Life's Matrix

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'If I were called in to construct a religion', said Philip Larkin, 'I should make use of water.' It is the poet's way of saying that the sanctity of water is ancient and universal. For Muslims water is fundamentally pure, and they must perform ritual cleansing before prayer. The mother of Christ is named as a sea goddess, and water initiates Christians into the Church in the rite of baptism; in early Christian tradition, the baptismal font was the womb of Mary. Natural springs and wells are commonly devoted to goddesses, like those at the temple of the Delphic Oracle in Greece, once sacred to the Earth goddess Gaea.

'The highest good', Lao Tzu says in the *Tao Te Ching*, 'is like water. Water gives life to the ten thousand things.' This is why the Hopi Native Americans of Arizona perform the *kachina*, the rain dance: to call down water from the heavens, so that, in the words of one Hopi man, not only they but 'all the animals, birds, insects and other life-forms will have enough to drink too.'

The essential role of water in sustaining life goes a long way towards explaining its religious significance, but it can't be the whole story. We have to remember that there are many different types of water. That which bubbles from an underground aquifer is (or at least, once was) sweet and pure: the milk of mother Earth, which nurtures us. 'Water is a milk', according to French philosopher Gaston Bachelard, 'as soon as it is extolled fervently, as soon as the feeling of adoration for the maternity of waters is passionate and sincere.' This is water worth worshipping.

But Job knew of other kinds of water. 'As water wears away stones, and torrents wash away the soil, so you destroy man's hope', he complained to his beleaguering God. Clearly he had seen what flash floods can do in a dry land. The Euphrates and the Tigris rivers posed constant danger to the civilizations of Mesopotamia ('between waters'), Sumeria and Assyria which grew up along their banks. The ancient cultures of China and India stood in similar peril from their precious sources of water.

And what, then, of the oceans? Here is bitter water, as the Ancient Mariner and countless becalmed sailors knew to their frustration and danger: drink it and die. Gods of the sea, argues mythologist Charles Ploix, are fundamentally gods of fresh water, because no god would be linked first of all to something so inimical as brine. 'Poseidon, then', he claims, 'belongs to fresh water.'

Not only does the ocean refuse to quench our thirst; it is apt to swallow us into its unplumbed depths. Out at sea, water shows its fury, and the cost is dear. 'O sea, wicked sea with your foaming waves', laments an old Balkan song, 'Where are our husbands, where are our loved ones?' On the coast of Bangladesh, great storm surge waves caused by tropical cyclones can, at a stroke, claim lives in their hundreds of thousands.

In myth, legend, literature and the popular imagination, then, water is not a single thing but a many-faced creature: a hydra, indeed. This is the essence of water's mystery, and it remains even when water is picked apart by science. Water is the archetypal fluid, the representative of all that flows, and yet science shows it also to be a profoundly anomalous liquid, unlike any other. Some scientists doubt whether water inside living cells, the very juice of life, is the same stuff as water in a glass; at the molecular scale, they think its structure may be altered; perhaps cell water even congeals into a kind of gel. Water behaves in unexpected ways when squeezed or cooled below freezing point. Life needs water, but it remains a profound mystery why water, a lively and reactive substance, didn't break apart the complex molecules of the earliest life forms on Earth almost as soon as they were formed.

In truth, water has something of the disreputable about it as a topic for scientific enquiry, for it seems constantly to create controversies, unlikely theories and puzzling experimental results. It is not to be trusted. In part, this is surely because water really is strange, surprising, hard to understand. But in part, I suspect it is because water is so fundamental to our thoughts, our dreams, our cultures. Science is meant to be an objective pursuit, but it is not easy to be objective about water. We care too much about it; it is too important to merit the cool and calculating gaze.

Water in the Creation

After all, did things not begin in water? That is not just what the Christian theology says, wherein the Spirit of God hovers over the waters until He separates them to create the sky before gathering them into the seas. This infinite, primeval ocean recurs in creation myths throughout the world, from Asia to America to Polynesia. Io, the great deity of the Polynesians, virtually paraphrases the Hebrew god when he says 'Let the waters be separated, let the heavens be formed, let the earth be!'

The scientific view of creation has rather more evidence in its favour, but it still arguably gives precedence to water. One of the two constituent chemical elements of water—hydrogen, the H of H_2O, whose name itself means 'water former'—was formed mostly in the Big Bang, the cosmic cataclysm in which time and space began. Three quarters of all the known matter in the Universe is hydrogen. The second most abundant element is helium, which is chemically inert; but water's other half, oxygen, is the third most common element in the cosmos. So the pairing of hydrogen and oxygen in water can be regarded as an inevitable union, a match made in heaven.

That happened long ago, before the Earth existed. But any creation myth must deal with the origin of things more familiar: the sky, the land, the sea. These things, science tells us, came into being about four and a half billion years ago, along with the sun and the other planets in the solar system. As for the water: it was possibly delivered to the young planet by icy comets, which rained down in those far-off days with sufficient force and frequency to sterilize the Earth repeatedly.

The oldest rocks today betray evidence that there were oceans on Earth 4.4 billion years ago. These must have gathered from the greatest deluge that planet has ever seen, for a mere 0.05 billion years earlier the Earth was too hot to support liquid water on its surface. Only when it had cooled sufficiently could the rains fall. And they fell, day after day for centuries, until the planet was blue and life could begin.

This first great flood is of course far too ancient to be a plausible stimulus for the legends of the Deluge that are ubiquitous around the world, from China to Peru. There were not even primitive bacteria to witness the formation of the oceans, let alone a foresightful and righteous Noah. So why do so many traditions insist that there came a time when 'all the springs of the great deep burst forth, and the floodgates of the heavens were opened'?

