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ARTICLE

Are Acids Natural Kinds?

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Abstract

Are acids natural kinds? Or are they merely relevant kinds? Although acidity has been one of the oldest and most important concepts in chemistry, surprisingly little ink has been spilled on the natural kind question. I approach the question from the perspective of microstructural essentialism. After explaining why both Brønsted acids and Lewis acids are considered functional kinds, I address the challenges of multiple realization and multiple determination. Contra Manafu and Hendry, I argue that the stereotypical properties of acids are not multiply realized. Instead, given the equivalence between the proton-donating and electron-accepting mechanisms of Brønsted and Lewis, respectively, I show that acidity as a property type can be identified with a unique microstructural property, namely the presence of a LUMO or other low energy empty orbital. In doing so, I defend the view that the Lewis theory encompasses Brønsted–Lowry, and that all Brønsted acids are also Lewis acids. Contra Hacking and Chang, I thus maintain that the different concepts of acidity do not crosscut, and that the hierarchy requirement is met. Finally, by characterizing natural kinds as powerful objects and by adopting a dispositional view of functions, I illustrate how the microessentialist can make sense of the latent and relational character of most acids. In sum, I contend that acids are genuine natural kinds, even for the microstructural essentialist.

Keywords: Brønsted–Lowry acids; Lewis acids; primary acid; secondary acid; natural kinds; functional kinds; chemical kinds; bifurcating kinds; essentialism; microstructuralism; microessentialism; multiple realization; multiple determination; ontological reductionism; hierarchy requirement; protonism; electronism; amphoterism; dispositional properties; powers.

*Dedicated to the memory of Gilbert N. Lewis, who first
proposed his acid–base definitions in 1923, a century ago.*

1. Introduction

Scientists like to sort the objects they encounter into different kinds and categories.[1] Most categorizations and classifications are artificial and arbitrary; they are imposed on nature and dependent on human interests.[2] But some groupings are privileged because they are believed to ‘carve nature at its joints’ (as Plato claimed in his *Phaedrus*). They are not invented, but discovered, and reflect real, mind-independent distinctions or divisions which exist in nature. Such groupings are called **natural kinds**.[3] And the belief in their existence is called **natural kind realism**.

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[1] Roughly speaking, a ‘kind’ pertains to the world, whereas a ‘category’ belongs to our language or scientific theories. As Muhammad Ali Khalidi (2013, p. xi) observes, “there is often a close connection between the kinds that are present in the world and the categories that we invent to understand the world”.

[2] Examples include the set of all coffee grinders under € 500, or the group of all European citizens born on a Tuesday.

[3] Natural kinds, then, can be construed as sets or classes of objects that resemble one another by virtue of sharing one or more natural properties. Whether natural kinds are just that (sets of objects), or whether they should be conceived of as universals, is a question that goes beyond the scope of the present paper. Similarly, I will not take a stand in the debate on

Paradigm cases of natural kinds, however, are few and growing fewer. **Biological species** were long held to be paradigmatic natural kinds, but it is no longer clear whether the notion of species captures ontological reality.[4] **Chemical species**, on the other hand, are still widely considered to be genuine natural kinds—at least in the broader philosophy of science community. In philosophy of chemistry, in contrast, even the status of chemical kinds[5] has become increasingly controversial.

While most discussions have focused on the kindhood of **elements** and their **compounds**, such as gold and water—two examples made famous by the work of Saul Kripke (1980) and Hilary Putnam (1975)—the question to be entertained in this paper is the following: **Are acids natural kinds?** Do acids meet the criteria for being a natural kind, or are they merely “relevant kinds” to use Nelson Goodman’s terminology? Although acidity has been one of the oldest and most important concepts in chemistry, surprisingly little ink has been spilled on the natural kind question.

2. Microstructural essentialism

I will approach the question from the perspective of **microstructural essentialism** (or microessentialism for short), since this is the most commonly cited framework in discussions on chemical kinds, both by its advocates and by its critics alike.[6]

Essentialism about natural kinds is the view according to which all members of a kind (and only members of that kind) resemble one another by virtue of sharing a common *essence*—a set of *intrinsic properties* that are systematically associated.[7] The possession of these essential properties is both necessary and jointly sufficient for belonging to that kind. “To be lacking any of these properties”, explains Anjan Chakravartty (2007, p. 156), “is to preclude membership and *vice versa*”. In short, the essence determines the identity of a kind, and is responsible for all the other properties that the members of a kind may share.[8]

Microstructuralism is the view according to which chemical substances ought to be individuated

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whether an ontology of natural properties is sufficient to make sense of natural kinds, or whether natural kinds are a *sui generis* type of entity requiring their own distinct ontological category. On the latter view, a natural kind would be an entity *over and above* the set of natural properties shared by all members of the kind, together with the laws holding these properties together. See Tobin (2013) for a proper analysis and in-depth examination of either option. Finally, in what follows, I will only focus on the *metaphysics* of natural kinds; the *semantics* of natural kind terms will not be discussed. For the latter, see the collection of papers in *The Semantics and Metaphysics of Natural Kinds* (2010).

[4] See, for example, the work of John Dupré (1993).

[5] Notice that the term ‘chemical kind’ may refer (i) to microscopic species, such as atoms, ions and molecules, (ii) to chemical substances (as macroscopic bodies of pure or impure stuff), and (iii) to groups of substances. For example, an isolated gold atom is a chemical kind; but so is a macroscopic sample of gold, and so are the coinage metals in group 11 of the periodic table to which gold belongs. Again, a single molecule of ethanol (CH_3CH_2OH) is a chemical kind; so is the chemical substance ethanol, and so are the alcohols of which ethanol is just one example (albeit the most famous one). The central question in the natural kind debate is whether these chemical kinds are *natural* kinds. Do they carve nature at its joints, or do they butcher it randomly and artificially?

[6] Although it would no doubt be interesting, and perhaps even illuminating, to also look at the question from the perspective of cluster kinds (as developed by Richard Boyd’s (1991; 1999) homeostatic property cluster theory) or promiscuous kinds (as developed by John Dupré), I will refrain from doing so in this paper.

[7] Tahko (2015, p. 796) defines natural kind essentialism thus: “There are at least some genuine, mind-independent natural kinds that are defined by their essential properties”. Notice that these essential properties need not be elusive; they can be discovered through scientific investigation. For a contemporary defense of natural kind essentialism and further developments, see Bird (2007), Hawley and Bird (2011), Tahko (2015), and the *New Essentialism* (or *scientific essentialism*) of Brian Ellis (2001; 2002; 2009) in which a dispositional view of kind essences is developed.

[8] Two brief remarks about the nature of kind essences according to the *New Essentialism* of Brian Ellis (2001; 2009): 1. An important aspect of Ellis’s framework is that natural kind essences must be intrinsic properties. 2. According to Ellis, these essential properties are conceived of as powers or dispositional properties. Not everyone agrees with Ellis’s requirements. For example, many advocates of essentialism have dropped the first requirement, arguing that essentialism is compatible with non-intrinsic essential properties. For discussion of the intrinsicness requirement, see Williams (2011), Tahko (2015) and Havstad (2018). I thank Tuomas Tahko for drawing my attention to this, and will return to both of these points in the last two sections of my paper when discussing the latent and relational character of acidity.

(and explained) by their *microstructures* (as opposed to by their macroscopic behavior or properties).[9] As such, microstructuralism is a specific brand of reductive physicalism (Bartol 2016, p. 535). It maintains that the macroscopic behavior and properties of a chemical kind are fully reducible to its microstructure.[10]

Microessentialism, then, is the view according to which the essences of chemical kinds are *microstructural essences*, instantiated at the microphysical level. Chemical substances, on this view, are what they are, and do what they do in virtue of their microstructural essence; their identity is determined by their microstructure. Or in slogan form: “microstructure is what makes a chemical substance what it is” (Hendry 2016, p. 272). As Zdenka Brzović (2023) explains, “[w]hile higher-level, observable properties can be used to identify what kind some entity belongs to, the microstructure has explanatory priority, and is the real arbiter of whether something belongs to a kind, because it is responsible for all the other properties and relations into which the entity can enter.”

Both Kripke (1980) and Putnam (1975) have defended microessentialist claims about chemical kinds. They thus argued that the essence of gold is its nuclear charge (having 79 protons in the nucleus), and that the essence of water is its molecular structure (being composed of H_2O molecules).[11] According to the microessentialist, having 79 protons in the nucleus is both necessary and sufficient for belonging to the chemical kind ‘gold’ (and similarly for ‘water’). In other words, gold has its nuclear charge *essentially*, and water has its molecular structure *essentially*. It is in virtue of their (nuclear or molecular) microstructure that we can draw inductive inferences and formulate scientific laws about (the other properties of) gold and water.

On the face of it, there seems to be no reason why the microessentialist account of chemical kinds couldn’t extend upward to more complex substances (such as crystals, polymers, proteins and other biochemical kinds) or even to classes of substances (such as metals, alcohols or acids). As Jordan Bartol (2016, p. 536) observes: “If microstructuralism can handle one step up the complexity scale, from elements [such as gold] to molecules [such as water], then what’s a few more?” Protein molecules, for example, are much larger than water molecules (they are called ‘macromolecules’ for a reason); their microstructure is therefore much more complex than that of water.[12] But the fact remains that all proteins are ultimately composed of protons, neutrons and electrons, and should therefore admit a microstructural analysis. The same applies to all other (bio)chemical kinds, no matter how complex they may be microstructurally. Or to quote from Bartol (2016, p. 536) once again: “There is great appeal in the thought that molecules, atoms, and macromolecules are all fundamentally the same types of things.” The microstructuralist stance thus offers the promise of a **natural kind monism** where all kinds are ultimately grounded in microphysical facts.

3. Functional kinds

Given that outlook, in order to be a natural kind for the microstructural essentialist, all acids should have a common essence—a common intrinsic property, structure or molecular constituent that is present in all acids and only in them. This idea resonates particularly well with the early views of acidity, which were all **constitutive**. Acids, I recall, have been known since antiquity. Long before

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[9] For a contemporary defense and elaboration of the microstructuralist thesis, please see Hendry (2006a; 2008; 2012).

[10] Notice that there are various levels of microstructural arrangement. As Tahko (2015, p. 804) points out, the term ‘microstructure’ should be understood as “a placeholder for whatever level of microstructural accuracy one wishes to focus on.” It could be nuclear, atomic, molecular or even supra-molecular.

