

Organising the metals and nonmetals: An update

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Abstract

This paper updates my 2020 article, “Organising the metals and nonmetals” in which I advocated for parsing the periodic table into four kinds of metals and four of nonmetals. This framework is retained and updated, and augmented with some additional chemistry-related and philosophical observations.

Keywords: Classification of elements · Descriptive chemistry · Electronegativity · Introductory chemistry · Periodic trends · Periodic table

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A. Introduction

There is a recurring history in the literature of noting a comparable range of metal and non-metal types, from highly reactive to less reactive, even noble. For example:

What, in general, is the difference between active metals, less active metals, less active non-metals, active non-metals, and inert gases...? (Friedenberg 1946, p. 230)

By the end of 8th grade, students should know that... there are groups of elements that have similar properties, including highly reactive metals, less reactive metals, highly reactive nonmetals (such as chlorine, fluorine and oxygen) and some almost completely unreactive gases (such as helium and neon). (AAAS 1994, p. 78)

Or more recently:

Those [elements] classified as metallic range from the highly reactive sodium and barium to the noble metals, such as gold and platinum. The nonmetals... encompass... the aggressive, highly-oxidizing fluorine and the unreactive gases such as helium. (Overton et al. 2018, preface)

That said, the traditional group-by-group approach to teaching chemistry, including a separate focus on hydrogen, results in a fragmented view of the periodic table. The problem arises most prominently in groups 1, 13, 14, 15, and 16, with their mix of nonmetals, metalloids, and nonmetals. Here, the nonmetals become fragmented across five groups, the metalloids across four, and the p-block metals across four.

The stove-piping arising from this educational methodology masks underlying similarities and differences that are critical for a comprehensive understanding of elemental properties across the periodic table.

The main reasons for this state of affairs appear to be:

Historical development of the periodic table: The periodic table was developed based on the observation of elemental properties and their periodicity. Grouping elements by their vertical columns (groups) naturally emphasized their shared chemical properties.

Simplicity and clarity in education: Group-by-group teaching can simplify the complex nature of the periodic table, making it easier for students to grasp fundamental concepts. This approach allows learners to focus on the distinct properties and reactions of each group.

The intended approach in this paper is to provide a bridge between (a) higher order conceptions of metals and nonmetals (including metalloids), and (b) the lower-order traditional group-by-group methodology. Of course, the latter will continue to have its place.





Parsing the metals and nonmetals into sets allows for:

- the construction of a framework that can aid in understanding the periodic table's complexity, reflecting the desire for order and clarity in scientific inquiry;
- acknowledges the continuity and gradations in nature rather than imposing a more limited dichotomy; and
- breaks down complex information into more digestible and relatable segments, facilitating a more coherent, inclusive and deeper understanding of chemical behaviour and trends across the periodic table, from reactive metals to noble gases.

In recognition of the educational gap between (a) and (b), the following sections delve into how such a holistic view can be understood.

B. A holistic view of metals and nonmetals

Table 1 (upper) shows how the periodic table can be readily grasped in terms of four complementary sets of metals and nonmetals. The accompanying exploded periodic table refers.

Metals	Reactivity ¹	Nonmetals	Notes	Key
sf-block	High to fairly	Halogen	1	
d-block (non-noble)	High to low	Unclassified	2	
p-block	None particularly	Metalloid	3	
Noble	Least	Noble gas	4	

Li	Be											B	C	N	O	H	He	
Na	Mg											Al	Si	P	S	F	Ne	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Cl	Ar	
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	Br	Kr	
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	I	Xe
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og	Rn
												Metals					Nonmetals	
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Ym	Yb					
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No					

1 Some overlaps will be seen to occur amongst the reactivity labels

2 The unclassified metals are generally H, C, N, O, P, S, and Se

3 a. For aluminium, Whitten and Davis (1996, p. 853) write, “[It] is quite reactive, but a thin, transparent film of Al₂O₃ forms when Al comes into contact with air. This protects it from further oxidation. For this reason, it is even passive toward nitric acid (HNO₃), a strong oxidizing agent. When the oxide coating is sanded off, Al reacts vigorously with HNO₃.” Parish (1977, p. 182) mentions that aluminium, tin and lead are widely used for their corrosion resistance. Thallium is unaffected by water or alkalis but is attacked by acids, and is slowly oxidized in room temperature air (Parish 1977, p. 183; Russell & Lee 2005, p. 419).
 b. Arsenic is stable in dry air. Extended exposure in moist air results in the formation of a black surface coating. “Arsenic is not readily attacked by water, alkaline solutions or non-oxidizing acids” (Greenwood & Earnshaw 2002, p. 552). It can occasionally be found in nature in an uncombined form (Eagleson 1994, p. 91) It has a positive standard reduction potential (As → As³⁺ + 3e = +0.30 V), corresponding to a classification of semi-noble metal (Huang 2018, pp. 30, 32).

4 The noble metals are a subset of d-block metals

Table 1: Types of metals and nonmetals

¹ Parish (1977, pp. 37, 52–53, 112, 115, 145, 163, 182). The halogens range from highly reactive F to fairly reactive I; the unclassified nonmetals range from high (O) to low (N). Parish deals only with the metals; the match-ups to the four types of nonmetals are this author’s contribution.

This approach has the advantage of relying on the standard electronic block letters s, f, d and p to distinguish the metals rather than collective names such as active metals, transition metals, and post-transition or poor metals, or numerous alternatives.² It avoids uncertainties as to where the transition metals start and end. For the same reason, it does not necessarily fix which d-block elements are noble metals.³ Individual authors can replace the block labels with their preferred class names.

