

Good Use of a ‘Bad’ Metaphor

Entropy as Disorder

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Published online: 27 April 2017

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Abstract Entropy is often introduced to students through the use of the disorder metaphor. However, many weaknesses and limitations of this metaphor have been identified, and it has therefore been argued that it is more harmful than useful in teaching. For instance, under the influence of the disorder metaphor, students tend to focus on spatial configuration with regard to entropy but disregard the role of energy, which may lead their intuition astray in problem solving. Albeit so, a review of research of students’ ideas about entropy in relation to the disorder metaphor shows that students can use the metaphor in developing a more nuanced, complex view of the concept, by connecting entropy as disorder to other concepts such as microstates and spreading. The disorder metaphor—in combination with other explanatory approaches—can be used as a resource for learning, in giving students an early flavour of what entropy means, so long as we acknowledge its limitations; we can put this “bad” metaphor to good use in teaching.

1 Introduction

Analogical thought—projection of aspects of what we know onto the unknown—has been identified as an essential aspect of human cognition (Gentner 2003; Hofstadter 2001). Consequently, analogies and metaphors have also been found to be valuable resources in science (Hesse 1966) and in science education (Duit 1991).

The immediate attraction of metaphors and analogies, however, also holds the seed of their main weakness. A powerful metaphorical expression locks our thoughts in one particular pattern, which emphasises certain aspects but downplays others. In addition, a listener, such as a student in school, with his/her particular knowledge and experiences, may interpret a metaphor—or a corresponding more elaborate analogy—in a different way that what the speaker had intended. In this way, Glynn (1989) has characterised analogies as ‘double-edged swords’ in science education. In order to help students interpret analogies and metaphors,

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teachers need to point out the explicit correspondences between the compared domains, how far they can be pushed, and where they break down.

In an editorial in *Science & Education*, Kampaourakis (2016) invited articles on the theme of ‘the bad use of metaphors and the use of bad metaphors in science education and communication’. Heeding this call, the present study discusses a metaphor that is common in science teaching, but nevertheless has received a lot of criticism: entropy as disorder.

2 Entropy and the Disorder Metaphor

Clausius (1867) coined the term ‘entropy’ for a physical quantity, S , that he introduced, as part of formulating the second law of thermodynamics in relation to heat and temperature, with the expression: $dS \geq \delta Q/T$. He derived entropy from the Greek word ‘τροπή’ (tropé), meaning ‘transformation’, following his investigation of transformations between heat and work. Although primarily laying the ground for macroscopic thermodynamics, Clausius’ approach to entropy also involved microscopic considerations (Pellegrino et al. 2015), as he named one of its constituent terms ‘disgregation’:

By disgregation is represented... the degree of dispersion of the body. /.../ The disgregation of a body is fully determined when the arrangement of its constituent particles is given (Clausius 1867, p. 226).

The disorder metaphor for entropy was introduced as a microscopic interpretation of the quantity. Baierlein and Gearhart (2003) trace the metaphor back to von Helmholtz (1883, p. 972):

Unordered motion, in contrast, would be such that the motion of each individual particle need have no similarity to that of its neighbours. We have ample ground to believe that heat-motion is of the latter kind, and one may in this sense characterise the magnitude of the entropy as the measure of the disorder.

Similarly, Boltzmann (1896/1964) related entropy to ‘molecular disorder’ and Gibbs (1906) explained entropy in terms of ‘mixed-up-ness’, as part of the development of statistical mechanics.

After its use within disciplinary science in the late nineteenth century, entropy as disorder has been adopted as a common metaphor in thermodynamics teaching, as a qualitative way to introduce this abstract concept. The metaphor ‘entropy is disorder’ has been developed into more explicit analogies. For instance, a thermodynamic system can be compared to a child’s room—there are more possible disorderly states where the clothes and toys are randomly lying around than there are ordered states where the clothes and toys are carefully stowed away at their designated places—or a deck of cards.

The metaphor can be useful for students to understand entropy of mixing. When two liquids of different substances are mixed, the total entropy of the liquids increases, since there are more possible configurations of the particles and energy involved. This process can be interpreted as change from an ordered state, where the liquids are held separated, to a more disordered state, where the liquids are allowed to mix together. The metaphor can serve as a heuristic to realise that the entropy of a system increases—goes from a more ordered state to a disordered state—as heat is added to the system, so that its temperature increases, and that it undergoes phase changes from solid to liquid, and from liquid to gas. Similarly, it can be used to make plausible endothermic chemical reactions, which can be spontaneous only under the condition of entropy increase, for instance through production of—disorderly—gas molecules. However, in spite of its wide use in the teaching practice, the disorder metaphor has received strong criticism in science and educational debates due to important shortcomings.