[11] As I mentioned above, the identification of the substance ‘water’ with the molecular structure ‘H_2O’ has been questioned by various philosophers of chemistry. See, for instance, Van Brakel (2000) and Needham (2000; 2002; 2011). More generally, the idea that kind essences are intrinsic and microstructural has faced major criticism. See, for example, LaPorte (2003).

[12] Given this complexity, a further distinction is typically introduced between the primary, secondary, tertiary and quaternary structure of proteins.

the rise of modern chemistry, most (vegetable and mineral)[13] acids were identified through a number of shared phenomenological characteristics: most acids were corrosive, had a sour taste (the word 'acid' derives from the Latin word *acere*, 'to be sour'), turned blue litmus paper red, and formed salts upon reacting with a base, or produced hydrogen gas upon contact with a metal. Those, in a nutshell, were the functional roles and identifying characteristics of acids. Chang (2012, p. 691) calls this the "quotidian operational meaning" of acidity; Hacking (1983, p. 84) calls it "the professional stereotype" for acids. A substance was judged to be an acid (to belong to the 'acid' kind) when it exhibited this stereotypical behavior.

The question was what caused all these acids to exhibit the same stereotypical acidic behavior, and a natural answer was to postulate the existence of an 'acidifying principle' or *essence* that was present in all acids. Antoine Laurent Lavoisier thus famously proposed that all acids were composed of the element oxygen (literally, *acid generator*, from the Greek *oxein* for 'sour' and *gennan* for 'to generate'),[14] whereas Humphry Davy, Pierre Louis Dulong, and later also Justus von Liebig, all took hydrogen to be the common ingredient (or 'acidifying principle') of acids.[15] Even before Lavoisier's time, when acidity was still explained in mechanistic terms (*e.g.* by Robert Boyle and Nicholas Lemery), the view was clearly constitutive: acids were said to be composed of pointy, sharp particles, which served to explain their corrosive nature and sour taste (Chang 2012, p. 691).[16]

But as Alexandru Manafu (2012) has argued, most modern views of acidity are **functional**, rather than constitutive; they define acids, not by a shared ingredient, but functionally, by their shared behavior in chemical reactions. That is, in order for a chemical kind to be an acid, it should do a certain job or have a clear function. Johannes Nicolaus Brønsted and Thomas Martin Lowry thus define acids as **proton donors**; the 'job' of an acid, according to them, is to donate protons in chemical reactions. Gilbert N. Lewis defines acids as **electron pair acceptors**; the function of an acid, according to him, is to accept an electron pair in chemical reactions.[17]

"All these definitions are functional," writes Manafu (2015, p. 48); "they pick out acids not by referring to their microphysical structure, but by referring to their behavior in relation to other chemical substances".[18] Robin Hendry (2015, p. 252) similarly refers to acids as a class of (compound chemical) substances (*i.e.* chemical kinds) which are grouped together in virtue of sharing "a pattern of chemical reactivity". Perhaps then it would be better to refer to acids as **functional kinds**—kinds whose members all share a common function, rather than an underlying essence?[19]

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[13] Acetic acid (CH_3COOH), for example, better known as vinegar in diluted form, is a plant-based substance, and therefore classified as a vegetable acid; hydrochloric acid (HCl) and sulphuric acid (H_2SO_4), in contrast, are mineral acids.

[14] As Hendry (2006a, p. 866) explains, Lavoisier considered the acids to be a 'chemical genus' (in the context of this paper, one could say a 'chemical kind') whose characteristic ingredient was the element oxygen, and whose 'differentiae' were the different acidifiable 'principles', such as nitrogen, sulphur and phosphorous. The more these principles were oxygenated, the stronger the resulting acid. For example, nitric acid (in modern notation, HNO_3) is a stronger acid than nitrous acid (HNO_2).

[15] Joseph Priestley, it may be added, advanced the idea that carbon dioxide ('fixed' or 'dephlogisticated' air, as it was called at the time) was the acidifying principle (Finston and Rychtman 1982, p. 2).

[16] The nature of acids and bases has been the subject of continued research and debate for more than three centuries. Both Jensen (1979, chapters 1 & 2) and Finston and Rychtman (1982, chapter 1) provide a historical overview of the evolution of the concept of acidity. See also Walden (1929, part I), Lowry (1936, chapter 2), Luder and Zuffanti (1961, chapter 1), Kauffman (1988), Jensen (2016), Ruthenberg and Chang (2017) and Gerontas (2023) for more on the history of acidity.

[17] Luder and Zuffanti (1961, p. ix), in their classic book on *The Electronic Theory of Acids and Bases*, emphasize that acidity, on the Lewis view, has "nothing to do with the presence of any one element or specific group of elements", contrary to most of the constitutive views that came before. The authors reiterate their point on p. 2.

[18] Although my focus in this paper will be on the Brønsted–Lowry and Lewis definitions, they are far from the only 'modern' definitions of acidity. Even before Brønsted and Lowry, Arrhenius already defined acids as substances that increase the hydrogen ion concentration in water. In analogy with this, the *solvent system theory* defines acids as solutes that increase the concentration of the cation generated in the autoionization reaction of the protic or aprotic solvent. What is important, for our purposes, is that all these alternate definitions of acidity are also *functional* definitions.

[19] The relationship between functional kinds and natural kinds is a complicated one, to be further explored in this paper. One worry is that by admitting functional kinds into our ontology, we would seem to end up with a plurality of kind categories.

As we will see further on, the nature of functional kinds introduces two important challenges for microessentialism. The first challenge is called **multiple realization** and occurs when *one* function is realized by *many* different microstructures. The second challenge is called **multiple determination** and occurs when *one* microstructure realizes *many* different functions. Although my focus will be on the first challenge, I will briefly tackle the second challenge towards the end of my paper.

4. Multiple realization

A common feature of functional kinds is their **multiple realizability**. Multiple realizability, briefly, is the thesis that the same upper-level behavior can be realized by multiple systems that differ in their lower-level details (Woodward 2022, p. 262).[20] As James Woodward explains, multiple realizability captures the idea that "sometimes lower-level details do not matter to upper-level behavior" (p. 262). For example, the members of the functional kind 'predator' are grouped together *because of something they do* (they all hunt for prey), rather than because of something they all share (some underlying essence). Hence, explains Brzović (2023), "very different species of animals can belong to the predator category, such as jaguar, human, rattlesnake, or stork." That is, the kind 'predator' is multiply realized. Or to give another example, 'watch' is a functional kind whose function is to keep time; it too can be realized in multiple ways, *e.g.* by analog and digital mechanisms. Whether the (lower-level) mechanism is analog or digital does not matter to the (upper-level) behavior of the watch, namely its keeping time. Now, since acids are functional kinds, they too must be **multiply realized** according to Manafu (2015). Or, to put it more accurately, acidity (the property of being an acid) must be multiply realized.

An important consequence of the alleged multiple realizability of acidity, according to Manafu (2015, p. 48), is that "the property of being an acid [...] does not 'reduce' [...] to any given microstructural property".[21] More specifically, while **token reductionism** may still hold true, **type reductionism** clearly fails: "acidity [...] as a property type cannot be identified to any given microstructural property". That is, while any particular instance of acidity may be reducible to *some* microstructural property or process (token reductionism), acidity in general may not actually be reducible to a single unique microstructural feature that is present in all instances of acidity (type reductionism).[22] In short, acidity cannot be grounded in microstructural facts.

For much the same reasons, Hendry (2006a, p. 873) argues that "[m]icrostructuralism clearly fails

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There would be kinds whose essences are microstructural, and other kinds whose essences are functional. This would go against the spirit of natural kind monism, and force us into accepting some form of **natural kind pluralism**. Notice that the monism/pluralism distinction just drawn is not always interpreted in this way. For many, natural kind monism is the thesis that there is only one correct way of carving nature at its joints; natural kind pluralism, then, is the thesis that nature can be carved up in many different, but equally valid ways. On the latter view, objects will oftentimes be cross-classified, depending on our scientific interests. I will return to the problem of crosscutting classifications in section 8.

[20] The multiple realizability thesis originated in the 1970s in discussions about the mind's relationship to the brain. It was argued that a single mental/psychological kind, such as pain, could be realized by multiple distinct physical kinds, *e.g.* by different brain states. The thesis was advanced to support antireductionism in philosophy of mind. After all, if the correlation between mental states and brain states is not one-one but one-many, then mental types are not identical to physical types. Mental states do not type-reduce to physical brain states, and so psychophysical reduction must be false, or so the argument went. The multiple realizability thesis, therefore, originally led many philosophers of mind to adopt some form of nonreductive physicalism.

[21] Manafu (2015, p. 48) contrasts the property of being an acid with the property of being an alcohol which, in his opinion, *does* 'reduce' to a microstructural property, namely to the presence of a hydroxyl group in the molecular structure that is bound to a saturated carbon atom. The property of being an alcohol, in other words, is *identical* (or, at least, co-extensive) with the microstructural property of possessing a hydroxyl group. Notice that this is a *type* identity theory. The claim, after all, is that *all* alcohols are hydroxyl-containing compounds.

[22] To put it somewhat differently, according to the multiple realizability thesis, the tokens of a certain type can be realized by the tokens of two or more distinct types (Jaworski 2023). Hence, type-type reduction fails, while token-token reduction still holds true.

for [. . .] the acids.” Echoing Ian Hacking (1983) and Kyle Stanford and Philip Kitcher (2000), Hendry (2006a, pp. 873–874) points out that “no microstructural feature unites the acids and the bases”. “There is probably nothing more to being an acid than displaying enough of the typically acidic kinds of behavior”, exclaims Hendry (2016, p. 263). With respect to the token–type distinction that was drawn above, Hendry (2016, p. 263) seems to be in full agreement with Manafu: “while there are, of course, detailed causal [and I would add, microstructural—P.T.] explanations of why each acid behaves the way it does [token reductionism], the explanations diverge, because no single component or structural property gives rise to all the different cases of acidity [type reductionism].”

