WHAT ARE THE MOLECULES DOING?

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ABSTRACT

Johnstone's identification of teaching and learning difficulties derived from the three levels of description in chemistry is well-known and much debated, but effective responses are still needed. It is suggested that a macro-micro dictionary could help. The dictionary concept is exemplified and its potential value in dealing with the difficulties associated with two of the levels explained. *[African Journal of Chemical Education—AJCE 6(2), July 2016]*

INTRODUCTION

Over some 250 years, scientists in general, and chemists in particular, developed a descriptive language for all the phenomena they observed. Much of this language remains in use today, sometimes with amended meanings. Over this same period the atomic-molecular interpretation of phenomena grew rapidly in range and strength, so that by present times it is integral with almost every scientist's work. A language has been developed to articulate atomic-molecular interpretations, some of this being new and some "appropriated" from the older language related to observed phenomena. Parallel streams of development, related to symbols used, can also be seen.

Johnstone [1] drew attention to the three different ways in which we communicate and understand science concepts: in essence these are macroscopic (phenomena), microscopic (or sub-microscopic) (atomic-molecular interpretation) and symbolic (relating to both the previous two). Importantly, he emphasized the difficulties for teaching and learning that can be traced to the co-existence of these three ways. These difficulties are aggravated by the failure of many teachers, lecturers, authors to distinguish whether they refer to phenomena or their atomic-molecular interpretation. The language of the description of phenomena (macroscopic) is mixed with the language of interpretation (microscopic) and symbols are used indiscriminately, thus ensuring an incomprehensible communication [2]. Dictionaries of chemistry are generally unhelpful in this regard. Even textbooks of chemistry that provide glossaries generally fail therein to provide definitions that cover the macro-, the micro- and the symbolic aspects of a concept.

It is generally accepted that the meaning of words changes over time and this can cause difficulties of understanding. However, here we are dealing with something different: two languages have grown up over the years and become intertwined in common usage. The result is not just a quaint vocabulary reflecting the history of the discipline, but a commonly used language of teaching and learning that is misleading, confusing and at odds with the basic distinction between observation and interpretation (or the reality and the model). The problem of scientific language literacy identified by Woldeamanuel, Atagana and Engida [3], may be one expression of the consequences.

TOWARDS A MACRO-MICRO DICTIONARY

Although the above teaching and learning problems have been recognized for several years, and approaches to dealing with them advocated [4], [5], [6], [7], [8] there is not much sign that the problems are being taken seriously beyond the confines of research articles. In this paper we start the development of a "macro-micro dictionary" which aims to clarify and guide teachers and learners. The approach is to select a descriptive term for some observable phenomenon, give a brief statement about the phenomenon (the macro description), and then address the micro question – what are the molecules doing? The level of discussion is intended to be suited to those teaching chemistry at the secondary and tertiary levels and should be read with this purpose in mind. It is hoped that by studying the examples included in this paper, the potential of such a dictionary can be assessed.

As a preliminary we should make clear that all entities consisting of two or more atoms are called molecules in our usage [9]. Since free single atoms are comparatively rarely met with, the omission of atoms from the question seems appropriate.

Gases

One of the states of matter is the usually invisible gaseous state. When the gas is coloured we can see it is there, but otherwise we have to rely upon inference (eg trying to compress air in a syringe). It is a state of matter where the substance fills all available space and has no shape or size of its own. It can expand and contract in response to temperature changes and we might say is the "softest" of all the states of matter. Nevertheless a gas exerts pressure and we can feel this when we try to compress air in a syringe.

What are the molecules doing?

Under the right conditions a collection of molecules may be a gas. The molecules are however not gases and they are not colored! The molecules are moving all the time and very fast, colliding with each other and with the walls of a container. Under typical conditions there is a lot of free space in a gas, and molecules actually occupy only a rather small fraction of the total volume of a gas held in a container. In a sample of gas, the molecules do not all travel at the same speed, and the speeds change as a result of collisions. However the total kinetic energy of a collection of molecules is constant as long as the temperature is constant. Increasing the temperature, increases the total kinetic energy of the collection of molecules; indeed the average kinetic energy is proportional to the temperature.

The pressure exerted by a gas results from the billions of collisions per second with the container walls.

