

Natural Kinds in Chemistry

In the world(s) of natural kinds literature, paradigm cases are few and growing fewer. The earliest literature pointed to biological species as exemplar natural kinds, what could be a more natural grouping than “tiger”? More recently, complications relating to the various groupings of biological species have been pointed out and there was a collective move to the stability of chemical elements, after all, what could be a more natural grouping than “gold” (Kripke, 119). Now, even the status of elements and related chemical kinds has come into question as problematic examples involving isotopes, isomers and more leave the field looking far less clean-cut than previously thought.

Settling on chemical kinds is a primarily essentialist move, rooted in the views proposed by Saul Kripke and Hilary Putnam. In this paper, I will explore the essentialist view of natural kinds by challenging the reductionist underpinning of their chemical kinds-based assumption and reanalyze the essentialist position having lost its microstructural support. I’ll begin with a brief overview of the modern essentialist account, followed by an examination of Kripke and Putnam’s paradigmatic chemical kinds (water and gold) and their causal theory of reference. This will spell trouble for their essences and reductionist inclinations, so I’ll present a possible solution through the use of meaningful reduction “barriers”.

I. Essential Kinds

The essentialist picture is fairly simple, Kripke and Putnam entertain various arguments regarding our discovery of kind terms, but their positions are essentially the same. All objects possess certain

properties, without which they would not be identified as being members of a kind. For example, “gold” is a natural kind term and things that are gold are so because of an essential property they share, atomic number 79.

Essentialists favor these often-inaccessible properties over traditional observational methods because natural kind terms appear to capture more than just accidental features of members’ appearances. Back to Kripke’s gold, if we were to suddenly discover that gold was not in fact yellow, but actually red that was masked due to some atmospheric anomaly, we would not discard “gold” simply because it was not yellow. Instead, we would learn that gold was not actually yellow and that subtle reflective peculiarities could make it display its *real* color (Kripke, 118). Similarly, an object may have nearly all of the identifying marks of gold and would still not be called gold. Fool’s gold (iron pyrite), despite looking exactly like gold is a kind unto itself not due to any ad hoc nominal modifications to “gold”, but because of discoveries into the essential properties of each.

Similarly, in Kripke’s tiger example we do not find the possibility of three-legged tigers inherently contradictory (despite the term’s definition as: “*a large carnivorous quadrupedal feline*”). Even if the very first discoverers of tigers had encountered the exception (four-legged) when tigers are in fact all three-legged, we wouldn’t say that there had been no tigers after all.

These examples show that we often effectively refer to a kind despite getting many things wrong about the associated primitive concept. The kind term is just an ostensive reference to “that sort of thing”, and we discover both errors in our accidental description and insight into the kind’s essence.

II. And Reduction

Tied closely to the essentialist account is the principle of reductionism. When attempting to identify the essence of a substance there is a natural tendency to look inward, to reduce the thing until it is no longer identifiable and find out what essential feature was lost.

Kripke and Putnam's essentialism took this principle further by providing the chemical examples gold and water and solidifying the role of science as the principal investigator:

“In general, science attempts, by investigating basic structural traits, to find the nature, and thus the essence (in the philosophical sense) of the kind.” (Kripke, 138)

This microreduction is the grounding for the discussion of chemical kinds, the perception being that a molecule or element's underlying microstructure is its essence¹.

III. Water is H₂O

A simple statement has consumed natural kinds research since the publication of the essentialist revivals of Kripke and Putnam: “water is H₂O” (Putnam, 231). The statement encompasses issues from reference and identity to (our concern) essence and microreduction. Fairly obviously, the implication is that having the “microstructure” H₂O is the essence of water, and somehow altering this microstructure would mean we no longer have water. The statement appears to hold up: pass a current through a sample of water and its constituent gasses will begin to bubble up at opposing electrodes. The

¹ A further discussion of intuitions and reduction appears in Section VII.

electrolysis destroys the essential microstructure through a pair of oxidation/reduction reactions resulting in 2H_2 and O_2 as final products, and no more water (Wade).