In conclusion, the argument seems to be that because the property of being an acid is multiply realized (with multiple microstructures realizing the same function), acidity is **type-irreducible** to a universal property at the microphysical level. In other words, since the various acids fail to share a common microstructure, the microessentialist goal of identifying all acids by a unique microstructure ultimately fails. Indeed, according to Manafu (2015, p. 48), acidity “is not discernible at the lower level as a microstructural property”. Rather, “it ‘**emerges**’ out of the microphysics, and becomes visible only [at a higher, chemical level] in the context of a chemical reaction, as a pattern of chemical behavior”.[23] Before continuing our discussion, the following two remarks may serve as further clarification:

1. First, I should note that Manafu and Hendry are not alone in reaching such anti-essentialist conclusions based on the phenomenon of multiple realizability. Tuomas Tahko (2020, p. 800), in his study of biochemical kinds, for example, also referred to multiple realizability as posing an important challenge to **ontological reductionism** (or what he alternatively calls ‘one-one reduction’ or ‘identity-based reduction’). As he explains, “multiple realization is at least a *prima facie* challenge for ontological reductionism precisely because the functions are underdetermined by the microstructure” (pp. 802–803).[24]
2. Second, notice that neither Manafu nor Hendry are denying the **physicalist thesis** according to which the macroscopic properties of a chemical substance are determined by its microscopic properties. What they *are* denying, is the **microstructuralist thesis** according to which there is a 1:1 correlation between the macroscopic and microscopic properties, such that the former are identical with, or at least reducible to, the latter. Their claim, after all, is that the same macroscopic behavior can be realized by multiple distinct microstructures.[25] The relation is thus rather one of **supervenience**, where the higher-level properties of a chemical substance are said to supervene on the lower-level properties of its constituents.[26]

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[23] According to Manafu, chemistry provides us with many other examples of functional, multiply realized properties (*e.g.* the property of being a base, a reductant, an oxidant, a metal, *etc.*). He uses this feature to argue for a novel approach to (ontological) emergence which he calls *functional emergence.* On this account, it is not the chemical entities, but chemical properties (like acidity), as well as laws and explanations, that emerge from the microphysical level. While these of course depend on the physical level, they do not reduce to it. In that sense, functional emergence is very similar to the position of *nonreductive physicalism* which also attempts to reconcile our physicalist intuitions that all there is, is ultimately physical with the fact that for some reason or another the special sciences are not reducible to physics. Manafu’s account thus attempts to secure the ontological autonomy of chemistry from physics and also circumvents some of the problems with Hendry’s alternative account of ontological emergence in chemistry, as developed in Hendry (2006b, 2010a, 2010b).

[24] To be fair, while Tahko accepts that biochemical kinds are multiply realized, he believes the challenge of multiple realization can be addressed and ends up defending ontological reductionism about biochemical kinds.

[25] Tahko (2015, p. 804) formulates the microstructuralist thesis as follows: “Necessarily, a sample of a chemical substance A is of the same chemical substance as B *if and only if* A and B have the same microstructural composition.” Considering the multiple realizability of functional kinds, Kistler (2018) takes issue with this biconditional, much like Manafu and Hendry above. That is, while he accepts the physicalist thesis that *if* A and B share the same microstructure, *then* A and B are the same chemical substance, he rejects the reverse microstructuralist thesis that *if* A and B are the same chemical substance, *then* they must necessarily have the same microstructure. According to Kistler, then, while the higher-level properties of a chemical substance are obviously not identical to its lower-level properties (*contra* microstructuralism), they are still ‘nothing over and above’ these lower-level properties (*pro* physicalism).

[26] A set of properties A is said to supervene upon another set of properties B when there cannot be an A-difference without

5. Are acids multiply realized?

In what follows, I want to challenge the claim that acids are multiply realized. *Pace* Manafu and Hendry, I will argue that acids are **uniquely realized** at the microstructural level, thereby lending further support to the microessentialist project. To that aim, I will first distinguish three reasons why acids may be said to be multiply realized, only to reject them one by one.

The **first reason** boils down to the following: since acids are a functional kind, they *must* be multiply realized (or multiply realizable, at the very least). Now, while some functionalists have indeed maintained that it is a conceptual truth that *all* functional kinds are multiply realizable, Eric Funkhouser (2007, p. 304) notes that the "cautious functionalists have acknowledged that their functionalism only opens up the *possibility* of [multiple realizability], and that empirical investigation is then needed to settle the issue" (emphasis added). Tahko (2020, p. 803) likewise argues for a case-by-case approach and admits that some functions may ultimately be reducible to a unique microstructure. In short, while some functions are undoubtedly multiply realized, others are uniquely realized. Ergo, the fact that acids are a functional kind is, in and of itself, not sufficient reason to conclude that acids *must* be multiply realized.

To illustrate this, let us consider the Brønsted definition of acidity, according to which acids are proton donors. Although this is a functional definition, it is easy to see how this functional property (the ability to donate a proton) can be 'reduced' to a unique microstructural property, namely the presence of a loosely bound (and thus transferable) proton in the molecular structure. Transferable protons of this kind are commonly called **acidic protons** to distinguish them from other nonacidic protons that may be present in the molecule (Atkins et al. 2010, p. 122).[27] Being a proton donor, in other words, is *identical* to having acidic protons in one's molecular structure. There is a one-one relationship between the proton-donating function of Brønsted acids and the microstructure related to that function. So this is a case of unique realization, not multiple realization.[28]

6. Relevantly the same, but relevantly different

The **second reason** for claiming that acids are multiply realized comes from Manafu (2013; 2014; 2015). After observing that "[m]any chemical properties are defined functionally, by pointing to a certain functional role or behavior", Manafu (2014, p. 39) insists that "[s]ince there are many systems of electrons and nuclei that can carry out the same chemical behavior, there is prima facie evidence that many chemical properties are multiply realized." Acidity is a case in point: since acidity is "first and foremost a behavior", writes Manafu (2015, p. 48), it too "can be realized by many systems of electrons and nuclei".[29]

In short, Manafu appears to suggest that acidity is multiply realized because many different substances (many different "systems of electrons and nuclei"), such as hydrochloric acid (HCl), sulphuric acid (H_2SO_4), and nitric acid (HNO_3), can all act as acids. Manafu (2013, pp. 672–673) thus concludes that since "one and the same chemical property (*e.g.*, acidity) is realized by a variety of microphysical lower level [. . .] systems of electrons, protons and neutrons [. . .], it cannot be identified with any particular microphysical constitutive property."

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a B-difference.

[27] For example, while the proton from the hydroxyl group (–OH group) in acetic acid (CH_3COOH) is weakly acidic, the three methyl protons are nonacidic. Not all hydrogen-containing compounds, therefore, are necessarily acidic, as Liebig and others before him had assumed.

[28] The same can be said for Lewis acids: being an electron pair acceptor is *identical* to having an empty orbital which is capable of accepting an electron pair from a Lewis base to form an acid–base adduct.

[29] Further on, Manafu (2015, p. 49) reiterates the point that functional properties in chemistry (such as acidity) are multiply realized "in the sense of their being many systems composed of electrons and nuclei that can carry out the specified role".

But this is clearly mistaken. HCl, H_2SO_4, and HNO_3 are admittedly different chemical substances, with entirely different microstructures. Yet despite these differences, there is one thing they all have in common, namely the presence of one or more acidic protons. Crucially, it is this (microstructural) property that helps to explain why they all behave in like manner during chemical reactions; it is the proton that is responsible for their acidic behavior. Now, whether that proton is bound to a chloride anion (Cl^-), a hydrogen sulphate group ($HSO_4{}^-$) or a nitrate group ($NO_3{}^-$), is of little relevance to its proton-donating ability.

Not all microstructural variation, in other words, counts as evidence of multiple realization, since not all differences are *relevant* differences.[30] Multiple realization, in short, requires the right kind of variation. But this of course raises the question: what variation qualifies as multiple realization and what variation does not? How does one distinguish relevant from irrelevant differences? According to Thomas W. Polger and Lawrence A. Shapiro (2016, p. 62), who have studied this question in depth, "[m]ultiple realization occurs if and only if two (or more) systems perform relevantly the same function *in relevantly different ways*" (emphasis added). Or, as they put it in slogan form: "**relevantly the same and relevantly different**". Importantly, a difference is only deemed relevant when it amounts to a different way of performing the said function.[31]

Polger and Shapiro offer the example of a **corkscrew** to illustrate their point. 'Corkscrew' is a functional kind.[32] The function of a corkscrew is to pull out corks from bottles by screwing into the cork. There are, however, many different ways in which that function can be realized. A double-lever corkscrew, for instance, operates very differently from a waiter's corkscrew. "They do the corkscrew job in different ways", write Polger and Shapiro (2016, p. 65). Hence, this is a clear case of multiple realization. Then again, double-lever corkscrews which only differ in material composition or color would *not* make for multiple realization, since these differences are not relevant to the way the double-lever corkscrew does its job.

Returning to our example above, HCl, H_2SO_4, and HNO_3 all do their proton-donating job *in the same way*. They all rely on the same kind of proton-releasing mechanism in order to exhibit their acidic behavior. So this is *not* a case of multiple realization, contra Manafu's claim. The microstructural differences between HCl, H_2SO_4, and HNO_3 are simply not relevant to the way these substances fulfill their functional role of proton donor.

Of course, even though the differences in microstructure are not relevant, they nonetheless amount to real differences. Consider, by way of another example, the different **hydrogen halides**—HF, HCl, HBr and HI. While the microstructural variation, once again, fails to count as evidence for the multiple realizability of acidity, it does give rise to real differences in the strength of the acids, with HF the weakest acid and HI the strongest acid.[33]

No one denies that HF, HCl, HI and HBr are different substances—different "systems of electrons and nuclei" as Manafu would say—with different causal profiles. The point is just that these distinctions are too fine-grained to be relevant in assessments of Brønsted acidity. Brønsted acids don't have to

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[30] As Polger and Shapiro (2016, p. 63) note: "Without reflecting on the issue of relevance, claims of multiple realization become trivial. If variation of any sort at all constitutes multiple realization, the thesis begins to sound more like an a priori commitment than an empirically risky conjecture." Or again (p. 67): "Variation is everywhere in nature, but multiple realization is not."

[31] There is a risk that interest-relative considerations may sneak into Polger and Shapiro's relevance criterion. I do not have the space to discuss this worry here, but see Tahko (2020) for more details.

[32] This is not entirely correct, since presumably one of the criteria for being a corkscrew is that a screw be present to screw into the cork. But this is a microstructural criterion, not a functional one.

[33] Arranging the hydrogen halides in order of increasing acid strength yields the following sequence: $HF < HCl < HBr < HI$. The reason for this is simple: as one goes down the halogen group in the periodic system, the size of the anion increases. As such, the internuclear distance between the proton and the halogen ion increases, which makes for a weaker bond, and thus a greater proton-releasing ability.

be exactly alike in every way. They need to be alike only with respect to the one essential feature that makes them acids: having an acidic proton in their molecular structure. As Smart (2007) observes: “Whether we say that two things are similar or not is a matter of abstractness of description.”

