John Dalton’s atomic theory: Using the history and nature of science to teach particle concepts?

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abstract

The atomic philosophy began with the Greeks and the atomic theory came of age in the 50 years following John Dalton's research. Two views of matter competed among the Greeks and during the 18-19th Centuries. Aristotle, Dalton and Faraday saw matter as continuous with particles in contact while Boyle, Gay-Lussac and Avogadro saw them as dynamic entities separated by space. Dalton's reputation and his continuous view of matter stalled the development of the atomic theory between 1810-60 and the atomic understandings of school and college students also are inhibited by intuitive continuous conceptions of matter. Most students - and a few textbooks - insist that the macroscopic properties of a substance are manifest by isolated atoms and molecules of the substance. This appears to be a source of the alternative framework held by many students. The paper reviews both the historical development of the modern atomic concept and students' alternative theories of matter and particles. The paper argues that there are excellent pedagogical reasons for retracing the history of atomism. The flawed projection of mass properties onto a substance's particles may be lessened by understanding how and why scientists from Newton to Avogadro concluded that matter is composed of dynamic, invisible and indivisible particles.

Introduction

Intuition suggests that all substances are made of minute particles because pavements slowly wear away; evaporating liquids produce diffusing scents; living things grow and decay; and water erodes soil and rocks. The invisible wind can propel yachts, clouds, dust and birds meaning that the air must contain moving particles, however small (Sakkopoulos & Vitoratos, 1995). Even “the bread we eat changes to bones, blood, nerves, skin, hair, etc., so it must contain some hidden form of all the elements”. Long ago in the 5th Century BC, Leucippus and Democritus inferred that all living and inanimate things were composed of indivisible and invisible particles called atoms. The modern particulate nature of matter is presented in a like philosophical way in some chemistry textbooks. One book reasons on what would happen if you halved a copper penny into ever-smaller pieces: "Eventually you would come upon a particle of copper that could no longer be divided, and still have the properties of copper. This particle would be an atom, the smallest particle of an element that
"retains the properties of that element" (emphasis in original) (Wilbraham, Staley & Matta, 1997).

Indeed, the word atom comes from *atomos*, meaning undivided or indivisible and mind experiments like the hypothetical division of a copper penny convinces most people of the existence of atoms. But what is an atom? What is this tiniest independent particle like? How does it behave? This is the point where intuitive ideas and scientists' science mostly part company. This is the reason for this paper: it explore possible ways to use the history and epistemology of science to enhance the teaching and learning of particle concepts.

It was the Greek intuitive and inductive philosophy that led the Latin poet Lucretius (BC 97-55) to write that all matter, and the mind, "must be composed of particles exceedingly minute and smooth and round". Greek atomism grew until it was opposed by Aristotle and lay dormant until the ideas represented in Lucretius' poem, *De Rerum Natura*, were resurrected during the 1400s. This atomism depicted matter as atoms moving in a void and it must be remembered that none of these ideas were based on empirical data. Aristotle's opposing view held that matter was continuous because 'nature abhors a vacuum' - again without evidence. Curiously, many school students' intuitive atomism resembles Aristotle's continuous matter and they attribute a substance's macroscopic properties to its atoms (Andersson, 1990; Ben-Zvi, Eylon & Silberstein, 1986).

Aristotle overcame the atomist's views because theirs was a tacit or axiomatic atomism justified in philosophical terms using everyday observations like growth and decay, diffusion and erosion. Greek atomism simply lacked the experimental evidence of modern science because empirical research was anathema to the academy. Yet textbook atomism is often described as beginning with Greek thinkers, distilling through the Renaissance and condensing in the Scientific Age into the modern scientific theory. This view ignores the scientific revolution that took place at the interface of the 18th-19th Centuries. The ideas of Lavoisier, Dalton, Gay-Lussac and Avogadro were truly revolutionary (Kuhn, 1970) and the science historians reviewed in this paper refute the notion that the atomic model evolved from the Greek doctrine into the modern theory. So, why do we teach particle theories the way we do?

This paper is interested in the ways that, and reasons why, school chemistry recapitulates the continuous evolutionary account of the atomic theory. The Greek academy's epistemology and ontology often repeats itself when school students are told that atoms exist, then informed of Brownian motion, and shown that the diffusion of odours 'proves' that molecules are dynamic (but the phenomenon itself is not explained). Students experience air pressure, the diffusion of odours and the spread of permanganate's colour in water and recognize that small particles must exist and move. But the concept of atoms and molecules as independent, invisible and indivisible entities is far from being 'seen' or understood. Students are given limited empirical evidence, few arguments for and against atoms, but are expected to think and problem solve with atoms, molecules and ions. The pivotal questions remains: Why do we believe in atoms? What evidence do students have for the modern atom? How can the history and philosophy of science aid learning?