Molecules in a gas are usually small, that is they usually have rather few atoms per molecule. Furthermore, the forces between the molecules (intermolecular forces) are comparatively weak. Hence when they collide they usually do not "stick" to one another.

Liquids

Liquids are another state of matter. They are visible and so we see their behavior directly. They flow and conform to the shape of a container, but they do not fill all available space. Although they do expand and contract in response to temperature increase and decrease, the volume change is small. Similarly, although they do flow they are not as “soft” as gases: falling into a swimming pool full of water can be painful!

What are the molecules doing?

The molecules are not liquids, or even bits of liquids and we do not see them; under the right conditions a collection of molecules may be a liquid. The molecules are moving all the time, but there is very little free space. Any one molecule is in contact with several other molecules at all times. Nevertheless, the molecules move around, slipping into holes or gaps in the surrounding crowd of molecules. Although the movements are short it does not mean the molecules have little kinetic energy. As with gases, the average kinetic energy is proportional to the temperature.

Molecules in a liquid may (but do not have to) be much larger than one finds in a gas. There may be scores of atoms per molecule. The forces between the molecules may (but do not have to) be distinctly larger than is found between molecules of a gas. Collisions between molecules of a liquid are continuous and the molecules “stick” to one another. However the “stickiness” is not so strong that a molecule stays with the same neighbors all the time!

Solids

Solids are the most prevalent of all the states of matter. Like liquids they are visible and we can see their behaviour directly. They do not flow or change their shape to fit a container. (Note: A powder is a made of tiny bits of solid, and may flow and change its shape. In this case we are describing the behaviour of a sample containing very many tiny bits of solid. The tiny bits of solid do not flow or change shape.) Solids are generally the densest state of matter; furthermore, temperature changes cause only small changes to the volume of a solid. They are the “hardest” of the states of matter, but the range of hardness is large – that is, there are some solids which are soft (eg wax) and some that are very hard indeed (eg diamond).

A solid has a definite shape and sometimes this can be very regular. Usually these solids with regular shapes are called crystals. Solids which have no regularity about their shape (eg glass) are usually said to be amorphous solids.

What are the molecules doing?

The molecules are not solid! However the molecules that constitute a solid may (but do not have to) be very large and have a very large number of atoms per molecule. Indeed with a perfect crystal (eg a flawless diamond) one may say that we have a single molecule made of billions of atoms of carbon. Such a molecule may be termed a giant molecule and we can see it! In general however, a solid is made of many molecules and these do not move from place to place. They are held quite tightly by neighbouring molecules and the intermolecular forces are quite strong. The molecules may however be able to rotate on the spot if they are sufficiently ball-shaped. They can also vibrate back-and-forth within the very limited space that neighbouring molecules allow. Here also the limits to the movement do not mean the kinetic energy is small; the average kinetic energy is determined by the temperature. A perfectly regular packing of molecules gives rise to a crystal.

Boiling

Boiling is the term we use to describe the change of a liquid to a gas when the vapor pressure of the liquid equals the ambient pressure. Evaporation also refers to the change of a liquid to a gas, but the vapour pressure of the liquid is less than the ambient pressure. The change of state is not due to the addition of some other substance; it happens to a substance when its temperature reaches a specific value (boiling point) at the ambient pressure.

What are the molecules doing?

They are not boiling! Molecules are leaving the liquid phase and entering the gas phase. They are escaping from the attractive forces that cause molecules to cling to each other, and they become free of such forces as they enter the gas phase. The same is true of evaporation.

Melting

Melting is the change of a solid substance to a liquid substance. This change is not due to the presence of another substance (as might happen in dissolving), but to the temperature. Melting takes place at the melting point of the pure substance, which is one of its characteristic properties. It is only slightly affected by the ambient pressure.

What are the molecules doing?

They are not melting! What they are doing depends on what kind of molecules constitute the solid. If the solid comprises relatively small molecules packed together in a regular fashion, then melting involves the molecules in loosening themselves from the constraints of neighbouring molecules, overcoming some of the intermolecular forces, and moving around – but still always in contact with several molecules. By contrast if the solid comprises an infinite network of atoms and bonds, that is a giant molecule, melting requires break up of the molecule. Bonds must be broken in order that smaller molecules form which are sufficiently mobile to constitute a liquid. Generally-speaking, melting due to this kind of molecular break up, requires much more energy than the simple freeing up of already-existing smaller molecules: this implies a high melting point (eg diamond melts above 3 500 C).