Floods, as I have mentioned, afflicted ancient civilizations frequently enough, but the mythical Great Deluge may have been something more. Twelve thousand years ago, the face of the Earth was transformed by a change in climate. For a hundred thousand years previously, ice had covered much of North America, southeast Asia, Europe and South America up to Chile and Peru, and the world was a cold place to live. With all this water locked away in vast ice sheets, the seas were less full: sea level was a massive 390 feet lower. The coastlines stretched to regions that are drowned today, and a Stone Age hunter could travel on foot from Asia to Indonesia, from Australia to New Guinea. This was the last ice age.

Then the great thaw began—prompted by gradual, rhythmic changes in the shape of the Earth's orbit around the sun, but no doubt accelerated by geological and biological processes on Earth that provide feedbacks on climate change. And so the ice melted, and over the space of a thousand years or so sea levels rose to around their current state. The transformation was hardly as rapid as Noah's forty days and nights, but it could certainly have been noticed within a lifetime, and may have given rise to oral traditions of a great flood in pre-agrarian societies.

Water as an element

Water comes first in many cosmogonies, but the first person to turn that primacy into something like a philosophical principle was Thales of Miletus, who lived in the seventh and the sixth centuries BC. He is generally regarded as the first of the great Greek philosophers, and the founder of the renowned Milesian (or Ionian) school, but we know rather little about him—and most of that comes second-hand from Aristotle.

Thales said that everything is made from water. As a launching point for the whole of Western philosophy, Bertrand Russell conceded, this is rather discouraging to young students who are 'struggling—perhaps not very hard—to feel that respect for philosophy which the curriculum seems to expect.' However much we might revere water today, we would have a hard time persuading ourselves that Thales had made a good first guess.

But Gaston Bachelard cautions that ‘the meaning of prescientific research cannot be thoroughly understood until we have formulated a psychology of the seeker.’ So what was Thales thinking of? He was well travelled, and might have been inspired by the Babylonian belief that all the universe is made from water. On the other hand, Thales was not looking for a creation myth but an explanation of mundane reality. Here is fluid water, but in winter (even in Miletus) it may be transformed to a solid: ice, which is more like a rock (geologists indeed still classify ice as a mineral). And then in the summer heat, the stream dwindles and eventually vanishes, for the water has evaporated and become ‘air’. Then the weather cools, the clouds gather, and water seems to congeal from the air.

So water seems capable of adopting other forms. This appeared, in the sixth century BC, to be a rare thing indeed. True enough, metals such as gold, lead and iron could be melted in a furnace, but nothing was known to be as versatile as water. Yet molten lead is evidently not water, nor is granite the same as ice. So how could everything be water?

We have to realise that the Greek concept of ‘elements’—fundamental substances from which all others are composed—is not to be taken too literally. Their elements referred more to a kind of *form* than to substance. Thales’s elemental water is better regarded as ‘that which flows’, of which the clear, tinkling stuff in the brooks of Ionia was simply a representative. When lead melts, it too was considered to become water in the sense of taking on certain qualities—those of fluidity—that real water exemplifies. So Thales’s water is really a kind of underpinning fabric, one step removed from mundane matter imbued with all kinds of superficial properties such as colour and smell.

Nonethless, Thales’s idea did not catch on. His follower Anaximemes suggested that air instead was the fundamental substance, while Heraclitus believed it was fire. Empedocles, that mercurial wizard of Greek philosophy who lived in the fifth century BC, hedged his bets by setting up a four-element scheme: earth, air, fire and water. This one stuck, because it was advocated by Aristotle, whose word became almost inviolable in the Christian theology of the Middle Ages.

The four so-called Aristotelian elements are again archetypes rather than tangible substances. ‘Earth’ stands for all things solid; ‘air’ for all vapours. Fire is a unique thing, and scientists barely understood it at all until the nineteenth century, but one interpretation is that it is an archetype of heat or light.

These four elements have exerted a tenacious hold on the poetic imagination, and it is perhaps not possible to understand our relationship to water without them. Their longevity no doubt derives from their congruity with our experience of the material world. The elements now recognized by chemists can seem to represent an arbitrary proliferation, for which of us has any feeling for the differences between samarium and gadolinium, or even any real notion of why these obscure substances should be *necessary* to the world? Yet we can perceive at once why water differs from earth or air, and how their characteristic qualities are manifested in nature. The Canadian writer Northrop Frye say that ‘the four elements are not a conception of much use to modern chemistry—that is, they are not the elements of nature. But... earth, air, water and fire are still the four elements of imaginative experience, and always will be.'

This is why we can find these ancient elements providing the themes and organizing principles in poetry ranging from Shakespeare's sonnets to T. S. Eliot's *Quartets*. Bachelard felt that one can mine myth and poetry for a *psychoanalytic* interpretation of the elements. 'I believe it is possible', he said, 'to establish in the realm of the imagination, a *law of the four elements* which classifies various kinds of material imagination by their connections with fire, air, water or earth... A material element must provide its own substance, its particular rules and poetics. It is not simply coincidental that primitive philosophies often made a decisive choice along these lines. They associated with their formal principles one of the four fundamental elements, which thus became signs of *philosophic disposition*.' For Bachelard himself, this disposition was aqueous: 'Dreaming by the river, I dedicated my imagination to water, to clear, green water, the water that makes the meadows green.'

Water remained an element to scientists until the late eighteenth century—and for some of them, beyond. In the mid-seventeenth century, the Flemish chemist Johann Baptista van Helmont was even inspired to revive Thales's idea that everything was made of water. This conclusion was impressively supported by an experiment in which he showed that a willow tree could grow in a pot to a substantial size while nourished only with rain water. Van Helmont watched the plant grow over a period of five waters, and found that over this time the soil had become deficient in weight by only two ounces, while the tree had gained 164 pounds. The implication was clear: 'All earth, clay, and every body that may be touched, is truly and materially the offspring of water only, and it reduced again into water, by nature and art [chemical science]'. (How could van Helmont know that the tree's woody fibre came from an even more insubstantial source, the carbon dioxide gas present in tiny proportions in air?)

