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Complete List of Authors:	Robertson, Amy; Seattle Pacific University, Physics Shaffer, Peter; University of Washington, Physics

“Combustion always produces carbon dioxide and water”: A discussion of university chemistry student use of rules in place of principles

Amy D. Robertson* and Peter S. Shaffer†

Department of Physics, University of Washington, Seattle, WA, 98195

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* Corresponding author; Mailing address: Seattle Pacific University Department of Physics, 3307 Third Ave W, Suite 307, Seattle, WA, 98119-1997; Telephone number: 206-386-7347; Email: robertsona2@spu.edu

† Mailing address: University of Washington Department of Physics, Box 351560, Seattle, WA, 98195-1560; Telephone number: 206-543-6705; Email: shaffer@uw.edu

Abstract. On the basis of responses to written questions administered to more than one thousand introductory chemistry students, we claim that students often rotely apply memorized combustion rules instead of reasoning based on explanatory models for what happens at the molecular level during chemical reactions. In particular, many students argue that combustion produces carbon dioxide and/or water, even when the reactants do not contain hydrogen or carbon, an answer that is inconsistent with the principle of atom conservation. Our study also corroborates the finding that students frequently say that oxygen is "necessary for" or "used in" combustion reactions without connecting this reasoning to conservation principles, suggesting that this likewise may be a rotely applied, memorized rule.

Keywords: chemical reactions, chemistry education, alternative conceptions

I. Introduction

The principle of conservation of matter and the concept of chemical change are two of the most fundamental ideas to the study of science and, in particular, to chemistry. Most of what is taught in university-level introductory chemistry courses – such as stoichiometry, aqueous solutions, chemical equilibrium, acids and bases, and the thermodynamics of formation – relies on an understanding of both. In fact, macroscopic chemical change – in which reactant substances are transformed into product substances – is often explained using a molecular model in which the constituent atoms are conserved and the new substances contain the same (albeit rearranged) atoms as the old ones did.

The Physics Education Group at the University of Washington (UW) conducted a multi-year investigation of university student reasoning about the particle nature of matter that emphasized chemical change. On the basis of our research, conducted in large-enrollment introductory chemistry courses at the UW, we claim that

> *Students often rotely apply memorized combustion rules, instead of reasoning based on explanatory models for what happens at the molecular level during chemical reactions.*

Prevalent patterns in student reasoning that emerge from students' written responses to questions about combustion serve as our evidence for this claim. Specifically, students argue that 'combustion always produces carbon dioxide and water' and that 'oxygen is necessary for or used in combustion,' even in situations in which the former is inconsistent with the principle of atom conservation.

Our research adds to existing literature on student understanding of combustion reactions.

Literature on student understanding of combustion consistently reports that students often rely on a descriptive – rather than an explanatory – characterization of burning. In other words, many students describe burning prescriptively – stating *what* they think happens and focusing on perceptible features of combustion, without articulating *why*. For example, students often say that some substances burn (*e.g.,* wood, cardboard, and paper) and others melt or evaporate (*e.g.,* metals, wax, and water) [1] (Boo, 1995; BouJaoude, 1991; Çalık & Alipaşa, 2005; Johnson, 2000, 2002; Lofgren & Hellden, 2008; Meheut, Saltiel, & Tiberghien, 1985; Pfundt, 1982; R. Watson, Prieto, & Dillon, 1995). In addition, students often say that oxygen is necessary for burning and that water and/or carbon dioxide is produced, but they do not specifically connect either to the presence of carbon and/or hydrogen in the reactants (BouJaoude, 1991; Driver, 1985; Lofgren & Hellden, 2009; Meheut et al., 1985; Ross, 1991; Schollum & Happs, 1982; J. R. Watson, Prieto, & Dillon, 1997; R. Watson et al., 1995).

Other studies articulate students' explanations for specific aspects of combustion. For example, the literature offers three common (incorrect) student explanations for the production of water vapor during combustion: (1) the water condenses from the air or environment (Johnson, 2002; Ross, 1991); (2) the water comes from the flame (Meheut et al., 1985; Ross, 1991); and (3) the water is displaced from the wood (Driver, 1985; R. Watson et al., 1995).

In addition, the literature repeatedly demonstrates that students answer questions in ways that are inconsistent with the conservation of matter. (Many such studies specifically focus on burning (Andersson, 1984, 1990; Barker & Millar, 1999; BouJaoude, 1991; Driver, 1985; Driver et al., 1984).) Research on conservation of matter at the molecular level suggests that students often do not associate meanings with chemical symbols in stoichiometric equations (Ben-Zvi, Eylon, & Silberstein, July 1987; Yarroch, 1985) and so do not conserve numbers of atoms (*e.g.,* they interchange subscripts and coefficients) (Kruse & Roehrig, 2005; Mulford & Robinson, 2002; Sanger, 2005).

Whereas the majority of the existing studies on student understanding of combustion/burning focus on *children's* reasoning, our study examines adult reasoning. We find that like the school-aged pupils described in previous research, adults in our university chemistry courses often state that oxygen is used by or necessary for combustion, corroborating and extending the literature base. We also find that university students use a specific combustion rule – that combustion always produces carbon dioxide and/or water – that, to our knowledge, is not reported elsewhere, adding to the extant literature.

Our research supplements existing literature on student use of heuristics and rules-based reasoning in chemistry.