After further investigation, some issues arise around the vagueness of the statement. “Water is H_2O ”, does this mean *just* H_2O , or a “naturally” occurring balance of ions and impurities? The previously described electrolysis proceeds at an appreciable pace only in an ion-healthy, natural sample and would occur much slower in pure water. Isolating pure water (only H_2O) is also incredibly difficult, and certainly wasn't the sample for the term's baptism.

The ambiguity of “water is H_2O ” extends even further: does the term refer to a substance with the proper proportions of each element or the unique HOH structure? The former case could potentially avoid some of the difficulties associated with (even pure) water's natural tendency to self-ionize under standard conditions to form hydrogen or hydronium ions (H^+ or H_3O^+) and hydroxide ions (OH^-). Samples of water spontaneously dissociate to reach equilibrium (making the isolation of pure H_2O so difficult), but ultimately maintain the two-to-one ratio the chemical composition interpretation of the statement deems critical. For the latter case, we can avoid some of the difficulties of considering *solutions* of water by focusing on its microstructure. What is essential for water is it being HOH, a polar molecule with unique properties resulting from its electrochemical structure. But, along with the structure of the molecule itself is the inter-molecular “structure” of solutions resulting from each molecule's polarity that cannot be ignored. Neither interpretation of the statement adequately clarifies what the essence is.

The essential description, “water is H_2O ”, is impossibly vague, with explanatory imprecision in both terms. For someone at a desalination plant attempting to produce “water” from “seawater”, the process would be considered complete when impurities were removed and a drinkable proportion of water and its ions was purified. For a chemist, “water” refers to a heavily distilled liquid with specific levels of

allowable contaminants. Finally, a hydrologist studying capillary action in plants would likely be more concerned with the molecular structure of water and how hydrogen bonding lends to its ability to move up roots against the force of gravity. For each of these applications, “water is H₂O” is neither relevant nor true.

IV. Water_{TE} is XYZ

As a result of these difficulties, the leaning is towards the dissolution of the concept of essences and the adoption of a pluralistic account that allows for such context-dependence. However, talk of essences is (temporarily) saved by Putnam’s entrance into possible worlds. Here, we can set aside the worries in the substances themselves and focus on his causal theory of reference and how referring terms apply rigidly via essences.

The thought experiment begins with a world exactly like ours in every respect (occurring in an identical universe or in otherwise “nearby” conditions). On this Twin Earth, there are even identical copies of every earthly person in identical psychological states. The only difference is that what is called water on earth is not composed of H₂O, but XYZ. So, ‘water’ on earth means H₂O, but on Twin Earth means XYZ.

“[...]In the sense in which it is used on Earth, the sense of water_E, what the Twin Earthians call ‘water’ simply isn’t water. The extension of ‘water’ in the sense of water_E is the set of all wholes consisting of H₂O molecules, or something like that.” (Putnam, 224)

The Twin Earth experiment gives cases where extensions differ for two groups with identical beliefs, the Twin Earthians whose water is XYZ, and our familiar water. For Putnam, water’s microstructure is its

essential property (suppressing Mellor's proposition of disjunctive essences: "H₂O or XYZ") and the Twin Earth example adequately proves the intuitive notion that Twin Earthian 'water' isn't water (Mellor, 303).

Putnam could not possibly have selected a worse sample case for his Twin Earth. Water is perhaps the most unique naturally occurring molecule and certainly one of the most critical for life. Many of its most distinctive characteristics arise directly from its "microstructure". Its high surface tension, capillary action, and adhesive/cohesive properties all result from the molecule's unique structure and polarity (with oxygen's lone pair electrons on one side and hydrogen atoms on the other). It is a molecule whose properties would be impossible to replicate by any other chemical formula, much less one with a "very long and complicated formula" like XYZ (Putnam, 223). Water is also essential to almost every form of life and covers the majority of our earth's surface. The physical, chemical, and social implications of the substitution of H₂O with *anything* else are unimaginable, and to suggest that my *Doppelgänger* would even exist when the most fundamental chemical processes have been violently disrupted is ludicrous.