Water's privileged status had a remarkably rapid demise, however. Henry Cavendish was a phenomenally wealthy English aristocrat, a scientist of genius, and one of the queerest people ever to cross the stage of science. He dressed like a pauper from the previous century (Cavendish was born in 1731), shunned the company of other men, and fled in panic from the presence of women. Consumed by a curiosity about science, he managed occasionally to travel from his laboratory home on Clapham Common, on the outskirts of south London, to show his face at the Royal Society—but even in this haven for eccentrics his habit of giving out a 'shrill cry… as he shuffled quietly from room to room' must have perplexed the other members.

Like many chemists of his day, Cavendish was interested in 'airs'—the gases that emanated from some materials when exposed to some agent of change such as heat or acid—and he interpreted the results of such studies according to the unifying chemical notion of phlogiston. This was supposed to be the element-like substance that made things flammable. When a material burned, it was thought to give off phlogiston. Substances that were particularly flammable, like wood and charcoal, were rich in phlogiston. Cavendish found in the 1760s that some acids would react with metals such as zinc and tin to release a gas that burnt explosively. He thought this ‘inflammable air’ might be pure phlogiston.

In 1774 the Englishman John Warltire found that if this inflammable air was mixed with normal air in a vessel and ignited, it produced droplets of water on the walls. The Frenchman Pierre Joseph Macquer reported much the same thing, as did James Watt and Joseph Priestley in England a few years later. But none of them realised quite what was happening.

Cavendish performed the same experiment in 1781. Characteristically, he measured everything carefully, and found that only about a fifth of the enclosed volume of ‘common air’ was consumed when inflammable air was ignited. In 1784 he described his experiments in a report to the Royal Society, saying ‘almost all the inflammable air, and about one-fifth of the common air, are turned into pure water.’ Cavendish had *made* water from its elements, for ‘inflammable air’ is in fact hydrogen, and a fifth of normal air is oxygen.

That’s not how Cavendish saw it, however; his interpretation was confused by his belief in the phlogiston theory. The truth is that there is no such thing as phlogiston, and the first person to see that clearly was also that man who gave hydrogen and oxygen their names, and who realised most clearly that in Cavendish’s experiments ‘water is made artificially and from scratch’. He was the cunning French chemist Antoine Laurent Lavoisier.

Eighteenth-century science can seem parochial and sedate from today’s perspective, but it was really every bit as competitive as it is today. It was also surprisingly international. Lavoisier learnt of Cavendish’s experiments in 1783, when the Englishman’s assistant Charles Blagden visited him in Paris. But Lavoisier was already on the same track, and he went on to make it even more clear that water was no element, but a compound: a mixture of two elements. He showed not only that water could be *synthesized* from its component elements, but that it could be split back into them. He passed steam through a red-hot gun barrel, whereupon the oxygen in the water reacts with the hot iron to form rust, liberating the hydrogen.

Lavoisier’s claim that water was a compound ran against the grain of two millennia of natural philosophy, and it was scarcely welcomed by some scientists. How could water, which put out fires (and so countered the effects of ‘phlogiston’) contain a gas as inflammable as hydrogen? In England, William Ford Stevenson complained that ‘this arch-magician so far imposed upon our credulity as to persuade us that water, the most powerful natural antiphlogistic we possess, is a compound of two gases, one of which surpasses all other substances in its inflammability.’ Cavendish and Priestley were not keen on the idea either. Already we see water stirring up dissent between scientists. But there was no denying the evidence of experiment, and Laviosier’s discovery carried the day.

It may seem like a fair point that these objectors had. For a mixture of hydrogen and oxygen gases is perilously explosive, yet we are being asked to believe that the two are also mixed in water, the antithesis of fire and flame. This, however, is the subtle thing about chemical compounds: when atoms combine chemically, their nature changes. In hydrogen gas, each atom of hydrogen is bound to another, making two-atom pairs or *molecules*. The same is true of oxygen atoms in oxygen gas. When the two gases are mixed, all that happens is that the hydrogen and oxygen molecules jostle among one another, while remaining in their pairs.

But in water, the unions of atoms are quite different. Each oxygen atom is linked to two hydrogen atoms, making a single molecule of water; hence the chemical formula H_2O. These atoms have no great inclination to rearrange themselves into new unions. When a mixture of hydrogen and oxygen gas ignites, on contrast, the chemical bonds holding the hydrogen and oxygen atoms in pairs are broken, and the atoms link up in new, three-atom unions: water molecules. This breaking and reforming of bonds releases a lot of energy—and that is why the Hindenburg airship went up in a fury of flames in 1937.

Why water is strange

Lavoisier knew nothing of this atomic-scale picture of what water is. Indeed, he wasn't at all sure that atoms were a very useful concept to the chemist, since no one could see them. It took another hundred years before chemists became comfortable with the idea that substances are made up of molecules in which atoms are arranged with particular architectures, like so many balls and sticks in a child's construction set. Some scientists were still sounding off about the futility of an atomic model of matter at the start of the twentieth century, and it wasn't until 1908 that there was any convincing experimental evidence that atoms existed.

But the notion of molecular structure is essential if we are to understand anything about why water is so strange. Queer as it may seem, the Earth would have no oceans if water molecules, those invisible little trios of oxygen and hydrogen atoms, did not have the shape and properties that they do.

Why do I say that water is strange? Anything seems normal, of course, until we have some basis for comparison, which is why some people accept the most peculiar of family circumstances. If asked to think of a liquid, water will surely be our choice. Many other familiar liquids, such as blood, milk, beer and orange juice, are simply water with other substances suspended or dissolved in them. With effort, we might conjure up a few non-aqueous liquids: petroleum, turpentine, olive oil. But we don't exactly have a wide experience with other liquids, and so water has come to represent the Ur-liquid, the Empedoclean ideal of a liquid.