A current trend in chemistry education research is to explain patterns of incorrect reasoning (e.g., misconceptions) on the basis of more general models of student thinking. For example, researchers have proposed heuristics (Christian & Talanquer, 2012; M. M. Cooper, Corley, & Underwood, 2013; Maeyer & Talanquer, 2010; McClary & Talanquer, 2011; Talanquer, 2006) and rules-based reasoning (Christian & Talanquer, 2012; Kraft, Strickland, & Bhattacharyya, 2010) as possible explanations for student use of rules (applied appropriately and inappropriately) in chemistry. "Heuristics" are "simple reasoning processes that reduce the effort associated with a task" (McClary & Talanquer, 2011). Heuristics research is often motivated by cognitive models of the mind, in which the level or amount of processing is constrained; in such a model, humans will often simplify or take short cuts, especially in situations in which time or knowledge is limited (Christian & Talanquer, 2012; M. M. Cooper et al., 2013; Maeyer & Talanquer, 2010; McClary & Talanquer, 2011; Talanquer, 2006). Although heuristics have an appropriate range of application, they sometimes "lead students astray" (Maeyer & Talanquer, 2010). For example, students may overgeneralize laws and principles that, in reality, have a limited range of application, asserting that the "entropy in any process always increases" or that "like dissolves like" (Talanquer, 2006).

Our research, although producing results consistent with the foci of research on heuristics and rules-based reasoning, has a fundamentally different aim. Rather than seeking to *explain* incorrect patterns in student reasoning, we seek to discern *what* those patterns are, to inform the development of curricular materials that elicit, confront, and resolve specific student difficulties. Our research group, in general, adopts the perspective of "instructor[s] whose primary motivation for research is to better understand what students find difficult about physics [science] and to use this information to help make instruction more effective" (L. McDermott, 1990). Our focus on student difficulties – or patterns in student reasoning that do not align with the canon – reflects our "practical, instruction-oriented approach": identifying a difficulty "provides a target for instruction" (Heron, 2004a). In particular, we focus on those incorrect reasoning patterns that are prevalent and/or fundamental to conceptual understanding. We have found that many such patterns emerge consistently across instructional contexts, regardless of other variables such as instructor or amount of prior instruction, and so represent patterns in reasoning that are both *common* and *persistent* (Heron, 2004b, 2013). We expect these incorrect reasoning patterns, in particular, to be useful for instructors and curriculum developers, who can use our research to anticipate where students might struggle and to plan instruction that seeks to address common misunderstandings [2]. In particular, that these patterns are common – *i.e.,* that they account for the reasoning of an appreciable fraction of students in multiple different instructional contexts – suggests some level of predictability; instructors of similar courses can plan instruction that addresses or builds on these ideas and expect this instruction to be well-aimed. The specific (sometimes incorrect) rules that students use in the context of combustion reported in this paper can serve as a guide to instructors and curriculum developers.

II. Research Design and Methodology

This specific study was motivated by an initial, informal observation that a small number of students used a specific combustion rule in response to the *powder-on-a-balance question* (Figure 1), which required students to use the principle of conservation of mass [3]. Although the reactant was not given (and thus could have been a non-hydrocarbon), 5% of the students who answered this question explicitly stated that the products were carbon dioxide and/or water. For example:

[Insert Figure 1 about here.]

> *"[Equal to 100 g:] Combustion involves CO_2 [and] H_2O in the form of gas being released from the substance being burned. Since these will still be in the glass container which is on the balance their mass will be accounted for so no mass is lost."*
>
> *"[Equal to 100 g:] When ignited the powder will be converted into CO_2 and H_2O but all of the new molecules will still be on the scale, and matter is neither created nor destroyed so it will weigh the same."*

> *"[Less than 100 g:] If the[re] is a reaction where things are ignited it indicates that the powder must have released CO_2. This means the scale would register less than 100 g since some of the substance is gas."*

In these cases, students seemed to be applying a rule that combustion always produces carbon dioxide and/or water: they did not connect the production of CO_2 and H_2O to hydrocarbon combustion (*i.e.,* a reactant that contains the requisite atoms of the products: hydrogen, carbon, and oxygen). The use of such a rule in non-hydrocarbon contexts would violate the fundamental principle of conservation of atoms, and we wondered whether students would use similar rules in other contexts. This prompted the development of a sequence of open-ended, written conceptual questions that ultimately framed this research study.

Question design. Each question was designed to address a specific research question. First, we developed the *beryllium oxide question* [4] (Figure 2) to determine whether the original 'combustion rule' that we discerned in a small number of student responses to the *powder-on-a-balance question* was (a) prevalent and (b) used in a non-hydrocarbon combustion reaction (*i.e.,* do students use the rule when the specified reactants do not contain carbon or hydrogen?). After administering the *beryllium oxide question* and confirming that the use of the combustion rule was prevalent and inappropriate, we developed three additional questions: the *symbolic beryllium oxide question,* the *unknown chemical question,* and the *burning candle question* (Figures 3, 4 [5], and 5, respectively). The first two were developed to address research questions about reproducibility: do students use the rule that 'carbon dioxide and/or water are always produced in combustion reactions' (1) in symbolic contexts, where the representation signifies the atoms themselves, and/or (2) when the question is asked in reverse, such that the reactants are given to students rather than the products? In the *unknown chemical context,* for example, we expected that students who reason that carbon dioxide and water are the products of *every* combustion reaction may choose *every* reactant given, regardless of its chemical makeup. The *burning candle question* was developed to investigate the extent to which students would use atom conservation to make sense of the production of carbon dioxide and water during a *hydrocarbon* combustion (in which the reactants do contain carbon, hydrogen, and oxygen atoms). Figure 6 summarizes our research design. Note that although "combustion" is a general term that is used to describe an exothermic chemical reaction between a fuel and an oxidant, we chose to use the word "burned" in each of our questions to avoid confusion between our contexts and hydrocarbon combustion. Chemistry faculty at the University of Washington reviewed each question and deemed it appropriate for use on written surveys given in their courses – which covered the topics of stoichiometery, chemical reactions, and basic conservation principles – establishing the face validity of the questions.

[Insert Figures 2-6 about here.]