While bringing the s- and f-block metals under one umbrella may seem questionable the similarities between the two sets are well documented in the literature. Thus, the lanthanides are described as behaving largely as if they were trivalent versions of the +2 cations Ca^{2+} , Mg^{2+} of group 2 (Jones 2017, p.1). More generally, King (1995, p. 289) associates the chemistry of the lanthanides in the +3 state with the chemistry of the alkali and alkaline earths. The actinides are similarly reactive (Parish 1977, p. 163) noting the early members show a wider range of oxidation states. Further:

“Many significant trends are apparent in the structures of the halides and their physical and chemical properties...The majority of pre-transition metals (Groups 1, 2) together with Group 3, the lanthanides and the actinides in the +2 and +3 oxidation states form halides that are predominately ionic in character, whereas the non-metals and metals in high oxidation states ($\geq +3$) tend to form covalent molecular halides.” (Greenwood & Earnshaw 2002, p. 823)

The nonmetals are parsed into three well-known sets: halogen, metalloid,⁴ and noble gas. The remaining “left-over” nonmetals are referred to as “unclassified” nonmetals.

Some quotes illustrating the parallels between sets of metals and nonmetals follow:

The properties of the...elements vary tremendously, from the very active metals...to the very active nonmetals of Group VIIA (the halogens) (Henold & Walmsley, 1984, p. 346).

[Between the] “virulent and violent” [metals on the left of the periodic table, and the] “calm and contented” [metals to the right are the transition metals, which form] “a transitional bridge between the two” [extremes]; (Atkins 2001, pp. 24–25) “The elements change from... metalloids, to moderately active nonmetals, to very active nonmetals, and to a noble gas.” (Welcher 2001, p. 3-32).

...the gap between the two extremes is bridged ...by the poor metals, and...the metalloids – which, perhaps by the same token, might collectively be renamed the poor non-metals. (Dingle 2017, p. 101).

In place of the noble gases, the transition metal grouping has the noble metals (Wiberg 2001, p. 1133).

² Rayner-Canham (2020, pp. 90, 92) for example, refers to a set of nine *chemically weak metals*: beryllium, zinc, aluminum, gallium, lead, tin, antimony, bismuth, and polonium. At the other end of the spectrum he refers to the alkali metals as *supermetals*.

³ Silver has so much more reactivity than other noble metals, and such different chemistry, that it is not always considered as such (Rayner-Canham 2018, p. 205). I consider it to be an outlier among the noble metals in the same way that oxygen is the most reactive of the unclassified nonmetals.

⁴ It has been known for over 120 years that metalloids have a predominately nonmetallic chemistry (Newth 1894; Friend 1914).

The resulting typology integrates well with the recognition of representative elements (s- and p-blocks), transition elements (d-block), and inner-transition elements (f-block).

The dividing line between metals and nonmetals is placed according to the following rubric:

Nonmetals have a density of less than 7 gm/cm³ and electronegativity values of less than 1.9; all other elements are metals.⁵

I refer here to the elements in their most stable forms in ambient conditions.

Table 2 shows the resulting distribution of metals and nonmetals. The nonmetals are in the top right-hand quadrant.

1. Outliers

Instructors may choose to vary the membership of some marginal elements including the group 3 metals; aluminium; and silver and the group 12 metals. The group 3 metals, and aluminium due to its putative reactivity,

can alternatively be collocated with the s- and f-block metals in which case the resulting set could be referred to as the *active metals*. Silver may be excluded from the noble metals due to its higher reactivity and predominately main-group chemistry. It and the group 12 metals plus the p-block metals could be referred to as *post-transition metals*. The remaining d-block metals become *transition metals*.

Density	Electronegativity	
	< 1.9	≥ 1.9
< 7 gm/cm ³	Groups 1 and 2 Sc, Y, La Ce, Pr, Eu, Yb Ti, Zr, V; Al, Ga	Noble gases F, Cl, Br, I H, C, N, P, O, S, Se <i>B, Si, Ge, As, Sb, Te</i> [^]
> 7 gm/cm ³	Nd, Pm, Sm, Gd, Tb, Dy, Ho, Er, Tm, Lu; Ac–Es; Hf, Nb, Ta; Cr, Mn, Fe, Co, Zn, Cd, In, Tl, Pb	Ni, Mo, W, Tc, Re, Platinum group metals, Coinage metals, Hg; Sn, Bi, Po, At
[^] italicized elements are commonly recognized by some authors as metalloids; they can be distinguished as being the only nonmetallic elements (having a metallic appearance) that form amphoteric oxides.		

Table 2: Metals and nonmetals sorted by density and electronegativity⁶

⁵ I refer here to the elements in their most stable forms in ambient conditions.

⁶ (a) Up to element 99 (Es), with the values taken from Aylward and Findlay (2008, pp. 6–13; 126). Weighable amounts of the extremely radioactive elements At (element 85), Fr (87), and elements with an atomic number higher than Es (99), have not been prepared (Edelstein & Morris 2009, p. 123). The density values used for At and Fr are theoretical estimates (Arblaster JW 2018, p. 269; Lavrukina & Pozdnyakov 1970, p. 269). A survey of definitions of the term "heavy metal" reported density criteria ranging from above 3.5 g/cm³ to above 7 g/cm³ (Duffus 2002, p. 798). Vernon (2013) specified a minimum electronegativity of 1.9 for the metalloids, on the revised Pauling scale.