There aren't terribly many scientists who study liquids, but I was once one of them, and we tended to shun water. This might make us sound like bakers with an aversion to bread, but we had a good reason: water broke all the rules. There is a perfectly good 'theory of liquids' that has been painstakingly developed since the late nineteenth century, and it is astonishing what it can accomplish in terms of explaining what liquids are and what they do. But it is of rather little use for understanding water.

Here's an example. Many solids can be melted to form liquids, but when they cool and freeze again, they typically shrink and get denser. Fill a cup with molten wax, say, and you'll find it slightly less than brim-full when the wax sets. The same with molten iron or lead, or molten rock, which is why lava contracts and cracks when it cools and we are left with formations like the Giant's Causeway.

But water? We know the answer already, for we take care never to freeze bottles of milk or champagne. The water *expands* when it becomes ice, and the bottle shatters. Because of this expansion, ice is less dense than water—the same volume of ice ways less than water—and so ice floats on water. If that were not so—if water behaved 'normally', and became denser when it froze—icebergs would sink instead of floating around the polar oceans. There would, in fact, be no North Pole to plant a flag in, for it is nothing but an ice sheet adrift on the Arctic Ocean.

The expansion of water when it freezes bursts our water pipes in winter, and weakens our buildings as water widens cracks when it turns to ice. Many years of such freeze-thaw cycles can reduce rocks to rubble. On the other hand, ice floating on a wintry pond provides a thermal blanket that can stop more heat escaping and keep the water below from freezing solid, to the benefit of pond life.

Aquatic life gets a further advantage from water's oddness. Even before a liquid freezes, it generally contracts slightly as it gets cooler. This is because the molecules in the water jiggle about less frantically when they are colder, and so they have less inclination to push one another apart—just as a regiment of soldiers can pack together more closely than a wildly jiving crowd on a dance floor. Water seems to observe this expectation—until it reaches 4 ºC, four degrees above its freezing point. If you cool water below 4 ºC, it starts to expand. Only slightly—not as much as it does when it freezes at 0 ºC—but enough to present a puzzle. It is almost as if the water begins to sense the approach of the freezing-induced expansion.

This means that water is densest at 4 ºC; at this temperature, it expands if you heat it *or* if you cool it. Why 4 ºC? In his *Guide to the Scientific Knowledge of Things Familiar* (1876), the sage Reverend Dr Brewer decides that this has been 'wisely ordained by God'. That explanation doesn't seem to have satisfied scientists for long, if indeed it ever did.

Nevertheless, one might perceive wisdom in this behaviour. It means that the water at the bottom of a cold pond—the densest water—is always a few degrees above freezing. So ponds freeze from the top down, not from the bottom up. This helps them to avoid freezing solid in a bad winter, something that would kill the fish and crush them for good measure.

One of the most striking and fortuitous anomalies of water is that it is a liquid at all. Naively, you would expect water to be a gas at the temperatures and pressures encountered on the Earth's surface. All other similar chemical compounds—hydrogen sulphide, ammonia, hydrogen chloride—are gases under these conditions. By rights, the oceans should all be up in the air, giving us a thick, muggy atmosphere over a parched earth. But something seems to hold water molecules together in the liquid, preventing them so easily from flying apart into a vapour.

Water has a surprising capacity to absorb heat. That's to say, if you want to make water hotter, you have to put in a larger amount of heat, relative to other liquids. This means that it takes longer than it 'should' to boil a kettle, but there are happier consequences too. The oceans are slow to change their temperature, maintaining a constant environment for the organisms that teem within it. Water's large 'heat capacity' also makes the oceans an astonishing reservoir of heat, which ocean currents carry from the tropics (where water is warmed by the sun) to high-latitude regions. This redistributes heat over the planet and reduces the temperature differences between high and low latitudes. The Gulf Stream, bringing warm water from the Gulf of Mexico across the Atlantic Ocean, keeps Northern Europe much warmer than Labrador at the same latitude on the American coast by transporting every day twice as much heat as would be produced by burning all of the coal mined globally in a year.

The list of water's anomalies, compared with other liquids or 'similar' chemical compounds, runs to a few dozen entries. Some are more recondite and revealed only by careful scientific measurement, such as the fact that water gets less rather than more viscous when squeezed. Ice is itself a strange substance too, which can adopt at least fourteen different forms when compressed to high pressures. Water, we must admit, is the most eccentric liquid we know.

To explain all of this, we must look closely at those little clusters of an oxygen atom and two hydrogens. It looks, at face value, like an ordinary enough molecule, even simple. But it was not until the past two decades that the molecular-scale structure of water was properly understood, and even now there remain some important open questions.

The two hydrogen atoms of the H_2O molecule dangle from the central oxygen atom rather like Mickey Mouse's ears from his head, and in the liquid these molecules jostle and bounce off one another—that much is true of just about any liquid. But in water it is an unusually orderly kind of jostling that takes place, and rather tenacious too. As they encounter one another, the molecules stick together—loosely, and just for an instant, but it is enough to influence the nature of the liquid profoundly.

The structure of liquid water is best imagined not as some kind of architectural arrangement of molecules, but as a dance. It is a dance that happens in all three dimensions in space, like a formation dancing team of astronauts. Each has two hands and two feet. The body represents the oxygen atom, and each pair of hands represents the molecule's two hydrogen atoms, splayed out wide in greeting. What about the feet? These are the molecule's hidden secret: they represent pairs of electrons on the oxygen atom, confined to two lobes called 'lone pairs'. It turns out that hydrogen atoms on one molecule like to stick to the lone pairs on another, as if one dancer clasps another by the ankle.

These clasps are the ‘glue’ that gives water its cohesion, making it a liquid where we might instead expect a gas. They are called hydrogen bonds, and while they are relatively weak and ephemeral, they unite the dancers into an ever-shifting network via the grasps of outstretched hands on nearby ankles. Each dancer can form hydrogen bonds with four others: it can grip two by the ankle, while two others seize its own ankles.