Correct answers to all four questions rely on appropriate use of the principle of conservation of atoms, which requires that the products in each case be comprised of the atoms of the reactants. The correct answer to the *beryllium oxide question* is (c), beryllium oxide, which contains the atoms of the reactant powder and the oxidizing agent – oxygen – from the air, and the correct answer to the *symbolic beryllium oxide question* is also (c), the balanced chemical equation $2Be + O_2 \rightarrow 2BeO$. The correct answers to the *unknown chemical question* are butane and wood: since the products of the reaction are carbon dioxide and water (made up of carbon, hydrogen, and oxygen atoms), the reactants must also contain carbon, hydrogen, and oxygen. Since oxygen is present in the air, the unknown chemical must contain carbon and hydrogen. This is true only of butane and wood. When a candle burns, as in the *burning candle question*, bonds between the carbon and the hydrogen in the paraffin wax break, and bonds form between carbon and oxygen (to make carbon dioxide) and between hydrogen and oxygen (to make water). Thus, the correct answer to this question is that the amount of oxygen in the container decreases, while the amounts of carbon dioxide and water increase.

Sample. Participants in this study were students in large (1) introductory and (2) advanced introductory chemistry sequences for physical and life science majors at the UW, a large, public university in the Pacific Northwest. Students in the advanced introductory chemistry course at the UW are required to have completed at least one quarter of calculus and the equivalent of a one-year high school chemistry course. The Chemistry Department at the UW estimates that these students constitute the top 10% of all students taking introductory chemistry. Both courses are three-quarter sequences that typically cover topics such as: atomic structure, stoichiometry, solutions and molarity, gases, equilibrium, acids and bases, chemical thermodynamics, electrochemistry, bonding, kinetics, and periodic trends.

Course demographics were not made available to us, so we cannot claim that our sample was representative. However, the questions in this study were included on course assignments and quizzes, and nearly all students in each course responded.

Data collection. Together, the four questions described above were administered to 1173 students in five introductory and advanced introductory chemistry courses (Courses A-E) at the University of Washington. (See Table I.) In some cases, the questions were administered as online surveys; students were given a survey link and responded to questions outside of class. Other questions were given on written quizzes in mandatory recitation sections staffed by teaching assistants. The types of reasoning given by students in response to the written and online questions were similar and thus are not distinguished in the text. Each question was given after all relevant lecture and textbook instruction on stoichiometry and chemical change.

[Insert Table I about here.]

This study was part of an investigation with Institutional Review Board exempt status. The questions were administered in the natural course of classroom activity. Students were informed of the purposes of the study when asked to complete online surveys or written quizzes. Their responses were stored on a secure server. Results reported in presentations or publications are never associated with an individual's name or identity.

Data analysis. We developed an emergent coding scheme (Krippendorff, 2013) on the basis of students' written responses to the *beryllium oxide question* described above. Categories in the scheme described students' reasons for giving a particular response, *e.g.,* the products of a reaction in which beryllium is burned in air are carbon dioxide and water, *because combustion always produces carbon dioxide and water.* We corroborated our original categories by asking the *symbolic beryllium oxide, unknown chemical,* and *burning candle questions* and discerning whether the same categories accounted for patterns in student responses to those questions. We modified and added to our original coding scheme on the basis of this additional data, and returned to the initial data to see whether new codes bore out. Individual student responses were coded (or re-coded) by the first author using our final scheme. A single response received more than one code in cases where student reasoning instantiated more than one category.

As in many other contexts, student reasoning in response to the questions we posed tended to fall into a small number of interpretive categories (Brown & Hammer, 2008;

Heron, 2004a). The consistent recurrence of these categories (Cook, 2002) suggests to us that they represent *common* misunderstandings about combustion. We report the prevalent, cross-contextual patterns in student reasoning in the section entitled, "Student Use of Combustion Rules."

Overview of results. Tables II through V summarize student performance on the four questions. We list the percentages of students who answered each question correctly and incorrectly as well as those who offered *explicit conservation reasoning* to accompany their responses. We interpreted a student response as "with explicit conservation reasoning" when they explicitly articulated (1) that the products must be comprised of the atoms of the reactants (or vice versa) or (2) that the equation must be balanced. Examples of student responses coded in this way are given in Appendix A.

[Insert Tables II-V about here.]

III. Student Use of Combustion Rules

In general, the resounding answer to our research design questions was *yes:* student use of combustion rules was prevalent, reproducible across contexts, and inappropriate (*i.e.,* used to explain non-hydrocarbon combustion). The two most common rules in use were "combustion produces carbon dioxide and/or water" and "oxygen is used by/necessary for/released during combustion." In this section, we report, illustrate, and begin to explain student use of these rules.

Between 4% and 7% of student responses to the *beryllium oxide question* (5% in Course A, 7% in Course B, and 4% in Course C), 4% of student responses to the *unknown chemical question,* and 39% of student responses to the *burning candle question* represent the use of the rule that oxygen is "used by" or "necessary for" combustion and thus corroborate extensive previous research (Andersson, 1990; BouJaoude, 1991; Driver, 1985; Lofgren & Hellden, 2009; Meheut et al., 1985; Ross, 1991; Schollum & Happs, 1982; J. R. Watson et al., 1997; R. Watson et al., 1995). Because this result has been so widely reported in the literature, we limit detailed discussion in this paper to the use of the rule "combustion always produces carbon dioxide and/or water."

a. Use of rule, "Combustion always produces carbon dioxide and/or water."

