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When metaphors come to life – at the interface of external representations, molecular phenomena, and student learning

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Abstract

Grasping the dynamics of molecular phenomenon appears to be rather challenging for students in the context of life science. To pursue the origin of such difficulties this paper investigates students' (n=43) meaning making, in interaction with peers and an animation, of the dynamic process of ATP-synthase. To support this inquiry we introduce the CharM-framework (Characteristics of Metaphors), which accounts for students' experiences of metaphors while interacting with external representations (ERs) when trying to make meaning of molecular phenomena. Student-expressed metaphors are outlined and related to the animator's intentions while designing the animation. The analysis shows that some of the used metaphors possess in-built problematic characteristics that could act as potential problems for learning. For example, the metaphors machine and watermill possess problematic characteristics that are a possible reason for students' difficulties with understanding the ATP-synthesis as a reversible and non-deterministic process. Furthermore, we also conclude that students' use of metaphors is highly influenced by the ER, which is designed according to the animator's internal representation of the scientific phenomenon and his intentions. The challenge associated with designing educational representations that sufficiently represent molecular processes is somewhat similar to the challenge student face while linking the characteristics of metaphors to the molecular processes. The CharM-framework can assist in the design process by allowing designers to reflect on how ERs could be interpreted or misinterpreted and also guide teachers' choice of educational representations.

Key words: affordance, design of external representations, higher education, metaphors, and molecular phenomena.

1 Introduction

When studying the molecular aspect of the life sciences, learners must be introduced to somewhat inaccessible phenomena that occur at the sub-microscopic scale. Despite the difficulties, students need to be familiar with and understand the highly dynamic nature of imperceptible molecular processes. Thus, external representations[1] (ERs) can be considered unavoidable and essential tools for student learning. In previous studies we found clear alignment among identified student difficulties with understanding a dynamic molecular process while interacting with an ER. The studies investigated how the ERs, an animation and a physical model respectively, affected students' understanding of the ATP-synthesis (Stadig Degerman & Tibell, 2012) and the process of self-assembly (Larsson, Höst, Anderson, & Tibell, 2011). In particular, students exhibited difficulties in predicting the reversibility of the highly dynamic processes. In an attempt to seek the origin of such students' difficulties we turn to students' use of metaphors in their meaning making of molecular processes. Both teachers and learners use metaphorical language as a way to relate molecular phenomena to more familiar ones from everyday life. Metaphors transfer a concept from one source domain to a new target domain.[2] Scientific papers, as well as textbooks and popular science articles, are packed with metaphors, analogies and intentional expressions. Like ERs, the use of metaphors and analogies is inevitable and necessary when communicating knowledge concerning molecular phenomena. In this paper we present a framework (CharM - Characteristics of Metaphors) as a way to examine and explain students misinterpretations of imperceptible molecular phenomena. This framework clarifies metaphorical language use in relation to ERs, molecular phenomena, and student learning. Therefore, to pursue the origin of students' difficulties with understanding dynamic molecular processes we apply the CharM-framework on a setting where students try to make meaning, in interaction with peers and an animation, of the sub-microscopic process of ATP-synthesis in Oxidative Phosphorylation. We seek to identify the metaphors that students use and also relate these metaphors to the animator's intentions while designing the animation. Two of the expressed metaphors will serve as examples for a metaphor analysis, in which the characteristics of metaphors are outlined. To our knowledge, no strategies to identify and understand the characteristics, benefits, and potential problems of particular metaphors have, to date, been presented in science education research. Our aspiration is to contribute valuable insights into metaphorical language use at the interface of ERs, molecular phenomena, and student learning.

1.1 Metaphors and the concept of affordance

In the life sciences, metaphors are not merely a linguistic phenomenon; they are a fundamental principle of thought and action (Lakoff & Johnson, 1980). The following discussion is based on the idea that language and thought are closely connected and interdependent. A metaphor is an expression that is used to convey a meaning that differs from its literal one in a particular context. By using a metaphor we transfer the meaning from its literal source domain to a new target domain, linked to the source domain by resemblance. Metaphors resemble external representations in the way that they support students meaning-making. Lakoff and Johnson (1980) claim that there are two types of concept: direct and imaginative. Direct concepts are grounded in our experience of the physical and social environment, including perception and body movement. Imaginative concepts, on the other hand, are not grounded in direct experience and have no relationship to everyday life. Such concepts are formed from external input, prior knowledge, and imagination. Processes and events on the sub-microscopic scale could be considered to be imaginative concepts since they are imperceptible and have no equivalence in humans' everyday life.