Allow me to make one final comparison to bring the message home. As I mentioned before, the **chemical elements** are individuated on the basis of their nuclear charge—the number of protons in the nucleus of an atom of an element. All systems with one proton in the nucleus, for example, belong to the natural kind hydrogen (H). Hydrogen, however, has three naturally occurring isotopes which differ in the number of neutrons: protium (^{1}H) has zero neutrons, deuterium (^{2}H) has one neutron, and tritium (^{3}H) has two neutrons. Do protium, deuterium and tritium count as multiple realizations of the kind hydrogen? No. Just as with the different Brønsted acids, the isotopic variation in hydrogen fails to qualify as multiple realization. Differences in neutron number, after all, are irrelevant to the chemical behavior of an element. What *is* relevant to the chemical behavior of an element is its electronic configuration. But the electronic configuration depends on the atomic number, *i.e.* on the number of protons in the nucleus, *not* on the number of neutrons.[34] This does not imply that isotopic variations don’t amount to real differences. The various isotopes of hydrogen, for example, exhibit clear kinetic and thermodynamic differences due to their differences in mass (this phenomenon is known as the **isotope effect**). But chemically speaking, these isotope effects are deemed irrelevant. While the isotopes may be physically distinct, they are chemically identical.[35]

7. Bifurcating kinds

So far, we have found no evidence for multiple realization in acids. But the preceding considerations have put us in a much better position to state what *would* count as evidence. Following Polger and Shapiro’s recipe for multiple realization, acids are multiply realized if and only if two (or more) chemical substances exhibit relevantly the same acidic behavior, yet in relevantly different ways. The ‘same acidic behavior’ is to be understood in terms of the stereotypical properties of acids, as given in section 3. A chemical substance is thus judged to be an acid (to belong to the ‘acid’ kind) when it exhibits this stereotypical behavior. A difference, I recall, is relevant only when it amounts to a different way of exhibiting the stereotypical behavior, *e.g.* through a different mechanism.

With these remarks in place, I can finally move to the **third reason** for saying that acids are multiply realized. In his paper *Are Chemical Kinds Natural Kinds?*, Hendry (2015, p. 260) explicitly refers to HCl, H_2SO_4 and HNO_3 as “core examples” of acids. As he correctly observes, “[t]he behavior of these three cases is genuinely similar in important respects, and so are the mechanisms by which the acidic behavior arises.” In other words, since relevantly the same behavior is realized in relevantly the same way, this is *not* a case of multiple realization—contra Manafu, and in line with the foregoing discussion. But Hendry (2015, p. 260) continues: “The problem is how [to] extend the category from these core examples to provide necessary and sufficient criteria for acidity, whether in compositional, structural or functional terms. In the history of chemistry, all such attempts failed.”

Indeed, according to Hendry (2006a, pp. 873–874), “no microstructural feature unites the acids and the bases”. As Hendry (2016, p. 263) goes on to explain, “while there are, of course, detailed causal explanations of why each acid behaves the way it does, the explanations diverge, because *no single component or structural property gives rise to all the different cases of acidity*” (emphasis added). As

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[34] Polger and Shapiro (2016, p. 68) use the same example in *The Multiple Realization Book*: “isotopes of gold are not different ways of having the atomic number 79 (i.e., being gold)—they are not multiple realizations of gold”.

[35] I am oversimplifying the case here. Not everyone agrees that the isotope effects are chemically irrelevant. VandeWall (2007, p. 918) thus argues that “it remains unclear whether different isotopes of the ‘same element’ belong to the same natural kind.” And Woody and Glymour (2000, p. 24) wonder: “which are the natural kinds, elements, or their isotopes, or both, and why?” But that is an entirely different discussion—one that is of little relevance to our considerations of multiple realization. However, please see Thyssen (2023) for a history of the isotope controversy.

a result, "[t]here is probably nothing more to being an acid than displaying enough of the typically acidic kinds of behaviour".

But what moved Hendry to make these claims? Although Hendry leaves it mostly implicit, he appears to be referring to the alleged conflict between the Brønsted–Lowry and Lewis theories of acidity. Brønsted (1923) first published his acid–base theory in 1923—a century ago this year!—defining acids as **proton donors**. Lowry (1923), independently, reached much the same ideas in the same year.[36] Coincidentally, in 1923, G. N. Lewis (1923) came up with an entirely different acid–base theory, defining acids as **electron pair acceptors**.[37] At first sight, this certainly comes across as a potential case of **multiple realization**. Two relevantly different microstructural mechanisms, after all, appear to be in play in order to produce relevantly the same acidic behaviour.[38] While Brønsted acids do so by donating protons, Lewis acids do so by accepting electron pairs. The situation thus seems comparable to the double-lever corkscrew and the waiter's corkscrew doing the same corkscrew job in different ways, or to the analog and digital watch doing the same timekeeping job in different ways. In short, it looks like the microstructural diversity of acids is so heterogeneous that no identity theory of acidity can accommodate it. Instead, (at least) two theories of acidity are needed: the Brønsted–Lowry theory and the Lewis theory.

According to Hacking (1983, p. 85), then, there is not *one* natural kind but "*two* natural kinds: Brønsted–Lowry acids and Lewis acids" (emphasis added).[39] Hacking argues that when Brønsted–Lowry and Lewis independently proposed their acid definitions, a **'bifurcation' of the 'acid' kind** occurred. As a result of this discontinuity in the historical evolution of the theories of acidity, "the question, 'Is it an acid?' cannot be answered without qualification", writes Hendry (2006a, p. 874). "We can [only] ask, 'Is it a Lewis acid?' or, 'Is it a Brønsted–Lowry acid?' ". Klaus Ruthenberg and Ave Mets (2020, p. 413) concur that "the *protonists* [*i.e.* the advocates of Brønsted–Lowry] and the *electronists* [*i.e.* the advocates of Lewis] use the same word [*i.e.* acid], but they mean different things."

The trouble is that if the stereotypical properties that have been historically associated with acidity are indeed **multiply realized** (in the sense that different microstructural mechanisms are causally responsible for the same acidic behavior), then this would undermine the microessentialist project whose aim is to find one common essence (one intrinsic property, structure or mechanism) that is possessed by *all* members of the 'acid' kind.

However, when we examine the Brønsted–Lowry definitions from an electronic standpoint, we actually find that both theories picture the reaction between an acid and a base in the same manner. Taking as an example the reaction between a hydronium (H_3O^+) and a hydroxyl (OH^-) ion, we can illustrate the equivalence between both views through the use of Lewis dot formulas:[40]

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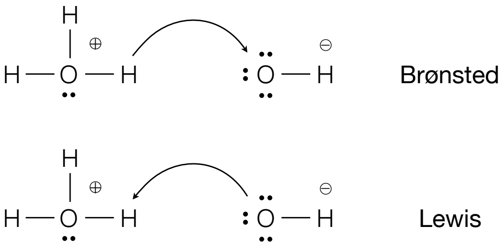
[36] This last statement has to be taken with a grain of salt. According to Ruthenberg (2023), "Thomas Martin Lowry, although a remarkable figure in the history of chemistry of the first half of the 20th century, has not been a co-creator of the modern protonist theory of acidity." This is in line with a footnote in Bell (1973, p. 4) where the author states: "although Lowry's paper undoubtedly contains many of the ideas underlying [the proton] definition, especially for bases, it does not contain an explicit definition [...] hence it does not seem justifiable to regard Lowry as one of the originators of the definition." Where possible, I have thus refrained from using the term 'Brønsted–Lowry acid', preferring 'Brønsted acid' instead. However, I will continue referring to the 'Brønsted–Lowry theory/view/definitions' to highlight the contrast with Lewis.

[37] G. N. Lewis (1923, p. 142) wrote: "It seems to me that with complete generality we may say that a basic substance is one which has a lone pair of electrons which may be used to complete the stable group of another atom and that an acid substance is one which can employ a lone pair from another molecule in completing the stable group of one of its own atoms. In other words, the basic substance furnishes a pair of electrons for a chemical bond; the acid substance accepts such a pair."

[38] Or in the words of Chang (2012, p. 695): "it seems that different acids do their acidic things for different reasons." Indeed, "It may be the case that there is nothing significant and interesting that is shared in common by all the substances that we classify as acids", continues Chang (2012, p. 697).

[39] Notice that Putnam (1970, p. 188) answered the question "Are acids natural kinds?" in the affirmative and took 'acid' to denote a single natural kind term. But he considered the property of being a proton donor to be the "essential nature" of acids, and thus seems to have been unaware of Lewis's alternative definition of acids as electron pair acceptors.

[40] Lewis dot formulas are used to graphically represent the outermost valence electrons of chemical species.

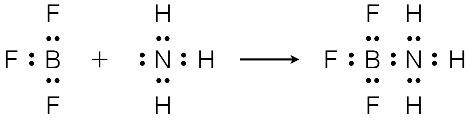


As should be clear from the diagram above, the Brønsted–Lowry acid H_3O^+ acts as a proton donor *by accepting an electron pair* from the base; the Brønsted–Lowry base OH^- plays the complementary role of proton acceptor *by donating an electron pair* to the acid. The proton-transfer mechanism of Brønsted–Lowry is thus *equivalent* to the electron-pair-transfer mechanism of Lewis. To cut a long story short, what may have looked like a case of multiple realization actually is a case of **unique realization** (once again!).

8. The hierarchy requirement

That is not to say, of course, that the Lewis view is identical to the Brønsted–Lowry one. Instead, the Lewis view is a **generalization** of the Brønsted–Lowry one. More specifically, while all Lewis bases are also Brønsted bases, not all Lewis acids are Brønsted acids. The reason for this is simple. Since all Lewis bases have a lone pair of electrons to donate, they can accept a proton through the formation of a dative bond,[41] and can therefore be considered Brønsted bases as well. However, not all Lewis acids need to contain an acidic proton in order to act as an electron pair acceptor. “Any species, molecule, atom, or cation, which can function as an electron acceptor, has as much claim to being considered an acid as a proton has”, observes Jensen (2016, p. 3). As a result, a much wider range of substances than the proton-containing Brønsted acids can be classified as Lewis acids.