The possibility of hydrogen bonds between separate molecules was first mooted in 1920 by American chemists, who perceived that it might hold the key to water’s uniqueness. Once again, the idea proved controversial: the outspoken English chemist Henry Armstrong ridiculed this notion that a hydrogen atom could make a link, however temporary, with more than one atom at a time and thus act as a ‘bigamist’. But the eminent American chemist Linus Pauling soon showed how this might, in theory, be possible.

If water molecules approach only as close as their outstretched ‘arms’ and ‘legs’ permit, this means they leave a fair amount of empty space between them. In ‘simple’ liquids, in contrast—the kind I once studied, with no complications from hydrogen bonds—there is no such constraint, and the molecules drift closer together. In water, however, the dance is not perfect: some molecules miss their grip, and drift closer together. When water freezes, the molecules become more regimented, and are stricter about maintaining the proper arrangement of four hydrogen bonds apiece. This means that the empty spaces between molecules are enforced, and so the network is more ‘open’ than in the liquid: the molecules are packed less densely. So the density decreases when water turns to ice.

Most of water’s other anomalies stem from the same considerations about maintaining a hydrogen-bonded network. Some of the controversies that remain about the properties of water stem from the question of how this network gets disrupted if, for example, the molecular ‘dancers’ are close to a wall, or if some big molecule is thrust among them (that is, dissolved in water).

The matrix of life

Both of those situations arise for the water that fills each of our cells. Here water is revealed as the lubricant of life, and it explains why we are about two-thirds water. Each cell in our body is like a water-filled balloon, awash with dissolved molecules such as proteins, sugars and DNA.

Scientists studying the molecular mechanisms of life used to regard this water as a kind of invisible background, neglected just as we ignore the air that surrounds us or a fish takes for granted (one assumes) its fluid environment. Little by little—and there is still some way to go—molecular biologists are starting to acknowledge that this is a misleading picture. Water is not simply the backdrop for life; it is a part of the way life works.

Consider proteins, for example. These are the molecular workers of the cell—they do nearly all of the hard labour. When we need a hormone to trigger some physiological process, protein enzymes put it together from the raw bits and pieces floating around cells. Protein gates and pumps shift salts in and out of cells to maintain a correct balance, so that we don't get pickled when we bathe in the sea. Protein motors propel other molecules from place to place in the cell's labyrinthine compartments. Proteins help DNA to copy itself before cells divide.

Proteins manage all this by being specially shaped for their task. Each of them is, in general, highly specialized, built to do a single task and that alone. This specialization depends on the protein having the right shape. Each protein begins its life as a long, floppy molecular chain, which develops its three-dimensional shape by folding up in the correct way. Water is essential to this process of protein folding, particularly because it encourages fat-like, insoluble parts of the protein chain to clump together, like oil separating out of the salad dressing.

Water molecules play many more subtle roles in the way proteins work. Some proteins, for example, use water molecules as a kind of snap-on tool, fine-tuning its shape or equipping it to conduct a certain chemical transformation. Other proteins arrange water molecules into chains that act as a kind of 'wire', down which hydrogen atoms can be passed like an electric current flowing down copper cable. Biologists are finding ever more examples of water taking an active role in life's chemistry, making it a kind of biomolecule in its own right.

Some biologists regard water as the *sine qua non* for life to exist, and with good reason: no organism is known that can function without it. (Some, like certain fungi or bacteria, can survive freeze-drying, but only in suspended animation: they can't actually do anything if deprived of all water.) Others argue that, while this may be true of life on Earth, it is not necessarily the case on other worlds, where life forms may have evolved that use completely different kinds of chemical processes.

This is not just an academic debate. The US space administration NASA has made the search for extraterrestrial life one of the central guiding policies of its space program. But where do you look? If you accept that life might take forms that do not need water, the answer is probably 'everywhere'. According to this view, there might be life—though we might have trouble recognizing it as such—in the hot acidic clouds of Venus, or the frigid oceans of liquid methane that are thought to perhaps exist on Saturn's moon Titan, or in the gaseous maelstrom of Jupiter's red eye. Some astronomers have even speculated that a kind of life might have arisen in the thin, ultracold veil of interstellar gas clouds.

Well, maybe. But NASA is currently taking a more cautious view. Its policy is 'Follow the water'. It thinks that the best prospects for life on other planets are to be found where there are signs of liquid water. (There is plenty of ice around—Pluto, and many comets, are composed of little else—but ice won't do, as it is solid and can't lubricate the molecular processes of life as we know it.)

Some scientists criticize this as a hydrocentric view, an unproven assumption that any life must be like that we know already. There is, of course, ample precedent for a tendency to cast other worlds as a version of our own, from Jules Verne's *First Men on the Moon* to Edgar Rice Burroughs' Arabian visions of Mars to the almost invariably humanoid aliens of *Star Trek*. But hydrocentrism need not be an extension of this unreflective anthropomorphism, for there are very good reasons for thinking that all life may need water—at least before it reaches the stage of being able to download its consciousness into a sophisticated computer. The more we get to know about the molecular machinery of the cell, the more we realise that it could not function in any liquid except water. No other liquid has a structure as subtle as that of water (even though some other compounds can form hydrogen bonds), and this structure seems to be essential for the kind of delicate chemistry that makes life possible. Even if alien organisms use molecules other than proteins and DNA, it's hard to see how they could avoid being comparably complex—and how, therefore, they could relinquish the need for an active, *sympathetic* solvent and mediator like water.

In the early twentieth century, an American biochemist named Lawrence Henderson argued that water seems so beautifully and uniquely suited for supporting life that it is hard not to perceive it as *designed* for this purpose. Henderson did not know about the fine details of how water gives a helping hand to the molecules of life (although he would have been quite delighted if he had). But he could see that the many 'anomalous' properties of water already known made it an incomparable 'matrix' for life. The large heat capacity, which helps the oceans maintain a steady temperature, does just the same thing for organisms (which are, remember, mostly water)—it is perfect for temperature regulation. Lawrence pointed out that another method of heat regulation is evaporation: when liquid water changes to water vapour, it imbibes a great deal of energy (more than other liquids). This provides a way to prevent overheating, and it is why we sweat. Lakes can stay at a constant temperature under intense sunlight for the same reason: as water evaporates from the surface, it is rather as if the lake is sweating.