Between 9% and 44% of the students in Courses A through E answered that carbon dioxide and/or water were the products of the burning reaction in question and justified their answers using statements like, “Combustion produces carbon dioxide and/or water” (see Table VI). That these statements represent the application of a rule – rather than a principle – is particularly evident in answers that violate atom conservation (between 2 and 10% of student responses; see Table VI). For example, in the *beryllium oxide* and *symbolic beryllium oxide questions,* students often excluded beryllium from the products or chemical equations they chose:

> *“[Carbon dioxide and water:] In all combustion problems* H_2O *and* CO_2 *are produced.”* (original beryllium oxide question)
>
> *“[Carbon dioxide and water vapor:] When anything combusts it gives off carbon dioxide and water vapor.”* (original beryllium oxide question)
>
> *“[*$Be + 2O_2 \rightarrow CO_2 + H_2O$*:] combustion equation.”* (symbolic beryllium oxide question)
>
> *“[*$Be + 2O_2 \rightarrow CO_2 + H_2O$*:] combustion equation; always yields* CO_2 *[and]* H_2O*.”* (symbolic beryllium oxide question)

Other students used a combustion rule but also included beryllium oxide as a product (see “partially consistent with conservation of atoms” in Table VI for exact percentages). These responses are particularly puzzling in their simultaneous conservation and non-conservation of atoms. In fact, some of these students explicitly justified their choice of beryllium oxide as a possible product by noting the presence of beryllium at the beginning of the experiment. For example:

> *“[Carbon dioxide, water, and beryllium oxide:] combustion produces carbon dioxide and water, but [I] also assume that beryllium oxide has to be formed because the beryllium can not just go away.”* (original beryllium oxide question)
>
> *“[Carbon dioxide and beryllium oxide:]…Since it is Beryllium powder, the product must give off something [with] beryllium, so Beryllium oxide makes sense. Also, since Beryllium powder is burning, it should produce* CO_2*.”* (original beryllium oxide question)
>
> *“Combustion requires* O_2 *and produces* CO_2 *and* H_2O *and Be cannot be unaccounted for. Therefore [*$2Be + 3O_2 \rightarrow CO_2 + 2H_2O + 2BeO$*] is the right answer.”* (symbolic beryllium oxide question)

Similarly, in the *unknown chemical question,* several students (6%) chose both hydrocarbon and non-hydrocarbon reactants, arguing that all of the reactants were possible since carbon dioxide and water are *always* products of combustion reactions. For example:

> *“[Magnesium, copper, wood, and butane:] Everything that burns in air produces CO2 and H2O[.]”*

> *"[Magnesium, copper, and butane:] These could be the chemical. Since the known is that it produces CO2 and H2O[,] which is the product of combustion. So I'm thinking if any of these chemicals underwent combustion the results would be the two compounds [carbon dioxide and water]."*

Students also applied the combustion rule in the context of hydrocarbon combustion (*e.g.,* in response to the *burning candle* and *unknown chemical questions).* For example, 44% of those students answering the *burning candle question* and 17% of those answering the *unknown chemical question* justified their answers on the basis of a generally-stated rule without explicit indication of its consistency with atom conservation. For example:

> *"[The amount of O_2 will:] Decrease. As the candle burns, it will consume oxygen from the environment around it. [The amount of CO_2 will:] Increase. This reaction is a combustion reaction, and CO_2 is always a product of a combustion reaction. [The amount of H_2O will:] Increase. This is a combustion reaction, and H_2O is always a product of a combustion reaction."* (burning candle context)
>
> *"[Butane:] Butane when reacted with air is a combustion reaction which forms carbon dioxide and water."* (unknown chemical context)
>
> *"[Butane and wood:] In any combustion situation the products are carbon dioxide, these [two] will burn so they will produce carbon dioxide and water[.]"* (unknown chemical context)

These responses are analogous to those that argue that 'oxygen is used during combustion': although true, this response offers no indication of the *reason* this is the case and may in fact mask a misunderstanding of *why* hydrocarbon combustion produces carbon dioxide and water.

In addition, many students who answered the *burning candle question* (15% of the total) used the rule only in the context of carbon dioxide. That is, they claimed that the amount of carbon dioxide in the container increases because it is a product of combustion, and at the same time they argued that the amount of water vapor decreases or remains the same. This suggests that some students were not simply neglecting to mention the underlying conservation principles (if so, they should have also conserved the hydrogen atoms in the wax) but instead were applying a memorized rule that included CO_2 but not H_2O. For example:

> *"[The amount of oxygen will:] decrease – combustion requires oxygen, and therefore the amount of oxygen will decrease…during the reaction. [The amount of carbon dioxide will:] Increase – CO_2 is usually the product of combustion and will therefore increase as the combustion reaction goes on. [The amount of water vapor will have:] No change – No water was in the container at first to be evaporated into vapor."*

> *"The oxygen will decrease; oxygen is used up by the reaction…The CO_2 will increase; reaction produced more CO_2 by burning…The water vapor remains the same. Water in liquid form is converted to vapor."*

Table VI provides the percentages of students in each context whose responses demonstrate use of this combustion rule. Note that our purpose in tabulating percentages is not to suggest that the numbers themselves are representative or reproducible but to demonstrate the relative prevalence of rule use across the contexts we examined. To establish the intuitive plausibility of this coding scheme – and the assignment of particular codes to specific student responses by the first author – Appendix A presents additional examples of student responses that correspond to the categories (rows) in Table VI.

[Insert Table VI about here.]

b. Proposed sources of combustion rule

A few recent articles (M. M. Cooper et al., 2013; Melanie M. Cooper, Grove, Underwood, & Klymkowsky, 2010) separate students' chemistry heuristics into "instructional" and "personal". In particular, Cooper, *et al.,* (2010) describe students' misapplication of the "octet rule," arguing that such "confusions" may be didaskalogenic, or instruction-induced, arising from or reinforced by instruction. We hypothesize that the combustion rules applied by students in this study may be similarly didaskalogenic, particularly in the case of 'carbon dioxide and/or water are always products of combustion.' This rule does not seem to be the kind of thing that one develops on the basis of intuition and everyday experiences; it makes more sense to us that it is the product of overgeneralizations about hydrocarbon combustion, which often serves as the sole example of burning reactions in chemistry courses.