C. Correlation between reactivity and electronegativity

There is a good correspondence between the types of metals and nonmetals, and electronegativity, as seen in Table 3.

Type	Average EN	Electronegativity span								#
		< 1	1–1.5	1.5–2	2–2.5	2.5–3	3–3.5	3.5–4	> 4	
<i>Metals</i>										
s- and f-block	1.16	9.5	29.5	1						40
d-block	1.70		5.5	13.5	3					22
p-block	1.87			6.5	2.5					9
Noble	2.27			1	6	1				8
<i>Nonmetals</i>										
Metalloid	2.05			1	5					6
Unclassified	2.65				2	3	2			7
Halogen	3.19					2	1	1		4
Noble gases	3.39					3	1	0	2	6

Table 3: Types of metals and nonmetals, their average electronegativity values, and electronegativity distributions arbitrarily divided into 0.5 spans (for the first 102 elements).

A progression of increasing electronegativity values occurs among the types of metals and the types of nonmetals. Values for the noble gases are from Rahm, Zeng and Hoffmann (2019, p. 345).

Indeed, “as has been frequently assumed in practical use, the correlation between atomic reactivity and electronegativity is, if we avoid the... inert gas atoms, very strong.” (Nordholm 2021)

The appendix to this paper considers the symmetrical distribution of the average electronegativity values of each of the four types of metals and four of nonmetals.

D. The kissing cousins

In the periodic table the p-block metals and the metalloids lie to either side of the dividing line between the metals and nonmetals and for this reason appear to be somewhat neglected due to their less distinctive descriptive chemistry.

1. p-block metals

Physically, they are soft (Mohs hardness 1.5–2.75) and malleable (or brittle in the case of Ga and Bi), have poor mechanical strength, and usually have melting points lower than those of the transition metals. Their crystalline structures tend to show covalent or directional bonding effects, having generally greater complexity or fewer nearest neighbours than other metallic elements. All the p-block metals have the electronic structures of metals. They are all used, or have been trialled, as soft metal lubricants. Their low melting points make them suitable for soldering materials. When mixed with metals they form alloys.

Chemically, they are characterised—to varying degrees—by covalent bonding tendencies, basic or amphoteric oxides⁷ and the formation, in solution, of cations, hydroxocations, or cations and oxyanions. They can also form Zintl phases (half-metallic compounds formed between highly electropositive metals and moderately electronegative metals or metalloids). The oxides are ionic; some are glass formers ((Al, Ga, In, Tl, Sn, Pb); and those of Cd, Hg, In, Tl and Bi are predominately basic, with the remainder amphoteric. The lower chlorides⁸ are typically ionic, involatile, insoluble in organic solvents, and water-soluble; higher chlorides tend to be more covalent, volatile, soluble in organic solvents, and susceptible to hydrolysis.

2. Metalloids

Physically, they are metallic-looking, brittle (Mohs hardness 2–9), and have no structural uses. Their melting points are generally the highest among the nonmetallic elements. Valence electrons in their crystalline structures are less freely delocalized than is generally the case for metals; complete or considerable covalent bonding is present. Boron, silicon, germanium and tellurium are semiconductors; arsenic and antimony are semimetals. Their association with semiconductors, by themselves or as type III-V semiconductors (e.g. GaAs, AlSb or GaInAsSb), led to the misconception that metalloids were in-between elements.⁹ When mixed with metals they can form alloys.

Chemically, metalloids are characterised—to varying degrees—by covalent bonding tendencies, acid-base amphotericism and the formation, in solution, of oxyanions. “They are distinguished from typical nonmetals by always giving compounds less acidic in character than the corresponding compounds of the nonmetals” (Rochow 1966, p. 4). The oxides are polymeric, glass formers, and amphoteric.¹⁰ The chlorides are covalent and volatile; usually dissolve in organic solvents; and are partly or completely hydrolysed in water, some reversibly so.

3. Faux transition metals

A relatively recent development in chemistry involves certain compounds of heavier p-block elements, such as silicon, indium, phosphorus, germanium, arsenic, antimony, and bismuth exhibiting behaviours typically associated with transition metal complexes. This phenomenon is linked to a small energy gap between their filled and empty molecular orbitals, which are the regions in a molecule where electrons reside and where they can be available for chemical reactions. In such compounds, this closer energy alignment allows for unusual reactivity with small molecules like hydrogen, ammonia, and ethylene and carbon dioxide, a characteristic previously observed primarily in transition metal compounds. These reactions could open new avenues in catalytic applications, offering potential for innovative chemical processes. (Power 2010; Crow 2013; Weetman & Inoue 2018; Pavesi 2022).

⁷ In, Tl and Bi are predominately basic; the remainder are amphoteric

⁸ In(I), Tl(I), Sn(II), Pb(II), Po(II)

⁹ Pauling’s assessment of the nature of metalloids, in 1947, was misconceived. He said they were in the centre of his electronegativity scale, with electronegativity values close to 2. In fact, his scale ran from 0.7 to 4, giving a midpoint of 2.35, whereas the metalloids had values of 1.8 to 2.1

¹⁰ Being weakly acidic, B₂O₃ reacts with NaOH to form various borates; in its hydrated form (as H₃BO₃, boric acid) it reacts with sulfur trioxide, the anhydride of sulfuric acid, to form a bisulfate B(HSO₄)₃. As₂O₃, being weakly acidic, dissolves readily in alkaline solutions to give arsenites; it reacts as an anhydrous base with the acid anhydride SO₃, yielding arsenic(III) sulfate, As₂(SO₄)₃.