A molecular process can be described in various ways, all more or less scientifically correct. Metaphors used to elucidate a particular process obviously have to relate to such descriptions. Often a molecular process is described in terms such as "someone is doing something" or "something is doing something", while the scientifically correct description is the more objective "something is happening", without any intentions ascribed to anyone or anything. Thus, the presentation of a process can afford a number of descriptions (Pea, 1993). But the opposite is also true. A given description, say a particular metaphor, can afford a number of perspectives on the process described. The noun Affordance has been defined as "the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used" (Norman, 1990). The term was originally coined by Gibson in 1966; he defined it as "something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment" (Gibson, 1979, pp. 127). He describes how the affordance of the environment refers to the things that the environment offers the animal. One of the fundamental assumptions is that objects influence the actions of the interpreter/viewer, hence objects are not neutral. In recent years, the term affordance has been embraced by different fields of research, for example in studies of human–machine interaction where the term applies to the design of ERs. However, we use the term affordance in the original sense, referring to the perceived and actual properties of an object.

1.2 Metaphors and learning

An important part of human learning is to discover and explore the world around us. Gardner (1987) explains how an individual needs not only to possess the abilities required to receive information but also to learn how to discover information and how to refine the skills that create meaning out of information. Selection of information depends on prior knowledge, that already exists in an individual's mental structures, and perception. Facing a novel situation, we need to amalgamate this new knowledge into our prior knowledge. When picturing something from received information, we create internal mental representations, which can be considered to take the form of internal pictures or/and language. As familiarity with a situation increases, the demand on our cognitive capacities decreases and we need to pay less attention to the subject (Lowe, 2003).

Metaphors derive from experiences; in an educational context this implies that prior knowledge of the real-life domain, as well as of the scientific domain, becomes the foundation for students' use of metaphorical language. For successful meaning making, students need to be familiar with the concepts being compared within the metaphor (Wormeli, 2009). Also know which characteristics of the metaphor are relevant and should be transferred to the conceptual domain to form an internal representation, and enable intuitive interpretations of the phenomenon. Thus, it must be emphasized that the match is not ever perfect. For learners, the metaphor itself mediates new meaning and new ways to interpret the natural world, and this has a direct impact on student conceptualization of the scientific concept under consideration. However, a metaphor needs to be adequate with respect to both the language in the ER and the sub-microscopic phenomenon it is designed to represent. Thus, whenever metaphors are used in molecular life science teaching and learning, students must be able to interpret the relationships between the scientific concept, the metaphors used and the associated ERs.

1.3 Learning molecular processes - prior knowledge, metaphors, ERs, and affordance

In order to clarify the theoretical framework this paper is based upon, here we develop a synthesis of the three main stepping-stones used when describing students' meaning making with respect to molecular processes. These are: 1) the significance of students' prior knowledge, 2) students' use and interpretation of metaphors and ERs, and 3) the concept of affordance.

Prior knowledge, past experiences, and knowledge, are stored in our network of mental structures and are vital for incorporating and understanding new knowledge (e.g. Anderson, 1977; Ausubel, 1968). Glaser (1983) explains how we use our mental schemas to interpret and predict new situations and knowledge; thus, one's prior knowledge and experiences become essential when encountering new knowledge. Sub-microscopic processes cannot be experienced in the macroscopic world and molecular events need to be imagined or represented in the environment through ERs and by linguistic means, in particular metaphors. These are helpful resources in students' meaning making with respect to imperceptible entities: they support cognitive processes and enable learning (e.g. Gallese & Lakoff, 2005). Learning tools support our imagination by making the imperceptible perceptible; allowing the abstract[3] to become concrete on an individual level. Further, molecular processes are often complex and act in multi-causal ways, representing a decentralized process. Molecular processes are not dependent on or attribute to human patterns of action, which puts a great demand on learners' cognitive capacity (Wilensky, 1991). It has even been suggested that humans have a tendency to explain all abstract processes by means of central control and deterministic causality in order to make them understandable (Jacobson & Wilensky, 2006; Resnick & Wilensky, 1993; Wilensky & Resnick, 1995, 1999).

With these features in mind we turn to the concept of affordance (Gibson, 1979; Norman, 1990) and how this relates to students' learning of molecular processes through metaphors and ERs. Learners are influenced by the perceptible reality around us, which may bias human learning (Kahneman & Tversky, 1972). Students' self-generated metaphors are prejudiced by their prior knowledge and experience of the lived world as well the designer's use of symbols in the ER (the designers' intention). The metaphors used by students (in this case while having peer discussions) make the students think of the molecular process in a certain (or several) way(s). Each metaphor has a set of characteristics in its source domain that students can transfer to the new target domain, the imperceptible molecular world. With appropriate prior knowledge, metaphors do not cause problems to learners since they know which characteristics of the metaphor apply to the target domain. However with limited prior knowledge and little experience, the metaphors might be taken literally (Gallese & Lakoff, 2005) and can cause students difficulties.

