited by A. C. Cooper, Ginn and Company, Boston, MA (1924).
[135] I. D. Coolbrith – "Longing", In: She Wields a Pen: American Women Poets of the Nineteenth Century, edited by J. Gray, University of Iowa Press, Iowa City, IA (1997).
[136] G. Gandolfi. Does a 'science-theatre' really exist? Museologia Scientifica 4, 187 – 193 (2010).
[137] C. Djerassi – "Contemporary 'science-in-theatre': a rare genre". Interdisciplinary Science Reviews 27, 193–201 (2002).
[138] B. Brecht – "Life of Galileo" (1955). In: Collected Plays: Five. Trans. John Willett. Ed. John Willett and Ralph Manheim. Bertolt Brecht: Plays, Poetry and Prose Ser. London: Methuen (1980).
[139] F. Dürrenmatt. The Physicists. Translated from German by James Kirkup. New York: Grove Press (1964).
[140] T. Stoppard. Arcadia: A Play in Two Acts, Samuel French, Los Angeles, CA (1993).
[141] S. A. Kazzazi. The Anatomy of the Science Play, New Theatre Quarterly 33, 333–344 (2017).
[142] The Stone Roses – "Made of Stone", In: The Stone Roses, Silvertone, Manchester, UK (1989).

wherever that desert may be. Excuse me, but here I must bring Medawar to mind.

MOM: Medawar? Peter Medawar? I can guess what Howard Florey would say, he who called Medawar's seminal paper on the growth of mesenchymal cells "more philosophical than scientific".[143]

DAD: "The scientific paper is a fraud", Peter said, "in the sense that it does give a totally misleading narrative of the processes of thought that go into the making of scientific discoveries… Scientists should not be ashamed to admit… that hypotheses… are imaginative and inspirational in character; that they are indeed adventures of the mind".[144] So he said in his attempt to convince the popular reader and the scientist that scientific articles could be written in a less dull, cold and technical manner than the way they are written today. Mpemba and Osborne did demonstrate that papers could be written as narratives, giving exact accounts of the thought processes and the life events that paved way to their discovery.

MOM: Life could be more beautiful if all these constraints of pretense just got dispelled.

DAUGHTER: I a prettyfull fairy. Look what ma magic wand can do. Jingle-tinkle-twinkle!

DAD: Science, too, would be instantly enlivened had these codes and conventions been obliterated and the way of the children followed.

MOM: The poorness in spirit can indeed be an utmost blessing.

DAD: But now that you bring this matter of poverty again, let us head over to a barn, not far from here. It will be a little over an hour walk.

ACT II

(A lazy autumn afternoon. 33.642259º N, -117.828296º W. Sky is translucent. It is breezeless. And warm. And yet. Nearby lobelias are shivering)

SON: Dad, why are we here? Why did you bring us to a barn?

DAD: Urbanites we are, bedazzled by the city lights, but this is not just any barn. It is the Grotowski barn - a space filled with intense energy. This is where the Polish theatre director, Jerzy Grotowski, disseminated his noble teaching and credos.

SON: "In this space". It all says here.

MOM: Where?
DAD: Here, on this placard hanging next to the entrance door to the barn, overlooking, symbolically, a bluish garbage can.

MOM: I see. "From 1983 to 1986". Who says that one cannot leave a timeless, indelible mark on the future in three years as a professor?

DAD: You do it, you shake the dirt from your sandals and off to another adventure you go. Into a new sunset.

MOM: Like the one that will glaze us with a lustrous bronze shade and drop the weighty bocce ball with which gods and demigods play atop clouds on our chests in an hour or two.

DAD: A treat to rebels with a heart of gold it is. Like those Jerzy, himself, paid homage to during one of his rare talks around here, when he remarked that "the true art is profoundly rebellious", that "the true art is not an obedient dog", and that "it's not by accident that the great artists were not in agreement not only with the establishment but also with society".[145] Of course, most of his teachings were gestural, not rhetorical. Hence the scarcity of didactic rays emanating from this space.

MOM: Alas, the barn is locked. The yurt too. We won't be able to get in today, it seems.

DAD: Shrines cannot be locked. Or else, if locked, they must be broken into. Gate-crashing, wall-crushing renegades we are. This trick will do it.

MOM: Wow!

SON: Let's sneak through this crack now.

[143] "Peter Brian Medawar", Encyclopedia.com, retrieved from https://www.encyclopedia.com/people/medicine/medicine-biographies/peter-brian-medawar (2019).
[144] P. Medawar – "Is the Scientific Paper a Fraud?", The Listener 377–378 (September 12, 1963).

[145] B. Brazil. Barn at UC Irvine reflects local legacy of famed theater director Jerzy Grotowski. Los Angeles Times (March 4, 2018), retrieved from https://www.latimes.com/local/lanow/la-me-ln-grotowski-barn-20180304-story.html.

DAUGHTER: Powwow!

MOM: We are in.

SON: So what energy is present here?

DAD: It ties to Jerzy's developing and disseminating his ideas about Poor Theatre. Here, I brought his book elaborating this call for poverty with us.[146]
SON: What was it about?

DAD: Like us here and like the countless spiritualists and philosophers all the world over, Jerzy sought the fundaments of art. His idea was to strip art from everything of superficial value that distracts the attention from the essence through making the art poor. It was his path toward making art spiritual and magical in effect, like in primeval days. And these are the very same qualities that we wish to awaken in science too. To make it less technical and more spiritual in essence, without compromising its analytical rigor, is our goal too.

MOM: This is what it says on this page. It's been underlined. "The acceptance of poverty in theatre, stripped of all that is not essential to it, revealed to us not only the backbone of the medium, but also the deep riches which lie in the very nature of the art-form".[147]

DAD: Also, one of the elementary aspects of the poor theatre, the way Jerzy imagined it, is stopping to strive to appeal to mass audiences and starting to create art in small, intimate settings, with the use of "chamber ensembles". We now have enough historical examples to be able to conclude that anything that becomes an unbelievably popular fad in our societies must be of trifling long-term value, the rarest of exceptions notwithstanding. And when a system is feedback-looped, then it really matters not if we start by adjusting our science or art to the taste of finely selected, bohemian audiences or by simply creating indie, DIY artworks without even a slightest ambition to win the world with them.

SON: But Dad, you said earlier how you were forced to replace two words only, the prince and the princess, to have your article published. I wonder who will publish this with all these childish words you are using?

[146] E. Barba (ed.) - "Towards a Poor Theater: Jerzy Grotowski", Routledge, New York, NY (1968).
[147] J. Grotowski – "Towards a Poor Theater", In: Towards a Poor Theater: Jerzy Grotowski, edited by Eugenio Barba, Routledge, New York, NY (1968), pp. 21.

DAD: We are not writing this for the publisher. No points for career intended. A touch of inspiration is all that we want. Therefore, we're writing this for the people. Including you. Your hearts will glisten when you reread this on a far and distant future day.

MOM: A parent, a teacher paving a good road for the children.

DAD: Talk about the multiple levels at which education takes place. Practical, abstract, moral, emotional, aesthetic. But invisible is the best.

MOM: Then it must be mystical and spiritual in essence.

DAD: Lao-Tzu would agree: "Nothing in the universe can be compared with the wordless teaching".[148]

MOM: Him again with his ideas that one must be crooked to be straight.[149]

DAD: All in a world where, as Paul Tillich deemed, straight is drawn strictly with crooked lines.[150]

SON: Look at these oblique wooden planks crisscrossing on this vaulted ceiling. It's like we're in some rustic cathedral for scouts and gamines and ewes and elapids.

DAD: You are not far from truth when you compare this barn with a cathedral. In fact, this whole city, just like the campus around which it was built, had been designed in a barn very similar to Grotowski's by our fellow Chicagoan, William Pereira. This barn stood right where Ford Road turns into Bonita Canyon Road,[151] on the other side of the hill, not far from here, and it served as Pereira's office in the 1960s, when all this was covered by lima bean vines, citrus groves, cattle ranches and sand dunes. Although Pereira indulged in futuristic architectural concepts, such as those embodied in the Transamerica Pyramid in SF or the Geisel Library, he preferred a barn to work from over halls with classical orders, neocolonial haciendas, Art Deco townhouses or many of the brutalist ziggurats he had designed. Bonita Canyon hippie storytelling holds that Pereira's barn got

[148] Lao-Tzu – "Tao-Te-Xing, Song 43", In: V. Uskoković – "Tao-Te-Xing: The Book for All Ages", Amazon Kindle Direct, Scotts Valley, CA (2011).
[149] Lao-Tzu – "Tao-Te-Xing, Song 22", Translated by Stephen Mitchell, Harper Perennial, New York, NY (2006).
[150] Sweet, Leonard – "Quantum Spirituality: A Postmodern Apologetic", United Theological Seminary, Trotwood, Ohio (1991).
[151] E. Batchelder – "Letter to the Editor", ZotZine 4, 4 (January 2012), retrieved from http://www.zotzine.uci.edu/v04/2012_01/quotables.php.

transferred here, but, in fact, it got disassembled in the 1990s, long after Grotowski's barn had been brought here per his wish from Dana Point, where it had been used as a ceramics studio.[152] After it was set here, most classes were held at night, by candlelight, and no decorations or alterations were allowed, lest the principle of poverty got transgressed.

MOM: Funny how this monument to poverty exists cuddled today within deluxe gated communities and the bleak riches to whom home is but a show window. Not to mention the posh houses with "heated pools and bars"[153] (♪♫♪) overlooking us eerily from these hills where plans on how to exploit, cruelly and callously, so as to conform to the new, capitalist and mercenary model of academic science, are being contrived. Just look at us: into beggars we have turned. Dozens of papers down for these sharks as a professor and there is not even a penny on the horizon.

DAD: And yet, all this exploitation and lack of communal spaces and convivial spirits aside, this master-planned city could be praised for its having been conceived as an urban design experiment of an unprecedented form and proportions. Its developers called it a "laboratory scale prototype of modern urban development – American style".[154]

MOM: It echoes the ideals of experimentalism that nest around our heads, impelling us to experiment in everything: from our thoughts to our words to our careers to our lives to, well, our sciences and the experiments we conceive, as metalogically as this sounds.

DAD: Not to mention that Jerzy called this space a laboratory because he thought that the role of an artist is to ceaselessly experiment with his art, as in compliance with the credo that guided generations of the most revolutionary artists. As per this credo, the artist is supposed to question the habits and premises present in his art and not only create art that emotionally moves the audiences. Hence Picasso's derogating his interviewers whenever he'd find out that "what they're talking about is *mere* painting"[155] instead of painting as a product of research on the whole past, present and future of artistic expression. It is this conceptual level at which art forms exist that is often neglected by the artists and the audiences alike. In science, too, it is a rarity and our contribution to raising the awareness of the importance of this conceptual approach came in the form of our christening our lab the world's first conceptual science lab.

SON: Look through the window. Airplane trails are crossing in the sky too.

DAD: This is to say that the form of scientific expression is equally important as its content. The words we air here out loud and the words that land on this virtual paper are testimony to this sublime goal. The scientific content of the study we tackle here is important, but so is this innovative form in which we present it.

SON: This cloud looks like Africa.

DAD: Also, remember that Jerzy's were times when art, unlike today, was still striving to conceptually evolve. Theatre felt more than ever that cinema was infringing on its territory and in search of preserving the authentic language of theatre, Jerzy advocated the following: "The theatre must recognize its own limitations. If it cannot be richer than the cinema, then let it be poor. If it cannot be as lavish as television, let it be ascetic. If it cannot be a technical attraction, let it renounce all outward technique. Thus we are left with a 'holy' actor in a poor theatre".[156] How well this resonates with the current times in the world of science, where the access to state-of-the-art instrumentation is mistaken for a scientific skill.

MOM: I see that he was also against the use of fancy lighting, sound effects, props, costumes and other artificial addenda to the onstage experience in his attempt to be loyal to the ideology of Poor Theatre.

DAD: Like us flirting with the idea of rejection of high technologies *en route* to making science poor and, with it, unprecedentedly beautiful. In that sense, I always remember the crossroads in Japanese post-World War II cinema whereat Akira Kurosawa and Yasujiro Ozu stood once. From there on, the former filmmaker went in the direction of increasing reliance on expensive equipment and grandiose sets that required enormous budgets, all with the intention to produce a cinematic experience of epic proportions, while Ozu went in the opposite direction, gradually shrinking the budget for his movies from

[152] A. Louie. Private correspondence (January 21, 2020).
[153] N. Young – "Thrasher", In: Rust Never Sleeps, Reprise, Los Angeles, CA (1979).
[154] E. B. Bell, Irvine Historical Society – "Irvine", Arcadia Publishing, Charleston, SC (2011), pp. 115.
[155] "David Hockney: A Retrospective", Los Angeles County Museum of Art, Los Angeles, CA (1988), pp. 83.
[156] "The Theatre's New Testament: an interview with Jerzy Grotowski by Eugenio Barba", In: Towards a Poor Theater: Jerzy Grotowski, edited by Eugenio Barba, Routledge, New York, NY (1968), pp. 21.

sizeable to moderate to barely any, but producing along the way films that were getting more and more beautiful. Therefore, very often, as I ruminate about these poor, holey shoes that destiny has put us in, I think of Ozu and his deliberate descent into poverty with the goal of showing to oneself and the world that art can be made even more authentic and moving when it comes from the use of the most meager of resources. How empowering this message is to those whom we wish to empower - the poor of this world. Verily, something fascinating happens to the human mind when it finds itself willing to create monumental science or art in the conditions of poverty. Wheels in the brain start to spin harder and inventive ideas begin to pour, as if through an act of magic, as opposed to being put to sleep in the conditions of extreme abundance.

SON: "How the curse of comfort has plagued your artistic life, I hope love, love, love gets in the way"[157] (♪♫♪).

MOM: So he advocated settling deliberately into states of poverty?

DAD: Jerzy came to believe that the actor's or the director's strivings for quick and massive success and all the material rewards that this would bring about are irreconcilable with performances that live up to the epithet of "spiritual" and that can shuffle mountains inside people's souls. This is what he concordantly observed in his book: "The poor theatre does not offer the actor the possibility of overnight success. It defies the bourgeois concept of a standard of living. It proposes the substitution of material wealth by moral wealth as the principal aim in life".

SON: Have we become poor on purpose?

DAD: Very much so, yes. But let us be quiet about it. It is still a secret whether this whole expulsion from academia was self-concerted or guided by the hand of fate.

MOM: Or it has been the logical outcome of nostalgia for the formative days of thy war-stricken youth, famished and destitute.

DAD: Whatever the case, all I know is that when Dante began to follow the spirit that reminded the poet of his wish "to possess virtue in poverty rather than great riches with vice", he emerged from Purgatory and entered Paradise.

SON: Let's get out to fresh air then.

DAD: A meadow where nothing is ours and yet all is ours.

DAUGHTER: Ah, bleathe.

SON: Look how many flowers. It is a flower garden.

MOM: Well, the shadetree nursery is right here.

DAD: The shuddery arundo plumes too.

MOM: And all these wild hyacinths and lupines.

SON: And a shooting star right there!

MOM: Is it a blue-eyed grass that I see in the distance?

DAUGHTER: And a jasmine, and a jasmine.

MOM: They look more like everlastings to me.

SON: I spotted a little baby pinecone.

DAD: On this enchanted-looking princess pine?

DAUGHTER: And two hearts.

MOM: Where?

DAUGHTER: Up. In the cloud.

DAD: These two patches of clear sky in that gray cloud really look like hearts.

MOM: Poof. By the time I pointed the camera at it, they have dissipated.

DAD: Like all the best things in life.

MOM: Where have these sweet looking clouds suddenly come from?

DAD: Shedding a shadow over this old swing with the seat sunken in the mud and overgrown with ivy.

SON: Are these kittentails over here? Or chicories? They look so cute.