Henderson collected together many other examples of the way water seems fine-tuned to support life. Its unusually large surface tension, for instance, means that water is pulled up through the empty pores and channels in soil by capillary action, making it accessible to plants growing at the surface even if the water table is several feet lower than the roots. Henderson believed that water was uniquely 'fit' in Darwin's sense: it was perfectly adapted to sustain life. Thus he believed that evolution of organisms—survival of the fittest, as the rather crude caricature of those times expressed it—takes place in a 'fit' environment. 'Water, of its very nature', he said, 'as it occurs automatically in the process of cosmic evolution, is fit, with a fitness no less marvelous and varied than that fitness of the organism which has been won by the process of adaptation in the course of organic evolution.' Henderson considered that carbon compounds are also remarkably and uniquely attuned to serve as the building blocks of life—that carbon in some sense makes life inevitable. 'The biologist', he concluded, 'may now rightly regard the universe in its very essence as biocentric.'

This looks, of course, very much like the 'argument from design' that theologians have advanced as evidence that God exists. The idea of Reverend William Pacey that living organisms are like carefully constructed watches which demand a watchmaker was defeated by Darwin's theory, which showed how this exquisite craftsmanship can be effected by the blind forces of random mutation and natural selection. But it is hard to see how such a process might have shaped the fundamental substances of the universe, such as water. Henderson was aware that his argument was veering into metaphysical, not to say, theological, realms, and he held back from making any kind of direct statement about whether water is indeed 'purposeful' and speaks of a supreme Designer. But such thoughts were clearly in his mind.

These notions don't hold much currency for today's explorers of life on other worlds. If they think about the issue at all, they might be inclined to take the pragmatic view that it is equally possible that the universe might *not* have enjoyed so subtle a matrix as water, but that if this were so, we wouldn't be around to remark on it. Thus water has a part to play in the debate about the so-called Anthropic Principle—the idea that the universe looks to us to be fine-tuned for developing solid matter, life and ultimately consciousness simply because of the very fact that we are here to observe it.

But the more practical question, as yet unanswered, is whether water is indeed a 'biocentric' material: whether its presence makes life merely possible, or inevitable. At present, we have no way of knowing, because we have only a single example (Earth) to judge by. If we were to find signs of life on the first other world we came across that contains liquid water, we'd have a fair reason to believe that yes, we'd probably find life *wherever* there is water.

The search for life

Where, then, is NASA looking for water? There is water on the Moon, and the discovery of this in 1998 created much excitement (conveniently overlooking the fact that much the same thing had been reported two years earlier). But not even the most optimistic astrobiologist (as the new breed of alien-hunters call themselves) expects to find life on the Moon, because the water is all frozen as hard as rock, hidden away in cold, shadowy craters at the lunar poles. The excitement is all about the prospect of using this water to sustain human settlements on the Moon (some scientists point out that this is not even remotely feasible in the foreseeable future).

There is much more interest in Mars, where dreams of alien life have found their focus for over a century. In the late nineteenth century the American astronomer Percival Lowell convinced himself that he could see the remnants of 'canals' on the red planet's surface: channels too straight to be natural formations, and therefore presumed to be the remains of an attempt by a doomed Martian civilization to irrigate the desiccating planet. Lowell's hypothesis was received sceptically at the time, and was soon shown to be the product of self-delusion. But the seed it sowed gave birth not only to Burroughs's Barsoom but to the creatures that 'regarded this earth with envious eyes' in H. G. Wells's epochal 1896 novel *War of the Worlds*, 'and slowly drew their plans against us.'

The legacy of Lowell and Wells is alive and well today, but so is the interest in the 'canals of Mars'. No intelligence shaped these features, but they are there nonetheless: sinuous channels, first seen by the Mariner 9 spacecraft in 1972 and lately revealed in breathtaking detail by the Mars Global Surveyor in the 1990s. They carve up the dusty deserts of Mars like some gargantuan Grand Canyon, and many of them cannot readily be explained by any geological process except erosion by liquid water.

The rivers of Mars are one of the most compelling justifications for the current belief that Mars was once warmer and wetter than it is today. There are no ponds or streams on Mars now, for they would either freeze in the mostly sub-arctic temperatures or evaporate almost instantly in the thin atmosphere. But there are signs that the dry martian 'soil' (a dusty, boulder-strewn veneer called the regolith) is pervaded by ice, which sits just below the surface like permafrost in the polar tundra of Earth, visible to the prying satellite called Mars Odyssey which has been orbiting the red planet since the beginning of 2002. There is ice too at the Martian poles, which grow and shrink with the changing seasons—but most of this is 'dry ice', solid carbon dioxide, rather than water ice.

Scientists think that, up to perhaps three billion years ago, Mars may have been somewhat like Earth, with rivers, lakes and small oceans beneath a cloudy sky as warm as an indifferent day in northern Europe. They suggest that because the geological cycling of water and carbon dioxide, a greenhouse gas, between the earth, the seas and the sky on Mars was less efficient than it was on Earth, the red planet may have become trapped in a gradual decline towards a permanent, gelid ice age.

But it took, according to the latest fossil record, no more than a few hundred million years for life to begin on Earth. If that is so, there many have been plenty of time for the same thing to happen on Mars—even if Martian evolution was curtailed abruptly, and Wells's 'intellects vast and cool' averted, when the planet froze. So some planetary scientists retain hopes that missions to Mars will one day uncover fossil evidence that it once hosted life.