I may inadvertently be making a case for essences here (the best result of this line of thought is: "water is H₂O" and we've already seen the difficulties with that), but the point is that this formulation of the H₂O/XYZ Twin Earth experiment is so counter-intuitive and would require the intentional neglect of so many issues that its practical use is minimal.

More Reference Woes and Causal Winds

Some use of the Twin Earth structure can be made in Putnam's alternative example where we roll back the clock to a less scientifically developed time like 1750. Rather than use any of Putnam's examples, let us quickly construct something reasonable. Our Oscars (E & TE) are now scientists seeking methods for allowing humans to metabolize wood, an ingestible wood-ase. Each Oscar (perhaps at the splitting

point of our otherwise identical universes) discovers a different enzyme, but they end up calling them the same thing because they are – due to the limited means of the time – unable to distinguish them. The enzymes continue to be referenced via the original ostensive definition and subsequently through “certain sameness relations” associated with their behavior near wood. Now suppose that many years have passed and Oscar_{TE}’s wood-ase was discovered to react first with the wood itself *before* being converted into Oscar_E’s wood-ase where its behavior became visible. On our earth, the Twin Earthian wood-ase spontaneously converts to our direct wood-ase and never appears in the Twin-Earthian form. What Twin Earthians referred to as wood-ase was actually an entirely different enzyme that did not itself exhibit the capability to break down wood.

Putnam suggests that this ostensive latitude is acceptable, and that we can at best provide only defeasible conditions for the sameness relation criteria. For example, if someone were to mistake gin for water in a sameness relationship test then they simply “do not intend [their] ostensive definition to be accepted” (Putnam, 225). The admission casts some doubt on the supposed “baptisms” or original ostensive definitions, and subsequently on the top-down order of reference and essence in Putnam’s system.

Essences are critical in Putnam’s account because they capture something mysterious about the efficacy of the kind’s “baptism”. However, if we can so easily be in error about our ostensive definitions, then it raises questions on the validity of the “baptism” model. Rather than rely on locating the paradigm example (basically by chance), perhaps we formulate a thorough description of a – potentially nonexistent – paradigm example by repeated experience with perceived samples. By building from the bottom-up, we no longer require the security of a real essence (as the property that binds all instances following a very contingent dubbing event), and a broader cluster concept of the kind can be formulated.

This view is echoed in Mellor's causal "winds", where he finds the direction of Putnam's reference fixing counterintuitive. Instead – citing the possibility for error – Mellor suggests that kind archetypes may be chosen or formulated to fit existing knowledge (Mellor, 305).

Putnam supports his essentialism with the Twin Earth experiments by presenting cases where extensions differ for two groups with identical beliefs, concluding that a substance can have different extensions despite being used in the same sense. However, the suggestion that the substance's extension differed between possible worlds does not follow from the Twin Earth experiments. Our wood-ase had the same extension on both worlds, except on Twin Earth it's microstructure was different, a chemical precursor to our wood-ase. Is the wood-ase's microstructure essential; are the conditions that prevent the occurrence of Twin Earthian wood-ase on earth essential (Mellor, 303)? Put simply, no, the conditions on Earth are such that earthly wood-ase has the microstructure it has, and on Twin Earth, its atmospheric conditions lead to Twin Earthian wood-ase having the precursory microstructure it does. The senses are the same, the extensions are the same ("wood-ase"), and the microstructure is not essential (for the stipulative conditions of the example, and the earlier discussion of water and essentialism).

V. Gold and other chemical kinds

Some of the issues discussed thus far have been specific to the unique properties of water and may have mischaracterized the field of chemical kinds. Kripke and Putnam's alternative chemical example, gold, appears to have a much simpler essence: atomic number 79.