DAD: The beauty of the landscape aside, we did not come here to pick wildflowers for decorative reasons or

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[157] The Thrills – "Curse of Comfort", In: Let's Bottle Bohemia, Virgin, London, UK (2004).

for our floral backyard studies.[158] We are here to discuss and learn about a more theatrical context in which science can be done, with the emphasis on the aesthetics of poverty. Because now that we are poor, there are limited research projects we could engage in. Our studies on the use of wildflowers as *in vivo* models for analyzing the biological properties of nanoparticles are one and the freezing of water, that one and only liquid the access to which is a universal right, is now another. Besides, we should never underestimate the power of us, as intellectual elites, seeking inspiration from poverty. There are countless historical examples that show how the world could be revolutionized by these means. When in doubt, just think of Godard's riding a camera tied to a shopping cart up and down Champs-Élysées to get a previously unachieved sense of liveliness on the silver screen. Think also of how the Stones owed their musical success and influence over every other song played on the radio today to a liberal political awareness and sympathy with the oppressed black culture in America. Or of how Paul Gauguin and Paul Cezanne owed the beauty and the momentum in their art to mimicking the poor art of children and primitivistic communities on tropical islands. Hence, why not having faith in our accomplishing something similar by descending to the heart of Africa and questing for treasure therein.

MOM: Besides, in this astrological age of Pisces transitioning to Sagittarius, water ought to be all around us. Blue and fluid, melancholic and mercurial.

DAD: Water, that simplest and the most fundamental of all materials. The bedrock of poverty, in all senses. It may help returning us to the poorest beginnings of it all. The rebirth of a *tabula rasa* mind open to inquiry over it all. The sunup for science at its purest and most innocent.

SON: Dad, I am still not getting, is the science that we do poor or the material we study, this water, is poor? And what does it have to do with the fact that we are poor?

DAD: All of it! The fact that we are poor predisposes us, I hope, to come up with some great insights about this poor material. The fundamental measuring principle states that one can detect an object only by having this object interact with another object of similar physical qualities.[159] Likewise, making discoveries in the realm of poor things may be the privilege of poor people. And when we say "poor", we do not use this epithet the way most people use it, which is to denote ignobility, low quality and a method full of errors. This, I believe, is an insult to the very word "poor", which I find holy.

MOM: What would Mother Teresa say?

DAD: With the aesthetics of poverty she taught, she might be rolling over in her Calcutta tomb catered by cupids if she could hear this inversion of meanings. Nevertheless, as I have written many times before, the quality that we wish to study or convey through our expressions must be embedded at each and every level of our inquiry and our being, lest our endeavors be denounced as hypocritical. For example, many people choose to write about love or inspirational being using dry, insipid academic languages and they, by the very definition, commit an act of treachery. It goes without saying that they would not be able to excel in the task of conveying the qualities that they profess to those to whom they write either.

SON: So poverty can be a fortune too.

DAD: Yes, because of millions of reasons. One that we briefly touched in the barn is that it prevents our excessive reliance on high technologies, which so many scientists and laymen mistakenly find creative ends in. Instead, it forces us to think creatively and reach apices of knowledge using the scarcest of resources. That is when the true ingenuity of a creative mind gets exercised.

MOM: Besides, we have already excelled in another poor man's material, hydroxyapatite, so why not trying it with water too?

DAD: Exactly. First the prince, then the princess.

MOM: Funny, this outing in nature has reminded me of the Yorkshire countryside through which I roamed as an exchange student on grungy Sundays.

DAD: I recall how David Hockney, after he got tired of the long southern Californian shadows and returned to Bradford, would follow the nature trails you mention and pick the most unremarkable and lackluster land-

[158] T. Uskoković, E. Uskoković, V. M. Wu, V. Uskoković – "Calcium Phosphate and Senescence of Orange Jubilees in the Summertime", ACS Applied Bio Materials 3, 3770–3784 (2020).

[159] W. Heisenberg – "Physics and Philosophy: The Revolution in Modern Science", HarperCollins, New York, NY (1958).

scapes to paint.[160] It was as if to say that when magic is discovered in the ordinary, it could be discovered with far less effort in the extraordinary too. This, of course, would not work so easily had the opposite approach been taken, that is, the one directly correlating the surface value with the value of the essence.

MOM: So finding richness in things rejected as poor enlarges our perception and enriches our spirits.

DAD: All this, of course, is not to say that those whose hearts side with the poor in a world worshipping luxury and striving for the riches, like the one we are immersed in, will not be ostracized for their peculiar affinities. Because God knows we have been penalized and sentenced to vagrancy by the scientific community for our strong desire to study the chemistry of hydroxyapatite, the material of the past, as opposed to trendier subjects. Our wish was to work on a material accessible to all, a material discarded by scientists as spent and useless,[161] instead of entering the realm of the privileged, segregating to the little populous coast of those who have and leaving behind those who have not.

SON: But Dad, if poverty equals simplicity, why are you often so difficult to understand? Why can't you just be as clear as Mpemba when he opened his paper with "My name is Erasto B. Mpemba, and I am going to tell you about my discovery, which was due to misusing a refrigerator"[11]?

DAD: I haven't reached those majestic levels of expression yet. I must grow more. The Little Prince is still a moonlight mile or so away from me. But I might get there someday.

SON: You always say that we, the children, should be your guides.

DAD: Not just mine, but of every grownup too. Yours is the only life worth living, I have come to conclude over the years.

SON: And yet we attend schools to be taught by the grownups. Maybe it should be the other way around.

DAD: We talked earlier about that unending, utopian quest for perfect expression. Now, every day we make thousands of moves, abstract and physical, but most of them, especially amongst the grownups, are driven by habit, and so they cannot be perfect by definition. When made in the kingdom of science, these inert moves reiterate the paradigmatic thinking and stand in the way of innovation, most of the time unknowably to their makers. Children, like you, are naturally more immune to inertia, and yet, sadly, in classrooms and labs, as you notice, it is adults, enslaved by the demons of dullness and doomed to the commitment of these fundamental fallacies, who teach children how to be like them. In a more ideal world, children would be placed on the most worshipped pedestals of attention, so that grownups could learn from them how to escape the mental and behavioral energy wells that constrict their creativity and squeeze life out of them. In other words, children should be the teachers, not the taught, if not in practical matters, then in the fundamental ones around which all the world's philosophies, sciences and arts revolve.

MOM: Meaning that the academic hierarchies ought to be toppled and turned up on their heads. A call for revolution it is.

DAUGHTER: Ahoy, ahoy, all hands hoay!

MOM: Down with the kings and queens and all these calls for power that corrupts the soul. Like on Velázquez's *Las Meninas*, where the painter reduced the king and the queen he portrayed to faint reflections in the mirror and placed a little princess at the forefront of the attention of suns and other stars.

DAD: Indeed, the smallest and the most innocent among us are to be our guides. It is them that all science should revolve around.

MOM: Besides, was it Pythagoras who hypothesized that the karmic journey of the souls proceeds from humans to animals to plants to minerals rather than from humans to suns and other celestial spheres of otherworldly being?

DAD: I often think about it. It puts children at the highest and most divine point of our composite existence and makes me envision children as celestial droplets of water that separate from some divine heights and essentially solidify through the karmic cycle of life. Meaning that we are falling, falling and falling, endlessly.

MOM: All until we precipitate as a crystal. And become eternal.

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[160] B. Wollheim – "David Hockney: A Bigger Picture", Coluga Pictures, London, UK (2009).

[161] V. Uskoković – "Ion-Doped Hydroxyapatite: An Impasse or the Road to Follow?" Ceramics International 6, 11443–11465 (2020).

DAD: It is thus that the Mpemba effect can become an alchemical question, stemming from the metaphysical bases which we should allow to guide us in our conceiving prolific research plans. But back to the merits of simplicity, my quiet adoration of it is not to say that the most mysterious ought not to be the most magnetic to those whose intellects are beautiful, like in Shelley's poem. For, "the best is perhaps what we understand least",[162] as C. S. Lewis had it. Wassily Kandinsky meant the same when he said that "the most readily understood, the most popular art is the least original and the least spiritual".[163] This, of course, applies not only to art, but also to sciences and to every other domain of life too.

MOM: When we listed physical properties that are common to hydroxyapatite and water, the prince and the princess of materials in our bodies, respectively, we did not linger too much on the fact that they are both poorly crystalline. I wonder how this ties to this talk about poverty. It may present a natural corollary to this necessity of hierarchical systems to adopt the same traits at each and every one of their metalogical levels.

DAD: Poor crystallinity in native solid states is indeed a commonality between hydroxyapatite and water. Were we to dig deeper, we might realize that this structural poorness has a key effect on a number of essential properties of both compounds, without which life as we know it would not have been able to exist.

SON: Like what?

DAD: For example, the poor crystallinity of hydroxyapatite is essential for increasing the propensity of this otherwise sparsely soluble mineral for bone remodeling. This reduced crystallinity is ensured by a number of effects, including a high concentration of intrinsic defects and ionic impurities, but also the ultrafine grain size. As of recently, we know that this poor crystallinity also benefits the luminescent properties of hydroxyapatite doped with photoactive ions, such as europium, terbium or other lanthanides. In these cases, luminescence tends to be more intense in disordered, amorphous structures because of the lower translational symmetry and the less consistent coordination of the luminescent ions. Namely, since the distance between atomic units in a crystal lattice normally increases as the crystallinity gets reduced, quenching and deactivation due to resonance energy transfer effects are suppressed in such poorly crystalline or plainly amorphous structures.[164]

SON: And what about water?

DAD: Ice is normally poorly crystalline, regardless of whether it is formed in atmospheric conditions or in purer laboratory settings.[165]

SON: I learned from one book on astronomy that all ice in the deep, interstellar space is amorphous. Is this still true?

DAD: How true is the connotation of the volatility of scientific truths in your asking if a truism is "still" true. Truths in science are indeed defined by the opinion of the majority and the long process of soliciting acceptance from the scientific community, as Thomas Kuhn wrote about technically[166] and Lewis Carroll anti-technically.[167] It is so true, as paradoxically as attaching the attribute of unreserved trueness to a truism that abolishes truisms by default can be. Like it is true, that is, backed by the reigning paradigms, that ice comprising the cosmic dust is almost entirely amorphous. Amorphous ice forms at very low temperatures, such as those found in the outer space. A 1.65 μm absorption is characteristic for amorphous ice and used to spectroscopically distinguish it from other forms of ice.[168]

MOM: Does it mean that the Universe is metastable?

DAD: It does. But so are we from the global thermodynamic perspective. Islands of life we are, destined to disappear in a sea of atomistic uniformity and thermodynamic stability. But we are alive and kicking so long as we retain our metastability.

MOM: So stability is not our friend. Neither is safety.

DAD: Whenever we find ourselves too safe and hushed, it is time to look for an edge overlooking an abyss and position ourselves there.

[162] C. S. Lewis – "A Grief Observed", The Seabury Press, New York, NY (1961), pp. 59.

[163] See Frank Whitford's Kandinsky: Watercolours and other Works on Paper, Thames and Hudson, London, UK (1999), pp. 25.

[164] T. Kataoka, S. Samitsu, M. Okuda, D. Kawagoe, M. Tagaya. Design of Hydroxyapatite Nanoparticles Interacting with Citric Acid for Their Bifunctional Cell-labeling and Cytostatic Suppression Properties. ACS Applied Nano Materials 3, 241–256 (2020).

[165] M. Kumai. Hexagonal and cubic ice at low temperatures. Journal of Glaciology 7, 95–108 (1968).

[166] T. Kuhn – "The Structure of Scientific Revolutions", Nolit, Belgrade, Yugoslavia (1969).

[167] L. Carroll - "Alice's Adventures in Wonderland", Penguin Books, London, UK (1865).

[168] T. Terai, Y. Itoh, Y. Oasa, R. Furusho, J. Watanabe. Photometric measurements of H_2O ice crystallinity on trans-Neptunian objects. Astrophysical Journal 827, 65 (2016).

MOM: Isn't it where the most beautiful views are anyway?

DAD: These are the most creative standpoints too. Volatile, changeable, dangerous, but the most rewarding too.

SON: And yet love is staying.

DAD: And yet love is staying.

MOM: Stay forever, an angel said to the things she knew.

DAD: Don't go, don't grow, she said too.[169]

MOM: And when atoms settle in those perfect spots and build a coherent crystal, do they talk about love?

DAD: They do. Every crystal is a testimony to the triumph of love over freedom.

SON: How come?

DAD: Let me go deeper into the language of thermodynamics for a second. A change in the free energy of a metastable crystallization precursor or an intermediate transforming into a thermodynamically stable crystal, ΔG, can be broken down to enthalpic and entropic terms: $\Delta G = \Delta H - T\Delta S$. While the former, enthalpic terms are partially stored in chemical bonds and are, as such, in alchemical terms, evocative of love, the latter, entropic terms are evocative of freedoms. As individual atoms cross large distances between one another, come into close vicinity and start forming bonds, their kinetic energy is being released. Crystallization process itself, without taking into account the solvent effects, is, namely, exothermic in nature, resulting in a net enthalpic gain ($\Delta H < 0$). At the same time, however, though the system becomes more energetically stable with the transition to the solid state, as reflected in $\Delta H < 0$, the freedom of movement of the atoms is being reduced, which results in the entropic cost ($\Delta S < 0$). Note that what constitutes gain or cost is not defined by the absolute direction of change in sign (+ or -), but in relation to its effect on the free energy term. More specifically, anything that increases G and makes ΔG of the process be > 0 is considered a cost, while anything that lowers G and makes ΔG of the process be < 0 is considered gain; hence, $\Delta H < 0$ is considered a gain and $\Delta S < 0$ a cost and *vice versa*. Now, what makes crystallization unfavorable in addition to the entropic cost is, according to the standard equation $\Delta G = \Delta H - T\Delta S$, lowered temperature too. For, as counterintuitively as it seems, even though crystallizations are initiated at lower thermal energies of the system, this equation implies that decreasing temperature increases ΔG, which does not favor the crystallization process at all, given that $\Delta G < 0$ is a prerequisite for a physical process to occur spontaneously. However, when the enthalpic gain is effectively greater than the entropic cost and the offset in the temperature, the free energy change, ΔG, becomes < 0 and the process of crystallization can begin, in spite the unfavorable changes in entropy. Conversely, for a crystal to melt, this thermodynamic picture requires the entropic gain provided by the release of atoms from the confines of the lattice to the solution, which they could traverse freely, to outweigh the enthalpic cost associated with the need to invest some energy to break the chemical bonds between atoms in the crystalline state or whatever else the crystal packing forces are. This is why when we hold a crystal in our hands and wonder why it formed, we should remember that it was because love in that little peaceful corner of the Universe prevailed over freedom.

MOM: As the behavioral fluidity of a child solidifies into rigid habitual patterns of the adulthood, that is love, too, then.

DAD: And when we renounce our wandering through gargantuan spaces that feed us kickshaws of fantasy to come close to a fellow soul, willowed and lonely, and vow to remain near it till the end of time.

SON: "Take my freedom for giving me sacred love"[170] (♪♫♪).

DAUGHTER: The sun is shining again!

SON: Clouds have dispelled. But it's still dark over there. Let's look for the rainbow, baby sister.

MOM: And what about the surrounding?

DAD: The surrounding? Like the space around us?

MOM: No, I mean what about the enthalpic and entropic changes in the environment surrounding the forming crystal? Need not these changes on the other side of the solid/solution interface be taken into account too?

DAD: They must be in order to assess the thermodynamic favorability of the phase transition. That is what

[169] P. Smith. M Train. Alfred A. Knopf, New York, NY (2015), pp. 209.

[170] Talk Talk – "Wealth", In: Spirit of Eden, Parlophone, London, UK (1988).

the principle of co-assembly argues for, after all. Very often it does happen indeed that the entropy in the solution increases as a result of the crystallization reaction and thus acts as an additional driving force for it. Water molecules comprising the hydration spheres around dissolved ions, for example, entropically benefit when ions departure into the lattice and they are liberated from this interface. The same goes for enthalpy. In fact, breaking down the total enthalpy of the solvent + solutes + crystal system to numerous finer enthalpies would make it evident that their totality decreases even though some of them, like the enthalpy stored in chemical bonds, rise through the roof ($\Delta H > 0$). Strictly speaking, the enthalpic effects taking place not in, but around the crystal lattice before and after the solidification are to be thanked for providing the enthalpic gain ($\Delta H < 0$). The formation of hydrogen bonds by the release of water molecules forming a hydration sphere around a solute accounts for one enthalpic gain favoring crystallization. But the effects could sometimes be opposite too. In fact, these effects of the chemical surrounding of a forming crystal explain why the crystallization of hydroxyapatite from a solution is an endothermic process rather an exothermic one, as all crystallizations *per se*, without taking into account the solvent effects, are.