3 Criticisms of the Disorder Metaphor

Blin-Stoyle et al. (1959, p. 50) introduced entropy in the following way: “Entropy essentially measures the degree of disorder in a physical system”. In a review of this book, Dingle (1959, p. 218) offhandedly dismissed the description as: “a most inessential visualization which has probably done much more harm than good”. More recently, Lambert (2002a) acknowledged that the disorder metaphor may have served as a ‘crutch’ for Boltzmann and others in achieving a statistical interpretation of entropy, but he regarded the metaphor as a ‘cracked crutch’ in science teaching and advised strongly against its use. This has received attention among textbook authors, as Lambert (2014) presented a list of: “The 36 Science Textbooks That Have Deleted ‘disorder’ From Their Description of the Nature of Entropy”. Similarly, Wei et al. (2014, p. 330) considered the metaphor as the main reason for students’ confusion with regard to entropy: “Ultimately, however, it is the pervasive yet inappropriate use of the disorder metaphor for entropy that has prevented more widespread incorporation of the second law into student thinking.”

So, what are the grounds for seeing entropy as disorder as a bad metaphor for teaching? The criticism of the metaphor is typically based on theoretical weaknesses and limitations, including:

- ‘Disorder’ is a vague, emotionally charged word, with many possible interpretations (Styer 2000).
- The disorder metaphor emphasises spatial configuration of the constituent particles of a system, but tends to neglect the role of energy (Lambert 2002b, 2007; Alonso and Finn 1995; Brosseau and Viard 1992).
- The messy room analogy and other examples, such as a particular poker hand, give a single snapshot view, rather than showing the large number of microstates, i.e. the multiplicity, of a high entropy system (Lambert 2002a; Styer 2000).
- There are several physical phenomena and processes where increasing entropy co-occurs with increasing visual order (Wright 1970), such as the formation of the ‘smectic’ state of liquid crystals where molecules are oriented regularly in sheets (Lambert 2002a; Styer 2000).
- Order is easily confused with organisation or complexity, which is problematic in particular in biology, where increasing complexity often comes hand in hand with increasing entropy (Haitun 1991).
- The disorder metaphor has limited value within macroscopic thermodynamics, where particle interaction is not considered. Leff (1996) considered the metaphor as ‘entirely mysterious’ in relation to the expression $dS = dQ_{rev}/T$. In particular, disorder fails to convey the extensive character of entropy, i.e. that it is dependent on the size of a system (Wright 1970; Lambert 2002a). Two moles of hydrogen gas have twice the entropy of 1 mol of hydrogen gas at the same temperature and pressure, but it does not come across as more disordered.

Complementing this theoretically founded criticism, there are also empirical studies of how the metaphor may hinder students in grasping the entropy concept and using it in problem solving. Johnstone et al. (1977) found that upper secondary pupils who had taken thermodynamics in chemistry tended to associate entropy with disorder, but did not manage to go beyond this in their understanding of the concept. Similarly, in their analysis of undergraduate chemistry students’ responses to a questionnaire and interviews in relation to entropy, Sözbilir and Bennett (2007) identified students’ connection of entropy to disorder as one of the main misunderstandings of the topic. In particular, the students tended to focus on visual disorder.

Brosseau and Viard (1992) asked university physics students what happens to entropy as a system undergoes reversible, adiabatic expansion, i.e. without exchange of heat with the surroundings. Only one out of ten students answered correctly that the entropy remains unchanged. Instead, most students intuitively answered that the entropy increases. They explained the students' erroneous line of reasoning with an association between increased volume and more disorder, without consideration of the reduced internal energy and temperature of the system as a consequence of the work it performs on its surrounding. In our research, we have found similar intuitions in relation to entropy change of adiabatic expansion among physics teacher students (Haglund and Jeppsson 2012, 2014) and chemical engineering students (Haglund et al. 2016). These studies lend support to Lambert's (2002a) argument that the disorder metaphor leads to over-emphasis of the role of spatial configuration in entropy change.