In addition, a limited number of student responses suggest hypotheses about observations or ways of conceptualizing combustion that may support use of combustion rules. In particular, between 0 and 4% of the students in Courses A through E did not choose beryllium oxide as a product and reasoned that the beryllium was *completely burned*. For example:

> *"[Carbon dioxide and water:] Carbon dioxide and water are both common products of a combustion reaction. It is unlik[e]ly that Beryllium oxide forms as it is stated all the powder completely burns…"* (original beryllium oxide question)

> *"[Be + $O_2 \rightarrow CO_2$:] this is because when the powder has burned off, carbon dioxide is released and the Be substance will be completely cancelled out too since it's 'burned off,' in the reaction, you can also note that the oxygen is balanced."* (symbolic beryllium oxide question)

In addition, approximately 1% of the students in each of Courses A through E *did* include beryllium oxide, but indicated that it is present only because the reaction did not go to completion. This implies that students might have been thinking that beryllium oxide was the 'left over' beryllium, and that, had the reaction continued, it, too, would have 'disappeared.' For example:

> *"[Carbon dioxide, water, and beryllium oxide:] because the combustion always result[s in] carbon dioxide and water. In addit[i]on, uncomplete combustion also produce beryllium oxide."* (original beryllium oxide question)
>
> *"[2Be + $3O_2 \rightarrow CO_2 + 2H_2O$ + 2BeO:] The burning of the beryllium is a combustion reaction, which means the products will be CO_2 (g) and H_2O (g). Since not all the beryllium will be vaporized, some of it will remain as blackened soot."* (symbolic beryllium oxide question)

Andersson (1990) describes several models that middle-school-aged pupils use to explain chemical reactions that are consistent with these responses. Two such models are 'disappearance,' where matter is treated as though it can come into and out of existence in chemical reactions, and 'transmutation,' where students respond as though one substance is (inexplicably) transformed into another. University students in our study likewise apply these models to combustion: burning is a mechanism by which reactants disappear or turn into products.

Some students explicitly attributed the production of carbon dioxide to the flames or fire. This was especially true in the *burning candle* context, representing 7% of the students in Course B. For example:

> *"Carbon dioxide will increase because fire produced it. No change [in the amount of water], the candle will neither consume nor produce H_2O."* (burning candle context)
>
> *"There would be an increase in CO_2 because CO_2 is a product of the flame. There would be no change [in the amount of water] because nothing is reacting to form H_2O."* (burning candle context)

These students may be thinking of the flame or the fire as a reactant (Haidar & Abraham, 1991; Hesse III & Anderson, 1992; Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993), rather than as a combination of heat and light (released in the exothermic reaction) and gaseous products.

c. Discussion

The response patterns described in this section often reflect the inappropriate use of *rules* about what takes place during combustion reactions. An expert might expect these rules to flow out of or connect to an understanding of conservation principles: the production of CO_2 and H_2O in many combustion reactions is tied to the presence of carbon, hydrogen, and oxygen atoms in the reactant substances. However, it appears instead that these rules in some cases displace and in other cases inappropriately supplement the application of the principle of conservation of atoms.

IV. Limitations of Our Study

The patterns we report in the previous section arose in multiple contexts and represent our interpretations of large percentages of students' responses – between 9 and 44%, depending on the course. For this reason, we believe that the patterns are not solely artifacts of individual questions. Rather, we believe that they tell us something more fundamental about the difficulties that students encounter when learning about combustion.

However, we acknowledge that there are a number of limitations to our analysis. The generalizability of our study is limited by our inability to determine the representativeness of our sample. However, this limitation is mitigated by: (1) the recurrence of our results across courses and question contexts and (2) our sampling method (including our questions on course assignments and quizzes) which meant that large fractions of each course responded to our questions.

In addition, our data are insufficient to determine on what basis these rules are formulated (*e.g.,* do they emerge from students' interpretations of lecture instruction in chemistry?) or why students might apply them when responding to our questions. We *speculate* that the use of such rules might be plausibly connected both to students' epistemological stance toward learning science as well as to overgeneralizations of demonstrations or examples used in instruction. The former speculation is informed by a significant body of research that suggests that students often think of science as a collection of facts and formulae and therefore approach the learning of science as the memorization and application of such (Hammer, 1994; May & Etkina, 2002; Redish, Saul, & Steinberg, 1998; Songer & Linn, 1991). The latter is based on (1) our understanding that the most commonly-cited examples and demonstrations of burning in introductory chemistry courses involve the combustion of hydrocarbons, and on (2) research on student use of heuristics (M. M. Cooper et al., 2013; Maeyer & Talanquer, 2010; McClary & Talanquer, 2011;

Talanquer, 2006). Together, one might posit that students see the production of carbon dioxide and water in combustion as a *rule* to be memorized and applied in other contexts, without seeking to understand the underlying mechanism for their production (*i.e.,* the rearrangement of constituent atoms). This remains an open question worth exploring further.

The purpose of this study was to report prevalent, cross-contextual student difficulties with combustion. However, others might wonder what variables affect student performance on the questions we have posed. We noted in the Introduction that we have generally found that variables such as amount of instruction, course instructor, and time of day do not seem to affect student performance on the kinds of conceptual questions we often pose (Heron, 2004b, 2013). However, we did notice in this study that students who received paired questions (*e.g.,* both the *beryllium oxide question* and the *burning candle question*) performed better on the *beryllium oxide question* than did students who received this question alone. Although a detailed statistical calculation of the variance attributable to the presence or absence of both questions is beyond the scope of this paper, we note that the presence of both questions may have enhanced student performance. If this is the case, it may artificially diminish the prevalence of some of the response patterns reported in Table VI. More data – and a more detailed analysis – is necessary to separate this effect from that of other possibly confounding variables.

V. Conclusions and Implications for Instruction and Curriculum Development

Introductory chemistry student responses to questions about combustion reflect a tendency to reason on the basis of *rules,* rather than on the basis of *principles.* Specifically, rather than reasoning on the basis of the principle of conservation of atoms, they reason that combustion always produces carbon dioxide and/or water and that oxygen is used by or necessary for combustion. In fact, many of their answers are *inconsistent* with conservation principles, suggesting that in some cases the rule is more salient than the principle.