MOM: Another anomaly of hydroxyapatite it is.

DAD: The consequence of this anomaly is that the solubility of hydroxyapatite, albeit sparse, decreases with an increase in temperature. For most salts, heating brings about higher solubility, but it is the opposite for hydroxyapatite. Which is why we often boil its fresh suspensions to block the grain surface and minimize coalescence. We see a similarly unusual effect in water in terms of the fact that the number of nearest neighbors of each molecule increases with temperature. This, of course, is quite unlike what is seen in most other liquids and what can be expected based on the common sense knowledge of physics, which predicts expansion due to an increase in the heat content of the system. There go two more entries on the list of abnormalities exhibited by both hydroxyapatite and water.

MOM: Well, they usually pile on top of one another.

SON: And love, is it an anomaly in this world too?

MOM: It is. But what a beautiful anomaly it is. As mysterious as this thermodynamic explanation of it.

DAD: And yet, as simple as it can be.

SON: Like Mpemba and his science.

MOM: Or the beauty of these downy artemisias. And the chamise chaparrals overlooking them.

DAD: Hence the magic of it. But let us head back. The sun has set behind the hill and it will be nighttime soon.

MOM: Which way is home? Across strawberry fields we'll go?

DAD: Follow the northern star and the Little Bear constellation. I need to pick up something from this juniper bush and I will meet you on top of the hill, by that unnamed road.

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ACT III

(Nighttime. Stars are out. The backyard of a townhouse overlooking a giant pepper tree, a few Madagascar palms and a Bougainvillea vine)

MOM: So quiet in here.

DAD: Except for that shake roof clanking and the jasmine flower bush jiggling.

DAUGHTER: Giggling?

DAD: That too.

SON: A bunny must be exploring it.

DAUGHTER: Eating carrot too.

SON: Or reading a book of leaves.

DAUGHTER: There is library on a tree!

MOM: And a flicker sliding down the roof.

DAD: Meanwhile, experiments are being done. Also, we gathered some thought-provoking data from my breaking into a few labs earlier today.

MOM: Is that what your venture in the juniper bush amounted to? The clandestine raid of the campus labs?

SON: A pan sliding down roofs on moonbeams and folding oneself in banana leaves to slumber in. That is what Dad warned us he was when we are not around.

DAD: We should be glad that I came back with sheets of interesting data in my hands. Hopefully, they will make sense with what is currently brewing in the garage and here, in the backyard.

MOM: Is that FTIR data you hold in your hands?

DAD: Yes, I have just processed them and here are the three different spectra, each an average of three independent measurements (Fig.5a). The major vibration modes of pure water detected using Fourier Transform Infrared (FTIR) spectroscopy included ν_1 peaking at ~ 3260 cm^{-1} for the symmetric OH stretch, ν_2 at ~ 1630 cm^{-1} for the scissoring bend of the two protons around the oxygen center, and ν_3 at ~ 3490 cm^{-1} for the antisymmetric OH stretch.[171] Detected were also the weak libration + ν_2 combination band at 2105 cm^{-1} and the overlapping libration modes at < 800 cm^{-1} range.[172] Note here that the frequencies of the stretches here are considerably redshifted compared to the corresponding stretches exhibited by gaseous water molecules, namely 3660 cm^{-1} and 3760 cm^{-1} for ν_1 and ν_3 modes, respectively, indicating strong interactions between individual molecules. The virtual absence of any signal at these wavenumbers is a testimony to the fact that water molecules are no loners, so to say, and that all of them get engaged in the formation of clusters held together by the fluctuant hydrogen bonds.

MOM: Talk about how contexts affect physical systems.

DAD: Nothing new. What surrounds the system will always have a say over what goes on inside it. Anyway, to check whether a different molecularly vibrational structure would exist in water depending on its thermal history, three water samples had their FTIR spectra recorded: water that was kept at room temperature, water heated to 70 °C, and water heated to 70 °C before being cooled down to room temperature.

SON: Alas, there seems to be no difference between these three spectra. Maybe our work was in vain after all.

DAD: It may indeed seem so, but when the integrated areas and full-widths at half-maxima (FWHM) of the ν_1/ν_3 band are compared, the difference, albeit tiny and not statistically significant ($p < 0.05$) for the major part, is evident. Specifically, it is seen that the area in the spectrum occupied by this band increases with heating, but does not relax completely to its preheated state after cooling down to room temperature (Fig. 5b). Finite, but far less significant delayed relaxation effect is observed for the FWHM of this band (Fig. 5b). Being inversely proportional to the level of order in a system, FWHM expectedly increases with temperature,[173,174] but does not get fully restored to its preheated, sharper state after cooling down. This suggests that some level of structural order getting established at higher temperatures gets retained in the material after it has been brought back to the ambient conditions.

MOM: At that point, there are two waters sitting side by side, having equal temperatures, but subtly different structures, simply because of their different thermal histories.

DAD: And these different internal structures, invariably involving hydrogen bonding, could explain different crystallization rates of these two aqueous specimens. The observed broadening of the ν_1/ν_3 band at a higher temperature, albeit extremely fine, is a strong indicator of the increased variety of hydrogen-bonding geometries.[175] The preservation of this increased variety of states in a freshly cooled system may help it find the optimal geometries facilitating the crystal growth faster than in a system comprising a narrower distribution of states.

MOM: These are very fine spectral differences from which we derive these rather remarkable conclusions. I wonder whether the changes to the spectra would become more prominent with the formation of ice.

DAD: The transition of water to ice is accompanied by the intensification of the symmetric, ν_1 component of

[171] J. G. Bayly, V. B. Kartha, W. H. Stevens. The absorption spectra of liquid phase H_2O, HDO, and D_2O from 0.7 um to 10 um. Infrared Phys. 3, 211–223 (1963).

[172] P. K. Verma, A. Kundu, M. S. Puretz, C. Choonmoon, O. S. Chegwidden, C. H. Londergan, M. Cho. The bend+libration combination band is an intrinsic, collective, and strongly solute-dependent reporter on the hydrogen bonding network of liquid water. J. Phys. Chem. B 122, 2587–2599 (2018).

[173] Y. Marechal. The molecular structure of liquid water delivered by absorption spectroscopy in the whole IR region completed with thermodynamic data. Journal of Molecular Structure 1004, 146–155 (2011).

[174] M. Zhang, E. K. H. Salje, M. A. Carpenter, J. Y. Wang, L. A. Groat, G. A. Lager, L. Wang, A. Beran, U. Bismayer. Temperature dependence of IR absorption of hydrous/hydroxyl species in minerals and synthetic materials. American Mineralogist 92, 1502–1517 (2007).

[175] T. Shimoaka, T. Hasegawa, K. Ohno and Y. Katsumoto, Correlation between the local OH stretching vibration wavenumber and the hydrogen bonding pattern of water in a condensed phase: Quantum chemical approach to analyze the broad OH band, Journal of Molecular Structure 1029, 209–216 (2012).

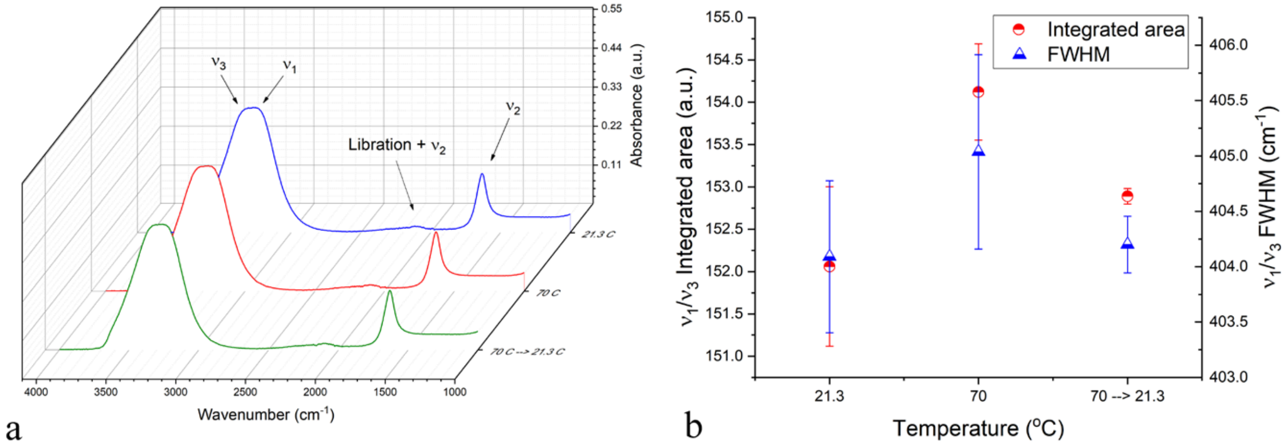

Figure 5. FTIR spectra of DI water droplets maintained at room temperature (21.3 °C), heated to 70 °C (70 °C) and cooled down to room temperature after being heated to 70 °C (70 °C → 21.3 °C) (a), along with the integrated areas and FWHM of the ν_1/ν_3 OH stretching mode in three different waters measured after the baseline removal procedure (b). Data points in (b) represent averages of three independent measurements, while error bars represent standard deviations of the mean.

the OH stretch in the 2900–3700 cm^{-1} range and the corresponding attenuation of the antisymmetric, ν_3 component of this stretch,[176] with the caveat that any straightforward distinction between the symmetric and antisymmetric normal modes in water is not very accurate in view of the considerable degree of symmetry breaking due to coupling of the vibration modes across whole molecular clusters.[177] In another prior study, it was shown that an increasing number of water molecules per cluster accompanies the transition from water vapor, liquid water or amorphous ice to crystalline ice, meaning that this transition is measurable by the red shift of the OH stretch maximum, from ~ 3400 cm^{-1} for amorphous ice and liquid water to ~ 3200 cm^{-1} for crystalline ice.[178] So yes, the spectral changes should be more conspicuous at the onset of the phase transition, as expected considering the more constrained freedom of movement of the vibration modes in the solid state.

SON: Children are best assessed when they sit still, my teacher says.

DAD: And yet, their life is best exhibited in movement. Free. Unbound.

MOM: Indeed. Out of safe harbors. Lest they wilt inside a bubble.

SON: "Here am I, sitting in a tin can, far above the world…"[179] (♪♫♪).

DAD: Now that you mention bubbles, while we were near the campus, I stopped by Earthman's lab and grabbed a sample of water infused with nanobubbles.

SON: You stole this sparkly water sample?

DAD: Well, if we pretend to be Robin Hoods, then I figure…

MOM: … rules and conventions do not apply to us?

DAD: Lest our creativity dwindle, we must be perpetual outlaws and rule-breakers. Besides, you are forgetting that Mpemba also sneaked into a lab to run his first experiment on tap water. He was also an invader and a trespasser into forbidden territories. As good ol' Woody said, anywhere there is a sign, No Trespassing, you and I belong to the other side.[180] Besides, what other choice do we, expats from the world of academia, have, but to be thieves. Thieves with a good heart. For…

[176] I. Đuričković, R. Claverie, P. Bourson, M. Marchetti, J. M. Chassot, M. D. Fontana. Water-ice phase transition probed by Raman spectroscopy. Journal of Raman Spectroscopy 42, 1408–1412 (2011).

[177] B. M. Auer, J. L. Skinner. IR and Raman spectra of liquid water: Theory and interpretation. J. Chem. Phys. 128, 224511 (2008).

[178] C. C. Pradzynski, R. M. Forck, T. Zeuch, P. Slavicek, U. Buck. A fully size-resolved perspective on the crystallization of water clusters. Science 337, 1529–1532 (2012).

[179] D. Bowie - "Space Oddity", Philips, London, UK (1969).

[180] W. Guthrie – "This Land is Your Land", In: The Asch Recordings, Smithsonian Folkways, Washington, DC (1944).

SON: "…when we ain't got nothing, we got nothing to lose"[181] (♪♫♪).

DAD: And water, remember, epitomizes this nothingness really well. Whenever we engage in measuring its physical properties, be it light scattering or UV/Vis absorbance or something else, it is an effort partly Zen-like in nature and partly bordering the act of sheer lunacy. It is like analyzing the medium that everybody looks at only as a holder of something worth measuring, while ignoring any of its intrinsic value. We, however, reverse this trend and try to show that "medium is the message",[182] as it were. This quest for explaining physical phenomena in water thereupon becomes akin to that of attempting to acquaint the divine spirit supposedly pervading every square nanometer of our realities: it is omnipresent and would cause an instantaneous enlightenment if it were perceived as such, and yet everybody ignores is. The end of the road, the fulfillment of our spiritual quests being right here, in front of our noses, on every step of the road, and yet we journey on, hypnotized by petty little things of no cosmic importance.

MOM: But bubbles suspended in water are, in a way, a dispersion of even more substantial nothingness in a relative form of nullity. And yet, they can influence the properties of this nothing, that is, water.

SON: Why are these bubbles important, though?

DAD: Well, regular water under atmospheric conditions contains around 1 mM of dissolved gas,[183] which means that by traversing a linear path with an atomic probe in tap water, after every 15–20 nm, that is, 50–60 water molecules, you would bump into a gas molecule. Or you could imagine staggering 600,000 gas molecules per each cubic micrometer of water. Naturally, because of their hydrophobicity, these molecules tend to congregate and form microscopic bubbles. And life in or at the border of a bubble, as we know, can be significantly different than life in the real medium. The same applies to the atomic and molecular scales.

MOM: But if water, which is hydrophilic, contains that much of the inert gas, how much more do cooking oils contain?

DAD: About ten times more. In fact, these gas bubbles intensify hydrophobic forces in water and other solvents. For example, a tenfold decrease in flocculation rates was detected after the removal of dissolved gas from a colloidal system composed of paraffin and stearic acid.[184]

MOM: Shouldn't we call bubbles in water cavities?

DAD: That is correct, given that bubbles, by definition, are dispersed in the same phase as that comprising their interior.[185] But these are purely etymological issues and except when they clarify specific physical phenomena,[186] we normally do not linger on them. Nor on any dry categorizations. Anyway, here are the results on comparing the solidification rates depending on whether these water samples containing nanobubbles were fresh or flat. We also added Perrier water into the comparison, with bubbles dispersed in it being of larger sizes than those in this nanobubbly water. Also, while nanobubbles were dispersed in DI water, the salinity of Perrier is around 0.45 mg/ml, slightly higher than that of our tap water (0.3 mg/ml).

MOM: If I can see correctly from Fig. 6, both microsized and nanosized bubbles increase the crystallization rate of water.

DAD: In spite of the hydrophobicity of their interiors, their surfaces obviously act as facilitators of heterogeneous nucleation.

MOM: And since we know that preheating lowers the concentration of bubbles dispersed in water, then they cannot be responsible for causing the Mpemba effect.

DAD: Now that we are on a good way to dispel the idea that bubbles are the main contributor to the Mpemba effect, we can turn to other experiments that may shed clearer light on the memory effect hypothesis.

SON: That is, the thawing and the refreezing experiments.

DAD: Exactly. As we froze the water in the freezer earlier today, we left it in to completely solidify. As we wandered to the barn, it sat in the freezer and when we got

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[181] B. Dylan – "Like a Rolling Stones", In: Highway 61 Revisited, Columbia Records, New York, NY (1965).
[182] D. Coupland – "Marshall McLuhan: You Know Nothing of My Work!", Atlas & Co., New York, NY (2010), pp. 87.
[183] P. L. Nostro, B. W. Ninham. After DLVO: Hans Lyklema and the keepers of the faith. Advances in Colloid and Interface Science 276, 102082 (2020).
[184] Ninham, B. Self-Assembly – Some Thoughts. In: Self-Assembly, edited by B. H. Robinson, IOS Press: Amsterdam (2003).
[185] Atkins, P.; de Paula, J. Physical Chemistry. 7th Edition, Oxford University Press: Oxford, UK, (2002).
[186] V. Uskoković, S. Ghosh – "Carriers for the Tunable Release of Therapeutics: Etymological Classification and Examples", Expert Opinion on Drug Delivery 13 (12) 1729–1741 (2016).

back, the first thing we did was to run a reverse experiment, where we looked if there was any difference in the melting rate between water solidified by cooling it from room temperature and water solidified after being preheated to 80–90 °C. One such experiment appears not to have been done before and it can be very informative about the mechanism of the Mpemba effect, which we are trying to decipher here.