**Modern Atomic Theory**

The atomic ideal that was resurrected in the renaissance grew in the hands and minds of Descartes, Newton, Boyle, Dalton, Thomson, Rutherford, Bohr, Schrödinger and Heisenberg into the modern theory we know and use. The history of the atomic theory from the early-1700s to the late-1800s is a tapestry of debate about the meaning of data, partial theories, anomalies and incommensurabilities (Mason, 1962; Nash, 1957; Toulmin & Goodfield, 1962). The crucial difference between Greek and modern atomism is the latter's reliance on
experimental evidence. It would, however, be wrong to claim that experimental data alone begat the modern atomic theory. Theory, mind experiments, perspicacity and data all played parts in transforming the mechanical particles of Newton and Boyle into the spacious dynamic molecules, ions and atoms of modern kinetic theory and chemical reactions.

There were revolutions in particle thinking and the major revolution in atomic thought is attributed to John Dalton - indeed, Dalton's theory "marks an epoch in the history of chemistry" (Thorpe, 1909, p.95; see also Bensaude-Vincent & Stengers, 1996; Brock, 1992). The 17th-18th C story of the atomic theory is one of ontological and epistemological change - sometimes forward, sometimes back - as atomic theory was added to, revised, and refined by chemists like Proust, Lavoisier, Dalton, Gay-Lussac and Avogadro. The conceptual growth of secondary school students resembles this evolution of knowledge and is "a gradual and piecemeal affair ... involv[ing] much fumbling about, many false starts and frequent reversals of direction" (Posner, Strike, Hewson & Gertzog, 1982). Research shows that the way students learn atomic and molecular concepts is mostly evolutionary and takes considerable time (e.g., Harrison & Treagust, 2000, Millar, 1990; Stavy, 1988). So, what better assistance can be found than retracing the history of science - a history that deals with real people struggling to make sense of one of science's most fundamental questions?

The century surrounding Dalton's work had a profound effect on chemistry and I claim that student learning in chemistry is enhanced when the history of the atomic theory is shared in informative and interesting ways [e.g., The atom (Jacobson, Kleinman, Hiack, Carr & Sugarbaker, 1969)]. Still, as I will shortly show, even such better purpose-written accounts are compromised by errors and I therefore turn to Joseph Schwab's seminal work, The teaching of science as inquiry (1966) for guidance. Schwab recommended enriching the curriculum with appropriate accounts of the challenges faced by science and how scientists worked through the 'big' theoretical and practical problems. Several courses in the 1970s implemented Schwab's recommendations (e.g., BSCS and ChemStudy) but inquiry and the history of science still often are casualties in science courses that represent science as "a rhetoric of conclusions" (Schwab, 1966, p.24) and which permit "the hegemony of subject matter" (p.22) to replace process with content. The story of Dalton's atomic theory is an ideal way to immerse student in what is probably the most important question in science - "why do we believe in atoms?"

This paper now divides into two parts. First, the chemistry education problem pertaining to atomic theory is defined by summarising the conceptions of matter and particles held by school and college chemistry students (Gabel, 1999; Lee, Eichinger, Anderson, Berkheimer & Blakeslee, 1993). Despite the variety of alternative conceptions, one framework is so pervasive that it may count as an intuitive or naïve theory of matter or alternative framework. This naïve theory centres on the view that matter is continuous and mass properties are manifest in a substance's particles. Part two recounts the history of the particle concept and highlights implications for teaching and learning chemistry; namely, how the history of the particle concept can be used to conceptually replace the continuous matter conceptions and the inductive projection of mass properties onto a substance's particles.

**Student Understanding Of Matter And Particles**

The idea that all substances are separable into tiny indivisible particles called atoms, molecules and ions is widely accepted. Children are introduced to atoms and molecules by the popular media well before particle theory is taught in school. But this is where the similarity between science and student preconceptions ends because students consistently attribute the macroscopic properties of matter to its sub-microscopic particles. It is intuitively logical that the particle properties should be the same as the properties of a visible piece of the pure substance and textbooks promote this link (e.g., Wilbraham et al., 1997). Now
Consider a glass of water. If you pour out half of the water, the remainder will still behave exactly like water. If you pour off half of what remains in the glass, the properties are still the same. But could you repeat this process indefinitely without changing the properties? Or would you reach a point beyond which further subdivision would result in portions which no longer resemble water? (Jacobson et al., 1969)

While this last question is not specifically answered, the next paragraph states that matter cannot "be indefinitely subdivided ... the smallest possible particles [are] atoms".