2 The CharM-framework

It appears that metaphors play an important role in students' learning of imperceptible molecular phenomena through the use of ERs. A framework for supporting the analysis of the complex relationship between metaphorical language use, ERs, molecular phenomena and students' learning is, therefore, highly desirable. The CharM-framework (see figure 1) is therefore, designed to vision the relationship between i) the message that is meant to be conveyed by the ER with its influence on spoken language, and ii) the characteristics of different metaphors and how these affect the formation of students' internal mental representations. This is of particular interest in the field of educational research in molecular life science, in which the content is communicated predominately with the aid of ERs.

A molecular phenomenon could be made visual and artifacted in the environment by designing an ER, which is, in general, a simplification of the phenomenon it is representing. The designer of the ER uses his/her prior knowledge and internal representations to design a pictorial language suitable for conveying the phenomenon. Learners interpret the ER either by themselves or during interaction with others. When discussing the ER and the molecular phenomenon metaphorical language surfaces, which is inspired by the ER and the interpreter's prior knowledge. The metaphorical language will influence the direction of thought. For example, the metaphors "wind turbine" and "table fan" each possess a set of characteristics, some shared and some divergent. Both metaphors include the idea of moving air and creating an air stream. However, the wind turbine converts kinetic energy into electricity and the table fan creates directional airflow of a particular velocity. The metaphors hold different characteristics that correlate more or less with the scientific phenomenon they are intended to represent, meaning they hold different affordances. The relevance of these characteristics becomes significant when interpreting the metaphor and trying to create an internal representation of the actual phenomenon. The sum of all the characteristics of a metaphor constitutes one affordance. Thus, a metaphor affords a molecular phenomenon certain characteristics, i.e. directing the 'audience' to think of the phenomenon in a specific way. Problematic characteristics with respect to the molecular phenomenon can be manifested as potential problems. At this point, the metaphor could break down, meaning that it does not provide a scientifically accurate correlation between the ER and the molecular phenomenon, and may create conceptual difficulties. Learners' attention and prior knowledge intimately affect how they interpret the characteristics, which in turn influences the creation of each individual's internal representation of the phenomenon. This internal representation is then incorporated in already existing mental structures, one's prior knowledge. Also, the internal representations can be more or less coherent with the scientifically correct view of the phenomenon (black dotted line in figure 1). The CharM-framework should be viewed as representing a highly dynamic course of events, where ones prior knowledge constantly alters.

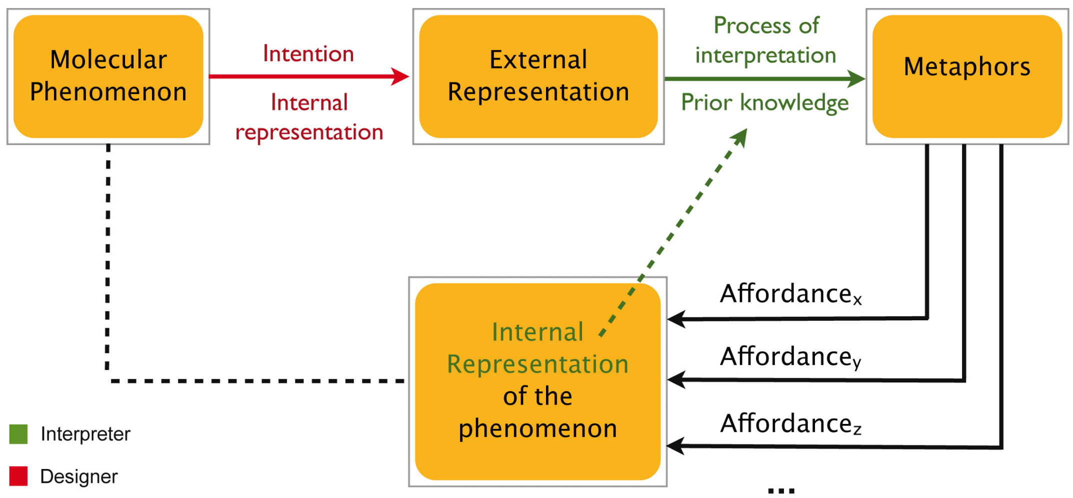

Figure 1. A framework for viewing metaphorical language use in relation to ERs, molecular phenomena, and students' learning.