MOM: So what do the results show? I'm all ears.

DAD: They show that there is some, but very minor

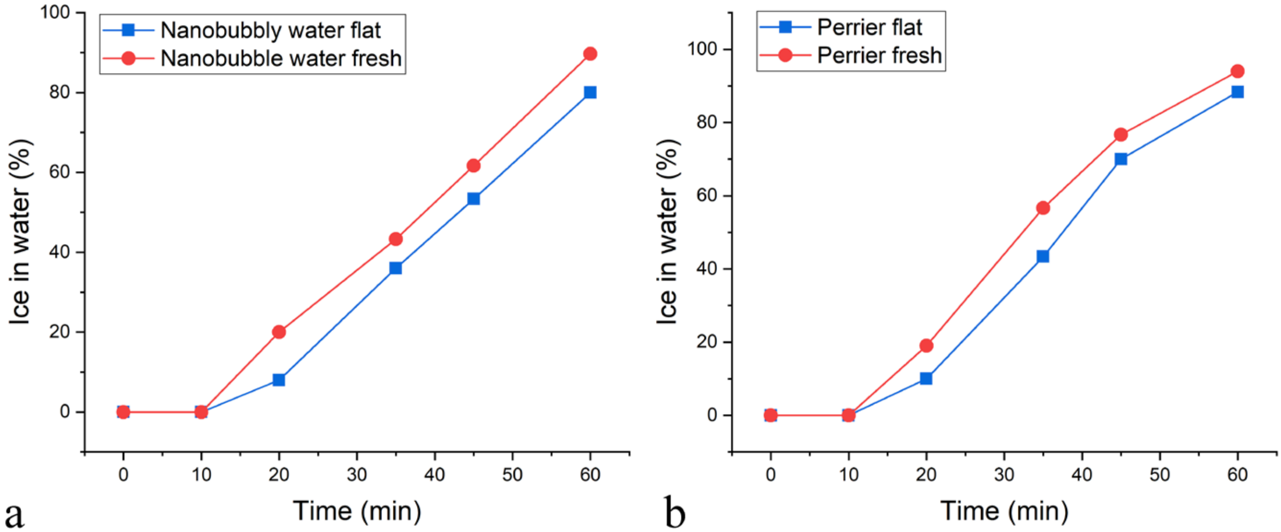

Figure 6. Percentage of the total volume of ice in the 30 ml water samples as a function of the time of incubation at -18 °C for the starting water temperature of 21.3 °C and for fresh and flat nanobubbles-containing water (a) and fresh and flat Perrier as a commercial carbonated mineral water (b).

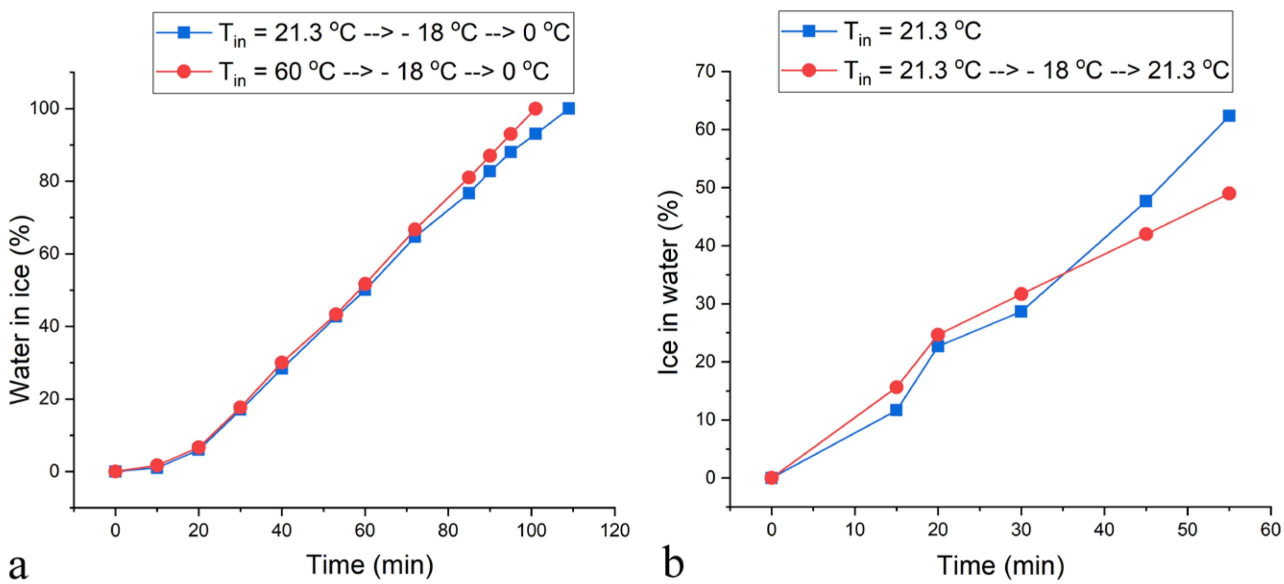

Figure 7. Percentage of the total volume of water in the 30 ml ice samples as a function of the time of incubation at room temperature for DI ice formed from water with different starting temperatures, including 25 and 60 °C (a). Percentage of the total volume of ice in the 30 ml water samples as a function of the time of incubation at -18 °C for the DI water with the starting temperature of 25 °C and the freshly thawed DI water at the same starting temperature (b).

increase in the melting rate for water that was preheated prior to being frozen compared to the water that was not preheated (Fig. 7a). The amount of ice in the former water samples was marginally higher than that in the latter, whereas the time it took for the former to completely thaw was by 7–8% shorter than for the latter. This minor effect might have been caused by the more polycrystalline nature of ice formed from the preheated water, as we observed previously. The correspondingly higher specific surface area would naturally promote a higher melting rate, but it is not clear whether the memory effect we have sought is simply masked by this more ostensible crystallinity effect. One idea behind this experiment was that if the Mpemba effect were to exist in the opposite direction, allowing the water that was inserted to the freezer warm to thaw faster than the water than was inserted to the freezer cold, it would implicitly suggest the key role of heterogeneous nucleation surfaces, such as nano- or micro-bubbles, given that these entities would favor the phase transition in both directions.

SON: You remember how once we accidentally froze mineral water and it became flat. Wouldn't the same happen to nanobubbles?

DAD: The concentration of nanobubbles in water does get reduced by about an order of magnitude with a single cycle of freezing-thawing, but it does remain finite.[187] And at concentrations in the order of hundreds of million per milliliter and with sizes often exceeding 100 nm and zeta potentials in the -20 – -30 mV range, they can present effective nucleation surfaces even for the liquid → solid phase transition. But if the effect is mainly caused by the cluster memory effects, then there would be either no difference in the thawing rate between the initially cold and the initially warm water or the ice formed from the initially warm water would have the tendency to retain its crystalline state longer than the ice formed from the initially cold water. And this is how we can, boldly, interpret these results by taking into account the aforementioned crystallinity effects.

MOM: And what about the results of the refreezing experiment? You seem to have compared the rate of refreezing of regular and freshly thawed DI water.

DAD: Ah, yes. The idea behind this experiment was that if the memory effects hold, then the freshly thawed water, containing molecular configurations that have not yet relaxed from those resembling the solid state, would refreeze faster. The results of this experiment are shown in Fig. 7b and they demonstrate that, contrary to the expectations, the freshly thawed water did not crystallize any faster than the water that has been kept under ambient conditions for years. The process of crystallization did begin more massively at early time points, but at later time points the crystallization rate got reversed and, in total, the rate was lower in the thawed water than in the regular one.

MOM: Does this refute the memory effect?

DAD: Not necessarily, though these two experiments (Fig. 7) can illustrate a loss of memory with a cycle of freezing/thawing. Memory can only exist for so much in an inanimate system, after all. Also, it is possible that whatever the relaxation processes from states resembling the symmetry of ice involve, they proceed more effectively at low temperatures, near the freezing point, than at elevated ones. Another effect that these results point at are more macroscopic, hydrodynamic instabilities, which are more prominent at higher temperatures, as potential hindrances for this relaxation and drivers of the memory effect. But you see that by probing these distant grounds from the real effect at hand, we tend to get overwhelmed by the possibilities. This is always so.

MOM: So the reverse experiments were positively negative?

DAD: They showed no effect for most part, but the experiments were designed in such a way that no difference between the samples was more illuminative than had there been any significant difference.

MOM: That is the beauty of science – turning No to Yes.

DAD: As if every Yes does not contain a No somewhere deep in its epistemological core. For, to affirm something is to implicitly negate something else.

SON: Dad, you always advised us that looking back and walking backwards is often the best way to advance forward.

DAD: Indeed. Like the spiral that the shape of our galaxy is in. For each two steps in the forward direction, one backward step must be made. Hence we engage in a free fall when we feel that we have soared too much. From these falls, as this study demonstrates, something very beautiful can emerge.

[187] N. Nirmalkar, A. W. Pacek, M. Barigou. On the Existence and Stability of Bulk Nanobubbles. Langmuir 34, 10964–10973 (2018).

MOM: In all walks of science and life, thinking in reverse is important. Remember Chesterton's norm that going against the mainstream is the privilege of living things.[188] In contrast, whatever drifts only with the stream is, effectively, dead.

DAD: Often equivalent to blind leading the blind.

SON: "Every time you wander – until the end of time – I'll be your eyes so you can see"[189] (♪♫♪).

DAUGHTER: I can see now.

MOM: Says the flower girl to the little tramp and the light of a million suns is born within us.

DAD: Now that you bring the point of light to the discussion, it may be time to proceed to the final and a less ambiguous set of experimental data that are to validate – or refute – our memory hypothesis.

DAD: Light scattering, now we know, can provide quite some information about the structure of water,[190] with the resolution going down to only 1 **Å**,[191] which is significantly lower than both the size of water hexamers ($[H_2O]_6$, ~ 6 **Å**)[192] and the size of Posner's clusters ($Ca_9(PO_4)_6$, 9 **Å**),[193] supposedly the most elementary building blocks of calcium phosphate crystals, coordinated clusters and crystalline nuclei. The data we obtained show that the amplitude of the correlation coefficient for light scattering on impurities dispersed in cool DI water is significantly higher than the amplitude of curves corresponding to both heated water and water that was first heated to 80 °C and then cooled down to room temperature (Fig. 8a). This indicates that the level of reliability with which the correlation function is established decreases with temperature. However, what is most interesting from the memory standpoint is that these fluctuations that prevent the derivation of stable correlation functions in warm water continue to be present even in the heated water soon after it has cooled. Concordantly, the count rate measuring the number of photons detected per second increases by an order of magnitude as the temperature of water increases from 25 to 60 °C, but when the temperature of the heated water is brought back to 25 °C, the count rate does not get fully restored to the value range typifying the cool and unheated water (Fig. 8b). It remains higher, indicating delayed relaxation of the environment surrounding the scattering entities as the temperature of the system is reduced from the elevated to the ambient. Apparently, scattering by the warm water is more intense, but also wilder and more stochastic, with neither of these two characteristics being fully relaxed immediately after the heated water gets cooled.

SON: More funny curves come from the absorbance analyses. Smoother too.

DAD: In fact, the effects that I have just mentioned may also explain the delayed relaxation of the optical density (OD) of heated water. Namely, as shown in Fig. 9a, the OD of water increases in the visible light range after it gets heated up to 80–90 °C and this increased OD gets retained after water has cooled down to room temperature. Similarly, the second derivative OD curves as the function of wavelength demonstrate peak splitting, shifts and differences in amplitude entailing the heating of DI water, with these more erratic spectral features being retained even after the water has been cooled down to room temperature (Fig. 9b). Knowing that hydrogen bonding has a direct effect on the vibrational absorption bands of pure water[194] and that temperature affects vibrational overtones and higher-order combination bands that extend into the visible range,[195] this effect may be traced to the expanded dispersity of hydrogen-bonded cluster states due to heating. The results agree with the consensus over the minimum in absorption in the visible range at ~ 450 nm[196,197] as well as with the rapid increase in absorption as the UV region is

[188] G. K. Chesterton – "The Everlasting Man", In: The Collected Works of G. K. Chesterton, Volume 2, Ignatius Press, San Francisco, CA (1925), pp. 388.

[189] Prince – "Blind", In: Sign o' the Times, Paisley Park, Chanhassen, MN (1987).

[190] K. J. Mysels. Light scattering and the structure of pure water. JACS 86, 3503–3505 (1964).

[191] M. Kaszuba, D. McKnight, M. T. Connah, F. K. McNeil-Watson, U. Nobbmann. Measuring sub nanometre sizes using dynamic light scattering. Journal of Nanoparticle Research 10 823–829 (2008).

[192] C. J. Tainter, J. L. Skinner. The water hexamer: Three-body interactions, structures, energetics, and OH-stretch spectroscopy at finite temperature. J. Chem. Phys. 137, 104304 (2012).

[193] G. Mancardi, C. E. H. Tamargo, D. D. Tommaso, N. H. de Leeuw. Detection of Posner's clusters during calcium phosphate nucleation: a molecular dynamics study. J. Mater. Chem. B 5, 7274–7284 (2017).

[194] M. Praprotnik, D. Janezic and J. Mavri, Temperature dependence of water vibrational spectrum: a molecular dynamics simulation study, Journal of Physical Chemistry A 108, 11056–11062 (2004).

[195] V. S. Langford, A. J. McKinley and T. I. Quickenden, Temperature dependence of the visible-near-infrared absorption spectrum of liquid water, Journal of Physical Chemistry A 105, 8916–8921 (2001).

[196] M. R. Querry, P. G. Cary, R. C. Waring. Split-pulse laser method for measuring attenuation coefficients of transparent liquids: application to deionized filtered water in the visible region. Appl. Opt. 17, 3587–3592 (1978).

[197] A. Morel, L. Prieur. Analysis of variations in ocean color. Limnol. Oceanogr. 22, 709–722 (1977).

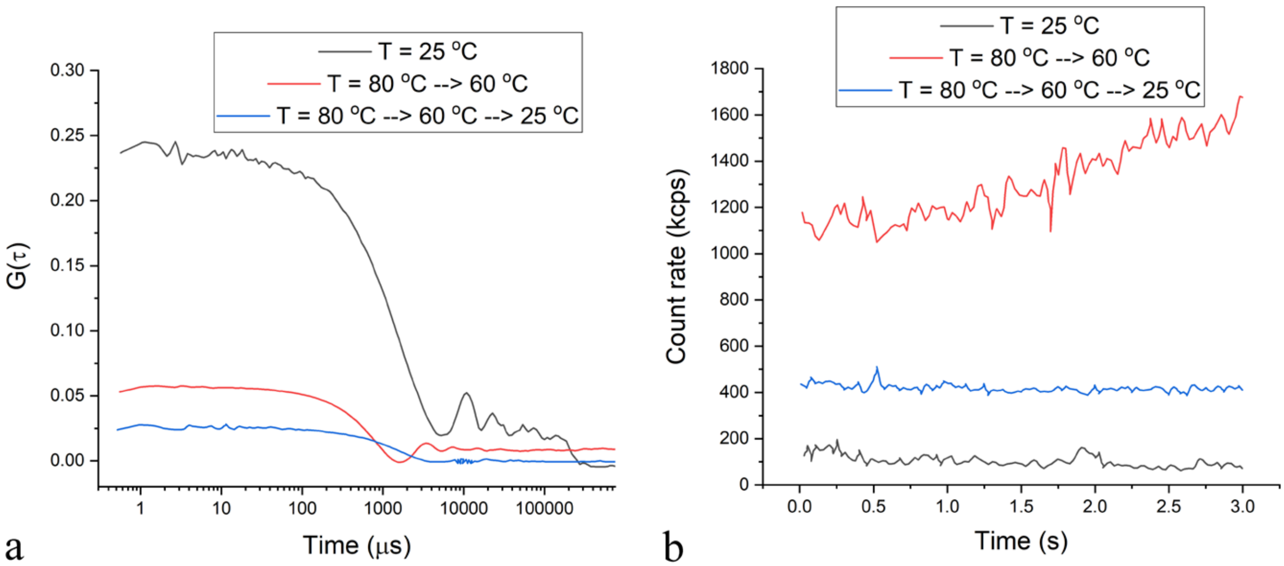

Figure 8. DLS correlation curves (a) and count rate curves (b) for DI water maintained at room temperature (25 °C) and DI water heated to 80 °C and measured first when it cooled down to 60 °C (T = 80 °C → 60 °C) and then when it cooled down to room temperature (T = 80 °C → 60 °C → 25 °C).