Consider, by way of example, the familiar case of boron trifluoride (BF_3) and its reaction with ammonia (NH_3) to form the stable ammonia boron trifluoride adduct ($BF_3{:}NH_3$):



Since BF_3 accepts a lone pair of electrons from NH_3 (to complete the octet for the boron atom), it clearly is an acid for Lewis; yet given its total lack of protons, it certainly isn’t an acid for Brønsted. In sum, while Brønsted generalized Arrhenius’s definition of a base by no longer restricting it to substances yielding hydroxyl ions on dissociation in water, Lewis further generalized Brønsted’s definition of an acid by no longer restricting it to substances yielding hydrogen ions.

It is probably this last observation (rather than the alleged differences in mechanism) that led Hacking to bifurcate the acid kind into two—the Brønsted–Lowry acids and the Lewis acids. As Hacking (1983, p. 85) explains, “[t]he two definitions happen to agree about bases *but not about acids*” (emphasis added). Indeed, “typical Lewis acids [such as boron trifluoride, BF_3] do not contain protons, which are a precondition of being a Brønsted–Lowry acid.” Consequently, “some substances [such as BF_3] are acids of only one of the two kinds.” Hendry (2006a, p. 874) seems to be of the same mindset. Part of the problem, according to him, is that the various definitions of acidity “do not corefer” even though “they do agree on certain core cases”.

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[41] A dative bond is a coordinate covalent bond where both bonding electrons are contributed by only one of the two atoms involved in the bond. In other words, dative bonding occurs when one atom donates an electron pair and the other atom accepts the electron pair.

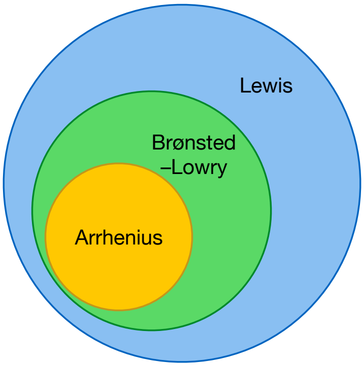

Figure 1. Venn diagram illustrating the interrelation between the Arrhenius, Brønsted–Lowry and Lewis acid–base theories.

But this need not be a problem for the scientific essentialist. Although most essentialists do not allow **crosscutting categories**, they do accept overlapping classifications when these are hierarchically ordered. As Hendry (2015, p. 254) himself explains, "the **hierarchy requirement** is that no two natural kinds may overlap (have instances in common) unless (on the strong version) one includes the other, or (on the weak version) both are included within a third" such that a single system is obtained—a nested hierarchy.[42]

Now, as I just argued above, most chemists maintain that the Lewis definition encompasses the Brønsted–Lowry definition; they consider the former to be a *generalization* of the latter. William Fay Luder & Saverio Zuffanti (1961, p. 6), for example, in their classic monograph on *The Electronic Theory of Acids and Bases*, consider the "proton-donor concept as a special case of [Lewis's] broader theory." Brønsted–Lowry acids, then, are just a specific kind of Lewis acids, namely the proton-donating kind. So although there is overlap between the Brønsted–Lowry kinds and the Lewis kinds, the former is clearly a **subkind** of the latter.[43] The situation can be represented as in Figure 1.

9. Is hydrochloric acid an acid?

And yet, not everyone agrees with the classification above. According to Hasok Chang (2012, p. 694), "the Lewis and the Brønsted–Lowry definitions refer to two different sets of chemical substances; there is an overlap between the two sets, *but one is not a subset of the other*" (emphasis added). Chang gives the example of **hydrochloric acid**: while HCl is a proton donor, and thus considered an acid according to the Brønsted–Lowry definition, Chang maintains it is not an acid according to the Lewis definition. Instead, HCl is considered to be an **acid-base adduct** of the acid H^+ (an electron pair acceptor) and the base Cl^- (an electron pair donor). Hence, "what is acidic [according to Lewis] is the H^+ ion, not HCl as a substance or a molecule, which is contrary to the Brønsted–Lowry concept (and to common parlance)."

If Chang is correct, then his diagnosis obviously generalizes to all Brønsted acids. Indeed, according

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[42] Or in the words of Ellis (2001, p. 56): "if anything is a member of more than one natural kind, then one of these kinds must be a species of the other." For further discussion of the hierarchy requirement, please see Hacking (1991; 2007), Khalidi (1998; 2013), Ellis (2001; 2002; 2009) and Tobin (2010; 2012). I should note that Khalidi, Hendry, and Tobin are all highly critical of the hierarchy thesis. Recently, Havstad (2021) has also argued against the "one true taxonomy" visions of natural kindhood.

[43] To cite from yet another author, Norris F. Hall (1940, p. 127) observes that the Lewis system "includes all the acids and bases of the Brønsted system and no other bases, while it points out a host of new acids [. . .] which the Brønsted system does not recognize as such." Not surprisingly, Hall includes a diagram much like the one above to illustrate the relationship between the Brønsted–Lowry and Lewis views. According to Luder and Zuffanti (1961, p. 15), finally, the Brønsted–Lowry view, while consistent, is "merely part of the whole picture."

to William B. Jensen (1979, p. 62), "**Brønsted acids are not Lewis acids**. They are adducts involving the Lewis acid H^+." Harmon L. Finston & Allen C. Rychtman (1982, p. 106), in their book on *A New View of Current Acid–Base Theories*, similarly state: "the electronic [Lewis] theory regards hydrogen acids not as true acids but, rather, as adducts of the acid H^+ and a base. [...] According to this viewpoint, hydrogen acids are *secondary acids* that contain the *primary acid* H^+" (emphasis added). I will return to the primary/secondary distinction in section 11.[44]

What lessons can be drawn from this? According to Chang (2012, p. 698), the example of hydrochloric acid serves to illustrate that "[t]he succession of acidity concepts [...] does not constitute a straightforward progression of increasing generality, each new concept completely encompassing the previous one" (p. 698). Instead, "the relationship between them is closer to **incommensurability** than reduction" (p. 698). The history and evolution of acidity concepts shows how "**a natural kind can become fractured**" (Chang 2016, p. 42).[45] While the Brønsted–Lowry theory was still "a perfectly straightforward and useful theoretical extension" of the Arrhenius theory (p. 41), Lewis's theory made too significant a departure (p. 42) from the previous theories of acidity. Echoing Hacking (1983), Chang (2016, p. 42) thus argues that "the Lewis and Brønsted–Lowry concepts each constitute natural kinds, but they point at different things. They are lumped together under the 'acid' rubric only through historical connections." Based on this and other considerations, Chang (2012, p. 697) concludes that "there is **no unified theory of acids**".

Now that, to be sure, is a conclusion I want to resist. To start, I should note that Chang's '**muriatic concerns**' are not new; they had already been raised by multiple adversaries of the electronic view in the years following Lewis's 1938 publication on *Acids and Bases*.[46] As such, it may be worth our while to briefly reconsider this historic debate between the protonists and electronists. What I hope will transpire from this, is that Chang's concerns, while valid to a certain degree, do not warrant his conclusion that "there is no unity to the scientific concept of acidity" (Chang 2012, p. 699).

10. Protonism vs. electronism

In 1945, William Fay Luder—an American chemist and staunch electronist—published a short paper in the *Journal of Chemical Education* on the topic of *Proton-Donors in the Electronic Theory of Acids and Bases*. Luder (1945, p. 301) pointed out that "there appears to be a tendency to imply a nonexistent **antagonism** between the [Brønsted–Lowry and Lewis] theories". Although he admitted "that there is some ground for confusion", he was quick to add that "[t]o the followers of Lewis, it is obvious

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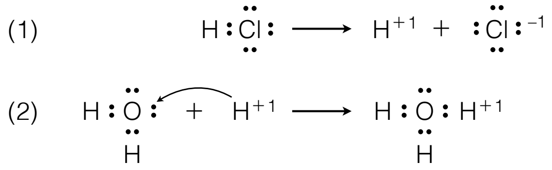
[44] In another paper, Jensen (2016, p. 4) writes: "the term acid in the Brønsted–Lowry theory refers to the species HB containing both H^+ and its conjugate base, whereas in the Lewis theory the term refers only to the H^+ portion of HB." Or, to quote from yet another author, VanderWerf (1961, pp. 72–73) writes: "In the Lewis system, hydrogen chloride is not a true acid, since the hydrogen has no available orbital in which to accommodate an additional pair of electrons. But we can conveniently consider hydrogen chloride as a coordinated complex made up of the acid portion proton (H^+) and the base portion chloride ion (Cl^-). In fact, any potential Brønsted acid HA may be viewed as a coordinated complex, made up of the acid portion H^+ and the base portion $:A^-$." Bell (1969, p. 102), finally, in his book *Acids and Bases: Their Quantitative Behaviour*, notes that the Lewis scheme "is commonly described as an 'extension' of the acid–base concept, but [...] it does in fact involve using the term acid for an essentially different group of substances."

[45] Utilizing his notion of "epistemic iteration", Chang (2016, pp. 40–42) identifies 6 different stages in the iterative development of the concept of acidity, "starting with bare sensations [*e.g.* the sour taste of vegetable acids] and then simple operations [*e.g.* the color change of indicators] and crude theoretical presumptions [*e.g.* Lavoisier's oxygen theory]" to the development of "fully coherent and scientifically accurate" notions of acidity [*e.g.* the theories of Arrhenius or Brønsted and Lowry].

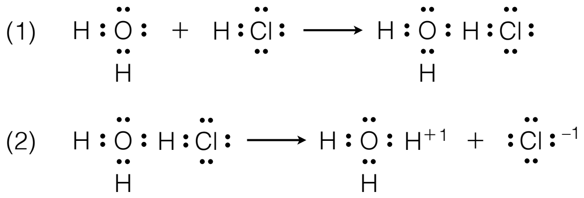
[46] Lewis initially presented his electronic acid–base definitions in his 1923 book entitled *Valence and the Structure of Atoms and Molecules*. However, as Jensen (2016, pp. 20–21) remarks, Lewis "did little more than state them, almost as a passing thought, in the middle of a book whose major theme appeared to bear little relation to the subject of acid–base chemistry." In doing so, Lewis failed to arouse the interest of the broader chemical community, who instead was swayed by the Brønsted–Lowry definitions that had been proposed that same year. It was not until 1938, 15 years later, when Lewis devoted an entire paper to his acid–base definitions—providing necessary examples in support of his electronic view and arguing for its general character—that chemists finally began to pay attention.

that there is no conflict between the two theories" (p. 301) and that—contrary to the opinion of the protonists—"special treatment is unnecessary for hydrogen acids" (p. 302). In a brief letter to the editors in *The Journal of Chemical Physics*, Luder (1952, p. 525) reiterated his point that "it is unnecessary to make any distinction between 'Lewis acidity' and 'Brønsted acidity.' On the contrary, when applied to hydrogen acids, the two theories are absolutely identical."