It is important to stress that one design is not "good" or "bad" *per se;* its value varies depending on the interpreters' prior knowledge as well as the social and cultural context. The same is true for metaphors and metaphorical language use. Metaphors do not inherently posses "good" or "bad" characteristics, the value of particular characteristics emerges in a given context with a given interpreter. One metaphor could be adequate in one context and less adequate in another. Therefore, it is essential to correlate the metaphors and ERs used with students' learning in a shared context.

3 Seeking the origin of students' difficulties

3.1 Aim and research questions

Herein, we apply the CharM-framework on a setting where students try to make meaning about the sub-microscopic process of ATP-synthesis, part of Oxidative Phosphorylation, by interpreting an animation. The aim is to explore the origin of students' difficulties with understanding dynamic molecular processes found in our previous studies (Larsson et al., 2011; Stadig Degerman & Tibell, 2012). The following research questions were posed:

- How can the design of an animation influence students' metaphorical language?
- What difficulties can result from students' application of metaphors to the imperceptible molecular processes of ATP-synthase?

To answer these research questions, we seek to find the metaphors that students use while explaining and trying to make meaning of an animation, and thus of the sub-microscopic process of ATP-synthase that the animation represents. The characteristics of the identified metaphors are outlined and evaluated according to two categories: i) relevant characteristics and ii) problematic characteristics (that might act as potential problems). This is then related to the animator's intentions while designing and creating the animation.

3.2 Methods

3.2.1 Sample and data collection

The animation used in this study is part of the educational material linked to the book *Molecular Biology of the Cell* (Alberts et al., 2002) and represents the reaction of the enzyme ATP-synthase and the formation of Adenosine triphosphate (ATP) in a metabolic process in the cell. The analysed data originated from Swedish university students (n=43), who were divided into six groups. All students had previously completed basic courses in chemistry and molecular biology, and had no or limited knowledge of ATP-synthesis. During the group discussion a pre-formulated discussion guideline was used; this contained six questions all related to the scientific content represented in the animation. Before the session, the students had worked individually with the animation to become familiar with the learning environment and to ensure that they all had approximately the same level of prior knowledge and create familiarity to the context presented by the ER. The interview with the animator was semi-structured and consisted of five parts: (1) introduction, (2) background to the commission for designing the animation, (3) the animator's intentions with the animation, (4) the semiotics associated with the animation, and (5) the animator's reflections on students' interpretation of the animation. Both the group discussions and the interview were audio recorded and transcribed verbatim.

There are two dimensions to learning i) in the mind of learners and ii) in learners' interaction with the environment; the challenge is to describe the link between the two. We cannot make claims about exactly what is happening in each individual's mind simply by interpreting language or language use. However, by letting students interact and communicate their ideas and thoughts about a specific subject, we can get a partial picture of their thoughts. Thus, group discussions were chosen as the data collection instrument because they represent an exploratory way of working, in which communication is required and language surfaces. In addition, a group discussion may be considered by students to be less intimidating than individual test situations.

3.2.2 Analysis

This paper's research questions focus on seeking the origin of students' difficulties. Thus, our study is more in the nature of natural history than in the nature of population biology, with qualitative results that need to be analysed appropriately.

The analysis of the transcripts of the group discussions revealed which metaphors students used and what these metaphors aimed to explain, allowing mapping between the source domain and the target domain. First, we categorized the target of each metaphor used by the students (see table 1) using an inductive content analytical model (Graneheim & Lundman, 2004). All the metaphors (linked to the

ATP-synthesis) that were identified were further classified using, for inspiration, Venville's (2008) organization and evaluation of common metaphors used in biology education. Second, we identified the metaphor(s) and the aspects of the process that the metaphors were targeting. Third, we identified intrinsic characteristics of the metaphors detached from the target domain (see table 2). Further, the characteristics identified were linked to possible targets in the process that the metaphor was intended to describe. In the last step of the analysis, the links between characteristics upon which the metaphor was based were scrutinized using Venville and Treagust's (1997) method. The characteristics can be connected to both the design of the animation and the molecular process that the animation represents. The aim of this part of the analysis was to decide which characteristics were relevant or exhibited problematic characteristics. When mapping the characteristics of the metaphors to the target domain (Venville & Treagust, 1997) some missing links were identified. Thus, from a scientific view, some of the metaphors' characteristics do not apply to the scientific process and the ER: we identified these as potential problems for students learning about the process (see table 3). We used a deductive approach to analyse the transcript of the interview with the animator in order to identify intentions. The results are exemplified with quotations from the interview.