Repeatedly halving the glass of water and the penny eliminates important properties of water and copper before the single molecule or atomic level is reached. The dissociation of water and its hydrogen bonding (on which its solution properties are based) is lost well before the single molecule level and copper loses its malleability, hardness, conductivity and colour before the single atom level. The philosophical divisibility of substances into particles is seductive but flawed because mass properties are aggregate properties and atoms just do not exist on their own (except noble gases). In their quest for elegance, modern writers fall into the same trap as the particle philosophers of the 17-19thC. The assumptions that drive the repeated-division mind experiment introduce inappropriate conceptions because there are crucial differences between the macroscopic and the quantum level that deny the applicability of macroscopic properties to isolated atoms and molecules.

The following seven particle conceptions qualify as an alternative framework because student thinking systematically differs from the scientific concept (Griffiths & Preston, 1992). It is called a naïve attribution theory because it is based on the inductive projection of an object's macroscopic properties onto its particles. These particle conceptions are simply not commensurate with atomic theory and we can derive pedagogies to change these conceptions from the history of the atomic and kinetic theories. Conceptions are only included in the naïve attribution theory if they are reported by two or more studies.

1. Matter is continuous. Particles are in contact and there is no empty space between them and Aristotle's maxim that 'nature abhors a vacuum' is conserved (Nussbaum, 1997). The scientific view is ontologically different - discrete, dynamic particles are separated by empty space (Harrison, 2001). Dalton and Faraday held the continuous matter view yet Newton, Boyle, Ampère, Gay-Lussac and Avogadro conceived of empty spaces between atoms and molecules (see the historical map following the paper's references).

2. "Molecules are in substances, rather than that substances are composed of molecules ... between the molecules of a substance, the same substance exists ... there are various kinds of 'stuff' [or air] between molecules" (Lee et al., 1993). Some reputable textbooks containing diagrams like Figure 1 below (Andersson, 1990; Nussbaum & Novick, 1982). The line across the top tells students that water molecules are floating in some other 'stuff'! The 'stuff' or matrix needs to be clearly replaced with appropriately sized empty spaces and the top surface removed to avoid these instruction-induced alternative conceptions.

Figure 1: A model of a liquid in a container drawn with surface line implying that the particles are suspended in another substance.
3. Solid particles are in contact, liquid particles are about one particle apart and gas particles have 3-4 particles space in-between (Nussbaum & Novick, 1982). The scientific spacing between solid-solid, liquid-liquid and gas-gas particles, however, is close to 1:1:10 (Andersson, 1990; Harrison, 2001). Incorrect spacing was an alternative conception that hindered the acceptance of Dalton's atomic theory for 50 years! Figure 2 shows how several textbooks model solid, liquid and gas differences.

Figure 2: A comparative model of solid, liquid and gas states found in several science textbooks.

4. Gas particles are mostly static and heated gas is lighter and rises to the top of its container (Lee et al., 1993); if some of the gas is sucked out of the container the remainder does not fill the container (de Vos & Verdonk, 1996) as demanded by the scientific model. Familiarity with the history of the particle concept should help students understand why Boyle, Bernoulli and Gay-Lussac insisted that gases must fill their containers.

5. Matter is not conserved in phase changes because matter is lost in changing from solid → liquid and liquid → gas and there are material differences between solid, liquid and gas particles and when ice melts, the "molecules in ice are hard and frozen ... and start moving when the ice melts" (Lee et al., 1993). Solute particles melt when they dissolve (Selley, 2000).

6. Particles also expand and contract as they are heated and cooled just like the substance of which they are part (Griffiths & Preston, 1992; Nakhleh, 1992). The scientific view insists that increased and decreased particle motion accounts for expansion and contraction. Movement based on energy content is an intrinsic property of particles. That is, particles jostle each other and the degree of jostling is a function of energy status.

7. Copper atoms are red-brown because that is the colour of copper; chlorine atoms are green because chlorine is a green-yellow gas; and scientific models use green balls for chlorine atoms (Ingham & Gilbert, 1991). Simple inductive experiments can help school students understand that particles are colourless (Nakhleh, 1992). If the substance conducts electricity or heat (e.g., a metal), individual atoms will conduct heat or electricity; if the substance is malleable, the atoms are malleable (Ben-Zvi et al., 1986).