The principal reason why HCl was not considered a Lewis acid by the protonists is because the hydrogen atom in HCl already has a filled 1s electron shell, and hence cannot accept an extra electron pair as Lewis demands. HCl, in other words, first has to dissociate into H^+ and Cl^- (call this first step ***ionization***) before the proton H^+ can accept an electron pair from a solvent molecule H_2O in order to form a coordinate covalent bond, with the formation of the hydronium ion H_3O^+ as a result (call this second step ***coordination***):

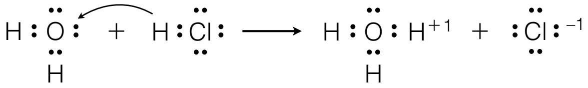


For Brønsted–Lowry, all the (proton-donating) action happens in the first step; hence HCl is the acid. For Lewis, all the (electron-pair-accepting) action happens in the second step; hence H^+ is the acid.[47] Protons, however, are notoriously unstable entities which never exist unsolvated in solution—thus calling the first reaction step above into question. Some chemists, such as Sidgwick (1927), therefore suggested reversing the order of ionization and coordination:



This time, HCl first forms a coordinate bond with H_2O by accepting one of oxygen's lone pair of electrons, and only then dissociates into a hydronium and chloride ion due to the electrical strain in the acid–base adduct: coordination before ionization. However, as Luder (1945, p. 302) observed, the existence of the "hypothetical intermediate addition compound" (H_2O:HCl) is "regarded as unlikely" since it would involve the formation of a "hydrogen bridge" between the HCl and H_2O molecules, involving the highly implausible "2-covalent hydrogen".

Accordingly, Luder (1945, p. 302) proposed that neither of the two-step pictures corresponds to reality, and that "it would be better to represent the formation of the coordinate bond as taking place *simultaneously* with ionization" (emphasis in original):



Notice that on this picture HCl is both Brønsted acid and Lewis acid, since it both donates a proton and accepts an electron pair.[48] "[T]he electronic [Lewis] theory", in other words, "pictures the

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[47] Chang seems to have this reaction mechanism in mind when arguing his case that HCl—at least in aqueous solution—is not a Lewis acid. Chang (2012, p. 691) thus insists that one is dealing with "*conflicting* theoretical definitions of acidity."

[48] Notice that Chang (2012, p. 694) acknowledges this type of reaction mechanism, but only for reactions in gas phase: "if we consider the reaction of HCl in its pure gas phase (not in aqueous solution), for example, with ammonia, we cannot think

reaction in exactly the same manner as the proton-donor theory" (Luder and Zuffanti 1961, p. 44). Luder (1945, p. 302) therefore concluded: "This is only one example of the many which could be given to show that the electronic theory of acids and bases *includes* the proton theory as a *special case.* The simultaneous coordination and ionization pictured by the Lewis theory is equivalent to the proton-transfer mechanism of the Brønsted theory" (emphasis in original).[49]

11. Semantic debates

While Luder, in view of the above equivalence, did not see any need for a "special treatment" of the hydrogen acids, others were not so convinced. Ronald Percy Bell (1947, p. 123; 1969, p. 102), for instance, stressed that "the acids of the older definitions (HCl, H_2SO_4, CH_3COOH, *etc.*) can only be included in the Lewis scheme by somewhat indirect means." The reason for this was the primary/secondary distinction alluded to above.

As Luder (1948, p. 557) himself explained, many Lewis acids, such as the proton (H^+), boron fluoride (BF_3), and stannic chloride ($SnCl_4$), have "electronic formulas in which the possibility of accepting pairs of electrons to form coordinate covalent bonds is obvious".[50] Due to the presence of electron deficiencies in their molecular structure, no structural alteration or activation energy is needed for these acids to react with Lewis bases such as ammonia or water. G. N. Lewis (1938, p. 303) called such acids '**primary acids**'.[51] The hydrogen acids (HCl, H_2SO_4, HNO_3, HCN, CH_3COOH, *etc.*), in contrast, were called '**secondary acids**' by G. N. Lewis (1938, p. 303) because they "do not reveal any electron deficiencies" (Bell 1947, p. 123). Hence, compared to the primary acids, their acidic properties are not immediately obvious, but in fact "depend upon the presence of a primary acid, the proton, which is in combination with a primary base" (Luder 1948, p. 557).[52,53]

As Jensen (2016, p. 23) recounts: "Proponents of the Brønsted definitions were understandably upset with this nomenclature. The traditional terms of acid and base were being appropriated for a new class of substances and the traditional substances were being renamed. They argued that it was the primary Lewis acids rather than the Brønsted acids that should be given the qualifying terminology, and a number of names were suggested for this purpose, including the terms antibase, acid analogous, proto acid, pseudo acid, and secondary acid"—none of which actually stuck by the way.

As should be clear from the foregoing, the debate between the protonists and electronists quickly

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in terms of the dissociated form of HCl [as in the 2-step picture–P.T.]. The standard explanation in that case seems to be that HCl is a polar molecule, with the electron density heavily distributed around the chlorine nucleus rather than the hydrogen nucleus, allowing the hydrogen end of the molecule *to act as an electron-pair acceptor*" (emphasis added).

[49] For related statements and further discussion, please see Luder (1940), Kolthoff (1944, p. 53), Bjerrum (1951), Kolthoff and Elving (1978, p. 14), and Luder and Zuffanti (1961, p. 44).

[50] While H^+ has an empty 1s orbital and therefore needs a pair of electrons to complete its duet, the boron atom in BF_3 has only six electrons in its valence shell, and thus needs an extra electron pair to complete its octet. It may therefore be surprising that $SnCl_4$ is also a Lewis acid. The tin atom in $SnCl_4$, after all, already has a full octet. However, due to the high electronegativity of chlorine, most of the electron density is pulled towards the chlorine atoms, leaving the tin atom with a partial positive charge. Due to this electron deficiency, it can nonetheless attract electrons from Lewis bases, thereby acting as a proper Lewis acid.

[51] A similar definition can be given, *mutatis mutandis*, for primary bases. Primary Lewis bases can readily donate a pair of electrons. Examples include the ammonia molecule (NH_3), the hydroxyl ion ($OH-$), and the cyanide ion ($CN-$) ions, among many other Lewis bases.

[52] Lewis further developed his ideas about primary and secondary acids in collaboration with Glenn T. Seaborg, who worked for him as a research associate during the period July 1937—June 1939. Their collaboration on acids and bases led to two publications: Lewis and Seaborg (1939a; 1939b). See also Seaborg (1984) for some personal recollections of his time as research assistant as well as a first-hand account of Lewis's research style.

[53] Finston and Rychtman (1982, p. 99) acknowledge that the secondary acid category includes "substances that are strictly Lewis acid–base adducts" (*viz.* the hydrogen acids), but echo Luder in arguing that "[t]here is a basis for this, since the proton does not exist in the free state". The distinction between primary and secondary acids, I may add, has become obsolete, and is no longer used in modern chemistry.

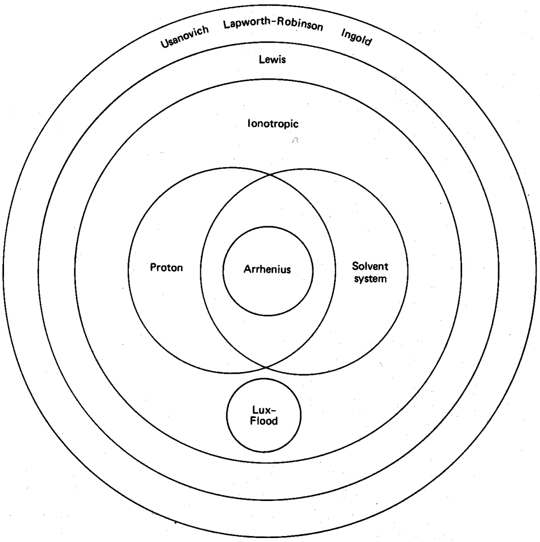

Figure 2. Venn diagram illustrating the interrelation of the various ionic and electronic acid–base definitions. Figure reproduced from Jensen (1979, p. 65).

turned to **terminological matters**; their arguments became of an increasingly semantic rather than fundamental nature, and "a great deal of **word juggling** [...] occurred in an attempt to restrict the term acid to the proton donors of the Brønsted definitions" (Jensen 1979, p. 64). Bell (1973, p. 7) thus admitted that the debate was "essentially one of the convenience and consistency of **verbal definitions**, and not of any fundamental differences in the interpretation of experimental facts". Indeed, "[s]uch questions of nomenclature are largely a matter of taste", wrote Bell (1969, p. 102), and it would be "misleading to elevate [them] to a matter of principle" (Bell 1947, p. 125). Marion Clyde Day and Joel Selbin (1962, p. 248) passed the debate off as "more or less trivial", and Kolthoff (1944, p. 52) reiterated the point that the alleged conflict between Lewis and Brønsted–Lowry was "not real": "it merely appears to exist through confusion in the terminology and nomenclature used."

12. A unified theory of acidity

To sum up, I have argued that Lewis is a clear improvement upon Brønsted–Lowry; it is broader, more encompassing, more general. According to Day and Selbin (1962, p. 246), the Lewis view has led to "the unification of virtually all of the existant acid–base definitions." "The electronic theory of acids and bases", write Finston and Rychtman (1982, p. 105), "includes all substances and concepts covered by the Arrhenius, Brønsted–Lowry, and solvent systems theories, as well as species and ideas not included in any of the other concepts." On page 65 of his book *The Lewis Acid-Base Concepts*, Jensen (1979) provides a **Venn diagram** illustrating the interrelations between the various ionic and electronic acid-base definitions (Figure 2).[54] On the diagram, the Lewis concept clearly encompasses the Brønsted–Lowry concept.

I thus agree with Scerri (2022, p. 7), who, in a reply to Chang's paper, argues that "Lewis acidity is [...] a generalization of the earlier definitions and certainly not a case of 'rupture'."[55] What is more, by formulating his acid–base definitions in electronic terms, Lewis embedded his newfangled

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[54] See also the diagrams in Jensen (1974) and Jensen (1978), reproduced in Jensen (2016, p. 3) and Jensen (2016, p. 33).