In interviews with participants in an introductory physics course for life science students on the second law of thermodynamics, Geller et al. (2014) found a tension between students' ideas of entropy in terms of a tendency towards increasing disorder and their knowledge of spontaneous formation of organisation, such as micelle formation. This provides empirical support to Haitun's (1991) argument with regard to disorder and complexity in biology. In addition, students were found to identify disorder with colloquial interpretations of chaos, which at times misled them in understanding thermal processes (Geller et al. 2014).

4 In Defence of the Disorder Metaphor

Against the background of this substantial criticism, one may wonder whether the disorder metaphor for entropy is salvageable; clearly many scholars argue that it does more harm than good. However, I would like to counter these views with some arguments in its favour.

Lambert (2002b) argued that 'entropy is simple, qualitatively', if it is explained macroscopically as a measure of the dispersal of energy and microscopically as the number of microstates of a system, and Leff (2012) set out 'removing the mystery of entropy' by relating it to the spreading of energy. Similarly, Ben-Naim (2007) proclaimed 'entropy demystified' and promised to reduce it to 'plain common sense' by interpreting it as identical to information. In contrast to these views of entropy as simple, provided that you explain it properly, I regard entropy as a genuinely challenging concept for students to grasp, due to its abstract, complex, and mathematical nature. In general, metaphors are promising for approaching such abstract concepts, in order to give a first flavour of their meaning. Even though Styer pointed out many of its shortcomings, he nevertheless found merit in using the disorder metaphor:

Disorder is a metaphor for entropy, not a definition for entropy. Metaphors are valuable only when they are *not* identical in all respects to their targets. /.../ The metaphor of disorder for entropy is valuable and thus imperfect (Styer 2008, p. 1031).

But this is obviously not the end of the story; if entropy is introduced as disorder, eventually the metaphor has to be unpacked and operationalised:

There is usually nothing wrong with referring to entropy as a measure of disorder. The phrase however, does not take one very far. To gain precision and something quantitative, one needs to connect disorder with 'absence of correlations' and then with multiplicity (Baierlein 1994, p. 24).

Geller et al. (2014) found that life science students face challenges in making sense of the disorder metaphor for entropy, but adopting a resources theoretical framework (Hammer 2000), they regard students' intuitive ideas as resources for learning. Students may initially

invoke resources in ways that lead to incorrect conclusions, but the goal of teaching is for students to use the resources more productively and refine their understanding of when and how to apply them:

For example, we do not seek to entirely eliminate student use of the ‘disorder’ metaphor for entropy, even if the metaphor is too vague to yield correct predictions in many complicated scenarios. Instead, our goal is to refine student ideas about disorder and build on them to develop a deeper and more coherent framework, one that increases the likelihood that students will use the metaphor productively (Geller et al. 2014, p. 395).

In particular, they show how students can leverage their interpretation of entropy as disorder and chaos in refining their understanding of the concept, and explaining phenomena such as diffusion and spontaneous separation of oil and water.

Let us take a closer look at another case of how students can make use of the disorder metaphor to develop and refine their understanding of entropy. As part of a study of undergraduate engineering students’ ideas of entropy, we asked them to answer questionnaires before and after a course in chemical thermodynamics (Andersson et al. 2015; Haglund et al. 2015). We asked the students to: explain what entropy means; list other scientific concepts that they relate to entropy; and—after the course—how their understanding had developed during the course. Before the course, 67% of students made use of the disorder metaphor in one way or another in their explanations. During the course, the lecturer explicitly pointed out limitations of the disorder metaphor. This included processes where increasing entropy comes together with visual order. For example, he compared formation of liquid crystals to placing books in a box; they will be able to move about more freely if they are orderly layered than if they are placed disorderly and interlocking each other. Nevertheless, an even larger percentage of the students, 77%, related entropy to disorder in their explanations after the course. However, many of them had developed a more thoughtful view, for example: “I have realised that entropy cannot always be described as the degree of disorder in a system”, and “In the beginning of the course I saw entropy as ‘disorder’. Now I have a more nuanced view on entropy... /.../ Entropy is the possibility for molecules to move/spread. High entropy = large possibility to spread in space” (Haglund et al. 2015, p. 545).

Even though the majority of students explained entropy in terms of disorder, none of them mentioned disorder as one of the scientific concepts they related to entropy (the most common answers were enthalpy and Gibbs free energy). In our view, in line with Styer (2008), this reveals an awareness that entropy as disorder should be interpreted metaphorically, and not as a definition (Haglund et al. 2015).

