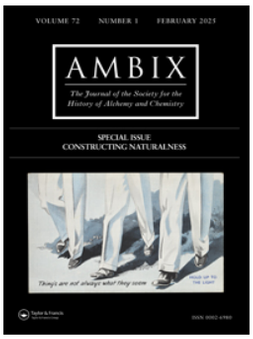

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Can Chemical Substances be Natural?

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This paper explores the philosophical and practical implications of the natural versus synthetic distinction in chemistry. I consider several interpretations of the term natural as pertaining to substances, and conclude that at its core, naturalness is best understood as a statement about material origin. The analysis reveals that calling a chemical substance natural risks committing a category mistake. The descriptor can only be coherently applied to samples of a chemical substance, not to a chemical substance as a set. Even in the case of samples, the utility of the term is limited. Care must be taken to avoid unwarranted implications.

Introduction

It is a truism among chemists that the distinction between natural and synthetic chemical substances is meaningless, or at best completely inconsequential. Nevertheless, the distinction is widely used in the broader public, from advertising to legal matters. Is this usage justified or is it indeed unfounded? This paper takes a philosophical approach to the natural/synthetic distinction in chemistry. The aim is to systematically spell out semantic and practical issues with the terminology and investigate its potential merits. These considerations may provide an analytical backdrop for navigating the shifting and seemingly paradoxical terrain of industrial settings as a site of discourses concerning naturalisation discussed in this issue.

In one sense, the term natural is anything but meaningless. The historical papers in this special issue impressively demonstrate that the use of the term natural has a rich history with varied connotations in chemical contexts, especially so in industrial settings. Nevertheless, the more abstract contentions surrounding the term deserve recognition. The worry is not that applying the term natural to chemical substances is a completely empty statement, but whether the conceptual core of

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the term is a truth-apt descriptor of any actual property of chemical substances. Truth-apt describes a proposition that is decidedly either true or false. If natural is a truth-apt descriptor of chemical substances, that means that for any particular chemical substance, the statement "this substance is natural" is either true or false, rather than nonsensical, paradoxical, or arbitrary. In this paper, I therefore seek to evaluate the core descriptive content of the term and its legitimate usage. The aim is one of conceptual clarification, complementing rather than contradicting historical analysis. In this philosophical analysis, I explicate a taxonomy of possible meanings of the term natural. I aim to provide a normative tool that can help navigate meanings and allow judgements concerning how the term should be used in relation to chemical substances.

I begin by defining chemical substance and exploring eight possible interpretations of natural in the context of chemical substances: material origin, production setting, purpose, material distribution, impact, ethics, aesthetics, and metaphysical non-arbitrariness. Material origin emerges as the most viable core meaning. I then discuss whether these descriptors are applicable to chemical substances, considering deductive necessity, physical necessity, and accidental properties as criteria for attributing a natural or synthetic origin to any chemical substance. I argue that such a description can be used for individual samples of a substance, but is unwarranted when referring to the entirety of a chemical substance as a set, i.e. all the stuff that shares a particular chemical structure. To support this position, I defend the view against two possible objections. Finally, I evaluate whether natural and its antonym synthetic should be abandoned even in the context of describing samples of substances. I conclude that the term natural is of limited use when describing chemical substances. Therefore, it should be used sparingly. Care should be taken to avoid unwarranted or misleading use.

What is a chemical substance?

Chemical substances are defined in terms of their composition, i.e. the types and numbers of atoms contained in a repeating unit (elemental cells, ions, molecules), and their constitution, i.e. how these atoms are connected. In conjunction, these two properties constitute the chemical structure of a substance. Any particular chemical substance is not just an individual assemblage of matter, but all matter that shares a characteristic chemical structure. A chemical substance can thus be thought of as a set with membership conditions. A set is just a collection of things, its membership conditions determine what is part of the set. In these terms, a chemical substance, such as ethanol, constitutes a set. The membership conditions of a chemical substance are its characteristic composition and constitution. The set comprises all past and future instances of a substance, such as ethanol, anywhere in the universe. The extension of such a set is indeterminate and potentially unlimited.

The relevant features for substance delineation are embedded in the representational language of chemistry: structural formulas, elemental cells, and in some

cases, sum formulas such as H_2O or NaCl. All these can be understood as summarising the membership conditions of a chemical substance. Interpreting these membership conditions is not straightforward. Today, structural formulas are commonly considered an idealised description of the microstructure of a substance, but there is some debate as to whether the messy, microstructural reality is adequately captured by these idealisations in a way that allows reliable substance delineation.[1] Famously, even water is not consistently H_2O at the molecular level.[2] Avoiding microstructural commitments altogether, one could instead interpret chemical representations as depictions of nodes in a network of possible reactions.[3] Although internally consistent, this view cannot account for the many chemical substances that are identified solely via interactions with microstructural features using techniques such as NMR spectroscopy. It is thus still up for debate which substance features exactly are described by composition and especially constitution,[4] but in practice, competing interpretations of any given structural formula are not contradictory but complementary. Reactivity predictions are derived based on microstructural considerations and vice versa. Using complementary interpretations and supplementary theories, one can predict substance behaviour. This gives us the means to test membership conditions using synthetic and analytical chemistry.

The phrase "chemical substance" is often used to refer both to the set and its members. I will call the members of a chemical substance set "samples" to avoid confusion. A sample of a substance is matter that possesses the chemical structure laid out in the membership criteria. A sample can comprise macroscopic assemblages or single molecular units. Either way, samples are material, meaning they have mass and spatial extension. The set is an abstract entity defined in terms of its membership conditions. As such, it includes all past, present, and future instances of the kind. The existence of a sample is materially contingent on its production. In the case of chemical substances, there are reaction conditions that have led to the material being transformed into an instance of the substance. These reaction conditions may have been brought about with or without human involvement.