[55] Note that Chang (2012; 2016) nowhere uses the word 'rupture'. Instead, Chang prefers to speak of the 'fracture' of a natural kind, leading to a 'lack of unity' and a 'damaging of the coherence' of the 'acid' kind.

concepts in the electronic theories of reactivity and of chemical bonding which Lewis had helped to forge in 1916, and which were rapidly becoming the basis of all modern chemistry. As such, and in stark contrast to Brønsted and Lowry, Lewis actually managed to provide an insight into the fundamental nature of acids and bases. "It is to this single feature that they owe their ability to organize and unify the facts of chemistry," concludes Jensen (2016, p. 5).

I should add that the development of the acidity concept obviously did not stop with Lewis, as should be evident from the diagram above.[56] In a recent paper, Dean J. Tantillo & Jeffrey I. Seeman (2023) have argued that the quantum chemical molecular orbital (MO) theory can be used to develop a **unified theory of acidity**, where all acid–base reactions are described as bonding interactions between the HOMO (highest occupied molecular orbital) of the base with the LUMO (lowest unoccupied molecular orbital) of the acid. They conclude (p. 18): "Both Lewis acid–base theory and Brønsted–Lowry acid–base theory are properly characterized by the **HOMO–LUMO bonding** phenomenon".

13. Beyond recognition?

At this point, I cannot avoid a few remarks upon the potential danger of **overgeneralizing** the acidity concept. Chang (2012, p. 699), for example, asks "whether Lewis did not generalize the acid concept almost beyond recognition". In point of fact, Chang is far from the first to raise this point. As Finston and Rychtman (1982, p. 105) explain: "Lewis' theory was criticized for several reasons, but mostly because of its generality. Critics argued that the concept practically equated 'acid' and 'base' with '**reactant**', and that the theory's correlation of a wide range of chemical phenomena, although valid, did not justify referring to acids and bases in such a general sense". In view of this, Jensen (2016, p. 23) suggests it would have been better had Lewis "adopted a terminology similar to that of Sidgwick's **donors and acceptors** and remained content with pointing out that the traditional categories of acid and base represented a familiar example of donor–acceptor displacement reactions".[57]

Tantillo and Seeman (2023), finally, note that the HOMO–LUMO paradigm "provides an understanding of *all* acid–base reactions *as well as other reactions, which, on the surface, may not seem like acid–base reactions*" (p. 1, emphasis added)—including bonding interactions with "substances that would hardly be recognized as Lewis acids and bases and certainly not as Brønsted–Lowry acids and bases" (p. 19)—which again begs the overgeneralization question. Indeed, according to Finston and Rychtman (1982, p. 210), "a unified, all-encompassing acid–base theory is actually equivalent to a **theory of general reactivity**." On this view, "*any* chemical process can [...] be regarded as an interaction between two species, an acid and a base (although traditionalists may propose other names to distinguish between reactants)" (emphasis added).

Then again, one cannot do without Lewis either. The Brønsted–Lowry theory is simply not "sufficiently universal" (Finston and Rychtman 1982, p. 62). Its "great weakness", explain Luder and Zuffanti (1961, p. 9), "is that it ignores a large body of experimental data by restricting the word *acid* to proton donors" (emphasis in original).[58] G. N. Lewis (1923, pp. 141–142), incidentally, and independently of Brønsted and Lowry, briefly considered the proton definition in 1923 as well, but he

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[56] Although a discussion of the Usanovich, Lapworth–Robinson and Ingold concepts of acids and bases would certainly be interesting, it would make an already long paper even longer. As such, I kindly refer the reader to the discussions in Jensen (1979). See also the illuminating paper in this *Special Issue* by Flechsig (2023) on the Usanovich definitions.

[57] Jensen herewith echoes Bell (1947, p. 125) who had made the same terminological suggestion to "restrict the term acid to those species covered by the Brønsted–Lowry definition, and to use [...] the term *acceptor* or *acceptor molecule*" for the Lewis acids (emphasis in original).

[58] In this respect, continue Finston and Rychtman (1982, p. 62), the Brønsted–Lowry theory "represents almost no advance [...] over concepts formalized nearly a century prior to its appearance."

considered it too narrow: "[T]he definition of an acid [...] as a substance which gives up [...] hydrogen ions would [...] not be universal", he wrote. Referring to "**the cult of the proton**" G. N. Lewis (1938, p. 297) exclaimed: "To restrict the group of acids to those substances which contain hydrogen interferes as seriously with the systematic understanding of chemistry as would the restriction of the term oxidizing agent to substances containing oxygen."

Acid–base phenomena are far more widespread than Brønsted and Lowry acknowledged. Indeed, many aprotic substances, such as BCl_3, CO_2, SO_3, $SnCl_4$, and SiO_2 are excluded from Brønsted's list of acids, despite manifesting acidic behaviour. As a matter of fact, "[m]any of these [compounds] had been considered acids *prior to the advent of any theory*, when acids were classified solely on the basis of **experimental observation**" and the stereotypical properties of acids (Finston and Rychtman 1982, p. 95, emphasis added; see also Luder and Zuffanti 1961, p. 3). Hence, "[b]y including such things as SO_3 and $SnCl_4$," writes Hall (1940, p. 127), the Lewis system constituted "a return to the 'good old days' before the hydrogen theory, when a thing that acted like an acid was called one without asking of what it consisted".[59]

I will not dwell any longer upon this subject. The overgeneralization question is an important one, undoubtedly worthy of further investigation, but one I will not explore any further in this paper. Instead, I want to conclude by raising two more substantial worries for the kindhood of acids—*viz.* their latent and relational character—and briefly outline how the microessentialist may respond to these threats.

14. Acidity as a dispositional property

Let us start with the **latent character** of acids. Consider the case of a Brønsted acid, such as hydrochloric acid (HCl), giving up a proton (H^+) to form the conjugate base Cl^-:

$$HCl \longrightarrow Cl^- + H^+. \tag{1}$$

The equation above, although stoichiometrically correct, does not depict a reaction that can actually occur, since protons cannot freely exist in solution.[60] A molecule of hydrochloric acid, therefore, will only donate its proton when a base, such as ammonia (NH_3), is present to accept the proton:

$$NH_3 + H^+ \longrightarrow NH_4^+. \tag{2}$$

It is only by combining these two equations that we obtain an actual chemical reaction:

$$HCl + NH_3 \longrightarrow Cl^- + NH_4^+, \tag{3}$$

representing the transfer of a proton from HCl to NH_3 (via the competition between the two bases, Cl^- and NH_3, for the proton).[61] Brønsted acids, then, will not perform their characteristic proton-releasing function unless a Brønsted base is present to accept the proton (Finston and Rychtman

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[59] In his 1938 paper, Lewis specified four phenomenological criteria for acid–base systems. As Jensen (1979, p. 59) explains, Lewis used these criteria to show that "experimental acidic behavior was not confined to the proton alone, but was exhibited by electron-pair acceptors in general", and that his electronic acid–base definitions thus "correctly identified [all those] species exhibiting the experimental behavior of acid–base systems".

[60] The hydrogen ion is unique among cations in having no electrons; it is nothing more than a proton. Due to its small size—its effective radius is about 10^{-13} cm as compared to 10^{-8} cm for most other simple ions—it has a very high charge density. As such, free protons are highly unstable, and not capable of independent existence in solution.

[61] All interactions between a Brønsted acid and base can be described by the type reaction: $A_1 + B_2 \longrightarrow B_1 + A_2$, with A_1–B_1 and A_2– B_2 two conjugate acid–base pairs. Such reactions are also called **protolytic reactions**.

1982, p. 21; Luder and Zuffanti 1961, p. 7). Their acidity, in other words, will remain *latent* as long as no base is added.

But this suggests that the acidic behaviour of hydrochloric acid, to use the example above, is as much a function of its own (internal) microstructure as it is of the (external) environment. However, while the microstructure of hydrochloric acid is an **intrinsic property** (a property that hydrochloric acid has in and of itself), its relation to ammonia is an **extrinsic property** (a property that obtains in virtue of hydrochloric's relation to and interaction with the chemical environment).[62] Such dependency on extrinsic properties would be in tension with the essentialist contention that all natural kind essences must be *intrinsic* properties (however, see footnote 8). Scerri (2022, p. 402), for example, argues that "HCl is not *intrinsically* acidic. It only *becomes* acidic on reacting with" a base (emphasis added).[63]

I beg to differ. As I will try to explain in the remainder of this section, and contra Scerri, HCl *is* intrinsically acidic; it does not *become* acidic on reacting with a base; it merely *reveals* its acidic character upon contact with a base.[64] More importantly, none of the above in any way undermines the microessentialist project. The key, then, to dealing with the latent character of acids, I maintain, is to understand functions as dispositional properties.

A **dispositional property** is a property that, if instantiated by an object, is manifest under specific conditions only.[65] An object's disposition may thus be dormant, and its manifestation non-occurrent and therefore non-observable. Hydrochloric acid, for example, is said to be an acid because it has the disposition to donate a proton. However, as long as it does not come into contact with a base, such as ammonia, its acidic character will remain hidden. Notice that Brønsted (1923, p. 719) himself already gave a dispositional definition of acidity: "Acids [...] are substances that are *capable of* splitting off [...] hydrogen ions", he wrote (emphasis added).[66] All it takes to be a Brønsted acid is to have the *capacity* or *tendency* to lose a proton.

Dispositions D, more generally, are characterized by a triggering condition T, also called the stimulus, and a manifestation M. That is, an object instantiating the dispositional property D has the disposition to react or behave in a certain way M when triggered by the right condition T. In shorthand notation: $D(T, M)$. All dispositions have such an intrinsic **trigger-manifestation profile**. For example, all Brønsted acids share the disposition D_a to donate a proton (M_a) when put into contact with a base (T_a).

This can be rewritten as a counterfactual conditional: *if* a Brønsted acid were put into contact with a base, *then* it would donate a proton. This suggests the following **conditional analysis** of Brønsted acidity:

$$D_a(T_a, M_a)\, x \longleftrightarrow T_a x \mathrel{\Box\!\!\rightarrow} M_a x. \tag{4}$$

In words: x is a Brønsted acid *iff* were x put into contact with a base, x would donate a proton. The

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[62] According to David D. Lewis (1983, p. 197), while "[a] thing has its intrinsic properties in virtue of the way that thing itself, and nothing else, is", it has its extrinsic properties in virtue of its interaction with the world.