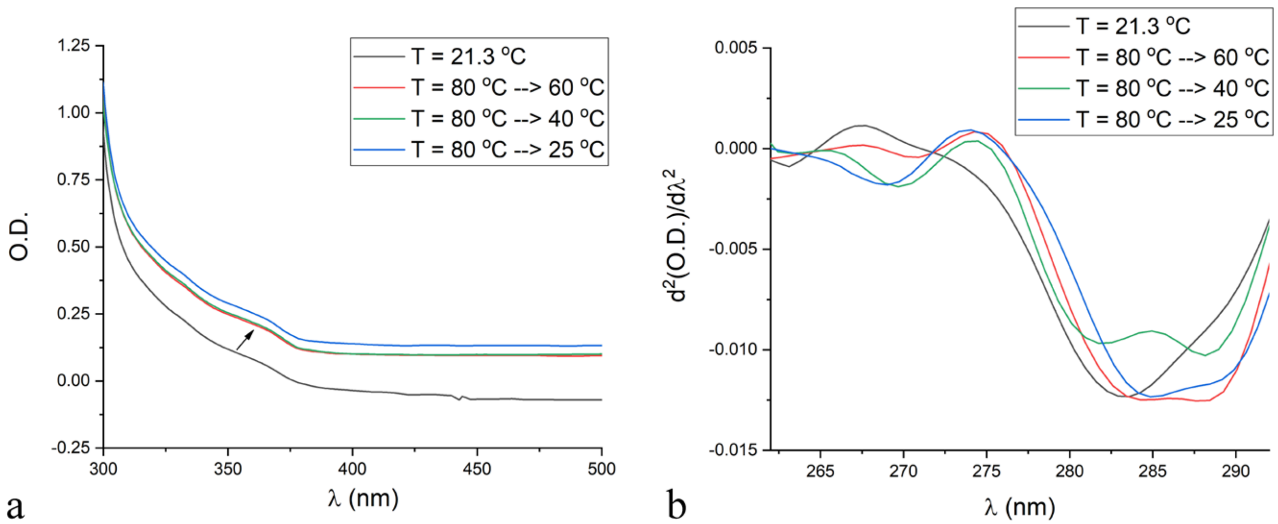

Figure 9. Optical density (a) and its second derivative (b) as a function of wavelength in the selected visible light ranges for DI water maintained at room temperature (21.3 °C) and DI water heated to 80 °C and measured first when it cooled down to 60 °C (T = 80 °C → 60 °C), then when it cooled down to 40 °C (T = 80 °C → 40 °C), and finally when it cooled down to room temperature (T = 80 °C → 25 °C).

approached from this minimum.[198] Be this absorption due to contamination, which is present to a finite extent even in the purest laboratory grade water,[199] or due to intrinsic properties of water, it is experimentally verifiable (Fig. 9a) and can serve as an evidence in favor of the retention of excited states that promote higher absorption of visible light by the water that has been heated and then cooled down to ambient conditions compared to water that has been maintained at ambient conditions for prolonged periods of time.

[198] R. C. Smith, K. S. Baker. Optical properties of the clearest natural waters (200–800 nm). Appl. Opt. 20, 177–184 (1981).
[199] F. M. Sogandares, E. S. Fry. Absorption spectrum (340 – 640 nm) of pure water. I. Photothermal measurements. Applied Optics 36, 8699–8709 (1997).

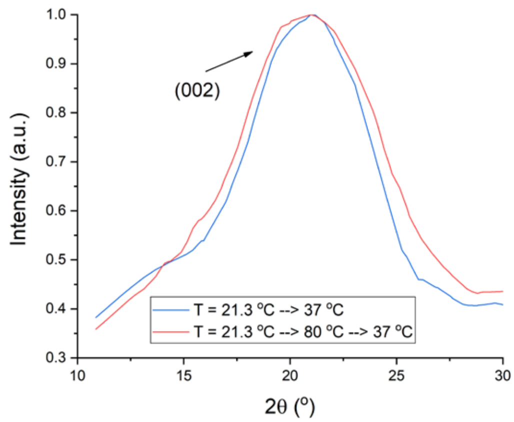

Figure 10. XRD patterns in the 2θ = 10 – 30 ° range for gelatin powders gelled at 37 °C using the initially cold water heated to 37 °C (T = 21.3 °C → 37 °C) and the water preheated to 80 °C and then cooled down to 37 °C (T = 21.3 °C → 80 °C → 37 °C).

MOM: Could it be that scattering is here misinterpreted as absorption?

DAD: It is possible, given that these two effects are comparable, particularly in the 400–500 nm region.[200] Still, whatever the effect at stake is, it arises in water due to heating and gets retained in it as a form of memory upon cooling.

SON: And what about the gelatin experiment?

DAD: We initially wanted to compare the properties of hydrogels, such as xylan/cellulose,[201] that were freeze-cast using two different waters at identical temperatures, one of which would be preheated and the other one not. However, in the absence of the equipment for lyophilization, we had to settle for a more modest experiment and we simply compared the crystallinity of gelatin converted from a powder to a gel at 37 °C using waters with different thermal histories. The results presented in Fig.10 show that the crystallinity of gelatin is indeed different to some degree depending on the recent temperature history of water. Specifically, water heated from room temperature to 37 °C produced a slightly more crystalline gel than water heated from room temperature to 60 °C before being cooled down to 37 °C. Here, it can be assumed that cooled to room temperature, water preserves some of the aspects of its turbulent structure prominent at elevated temperatures. This structural erraticism, in turn, produces a somewhat greater level of structural disorder in gelatin and lowers its crystallinity compared to the gels prepared using the thermally untreated water. Crystallinity, of course, assuming the correctness of the premises of the Debye-Scherrer equation, is calculated as inversely proportional to the half-width of the major, (002) diffraction peak of gelatin, equaling 12.4 and 10.6 **Å** for gelatins prepared using the thermally untreated and treated water, respectively.

MOM: Yet another corroboration of the veracity of the memory effect this may be.

SON: And the big picture? The enchanted forest, the starry sky. How may it look?

DAD: This is the graph, the final one today, that illustrates the cluster symmetry formation and retention during heating and cooling, respectively, as presumably the key factor in allowing water to exhibit this internal memory and, thereupon, the Mpemba effect.

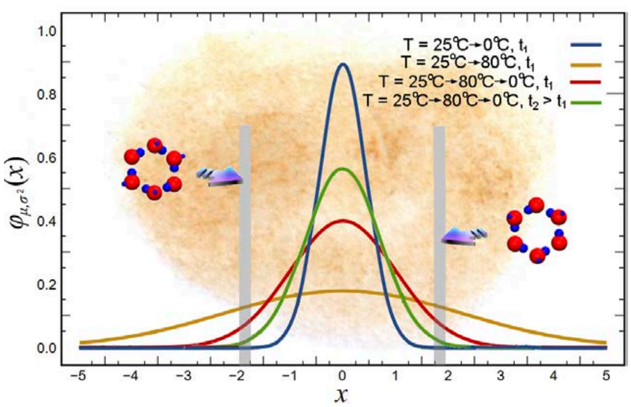

Figure 11. Probability density function of a hypothetically Gaussian, normally distributed variable where different *x* values correspond to specific water molecule cluster symmetry states. Gray bars denote the hypothetic cluster states common to water at high temperatures (circa 80 °C), but also bearing resemblance to the crystalline symmetry present in hexagonal ice. These could be, most realistically, hexamer states, such as those that present the basic translational symmetry units in ice I_h. At the same time, the delayed relaxation of high-temperature clusters and their preservation in a more dynamic, polydisperse state shortens the stochastic search for configurations that facilitate the transition to the solid state and allows the preheated water to crystallize faster when it reaches the freezing point. The representation should be noted for its simplicity, given the greater complexity of water cluster states, in perpetually fluctuant states of constant formation and dissipation, than that depicted here.

[200] A. Morel – "Optical properties of pure water and pure sea water", In: Optical Aspects of Oceanography, edited by G. Jerlov and E. S. Nielson, Academic Press, New York, NY (1974), pp. 1–24.
[201] T. Kohnke, T. Elder, H. Theliander, A. J. Ragauskas. Ice template and cross-linked xylan/nanocrystalline cellulose hydrogels. Carbohydrate Polymers 100, 24–30 (2014).

MOM: I see that not even this purely theoretical graph could escape chocolate smears.

DAD: A rather giant one it is this time.

DAUGHTER: Chocolate is the best.

DAD: Anyway, as depicted in Fig. 11, the distribution of water molecule cluster states expectedly broadens with temperature due to a greater kinetic energy imparted to the molecules. In parallel with this state distribution broadening process at higher temperatures, water clusters begin to adopt states that are normally not significantly present in water at room temperature. The distribution – or kurtosis[202] – of water clustering states thus gets naturally broader in warm water, even though the average sizes and geometries of the clusters may be the same as in the cold water. However, this greater polydispersity implies a greater population of states identical to those present in ice, around which nucleation proceeds more favorably than around the more populous states that are more characteristic of water rather than ice, so long as these nucleation-promoting cluster conformations get quenched upon cooling. What is particularly important to notice here is that ice is less dense than cold water, but hot water is also less dense than the cold water, meaning that heating causes the mild separation of water molecules so that clusters become looser, more open and bearing more resemblance to those present in ice. Gray bars drawn on both sides of the distribution curve centroid depict a fine range of such hypothetic states that are not present at all in cold water (blue curve). Their density increases at high temperatures (marigold curve) and then gets retained to some extent when the temperature of water drops down to atmospheric conditions (red curve), with the caveat that it progressively decreases with time (green curve). These states corresponding to the ranges in the Gaussian distribution labeled with the gray columns supposedly play a key role in enabling the hot water to freeze first.

SON: I am trying to imagine the atoms moving around, meeting, stopping to greet and reconnect with each other, then moving on and on and on, in circles and figure eights.

DAD: What precedes the onset of crystal formation is a lengthy preparatory process during which water molecules, whose kinetic energy gradually drops as the water temperature decreases, vigorously move around, rotate and translate trying to find the perfect fit together with their neighbors and form a stable crystalline nucleus. These are complex coordinated molecular movements happening across scales of a few nanometers or so. During this process, little embryos of the crystal phase form, but most of them immediately dissipate and turn into liquid. This is when the memory effect and the hypothetic states marked by the gray bars come into play. These are the states that bear high resemblance with the crystal structure of ice and their presence in the liquid facilitates this stochastic process of reorganization on the molecular scale during which water molecules seek that perfect cluster symmetry from which the crystal could grow. Eventually, the stable nuclei form at multiple points in the liquid, resulting in polycrystalline ice.

MOM: And hydrogen bonding here must play a key role.

DAD: That hydrogen bonding bringing water molecules together into clusters plays a key role in facilitating the memory effect can be deduced from the fact that no liquid other than water has been observed to date to undergo Mpemba effect. The type of memory we elaborate here, in fact, ties well with that conjured up by Sun *et al.*,[203,204] who presented experimental evidence in favor of memory intrinsic to the hydrogen bond, O:H-O. Based on this model, the heating stretches the O:H nonbond and shortens the H-O bond through O-O repulsion, thus making water molecules somewhat smaller and their separations larger, resulting in the reduction of density. The bond relaxation occurs gradually, not instantaneously in a cooler environment, enabling water to retain this memory of a past state for finite periods of time. When such preheated water hits the freezing point, the memory of interaction set at the high temperature is still fresh in the material. Quenched in the freezer, it gets preserved at these lower temperatures, but not for infinite periods of time. This preservation of dynamic states is possible because crystallization as a phase transformation is a stochastic process during which the sampling of a number of possible states by a system locally must precede the arrival at a correct cluster symmetry wherefrom nucleus formation and the subsequent crystal growth will proceed. One such hypothetic mechanism can find support in earlier molecular dynamics simulations, which showed that because hydrogen

[202] A. Lasanta, F. V. Reyes, A. Prados, A. Santos. When the hotter cools more quickly: Mpemba effect in granular fluids. Phys. Rev. Lett. 119, 148001 (2017).

[203] Zhang X, Huang Y, Ma Z, Zhou Y, Zhou J, Zheng W, Jiang Q, Sun CQ. Hydrogen-bond memory and water-skin supersolidity resolving the Mpemba paradox. Phys Chem Chem Phys. 16(42), 22995–23002 (2014).

[204] C. Q. Sun. Mpemba paradox: Hydrogen bond memory and water-skin supersolidity. arXiv 1501.00765 (2015).

bonding between water molecules forming neighboring hexamers is favored at elevated temperatures, warm water upon freezing displays a higher population of the hexagonal ice nuclei than the cooler water.[205] Although such hexameric water molecule clusters may present the link between the liquid state symmetry and the solid state symmetry, pinpointing the exact distribution of their numerous possible geometries, including prisms, cages, gloves, bags, boats and books, is a challenge for both theoretical and experimental approaches.[206,207] The challenge appears even more arduous when it is taken into account that there are 24 structural isomers of the water hexamer, W_6, with 14 different structures and 27 local minima for only one of them: the cage.[208] Knowing that the clusters standing at the gateway from water to ice number around 400 molecules,[209] the difficulty of the task of finding links between the small clusters, such as hexamers, and these larger structures further grows in scope. Now, hydrogen bonds in water, it should always be kept in mind, are dynamic phenomena, constantly forming and breaking, at the timescale of picoseconds,[210] and because of the higher heat content and thermal motion at higher temperatures, there will be islands of hydrogen bonds of a higher concentration and strength dispersed within the overall weaker and less concentrated bond milieu, meaning that water clusters exist in a greater distribution of states at higher temperatures and some time after the exposure to them on both sides of the distribution curve centroid illustrated in Fig. 11. Some of them will form bonds resembling those present in hexagonal ice and their delayed relaxation as the temperature is lowered promotes faster nucleation and crystallization rates at the freezing point in the preheated water.[211] In these hexagonal clusters may also lie the commonality between the memory effects displayable by hydroxyapatite and by water. As for hydroxyapatite, for example, we have seen that the longer time amorphized hydroxyapatite spent in the crystalline state prior to amorphization, the less time it takes for it to restore the crystalline state. The reason hypothetically lies in hexagonal Posner's clusters, the elementary building blocks of the crystal structure of hydroxyapatite: their preservation at higher concentrations following amorphization may be the source of memory of the crystalline state the material once adopted. By remembering this past state, it gets restored faster than in a material where this memory - equivalent to the abundance and order of hexagonal clusters - is less prominent. It is possible that a similar effect, involving the finite preservation of hexagonal water clusters under metastable conditions, may be responsible for the memory latent in water too.

MOM: I wonder if these cluster symmetries that facilitate crystallization must be hexagonal.

DAD: It is possible that symmetries other than hexagonal present the link between the preheated and the supercooled water, enabling the effective bridging of the gulf between the liquid state and the solid state. It is, for example, conceivable that the preexistence of cluster symmetries corresponding to the "strong" structure that the liquid state adopts prior to forming the first nuclei in the so-called "no man's land"[212] of the supercooled range rather than to the crystallographic order present in ice *per se* is what facilitates the phase transition.

MOM: But wouldn't such a short lifetime of hydrogen bonds, in the order of picoseconds, as you say, make sure that no clusters unique to high temperatures, even at such low concentrations, survive the drop to the ambient conditions, which takes a couple of minutes at least?