For an atom to be gold, it must have 79 protons in its nucleus, and again, this appears to be fairly secure at first glance. Theoretically, element transmutation is possible, and with enough energy any

element can be bombarded into another. If the means existed for it, we could convert a hunk of platinum to gold by changing every particle from ^{78}Pt to ^{79}Au . This seems quite promising for the essentialist picture, after all, if atomic number 79 is the essential property of gold, it is supported that having acquired this property, we now have real gold.

In the following examples, I will attempt to show how atomic numbers and Kripke-Putnam essences in general are either too broad or too vague to be useful as delimiters of natural kinds.

Isotopes and Allotropes

Atomic numbers leave out quite a bit of the chemical picture. Substances that share the same atomic number have the same number of protons, but they can have a varying number of neutrons, resulting in isotopes.

In many cases, the extra or missing neutrons have little discernable effect on the element's properties. These properties are usually determined by the electrochemical structure of the element and the electrically neutral neutrons often have negligible effects. They do, however, come into play in smaller elements where the mass of the additional/lacking neutrons can affect their rates of reaction. The extra weight of additional neutrons tends to slow down the formation of bonds and vice versa for fewer neutrons. For example, the isotopes of hydrogen exhibit significantly different properties and applications where the addition of each neutron adds a multiple of mass to the atom. Deuterium (^2H) and Tritium (^3H) share many chemical properties with the more common hydrogen (^1H , "protium") isotope, but the activity of their additional neutrons allow them to be used as chemical markers, nuclear fission moderators, and even hydrogen bomb fuels. The isotopes of hydrogen are also unique in having

widely accepted names (most are identified solely by the element name and mass number, *carbon-12*), heavy water, where ^1H is replaced with ^2H , for example, is often symbolized D_2O .

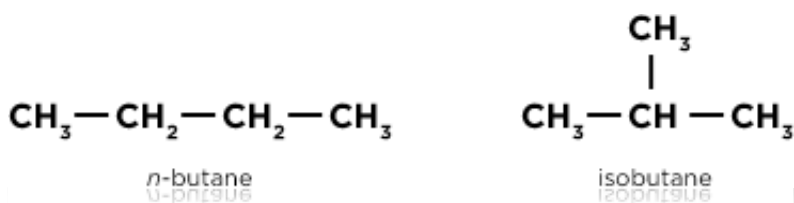
In most cases, when people refer to hydrogen, they mean hydrogen-1 (this is a pretty safe bet, the ^1H isotope has an abundance of over 99.98%). However, deuterium and tritium are isotopes *of hydrogen*, have atomic number 1, but are clearly not included when we refer to hydrogen. Is the essence now just the atomic number or does it include the number of neutrons?

Another troublesome case involves allotropes, which are composed of a single type of atom bonded together differently. Diamond and graphite, for example, are both composed entirely of carbon atoms, so they share the same atomic number, 6. However, diamonds have their carbons bonded in a tetrahedral lattice (a solid, three-dimensional network that lends to the mineral's strength), while in graphite the carbons are in sheets of hexagonal lattices (Wade). In this case, both of the essentialist's notions of essences (formula and atomic number) seem to operate at levels where the distinction between the substances is not accessible. The two substances are very different and clearly distinct kinds, diamond is the hardest known natural material while graphite is one of the softest, but atomic number essences ignore the critical inter-atomic network.