The interview transcript was validated through *transcription checking* (Gibbs, 2007). By letting the animator check the transcript, we sought to avoid mistakes in our interpretation of his answers to our questions. Even if we used a verbatim transcription, the transcription process is a translation from one medium to another, and there will always be a possibility of misinterpretations. Codes were identified and a memo was constructed to be used as a *constant comparison tool*, in order to avoid code drifting and keep the categories reliable during the whole categorisation process. To guarantee the quality of our results, we used a *code cross-checking* method to "minimize researchers bias and get a measure of the reliability of coding" (Gibbs, 2007 p. 99-100). This was done by letting the categorization of the metaphors, the transcripts from the group discussions, and the transcripts from the interview first be examined by the authors individually. In order to reach agreement, this was followed by a discussion between the authors. Lastly, the analysis was reviewed and validated in a larger research group consisting of people with backgrounds in molecular life sciences, protein chemistry, biochemistry, cognitive linguistics, visual learning and communication, educational sciences, and media technology. Table 1, 2 and 3 are the larger group's negotiated results. The categories in table 1 did not change during the discussion. Most of the discussions concerned the state of the art of ATP-synthesis and if ATP-synthase (the protein) is a machine or not.

3.3 Results

3.3.1 Identified metaphors

In this section, we describe the metaphors that students' used while communicating with their peers. The initial analysis showed that all six groups used metaphors in their discussions to create meaning out of the animation (table 1) and, therefore, associated the language in the design with the molecular process. We can conclude that many of the students' self generated metaphors were very machine-focused, for example mill, pump, robot, and mechanical spring, and we choose to focus further on the metaphors *machine*[4] (used by all six groups) and *watermill* (used by three groups). Below are two excerpts from different groups that illustrate how students used the metaphors machinery, dynamo, watermill, and waterwheel.

> ***Group 4***
> *Student 1: This red arm, isn't it the GI-motor?*
> *[…]*
> *Student 3: It is like it moves slowly and when it releases it gains speed again, like a dynamo.*

Student 4: It is a patchy process.
[…]
Student 2: Isn't it like a cycle lamp, like you push the pedal and store energy… and then the lamp is glowing… cos if energy is consumed…
Student 5: Energy is consumed to synthesise it [ATP].
[…]
Student 5: And then you have to run the bike faster…
Student 2: And every three quarters of a cycle energy is released… so that can produce it [ATP]

Group 6
Student 1: How are transport of protons and ATP-synthesis connected?
[…]
Student 3: Aren't you using the differences in concentration to run… a small… like a small watermill?
[…]
The water runs the wheel and… energy is transferred to energy that… is stored… so you can produce…
[…]
I thought of it... like a waterwheel that runs… to gain energy.

Table 1. The different metaphorical expressions used by the students in the group discussions, categorized according to the target domain.

Target Domain	**Metaphor**
Transport of protons	Vacuum pump Machinery/apparatus Mill Robot Dynamo Watermill The effect of a watermill Waterwheel Windmill Motor
Protons as the driving force of ATP-synthesis	Aspects of machine-like metaphors associated with something pushing, pulling or going away somewhere
Conformational change in the protein	A beating heart Paddle wheel
The ATP-synthase mechanism as non-reversible (not a scientifically correct assumption)	Time as an obstacle to hinder the process Wrong connections are made Machinery
Energy transformation	Mechanical spring Spins like a mill Toy factory /combustion machine
Structure of the protein gives it its function	Mechanical structures Assembly robot at the nano-scale

3.3.2 Two metaphors – machine and watermill

In the qualitative analysis of the metaphors *per se* and their correlation to the molecular process, we can see that the metaphors do, indeed, communicate the scientific content adequately. In the following section, therefore, we examine the two selected metaphors in order to reveal any relevant characteristics (table 2) and problematic characteristics that could be considered potential problems (table 3) when using these metaphors to explain and understand ATP-synthesis on the basis of the ERs. All possible relevant characteristics of the metaphors is listed and compared to the target domain (table 2). In the analysis we identified five characteristics of the machine metaphor that are the same as those of the watermill metaphor. However, the analysis of the watermill metaphor revealed two other characteristics relevant to both the ER and the molecular process that the ER communicates (table 2).

Table 2. This table show the qualitative analysis of the two selected metaphors, machine and watermill, and their relevant characteristics that map correctly to the new target – the ATP-synthase reaction.