DAD: Not necessarily because the constant formation and breaking of short-lived hydrogen bonds ensures that the average lifetime of a cluster is longer than the ultrashort lifetime of any individual bond holding it together. The non-equilibrium nature of the cluster relaxation process aside, similar phenomena occur in most chemical equilibria, where reactions continue to proceed in both directions, but in a balanced manner, maintaining the system in an unchanged state from the macroscopic

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205 J. Jin, W. A. Goddard. Mechanisms underlying the Mpemba effect in water from molecular dynamics simulations. J. Phys. Chem. C 119, 2622–2629 (2015).

206 R. J. Saykally, D. J. Wales. Pinning Down the Water Hexamer. Science 336, 814–815 (2012).

207 L. Albrecht, S. Chowdhury, R. J. Boyd. Hydrogen Bond Cooperativity in Water Hexamers: Atomic Energy Perspective of Local Stabilities. J. Phys. Chem. A 117, 41, 10790–10799 (2013)

208 S. Jenkins, A. Restrepo, J. David, D. Yin, S. R. Kirk. Spanning QTAIM topology phase diagrams of water isomers W_4, W_5 and W_6. Phys. Chem. Chem. Phys. 2011,**13**, 11644–11656 (2011).

209 U. Buck, C. C. Pradzynski, T. Zeuch, J. M. Dieterich and B. Hartke, A size resolved investigation of large water clusters, Physical Chemistry Chemical Physics, 16, 6859–6871 (2014).

210 A. Luzar, D. Chandler. Hydrogen-bond kinetics in liquid water. Nature 379, 55–57 (1996).

211 Y. Tao, W. Zou, J. Jia, W. Li, D. Cremer - "Different Ways of Hydrogen Bonding in Water - Why Does Warm Water Freeze Faster than Cold Water?", Journal of Chemical Theory and Computation 13, 55–76 (2017).

212 Laksmono H, McQueen TA, Sellberg JA, Loh ND, Huang C, Schlesinger D, Sierra RG, Hampton CY, Nordlund D, Beye M, Martin AV, Barty A, Seibert MM, Messerschmidt M, Williams GJ, Boutet S, Amann-Winkel K, Loerting T, Pettersson LG, Bogan MJ, Nilsson A. Anomalous Behavior of the Homogeneous Ice Nucleation Rate in "No-Man's Land". J Phys Chem Lett. 2015 Jul 16; 6, 2826–2832 (2015).

perspective, despite the continuous changes it undergoes at the atomic level. This dynamic nature of the existence of individual clusters implies that even though individual clusters constantly dissolve, their total concentration may minimally change as the system changes conditions, such as by cooling. As a result, their traversing the medium in waves or flickering at random spots has been theoretically predicted.[213] Here it should be added that hydrogen bonding in water is a cooperative phenomenon, where the forming of one bond typically strengthens the bonds of its neighbors,[214] albeit with a great dependency on the bond angle and extrinsic parameters. These cooperative effects certainly increase the probability that memory effects are displayable in a real physical setting, such as that conducive to the Mpemba effect. These results tie well with the ability of salts to reduce and often, as in the case of ocean water, reverse the Mpemba effect (Fig. 2). Namely, as the concentration of salt in water increases, more and more water molecules engage in forming the hydration spheres around these ions, thus breaking the cluster symmetry predispositions intrinsic to pure water. With these symmetries broken, the density of states favoring freezing (gray bars in Fig. 11) automatically gets lower at high temperatures, but also the relaxation of these states proceeds faster as the water is cooled, meaning that the capacity of water to memorize states facilitating the phase transition to solid state is minimized. Also, it is worth adding that one peculiarity of water that we did not mention before is that fluctuations in entropy and density unexpectedly increase as the water enters the supercooled state.[215] In a way, the wild, broad and highly entropic distribution of states water has at high temperatures gets first minimized as the water is cooled, but then suddenly restored after it passes through the freezing point *en route* to the solid state. This effect increases the chances of having those past states memorized in the structure effective in facilitating the transition to the crystalline state. It may add up to another entropic argument in support of the memory effect, namely that of the hydrogen bonding being more ordered and less entropic at lower temperatures, where it adopts cluster symmetries differing significantly from the ice hexagons. At 4 °C, for example, the very gateway to the freezing point, water is at its densest and, thus, presumably the least entropic from the water/ice cluster symmetry correspondence perspective.

[213] M. Chaplin – "Water clusters: overview", In: Water Structure and Science, retrieved from http://www1.lsbu.ac.uk/water/clusters_overview.html#bb (2019).
[214] M. Chaplin – "Water's Hydrogen Bond Strength", arXiv 0706.1355 (2008).
[215] A. Nilsson, L. G. M. Pettersson. Perspective on the structure of liquid water. Chem. Phys. 389, 1–34 (2011).

MOM: It seems that this long explanation has put angels to sleep.

DAD: Or this imagining atoms wandering through space in search of coordination that would grow into stable clusters and then embryos and then nuclei and then crystals proved as a better sleep aid than counting sheep.

MOM: I wonder what happens to memory when the animate systems are asleep?

DAD: It solidifies. Crystallizes. A part of it deemed unnecessary sublimates and a part of it deemed useful sets into the neuronal bedrock of the brain.

MOM: I am still puzzled by the connotation of memory in inanimate systems. If materials can exhibit it, what is left of the uniqueness of the higher forms of life in the Cosmos?

DAD: Not all materials are presumably capable of displaying memory effects. But some materials under some conditions are. In fact, memory can be exhibited only by an out-of-equilibrium system, which in the case of the Mpemba effect takes the form of water relaxing from a thermally excited state to a state of equilibrium with the ambient conditions. Such inanimate, material systems capable of exhibiting memory effects consist of rugged energy landscapes instead of well-defined and deep energy wells.[216] Unlike a physical system with a deep energy minimum, tending to settle therein and not move anywhere, a system typified by a ragged energy landscape hops freely from one state to another.

MOM: Complex biomolecules, such as proteins, have similarly rugged energy landscapes.

DAD: This is why it is said that they "breathe", constantly changing conformations at the finest, atomistic and quantum mechanical scales and never, strictly speaking, existing in the same state twice.[217]

MOM: Embodiments of a jazzy state of mind, of unending improvisation and resistance to repeat oneself, they are.

[216] N. C. Keim, J. D. Paulsen, Z. Zeravcic, S. Sastry, S. R. Nagel. Memory formation in matter. Rev. Mod. Phys. 91, 035002 (2019).
[217] A. Cooper – "Thermodynamics of Protein Folding and Stability", In Protein: A Comprehensive Treatise Vol. 2, pp. 217–270, edited by Geoffrey Allen, JAI Press, Stamford, CN (1999).

DAD: Water, not surprisingly, counts among such materials with wrinkly energy landscapes. This is evident from the insignificant changes in the energy of the water molecules entailing relatively large changes in the H-O-H bond angle and the O-H bond length,[218] meaning that a water molecule normally sways between an infinitude of easily accessible geometries and the corresponding energy states, constantly changing its configuration over time. This is why when it is said that no single protein molecule exists in the same state twice, the same could be said about a similarly sized hydrogen-bonded congregation of water molecules, if not a single water molecule.

MOM: And with such rugged energy landscapes that facilitate effortless transitions from one energy state to another, while still allowing the system to anchor firmly onto the bedrocks of individual energy wells, albeit transiently, comes the ability to display memory.

DAD: Moreover, in such materials that are able to memorize past states and react to present stimuli differently depending on whether they do or do not remember them lies the future of materials science and engineering. The advent of smart materials, materials endowed with memory goes hand-in-hand with the progress in non-equilibrium materials and future days will undoubtedly witness their expansion.

SON: "Have to make an apology for the sake of future days"[219] (♪♫♪).

DAD: I see somebody is talking in their dream.

MOM: Talking nonsense too. "No apologies ever need be made, I know you better than you fake it"[220] (♪♫♪).

DAD: Ah, that craft beer tasting night in a Mission warehouse where we met and then hit it off "with the headlights pointed at the dawn" (♪♫♪).

MOM: Never enough dreaming.

DAD: And resorting to memory.

MOM: How powerful of an effect on our beings it has. One could argue that what we do with it is what ultimately elevates us from all other forms of life.

DAD: When we remember beautiful things, we may live in the past, but oh how marvelous our thoughts and actions in the present can be and how beautiful future can become. Good memory can be a blessing.

MOM: And a curse too, as when it scrambles the mind bearing them into shards, if only memories turn out to be persistently hostile and hurtful.

DAD: All this endless dwelling on dialectical dualities that pervade our reality. Everything that we make use of cannot be but a double-edged sword, having its dark side too.

SON: "So what's wrong with living in the past? It just happens to be the place I saw you last…" (♪♫♪).

MOM: "…and what's wrong with living in a dream? That one day the echo answers deep inside of me"[221] (♪♫♪).

DAD: But what is most interesting when it comes to this memory effect in the context of *Cool?* is that even though Osborne had a different explanation for the Mpemba effect in mind, referring to the supposedly higher convection heat loss rate because of the more fluid surface of the hot liquid, he did insinuate, albeit very subtly, the memory effect. Moreover, he correctly tied memory to the distribution of water temperature regions in a sample and the consequent water energy states. The seventh sentence before the end of their paper thus states the following: "The systems are not described adequately by a single temperature for they have temperature gradients that depend upon their previous history". One consequence of this is crystallization at temperatures above 0 °C that we observed in the preheated water containing higher temperature gradients than the thermally untreated water.

MOM: And yet, in spite of this awareness of the history effects, he did not find it appropriate to acknowledge any prior study in the paper.

DAD: Strangely, *Cool?* had no citations, like Einstein's special theory of relativity paper.[222] Both papers do

[218] M. R. Milovanović, J. M. Živković, D. B. Ninković, I. M. Stanković, S. D. Zarić. How flexible is the water molecule structure? Analysis of crystal structure and the potential energy surface. Phys. Chem. Chem. Phys. 22, 4138–4143 (2020).
[219] Can – "Future Days", In: Future Days, United Artists Records, New York, NY (1973).
[220] Smashing Pumpkins – "1979", In: Mellon Collie and the Infinite Sadness, Virgin, London, UK (1995).

[221] M. Nilsson – "1995", In: Zenith, Dark Skies Association, Berlin, Germany (2015).
[222] A. Einstein - "Zur Elektrodynamik bewegter Körper", Annalen der Physik 322 (10), 891–921 (1905).

explicitly acknowledge other people's work, though: Osborne acknowledges studies of frozen water pipes and correctly predicts that hot pipes would be more prone to bursting in cold weather than cold water pipes, while Einstein gives credit to Doppler, Hertz, Lorentz, Maxwell and Newton, albeit with nil references. This would be considered sloppy by today's publication standards and yet think of the mountains rolling by the sheer greatness of these works.

MOM: So how does this model that we propose stand in relation with other models? There must be many by now.

DAD: In fact, the Royal Society of Chemistry in the UK ran a competition in 2012 for the best explanation of the Mpemba effect and received 22,000 entries. Since the effect is still considered unexplained, this is not to say that the winner provided the correct explanation. My former fellow countryman, Nikola Bregović, who won the contest, ruminated over a couple of phenomena possibly explaining the effect before concluding that "the convective flows induced by heat gradients during cooling are most certainly responsible for the Mpemba effect",[223] but without excluding the supercooling effects, which can be affected in different ways by preheating, depending on the nature of the sample and the container.[224] With the latter idea, he reconnected with an earlier proposal that hot water would freeze before the cooler water only when it supercools to a lower temperature than the initially cool water.[225] Our experimental observations stand in support of some effect of convective flows and temperature gradients, but they refute this supercooling premise by showing that the preheated water exhibits a lesser degree of supercooling that the initially cold water.

MOM: Have there been any other notable attempts to explain it?

DAD: There have been many. The evaporation hypothesis proposed that the faster endothermic evaporation of warmer liquid leads to quicker heat dissipation, if not the more naïve reduction of the volume, thus increasing the cooling rate.[226] This had been the dominant way of explaining the Mpemba effect until 10 years ago,[227] when other models began to proliferate. Reference to air bubbles is another common way of explaining this effect,[228] which we have shed a huge question mark on. Another one of the often encountered ways of explaining it has been actually rooted in an experimental fallacy of placing the water containers in the freezer atop a layer of frost. This would cause this frosty layer to partially melt under the warmer liquid and increase its thermal conductivity. Thereafter, it has been thought by many that "hot water freezes sooner because of the higher thermal conductivity between the water container and the surface of the subzero environment".[229] This hypothesis, in a more sophisticated form, follows closely the aforementioned one referring to a higher cooling rate in warmer water due to its lower viscosity and better heat flow. Namely, warmer water contains greater temperature gradients on the microscale and with the heat transfer being proportional to the temperature gradient, this implies that the warmer liquid would be both cooled and heated more easily than the cold water.[230] In addition to the higher temperature gradient in warmer water, there is another effect that favors its faster cooling, namely convection. As the temperature of water increases, so do the convection streams in it become denser and more intense, meaning that the heat gets to be transferred to the air/liquid interface and the vessel/liquid interface faster, thus increasing the cooling rate. For this reason, the rate at which water cools is higher when the water is warm than when it is cold (Fig. 1a). In fact, the temperature of water rapidly drops from the boiling point to circa 50–60 °C, at which point the cooling rate significantly slows down. This explanation, like the evaporation hypothesis, however, ignores the fact that the Mpemba effect, as it can be deduced from the data presented in Fig. 1a, is not about the faster cooling rate, given that it is obvious from it that the cooler sample does reach the freezing point faster. This is not to say that a number of literature reports "take the term Mpemba-like to mean a faster rate of cooling (or heating) without involving a phase transition".[231] According to them, the Mpemba effect represents the anomalously faster cool-

[223] N. Bregović. Mpemba effect from a viewpoint of an experimental physical chemist. Royal Society of Chemistry, retrieved from https://www.rsc.org/images/nikola-bregovic-entry_tcm18-225169.pdf (2012).

[224] N. E. Dorsey, The freezing of supercooled water. Trans. Am. Phil. Soc. 38, 247–326 (1948).

[225] J. D. Brownridge. A search for the Mpemba effect: When hot water freezes faster then cold water. arXiv: 1003.3185 (2010).

[226] G. S. Kell - "The freezing of hot and cold water". American Journal of Physics 37, 564–565 (1969).

[227] M. Vynnycky, S. L. Mitchell. Evaporative cooling and the Mpemba effect. Heat and Mass Transfer 46, 881–890 (2010).

[228] B. Wojciechowski. Freezing of Aqueous Solutions Containing Gases. Cryst. Res. Technol. 23, 843–848 (1988).

[229] J. D. Brownridge. When does hot water freeze faster than cold water? A search for the Mpemba effect. Am. J. Phys. 79, 78–84 (2011).

[230] M. Balážovič, B. Tomášik. Paradox of temperature decreasing without unique explanation. Temperature (Austin) 2(1), 61–62 (2015).

[231] A. Gijon, A. Lasanta, E. R. Hernandez. Paths toward equilibrium in molecular systems: the case of water. Phys. Rev. E 100, 032103 (2019).

ing of a warmer system than of its cooler analogue[232] as well as the faster heating of a cooler system than of its warmer analogue,[233] when both are kept in the same thermal reservoir. However, although such effects occur for real in certain physical systems and may be traceable to memory effects too,[234] they do not veritably represent what the Mpemba effect was originally about. Quite contrary to the definition of "Mpemba-like" in this quote by Gijon *et al.*, the Mpemba effect was initially about the phase transition and not about the cooling rate effects. Osborne's students did measure the rate of cooling, but they did not compare the cooling rates between the hot and the cold water. They did, however, compare the time it takes for freezing to commence depending on the initial temperature of water. Which is to say that as far as the key to explaining the Mpemba effect is concerned, it must be about something that water brings with itself from the higher temperature and that makes the freezing from the point it reaches 0 °C onwards faster.

MOM: So what is this mysterious baggage?

DAD: That is what we were here to figure out. We caught a good glimpse of it, but it is so dynamic and volatile that it cannot be easily captured with the simple nets of our homemade experimentation and rudimentary conceptualization. But whatever it is, it falls under the umbrella of memory. Whether it is stored in the way water clusters organize, that is, in symmetry-related effects defined by the specificities of hydrogen bonding, or in something that water brings from higher temperatures on more macroscopic scales, such as specific hydrodynamic flows and gradients, it can be classified as a memory, albeit much more validly in the former scenario than in the latter.