What is natural?

Having defined chemical substances, naturalness must be specified further. I consider several interpretations of naturalness with regards to chemical substances to identify what may be construed as a conceptual core that remains to be evaluated.

[1] Robin Findlay Hendry, "Elements, Compounds, and Other Chemical Kinds," *Philosophy of Science* 73, no. 5 (December 2006): 864–75; Paul Needham, "Microessentialism: What Is the Argument?," *Noûs* 45, no. 1 (2011): 1–21.

[2] Holly VandeWall, "Why Water is not H_2O, and Other Critiques of Essentialist Ontology from the Philosophy of Chemistry," *Philosophy of Science* 74, no. 5 (2007): 906–19.

[3] Joachim Schummer, "The Chemical Core of Chemistry I: A Conceptual Approach," *HYLE – International Journal for Philosophy of Chemistry* 4 (1998): 129–62.

[4] Robin Findlay Hendry, "Two Conceptions of the Chemical Bond," *Philosophy of Science* 75, no. 5 (2008): 909–20; Vanessa A. Seifert, "The Chemical Bond Is a Real Pattern," *Philosophy of Science* 90, no. 2 (2023): 269–87.

Material origin

The term natural can be understood as a statement about the origin of a chemical substance or a sample thereof. In this sense, *natural* signifies something derived from nature without significant alteration due to human intervention. The antonym of natural in origin is *synthetic*, which signifies that something was created by humans through artificial processes. Artificial is often used interchangeably. In the case of chemical substances, the crucial point of origin is the reaction that produces the substance in question – the material origin at which chemical structure is rearranged. Human interventions that do not produce such a chemical change, such as extraction or purification, are typically disregarded in the assessment of whether a substance is natural or synthetic. For example, ethanol that is distilled from fermented grains is not normally considered synthetic, whereas ethanol that is produced via hydration of ethylene is usually considered synthetic, regardless of any steps taken before or after its synthesis.

Natural as a descriptor of material origin in nature without chemical change is consistent with the usage of the term in legal texts and norms. These usually define which materials a natural substance may be derived from and constrain the types of processing it may have undergone. The types of processing are usually constrained in a way that excludes chemical change. For example, European Regulation (EC) No 1334/2008 Article 3 (2) (c) defines natural flavouring substances as "obtained by appropriate physical, enzymatic or microbiological processes from material of vegetable, animal or microbiological origin […]."[5] Similarly, BS ISO 16128-1:2016 deems cosmetic ingredients natural when they are derived from plants, minerals, animals, or micro-organisms, explicitly excluding fossil fuels from the definition.[6] They may only be derived by a specific set of processes, which include physical processes such as grinding and distillation, and extraction with solvents. EU Regulation (EC) No 1907/2006 (REACH), which regulates the registration, evaluation, authorisation, and restriction of chemicals, does not define natural substances. However, it creates exemptions for "substances which occur in nature," a subset of substances derived from natural origins that is only lightly processed.[7]

The use of the term natural as a statement of origin is aligned with popular definitions of the general term natural (not specifically pertaining to chemical

[5] "Regulation (EC) No 1334/2008 of the European Parliament and of the Council of 16 December 2008 on Flavourings and Certain Food Ingredients with Flavouring Properties for Use in and on Foods and Amending Council Regulation (EEC) No 1601/91, Regulations (EC) No 2232/96 and (EC) No 110/2008 and Directive 2000/13/EC," *Official Journal of the European Union* L354 (2008): 34–50.

[6] "Guidelines on Technical Definitions and Criteria for Natural and Organic Cosmetic Ingredients and Products Part 1: Definitions for Ingredients," *BS ISO* 16128-1:2016 (London: British Standards Institution, 2016).

[7] "Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 Concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), Establishing a European Chemicals Agency, Amending Directive 1999/45/EC and Repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as Well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC," *Official Journal of the European Union* L396 (2018): 1–849.

substances) in European and US contexts, as investigated by Rozin et al.[8] In this study, "no processing" was listed as the most frequent category in definitions of natural, "origin in nature" was in third place. The second most frequent category was "no additives," which is obviously not applicable to chemical substances as defined above. Ironically, this category included the sub-category "no chemicals."

Material origin thus remains a strong contender for the conceptual core of "natural."

Production setting

One could maintain that the point of production determines naturalness, but amend the above criterion to abandon the very broad notion of human involvement. Instead, the key point may be whether the production occurs in an industrial setting. In this sense, anything produced outside of an industrial setting (rather than in absence of any kind of human intervention) is to be considered natural. Conversely, anything produced in an industrial setting cannot be considered natural. This approach captures some common intuitions about naturalness. Processes such as cooking or the traditional processing of plant materials, for example to produce indigo dye, are often seen as natural, even though they constitute material manipulation at the chemical level. However, most pre-industrial techniques of material manipulation can be, and many have indeed been, shifted to industrial modes of production. Popular designations of what counts as natural have not necessarily kept up with these changes, and thus reflect arbitrary and highly circumstantial sentiments. They cannot be grounds for a reliable taxonomy of chemical substances.