Isomerism

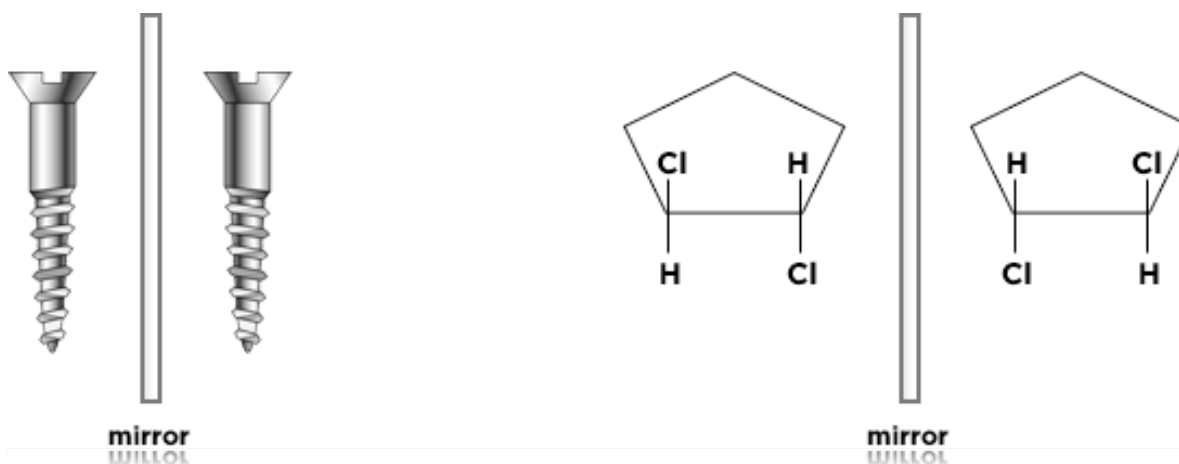
Zooming out one micro-step, we're now looking at chemical compounds and their structures. If the essence of water is H_2O , then an analogous reduction of the essences of other compounds to their chemical formulae follows. However, this kind of reduction overlooks yet another critical component of the equation, the bond structure (an ironic omission given the essentialist's interest in "microstructure").

Knowing that a compound is *composed* of certain elements tells us little about its bond structure or spatial orientation. For example, butane has (supposedly, as its essence) the chemical formula C₄H₁₀. What we don't know, however, is how these atoms are connected. There are actually two constitutional isomers for butane, they have the same chemical formula but their components are connected differently. Each isomer has a different density, different melting/boiling point, and even differing solubility behaviors (*n*-butane is soluble in water while isobutane is not). They are clearly distinct molecules that happen to share the same chemical formula.



Constitutional Isomers – the two constitutional or structural isomers of butane, C₄H₁₀

Perhaps Putnam simply encountered a technical limitation with the naming standard in use, as chemical formulae may be too cumbersome if they included bond structures. However, the field of stereochemistry, the study of the three-dimensional structure of molecules, provides us with excellent examples of compounds with the same chemical formula *and* bond structure that are still discernibly different entities. Enantiomers, a type of stereoisomer, result from the chirality or “handedness” of certain molecules that produce distinct, nonsuperimposable mirror images. Take your hands, for a real-world example, the left and right hands are identical except for being mirror images of one another, and there is no way you can turn them so that they lay atop each other and are entirely identical (Wade).



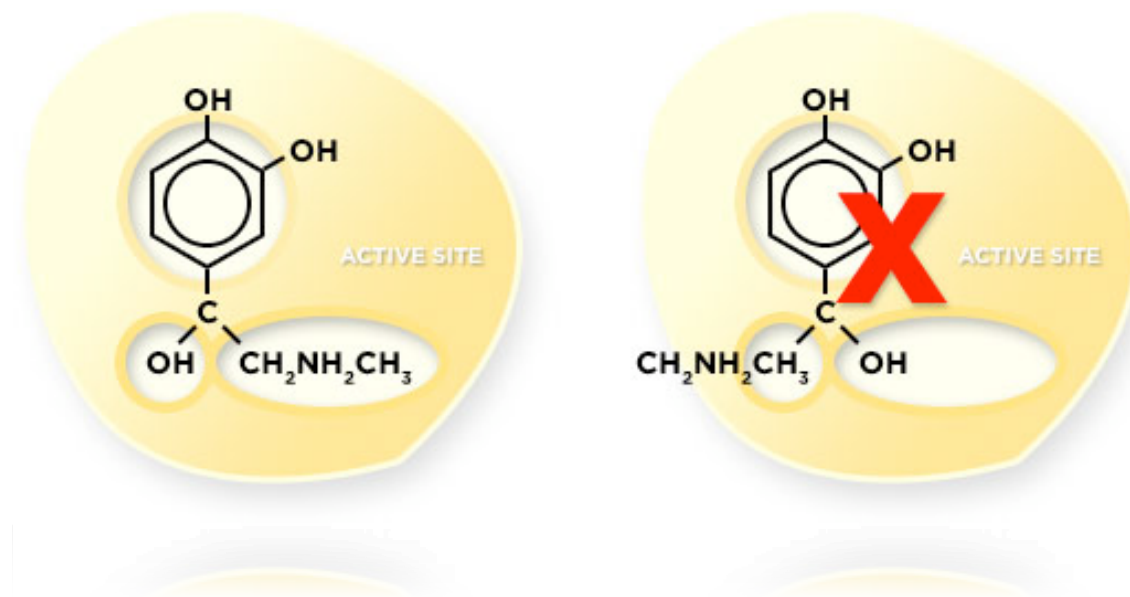
Stereoisomers – Each of these comes in “left-handed” and “right-handed” versions

