Can Definitions contribute to Alternative Conceptions?

Abstract

There has been disagreement on the importance of definitions in science education. Yager (1983) believed that one crisis in science education was due to the considerable emphasis upon the learning of words, terminologies or definitions. Hobson (2004) disagrees with sixteen introductory physics textbooks which do not provide general definition on energy. Some textbooks explain that "there is no completely satisfactory definition of energy" or they can only "struggle to define it." In addition, Rossing (1995) explained that the lack of understanding of magnetic forces can be due to the confusion in terminology and definitions that exists in our physics courses and textbooks.

In general, imprecise definitions in textbooks (Bauman, 1992) and inaccuracies in definition provided by teachers (Galili & Lehavi, 2006) may cause confusions or alternative conceptions. Besides, there are at least four challenges in defining physics concepts, namely the problems of circularity, precision, context and completeness in knowledge (Wong & Yap, 2010). These definitional problems which have been discussed or mentioned in *The Feynman Lectures*, may impede understanding of the nature of physics knowledge.

In this study, qualitative meta-synthesis is employed to examine over hundreds of research papers, as well as some editorial comments and letters to the editor on definitions in physics, problems in defining physics concepts and how they may result in alternative conceptions. These research papers and articles are mainly selected from peer-reviewed journals such as *American Journal of Physics*, *International Journal of Science Education*, *Journal of Research in Science Teaching*, *Physics Education*, *Science & Education*, *The Physics Teachers*, and so on. There are also comparisons of definitions from research papers with selected definitions from textbooks, Dictionaries of Physics, and English Dictionaries.

To understand the nature of alternative conception, Gyoungho Lee et al. (2010) have suggested a theoretical framework to describe the learning issues by synthesizing cognitive psychology and science education approaches. Taking it a step further, the current study incorporating the challenges in semantics and epistemology, proposes that there are at least four main variants of alternative conceptions which may arise from the four definitional problems in physics. The four variants of alternative conceptions are namely:

1. Operational Conceptions (Based on operational definitions)
2. Imprecise (Vague) Conceptions
3. Mixed Conceptions (Mixing technical meaning with concepts from other contexts)
4. Incomplete Conceptions (Limited knowledge on concepts)

We may coin the term, "alternative definitions", to refer to the commonly available definitions which have at least four main problems in defining physics concepts, namely, circularity, precision, context and completeness. Based on this qualitative meta-syntheses study, alternative definitions may result in at least four variants of alternative conceptions. Note that these four definitional problems or challenges in definitions cannot be easily resolved. Educators should be cognizant of the four variants of alternative conceptions which can arise from alternative definitions. The concepts of alternative definitions can be useful and generalizable to science education and possibly beyond. The importance of definitions should deserve more attention from educators and students.

INTRODUCTION

There has been disagreement on the importance of definitions in science education. Yager (1983) believed that one crisis in science education was due to the considerable emphasis upon the learning of words, terminologies or definitions. Hobson (2004) disagrees with sixteen introductory physics textbooks which do not provide general definition on energy. Some textbooks explain that "there is no completely satisfactory definition of energy" or they can only "struggle to define it." In addition, Rossing (1995) explained that the lack of understanding of magnetic forces can be due to the confusion in terminology and definitions that exists in our physics courses and textbooks.

In general, imprecise definitions in textbooks (Bauman, 1992) and inaccuracies in definition provided by teachers (Galili & Lehavi, 2006) may cause confusions. Besides, there are at least four challenges in defining physics concepts, namely the problems of circularity, precision, context and completeness in knowledge (Wong & Yap, 2010). These definitional problems which have been discussed or mentioned in *The Feynman Lectures*, may impede understanding of the nature of physics knowledge, and possibly result in alternative conceptions.

To illustrate how definitions may result in alternative conception, and possibly problem solving, here is one interesting question: *What is the buoyant force on a book which is at rest on a table top*? In some venerable textbooks (Halliday et al. 2005; Sears, 1950), the buoyant force is defined to be "*upward and has a magnitude equal to the weight of the fluid that has been displaced by the body*." If teachers adopt this definition on buoyant force, then one would calculate the weight of the air displaced. Hence, some physics education researchers (Hestenes et al., 1992; Redish, 2003, p.77–78) and teachers suggest that as long as an object is submerged in the fluid or air, there will be buoyant force. Students who provide the answer that there is no buoyant force can be penalized or considered to have misunderstanding (Harper, 2003) or alternative conception.

On the other hand, we propose to include the *condition of applicability* and the *cause* of buoyancy in the definition of the buoyant force: *the upward force on an object produced by the surrounding fluid* (i.e., a liquid or a gas*) in which it is fully, or partially immersed, is due to the pressure difference of the fluid between the top and bottom of the object*. With this definition in mind, one would need no calculation, and deduce that the correct answer is no buoyant force. As there is no fluid below this book, there is no net upward force due to the pressure difference of the fluid. Nevertheless, there can still be an upward force which is known as the normal contact force, or reaction force. We may now explain that those students who calculate the buoyant force using weight of the fluid displaced, have alternative conception.