Purpose

In addition to material origin, the philosophical literature on artifacts distinguishes a second key criterion as to whether something can be understood as an artifact, namely whether it is intentionally made for a purpose.[9] Doing so requires human involvement. Thus, the criterion of purpose entails the criterion of material origin. In the case of the production of chemical substances, there are serious problems around placing byproducts within a framework of purposeful production. The synthesis of chemical products, due to the nature of reaction pathways, often unavoidably produces significant amounts of additional substances as byproducts. These can sometimes be repurposed, but often end up as industrial waste or as pollutants. Such purposeless byproducts would, analogously to wood shavings, not be counted as artifacts by present philosophical accounts. However, they still fit the broader umbrella of material culture[10] much better than naturalness. There are certainly interesting debates to be had around purpose in the production of chemical

[8] Paul Rozin, Claude Fischler, and Christy Shields-Argelès, "European and American Perspectives on the Meaning of Natural," *Appetite* 59, no. 2 (2012): 448–55.

[9] Beth Preston, "Artifact," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta and Uri Nodelman, Winter 2022 (Stanford: Metaphysics Research Lab, Stanford University, 2022): https://plato.stanford.edu/archives/win2022/entries/artifact/ (accessed 2 January 2025).

[10] Beth Preston, *A Philosophy of Material Culture: Action, Function, and Mind* (New York: Routledge, 2012).

kinds, but for the present discussion around whether chemical substances may ever be counted as natural, material origin covers anything that could be captured by purpose, with the added benefit of a clear-cut inclusion of pollution and industrial waste in the realm of the synthetic/artificial rather than the natural.

Material distribution

Shifting the sight away from the location or purpose at the point of a substance's production, one may instead want to consider where it ends up – a substance's material distribution.[11] In this sense, substances closely associated with human settlements and industrial production sites may not be considered natural, whereas substances that are either ubiquitous or that largely occur outside the sphere of civilisational influence are to be considered natural. This designation has the advantage of being able to identify natural substances without tracing exactly how they came to be. A substance that is overwhelmingly found in a specific type of wild plant tends to be seen as natural, even if the pathways of its production are poorly understood. If a substance occurs primarily in landfills, it may be regarded as non-natural by many, even if it was produced within the waste ground as a result of unknown chemical processes without direct human intervention at the point of its generation. This meaning of natural has the interesting implication that a substance can naturalise or de-naturalise over time as its distribution patterns change. For example, a substance that is present in a natural setting in small amounts may not be considered natural anymore once there is large-scale production in industrial settings. A plant material, such as indigo dye, may no longer be considered natural once it is produced at large scales, either via chemical synthesis or even via domestication and intensive agricultural practices. Conversely, some substances may over time be naturalised, as they become globally ubiquitous. For example, persistent pollutants such as PFAS (per – and polyfluoroalkyl substances), a group of highly stable and mobile chemicals commonly used for resistant coatings in a variety of consumer products, have been distributed to even the most remote of locations.[12] In these settings, they, for better or worse, become part of natural processes as they interact with the environment. However, in both instances, one may question if there really is a change in the naturalness of the substance. It seems that the examples are more aptly categorised as examples of recontextualisation and possibly normalisation, rather than genuine instances of (de-)naturalisation. At this point in time, human civilisational influence spans the entire globe, as do, of course, natural processes, and there is no feasible way of disentangling the two in terms of location.

Impact

Sometimes, the term natural is used to describe the impact of a substance rather than its origin. Natural is used to indicate that the impact of a product on

[11] Many thanks to one of the reviewers, who kindly brought this issue to my attention.

[12] Sudarshan Kurwadkar et al., "*Per-* and Polyfluoroalkyl Substances in Water and Wastewater: A Critical Review of Their Global Occurrence and Distribution," *Science of The Total Environment* 809 (2022): 151003.

human health and the natural environment is particularly mild and unproblematic. It can even imply that a chemical substance is positively protective against harms of an industrialised, urban environment, as shown in Klein's discussion of cosmetic products.[13] In contrast, synthetic substances are considered more risky or harmful.

There are many substances that trouble this distinction, showing that origin is the arbiter of naturalness rather than impact. For example, botulinum toxins, a group of neurotoxic proteins produced by certain bacteria, are some of the unhealthiest substances known to mankind, yet one would not consider calling them synthetic because they are toxic. Notably, when naturalness in terms of origin and effect seem to contradict, origin remains the primary distinction. When effects deviate from what is commonly expected of a natural substance, this does not overturn the assessment based on origin. This usage of the term natural as a statement about effects possibly derives from the misguided assumption that a natural origin is associated with being healthier or more environmentally friendly. Implications of effects must thus be regarded a connotation rather than the core meaning of the term.

Assessments of impact clearly contain implicit value judgements about what constitutes risk and harm. Thus, impact connotations are widely used in advertising. In the case of flavourings, Gennermann notes that there is a divide between consumers, who tend to associate the term natural with positive effects, and industrial actors, who use the term in a more technical sense relating to production processes.[14] In her case study, this divide was strategically employed to shape flavouring regulations, making them more favourable to the industry. Furthermore, impact connotations are most clearly connected to a normalising impulse within naturalness debates. Wagemann shows that ascribing naturalness may not only reinforce but even redefine standards of perceived normality and regularity.[15] These examples show that impact connotations are both powerful and easily abused for manipulative purposes.

Ethics

Some interpretations of naturalness are fundamentally not applicable to chemical substances. For example, the term natural is sometimes used in an ethical sense. The opposite of this meaning of natural is unnatural, as in contrary to nature. In this sense, unnatural describes something that constitutes an ethical violation or perversion. Chemical substances can of course be used as a means to commit ethical violations that can be construed as contrary to nature, for example in the case of chemical weapons of mass destruction. However, such uses are not inherent

[13] Gina Maria Klein, "The Nature of Skincare: Categorising Cosmetics with Bioactive Ingredients in the Case of Quenty-Cosmetic," *Ambix*: this issue.