Chemical Reaction

Chemical reaction (or reaction) is the term used for the change in the composition of a substance brought about either by some other substance or by supplying energy (thermal, electrical, radiant), or both. The original substance (or substances) is/are termed reactants and the new substance(s) is/are termed products. Reactions are classified in many different ways based upon the experimental procedure, source of energy, nature of composition change, etc.

What are the molecules doing?

Molecules are changing their structure and/or composition in a process that involves bond breaking and/or making. It is usually both. Often the overall change takes place by a set of steps, each one of which is very simple. Reaction only happens when molecules collide with other molecules or with other particles such as photons of radiation.

Are the molecules reacting? Perhaps! Bond changing might be a better term. Taber has suggested quantacting [10].

Acid

Acid is the term used for a class of substances that change the colour of indicators, have a sour taste, neutralize alkalis, cause formation of hydrogen from metals and carbon dioxide from carbonates. Acids may be strong or weak.

What are the molecules doing?

The molecules are not acids! The molecules have at least one H atom in their composition, and in aqueous solution the molecules (say HA) dissociate into a hydrogen ion, H+ (aq) and an anion, A-(aq). This is a chemical reaction since bond breaking is involved. This dissociation may be complete or partial; the former case arises with strong acids and the latter case with weak acids. Reactions of acids often involve the hydrogen ions formed by dissociation of the molecules, rather than the molecules themselves.

The term dissociation is a general term that is used to describe molecular break-up into smaller entities. It can be made more specific to acids perhaps by saying acid dissociation. Substances do not dissociate; molecules do.

Acid-base indicator

Acid-base indicators (often abbreviated to indicators) are substances that change colour when in solution with acids and/or bases. The colour change is reversible indefinitely. Different indicators show different colour changes and change their colours at different concentrations of acid or base.

What are the molecules doing?

The color of substances results from the absorption of selected components of white light by the collection of molecules constituting a visible sample of the substance. The molecules are however not coloured. Indicator molecules change their structure and composition when exposed to acids or bases, because they react with them. When they change their structure and composition they change their ability to absorb light. Thus a molecule that absorbs the red component of white light might change to absorbing blue light when reacting with an acid in solution. Adding some base to this solution reverses the changes to the molecular structure of the indicator and hence reverses the color change.

Dissolving

Dissolving (also dissolution) is the term used for a process in which two different substances form a homogeneous mixture (known as a solution). The term is also applied to cases where the formation of a solution is accompanied by formation of a gas that is not part of the solution (eg metals are often said to dissolve in acids, but this is accompanied by the formation of hydrogen).

What are the molecules doing?

The molecules are not dissolving! What they are doing depends on the kinds of substances involved. In some cases (eg sugar + water), the two types of molecules mix uniformly. They intermingle and do not change their composition. In other cases there is a chemical reaction (eg salt + water, or metal + acid) and the molecules change their composition.

Precipitation

Precipitation is a general term for formation of a heterogeneous mixture from a homogeneous one. This may arise from a temperature change or from a reaction.

What are the molecules doing?

The molecules are not precipitating! Usually precipitation due to temperature change takes place due to temperature decrease. This is what we see when clouds form in the sky or there is rain. Molecules of water in the air stick together on collision and when thousands of them do this we see a droplet of liquid water. There is no chemical reaction.

Chemical reaction may however be the cause of precipitation. Most commonly we see this when two aqueous solutions are mixed and a solid forms. This usually sinks to the bottom of the mixture because (as noted previously) solids are generally of greater density than liquids.

Exothermic Change

When substances change, energy also changes. This is true of boiling and also of reaction. If energy is transferred from the substance(s) to the surroundings we call it an exothermic change. (The opposite is an endothermic change.) Of all the myriad events happening within us and around us all the time, exothermic ones are the most common.

What are the molecules doing?

When molecules change their environment or change their composition, there are energy changes. Changing environment may refer to a change of state (eg as when clouds and rain form in the atmosphere). The sticking together of molecules through intermolecular forces, lowers the potential energy of the molecules and the energy released is transferred to the environment (initially via the kinetic energy of neighboring molecules). Changing the composition of molecules occurs when there is a chemical reaction. Bond-breaking and forming takes place, with stronger bonds on average being the result. This too implies the potential energy of the product molecules is lower than the potential energy of the reactant molecules and the energy released is transferred to the surroundings (again via the intermediacy of the kinetic energy of neighboring molecules).