There's certainly no sign of it now. NASA's robotic Viking lander craft in the 1970s touched down on a planet sterilized by the ultraviolet light that rakes the surface, and it found no evidence of micro-organisms in the regolith. The Pathfinder mission of 1997 was less geared to searching for life, but that is the aim of the Beagle 2 mission (named after the ship that bore Charles Darwin on his famous voyage), which is scheduled for launch in early 2003, to arrive at Mars in time for Christmas. This quest for Martian life has been given fresh impetus by the claim, based on the pictures taken by the Mars Global Surveyor, that there could have been occasional outbursts of water flowing across the Martian surface from the melting of sub-surface ice as 'recently' as a million years ago. Could primitive life still be eking out a precarious existence around such isolated and transient oases?

There's a lot to be excited about on Mars, but the persistence of the idea of Martian life may be based more on historical precedent than on a hard-headed assessment of the facts.

There may be much more to be gained from a close look at the remote moon of Jupiter called Europa, first seen by Galileo in 1610. It seems an unpromising place to prospect for water—too far from the sun for solar heat to raise the surface temperature to anything like water's melting point. But Europa, like the other three 'Galilean' moons of Jupiter, has another source of heat. Jupiter is so immense that its gravity sets up strong tidal forces on its orbiting moons, like those much weaker forces that pull our seas into the rhythm of the Moon. These forces heat up the moons—so much so that the closest to Jupiter, Io, is a fiery inferno of brimstone-spewing volcanoes.

On Europa things are much cooler—the surface is well below freezing. Like the other two moons Ganymede and Callisto, it is covered with ice. But whereas those worlds are pitted with craters, like the moon, Europa is different. There are very few large craters, and the ice is covered in a web of streaks. When NASA's Galileo spacecraft took a close look in the 1990s, it found that the icy shell of Europa is cracked and fragmented, covered in features that look for all the world like the 'ice rafts' that float in the polar oceans on Earth as the sea ice breaks up in the warm season. In some cases these rafts seem to form a jigsaw that can be reconstructed, showing that indeed they are fragments of a once unified ice sheet.

This has led scientists to think that Europa's icy surface is just a thin crust, floating on an ocean of water kept liquid by the tidal heating of Jupiter. That picture is supported by the detection of a magnetic field on Europa by the Galileo spacecraft, which might be produced by currents in a salty, electrically conducting ocean.

Could this ocean contain life? On Earth, it is widely thought that life may have begun in the deep sea, where small undersea volcanoes spew out hot water rich in mineral nutrients. Perhaps something similar happens on Europa, allowing organisms to thrive even though the icy crust shuts out sunlight? The recent discovery of primitive, single-celled organisms living in the mushy ice at the bottom of an ice-covered lake in Antarctica makes it look all the more possible that life can arise and persist in water buried beneath thick ice.

The only way to know for certain is to go and look. But that's a real challenge, because the latest estimates suggest that the ice crust is about 60 kilometres thick. It would have to be a plucky and inventive spacecraft indeed that could burrow through such an obstacle. NASA is not yet planning anything quite so bold, but intends to send an orbiting craft to Europa in 2008, which will arrive two years later to map out the moon's surface in more detail and search for promising landing sites for some future mission.

Some scientists are not optimistic about what such a mission would find; one confessed his doubts in an ode indebted to Lewis Carroll:

> Europa's crust was dry as dry
> Was underneath it wet?
> You could not see below, because
> The ice above had set,
> You could not see the fish, because

There were no fish as yet.

One day we will surely go fishing on Europa and discover the truth.

Water science and water myth

In the early 1970s, the scientific investigation of the fundamental structure and properties of water was unpopular not just because it was a very difficult question but because one risked being branded a gull or a charlatan if one studied it. Science was still smarting from the embarrassment of the ‘polywater’ scandal: the claim, made in the late 1960s, that water could exist (above its normal freezing point) in a viscous, gummy form called polywater.

This claim was first made by a group of well-respected Soviet scientists, and when British and American scientists reported much the same thing in 1968, polywater created a frenzy of research activity all over the world. Many of these researchers suspected that polywater was a kind of polymerized form of ordinary water, in which the molecules had become joined into fairly robust chains and networks. We know that there *is* a network of molecules in liquid water, joined together by hydrogen bonds—but this is a loose and ephemeral thing, as the hydrogen bonds are constantly being broken and reformed, keeping the substance liquid. In polywater, so the idea went, the bonds were stronger, and the liquid congealed into a gel with a consistency similar to paraffin wax.

It was remarkable enough that water might have an alternative form, never before seen. But then one scientist suggested that this ‘waxy’ water might even be the most *stable* form, into which liquid water might become instantly transformed if given the chance. ‘I regard the polymer [polywater] as the most dangerous material on earth’, he wrote in the journal *Nature*. ‘Even as I write there are undoubtedly scores of groups preparing polywater… Treat it as the most deadly virus until its safety is established.’

Why was it deemed so dangerous? If you cool a beaker of water slowly below freezing point, it can sometimes remain liquid. But add a crystal of ice to this ‘supercooled’ liquid, and it all freezes. The ice crystal acts as a seed that triggers the transformation to the more stable form of the substance (ice). What if a small sample of polywater were to do the same, seeding the gelation of all the water in our tissues, or all of it in the oceans?

This apocalyptic scenario was depicted by the American writer Kurt Vonnegut in his novel *Cat’s Cradle* (1963). Vonnegut posits a form of ice, called ice-nine, which is stable even at temperatures above that at which water normally boils. When a sliver of ice-nine is dropped into the oceans at the end of the book, they freeze solid—for ever.

The dire warnings about polywater were soon rubbished by a group of British scientists, who commented reassuringly that ‘Robert Burns’s affections were guaranteed to remain constant ‘till all the seas run dry’. While he may not have envisaged the possibility that the oceans might instead become anomalous [that is, made of polywater], we feel that his shade may derive some consolation from the fact that they have not already done so.’