[14] Paulina S. Gennermann, "A Game of Terms: Constructing Naturalness in German Flavour Regulation, 1959-2008," *Ambix*: this issue.

[15] Sophia Wagemann, "'Cycles of Clockwork Precision': Hormonal Contraception and Natural Menstruation," *Ambix*: this issue.

in the chemical substances themselves. For example, chlorine has been used as a weapon of mass destruction, but it is also an invaluable base chemical for many applications that constitute no such ethical violations. Chemical substances in themselves lack the agency to commit acts that can be assessed in terms of their alignment with ethical norms. It has been argued that the industrial production of synthetic chemicals engages in "harmful molecular relations" in chemical regimes of living,[16] but even through this analytical lens, harms play out at molecular sites but are largely produced and reinforced by unjust human-made systems. The interpretation of naturalness as an ethical property is not strictly applicable to chemical substances themselves.

Aesthetics

Natural can also be understood as an aesthetic judgement. As Neves demonstrates in his investigation of bioplastics, perceptions of naturalness can be intricately linked to the sensory qualities of materials.[17] However, it is difficult to generalise these judgements for chemical substances. The identity of a chemical substance remains unchanged across phase changes, as does naturalness, if it is to be considered a stable attribute of a substance. However, the sensory qualities of a substance vary dramatically between phases. Similarly, impurities and admixtures can have dramatic effects on sensory qualities. Furthermore, the aesthetic impression of naturalness is a compound judgement that includes properties that are not functions of chemical substance identity, such as surface texture and imperfections. Although there are aesthetic expectations linked to the naturalness of chemical substances, they are unreliable in determining it.

Beyond sensory qualities, aesthetic judgements play an important role in many of the naturalisation discourses in industrial settings discussed in this special issue. Most importantly, the normal is an aesthetic judgement, as is purity in the non-technical sense, as well as attributes like wholesomeness or beauty. The special issue shows that these aesthetic judgements are continuously renegotiated. They are in no way fixed by any inherent quality of a substance, but produced in a discourse that is often driven by commercial interests. The interplay between the attribution of naturalness and these judgements is context-specific and non-trivial – as can be seen in this issue, aesthetic considerations may motivate actors in industrial settings to strategically utilise the term.

Consequently, one may be tempted to define naturalness solely in aesthetic terms with reference to similar terms such as normal. However, the aesthetic attributions of the natural are manifold and shifting, sometimes even contradictory. For example, natural may either be seen as unruly or as more regular than nature itself.[18] Hence, it may well be impossible to come up with a way of capturing the

[16] Michelle Murphy, "Chemical Regimes of Living," *Environmental History* 13, no. 4 (2008): 695–703 (on 698).
[17] Artur Neves, "Ivory Emulation: The Naturalness of Early Bioinspired Plastics," *Ambix*: this issue.
[18] Wagemann, "'Cycles of Clockwork Precision': Hormonal Contraception and Natural Menstruation."

aesthetic qualities attributed to the natural in a way that can reliably pick out a non-arbitrary use across contexts. Thus, the aesthetic judgement may more usefully be thought of as (shifting) connotations than a single core meaning. In descriptive projects, these connotations may indeed become the core of the analysis, but a normative search for a conceptual core of the term demands reliability and discernibility, which the use as an aesthetic judgement cannot provide in this case.

Metaphysical non-arbitrariness in the context of natural kinds

In philosophy of science, the term natural is most often used in the context of the natural kinds debate. This usage is distinct from the assignment of natural as opposed to synthetic. The natural kinds debate is a metaphysical debate that, in short, concerns the existence of non-arbitrary kinds, that track the structure of the natural world.[19] There are many different natural kinds accounts, many of which use chemical substances such as water or gold as paradigmatic examples.[20] Within philosophy of chemistry, there are extensive debates on whether naturalness in this sense applies to chemical kinds.[21] In the natural kinds debate, natural is used in opposition to arbitrary: A natural kind tracks distinctions that are not subject to human whim. In the natural kinds sense, naturalness hinges on chemical ontology. Chemical substance distinctions are a systematic affair. The system applies regardless of whether any particular substance was synthesised by humans or discovered outside the laboratory. Whether any chemical substance is a natural kind is not a case-by-case assessment but depends on whether the system as a whole tracks real distinctions in the world. Therefore, naturalness in the natural kinds sense either applies to all chemical substances, or to none.

Clearly, metaphysical non-arbitrariness of kinds does not capture popular usage, which assigns naturalness on a case-by-case basis: some, but not all, chemical substances are normally deemed natural. The natural kinds question is a separate one, that is not of primary interest in this paper. Still, it is useful to briefly assess whether the natural kinds question has any bearing on other interpretations of naturalness,

[19] Alexander Bird and Emma Tobin, "Natural Kinds," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Spring 2022 (Stanford: Metaphysics Research Lab, Stanford University, 2022): https://plato.stanford.edu/archives/spr2022/entries/natural-kinds/ (accessed 2 January 2025).