In summary an exothermic change is one in which either the strength of the intermolecular forces increases or the strengths of bonds in the molecules increase. Both of these lower the potential energy of the molecules, the bond changes usually resulting in a quantitatively greater energy lowering.

Oxidation

Oxidation is one category of chemical reaction. Actually it is only half a reaction, because oxidation is always accompanied by reduction. One cannot occur without the other. Originally the term may have been applied only to reaction of a substance with oxygen. In such a case the substance was oxidized whilst the oxygen was reduced (often to water and/or carbon dioxide). The use of the term was then extended to analogous reactions involving chlorine (although an alternative term would then be chlorination) and to the loss of hydrogen (also called dehydrogenation). As a generalization it may be said that oxidation-reduction reactions involve bigger energy changes than other types of reaction. Combustion of fuels would exemplify the large energy changes accompanying such reactions.

What are the molecules doing?

The molecules of the reactants are colliding and undergoing bond changes. This is characteristic of a chemical reaction. The particular features of an oxidation-reduction reaction are that as the bonds change the electron density around some atoms increases significantly whilst around other atoms it decreases significantly. In some cases this involves outright electron transfer whilst in others it is a partial electron transfer. Electrons tend to move towards the more electronegative atom – this sort of atom is found in the oxidant molecule. The concept of oxidation state is used in describing such changes. The reality of the electron shifts is evident in the electrochemical cell where the oxidant and reductant are physically separated from one another. Electron transfer takes place via an external circuit rather than in the direct collision of molecules.

Elements (chemical elements)

Elements (or elementary substances) were first clearly defined by Lavoisier (1789) who described them as the simplest of substances that cannot be broken down into any simpler substances. His definition is often said to be an operational definition – which means it implies a method for finding out whether a substance is an element or not. “Breaking down” meant using thermal, radiative or electrical methods (energy inputs!). The definition is maintained today although there are more sophisticated methods of identifying elements now. Despite the passage of time, there are still only slightly more than 100 elements known. Allotropes of some elements are known and they may have markedly different properties.

<u>What are the molecules doing?</u>

The molecules are not elements! Molecules of elements are the simplest of molecules, but only in the sense that they are made from just one type of atom. In other respects the molecules may not be so simple. Aside from the few cases (Noble Gases) where single atoms occur (eg Ar), the molecules may be simple and diatomic (eg O_2) or polyatomic and complex (eg P_4 , S_8 , C_n , Fe_n). In addition the molecules of one element may be found in different shapes and sizes (eg O_3 and O_2 , and C_{60} and C_n). Amongst the molecular formulae given as examples are ones with a subscript "n". This implies that the number of atoms per molecule is not fixed: the molecules have an extensive network of atoms bonded together and the value of "n" may be extremely large (billions!).

Compounds

Compounds (or compound substances) are pure substances with a fixed composition that can be broken down into two or more elements. They are not the simplest of substances. However they are just as much pure substances as elements are. The reference to fixed composition needs some slight reservation because there are a few compounds where the composition is variable. Altogether there are more than 10 million compounds known, and several new ones are being made or discovered every day.

<u>What are the molecules doing?</u>

Molecules of compounds are made of more than one type of atom. However, as with elements, the molecules may (in a structural sense) be either simple or complex. The molecules may be as small as HCl or H_2O or as complex as DNA or PVC. There is a virtually infinite range of molecular possibilities. Included in this range is the possibility of isomerism – molecules with the same atomic composition but different structures.

Decomposition

Compounds can be broken down into two or more elements. However they can also be broken down to simpler substances that are still compounds. Decomposition is the general term for the chemical reactions in both cases. Once again the description "simpler" refers to composition. Thus for example, heating, decomposes calcium carbonate, CaCO3, leading to formation of calcium oxide, CaO, and carbon dioxide, CO2: two substances are formed and the formulae of each is simpler (compounds of only 2 elements) than that of the original compound (compound of 3 elements).

What are the molecules doing?

When compounds are broken down, it is true to say their molecules are broken down. However it is important to add that two or more new types of molecules are formed: decomposition does not usually result in atoms, although this is achievable with more violent conditions (the special term atomization may then be used).