Items 6 and 7 are especially worrying. Students project the mass properties of a substance onto its particles, that is, they reason from large to small. The scientific model reasons the opposite way using particle action to explain processes like conduction. Intuition is
ontologically different to the scientific explanation because science uses constraint-based interactions (Chi, Slotta & de Leeuw, 1994) to explain colour, conduction and dissolution.

Ontological change is needed if students are to exchange the static, continuous model of matter for a random, dynamic model in which the particles are separated by large spaces. In the kinetic theory, particle spacing (or pressure) is a function of the particles' kinetic energy. Learning the scientific view requires students to think less about particles as objects and more about the forces and energy that shape particle interactions. This is the strongest form of conceptual change because it radically changes the way students understand matter. The desired conceptual change from intuitive particle ideas to scientific thinking is ontological because students intuitively reason in a reverse way to the scientists.

Other Intuitive and Alternative Conceptions

Younger students think that light and heat are "different forms of matter" and occupy space (Lee et al., 1993, Osborne & Freyberg, 1985). Students holding this view need to conceptually differentiate matter and energy. Such confusion was evident in Dalton's and Avogadro's time as both viewed heat, or "caloric" as a material "fluid" (Nash, 1957). Familiarity with the growth of the atomic theory may therefore help students resolve this confusion by seeing how the idea arose and why it was inappropriate.

Some students "believed that they could see molecules with microscopes or 'magnifying lenses'" (Lee et al., 1993). The publication of scanning tunneling micrographs of atoms supports this erroneous view. STM images are computer generated models designed to show atoms as solid spheres (which they are not) and science still has not 'seen' an atom. It is, therefore, troubling to meet textbook statements like, "despite their small size, individual atoms are visible with the proper instrument" (Wilbraham et al., 1997). Griffith and Preston (1992) reported that students believe atoms are large enough to be seen with a powerful microscope. Ten of their 30 Grade 11-12 interviewees claimed that "atoms are alive because they move" and 10 of 48 Grade 8-10 students interviewed by Harrison and Treagust (1996) believed that atoms were living. The 'divide and grow' conception is relatively common suggesting that the undifferentiated use of the word 'nucleus' is responsible for this conception. Lee et al. (1993) conclude that "many students learned to use molecular language as a 'veneer' without substantially changing their conceptions of matter".

The last conception worthy of mention is Osborne and Freyberg's (1985) finding that students believe boiling changes water's chemical make-up. The 12-17 year-old students they interviewed said that the bubbles in boiling water can be heat, oxygen, hydrogen or steam. With increasing age, the 'heat bubbles' response dropped to almost zero, the air response rose to just under 25% and the steam and the oxygen plus hydrogen response each stood at about 35%. The decline of the 'heat' response with increasing maturity agrees with Millar's (1990) and Stavy's (1988) argument that conceptual change takes time. I claim that student-friendly stories from the history of science will help accelerate this conceptual change. A condensed history of the atomic story is now discussed.

The History of the Particle Theory

Two particle theories feature in chemistry textbooks - Dalton's atomic theory and the molecular kinetic theory; however, they rarely appear together and the account of each is more descriptive than explanatory. Dalton's atomic theory and the molecular kinetic theory are usually presented using some of the postulates in this list (Garnett, 1996; Bucat, 1984).

1. Matter consists of submicroscopic, indestructible particles called atoms.
2. All atoms of an element are identical and have the same mass but atoms of different elements have different masses.
3. Particles join together in simple consistent ratios when two different substances react to form a third substance.
4. Mass is conserved in these reactions.
5. Gas particles are evenly scattered in an enclosed space and there are empty space between particles.
6. Gas particles are in constant random motion and collisions are perfectly elastic.
7. Particles move slower in liquids and vibrate about fixed positions in solids.
8. The spacing between solid-solid, liquid-liquid and gas-gas particles is close to 1:1:10 (Andersson, 1990; de Vos and Verdonk, 1996)

The first postulate is intuitive (matter comprises tiny indivisible particles called atoms) but the remainder are counterintuitive and abstract (e.g., empty spaces separate particles; particles are in constant random motion). Secondary students find this theory difficult to mentally model. Postulate 8 is not discussed in many textbooks and, when it is, the spacing is mostly incorrect (Wilbraham et al., 1997).