E. Unclassified nonmetals

While the properties of each of these seven nonmetals are thoroughly documented, their collectively shared physical and chemical properties have been regarded as being too diverse to bother. Consequently, they have sometimes been referred to as, for example, [mere] “nonmetals”; “miscellaneous nonmetals”; “orphan nonmetals”; or “other nonmetals”, as if consigned to a classification science junkyard or “too hard” basket.¹¹

As noted, the net result of this disaggregated approach was expressed by Zuckerman and Nachod (1977, preface)...

“The marvellous variety and infinite subtlety of the non-metallic elements, their compounds, structures and reactions, is not sufficiently acknowledged in the current teaching of chemistry.”

...and it is still relevant in the context of the unclassified nonmetals (and the metalloids).

An exploration of the shared properties of the unclassified nonmetals reveals a rich array of shared characteristics and facilitates a nuanced appreciation of this fascinating yet neglected part of the periodic table. Their shared properties may be summarised as:

1. small to intermediate atomic radii
2. moderate net non-metallic character
3. sub-metallic, coloured or colourless appearance; brittle comportment if solid; intermediate stoichiometry
4. catenation
5. covalent or polymeric compounds
6. interstitial or refractory compounds
7. organocatalysis
8. multiple vertical, horizontal and diagonal relationships
9. biogeochemical roles
10. luminescence
11. uses in explosives
12. uses in nerve agents
13. dualistic Jekyll (#9) and Hyde (#11, 12) behaviours, including being unified by their shared attributes despite their diverse individual natures

Further information is set out in the Electronic Supplementary Material.

¹¹ The unclassified nonmetals could be referred to as the “SeSPONCH” nonmetals given their involvement in biogeochemistry and the prevailing view that sea sponges were possibly the first to branch off the evolutionary tree from the last common ancestor of all animals. This would make them the sister group of all other animals (Feuda R et al. 2017). The acronym SeSPONCH follows reverse atomic number order.

F. Correlation with machine learning

A machine-based analysis of the proximity of names of the elements based on 3.3 million abstracts published between 1922 and 2018 in more than 1,000 journals was conducted in 2019 (Tshitoyan et al.). It revealed a topology (Fig. 1) reminiscent of the eight-fold classification.

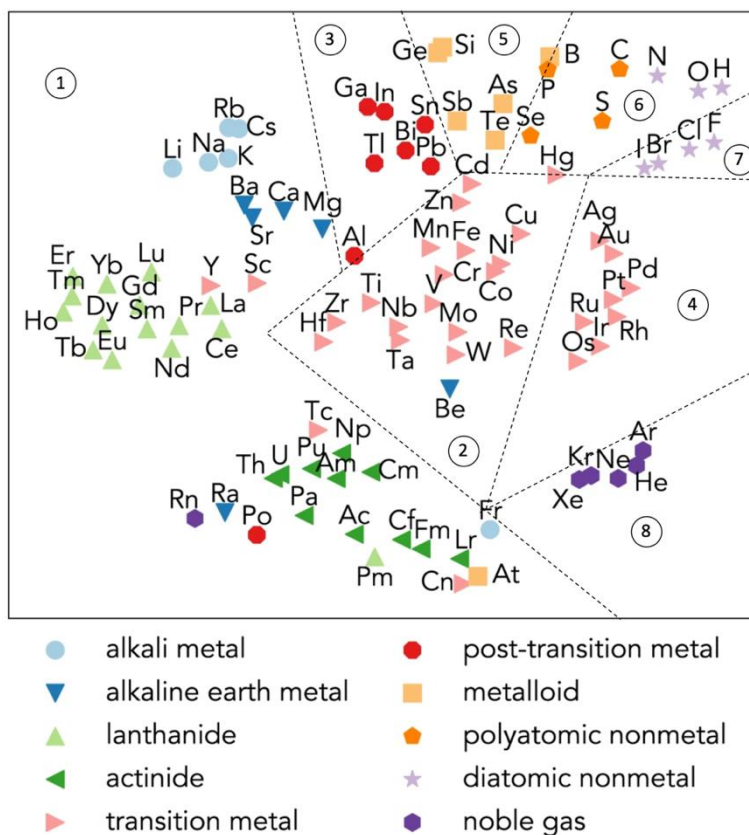
Fig. 1 is a two-dimensional projection of the word embeddings of 100 chemical element names (for example, ‘hydrogen’) labelled with the corresponding element symbols and clustered (upper legend) according to a tenfold classification. Here the noble metals are treated as transition metals, which they are, rather than being specifically identified.

The lower legend distributes the same elements according to an eightfold classification.

Chemically similar elements are seen to cluster together. Due to their radioactivity, radon, radium and polonium are found in closer proximity to uranium and thorium in the plot than to their neighbours in the periodic table.

Some elements are out of place for non-physical reasons. Their symbols overlap with common words that have the same spelling, such as “be” for beryllium, “at” for astatine, and “Tc” for technetium which is also used to denote critical temperatures.

The d-block metals scandium and yttrium appear collocated with the 4f-metals, as is the general practice in the literature, since their chemistry is regarded as bearing a closer resemblance to the latter. They are nevertheless highly reactive elements regardless of whether they are treated as d-block metals or together with the 4f-metals.