MOM: And what, I wonder, if a number of effects, some more intense, some less, combine to make up for this phenomenon? Like in the antimicrobial mechanism of action of hydroxyapatite, which we recently scrutinized.[235]

DAD: It is the likeliest scenario. Besides, we have seen that the cool water forms an even ice cap uniformly covering the surface of the liquid and acting as a thermally insulating layer. This layer was absent in the preheated liquid, which suggests that some memory effects of heating may be surface-specific, if not direct corollaries of the delayed relaxation of the internal reordering of water clusters induced by heating. This would agree with the aforementioned study reporting on one such memory effect involving surface tension of water after microwave heating. Also, the internal, cluster dynamics memory coupled with the surface memory concords to the model of the Mpemba effect proposed by Sun *et al.*, according to which "hydrogen-bond memory and water-skin supersolidity" are the two dominant physical effects explaining it. As per this model, contrary to most other materials, which display high skin mass densities because of the bond contractions caused by the atomic undercoordination at the surface, the cooperative relaxation of O:H-O molecules lowers the skin density and its specific heat, which raises the thermal diffusivity to favor the heat outflow from the liquid.[236] These surface effects, coupled to the memory intrinsic to O:H-O, set grounds for the unusual heat dissipations, including the Mpemba effect and its inverse. On top of this, we have seen that higher temperature gradients and densities of convection streams in the preheated water get partially preserved during cooling, favoring the Mpemba effect. Whether this comparatively cruder, macroscopic form of memory is reducible to the cooperative hydrogen bonding dynamics and cluster densities of state at the molecular and the nano scales or it is a product of more macroscopic hydrodynamic phenomena, including perhaps the nonlinearity of the turbulent flow, is unclear. But what is clear is that all these effects, cluster symmetry ones, surface ones and hydrodynamic ones, represent a form of memory, albeit emergent at different scales. And if there is a multiplicity of sources of memory in water, then they must influence each other, if not having the more macroscopic effects caused solely by the effects present on the finer scales. At the end of the fairytale, in a multivariable world we live, where there is no such thing as a variable disconnected from any other. It is all tangled, like in a forest.

MOM: It is time to wake up the angels. Bunnies are here too.

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[232] A. Torrente, M. A. López-Castaño, A. Lasanta, F. V. Reyes, A.Prados, A. Santos, Large Mpemba-like effect in a gas of inelastic rough hard spheres, Physical Review E 99, 060901 (2019).
[233] Z. Lu, O. Raz. Nonequilibrium thermodynamics of the Markovian Mpemba effect and its inverse. Proc Natl Acad Sci U S A. 114(20): 5083–5088 (2017).
[234] M. Baity-Jesi, E. Calore, A. Cruz, L. A. Fernandez, J. M. Gil-Narvión, A. Gordillo-Guerrero, D. Iñiguez, A. Lasanta, A. Maiorano, E. Marinari, V. Martin-Mayor, J. Moreno-Gordo, A. Muñoz Sudupe, D. Navarro, G. Parisi, S. Perez-Gaviro, F. Ricci-Tersenghi, J. J. Ruiz-Lorenzo, S. F. Schifano, B. Seoane, A. Tarancón, R. Tripiccione, D. Yllanes. The Mpemba effect in spin glasses is a persistent memory effect. Proceedings of the National Academy of Sciences 116, 15350–15355 (2019).
[235] V. Uskoković, S. Tang, M. G. Nikolić, S. Marković, V. M. Wu – "Calcium Phosphate Nanoparticles as Intrinsic Inorganic Antimicrobials: In Search of a Key Particle Property", Biointerphases 14, 031001 (2019).
[236] C. Q. Sun. Relaxation of the Chemical Bond, Springer-Verlag, New York, NY (2014).

DAD: This patting the pets, lightly, echoes across the farthest ends of the universe. It may get embedded in its memory for a whole eternity, never to be erased. So tightly tied one to another everything is in this enchanted reality.

MOM: Ahoy. Enough dreaming. Let us pack the necessities. Mpemba experimented on ice-creams, so let us grab a couple of them from the freezer and head over to the beach to see the sunrise and celebrate this moment.

SON: Can we stop by the playground on the way there?

DAD: We could swing by the Arrowhead.

DAUGHTER: Yay, the playground!

SON: Did we miss out on something?

MOM: You were awake for the most part. You only overslept the conclusions.

DAD: Very keen of you it was. There are no conclusions in this unending exploration of reality that science offers us. Regardless of how many answers we propose, there will be ever more questions latent in them to be plucked, wondered over and set as foundations for further research.

MOM: Aye. Here we go. With the sip of the morning lemonade from the seven little lemons from that lone and hunched citrus tree from our garden.

DAD: And pet sounds in our ears.

MOM: To playgrounds all the world over.

DAD: To the heartrending squeal of Kanji's sleeted swing, the gay lilt of the Echo park airplane and the million-year old wheeze of falling sand.

MOM: To children of all ages.

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ACT IV

(Ocean shore at sunrise. Air is translucent. Joy falls from the sky.)

SON: Pass the ball.

DAUGHTER: Here, catch.

SON: The sun is going to my eyes. Move a little bit this way.

DAUGHTER: OK.

MOM: The sun begins to rise. It peaks above the hills.

DAD: And waves glisten.

MOM: The endless ocean before us and these gruesome granite cliffs behind us. Here's the ball.

DAD: A scenery so delightful and yet so oppressive.

MOM: Gorgeous but grievous. This stern headland says it all.

DAD: Southern California, cold and soulless, wake up.

MOM: Wake up to the sound of splashes and children's laughter.

DAD: And the listless thoughts of benumbed faces confined to metal monsters, knives out, one against the world, that will soon start clogging the motorways behind our back.

MOM: Billows of O. C. melancholy, wash over us.

DAD: I feel like this cliff is going to swallow me.

SON: "One day I am gonna grow wings in chemical reaction"[237] (♪♫♪).

DAD: And fly over these crescent waves.

MOM: Like a seagull.

DAD: Here, catch.

SON: Yay!

DAUGHTER: Playing ball is fun.

DAD: Not just any ball. A colorful ball. A ball casting down the glass-bead covered bell decks of my mind the shadows of memories of shuffled future, present and past from another play,[238] more poignant than this. A ball

[237] Radiohead – "Let Down", In: OK Computer, Parlophone, London, UK (1997).

[238] I. Torkar – "Pisana žoga", Mladinska Knjiga, Ljubljana, Yugoslavia (1955).

that plucks a teardrop bigger than this ocean from this lonesome eye of a "river poet search naiveté".

MOM: We have made a long way from asteroids flying through space and hitting planets to this gentle and elating passing of a soft and colorful beach ball.

DAD: A metaphor of our aspiring to humanize natural science with these words it is. We hope that a day will come when dull technical papers sent out to fly through a cold and vacuous aether, with no soul to arouse along the way, will cede place to research papers like this one, which warm hearts and enkindle spirits just as much as they enrich the scientific knowledge.

MOM: I think I shall hold this ball that speaks volumes about romanticizing natural science close to me heart.

SON: No mom, the ball must be passed.

DAD: That is exactly what we are doing. Passing it on.

MOM: Now may be the time to recapitulate what we have learnt about the Mpemba effect and what this strange phase transition has instructed us with respect to broader domains of our lives.

DAD: Aye. Maybe it will brighten another famished day ahead of us.

MOM: Us four rolling stones.

SON: Alright. We showed that the Mpemba effect was real and discovered that water memory makes it possible.

MOM: Although the effect was present in DI and tap water, it was annulled at high salinities, such as those in the ocean water that lies just ahead of us.

DAD: We showed that the Mpemba effect does not involve the faster reaching of the transition point by the hot water, but rather the faster passage through it. The freezing point is reached by the cold water first, but the hot water unlocks its secret code and passes through it faster.

SON: The effect of the memory was also hinted at by other analyses we ran.

DAD: Like DLS, which showed that the low distinctiveness of the correlation function of water at higher temperatures gets preserved after the water has cooled, making it significantly structurally different from the unheated water. The scattering count rate also preserved some of its elevation after the heated water has cooled.

MOM: Then the vibrational spectroscopy, which showed that the hydroxyl stretch peak increases slightly in integrated area with heating, but does not fully relax to the preheated state after cooling, unlike the FWHM, which mostly does.

DAD: Optical density also displayed higher values in the entire visible range in heated water and, as in light scattering and vibrational spectroscopy analyses, its value did not get reduced to the preheated state after cooling. All of this has strengthen our hypothesis that there are structural features making up hot water that get memorized in it for some time after it has cooled, enabling it to act thoroughly differently in some respects compared to water that never underwent any thermal treatment.

MOM: Finally, our modest attempt at producing a gelatin-based hydrogel using two water samples with identical temperatures, one brought to it from the ambient conditions and another one brought to it from elevated temperature ranges, resulted in slightly different polymer crystallinities thanks to presumably different hydration of the polypeptide chains by waters with different thermal histories.

SON: We also learned that bubbles do not cause the Mpemba effect and that it is not about cooling faster when you start off warm, but crystallizing faster instead.

DAD: Indeed. The time it takes for the freezing point to be reached is directly proportional to the initial temperature of water, but the preheated water begins to crystallize even before the freezing point has been uniformly reached by all pockets in the liquid. This has suggested that more broadly distributed static and dynamic cluster symmetry correlations, but also larger temperature gradients and densities of convection streams in the preheated water get partially preserved during cooling, favoring the stochastics of the Mpemba effect.

SON: And so we concluded that memory is the secret force behind the Mpemba effect.

MOM: But if memory endows water, does this mean that traces of the most sublime qualities of higher forms of life are scattered all through the inanimate world?

DAD: And that everything is alive? Every toy, every cloud, every grain of sand. As if in a dream.

MOM: As if in a dream, they may all feel our sympathy for them.

DAD: Indeed, what if life is really such that when we reach out to this water before us with the hands of the heart, the ocean, like the sea of Solaris,[239] swells invisibly and greets us back.

SON: In its funny language of atoms and molecules.

MOM: And hydrogen bonds too.

DAD: And takes the memory of meeting us to its depths. For secrets must let be, lest the questions driving research and progress on scientific and spiritual planes alike vanish and vapidity of the intellect installs itself in their place.

MOM: So it is with this memory of water. It has been taken to some mysterious depths.

DAD: Exquisite explorations notwithstanding, we do not know what depths this power of memory lies cocooned in, if it is dormant in hydrogen-bond controlled cluster reorganization or hydrodynamic nonlinearities or some other thermodynamic non-equilibria or all these things together, tangled up into an inextricable knot.

MOM: Like in that dark cocoon that waits patiently to get "go-o-o-orgeous wings and fly away"[240] (♪♫♪).

SON: 10 REM ♥. My first line of code.

DAD: "I remember that"[241] (♪♫♪). That is, the first three letters of the word "remember", REM, the favorite programming command of mine, introducing a hidden message to the code, visible only to its excavator, but not to the executor. It is also laughable how you used a non-ASCII character, an instant bug for the computer.

MOM: Does the power of love not do exactly that to robots around us? Throw them off their inertly followed paths and awaken them in an instant, like a punch of a thousand stars.

DAD: Verily, the best way to unmake a robot is to ask it a fundamental question, like the one love is. In fact, any cognitive system passively relying on sets of premises and paradigms embedded in it, including those of Mpemba's erudite disbelievers, is best deranged by asking it to revisit its foundations. It is thus that the machinelike and the industrial in us die out and the lifelike and the humane proliferate, making us, romanticists and luddites at heart, smile underneath these breaths apneic from the displays of a chronic Florence syndrome, breathlessly, as it were.

SON: Essence over surface, mind over matter, you always say.

MOM: To remember, then, is also to cast light onto the foundations of our cognition.

DAD: And with the right memory, the hidden doors leading to the seats of our souls can be illuminated, unlocked, opened and entered, potentially turning these blues into bliss in the blink of an eye.

MOM: But what has the Mpemba effect taught us through the analogy, about the way we ought to approach life and creative work?

DAD: To be hotheaded, warmhearted, to steam with passions and shy away from being cold, callous and calculative. Because in such a way we transition faster and more facilely to the crystalline state, the state of perfection and, in abovementioned thermodynamic terms, love.

MOM: Also, to be strange, outlandish. abnormal, anomalous, crazy.

DAD: All those attributes that Einstein wished to see in his mundane students when he disparaged them and their ideas for "not being crazy enough".[242]

SON: Because "imagination is more important than knowledge".[243]

MOM: And the glow of a bare star emitted in a second cannot be matched but by ages of the existence of earths and all their luminous ionospheres and technospheres.

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[239] S. Lem – "Solaris", Mariner, Boston, MA (1961).
[240] J. Mitchell – "The Last Time I Saw Richard", In: Blue, Reprise, Los Angeles, CA (1971).
[241] Prefab Sprout – "I Remember That", In: From Langley Park to Memphis, Kitchenware, Newcastle upon Tyne, UK (1988).
[242] V. Uskoković – "SF Pensées", Amazon Kindle Direct Publishing, Scotts Valley, CA (2019).
[243] C. Ferrie – "Goodnight Lab: A Scientific Parody", Sourcebooks, Naperville, IL (2017).

DAD: Remember the inappropriateness of Mpemba's question during Osborne's talk at the Mkwawa High School in Iringa. It was utterly out of place and if it were asked today, it would undoubtedly earn the questioner the epithet of a fool, but it presented the most significant question, a crossroad of a kind in the scientific careers of Mpemba and Osborne, both of whom became known in the scientific world by this phenomenon only. Besides, Mpemba went on to become a gamekeeper, while Osborne accepted a diplomatic position after a few years, when he resigned from academia, long before it became a cutthroat rat race for the politically apt that it is today.

SON: So we must be, as you say, unacceptable, inept, out of common sense. Like children? Like us?

MOM: Yes, like children. Like you. The story behind the Mpemba effect teaches us to trust the outliers and fall in love with abnormalities and all the other unusual things that resist to be aligned with the mainstream.

DAD: The Mpemba effect also teaches us to be disobedient. To disbelieve the authority. To resist being a sheepish mop, a sheer derivative in the face of abidance-seeking powers.

MOM: Even if this brings us to the edge of the cliff and puts our livelihood and bare survival to stake? The cliff whereon the four of us stand at this crossroad in space and time?

DAD: Such cliffs open the most beautiful of views before the hangers thereon, which is a spiritual reward wholly foreign to all the world's yes men locked inside the sarcophagi of sycophantic safety.

DAUGHTER: Pawn walk up, be a queen.

DAD: In addition to this, excommunication from the reigning order and the embracement of poverty, as the broad picture of what we have done here suggests, is a gateway to empirical inquiries that could revolutionize science with their intrinsic beauties. Mpemba's story, in that sense, is a lesson on how to play well in the role of an outsider and willingly fall out of the mainstream circles and into the boney hands of poverty to give birth to worldviews of groundbreaking novelty.

MOM: And what about his allegedly being late for his class? Does it teach us to be untimely too?

DAD: Most definitely. Because to be compliant with time is to miss a lot of insights about the past, without which, as we have seen, the understanding of the present is practically impossible. Only by stepping away from specific points of view can we catch a glimpse of their key traits, which would have otherwise rested in our blind spots had we resisted to make these steps to the side.

SON: So our clocks should always be late.

DAD: Our inner clocks, yes. Punctuality and all other varieties of conformity are to be tossed into the ocean and let sink under these waves. We ought to return to the consciousness of a child, with creativity still living inside it, untouched by the discipline, regurgitation of facts, adherence to the paradigms, compliance with the dull rules of conduct, authoritarianism and other aspects of schooling that take life out of it. Mpemba and Osborne knew this instinctively and in their paper they warned against the "danger of an authoritarian physics".[11] In that sense, theirs was largely a message of mistrusting the authority, scientific, pedagogic, social, you name it. Liberating oneself from any authoritarian influence and the sense of obligation to subjugate oneself to it. That is what the Mpemba effect speaks to us here, with this Pacific breeze grazing our wizened faces.

MOM: Being free. That is the key.