**History of the Atomic Theory**

The following account argues that there are good knowledge and epistemological reasons for retracing the history of the atomic concept. The atomic and kinetic theories grew side-by-side from the rigorous investigations of the 'pneumatic' chemists (e.g., Boyle, Gay-Lussac and Avogadro) and the 'mass' chemists (e.g., Lavoisier, Proust, and Dalton). The atomic theory enunciated by Dalton was revolutionary because he proposed a causal particle explanation for chemical reactions. He explained that reacting masses combine in repeatable, simple ratios because the mass-ratios of reactants and products are the macroscopic manifestation of simple rearrangements of invisible and independent particles. Dalton's theory was powerful because it included a causal explanation that agreed with the available evidence and made predictions that could be tested and falsified. He argued his theory of particle action in 1803-8 yet the full acceptance of the atomic theory and Avogadro's Law took almost 50 years. In this period, chemists argued for and against atoms and Ostwald maintained his objection to the atomic theory well into the 20th Century. If great chemists had problems with atoms and molecules, why do we diminish the problems students face?

The delay was almost entirely due to the dominance of Dalton's "rule of greatest simplicity" and Dalton's insistence that gas particles differ significantly in size, meaning that equal volumes of gas under the same conditions of temperature and pressure do not contain equal numbers of particles (Nash, 1957). In 1808, Gay-Lussac showed that when hydrogen and oxygen react to form water vapour, the combining volumes (and the products under the same conditions) are simple whole number ratios. These data mirrored Dalton's findings but Gay-Lussac's data were more accurate and precise and, when repeated and interpreted by Avogadro in 1811, led Avogadro to assert that equal volumes of gas at the same temperature and pressure do contain equal number of particles and that oxygen and hydrogen particles are diatomic molecules. Dalton's insistence that oxygen and hydrogen particles are single atoms inhibited the full realization of the importance of Gay-Lussac's and Avogadro's ideas until 1860 and stalled the progress of his own atomic theory.

Dalton's "rule of greatest simplicity" insisted that when two elements, A and B combined to form just one new substance, the combining ratio is 1:1 or AB unless there are very good reasons for a different ratio. The rule can be understood as an application of Occam's Razor where the simplest explanation, the one that makes the least assumptions, is deemed best. The rule went on to say that if two compounds resulted from A + B, then the compounds
should be AB and A₂B or AB₂; if three are possible then the additional formula should be AB₃ or A₂B. Dalton held this assumption so strongly that it prevented him from perceiving that the formula of water is H₂O as shown by Gay-Lussac's data and Avogadro's reasoning. The rule insisted that because oxygen and hydrogen combine in just one way, the product should be HO (Mason, 1962). This assumption also led him to conclude that the mass ratio of hydrogen to oxygen was 1:7 when he could have arrived at 1:14 (difference between 14 and 16 being experimental error). It was not until Cannizaro cleverly reargued Avogadro's hypothesis at the Karlsruhe Congress in 1860 that oxygen and hydrogen were accepted as diatomic gases and the impasse between Dalton and Gay-Lussac was resolved in Gay-Lussac's favour. The rule was then refined to state that when two elements combine, the ratios are simple integers and that 1:1 has no natural precedence over 1:2, 2:3, 1:3, etc. Still, the rule of greatest simplicity was "Dalton's greatest single contribution to the formulation of an atomic theory" (Nash, 1957). The rule was a crucial theoretical advance because it insisted that chemical reactions are orderly and that predictable changes occur between discrete invisible particles.

Whereas the "rule of greatest simplicity" was a barrier to Avogadro's conclusion that equal gas volumes contain equal numbers of particles; it also was the key to the atomic theory's success at the start of the 19th Century. Dalton's belief that reacting elements comprised a multitude of identical and discrete particles was a significant improvement on Newton's and Boyle's corpuscular theories because Dalton's theory explained and was built on experimental data. The atomic theory was supportable even if the 'equal gas volumes contain different numbers of particles' was not. Despite its weaknesses, Dalton's belief in atoms was theoretically sound and allowed him to make the crucial predictions that suggested the decisive experiments that tested the theory's predictions and produced, over the next 50 years, the key tenets of the atomic theory. Still, the strength of Dalton's reputation, the rule of greatest simplicity and Dalton's "conception of a gas as solidly packed with particles, like a pile of shot" (Nash, 1957) inhibited Gay-Lussac's and Avogadro's theoretical advances.