[20] Saul A. Kripke, "Naming and Necessity," in *Semantics of Natural Language*, ed. Donald Davidson and Gilbert Harman (Dordrecht: Springer Netherlands, 1972), 253–355; Hilary Putnam, "The Meaning of 'Meaning'," *Philosophical Papers* 2 (1975): 131–93; Richard Boyd, "Realism, Anti-Foundationalism and the Enthusiasm for Natural Kinds," *Philosophical Studies: An International Journal for Philosophy in the Analytic Tradition* 61, no. 1/2 (1991): 127–48; P. D. Magnus, *Scientific Enquiry and Natural Kinds* (London: Palgrave Macmillan UK, 2012); Muhammad Ali Khalidi, "Natural Kinds as Nodes in Causal Networks," *Synthese* 195, no. 4 (2018): 1379–96; Marc Ereshefsky and Thomas A. C. Reydon, "The Grounded Functionality Account of Natural Kinds," in *From Biological Practice to Scientific Metaphysics, Minnesota Studies in the Philosophy of Science*, ed. W. Bausman et al. (Minneapolis: University of Minnesota Press, 2019) 236–266.

[21] VandeWall, "Why Water Is Not H_2O, and Other Critiques of Essentialist Ontology from the Philosophy of Chemistry"; Robin Findlay Hendry, "Are Chemical Kinds Natural Kinds?," in *Recent Developments in the Philosophy of Science: EPSA13 Helsinki*, ed. Uskali Mäki et al. (Helsinki: Springer International Publishing, 2015), 251–61; Eric R. Scerri, "On Chemical Natural Kinds," *Journal for General Philosophy of Science* 51, no. 3 (2020): 427–45; Pieter Thyssen, "Are Acids Natural Kinds," *Foundations of Chemistry* 26 (2024): 225–253; Clevis Headley, "Natural Kinds, Chemical Practice, and Interpretive Communities," *Foundations of Chemistry* 25 (2023): 167–87.

particularly on the natural vs. synthetic dichotomy. To attribute naturalness in the sense of material origin, it does not matter whether one believes that chemical substances are natural kinds. If chemical substances are generally natural kinds, natural and synthetic origin can be construed as non-essential properties of individual substance kinds. It may make complete sense to group them accordingly, while upholding that all chemical substances track real, non-arbitrary kinds in the world regardless of origin. Conversely, if substance distinctions are fundamentally imposed based on an arbitrary human system, the material origin of any particular kind within the system may still be tracked. Thus, the question of whether chemical substances are natural kinds is orthogonal to the question of whether individual chemical substances can justifiably be categorised as natural as opposed to synthetic.

To summarise this section, there are several possible ways of interpreting the term natural. The uses of the term are too manifold to be explored in their entirety here. I have considered eight possible interpretations to identify a conceptual core pertaining to chemical substances: material origin, production setting, purpose, material distribution, impact, metaphysical non-arbitrariness, as well as ethical and aesthetic dimensions. Unquestioningly, our perception of the term natural in the context of chemical substances is coloured by several or even all of these. The above may serve as a useful taxonomy of connotations and possible meanings of the term natural as a descriptor of chemical substances.

In an attempt to distinguish connotations of the term from an analytically defensible core meaning, I have shown that most interpretations can either be relegated to connotations, as is the case for impact, ethical and aesthetic dimensions, or, in the case of the natural kinds debate, concern technical terms that are orthogonal to the popular use of the term natural. Material origin has emerged as a plausible conceptual core that is more precise and reliable than conceivable alternatives, capturing how the term natural is commonly used in relation to chemical substances. It is reflected in the dichotomy of natural and synthetic chemical substances. The remainder of this piece thus evaluates the use of natural (and, conversely, synthetic) as a statement of material origin of chemical substances.

Can a chemical substance be natural?

All samples of any chemical substance have a material origin that can in principle be described as natural or synthetic. Of course, the exact type and extent of human involvement that takes something from natural to synthetic is not exactly clear. Is ethanol produced by modified bacteria synthetic or natural? Are the products of a Maillard reaction, the browning that occurs during cooking processes, natural or synthetic? A dichotomy may be ill-fitted to such human/non-human co-production processes, but the existence of a grey area does not invalidate the distinction as a whole. In the same way that the existence of grey does not render the distinction between black and white meaningless, a few borderline cases of

naturalness are no fundamental obstacle to deeming other substances decidedly synthetic or natural. Cases like the products of the Maillard reaction can be put aside as indeterminate while the dichotomy is applied to more clear-cut cases, or they can be eliminated by constructing a rigid and detailed set of standards. Putting aside borderline cases, it is clearly warranted to call the origin of some samples natural, for example minerals produced in geochemical processes, or metabolic products of non-domesticated plants and animals, whereas other substance samples, such as nylon in a pair of tights or a block of Styrofoam were synthesised in human-build production plants according to protocols devised by scientists in laboratories.

Just because a property can be attributed to a sample does not mean it can be attributed to the set without committing a category mistake. A category mistake is committed when a property is ascribed to something that could not possibly have this property. For example, if all members of a sports team are wearing a jersey, that does not mean that the team is wearing a jersey. A team is a collective, and as such, it cannot actually wear anything, strictly speaking. Similarly, a set is an abstract entity, as such it cannot have a material history. When we speak of the origin of a set, it is only possible to speak of its conceptual history. Even to a natural kinds realist, a set remains an abstract entity, albeit one that accurately describes the structure of the world. Thus, ascribing material origin to the set itself is a category mistake. All that said, we do of course colloquially say things like "the team is wearing a jersey," by which we mean that all members of the team are wearing a jersey. The property itself (wearing jerseys) cannot be a property of the collective, but the fallacy can easily be avoided by more carefully phrasing the property of a set as "all members of the set share [property]." Analogously, a chemical substance might be said to have the property "all samples of the substance are of natural/synthetic origin." Calling a chemical substance natural or synthetic can charitably be interpreted as a shorthand for this statement, and I will use it as such in the following.