Our research adds to the existing literature in two significant ways. First, we found that adults in our population often argue that oxygen is used by or required for combustion, a commonly-cited result in the literature on children's ideas about burning (BouJaoude, 1991; Driver, 1985; Lofgren & Hellden, 2009; Meheut et al., 1985; Ross, 1991; Schollum & Happs, 1982; J. R. Watson et al., 1997; R. Watson et al., 1995). Second, to our knowledge, our finding that large percentages of introductory and advanced introductory chemistry students justify their answers with a combustion *rule* that is often inconsistent with conservation principles has not been reported elsewhere. However, it is consistent with recent research (Christian & Talanquer, 2012; M. M. Cooper et al., 2013; Melanie M. Cooper et al., 2010; Kraft et al., 2010; Maeyer & Talanquer, 2010; McClary & Talanquer, 2011; Taber, 2009; Taber & Bricheno, 2009; Talanquer, 2006) in which students treat complex chemical principles as rules to be memorized and is more generally consistent with research about students' epistemological stances toward science learning (Hammer, 1994; May & Etkina, 2002; Redish et al., 1998; Songer & Linn, 1991).

The research described in this paper has a number of implications for instruction and curriculum development. In particular, instructors and curriculum developers can use the patterns in student reasoning we describe to anticipate where students might struggle as they learn about combustion and to design instructional materials that seek to specifically address student difficulties. For example, on the basis of our research, we recommend that instruction on combustion should both: (1) focus on *why* carbon dioxide and water are produced during the combustion of hydrocarbons (*i.e.,* because there are carbon and hydrogen atoms available in the hydrocarbon reactant and oxygen atoms available from the air); and (2) provide salient examples of combustion reactions that do not result in the production of carbon dioxide and water (*e.g.,* burning magnesium or beryllium). It is important to note that the incorrect reasoning patterns we identified persist beyond instruction and arose in multiple contexts. The experience of the Physics Education Group at the UW has been that standard lecture instruction is often insufficient to address these types of difficulties and that instead students must go through the reasoning required to develop and apply the ideas themselves. (This approach is consistent with the constructivist theory of learning (Driver, Asoko, Leach, Mortimer, & Scott, 1994; Driver & Bell, 1986; Fosnot, 1996; von Glasersfeld, 1983).) Thus, we do not suggest that instruction simply incorporate the emphases above into a standard lecture; rather, we suggest the development of instructional activities that offer students an opportunity to actively participate in the construction of an explanatory model for combustion.

In addition, we suspect that students' tendency to use inappropriate rules is not limited to the context of combustion. Instead, we speculate that this is representative of a broader phenomenon in which students treat chemistry learning as the memorization and rote application of facts and formulas rather than as seeking to understand and explain chemical phenomena. This has implications for all of chemistry learning. Not only does it suggest that we should pay attention to and seek to address the incorrect formulation and application of specific rules; we should also seek to foster an epistemologically and metacognitively robust stance toward learning chemistry, as making sense of chemical phenomena using general models and principles.

Finally, the results of this investigation have implications for inquiry into student understanding. The application of the specific combustion rules reported here is only problematic in the context of non-hydrocarbon combustion; in all situations in which hydrocarbons are burned in the presence of oxygen, carbon dioxide and water vapor *are* produced. Thus, students' misunderstandings may be masked by exam or other research questions (such as the *burning candle question*) posed in the context of hydrocarbon combustion. Instructors and researchers may need to ask questions in multiple contexts in order to understand student thinking.

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Appendix A: Examples of coded data

	Context			
	Beryllium oxide question	*Symbolic beryllium oxide question*	*Burning candle question*	*Unknown chemical question*
Examples of "with explicit conservation reasoning"	"Beryllium burning means Be and O are the reactants. The products can only have whatever	"Can't be a, b, d, e because products side contains elements that weren't added on	"[The amount of oxygen will:] Decrease – some of the O_2 in the air is bonding [with] the	"This product could either be wood or Butane. This is because water and carbon

	is in the reactant so Beryllium oxide would be the only possible product from the list.” “None of the other products have Beryllium, which is still an element (e.g., contains only Beryllium) and is only reactant said to burn. You cannot burn Iron filings and get copper oxide.”	the reactant side. Burning something involves adding oxygen so c is best fit, and it’s also balanced.” “I chose (c) because in reactions (a), (b), (d), and (e) there are atoms in the product molecules that are not present in the reactant side. It is not possible to generate, in the case of reaction (b), CO_2 molecules without the presence of carbon atoms in the first place. If one argues that carbon is present in the air and is utilized in the reaction, then it must be included in the reactant side to make the equation valid.”	C and H in the wax to form CO_2 and H_2O. Therefore, less O_2 will be in the air over time.” “[The amount of carbon dioxide will:] Increase – as the wax is burning, the carbons are joining with the O_2 to create CO_2 product. [The amount of water vapor will:] Increase – as the wax is burning, the hydrogen atoms will combine with the O_2 present in the container.”	dioxide are made up of carbon[,] hydrogen[,] and oxygen. The Oxygen comes from the air as O2. However, the Carbon and the Hydrogen must come from one of the reactants. Both wood and butane have carbon and hydrogen in them so they could have been burned.” “Butane is the only possible identity of the chemical because it[‘]s the only one containing Hydrogen and Carbon; we can’t magically create the hydrogen needed for H2O and the carbon needed for CO2, it has to come from the reactants and Butane is the only [one] with H and C.”
Examples of “combustion always produces carbon dioxide and water”:				
“in no way consistent with conservation of atoms”	“[Carbon dioxide and water:] In combustion reactions, the products are carbon dioxide and water!!” “[Carbon dioxide and water:] Combustion forms carbon dioxide and water, and this is a combustion reaction since the beryllium powder is being burned.”	“[$Be + 2O_2 \rightarrow CO_2 + 2H_2O$:] When something combusts, O_2 is always a reactant [and] $CO_2 + H_2O$ is a product.” “[$Be + 2O_2 \rightarrow CO_2 + 2H_2O$:] It[‘]s a combustion reaction O_2 is always a reactant [and] CO_2 [and] H_2O are always products.”	---	---
“partially consistent with conservation of atoms”	“[Carbon dioxide and beryllium oxide:] Carbon dioxide and beryllium oxide are possible products after beryllium is burned be-	“[$2Be + 3O_2 \rightarrow CO_2 + 2H_2O + 2BeO$:] A combustion [reaction] produces CO_2 [and] H_2O and since the Be has to	---	“[Magnesium, copper, and wood:] Carbon dioxide and water are products of combustion.” “[Magnesium, cop-