We further compared individual students’ answers before and after the course. Some students, probably with a superficial understanding of entropy beforehand, adopted the disorder metaphor. A dominant trend, however, was that students developed a more complex view, where they used the disorder metaphor in conjunction with other microscopic interpretations, such as relating entropy to microstates or spreading (Haglund et al. 2015). A few students, in particular on study programmes where they had taken many credits in chemistry prior to the course, abandoned the disorder metaphors in their explanations, and opted for more formal descriptions, involving for example the number of microstates (Andersson et al. 2015). To borrow Lambert’s (2002a) term, the crutch had served them well throughout their education, but they no longer needed it.

In spite of these trends in students’ explanations of entropy, we found no significant correlations between their use of disorder in their explanations before or after the course, and their exam results. This may indicate disconnection between the exam—which was

dominated by quantitative problem solving—and qualitative, conceptual understanding, or possibly that the disorder metaphor was neither particularly harmful, nor helpful (Haglund et al. 2015).

In a subsequent interview study, a year after the course, we asked students in pairs to rank a list of words or expressions—such as heat, the second law of thermodynamics, and disorder—with regards to how closely related to entropy they are; how scientific they are; and how useful they are for explaining what entropy is. The students found disorder to be highly unscientific, but closely related to entropy and very useful for explaining what entropy is. One of the students recalled the example of placing books in layers in a box as an ordered high entropy system, but considered this an exception and the disorder metaphor to be applicable ‘in 2000 cases against one’ (Haglund et al. 2016, p. 498).

5 How to Use the Disorder Metaphor in Science Education

It is a natural response to refrain from using the disorder metaphor in teaching because of its amassed weaknesses and limitations. I think that this would be unfortunate, however, as the metaphor gives a flavour of what entropy means when students are first introduced to this concept. As argued by Geller et al. (2014), students can be helped to use the disorder metaphor in a productive way in developing their understanding of entropy. Then again, as teachers, we have to be aware of the limitations of every metaphor, analogy, or explanatory model we use in our teaching, and invite our students to scrutinise them. Entropy as disorder is not an exception to this rule. Glynn (1989) proposed the following approach to ‘Teaching With Analogies’ (TWA):

- Introduce the target concept
- Recall the analogue concept
- Identify similar features of the concepts
- Map similar features
- Draw conclusions about the concepts
- Indicate where the analogy breaks down

While an apt metaphorical expression typically has some suspense and leaves its interpretation to the listener or reader (Duit 1991), with TWA the involved domains (in our case disorder and entropy) and the correspondences between them have to be pointed out and be explained explicitly. In other words, if we are to use the disorder metaphor in teaching, we have to give sufficient information of what entropy is in the context of a thermodynamic system, what sense of disorder we refer to, and how they are meant to be related to one another.

Given students’ challenges in problem solving (e.g. Brosseau and Viard 1992), it is important to point out that the interpretation of disorder should not be confined to spatial configuration or a single snapshot. In this regard, I find Pflug’s (1983) distinction between a spatial ‘desktop disorder’ and a more dynamic ‘disco disorder’ quite striking. Also Atkins (2003) emphasised that an entropy increase can be due to increased thermal disorder, as well as positional disorder (cf. Lambert 2007 for critique of distinguishing configurational entropy). Atkins (2003, pp. 122–123) further offered an analogy between heating a thermal system and sneezing in a busy street versus in a quiet library as a way to connect macroscopic and

microscopic interpretations of entropy. In explaining the analogy, he carefully pointed out the correspondences across the domains, in terms of disorder and energy:

A sneeze is like a disorderly input of energy, very much like energy transferred as heat. It should be easy to accept that the bigger the sneeze, the greater the disorder introduced in the street or in the library. That is the fundamental reason why the ‘energy supplied as heat’ appears in the numerator of Clausius’s expression, for the greater the energy supplied as heat, the greater the increase in disorder and therefore the greater the increase in entropy. The presence of the temperature in the denominator fits with this analogy too, with its implication that for a given supply of heat, the entropy increases more if the temperature is low than if it is high. A cool object, in which there is little thermal motion, corresponds to a quiet library. A sudden sneeze will introduce a lot of disturbance, corresponding to a big rise in entropy. A hot object, in which there is a lot of thermal motion already present, corresponds to a busy street. Now a sneeze of the same size as in the library has relatively little effect, and the increase in entropy is small.