Metaphor – machine	Metaphor – Watermill	Target – ATP-synthase reaction
Mechanical work needs fuel to run	A watermill needs water to spin the waterwheel	The proton gradient over the mitochondrial membrane driving force for ATP-synthesis The proton gradient stores energy
A machine spins when it is turned on	A watermill spins when the water flows	The ATP-synthase spins when there is a proton gradient across the membrane
A machine pushes something forwards	The water pushes the waterwheel and makes it move	The shape and movement of the protein creates conformational change
Energy stored in the fuel is converted into mechanical energy	The water in a dam is transported via a waterwheel, which makes use of use the energy released as the water falls	Energy stored in the gradient is converted into mechanical energy
The mechanical energy can be used to do work	The mechanical energy can be used to do work	ATP-synthesis is possible
-	You can stop the mechanical work by stopping the water flowing	There are opportunities to inhibit the reaction
-	The water is not consumed	Protons are not consumed, they can be used again in another reaction

Further, the metaphors could also tempt students to focus on characteristics that are unsatisfactory when discussing the ATP-synthesis. In the analysis, we have found six problematic characteristics, four for the machine-metaphor and two for the watermill-metaphor, which are unsatisfactory for explaining the ATP-synthesis (table 3). These are further divided into two types of potential problems that students may experience: the metaphor could tempt students to believe that (a) the process is deterministic and man-made and (b) the process as irreversible.

Table 3: The problematic characteristics of the two metaphors linked to potential problems, where the metaphor breaks down.

Problematic characteristics of the machine metaphor. Where the metaphor breaks down	Problematic characteristics of the watermill metaphor. Where the metaphor breaks down	Potential problems
A machine can have causal effects A machine can start and stop	A watermill can have causal effects	This may create problems in seeing the controlled chaos and stochastic movements (a)
Normally a machine is designed to work in one direction	A watermill is designed to work in one direction; it needs another mechanism to pump the water upstream	This may create problems in seeing the reversibility of the reaction (b)
The fuel in a machine is consumed	--	This may create problems in seeing that protons are not consumed, they can be used again in other reactions (b)

3.3.3 Animator's intentions

In the following section, we emphasize the intentions of the animator when designing the animation. We also elucidate the metaphorical language he used in his design. In the interview, the animator stated that, when designing the animation, he followed instructions given by the author of the textbook and the written text from the book. In the textbook the authors give the reader a metaphorical explanation of the enzymatic mechanism as a dam connected to a waterwheel, with water as the moving force.

> *Animator (A): In the Alberts' book, Molecular Biology of the Cell – I think they first introduce enzymatic activity, with a dam releasing water onto a waterwheel, and next to the dam there's a pump that's putting water back into the dam.*

In addition, several biology, cell biology and biochemistry textbooks uses the analogy of a dam releasing water on a turbine to convert energy into chemical energy to explain the specific ATPsyntase reactions. The animator also states that his intention was to show the energy transformation from electrical energy, via mechanical energy, to chemical energy. In addition, the narrative associated with the animation states that the purpose of the ER is to "show a molecular machine that works like a turbine to convert the energy stored in a proton gradient into chemical energy stored in the bound energy of ATP". According to the animator, the textbook contains several metaphors and he actually wanted to be less metaphorical in his pictorial language, but this was not suited to the textbook design:

> *Animator (A): Yeah. I, I guess what I was saying throughout is that that I wanted to be less metaphorical and stick more to the data yeah...*
> *Interviewer (I): How would you have done that?*
> *A: The ATPsynthase, bi-layer, other structural details, concentration details and motion details are things I would have tried to change in development.*
> *I: Could you say that your own metaphorical ideas, you had to sacrifice many of them, in this particular animation?*
> *A: The language is interesting because my level of simplification I guess, is metaphorical but when I'm comparing it to the textbook's level of simplification, it's anti-metaphorical.*

The animator wanted to get closer to the scientific reality of the ATP-synthase reaction and he also related the metaphorical language in an ER to more simplified use of symbolism. The interview continued with a discussion about which machine-like metaphors he had in mind when designing the animation, this is illustrated in the next excerpt.

> *Animator (A): ...it is much more of a machine. It's described by the vocabulary of it as a machine, like something that belongs in a factory...*
> *Interviewer (I): Mmm A: ...and especially when you see this rotor with a cam-shot pushing on, I guess, the analogy is to the pistons. [...]*
> *I: And what are the machines you're using [when designing the animation]?*
> *A: I'm trying to think if there's a simple machine. – So this simplest of possible machines would be a see-saw, because you know the little wedge where you learn in physics about energy and that's the same amount of energy if you lift it straight up or if you slide it up if there's no friction, etc. These types of things are considered reversible probably by most students but, but yeah, a complex, internal combustion machine that they associate with.*

The animator had the general idea of a machine in his mind while designing the animation. ATP-synthase could be viewed as a machine on the nano-scale. When confronted with the students' interpretation of the animation he recognized why students would use machine-like metaphors and found this reasonable for explaining the protein/enzyme mechanism.