Dalton's belief that gas particle size is directly related to its mass is not uncommon. Students predict that when water is electrolysed, the one volume of oxygen produced will occupy a greater volume than the two volumes of hydrogen at the same temperature and pressure because oxygen with 8 protons + 8 neutrons is much larger than hydrogen's single proton (Gabel, Samuel & Hunn, 1987). This alternative conception could be avoided by explicitly showing how this idea hindered the development of Avogadro's hypothesis [which "is not self-evident" (Gabel, 1999)]. The history of science is more than an interesting story because it can show the way to effective conceptual growth and conceptual change. Histories like this story also show students that science is a human enterprise, scientists do make mistakes, and the scientific academy is rigorous and imaginative. Incorporating history into the teaching of chemistry may well increase chemistry's appeal to students.

**Atoms are Independent, Invisible and Indivisible**

Dalton observed that when two elements react to form a new substance, the reacting masses always react in simple and consistent ratios. Gay-Lussac also recognised this pattern in the volumes of gas that reacted in similar reactions. As a result, Dalton and Gay-Lussac understood that when two elements react to form a specific compound, they always combine in the same simple proportions. How could this be explained in terms of the underlying structure of matter?

During the 1780s, Lavoisier's accurate experiments established the Law of Conservation of Matter by demonstrating that the total mass of the products always equaled the mass of reactants. Matter was neither created nor destroyed. In 1797 Proust showed that for each
compound he studied, the reacting elements combine in a constant ratio yielding the Law of Constant Composition. Dalton's experiments with nitrogen and oxygen showed that three oxides were possible: nitrous oxide, nitric oxide and nitrogen dioxide. He first demonstrated that when the reacting conditions for each oxide were present, only that oxide resulted and his data obeyed the Law of Constant Composition. Three different combining ratios for nitrogen and oxygen led him to formulate the Law of Multiple Proportions. These laws are most remarkable when we remember that Proust, Lavoisier and Dalton worked with limited knowledge and equipment. But Dalton was an insightful theoretician and he saw the pattern that others missed. He saw what the Law of Constant Composition and the Law of Multiple Proportions were telling him: that the simple and constant ratios reported by Proust in France and Richter in Germany could only be explained if hydrogen, nitrogen, oxygen and the other known elements were made up of indivisible, invisible and independent particles that combine in simple and predictable ratios. This insight became the cornerstone of his atomic theory.

Nash (1957) calls Dalton the "skilful observer" who "contributed a notably plausible, precise and unambiguous statement of the basic postulates of the atomic theory" that was based on his conceptual scheme of how matter is constructed and behaves.

Proust and his contemporaries held the critical data in their hands and failed to see the significance of what they "knew". With the advent of Dalton's atomic theory, the new beliefs it encouraged brought about a remarkable sharpening of the empiricist's vision. They were told what to look for, and where and how to look for it - and behold, it was there. Dalton's ... fundamental contribution was the powerful stimulus to investigation provided by his conceptual scheme. (Nash, 1957)

But how did Dalton see what others "knew" yet failed to perceive? A striking feature of his own accounts of the atomic theory is the consistent way he uses "atom" to denote a fundamental elemental particle, one that is indivisible and too small, in his opinion, to ever be seen. He talks of compound atoms (our molecules) and develops his theory using "thought experiments". In an 1810 lecture to the Royal Institution using "the Newtonian doctrine of repulsive atoms and particles, I set to work to combine my atoms on paper". Dalton's thought experiment tells how, at length, he deduced that the atmosphere was a mixture, not a compound. In other accounts he explains how his thinking about the available data (quite limited data in scope and number) led him to the "rule of greatest simplicity" and, subsequently, to his atomic theory. Both Nash, and Toulmin and Goodfield reveal how important thought experiments were in directing Dalton away from the pursuit of unsystematic data towards the fruitful concepts of his atomic theory.

Popular textbook accounts of the scientific method represent science as a logical procession from observation through experiment to hypotheses culminating in a new or revised theory. Neither Boyle (Toulmin & Goodfield, 1962) nor Dalton followed this route; instead, 'intuitive' theories guided their thinking. "Dalton did not proceed in a clear-cut fashion from postulate to argument, ... rather, he followed the reverse course" (Nash, 1957). While thought experiments and theorizing before the crucial experiment is conducted is common in the history of the quantum theory, it is less often supposed to have occurred in the 18-19th Centuries. But this is a striking feature of the stories of Lavoisier, Dalton, Gay-Lussac and Avogadro. The fruitful 'intuitive' theory is a hallmark of their thinking; and their investigations were purposefully focused by the predictions that emerged from their theories. Theory was pre- eminent in their thinking and Chalmers (1997) shows that theory is an indispensable ingredient in all scientific progress; that is, no scientist can make sense of his or her data without an organizing framework. The theory may soon need to be modified, but such a theory is better than no theory at all. This principle should be pursued in secondary science teaching because it helps students understand that science is a way of knowing
rather than a body of knowledge. Such thinking is the foundation of 'working scientifically' (or 'inquiry') and is the rationale for most modern science curricula (e.g., Queensland Schools Curriculum Council, 1999).