A compound's enantiomers can have hugely different properties and behaviors. Thalidomide, for example, is a chiral compound whose enantiomers differ significantly. Originally developed as a drug to suppress morning sickness in pregnant women, thalidomide was later discovered to be a chiral compound with devastating effects. While the (R) enantiomer *was* effective against morning sickness, the (S) enantiomer was found to be teratogenic, causing birth defects in almost ten thousand children (Kroksgaard-Larsen).

The often-biological effects of chirality are caused by the spatial inversion of enantiomers and the “induced-fit” mechanism of many enzymes. Just as it is impossible to fit a right-handed glove on your left hand, it is impossible for a right-handed enzyme to form the appropriate enzyme/substrate complex with the left-handed compound. The presence of the wrong enantiomer often has no effect, like ibuprofen, where most over-the-counter varieties actually include double the dosage as the inert enantiomer is costly to remove. However, as was the case with thalidomide, the incorrect enantiomer can react awkwardly with very different results.

Enantiomers and even “racemic” mixtures of them (those including equal and inter-converting amounts of each enantiomer) can have very different behaviors. These behaviors form distinct kinds

that are of interest to chemists, biologists and everyone else. So now, is the essence the atomic number, number of neutrons, bond structure, *and* spatial arrangement?



Epinephrine – effect of chirality at enzyme active site.

VI. Problems with essences

There are obviously many difficulties with the notion that a chemical formula (like H₂O) or an atomic number (like ⁷⁹Au) is an essential property of a kind. These descriptions are far too ambiguous, as other details are also “essential”: in the case of compounds, bond structure and spatial arrangement, and for elements, isotope specification and mixture purity. By the essentialist’s own constraints, however, this ambiguity is neither epistemically nor metaphysically admissible. We are, after all, describing the essential property which nothing can lack and still be of the kind. As I have shown in the examples above, chemical kinds are no longer the secure lair for microstructural essences they once were.

Simplified statements of essences are as impractical here as they are with species and other lost essentialist fronts, and pose concerns about essentialism in natural kinds globally. After all, as Mellor

points out in his (1977), Putnam – more often interested in problems of reference and rigid designators – never addresses why exactly some properties are essential and must be common to all instances of the same kind. With so many reasons to move away from essentialism, why is there still so much interest?

VII. Intuitions and nature's joint

One possible explanation for the continued interest in essentialism is its intuitive support. As described earlier, ideas of microstructure and reduction are naturally appealing. In normal investigation, one is likely to look inward at a substance's supposed "core" for some attribute or collection of attributes that define the properties of the substance as a whole. This intuition, however, becomes increasingly less applicable as we delve deeper into substances' cores, as science tends to. Primitively, the essence of a substance or event was fixed by simple, immediately accessible investigation. For Aristotle, the essence of a lunar eclipse, for example, is its screening by earth. This simple essence explains the properties observed during the eclipse (dark shadow moving across the moon, etc) (Charles). In modern science, however, any "essences" derived are far-removed from intuitive, and even physical access. The theory-laden subatomic particles that describe the farthest reduced substances are difficult to comprehend and are (maybe necessarily) unobservable. We cannot justify intuitive guidance in the investigation of quarks and leptons whose qualities only a handful of particle physicists can truly grasp.