1 s- and f-block metals	5 Metalloid nonmetals
2 d-block metals	6 Unclassified nonmetals
3 p-block metals	7 Halogen nonmetals
4 Noble metals	8 Noble gases

Figure 1: Proximity map of the names of elements, with two legends (upper, lower)

G. Some additional philosophical considerations

1. Didactic utility. In my 2020 article I mentioned the didactic utility of organizing the metals and nonmetals in terms of the use of tradition; analogy; descriptive chemistry; systematics; symmetry; contrast; and aspects of learning theory.

By first explaining the conventional dichotomy of metals and nonmetals, or as a trichotomy that adds metalloids as an intermediary class, the stage is set for a more refined classification. Parsing the elements into four complementary sets allows for a prelude to group-by-group chemistry that better recognizes the continuity and gradations inherent in nature. This reflects a philosophical stance that recognizes a spectrum of properties in the natural world.

Kinsey (1937, p. 174) commented that one of the objectives of taxonomy (in biology) was:

To present the scientific method through a system of classification. Science has been defined as systematized knowledge, and a biologic classification, dealing as it does with an inconceivable number of items, beautifully illustrates the meaning and convenience of systematized facts. There is a beauty in a complete and yet simple classification which even the beginning student can be led to see.

While the field of study is different the principle applies just as well to the periodic table.

2. The significance of the number eight and dimensionality. The number eight holds a special place in the structure of the periodic table, reflecting deeper principles about the nature of our universe. Theoretical astrophysicist and cosmologist Vincent Icke (Icke 1995, p. 158) articulated this connection, stating:

In the periodic table of the elements, this regularity shows up as the famous “period eight”: chemical elements can be arranged in eight columns, in each of which elements with comparable chemical properties are grouped together. The number eight follows directly from the rotational symmetry in three-dimensional space. In other dimensions that number would be different. If we did not know that we live in three-space, we would be able to deduce that fact from the eightfold period in the table of the elements

This notion is echoed by Spielberg and Anderson (1987, p. 298), who observed that the structure of atomic theory, particularly the four quantum numbers associated with an electron, is intrinsically linked to the dimensions of space-time. They wrote: “It becomes quite clear why there are four quantum numbers associated with an electron: boundary conditions and mathematical symmetries must be associated with the four dimensions of space-time.” This insight underlines the fundamental relationship between the physical laws of the universe and the organizational structure of the elements.

The significance of the number eight extends beyond the periodic table, finding parallels in the field of particle physics. In 1961, Murray Gell-Mann, an American physicist, and Yuval Ne'eman, an Israeli physicist, proposed the Eightfold Way classification of subatomic particles. This system organizes particles into groups of 1, 8 (most frequently), 10, or 27. One of the early achievements of this classification was the prediction and subsequent 1964 discovery of the omega-minus particle, necessary to complete one of the octets. This success led Gell-Mann to propose the concept of quarks, laying the foundation for the modern quark model of hadrons.

The arrangement of elements into four sets of metals and nonmetals, while a practical method for understanding physical and chemical properties, also inadvertently aligns with this deeper, dimensional symmetry. This alignment invites a philosophical exploration of how scientific models and classifications, even when developed for pragmatic purposes, can inadvertently reveal fundamental truths about the universe.

Icke's observation encourages a contemplation of the interconnectedness between various fields of science – from the abstract realms of theoretical physics to the more tangible domain of chemistry – and how they collectively contribute to a unified understanding of the natural world.

3. Historical development of scientific thought. Reflecting on how classifications have changed over time can offers insight into the historical development of scientific thought and the evolution of concepts in chemistry.

Humans naturally classify and simplify complex information for better understanding and practical use.

In many primitive languages, the term for 'eight' is often derived as 'twice four.' This suggests that in the proto-Indo-European language, spoken from around 4,500 to 2,500 BCE, the concept of an independent numeral for eight might not have existed initially. Once 'four' was doubled to form 'eight,' there would be a need for introducing another numeral to continue the count.

Likewise, in many Indo-European languages, there is a notable resemblance between the words for 'nine' and 'new.' Examples include Sanskrit (*nava* and *navas*), Latin (*novem* and *novus*), Gothic (*niun* and *niujis*), and Tokharian (*nu* for both). While this parallel is not definitive proof, it suggests a linguistic pattern.

The choice of stopping the count at four could be due to two factors. Firstly, the human hand consists of four fingers, excluding the thumb. In this context, the thumb was possibly not considered a 'finger' like the others. Secondly, a handsbreadth measurement, excluding the thumb, was a common unit in many ancient civilizations. For instance, the Greek and Egyptian *ell* was comprised of six handsbreadths, each with four fingers, totalling 24 fingers. Similarly, the Roman foot, or *pes*, was divided into four *palmae*, each of four *digiti*. This historical use of the hand as a measurement tool could explain the emphasis on the number four in early counting systems.¹²

¹² Flegg G 1989, *Numbers Through the Ages*, MacMillan, Basingstoke, pp. 60–61

A subsequent preference for quartets, or four-part divisions, in various classification systems may further reflect a cognitive tendency to find balance and comprehensibility in the number four. This tendency is evident in various cultural, philosophical, and scientific contexts. For example, in (Western) philosophy there are the classical elements (earth, water, air, fire); in biology, the four bases of DNA (adenine, cytosine, guanine, thymine); and in proto-psychology, the four temperaments. These examples illustrate how quartets bring structure and understanding to complex systems.