All the same, doomsday warnings served only to fan the flames of the polywater affair. Despite all the excitement, polywater had been prepared only in excruciatingly small amounts, which made it very hard to establish what it really consisted of. But when such investigations were finally made, scientists discovered that the gummy stuff was not pure water at all, but was full of various impurities. Some concluded that it was in fact a sort of gel made from microscopic particles of glass, or wet salt, or even a concoction formed from the sweat of the experimenters. Whatever it was, it did not seem to be a new form of water. By 1971, polywater was generally discredited.

This episode shows how easy it is to be misled by water, even in apparently careful scientific experiments. The history of science is of course full of such false leads and futile claims, but water seems to be particularly prone to them. In part, this is surely because water really is strange—so it does not take a great leap of faith to believe that it can behave in ways that are stranger still. But I think that the outbreaks of so-called pathological science associated with water can also be traced to its mythical resonances. There are certain ideas that attach themselves to water, and even scientists cannot help but be influenced by them.

Take cold fusion, for instance. Two chemists working in Utah in the USA claimed in 1989 that they had developed a method for inducing nuclear fusion—the process that fuels the sun, and which is triggered uncontrollably in a hydrogen bomb—using nothing more than a beaker of water and two metal electrodes.

Physicists have pursued nuclear fusion for decades as a means of energy generation. Current nuclear reactors use the fission process instead—the splitting apart of big, heavy atoms such as uranium. This releases a lot of energy, but is messy. Fusion, in which atoms of hydrogen are fused to make helium, produces more energy and less hazardous waste. But, despite research efforts costing millions of dollars, no one has yet found a way to sustain a nuclear fusion reaction controllably in a way that allows more energy to be extracted than is needed to keep the process going.

This is what the Utah chemists claimed to have done, using apparatus that could be bought for a few dollars and which a school child could put together. (Indeed, some school children subsequently tried.) They said that fusion took place at the surface of electrodes made from palladium when they were immersed in heavy water and an electric current was passed between them. (In heavy water the molecules contain a ‘heavy’ form of hydrogen called deuterium; in other respects they are normal H_2O molecules.)

This ‘cold fusion’ excited a flurry of activity worldwide, in much the same way as polywater had. And likewise, it turned out to be a will o’the wisp: within a matter of months, cold fusion was exposed as a concoction of self-delusion, poor experimentation, and perhaps even a smattering of something worse.

Some scientists asserted retrospectively that cold fusion had always been an absurd claim. So why did so many believe it? Partly this was because the potential rewards were so great. But it also taps into a surprisingly pervasive myth of *water as fuel*. There have been, and continue to be, occasional reports of 'water engines': machines that extract energy from water. (Steam engines and steam turbines do this in a sense, but the water there is not the fuel: it is simply heated by some conventional fuel such as coal or gas so that it can drive pistons or turbines as it expands.) There remains no scientific justification for how this might be done, yet the myth continues to resurface. It is, perhaps, fed in part by the fact that fuel can be *extracted* from water—by using electricity to split it apart, one can make hydrogen from water. Hydrogen is a 'clean' fuel that can be burnt in air. But this is not a case of turning water into a fuel, for energy must be consumed to split it into its elemental constituents. It is a circular process: you put in energy to break water into hydrogen and oxygen, and then release energy when these two elements are recombined into water. If the energy that is consumed comes from some cheap and abundant source such as sunlight, then it is worth the effort, which is why this so-called 'photocatalytic' splitting of water is an area of intense research. But it does not make water a fuel.

Another myth that has enticed science, siren-like, to its embarrassment, is that of *water as medicine*. There is no doubt that water is good for us; but in homoeopathy water is used to cure very specific ailments. Different homoeopathic tinctures are applied for different afflictions, yet all are more or less nothing more than plain water, for homoeopathic remedies are so dilute that no molecules of the 'active' ingredients remain.

In 1988 a team of scientists at a respected laboratory of the French medical research organization INSERM claimed to have evidence that solutions of certain biomolecules remained biologically 'active' even when diluted to homoeopathic levels. They suggested that water somehow has a 'memory' of the substances that have been dissolved in it, so that it can carry out the same functions as those substances even when none remain.

Again, these claims proved to be impossible to repeat reliably, and the notion of a 'memory of water' is now discredited. It is certainly inexplicable in terms of what we currently know about the molecular-scale structure of water. The lack of a plausible mechanism does not, of course, prevent homoeopathy from being widely used today, but it is a major obstacle to acceptance by the medical community. (The lack of reliable evidence for the efficacy of homoeopathic treatments is an even bigger obstacle.) Yet the mysteries and complexities of water's structure still provide plenty of scope for hand-waving arguments about how homoeopathic remedies *might* do their job. More potent still, I suspect, is the ancient notion that water can *save* us, it can wash away our illnesses and our sins. Gaston Bachelard says 'The human mind has claimed for water one of its highest values—the value of purity.' If we drink from the Fountain of Youth, its incorruptibility can let us live forever.

When a substance becomes mythical, it works curious things on our imagination, even without our knowing it. Substances like this are ancient, and they have magical powers. Gold and diamonds, bread and wine, blood and tears are agents of transformation in story and legend. But none, I think, surpasses the beauty, the grandeur, the fecundity and the potency of water. This is why water is, and must always be, much more than a simple compound of hydrogen and oxygen, or a dance of molecules. To explain its role in our imaginations, its life-giving potential, its bizarre and perplexing properties, its sweet nourishment and its glittering surface—to fully explain these things, we do perhaps have to reduce water to its mundane constituents. But even when we do so, we have to remember what we are dealing with: not just a chemical compound, but a fundamental part of nature, with aspects that are serene, enchanting, enlivening, profound, spiritual and even terrible. In the voice of the babbling stream, says Wordsworth, 'is a music of humanity'. And Bachelard bids us listen well to this music: 'Come, oh my friends, on a clear morning to sing the stream's vowels! Not a moment will pass without repeating some lovely round word that rolls over the stones.'