The thought experiment was prominent in Newton's corpuscular theory of light and in Boyle's method of modelling elastic gas molecules as tiny springs. The thought experiment is shown to be an excellent tool for doing science. The benefit for students in sharing these stories is the legitimation of imagination and creativity in science. Students should be encouraged to play with ideas as this will likely increase their interest in scientific thinking. But they are unlikely to understand the power of theorising about data and evidence without exposure to the historic struggles of scientists like Newton, Dalton and Avogadro. All of these scientists dealt with things they could not see, yet in their mind's eye they "saw" the important concepts because they used a theoretical lens to interpret their data.

*The Kinetic Theory of Gases*

From early on, Boyle was a supporter of [Newton's] corpuscular philosophy, believing that all the properties and changes of material things could eventually be explained by the shapes, motions and arrangements of their tiny constituent particles. (Toulmin & Goodfield, 1962)

Newton proposed that a gas's particles were evenly spread through its enclosing space due to the particles' short-range repulsive forces. Boyle attributed the even spacing of gases to their springiness and modelled gas particles as tiny coiled springs. Boyle's experiments led him to insist that gas particles must possess mass, characteristic shapes and motion. He also argued that the inverse volume-pressure relationship for gases could only be explained in atomistic terms. However, this was all pre-Dalton and Boyle's atomism was principally philosophical, that is, his theoretical explanation for the data he collected demanded that gas particles be as he described them. Still, his dynamic particles with no intervening matter other than Newton's universal aether, supports the modern picture. When the Michelson-Morley experiment (1887) dispelled the aether, the modern image of a gas composed of independent, invisible and immutable particles became credible.

Dalton held views contrary to Boyle that inhibited the formulation of the kinetic theory as we know it. Dalton visualized a gas as a "pile of shot". Dalton's gas particles were single atoms in contact with each other and each atom's size matched its mass. This view differed from the modern trend that atomic radii gradually increase with rising atomic number because he saw oxygen as many times larger than hydrogen. Gay-Lussac, on the other hand, insisted that "the distances between individual gaseous particles are assumed to be so great in comparison with their diameters that the variable attractive forces between neighboring particles are negligible" (Nash, 1957). As early as 1738, Bernoulli provided a modern explanation of gas pressure and volume by assuming that "the atoms of a gas were in random motion, the pressure of the gas being nothing more than impact of the atoms on the wall of the containing vessel" (Mason, 1962). Grasping the significance of these ideas, Avogadro proposed that equal volumes of different gases at the same temperature and pressure contain the same number of particles. In 1814, Ampère, drew a similar conclusion. Avogadro then argued in his famous paper of 1811 that oxygen and hydrogen must be diatomic to explain how 1 volume oxygen + 2 volumes hydrogen produce 2 volumes of water vapour.

But Dalton could not accept Gay-Lussac's data nor Avogadro's hypothesis. Dalton's "the rule of greatest simplicity" said that the ratio of hydrogen : oxygen in water must be 1:1 or HO. He also believed that a volume of oxygen comprised numerous atoms which, in this example, we will call \( n \) atoms of oxygen. When the \( n \) atoms in one volume of oxygen react with hydrogen, two volumes of water vapour result. Dalton's theory disallowed there being
2n molecules of water because only n oxygen atoms were available and oxygen atoms are indivisible. Thus, he proposed that each of the two volumes of water vapour contained \( \frac{n}{2} \) molecules of OH. To justify the assertion that one volume of oxygen contains n atoms and one volume of water vapour contains \( \frac{n}{2} \) molecules, he wrote, “the globular particles in a volume of pure elastic fluid [gas], ... must be analogous to that of a square pile of shot ... each particle rests of four particles below” (Dalton, 1808). His conception that gas particles are in contact with each other, led him to conclude that a two atoms per particle gas (water, HO) occupies twice the volume of a one atom per particle gas (oxygen, O).