Antoine Lavoisier, celebrated as the father of modern chemistry, made a seminal contribution in 1789 with a fourfold classification of simple substances (Lavoisier 1789, p. 192). He divided substances into gases, nonmetals, metals, and earths (infusible oxides), departing from alchemical traditions and marking a significant stride towards systematic and rational chemical understanding. He further mentioned a distinction between metals of differing fusibility (Lavoisier 1789, pp. 116–117). Combined with a general awareness at that time of a distinction between noble metals and base metals, Lavoisier’s work would prove to be backwards compatible with ensuing developments.

In 1807 the kernel of a fourfold classification of metals emerged with Davy’s isolation of sodium and potassium, challenging the notion that metals were exclusively ponderous substances. The “heavy” metals were thus accompanied by light metals, with the noble metals having been already been historically acknowledged as a distinct type.

Subsequently, Berzelius (1831, p. 222) arranged the metals in four classes: the alkali metals, alkaline earth metals, earth metals, and heavy metals. The last of these were divided by him into noble metals and common metals. He noted the varying fusibility of metals but made no typological use of it.

Gmelin (1849, p. 2) recognised four types of metals:

Designation	Generally corresponding to
Light	More electropositive group 1–3 metals including the lanthanides
Heavy, high-melting	Transition metals
Heavy, low-melting	More electronegative post-transition metals
Noble metals	Noble metals

There were advantages to distinguishing light and heavy metals; for instance, light metals tended to more basic than heavier metals.

In alignment with Gmelin’s typology, including between electropositive and electronegative metals, Hinrichs (1871, pp. 58–59; 1894, p. 233) wrote that, “The leading physical property of the elements, next to density, is their deportment toward heat.”

The taxonomy of Dobbin and Walker (1892, pp. 227, 233, 246) represented an interesting hiccup in classification science. Their taxonomy was: light metals; rare metals of the earths; and “metallurgical” elements i.e. the heavy metals. The noble metals were not mentioned aside from noting that elements such as gold and platinum did not combine with oxygen, at all.

They were not satisfied with Mendeleev’s layout, in which Mn was aligned with F, since such arrangement, “scarcely agrees so well with the general chemical nature of the elements as the one which we have here adopted.” (op. cit. p. 226) Nor were they satisfied with their own table in which Li and Na were in the same group as Cu, Ag, and Au.

However, they added that:

[Such] irregularities ... do not impair the great theoretical significance of the periodic classification, although for practical purposes the elements have often been subject to a different arrangement.” (op. cit. p. 236)

What Dobbin and Walker said about different arrangements of the elements is pertinent: there is nothing in this paper ostensibly claiming the inherent superiority of its four-fold classification. Approaches to classification can vary depending on the perspective of relevance at the time.

Additional four-fold metal taxonomies of metals were subsequently developed by various authors:

**Guertler¹³
(1921)**

- light metals (groups 1–2, RE)
- difficultly fusible (groups 4–6)
- transition and noble metals
- low melting point metals (groups 12–15)

**Van Wert
(1936, p. 17)**

- strongly electropositive, including light metals (Groups 1 to 3, Ln)
- high-melting heavy metals (≡ transition metals)¹⁴
- low-melting heavy metals (≡ post-transition metals)

[^] Van Wert separately mentioned the noble metals (1936, pp. 27, 38, 183)

**Scott and Kanda
(1962, pp 385–387)**

- very active metals
- ferrous metals
- noble metals
- soft metals (excl. very active metals)

From Lavoisier in 1789 to Scott and Kanda in 1962, the classification of metallic elements has reflected changes in scientific thinking. Fittingly, in a cross-discipline fashion, the latter two authors noted that metals in a given class were closely related chemically, electronically, and in the physical characteristics that gave rise to their use in particular alloys (loc. cit.). The relationships within these classes has thus extended to ultimately influencing their utility in various technologies.

* * *

In 1844, a four-fold taxonomy of nonmetals was set out by Alphonse Dupasquier, a French doctor, pharmacist and chemist, as follows:

Organogens O, N, H, C
Sulphuroids S, Se, P
Chloroides F, Cl, Br, I
Boroids B, Si.

¹³ The taxonomy of Guertler (loc. cit.) is that summarized by A.R.P. (1921, p. 547).

¹⁴ The high-melting heavy metals were further divided into those that were brittle (Ti, V, Vr, Mn, Zr and Nb); and those that were ductile (Van Wert 1936, p. 16)

This approach represented a significant departure from other contemporary classifications, since it grouped together oxygen, nitrogen, hydrogen, and carbon, (Hoefler 1845, p. 85). Dupasquier's taxonomy was commended for its natural basis, contrasting it with the artificial systems of that period (Bertomeu-Sánchez et al. 2002, p. 249).¹⁵

It is further notable for the fact that, a quarter of a century before Mendeleev published his first periodic table, it laid the foundations for some subsequent developments in the classification science of nonmetals, as follows:

- the boroid nonmetals came to expand into the metalloids, starting from as early as 1864; and
- varying configurations of the organogen and the sulphuroid nonmetals have been referred to as, for example, basic nonmetals; biogens; central nonmetals; CHNOPS; essential elements; “nonmetals”; orphan nonmetals; or redox nonmetals; they are referred to in this article as *unclassified nonmetals*.

(Of course, the chloroide nonmetals came to be independently referred to as halogens; and the noble gases, the first of which were not discovered until 1868, were counted among the nonmetals from as early as 1900.)