As noted the molecules formed in a decomposition may be simpler in terms of composition, but they may not be structurally simpler. For example, in the case of the decomposition of calcium carbonate, we begin with molecules that are extremely large (the formula of the molecules would be best represented as (CaCO3)n) and complex. However the same may be said of the calcium oxide (best represented as (CaO)n) molecules; it is only the carbon dioxide molecules, CO2, that are simpler in every respect.

Activation Energy

Chemical reactions may be exothermic or endothermic, but how fast the reaction occurs is a different question. The majority of reactions need some energy input (thermal, radiant, electrical) to get started. The required energy input is termed the activation energy. Substances with a low activation energy for many of their reactions are "reactive"; substances with a high activation energy for many of their reactions are "unreactive" or inert. However it should be noted that one cannot assign an activation energy to a substance; it is reactions that have activation energies.

What are the molecules doing?

In chemical reactions molecules are breaking and forming bonds. Breaking bonds requires energy; forming bonds releases energy. It is common for one bond (at least) of a molecule to have to break before a new bond can be formed. Hence energy input runs ahead of energy output as far as the molecules are concerned. This fact of molecular life is a logical expectation: if one or more of the atoms in a molecule could form more bonds (without breaking any others) then it would have done so a long time ago! Atoms form bonds until their valency is satisfied. The energy required for bonding changes in the molecules is a potential energy; colliding molecules derive this from their collisional kinetic energy. The same figures do not apply to all collisions because the trajectories of the molecules affect the energy requirements.

Catalyst

Catalysts are substances the speed up chemical reactions between reactants. Catalysts are usually added to the reactant mixture in small quantities and can be recovered at the end of the process. They are not used up and they do not change the products of the reaction. They cause the speed increase by lowering the activation energy of the reaction. The phenomenon is termed catalysis. Catalysts do not slow reactions: substances that do that are termed inhibitors and they do get used up.

Catalysts may be quite specific for particular chemical reactions; one cannot just say "this substance is a catalyst" but rather "this substance is a catalyst for this reaction". Enzymes are natural catalysts for biochemical reactions and often are very specific in the reactions they catalyse.

What are the molecules doing?

Molecules of a catalyst interact with reactant molecules to make them more reactive. The catalyst molecule reacts rapidly with one of the reactant molecules. It reacts rapidly because it has a low activation energy for the interaction. The molecule produced by the interaction has one or more weaker bonds than the original reactant molecule. Therefore it reacts with a lower activation energy. When the product molecule is formed, it is still bonded to the catalyst molecule, and the final step in the catalytic process is the breaking of this bond with the catalyst molecule. Overall there are more steps in the reaction, but each has a lower activation energy: this increases the overall speed.

Chemical equilibrium

Chemical reactions may or may not proceed to completion. Sometimes reaction stops even when some reactants remain. The reaction is then said to have reached equilibrium – or in full, chemical equilibrium. The equilibrium condition can only be observed in a closed system, that is a system in which no substances can enter or leave the reaction mixture. The proportions in which reactants and products co-exist at equilibrium can be expressed through an equilibrium constant, which has a specific value for a reaction at a given temperature.

What are the molecules doing?

The molecules are still changing, even though the reaction seems to have stopped! The equilibrium condition arises because product molecules are changing back to reactant molecules at the same rate at which the forward reaction is taking place. Thus there is both a forward and reverse reaction proceeding and no net change is observable when their rates are equal. It is a dynamic equilibrium. The forward and reverse reactions in general have different activation energies, and so they are affected by temperature changes to a quantitatively different extent. This is why the overall equilibrium condition is dependent on the temperature.

Electrical conduction

One of the ways of classifying substances is in terms of their electrical conductivity (or its inverse, resistivity). There are conductors, semiconductors and insulators. Under normal circumstances gases are insulators, liquids may be conductors or insulators, and solids may be any of the three categories.

What are the molecules doing?

An electric current is a flow of charges. The charges may be negatively-charged electrons or ions – charged atoms or molecules – with either a positive charge or a negative charge. The two cases are referred to as electronic and ionic current, respectively. Substances within which these currents occur can then be called electronic or ionic conductors. Semiconductivity is always electronic.