There are three scenarios in which it is permissible to attribute properties to a chemical substance:

(1) The property is deductively entailed in the membership conditions of the chemical substance
(2) all samples of the substance share a property as a matter of (meta-)physical necessity
(3) all samples of the substance accidentally share the property.

In the following, I evaluate each scenario with regards to the properties natural and synthetic.

Deductive necessity

Option (1) can be dismissed easily. A chemical substance is fully specified by its chemical structure. The defining structural features of a chemical substance do

not contain any information about the origin of all or any samples of that substance. In fact, there is very little we can deduce solely from the composition and constitution of a sample without making interpretative assumptions and taking into account additional theories. Without such steps, the only statements that can strictly be deduced from composition and constitution are statements about these two properties and their combinations. For example, we can deduce from the structural formula of ethanol that two carbons are connected to each other, and that ethanol contains the element oxygen. This is true for all members of the set ethanol as a matter of necessity. Conversely, any statement on human involvement in the production of a sample requires information not entailed by its chemical structure. Based solely on its chemical structure, it is not possible to tell whether a drop of ethanol has been produced by bacteria converting sugars in a rotting apple, via the industrial hydration of ethylene, or even simply materialised in a vacuum, violating all of known physics. Any statement on the origin of a sample requires additional premises and cannot be deduced from composition and constitution alone.

Physical necessity

Having shown that chemical substances cannot be considered natural or synthetic as a matter of deductive necessity, I move on to option 2, physical necessity. Physically necessary properties are those that all samples of a chemical substance share due to their chemical structure in conjunction with additional physical regularities. These physical regularities are not a matter of definition but of observation, so there is an inductive element in assessing physical necessity. For example, ethanol reliably boils at 78 °C.[22] The boiling point cannot be deduced from the chemical structure alone. Rather, it arises from the physical (mostly electrostatic) interactions between ethanol molecules. The type and strength of interactions as well as their overall effect is dependent on chemical structure and thus shared across all samples of the set. In this case, the physical regularities at play might (imperfectly) be subsumed as an interplay between chemical structure and the physical laws of electrostatic attraction.

Physical necessity is never established with complete certainty, since there is always induction involved. One can either employ law-like generalisations that derive inductive support elsewhere, as in the example above, or one can generalise directly from an observed regularity. For example, the consumption of ethanol is a risk factor for certain types of cancer.[23] In either case, the observed effect must plausibly be a function of the chemical structure involved to qualify as a substance

[22] Robert L. Brown and Stephen E. Stein, "Phase Change Data," in *NIST Chemistry WebBook, NIST Standard Reference Database Number 69*, ed. P.J. Linstrom and W.G. Mallard (Gaithersburg MD: National Institute of Standards and Technology, 2023): https://webbook.nist.gov/cgi/cbook.cgi?ID=C64175&Mask=4 (accessed 2 January 2024).

[23] V. Bagnardi et al., "Alcohol Consumption and Site-Specific Cancer Risk: A Comprehensive Dose–Response Meta-Analysis," *British Journal of Cancer* 112, no. 3 (February 2015): 580–93.

property. Samples of the same chemical substance must reliably produce the same effect when samples of other chemical substances would not. Both is fulfilled in the cases of boiling points and cancer risks.[24] Of course, the observed associations can be more or less well-supported. Beyond high-quality inductive support, mechanistic reasoning is often crucial for assessing whether an observed effect is a candidate for physical necessity.

There are some aspects of the material origin of a sample that can justifiably be considered a matter of physical necessity. Possible material origins are constrained by the conservation of mass, kinetics, and thermodynamics that dictate possible reaction pathways. For example, ethanol cannot exist in a plasma, so no sample of ethanol can originate directly from the sun. Similarly, a lump of iron will never be the direct material predecessor of ethanol, as there are no direct reaction pathways (including nuclear reactions) that can transform iron to ethanol. By considering physical necessity, we can thus derive some general statements about the origin of a chemical substance that we can safely assume apply to the entire set.

Is it possible to use physical necessity to derive whether a substance is of natural or synthetic origin along similar lines? No. The distinction between natural and synthetic is far more specific than any of the constraints discussed above and can never be considered uniquely necessary. Consider the synthetic production of a substance: The synthesis is achieved by carefully manipulating reaction conditions, controlling starting materials, pressure, temperature etc. None of these factors actually require human involvement. Any reaction conditions that can be produced by humans can also be produced by cosmic coincidence. The random occurrence of even complex reaction steps is somewhat likely given the vastness of the universe. In complex atomic sequences, it is quite possible that not every permutation is actually realised by such cosmic coincidence, as these permutations rapidly outpace the number of atoms required to produce them, easily surpassing the number of atoms in the known universe even for comparatively short sequences. However, even in these cases, the mere possibility of a cosmic coincidence suffices to reject a physically necessary connection between chemical structure and human involvement.

Accidental property

Finally, we must consider option 3: natural/synthetic origin as an accidental property of the entire set. In principle, it is highly likely almost to the point of certainty that there are chemical substances for which all instances are of natural origin not by necessity but by accident. Even only looking at the earth, nature produces many more chemical substances than humans could ever make in a laboratory. The DNA chains of every individual of every species exhibit distinct composition and constitution, thus they must be counted as distinct chemical substances. Synthesising

[24] The cancer-causing effect of ethanol is statistical, and thus not observed in every instance. However, every sample has the same potential of causing cancer, therefore the property is indeed uniform across the entire set.

every single one of these substances, i.e. the DNA of every individual of every species, is futile to the point of impossibility. As a consequence, at least some substances that exist in nature will in all likelihood never be produced synthetically. Conversely, there are probably some substances that will only ever be synthesised. These are substances that are generally unlikely to exist because they are very unstable, very complex, or both. Presumably, intentional human intervention drastically increases the odds of such a substance being produced. Again, DNA is a good illustration. Considering the vast number of permutations of DNA strands, there is a chance that some synthetic DNA strands do not have a naturally produced equivalent.