However, the work of Dumas (1828; and again in 1859), which classified nonmetals in a manner emphasizing their family relationships, introduced a focus on vertical groupings that would become a feature of Mendeleev's table. Dumas classified the nonmetals into families, as follows: 1. Hydrogen; 2. Fluorine to iodine; oxygen to sulfur; 4. Nitrogen to arsenic; 5. Carbon, boron and silicon. In the context of Dumas's typology, Mellor (1922, p. 251) curiously added that, “hydrogen was supposed to be a metal.”

This emphasis on verticality, while advancing our understanding of group behaviours, had a significant downside. It inadvertently obscured the rich cross-cutting relationships among the metalloids and among the unclassified nonmetals. This resulted in the ongoing confusion in delineating metals from nonmetals, and the classification science wilderness of the unclassified nonmetals.

Curiously, popular science books not infrequently feature periodic tables colour-coded to highlight: metalloids; other nonmetals; halogens; and noble gases (e.g. *How Science Works* 2018, pp. 34–35). By prioritizing engagement and accessibility, these works—usually dismissed by academics for their perceived superficiality—have inadvertently uncovered a piece of “lost history” or “buried treasure” in classification science that offers potentially valuable insights into the broader relationships and distinctions among nonmetals. I say “potentially” since the accompanying text in such books noting the nature of the “other nonmetals” is invariably superficial.

¹⁵ A natural classification was based on “all the characters of the substances to be classified as opposed to the ‘artificial classifications’ based on one single character” such as the affinity of metals for oxygen. “A natural classification in chemistry would consider the most numerous and most essential analogies.” (Bertomeu-Sánchez et al. 2002, p. 236)

H. Conclusion

The eightfold typology offers a more systematic framework than the traditional educational practice of focusing on elemental dichotomies or trichotomies followed by group-by-group chemistry. It bridges the gap between the conventional teaching approach and a more holistic view of the periodic table that enhances understanding of chemical properties.

Reflecting on its philosophical significance, there is an inadvertent alignment with broader principles of natural science and the inherent structure of the universe. Vincent Icke's insights on the number eight, relating to the dimensional symmetry of space, exemplify how such classifications can reveal deeper truths about the world we live in. This connection extends beyond chemistry, finding resonance in fields like particle physics, as shown by the Eightfold Way classification of subatomic particles. Similarly, Spielberg and Anderson's discussion of the four quantum numbers associated with an electron further underlines the significance of space-time dimensions in scientific classification systems, providing another layer of depth to our understanding of elemental structure.

Historical perspectives on element classification further enrich our understanding, demonstrating the evolving nature of scientific thought. The precedents set by Lavoisier's four-fold classification, Hinrichs' metal characterisations and Alphonse Dupasquier's taxonomy of nonmetals underscore continuity and progression in the scientific quest to systematize the natural world. These examples provide context to the current classification scheme and highlight its place in the ongoing journey of scientific discovery.

A typology of four pairs of metals and nonmetals serves not only as a practical approach to characterizing elements but also invites philosophical contemplation and interdisciplinary exploration. This classification thus stands as a marker in the narrative of scientific knowledge, encouraging a deeper appreciation of the interconnectedness and potential complexity inherent in the study of the elements.

The periodic table is not just about horizontal, vertical and diagonal patterns; parallels between sets of elements, or individual elements, add to the repertoires of chemists, chemistry educators, and their students.

Appendix: The symmetry of electronegativity

There is a balanced and regular distribution of the electronegativity differences between the four paired sets of metals and nonmetals (Fig. 2).

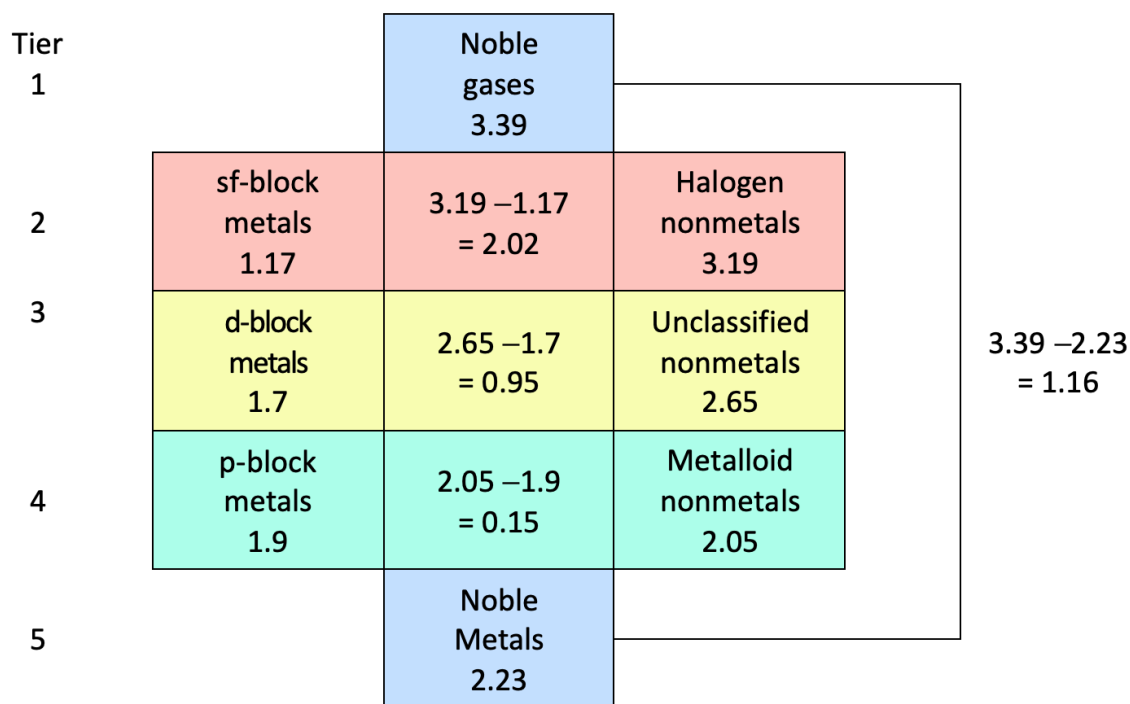


Figure 2 Wedding cake framework of metal and non-metal types showing average electronegativity values, differences within each tier, and between tiers 1 and 5