Dalton's thinking is repeated time over in science and in the classroom. In 1833 Faraday "established that the same amount of electricity brought about the decomposition of the same number of equivalents of different chemical substances" (Mason, 1962) and went on to show that the same amount of electricity yielded the same quantity of, say, hydrogen or zinc, from all of their compounds. Maxwell was unable to accommodate these findings within his or Faraday's theories and wrote that

> we leap over this difficulty by simply asserting the fact of the constant value of the molecular charge, and that we call this constant molecular charge.... *one molecule of electricity*.... It is extremely improbable however that when we come to understand the true nature of electrolysis we shall retain in any form the theory of molecular charges. (Mason, 1962)

Unbeknown to them, Faraday and Maxwell were adding support to the already strong atomic theory by asserting that particles and charge are quantised. The only theory that allows such a conclusion is the one that says that all matter (and now electric charge) is composed of discrete, predictably behaved, tiny particles called atoms (and charge). Faraday denied the atomic theory per se and conceived, like Dalton, “that matter is everywhere present, and there is no intervening space unoccupied by it” (Mason, 1962); Maxwell skeptically expected his conclusion to soon be denied and Dalton consistently rejected Avogadro's refinement of his own atomic theory. These examples amply demonstrate the conceptual compromises that even one alternative conception can wreak in a conceptual framework. Similarly, science education has shown the problems that a continuous view of matter and inductive projection of mass properties onto particles creates in the classroom (de Vos & Verdonk, 1996).

Macroscopic, Submicroscopic and Symbolic Representations

Gabel (1999) discusses Johnstone's (1991) observation that chemical phenomena are explainable in three ways - in macro, sub-micro and symbolic terms. Reactions are visible as changes in mass, state, volume, solubility, colour and temperature. But descriptive information has limited power in explaining what happens at the particle level, so chemists turn to submicroscopic and symbolic models. The macroscopic-submicroscopic-symbolic triangle that has proved so valuable in explaining chemical phenomena was first used by Dalton. Once Dalton saw what the Laws of Conservation of Mass, Constant Composition, and Multiple Proportions were telling him - that all matter is composed of invisible and indivisible atoms - he realized that he had to explain his observations in terms of particles and symbols or his theory would be neither credible nor communicable. He tells how he manipulated his "atoms" and "compound atoms" on paper to show that the atmosphere is a mixture, not a compound. And he invented a set of symbols to systematically describe the compounds and reactions he observed. Dalton's symbols were quickly replaced by Berzelius' one or two initials taken from each element's name; nevertheless, it was Dalton who saw the need to symbolize chemical action in an elegant and parsimonious way. It can
therefore be argued that Dalton is the father of the tripartite macro, sub-micro and symbolic ways of describing and explaining chemical reactions.

Conclusion

Boyle's and Dalton's science was not the random experimentation out of which the 'truth' serendipitously emerged. Instead, it is a story of intellectual wrestling with an intelligible and plausible theory that resulted in fruitful predictions. These are excellent epistemological reasons why students should engage with custom written historical accounts of the atomic and kinetic theories and their arguments. One of the reasons for alternative conceptions like the continuous nature of matter is a lack of understanding by students of the way in which scientists like Newton, Boyle, Lavoiser, Proust, Dalton, Gay-Lussac, Berzelius and Avogadro crafted their atomic and kinetic theories. While it is called Dalton's atomic theory, the theory belonged to all the participants because it is a story of individual and collective research. The full story celebrates the importance of curiosity and innovation, of politics and history and the dependence of each researcher on the other.

Knowledge of the struggles overcome and the ideas considered and rejected should provide students with more science-like conceptions and a better understanding of how science works. Scientific knowledge is no accident; science is the hard-fought understanding of people who asked how and why everyday phenomena work the way they do. Indeed, stories like these help sweep away some of the myths about the scientific method and help students understand that science is a human enterprise in which they can participate. Studying the history of the atomic theory should, therefore, help students demonstrate the outcome that "[k]nowledge of the behavior of matter in different states is important in itself for science literacy, and contributes centrally to atomic/molecular theory" (American Association for the Advancement of Science, 2001). The task that Joseph Schwab set us in 1966 still needs to be realized. Teachers and students need easy to read but informative histories of the intellectual victories that make science so interesting and relevant. And, I believe, chemistry will prosper as a result.

References


Dalton, J. (1808-10). *New system of chemical philosophy, Parts I and II.* Manchester