To fully ascertain whether all members of a set exhibit the same accidental property, we need to assess all of them individually. Considering our very limited access to everything that exists, ever has existed, and ever will exist in the universe, knowingly assessing all samples of a chemical substance is impossible. That said, I do not dispute that educated guesses can be made regarding the most common or perhaps even only origins of at least some chemical substances based on statistical and astrochemical considerations. The indeterminacy of future human interventions further complicates the assessment. The synthesis of a substance could occur in any possible future, which is a major problem if the universe is not deterministic, i.e. if there are many or even infinite possible futures. For any chemical substance, it is impossible to rule out that there is both a possible future in which it is synthesised by humans and one in which it is only ever produced naturally without any human involvement. There is no known or plausible mechanism that necessarily prevents one possibility but not the other.

Objections

In the above, I have shown that the natural vs. synthetic dichotomy as a statement of material origin is not applicable to chemical substances as sets, although it is permissible to apply it to individual samples of chemical substances. In the following, I strengthen this view by countering a potential objection. One might object that the criterion of material origin is too strict, because it requires knowledge of the origin of every sample of a substance ever produced. Could the category mistake not be evaded by simply weakening what counts as material origin? Indeed, there is a way of doing so. One could assign material origin to a substance based on typical or paradigmatic instances, rather than taking the material origin of all members of the substance set into consideration. For example, a substance such as ethanol could be considered natural not because it is never produced synthetically, but because it was first isolated as the product of natural fermentation processes and is commonly produced like that to this day. The category mistake is resolved by relying on actual instances of the substance to determine naturalness, which necessarily have an origin. However, amending the criterion invites more problems than it resolves.

There is no unproblematic way of deciding which instance of a substance is paradigmatic or typical. Do we count the majority of the substance produced? By weight, volume, number of production sites? Even if we settle on one, determining how much of a substance is produced at any given moment is a practical impossibility. Temporal aspects further complicate the case. For example, quinine, a powerful antimalaria drug, was first extracted from the bark of the cinchona tree, but is now produced synthetically at a scale that far outstrips its natural occurrence.[25] It seems counterintuitive to believe that the naturalness of the substance itself has changed as a result of changing production dynamics. Instead, we could go the paradigmatic example route and conclude that quinine still is a natural substance because it was first found in nature. However, going by the first known instance of a substance equally produces counterintuitive conclusions. Acetone was synthesised long before it was found to exist in nature.[26] It seems strange to conclude that it therefore counts as synthetic, even though it presumably existed in nature before its first synthesis. So maybe we should simply ask whether a substance exists in nature at all. This approach is laden with uncertainty, as we cannot possibly know whether a substance that was synthesised may also exist somewhere in the universe without human intervention. Of all these options, each has drawbacks and seems to intuitively make sense in the case of some substances but not others. Seeking to evade the category mistake in this way thus makes the naturalness of chemical substances intolerably arbitrary. Hence, the weakened criterion is no more applicable to chemical substances than the stricter version.

What about samples of chemical substances?

So far, it has been established that chemical substances cannot legitimately be described as natural when referring to the entire set. Statements such as "Ethanol is a natural substance" constitute category mistakes. Let us return to samples of chemical substances. These are not subject to the same category mistake – an individual sample of a substance necessarily has an origin. But just because a description crosses the low bar of being coherently applicable does not imply that we should use it. More angles need to be considered. First and foremost, describing the origin of a chemical sample is chemically inconsequential. The origin of a sample does not affect its chemical behaviour in any way. A synthetic sample of a substance will undergo exactly the same reactions under exactly the same circumstances as a sample extracted from natural sources. Importantly, there is no difference in risks or the potential for harmful effects as a result. Quite often, chemists, who naturally consider the chemical effects of a substance the most important aspect of it, stop here when dismissing naturalness as inconsequential, but there are some practical and social considerations that slightly complicate the picture.

[25] Teodoro S. Kaufman and Edmundo A. Rúveda, "The Quest for Quinine: Those Who Won the Battles and Those Who Won the War," *Angewandte Chemie International Edition* 44, no. 6 (2005): 854–85.
[26] Mel Gorman, "The History of Acetone, 1600-1850," *Chymia* 8 (1962): 97–104.

Saying that the difference is chemically inconsequential does not imply that it is always impossible to tell whether a sample is of synthetic or natural origin just based on properties of the sample. Real samples have traces and isotope compositions that may give indications of their origin. For example, in doping tests, the isotope composition of testosterone in a blood sample can be used to reveal whether it was naturally produced within the athlete's body or injected after being produced synthetically.[27] Nevertheless, the effects of that testosterone on the body are the same regardless. Although they can provide indications of naturalness in some cases, neither isotope ratios nor impurities are a universally and reliably associated with naturalness. These correlations are not necessary connections and their applicability is anything but universal. Still, in some applications, such as sports medicine, archaeological science, art history, and quality control, these markers of origin can provide invaluable information. That said, the distinctions of origin often track distinctions of geographical or temporal origin more closely than distinctions between natural and synthetic. Even when the natural/synthetic dichotomy can be approximated using analytical chemistry, it is often possible and appropriate to use more precise language to draw attention to the contextually important property. For example, testosterone in doping control is more usefully characterised as endogenous vs. exogenous. Exogenous testosterone can be of natural or artificial origin, it does not matter either way. The concern in forensic sports medicine is whether the testosterone was injected or not, not whether it was chemically transformed through human intervention. Conversely, in medical treatment, neither distinction is of importance. Here, referring to exogenous testosterone that is chemically identical to endogenous testosterone as unnatural can foster false and even stigmatizing beliefs about its effects.