DAD: The key that unkeys. The key that opens and leaves the chests, the portals and all other kinds of doors open, like al-Bisṭāmī's doorway through which the wisdom entered his heart.[244]

DAUGHTER: Before the wind?

DAD: Remember, the draft of air was threatening to shut the door to a room where his mom lay ill. In a stifled voice, she asked him to keep the door open and he spent night after night by the door to make sure that they do not close. The legend says that this is how the wisdom of gods creeped into the Sufi's heart.

SON: "…you find inspiration in anyone who's ever gone and opened up a closing door…"[245] (♪♫♪).

MOM: Open doors are gateways to wisdom, everywhere and at all times.

[244] E. de Vitray-Meyerovitch – "An Anthology of Sufi Texts", Naprijed, Zagreb, Yugoslavia (1978).
[245] Pet Shop Boys – "Being Boring", In: Behaviour, Parlophone, London, UK (1990).

DAD: Whereas closed ones are evocative of animosities, dogmatism, arrogance and know-it-all pretense.

SON: Is that why the keys are always lost?[246]

MOM: Because all we are to find here are mysteries.

DAD: Never answering, always questioning the answers and settling in our explorations at but more beautiful questions to questions asked in the first place.

MOM: The curtains open, the guards drop, the masks fall. The stage is children's.

DAD: The world is yours. "You can make it last forever"[247] (♪♫♪).

MOM: Live life as if it was a dream. Glide across the world's stage with the winds of change in your sails.

DAD: And when the story is about to hit the ending, be ready to leap into the sunset, in style, but with treasure in your hands. *Iz bajke iza*đi, al*' blago ponesi*, as my birthplace fairies whispered into the air.

MOM: A treasure that is all but visible and tangible it must be.

DAD: A treasure that adorns the atria of our memory.

MOM: A treasure that brightens the soul and nothing more.

DAD: "All is memory taken home with me" (♪♫♪).

MOM: "The opera, the stolen tea, the sand drawing, the verging sea"[248] (♪♫♪).

DAD: "All years ago" (♪♫♪). And tears, tears roll in streams.

MOM: But wait, before we melt I have some ice-creams for everyone. To celebrate the cool of the snow and all the world's jangly walks over it and the earth's laughter under.

DAD: I brought some of the ice we made in the experiments, too. I will place it here. We all know by now that the best things in life are for free. So is this ice, this ephemeral totem humming crackly tunes of devotion to the higher good under this early morning sun.

MOM: To *Glasperlenspiel*?

DAD: To *Glasperlenspiel*. And beyond. Let us have the water from this strangely shaped crystal evocative of home melt at the end of this ballad and slide gently into the ocean.

SON: "Me, my thoughts are flower strewn, ocean storm, bayberry moon…"[249] (♪♫♪).

MOM: Either way, it will go up into the clouds, into the firmament before it drops down, so the cycle of life continues.

DAUGHTER: Rain fall, come rainbow.

DAD: Somebody's eyes are brightening, ego vanishing. This way everybody becomes One and our mission today is over. We can look forward into new voyages and explorations in this endless adventure that science is, but what was done yesterday we let go. Anchors lifted, unattached we slip away. It is world's from now on.

SON: Look, another chocolate drop on the gravel!

DAUGHTER: Yay, another discobery!

MOM: Disco berry?

DAUGHTER: Discobery!

MOM: Ah, discovery.

SON: Are we ready for a new discovery?

DAD: New ideas, new experiments, new findings and new interpretations for an endless series of backyard studies, all lying dormant in a drop of chocolate ice-cream.

MOM: The look of it may put art on display in the loftiest galleries all the world over to shame.

SON: How beautiful is this ice-cream smearing over the pebbly ground. I can recognize all sorts of shapes.

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246 R. McGuire – "Here", Pantheon, New York, NY (2014).
247 Smashing Pumpkins – "Thirty-three", In: Mellon Collie and the Infinite Sadness, Virgin, London, UK (1995).
248 10,000 Maniacs – "Verdi Cries", In: In My Tribe, Elektra, New York, NY (1987).
249 R. E. M. – "Find the River", In: Automatic for the People, Warner Bros, Burbank, CA (1993).

DAD: As usual, this reminds me of a story.

SON: Again?

MOM: About a different Mpemba?

DAD: It is a story about a boy who loved to walk up and down the beach and play with pebbles and stones. He would gaze at them with a delicate sense of wonder, as if he had come into contact with the most ancient hieroglyphs or extraterrestrial messages.

DAUGHTER: The ice-cream is feisty.

DAD: And then, a girl with an ice-cream in her hands showed up, walking down the path that the boy had taken earlier. The boy was not there anymore, but the rocks he played with were. The girl accidentally tripped on one and her ice-cream fell to the ground. She began to cry, but then noticed the shimmery surface of the sea in the distance and the curious shapes yielded by the spilled ice-cream. A strange train of thought got propelled inside her at that instant by the images from memory, the destination of which was the conviction that things giving us simple pleasures in life are often to be spilled and bled all over us and the world to yield a truest beauty in it, being a prelude to an even deeper insight, which was that the material things in our possession are nowhere as important as wonder and love that illuminate our insides. Without her being aware of it, this tiny spark of an insight became so deeply ingrained in this girl's mindset that it began to resemble a grain of sand around which a pearly intellect, like in an abalone shell, crystallized over time. This ice-cream, thus, turned into a fountainhead of morality that kept the girl repeatedly on the right path, whenever she would find herself in doubt over whether to seek the accrual of material wealth or descend into poverty for the sake of spiritual enrichment.

SON: Whose story is this, Dad?

DAD: I improvised this story at my philosophy of science exam as a senior student, to accompany an empty piece of paper I brought to it to demonstrate the principle of causality. Instead of discussing this philosophical principle from academically eloquent standpoints, I told this story, which was meant to provide an analogy of how hidden and subtle cause-and-effect relationships in reality are.

MOM: May I assume that the exam was successfully passed?

DAD: "Falling, falling"[250] (♪♫♪), in every time and age. But what else to expect from a dreamer and fosterer of freedoms locked in a system of authoritarian ethic, let alone a poet in the clutches of hard science to which lyricism is alien? Nevertheless, to be true to the ideals of the past, the first test I have ever given to students was in the form of a blank piece of paper to be filled with one's own questions and answers.

SON: Why was that?

DAUGHTER: Wise was that.

DAD: It was to crush the barbed wall of academic assessments in an act of rebellion, but also to insinuate that the essence of science lies in self-doubt and subjugation of everything to selfless scrutiny, including, more than anything, the premises, the routes and the outcomes of one's own thought and perception.

MOM: The most important questions in life indeed arise from the inside.

DAD: And a traveler on the long and winding road of science is to turn oneself into a humble question mark rather than be an arrogant exclamation point that pretends to know the answer to it all. He should keep his mind untainted and pure, open to possibilities, always looking forward to a miracle that may just about to occur from behind every corner of his experience.

MOM: A truly magical frame of mind this would be.

DAD: And today my favorite assignments are those containing a single Fermi question.

MOM: Like what?

DAD: Like "how many piano tuners live in the city of Chicago" in a class on high-energy physics.

MOM: Doesn't that seem irrelevant and a little bit harebrained?

DAD: Not really. A question like this would seemingly fall out of the blue onto the sheet of paper, prompting the answerer to ascend in imagination to the depths of the bluish sky above her dreamy head and bounce back from the far edge of the firmament before arriving back with an insight that all is connected in the Cosmos and

[250] J. Cruise – "Falling", In: Floating into the Night, Warner Bros, Los Angeles, CA (1989).

that there is no such thing as a random question with no relevance for her science and for her existence right there and then.

MOM: I can foresee the outrage of robots, who demand a precise answer, when forced to deal with this infinite open-endedness.

DAD: Another thing that these clean sheets and occasional outlandish questions adorning them were supposed to symbolize was the necessity of befriending our intuition, switching on all our surprise senses and improvising our ways through the forest of knowledge, day in, day out.

MOM: Using a blank sheet to illustrate causal effects is such a Zen thing to do.

SON: "I am unwritten, can't read my mind"[251] (♪♫♪).

MOM: Indeed, all is open ahead of us, like the sea.

DAD: Questions outweighing the answers.

MOM: The mind is blank. Pure. Undefiled. Forgiving.

DAD: The sky. The sun.

SON: The space.

DAD: For eternity.

DAUGHTER: Or a day.[252]

SON: Can eternity fit in a day?

DAD: For all I care, it can fit in the blink of an eye. Reality is like Pascal's circle - its circumference is nowhere and center everywhere.

SON: Dad, it is true. We did this all in a day.

DAD: From the basic ideas to the experiments to coming up with a relevant scientific finding.

MOM: Yesterday at noon we came up with questions about the Mpemba effect, in the afternoon we journeyed to the barn and raided the campus secretly, then we spent most of the night running the experiments and discussing the data and now we are here to watch the sunrise together and think about the new beginnings.

SON: "Find yourself in a new direction, eons far from the Sun"[253] (♪♫♪).

DAD: From station to station, from ice-cream to ice-cream, the circle closes. That's the beauty of science. And that is perhaps how science should be done. And how it should be let live and evolve. The way a rock 'n' roll song is made. In a heartbeat. Overwork it and it falls flat on its face. It loses its grace and goes stale if it sits for too long.

MOM: Meaning that imperfections are not to be patiently and slowly weeded out.

DAD: No. They give life to the work.

MOM: Talk about wheat and tar growing together.

DAD: The bliss and the wrath. Like the swinging moods of a child.

MOM: Or four seasons. All at once.

DAD: Here we touch the key to the most mesmerizing artistic expression. And then bounce off it right away.

SON: We diffuse into space.

DAUGHTER: We travel.

MOM: And moment by moment, we get closer to that crystal that is in and around us, the crystal symbolizing love, the one we touched yesterday for a brief moment of time, under the open skies, but, likewise, bounced off it.

DAD: A metaphor of the grand sacrifice we must make is imprinted in this transition from a wavy and summery fluid that water is to a cold and wintery solid that ice is, all for the sake of awakening that greatest of all cosmic powers.

MOM: Love.

DAD: The power that could be roused from sleep only by making such grand sacrifices.

[251] N. Bedingfield – "Unwritten", In: Unwritten, Phonogenic, London, UK (2004).
[252] S. Jacoby – "Forever or a day", Chronicle Books, San Francisco, CA (2018).
[253] The Beach House – "Myth", In: Bloom, Sub Pop, Seattle, WA (2012).

SON: So say bye to wavy blue ocean we must.

DAD: And to boat rides on turquoise lakes with baby turtles and butterflies.

MOM: And to sprinkler showers at sunset, with rainbows in our eyes.

DAD: And to afternoon teas under luscious hackberries and leaps into pools and ponds with ducks and walleyes.

MOM: So goodbye California it is?

DAD: And hello life.

MOM: Hand-in-hand, all aboard?

SON: Yes!

DAUGHTER: Yes!

DAD: The dream exited, the treasure taken?

DAUGHTER: Aye!
SON: Aye!

MOM: We go.

SON: We go.

DAD: And don't forget the ball.

(*Everybody looks back, toward the ocean. The waves, gentle and yet powerful, glisten with an early morning sunshine. The beach ball is not there anymore. It has been carried away by the wind. A long silence ensues. Hairs wave, hands held.*)

SON: Forget?

DAUGHTER: 'Memba.

MATERIALS & METHODS

Three different types of water were analyzed in this study: DI water obtained using the *Milli-Q® IQ 7000* purification system, tap water from Irvine, CA, and ocean water sampled from the coast of Newport Beach, CA. Standard measurements of the crystallization rate involved preheating 30 ml water samples inside ceramic mugs in microwave oven for 30–40 seconds, that is, until reaching 80–90 °C, and then pouring them inside flexible polydimethylsiloxane (PDMS, a.k.a. silicone) food-grade cupcake liners (*OXO*) with round bottoms measuring 45 mm in diameter of the base, 35 mm in height and 66 mm in diameter of the open top surface. The height of the 30 ml water volume inside PDMS vessels was 13 mm, with the diameters of the bottom and top surface being 45 and 54 mm, respectively. Containers with the heated water were cooled down until the water temperature reached 60 °C and then placed onto an unfrosted freezer (*LG Inverter Linear*) shelf together with the vessels filled with the same type of unheated water. The volume of the water, not exceeding 0.3 dm^3 for the highest numbers of simultaneously run samples in replicates, was negligible compared to 82 dm^3 of the interior volume of the freezer. Temperature readings were taken periodically using a thermocouple (*Thermo Fisher Scientific*), without removing the water from the freezer. Crystallization rate was measured by cracking the ice cap formed over the liquid and pipetting out the content of the liquid phase from the semi-frozen samples at different time points between the 10^{th} and the 90^{th} min of incubation. The volumes of the liquid phase were subtracted from the initial volume of 30 ml and the converted to percentages. Experiments measuring the thawing and refreezing rates involved freezing water samples for 4 h and repeating the solid state volume measurement procedure at different time points. The average standard deviation across the entire data point set of the study was ± 5.2 % (or ± 1.57 ml) for the solid state volume measurements and ± 1.3 °C for the temperature measurements.

A variant of the Johnson-Mehl-Avrami-Kolmogorov model was used to derive the Avrami exponent for the crystallization reaction involving different initial temperatures of the liquid phase. The following equation was used, where x was the degree of transformation of the liquid to the solid phase, ranging from 0 to 1:

$$\log\log(1/(1-x)) = n\log t + n\log k - \log 2.3 \qquad (1)$$

Plots depicting $\log\log(1/(1-x))$ as a function of $\log t$, where t was the reaction time in minutes, allowed for the Avrami exponent, n, to be calculated from the slope in the first step and the Avrami reaction constant, k, to be calculated from the intercept in the second step.

Crystal structures of hydroxyapatite and water were constructed from CIF files reported in the literature on the Crystal Maker 10.3.2 platform. To produce gels, gelatin powder was mixed with either water at room temperature before being heated to 37 °C or water preheated to 80–90 °C before being cooled down to 37 °C. Mixtures were manually agitated and analyzed on a *Bruker D2*

Phaser diffractometer. Diffractometric patterns were smoothened using the Lowess routine and an equal proportion for span for all the patterns (*Origin Pro 2018*). The average crystallite size, *d*, was estimated by applying the Debye-Scherrer equation on the half-width of the (002) diffraction peak of gelatin expressed in radians ($\beta_{1/2}$), using 1.5418 Å as the wavelength of $Cu_{K\alpha}$ as the radiation source (λ):

$$d = 0.94\lambda/\beta_{1/2}\cos\theta \quad (2)$$

Dynamic light scattering (DLS) analyses were performed on a *Malvern Zetasizer Nano-ZS* device. Fourier transform infrared spectroscopy (FTIR) measurements were performed on water droplets with different temperatures and histories of heating on a *Bruker Alpha Platinum* attenuated total reflection (ATR) spectrometer with a single-reflection diamond/WC composite ATR module, in the 400–4000 cm^{-1} wavenumber range and the maximal spectral resolution of 2 cm^{-1}. Backgrounds of the spectra were subtracted prior to the peak integration routine using manually selected 2^{nd} derivative anchor points (*Origin Pro 2018*). Optical density analyses were performed on 500 μl water aliquots in the 250–700 nm wavelength range on a *BMG Labtech FLUostar Omega* plate reader. To produce the normal and/or differentiated optical density curves and IR absorption spectra for each water sample and to compare their spectral features, including FWHM and integrated peak areas, the results of three independent measurements were plotted and averaged in *Origin Pro 2018*.

CONTRIBUTIONS

Per CRediT taxonomy: E. Uskoković – Visualization; T. Uskoković – Investigation, Visualization; V. Wu – Resources; V. Uskoković – Conceptualization, Methodology, Formal Analysis, Investigation, Writing, Visualization, Supervision, Project Administration.

ACKNOWLEDGMENTS

We acknowledge the technical assistance of Sean Tang with FTIR measurements, Carles Molina Vidal with absorbance analyses and NIH R00-DE021416 for equipment support. We dedicate this one to all the clockless bunnies that partied in our backyard and chomped on our porch when we were not around and to the memory of one angel who has overseen this study from a nearby cloud.