> *Animator: I'm just thinking back to my own enzyme background – where you picture just one active site of some small follicle changing some protein changing some small molecule. And this has many active sites, many interacting parts. So I can see how they would imagine that a wrench could be thrown into the works because it is much more of a machine. It's described by the vocabulary of it as a machine, like something that belongs in a factory.*

4 Discussion

The analysis clearly shows how students use a variety of metaphors while thinking about ATP-synthesis, for example mill, robot, motor and/or spring. Marton & Tsui (2004) withhold that different interpreters perceive different aspects of an observed phenomenon, in this case different aspects of the ER. This variety in perception is then believed to depend on prior knowledge and how the design of the ER allows the user to see such elements through its visual appearance (Wiss, Carr, & Jonsson, 1998). Two intended metaphors in the animation design were revealed; a machine, introduced by the animator himself, and a watermill, derived from the written text in the textbook. The majority of the students did pick up on the cues for interpreting the molecular process as either a machine or a watermill and their metaphorical language appeared to be induced by the animation. This observation suggests that the animator's choice of design highly influence students' metaphorical language use, in other words, influencing them to assign the scientific content certain affordances. The interpreter's prior knowledge and the design of the ER then become key-factors in the process of interpretation.

As a result of the analysis we were able to identify numerous characteristics of the two chosen metaphors. Some of these characteristics were relevant (see table 2) and mapped properly from its literal source domain to the new target domain. For example a machine needs fuel to run and a watermill needs water to spin. These specific characteristics equate to the fact that the proton gradient over the mitochondrial membrane is fuel for ATP-synthesis. However, some problematic characteristics of the metaphors were also recognised (see table 3). These problematic characteristics could act as potential problems for successful learning.

4.1 Student's difficulties caused by the use of metaphors

In the analysis, we have found six problematic characteristics, four for the machine-metaphor and two for the watermill-metaphor, which are unsatisfactory for explaining the ATP-synthesis (table 3). These are further divided into two types of potential problems that students may experience: the metaphor could tempt students to believe that the process is *deterministic* and *irreversible*. These potential problems might lead students to interpret aspects of the molecular process incorrectly. Student difficulties to interpret the process as reversible (students do not interpret the process as a equilibrium reaction and that the protons is not consumed) originate from the following characteristics:

- Normally a machine/watermill is designed to work in one direction
- The fuel in a machine is consumed

Student difficulties to interpret the process as deterministic (students do not interpret the controlled chaos and stochastic movement) originate from the following characteristics:

- A machine/watermill can have causal effects
- A machine can start and stop

Machine-like metaphors are frequently used in life science and life science education. In a report Orgill & Bodner (2006) state that the use of the term machine when explaining the process of ATP-synthesis involving ATP-synthase is not a metaphor because Webster's American Dictionary defines ATP-synthase as a motor at the nano-scale (Knoblauch & Peters, 2004). Before the development of the nano-technique, however, mechanical metaphors were used to explain biochemical catalyse reactions and principles (Asimov, 1959). Today, it is possible to use cellular activity, to construct nano-scaled machines. However, this new technology is not familiar to the every day society and the lack of experience of a nano-machine leads to an imaginative metaphor (Lakoff & Johnson, 1980), which attribute to the properties that they consider most likely. The machine can still work as a metaphor, but some of the attributes may cause problems. For example, one potential problem with using the machine and watermill metaphors when explaining ATP-synthesis is that they can lead students into thinking of the process as deterministic, in that sense that it is man-made (Pigliucci & Boudry, 2010).

Whether or not students apply these "potential problems" in order to learn about the ATP-synthesis still needs to be investigated. However, the strong correlation to students' difficulties revealed in our previous studies (Larsson et al., 2011; Stadig Degerman & Tibell, 2012) suggest that these problems, derived from the characteristics of the metaphors, influence students' meaning making.