	cause this is a combustion reaction. Whenever there is combustion involved, it will produce CO2. Beryllium can't be completely gone so Beryllium oxide could result since there is gas involved and is released." "[Carbon dioxide and beryllium oxide:]…Since it is Beryllium powder, the product must give off something [with] beryllium, so Beryllium oxide makes sense. Also, since Beryllium powder is burning, it should produce CO_2."	go somewhere it must be on both sides of the [reaction] in a different form." "[$2Be + 3O_2 \rightarrow CO_2 + 2H_2O + 2BeO$:] The burning of the beryllium is a combustion reaction, which means the products will be CO_2 (g) and H_2O (g). Since not all the beryllium will be vaporized, some of it will remain as blackened soot."		per, butane, and wood:] Any combustion reaction, involves Carbon Dioxide and water as some of the products. Since it did not say that carbon dioxide and water are the ONLY products of the reaction, it is possible that any one of the 4 choices could have been what was burned."
"consistent with conservation of atoms but interpreted as rote application of rule"	---	"[$C + Be + 4O_2 + H_2 \rightarrow CO_2 + H_2O + BeO$:] The only balanced equation is c, but when things burn, CO_2 and water are typically products, which means that their components must also be reactants. There is hydrogen in the air, so we know it is a reactant."	"[The amount of oxygen will:] Decrease – the candle needs oxygen to burn. [The amount of carbon dioxide will:] Increase – oxygen is converted to CO_2 as the candle burns. [The amount of water vapor will:] Increase – water vapor is a by-product of combustion." "[The amount of oxygen will] decrease; combustion consumes the oxygen. [The amount of carbon dioxide will] increase; CO_2 is a byproduct of combustion. [The sensor for water vapor will detect] no change; doesn't affect water vapor."	"[Butane:] Butane when reacted with air is a combustion reaction which forms carbon dioxide and water." "[Butane and wood:] This is a combustion reaction, therefore Butane is a valid answer since CO2 and H2O are always products of a combustion process, and a hydrocarbon is always a reactant. Wood is also an applicable answer because it gives off steam and carbon dioxide, it may not be a hydrocarbon though as far as my knowledge goes."

Authors

- **Amy D. Robertson** is a Research Assistant Professor in the Department of Physics at Seattle Pacific University. Her research interests include research paradigms and methodologies in physics education research, responsive teaching, the development of curricular knowledge among novice teachers, and issues of identity and empowerment.
- **Peter S. Shaffer** is a Professor in the Department of Physics at the University of Washington. His research focuses on the learning and teaching of physics and physical science among populations that range from preservice and inservice teachers to beginning and advanced undergraduates in university physics courses.

Endnotes

1. Although it is true that only certain materials can burn, the classification schemes used by these students did not reflect this sophisticated view. Rather, students used visual cues to characterize a reaction as burning (e.g., the appearance of a flame) or melting (e.g., a decrease in the level of liquid).
2. Our research group has a long history of success in the design and dissemination of research-validated, effective instructional materials that include strategies for specifically addressing student difficulties (L. C. McDermott, Shaffer, & Washington, 2011; L. C. McDermott & Washington, 1995, 1996).
3. Early in our study, we gave students enrolled in an advanced introductory chemistry course (a population described more fully below) a quiz that included the *powder-on-a-balance question* (reproduced in Figure 1), a modified version of an end-of-chapter question from their course textbook, *Chemical Principles* (Zumdahl, 2009) and similar to questions reported elsewhere (e.g., Andersson (1990)). The correct answer to this question is (c): since the system is closed, the mass of the system will remain the same, regardless of the chemical process that occurs. A majority of the students (75% of the 257 who answered the question) gave the correct answer.
4. There were rare cases in which students either stated (or questioned) that beryllium is a compound or that the combustion reaction involves other elements from the air (*i.e.,* there were rare cases in which students created a situation that conserves atoms and produces carbon dioxide and water vapor when beryllium burns). In such cases, we categorized the student's response as incorrect but "with explicit conservation reasoning."
5. The *unknown chemical question* did not state explicitly that carbon dioxide and water are the only products of the reaction. The reader may wonder whether any of the students who chose

magnesium or copper imagined a reaction that produced carbon dioxide, water, *and* copper or magnesium. Only three students (of the 235) chose Mg or Cu and supported their answer with such reasoning.

6. Table IV shows that 31% answered correctly that both butane and wood could have been the 'unknown chemical.' Many students chose butane as a possible reactant but not wood. We can think of several reasons that this may be the case: (1) Students may have missed our request that they select *all* possible reactants. (2) Students may not consider wood a 'chemical.' This was indicated explicitly by only 4 of the 235 student responses, but it may have implicitly affected a greater number. For example, a study with university chemistry students (Nicoll, 1997) indicated that students often have alternative interpretations of the word "chemical" (*e.g.,* chemicals are unhealthy substances). (3) Students may not know that wood is a hydrocarbon. For these reasons, we regard the 89% figure for those who chose butane and/or wood as correct.
7. 34% of the introductory chemistry students and 57% of the advanced introductory students who answered the *symbolic beryllium oxide question* did not provide reasoning for their responses. Many students who chose answer choices (a), (b), and (d) – all consistent with the use of a combustion rule – gave no reasoning. Thus, we hypothesize that the percentages of students using a combustion rule, as well as the percentages of students who provided explicit conservation reasoning, are underestimates.