Ionic conduction is most common in liquids because in this state movement of charged atoms and molecules can take place. Generally speaking such movement is not possible in solids. By contrast, electronic conduction is more common in solids (although it is found in liquid (molten) metals). Electronic conduction in solids is commonly found when the solid comprises giant molecules with an infinite network of atoms and bonds. In addition the atoms making up the molecule need to hold electrons weakly. Such atoms will usually be of metal elements. In these circumstances the electrons move throughout the network of atoms and bonds relatively freely. Where such a network exists but the atoms hold electrons more strongly, the solid may be a semiconductor. In electronic conductors it is the electrons that move through the molecule: the atoms do not move, and the molecule does not change. This contrasts with ionic conduction where chemical changes occur at the electrodes.

Electrolysis

Electrolysis is the decomposition of a substance with electrical energy. It can take place with suitable aqueous solutions (must be conducting) and requires an external source of energy (cell or battery), connecting wires and two electrodes made of conducting material. Reactions are observed at both the electrode surfaces, but not in the body of the liquid.

What are the molecules doing?

At the electrode surface molecules either lose or gain electrons: at the anode (conventionally labeled +) they lose electrons, whilst at the cathode (conventionally labelled -) they gain electrons. Losing electrons is also called oxidation; gaining electrons is also called reduction. The molecules are forced to undergo these electron transfers as a result of the potential difference between the two electrodes. There can be a variety of consequences of these transfers:

1. positive hydrated ions are neutralized at the cathode and negative hydrated ions are neutralized at the anode. For example $2H^+ + 2e^- \rightarrow H_2$ and $2Cl^- - 2e^- \rightarrow Cl_2$.
2. neutral molecules become charged due to loss of electrons at the anode or gain of electrons at the cathode – as a result the charged molecules break-up to form a more stable ion and a neutral molecule. For example $2H_2O^+ \rightarrow 4H^+ + O_2$ and $2H_2O^- \rightarrow H_2 + 2OH^-$

There are always auxiliary events when these violent electron transfers take place at the electrode surfaces. These include movement of ions through the solution to balance charges created or destroyed in the regions around the electrodes: uniformity in the distribution of charges in the solution is essential for continuing electrolysis.

REFLECTIONS

In the above descriptions of the meaning of some common terms, we have only scratched the surface of a substantial task. The terms selected are all ones that originated in the description of phenomena during the development of chemistry, predominantly since the days of Lavoisier in the 18th century. Generally-speaking dictionaries, compendia and glossaries define and explain (to a limited extent) the terms, either adopting a macro-level description or a micro-level description, but not both. Furthermore there is usually no uniformity within one listing, the author(s) seemingly making different choices of level for different terms. The macro-micro dictionary approach exemplified above, juxtaposes the two levels of description. This emphatically draws attention to their co-existence and their relationship.

In the micro-level descriptions that were given in the previous section, no reference was made to details of chemical bonding or atomic structure. We may relate this to the logical structure of chemistry identified by Jensen [4], by stating that we have penetrated into his "molar" and "molecular" levels, but not the "electrical" level. This position reflects a belief that we are often over-eager in chemistry teaching to talk of the electronic configurations of atoms, ionic and covalent bonding, etc, that is to plunge into the electrical level of Jensen, without paying enough attention to relating the molar and molecular levels.

Reviewing the micro descriptions, we can discern a few simple things about molecules, namely that they may be diatomic or polyatomic (up to giant size) and that they may be homonuclear or heteronuclear. Whatever their classification they may:

1. move and have energy (both potential and kinetic) which may change;
2. change their molecular environment;
3. change their composition and structure (bond breaking and forming);

4. absorb and emit radiation;

5. gain and lose electrons.

Most chemical phenomena can be interpreted through this understanding of what molecules do. However, the vocabulary at our disposal to say what the molecules are doing is very weak. This often drives us to use words from the macro-level to talk about molecular events, thus confusing in the very act of clarifying. In the examples above, we have sometimes been guilty of this.

In conclusion, it was suggested previously [6] that the "chemist's triangle", relating the macroscopic, microscopic and symbolic descriptions, may be recognized as a closed-cluster concept map [11]. Perspective on chemistry as a whole, and on its many topics, can be aided by recognizing this. It therefore has potential as a basic organizing framework for teaching and learning. Realising that potential should be facilitated by developing a macro-micro dictionary of terms. This being said, the symbolic corner of the triangle, and its relation to the other two, also deserves attention, and this will be the subject of a further paper.

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