The wedding cake framework has five tiers. Tier 1 has only the noble gases. Tier 2 has the sf-block metals and the halogen nonmetals, their average electronegativity values and the difference between the averages. Tier 3 has the d-block metals and the unclassified nonmetals; tier 4 has the p-block metals and metalloid nonmetals. Tier 5 has the noble metals. The difference between the average electronegativity values for the noble gases and the noble metals is shown to the right of tier 3.

The noble metals (tier 1) and the noble gases (tier 5) are largely reluctant players, being disinclined to react with other elements.

In tier 2, the sf-block metals and halogen nonmetals are reactive exemplars, albeit diametrically opposed in their mechanism of action. That said, the s-block metals sodium, potassium, rubidium, cesium, and barium can form anions of the form X_n^- ($n = 1$, except $Ba = 2$) as can the halogen nonmetals chlorine, bromine and iodine form isolable cations: Cl_3^+ , Br_2^+ , Br_3^+ , BrI_5^+ , and I_2^+ , I_3^+ , I_4^{+2} , I_5^+ , I_7^+ and I_{15}^{+3} .

In tier 3, the d-block metals represent a “transition” from the sf-block metals to their right and the p-block metals to the left, just as the unclassified nonmetals occupy a changeover zone between the weakly nonmetallic metalloids to their left and the halogen nonmetals to the right. The d-block metals are known for their catalytic properties; the unclassified nonmetals are known for their uses in explosives.

In tier 4, the chemically weak p-block metals and their counterparts, the weakly nonmetallic metalloids, share a proclivity for amphoteric behavior (as does beryllium, being adjacent to the s-block metals). The line between the p-block metals and the metalloids can meander, with polonium and astatine sometimes counted as metalloid nonmetals, and germanium, and antimony sometimes regarded as p-block metals.

An elucidation of some further electronegativity-based features of the framework follows.

Horizontal balance. The middle three tiers show average electronegativity differences of approximately 2, 1, and 0. This sequence suggests a gradation or a descending trend from higher to lower differences. The value of 2 (tier 2) at one end and 0 (tier 4) at the other, with 1 (tier 3) in between, creates a kind of balanced sequence. The average of the extremes (2 and 0) is 1, which coincidentally matches the middle value.

Vertical balance. The difference in average electronegativity values between the top (tier 1) and bottom (tier 5) is also around 1.

Intersecting averages. The fact that the horizontal average of the middle tiers (2, 1, 0) intersects with the vertical average of the extreme tiers (1 and 5) at around 1 adds an additional layer of perceived balance or symmetry to the framework.

Integration of properties. On electronegativity, Leach (2013) observed that:

There are such strong correlations between numerous atomic parameters, physical and chemical, that the term “electronegativity” has the effect of integrating them into a single dimensionless number between 0.78 and 4.00. Consequently, the electronegativity of an element can be used to predict/describe/model much of its empirical physical character and chemical behaviour.¹⁶

Natural system basis. Earlier, Jensen (1986) had suggested, with some caution, that any significant typology of the elements had to be based on a “natural system” of some sort, that is, it should arise naturally or spontaneously from a study of the elements’ properties rather than being based on some artificial or arbitrarily selected criterion or theoretical preconception.¹⁷

The fact that the electronegativity values in the framework correlate with multiple properties and appear in symmetry-related positions without prior imposition suggests that the typology is arising spontaneously and naturally. That the metal typology is based on electronic block membership is further confirmation of a natural basis.

Relevance. The framework’s relevance lies in its ability to visually and conceptually represent periodic trends and relationships in a structured manner. It allows for an intuitive understanding of how various types of elements relate to each other in terms of their electronegativity, and by extension, their chemical and physical properties.

Extra pairings. There are four other pair differences, two vertical and two diagonal:

- sf-block metals and p-block metals = 0.73
- halogen nonmetals and metalloid nonmetals = 1.14
- sf-block metals and metalloid nonmetals = 0.88
- halogen nonmetals and p-block metals = 1.29

Here, $0.73 + 1.14 + 0.88 + 1.29 = 4.04/4 = 1.01$.

The average of these four additional pair differences is 1.01, a value remarkably close to the previously observed averages in the main body of the framework. So, there are eight pairs in total.

This additional consistency reinforces the idea of a coherent and balanced structure within the periodic table, as represented by the eight-fold typology of metals and nonmetals.

¹⁶ Leach M 2013, Concerning electronegativity as a basic elemental property and why the Periodic table is usually represented in its medium form, *Foundations of Chemistry*, vol. 15, no. 1, pp. 13–29

¹⁷ Jensen WB 1986, Classification, symmetry, and the periodic table, *Computers & Mathematics with Applications*, vol. 12B (1–2), pp. 487–510 (496)

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