Nonetheless, as all metaphors, seeing entropy as disorder breaks down at one point, where it no longer has explanatory value. If used in teaching, we should provide such examples of shortcomings of the disorder metaphor. The comparison of formation of liquid crystals with placing books in ordered layers in a box provided by the teacher in chemical thermodynamics (Haglund et al. 2015) is a good example.

Apart from entropy as disorder—and often as alternatives to this metaphor—several other metaphors have been proposed for explaining the concept qualitatively in teaching (Jeppsson et al. 2011). As we have seen, Leff (1996, 2012) and Lambert (2002a, b) proposed seeing entropy as the spreading of energy, an idea that also has attracted other scholars (Denbigh 1989; Wei et al. 2014; Guggenheim 1949). This metaphor is valuable in connecting entropy to the tendency for energy to spread out in space and across microstates in time within a system, until it reaches thermal equilibrium. Like the disorder metaphor, however, seeing entropy as spreading also has limitations. In our study in relation to the chemical thermodynamics course, we found that students that related entropy to spreading—just like for disorder—tended to focus on spatial configuration in terms of spreading of particles, rather than spreading of energy (Haglund et al. 2015). Clausius’ (1867) interpretation of one of the terms of entropy as ‘disgregation’—dispersal of particles—seems to point to a similar direction.

The disorder metaphor primarily emphasises microscopic aspects of entropy, and therefore downplays macroscopic aspects, such as its extensive, size-dependent character. In his investigation of the theoretical limitations to the efficiency of heat engines, Carnot (1824) used an analogy between a waterfall and a heat engine: The height of the waterfall corresponds to the temperature difference between two thermodynamic systems, and the weight or mass of the water corresponds to the heat that is transferred between the systems. In reference to Carnot’s analogy between mechanical and thermal phenomena, Trevor (1899) suggested interpreting entropy as the ‘heat-weight’ of a thermal system. More recently, Kaper and Goedhart (2005) developed a teaching sequence on entropy that takes the waterfall analogy as its starting point. Steinour (1948) extended and generalised the analogy of transfer of quantities that are driven by potential differences to other domains (e.g. an electric current driven by voltage, a difference in electric potential), and interpreted entropy as a carrier of energy. A similar approach has been adopted within the Karlsruhe Physics Course (Falk et al. 1983; Herrmann 2000), in which Herrmann (2004) suggested interpreting entropy as the everyday understanding of heat¹: “The higher the temperature of an object, the more entropy is

¹ In this everyday understanding of heat a warm object can be conceived of as containing heat, not to be confused with the scientific interpretation of heat in thermodynamics in terms of exchange of energy between two thermodynamic systems due to a temperature difference.

contained in it. The greater the mass of an object, the more entropy is contained in it” (p. 38). Although unorthodox in physics and chemistry—and possibly challenging to reconcile with the challenge of realising that entropy is a non-conserved quantity (Christensen et al. 2009)—seeing entropy as everyday heat clearly brings its extensive character to the fore.

More generally, Spiro et al. (1989) proposed the use of multiple analogies, i.e. a combination of several analogies, in the teaching of complex phenomena, and presented the case of the physiology of muscle cells. As a parallel, due to the multi-faceted character of entropy, we see merit in using a combination of complementary metaphors—which emphasise different aspects—when introducing the concept (Jeppsson et al. 2011). For instance, Styer (2000) argued for a combination of the disorder metaphor and seeing entropy as freedom, partly because the negative connotations of the former are balanced by positive connotations of the latter. In this regard, in the questionnaire after the course in chemical thermodynamics presented above, several students related disorder to the freedom of particles to move in their explanations of what entropy means (Haglund et al. 2015).

The disorder metaphor, and other metaphors, may be used to give students a qualitative understanding of what entropy means. As pointed out by Baierlein (1994) and others, however, this is only the starting point. Eventually, this qualitative interpretation has to be complemented by formal treatment of the quantity, macroscopically and microscopically. In this respect, Baierlein (1994) and Schoepf (2002) argued in favour of a microscopic approach to thermal physics, in which entropy is introduced through Boltzmann’s approach to the multiplicity of microstates.

In conclusion, I would argue that the disorder metaphor—in conjunction with other explanatory approaches—can be used to give students an initial, qualitative interpretation of what entropy means, so long as we acknowledge its limitations; we can put this ‘bad’ metaphor to good use in teaching.

Compliance with Ethical Standards

Conflict of Interest No potential conflict of interest was reported by the authors.

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