Even if just the *concept* of reduction is intuitive, regardless of the intermediary equipment (both theoretical and physical), essentialism and reduction face difficulties. As physicists continue to delve deeper into atoms' contents, essences are packed into tinier and more obscure entities. With each substructural level, the criteria for differentiation get more specific and the higher-level distinctions

become null. The impact of an essential description 'H₂O' becomes less important if subatomic vibrating strings explain all the contributing properties of each element. Theoretically, the eventual result of essential reductionism could be a single kind, one type of vibrating string whose varying frequency accounts for all the substances in the universe, and with only a single type, we have no natural kinds.

Fully reduced essences are of no explanatory value, and the alternative (for example, selecting H₂O as the essence for water) applies an arbitrary reduction barrier, and a vague one at that.

VIII. Explanatory value barrier

There is, however, a way to make this barrier meaningful, by maintaining a form of essentialism based on explanatory value. The concept of essential properties is itself valuable, though difficulties arise when attempting to universalize their definitions (imprecise descriptions, and the single-kind end game). It is important for a normal investigator to be able to create definitive criteria for identifying the substances with which he or she is concerned. Often times these criteria are shared with their normal-use descriptions, but they sometimes require clarification or redefinition altogether. Kripke's essences are metaphysically necessary (not just knowable *a priori*), so these are not, strictly speaking, essences. What I maintain is the concept's heuristic value, its way of demarcating absolutely whether or not a substance is of the kind in question.

This "essential" pluralism relies on what I have called explanatory value-based reduction barriers. The previously described desalination plant worker, chemist and hydrologist each had very different descriptions for "water" based on what they were using it for. The essential property of "water" for the desalination plant worker is that it comes out below the government-approved proportions of

pollutions. Water is examined and described on a large scale here, on the order of millions of gallons. The level of reduction required to precisely describe the essential property is minimal; the essential property in question is detectable macroscopically (namely, not salty).

For the chemist, “water” is the substance that can be used to quench and buffer acidic solutions, or used to dissolve virtually anything. Here the scale is smaller, as the molecular structure of the molecule is critical, but we are still concerned with observable *quantities* of liquid (and that they be reasonably distilled/purified, etc). In an acid-base reaction, for example, the essential property of water is “autoionizing, distilled H₂O” which captures both the chemical formula and the liquid’s tendency to interconvert between its ions (a critical component of this type of reaction).

The hydrologist who is studying capillary action would also have a different notion for the essential property of water. They would find the molecule’s bond angles and the intermolecular interactions most important, as these features account for the liquid’s wicking behavior. In this case, the reduction barrier is further lowered, as the hydrologist’s concerns are more theoretical and delve deeper into the molecule’s structure. A description like “polarized HOH” captures the hydrologist’s “essential” property, containing the polarity that allows for hydrogen bonding between molecules and the interchanged chemical formula indicating its bond structure.

Outside of their respective employments, they may all share similar notions towards water’s essential property, but that is only because their interests are also shared, namely they’re thirsty and water is (essentially) that clear, potable liquid that quenches thirst.

This pluralism allows us to preserve the utility of essences without the difficulties of Kripke and Putnam’s universal definitions.

IX. Conclusion

Kripke and Putnam's essentialism faces too many problems to remain a viable account of natural kinds. Even in the previously secure realm of chemical kinds, essences are impractically rigid. The pigeonholes of the periodic table are deceiving (element isotopes are distinct kinds), and chemical formulae are ambiguous (isomers have the same components arranged differently). However, the impossibility of describing universally applicable essences does not detract from the utility of essential properties themselves. By allowing for various levels of reduction based on investigators' needs, we can maintain the practical value of essentialism – that is, the ability to absolutely specify if a substance is a member of a kind.

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