4.2 The design problem

Pea (1993) suggests that knowledge is carried in artefacts, because a designer (in this case an animator) uses his/her prior knowledge and internal representation of a scientific phenomenon to create an artefact. This knowledge is then exploited in the interaction with learners. Furthermore, the message that an artefact conveys may be more or less difficult to communicate to novice learners (Pea, 1993). The information presented in ERs can be overwhelmingly large and cause problems when being interpreted (Lowe, 2003). Thus, when representing an imperceptible molecular phenomenon, we need to design its characteristics into more interpretable features. The designer and creator of an ER creates a symbolic and visual language using different aspects of graphic design to overcome the difficulties of making a perceptible and accurate representation of an imperceptible molecular phenomenon. A common way for designers to address the problem of too much information is to cluster information together, whilst retaining all relevant information. This is unlike filtering of information, which often involves the loss of some information. According to the Gestalt laws of psychology, the human brain instinctively groups and clusters visual symbols that are situated close together or have the same colour or shape. From these simplified structures, humans are able to see patterns that actually are not there. The brain can also make concrete features more abstract (Wilensky, 1991) by using already existing mental structures and prior knowledge to derive meaning from the representation. For example a pen in a representation can communicate the less tangible concept of writing, a box gives an intuitive cue to open something up or a doorknob suggests turning. Even if abstraction serves to expand the range of interpretations of ERs, there is a risk that the abstracted cues are over interpreted or even hinder students in their meaning making. However, the design problem is more complex than the use of symbols and signs in an ER. A designer is also dedicated to use design laws to elucidate necessary aspects of the phenomenon that is not explicit visual in the ER, but is central to the understanding of the phenomenon depict. For example, the use of generic techniques that make interpreter focus where you want them to focus. This can provide the interpreter with intuitive notion of the phenomenon (Rundgren & Tibell, 2010), even though it might cause alternative conceptions or student difficulties (Stadig Degerman & Tibell, 2012).

5 Conclusion and Implications

Metaphors come to life at the interface of ERs, molecular processes and student learning. We want to emphasize the difficulty of explaining sub-microscopic processes, which have no link to everyday life or to the macro world; students' interpretation of metaphors becomes crucial for their meaning making. The CharM-framework provide us with an approach for understanding these complex relationships; which is of particular interest in the field of molecular life science education where the content is communicated with aid from ERs. In the presented investigation some of the found problematic characteristics of the metaphors machine and watermill is a possible reason for students' difficulties with understanding that the ATP-synthesis as a reversible and non-deterministic process. When the students are trying to make sense of the molecular process of ATP synthesis they need to interpret the language in the design and have discussions with their peers. In both cases, metaphors are used to compare the abstract process with familiar processes by mapping experience and prior knowledge from a known source domain to a new target domain. Each metaphor affords the molecular phenomenon certain characteristics, which stimulate students to think of the phenomenon in a specific way. However, metaphors never map their source domains onto the new target domains in a perfect way. Therefore, difficulties arise in students' interpretation of metaphors.

The analysis of the empirical data supports our claim that the design (choice of symbols and signs) of ERs are highly important and is one account that influences students' intuitive thinking and use of metaphors in their meaning making of molecular phenomenon. The language in the ERs is mirrors the designer's (animator's in this case) intentions and prior knowledge of the process. Since each learning situation is unique, with different students, designers, and content, a perfect and universally valid design cannot exist. Moreover, the designer must be influenced by practical issues such as how to visualize molecules, the constrains of the software used, and budget issues. However, the CharM-framework could assist in the design process by allowing designers to reflect on how ERs could be interpreted or misinterpreted. In this way it would be possible to create a design that effectively supports learning. The difficulties associated with designing ERs that sufficiently represent molecular processes are similar to the difficulties for students in linking the characteristics of metaphors to the molecular processes.

Furthermore, the framework could also have didactic value, guiding teachers' choice of ERs in an educational setting. We suggest an approach in which the teacher elucidates the characteristics of any possible metaphor, brought by the ER, to be able to discuss any problematic characteristics with the students. By including the concept of affordance and characteristics for each given metaphor, the relationship between the molecular phenomenon and the outcomes of metaphorical language use are made more explicit. That is to say, attention is focussed on the characteristics of the metaphors and its relevance to the molecular phenomenon. Then student's prior knowledge and the design of the ER become key-factors in the process of teaching and learning molecular life science.

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Endnotes

[1] External representation are defined as physical manifestations of information, for example a sequence of words, models, diagrams, pictures or animations (Bodner & Domin, 2000).

[2] We treat the studied words as metaphors, rather than cases of semantic analogy or meaning extension, because the meaning change is so drastic for them, involving a mapping of concepts from a domain of macro-level, artificial, and mechanical objects to a domain of micro-level, biochemical processes.

[3] Abstract objects cannot be mediated through our senses and are the opposite of concrete objects, which are ”graspable” in many modalities (Wilensky, 1991). However, concepts that are abstract at one point can become concrete for an individual given the relationships between the concept and the individual. This means that objects that are not mediated by our senses, such as imperceptible molecular processes, are considered abstract but can become concrete to learners if the right relationships with the concept are created.

[4] There are different types of machines. When students use machine-like metaphors they seem to refer to a combustion engine. Therefore, here the term machine refers to a combustion engine.

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