[63] I omitted the last part of Scerri's quote for rhetorical reasons. The original read: "It only becomes acidic on reacting with water or another polar solvent", but the crucial point here is that water (or the other solvent) would thereby act as a base.

[64] Bell (1947, p. 115) notes that in relation to the Arrhenius definition of acids (*i.e.* substances that produce hydrogen ions in aqueous solution), "it was not clear whether a pure non-conducting substance like anhydrous hydrogen chloride should be called an acid, or whether it became one only in contact with water". In line with my own view, Bell explains that "it was usually considered that the anhydrous compound was an acid *in virtue of its latent tendency to split off hydrogen ions*" (emphasis added).

[65] This can be contrasted with **categorical properties**. A categorical property is a property that, if instantiated by an object, is manifest under all conditions.

[66] The original reads: "Sauren [...] sind Stoffe die einer Abspaltung [...] von Wasserstoffionen fähig sind."

same conditional analysis can be given for the concept of Brønsted–Lowry basicity, where all bases share the disposition D_b to accept a proton (M_b) when put into contact with an acid (T_b):

$$D_b\,(T_b, M_b)\,x \longleftrightarrow T_b x \;\Box\!\!\rightarrow\; M_b x. \tag{5}$$

In words: x is a Brønsted base *iff* were x put into contact with an acid, x would accept a proton. The dispositional analysis just given helps to better understand the role of the (chemical) environment. The environment does not turn hydrochloric acid into an acid (as Scerri seems to suggest), it merely triggers its acidic behaviour, which was present all along, albeit in dormant form. As Tahko (2020, p. 810) correctly observes: "it would be odd to claim that the capacity [...] to react as [...] an acid or a base is something over and above its microstructural properties, a capacity that the substance gains only when the relevant environmental circumstances are in place." Rather, "the capacity to act as an acid or a base is [already] contained in [the molecular] structure." So, far from undermining the microessentialist thesis, the latent character of acids and bases merely serves to highlight their dispositional trigger-manifestation profile.

The following example from Finston and Rychtman (1982, p. 24) should help to illustrate the point just made. As the authors explain, hydrochloric acid fails to manifest its acidic properties when dissolved in benzene because benzene lacks basic properties, and therefore cannot accept any protons. However, as soon as a basic solute is added to the solution, an immediate acid–base reaction results between the solute and hydrochloric acid. Benzene, in other words, cannot trigger the acidic behaviour of HCl, whereas a basic solute can. But that doesn't change the fact that hydrochloric acid already had the disposition to donate a proton all along. As the authors conclude: "The distinctive acid property is *the availability of a proton* [D_a] instead of the actual donation process [M_a], allowing Brønsted to unequivocally regard [...] HCl as an acid in benzene solution" (emphasis added).

15. Amphoteric substances and multiple determination

A final worry for the kindhood of acids is their **relational character**. As Scerri (2022, p. 390) observes, "[t]he notions of acidity and basicity are [...] *relational*: no single substance may be said to be an acid or a base *in all circumstances*" (emphasis added). Luder and Zuffanti (1961, p. ix) concur that "[a]cidity and basicity are relative terms"; no substance can "be considered an acid or a base in an absolute sense." Both authors are referring to the fact that many substances have the ability to act both as an acid and a base, depending on the circumstances.[67] Such substances are said to be **amphoteric** (from the Greek *amphoteroi* for 'both'). Water, for example, will act as an acid in the presence of a strong base, such as ammonia:

$$\mathrm{NH_3 + H_2O \longrightarrow NH_4^+ + OH^-}, \tag{6}$$

but will act as a base in the presence of a strong acid, such as hydrochloric acid:

$$\mathrm{HCl + H_2O \longrightarrow H_3O^+ + Cl^-}. \tag{7}$$

In the molecular autoionization of water, too, one water molecule acts as an acid and the other water molecule acts as a base:[68]

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[67] Scerri, for one, seems to attach some philosophical importance to this fact. After all, in the section on "[s]ome genuine philosophical issues concerning Lewis acidity", Scerri (2022, p. 401) emphasizes the fact that "a substance is acidic or basic depending on what substance it is chemically related to".

[68] Water, more precisely, is said to be **amphiprotic**, because it can either gain a proton (to form the hydronium ion H_3O^+)

$$H_2O + H_2O \rightleftharpoons H_3O^+ + OH^- . \tag{8}$$

Amphoterism is not a rare phenomenon. As Chang (2012, p. 699) observes, "[t]o a certain degree, all compounds are amphoteric because even a clearly acidic substance can be protonated by an even stronger acid".[69] Amphoterism is also not restricted to Brønsted acids and bases. As Jensen (2016, p. 11) notes, "all species are in a way electronically amphoteric". Tantillo and Seeman (2023, p. 7), finally, argue that "all compounds having unfilled molecular orbitals are, under the right circumstances, acids; and all compounds having filled orbitals are, under the right circumstances, bases."

Notice that in such cases, one and the same substance can realize multiple functions. Amphoteric substances are "functionally multi-track", writes Tahko (2020, p. 804); they "perform multiple jobs or act in multiple roles", depending on the circumstances.[70] Kistler (2018, p. 15) calls this phenomenon **multi-functionality**; Tahko (2020, p. 801) calls it **multiple determinations** or one-many determination. Indeed, compared to the thesis of multiple realization, where the relation was many-one (many microstructures realizing one function), the relation here is one-many (one microstructure realizing many functions).

However, as many authors before me have observed,[71] microessentialism is perfectly well-equipped to deal with cases of multiple determinations (such as the case of amphoterism). The idea, briefly, is that the *intrinsic* microstructure of an amphoteric substance imposes a **space of possibilities** from which a particular behaviour is then *extrinsically* selected and actualized (Bartol 2016, p. 541). The microstructure of water, for example, allows for both acidic and basic behaviour (as we have seen above, it can either lose a proton or accept a proton). Which behaviour will obtain is a function of the environment. "Indeterminate intrinsic physical microstructure at the lower level plus context equals determinate outcome at the higher level", writes Bartol (2016, p. 543).

This idea can be made more concrete using our characterization of natural kinds as **powerful objects** (see section 14). According to Tahko (2020, p. 804), "we may consider the various functional capacities [. . .] to be just that: capacities—**unactualized dispositions**—that only manifest in the appropriate environment." Tahko herewith echoes Kistler (2018, p. 15) who explains that the members of a natural kind can have "a certain number of dispositions to behave and interact in various circumstances. [. . .] Only part of these dispositions is actually manifested at any given moment. [. . .] Each function [. . .] can be interpreted as a manifestation corresponding to one of its dispositions."

Applying this to the case at hand, amphiprotic substances (such as water) have the following two dispositions: the disposition D_a to donate a proton, and the disposition D_b to accept a proton. Following Kistler (2018), an amphiprotic substance can be interpreted as a powerful object x with the dispositions D_a and D_b such that in the right triggering conditions T_a or T_b respectively, x will manifest a specific functional behaviour M_a or M_b:

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or lose a proton (to form the hydroxyl ion OH^-). Amino acids are another common example of amphiprotic substances due to the presence of both basic and acidic functional groups in their molecular structure, namely the amino group $-NH_2$ and the carboxylic group $-COOH$.

[69] Nitric acid (HNO_3), for example, was formerly known as *aqua fortis* (or 'strong water'). Not surprisingly, it is generally considered to be a strong acid. Yet, in the presence of an even stronger acid such as sulphuric acid (H_2SO_4), HNO_3 will act as a base, yielding the nitronium ion ($NO_2{}^+$) after elimination of a water molecule from the protonated nitric acid ($H_2NO_3{}^+$) according to the following acid–base reaction: $HNO_3 + 2H_2SO_4 \rightleftharpoons NO_2^+ + H_3O^+ + 2HSO_4^-$. Due to its amphoteric character, HNO_3 can even undergo an autoprotolysis reaction, much like water: $2HNO_3 \rightleftharpoons NO_2^+ + NO_3^- + H_2O$.

[70] To be clear, Tahko did not have amphoteric substances in mind when he wrote this, but was referring to the work of Tobin (2010b) on moonlighting proteins. Be that as it may, I take Tahko's views on moonlighting proteins to be directly transferrable to amphoteric substances. Indeed, Tahko (2020, p. 810) himself observes that "amphoteric substances are comparable to functionally promiscuous moonlighting proteins."

[71] Please see Bartol (2016), Kistler (2016; 2018), and Tahko (2020), among others.

$$D_i\,(T_i, M_i)\,x \longleftrightarrow T_i x \mathrel{\square\!\!\rightarrow} M_i x, \qquad i = a, b. \tag{9}$$

The dispositional view of kind essences is thus particularly well-equipped to account for the multi-functional profile of chemical kinds.[72] Importantly, however many functions a chemical kind may have, their number will always be constrained by the kind's microstructure. The multi-functionality of chemical kinds (or 'functional promiscuity' as Tobin 2010b, p. 52, calls it) thus poses no threat to the microessentialist view.

16. Conclusions

Where does all this leave us with respect to our initial question: "Are acids natural kinds?" Since Lewis encompasses Brønsted–Lowry, the different concepts of acidity do not crosscut. Contra Hacking (1983), Stanford and Kitcher (2000), Hendry (2006a), and Chang (2012), among others, I maintain that the hierarchy requirement is met: the Brønsted acids form a proper subset of the Lewis acids. What is more, given the equivalence between the proton-donating and electron-accepting mechanisms, the property of being an acid is *not* multiply realized, as Manafu (2015) has argued. As Tantillo and Seeman (2023) have shown, and contra Hendry (2006a) and Manafu (2015), acidity as a property type can be identified with a microstructural property, namely with the presence of a LUMO or other low energy empty orbital. Neither do the latent and relational character of acids pose any threat to the microessentialist view. The answer to our question, therefore, is a resounding "Yes!" Acids are a natural kind, even for the microstructural essentialist.

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[72] Tahko (2020) develops this dispositional view even further, adopting a **powers-based subset strategy** to address the challenges of multiple realization and multiple determination. Applying this strategy to the case of amphoterism, the acidic and basic behaviour of an amphoteric substance is to be identified with two distinct sets of causal powers. Importantly, both sets are proper subsets of the larger set of causal powers associated with the microstructure of the amphoteric substance. That is, both sets are realized by the same chemical substance; both the acidic and basic (higher-level) functions are thus included in the (lower-level) causal profile, thereby accounting for the phenomenon of multiple determination.

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