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Tables

Table I. Populations that received each written question

	Populations
Beryllium oxide question	Courses A, B, and C: Introductory chemistry students (N = 831)
Symbolic beryllium oxide question	Course D: Introductory chemistry students (N = 250) Course E: Advanced introductory chemistry students (N = 92)
Unknown chemical question	Course B: Introductory chemistry students (N = 229)
Burning candle question	Course C: Introductory chemistry students (N = 235)

Table II. Percentages of students who chose each product in response to the *beryllium oxide question*

	Introductory chemistry students (*N* = 831)		
	Introductory chemistry students, Course A (*N* = 367)	Introductory chemistry students, Course B (*N* = 229)	Introductory chemistry students, Course C (*N* = 229)
Only beryllium oxide (correct)	**44%**	**58%**	**69%**
With explicit conservation reasoning	22%	21%	34%
Only products other than beryllium oxide (total)	**17%**	**7%**	**7%**
Only carbon dioxide	7%	3%	2%
Both carbon dioxide and water	7%	3%	3%
Beryllium oxide plus other products (total)	**35%**	**34%**	**20%**
Beryllium oxide and carbon dioxide	12%	13%	5%
Beryllium oxide and water	3%	6%	1%
Beryllium oxide, carbon dioxide, and water	7%	13%	6%
None of the above.	**4%**	**2%**	**5%**

[a] In all tables, percentages reported in regular (non-bold) text are percentages of the total, not percentages of bolded text.

Table III. Percentages of students who selected each chemical equation in response to the *symbolic beryllium oxide question*

	Introductory chemistry students, Course D (*N* = 250)	**Advanced introductory chemistry students, Course E (*N* = 92)**
$2Be + O_2 \rightarrow 2BeO$ (correct)	**49%**	**71%**
With explicit conservation reasoning	23%	16%
Only products other than beryllium oxide (total)	**13%**	**5%**
$Be + O_2 \rightarrow CO_2$	6%	---
$Be + 2O_2 \rightarrow CO_2 + 2H_2O$	8%	5%
Beryllium oxide plus other products (total)	**30%**	**13%**
$2Be + 3O_2 \rightarrow CO_2 + 2H_2O + 2BeO$	21%	11%
$2Be + 4O_2 \rightarrow 2BeO + NO_2 + 2H_2O + CO_2$	6%	2%
Other. (Students chose to write their own chemical equation.)	**4%**	**7%**

Table IV. Percentages of students who chose each reactant in response to the *unknown chemical question*

	Introductory chemistry students, Course C (*N* = 235)
Only hydrocarbons (total, correct)	**89%** [6]
Butane and wood	31%
Butane only	55%
Wood only	3%
With explicit conservation reasoning	50%
Only non-hydrocarbons (*e.g.*, only copper)	**3%**
Combination of hydrocarbons and non-hydrocarbons	**8%**

Table V. Percentages of students who indicated changes in amounts of oxygen, carbon dioxide, and water vapor in response to the *burning candle question*

	Introductory chemistry students, Course B (*N* = 229)
Oxygen	
Decreases (correct)	95%
Increases	2%
Remains the same	3%
Carbon dioxide	
Increases (correct)	95%
Decreases	3%
Remains the same	2%
Water vapor	
Increases (correct)	79%
Decreases	5%
Remains the same	13%
Correct on all three	**73%**
With explicit conservation reasoning	34%

Table VI. Percentages of students who used each rule in the *beryllium oxide, symbolic beryllium oxide, unknown chemical,* and *burning candle contexts*

	Beryllium oxide question			***Symbolic beryllium oxide question***		***Burning candle question***	***Unknown chemical question***
	Intro chem students ($N = 831$)						
	Course A ($N = 367$)	Course B ($N = 229$)	Course C ($N = 229$)	Intro chem students, Course D ($N = 250$)	Advanced intro chem students, Course E ($N = 92$)	Intro chem students, Course B ($N = 229$)	Intro chem students , Course C ($N = 235$)
Correct answer with explicit conservation reasoning	**22%**	**21%**	**34%**	**23%**	**16%**	**34%**	**50%**
"Combustion always produces carbon dioxide and/or water."	**25%**	**27%**	**12%**	**22%** [7]	**9%**	**44%**	**23-25%**
In no way consistent with conservation of atoms (*e.g.,* students chose only CO_2 and/or H_2O as products of beryllium combustion)	10%	5%	5%	7%	2%	---	---
Partially consistent with conservation of atoms (*e.g.,* students chose BeO, CO_2, and H_2O as products of beryllium combustion)	15%	22%	8%	13%	4%	---	6%
Consistent with conservation of atoms but interpreted as rote application of rule (*e.g.,* students answered that burning candle produces CO_2 because combustion always produces CO_2)	---	---	---	---	2%	44%	17%

Figure captions

Figure 1. *Powder-on-a-balance question,* adapted from *CHEMICAL PRINCIPLES,* Sixth Edition, Student Edition. Copyright © 2009 by Houghton Mifflin Company. All rights reserved. Reproduced by permission of the publisher, Houghton Mifflin Harcourt Publishing Company.

Figure 2. *Beryllium oxide question*

Figure 3. *Symbolic beryllium oxide question.* The specific answer choices in this question were based on the most common student responses to the original *beryllium oxide question* (Fig. 2).

Figure 4. *Unknown chemical question*

Figure 5. *Burning chemical question*

Figure 6. Design of written questions