There are some contexts in which differences in purity and the presence of different contaminants affect risk assessment in a way that is correlated with natural and synthetic origin. In these contexts, it may be permissible to use these terms as a proxy.

No sample of any substance is ever completely pure. Contaminants are not considered when assessing the properties of a chemical substance per se, as they are not inherently part of it. However, they cannot be avoided in any real context. Which contaminants are present in a sample depends on the method of production, which may include both synthetic processes and extraction from natural sources. One may be justified in drawing a natural/synthetic distinction to highlight the potential presence of different contaminants, especially when available methods of production introduce contaminants with significantly different risk profiles. Of course, it depends on the substance in question whether natural or synthetic origin coincide with more dangerous contaminants. Although it may be legitimate as a shorthand in some cases, natural/synthetic is too crude to usefully track

[27] C. Saudan et al., "Testosterone and Doping Control," *British Journal of Sports Medicine* 40, no. Suppl. 1 (2006): i21–i24.

contaminants in most. Usually, there are several possible ways of both synthesising and extracting a substance, each associated with different contaminants and risks. Furthermore, the impact of purification far outweighs the importance of the context in which a sample was produced when it comes to the dangers of any potential contaminants.

Relying on origin may be a very crude way of tracking contaminant risks, but it is occasionally useful in practice. The most prominent example is ethanol. In the EU, synthetic ethanol must not be added to beverages.[28] The ethanol itself is of course no more or less safe than naturally produced ethanol. However, the types of contaminants that may be present in synthetic ethanol differ from those present in naturally produced ethanol. More importantly, agricultural ethanol is subject to food-grade quality control, which means that risks from contaminants are currently much lower in practice. The example shows that even in one of the few cases where it arguably works, tracking risks using naturalness is spurious and highly contextual. Once again, a more precise description that addresses specific contaminants and thresholds is quite possibly preferable. Even though origin is of little chemical importance, meaning may be ascribed to it socially and institutionally. Of course, these impulses must be resisted when they are the result of misguided beliefs about correlations between origin and effects. However, there are cases in which there are good social reasons to think about substances in terms of natural and synthetic. One such example is, again, ethanol. Beyond consumer risks, keeping beverages limited to alcohol derived from agricultural products protects traditional brewing practices and maintains a standard of transparency. Another case can be identified in REACH:[29] Even though substances of natural origin are not presumed to be essentially different from chemical substances, they are more usefully captured in different regulatory frameworks – if this category were not distinguished, any food item, leather product, or even rock that is sold would fall under regulations of chemical substances, a hugely inefficient way to regulate these products.

Thus, ascribing naturalness to samples of a chemical substance is warranted only in a very limited number of cases. In most cases, another descriptor more aptly describes the distinction sought to be captured. Sometimes, the natural/synthetic dichotomy may legitimately be used for pragmatic reasons in social and institutional contexts. However, natural is a particularly laden term. Therefore, extra care

[28] "Regulation (EU) 2019/787 of the European Parliament and of the Council of 17 April 2019 on the Definition, Description, Presentation and Labelling of Spirit Drinks, the Use of the Names of Spirit Drinks in the Presentation and Labelling of Other Foodstuffs, the Protection of Geographical Indications for Spirit Drinks, the Use of Ethyl Alcohol and Distillates of Agricultural Origin in Alcoholic Beverages, and Repealing Regulation (EC) No 110/2008," *Official Journal of the European Union* L130 (2019): 1–54.

[29] "Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC."

must be taken to avoid unwarranted implications. The easiest way to do so is by adopting alternatives wherever possible.

Conclusion

While the term natural carries various connotations and historical weight, its most justifiable and practical application in the context of chemical substances is as a descriptor of material origin. This interpretation aligns with regulatory definitions and popular understanding, framing "natural" substances as those derived from nature without significant chemical alteration due to human intervention. Conversely, "synthetic" substances are those produced through human-mediated chemical processes. Material origin not only provides a clear and concise definition in this context, but overrides other connotations of naturalness. It can plausibly be considered the conceptual core of the term in this particular context of application. I have then shown that in this core meaning, calling chemical substances as sets natural constitutes a category mistake. This is a serious and previously unexplored objection to the use of the term natural in chemistry.

At best, the terms "natural" and "synthetic" can be applied to samples of chemical substances. Even in these cases, the descriptors should be approached with caution. While the terms may retain some pragmatic value in specific contexts, their overall utility is limited. They often carry unwarranted implications and fail to capture the nuances of chemical properties and risks. More precise language is generally preferable to foster clear, targeted communication and avoid widespread misconceptions. Consumers, chemists and policymakers alike should strive for clarity and precision, reserving the natural/synthetic distinction for cases where it genuinely adds value. The narrow range of applications revealed in the conceptual analysis is in stark contrast with the widespread and liberal use of the term, both historically and in the present. Its rich connotations often take centre stage at the expense of consistency. These connotations are varied and often contested, especially in industrial settings, as demonstrated throughout this special issue.

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