The issues on definitions were not resolved as there could be disagreements on many definitions in physics (Slisko & Dykstra, 1997). For example, Zemansky (1970) preferred to define heat as a noun instead of verb, that is, heat is the “energy” transferred because of temperature difference. The alternative conception identified by him was “heat could be stored in a body”. This is still present in students because of our usage of language such as heat absorbed (Shaw, 1969). The phrase, ‘flow of heat’, may suggest how heat was stored in an object, and it can flow from one object to another.

Currently, there is no agreement on whether heat should be defined as a process or verb. For example, heat can be defined as “transfer” of energy because of temperature difference (Romer, 2000). Based on this definition, teachers and students who conceive heat as a form of energy are considered to have alternative conception. Although Zemansky’s definition on heat was considered by many as the “correct” conception in the 1970s, it is currently explained by some to be an alternative conception (Romer, 2000). Note that some textbook authors still prefer to define heat as a noun (Hecht, 2003; Wilson, Buffa & Lou, 2003). In addition, some may prefer to define heat as an interaction (Helsdon, 1976). Hence, there is subjectivity in determining “alternative conception” for physics concepts when there is no consensus on the correct definition.

If we teach students with “simple definition” of energy as the ability to do work (Papadouris & Constantinou, 2010), they may develop “naïve” conception. That is, it is not a surprise that students conceive energy as a form of substance (Warren, 1983). If students are provided with an “abstract definition”: Energy is *not* concrete; it is *not* a material substance; it is given meaning through the calculation of numbers” (Arons, 1999), they may have more sophisticated conception of energy. Lesser students may conceive energy as a substance as they remember this definition which specifies the ontology of energy. The examples on the effect of definitions are not exhaustive.

LITERATURE REVIEW

There is no agreement whether “alternative conception”, “alternative conceptual frameworks”, “misconceptions”, “naive beliefs”, “naïve theories”, or “intuitive beliefs” is the most appropriate terminology in science education (Brookes, 2009). There is also no agreement on the definition of alternative conception. One of the definitions on alternative conceptions is *the students’ existing ideas and beliefs may be significantly different from accepted scientific viewpoints* (Palmer, 2001). However, as discussed earlier, there may not be consensus on scientific knowledge. We propose to define alternative conception as *a knowledge structure that is activated in a wide variety of contexts, is stable and resistant to change, and is in disagreement with accepted scientific knowledge within a community; the scientists from other communities may not have consensus on this accepted scientific knowledge*. This definition of alternative conception is slightly modified from Redish's (2004) definition of misconception because different communities in Science, such as Biology, Chemistry and Physics, may have different accepted scientific knowledge and definitions. In addition, it is common within physics community to have different preference on definitions of physics concepts (Slisko & Dykstra, 1997).

There can be advantages for alternative conception to be broadly defined, to include all kinds of confusion during the learning process. However, it can also be useful to be specific in what way the alternative conceptions are alternative or different. To have deeper understanding, we will explain how the problems of definition can result in variants of alternative conceptions. Note that these definitional problems are not due to carelessness of physicists and textbook authors, but they are inherent limitations of definitions. They can be useful knowledge for physicists, teachers and students. Interestingly, many of these problems have been discussed in *The Feynman Lectures* (Wong & Yap, 2010). We will discuss literature on problems of definitions followed by a framework on alternative conception.

1. The Problems of Definitions

Feynman observed that, "Webster defines "a time" as "a period," and the latter as "a time," which doesn't seem to be very useful." (Feynman, 1963, Vol I, 5-1) This problem of definition could be coined as "problem of circularity" as the two concepts are defined in terms of each other. This problem of circularity was highlighted by Mach as pseudo-definition, and described to be wholly unnecessary tautology (Mach, 1989). Galili and Lehavi (2006) coined the above problem as cyclic definition which points to the failure in applying logic. In their research study, as many as forty-seven percent of teachers defined *charge* as the cause of electric field (force). However, the standard definition of a *field* is based on the concept of *charge*.

Precision is another common problem of definition. Although Feynman explained the necessity to define physics concepts precisely, he disagreed with philosophers that words must be defined with extreme precision (Feynman, 1998, p. 20). For example, it is formidable to define a chair precisely, to say exactly which atoms are chair, and which atoms are air, or which atoms are dirt (Feynman, 1963, Vol I, 12-2). Hence, definition should be as precise as *reasonable*. Ambiguity in definition is also a problem for students and teachers. For example, temperature is preferred by Taber (2000) to be defined as "average kinetic energy of the molecules" as compared to "concentration of heat energy" (Carlton, 2000). Another more precise definition would be "Temperature is a measure of the average internal molecular kinetic energy of an object" (Tipler & Mosca, 2004). This challenge of defining a more precise physics concept can be coined as "problem of precision" or "exactness".

The third definitional problem is context. One should take note that temperature, for example, can be defined differently depending on the context. The word "context" (Bazire & Brezillon, 2005), for example, has more than 150 definitions. Words which have many technical meanings are theory–laden, can differ significantly from their historical meanings or daily usage. In daily context, temperature is a measure of degree of hotness. In the context of kinetic theory, temperature is a measure of the average random *translational* kinetic energy of the molecules. As another example, "momentum" is not simply measured by *mass* × *velocity* in Quantum Mechanics (Feynman, 1963, Vol I, 10-9). In a research study (Itza-Ortiz et al., 2003), the words, "force", "momentum", and "impulse", provided by students were found to be influenced by the meanings in everyday context. The problems of context in definitions are present across different subjects and even within the same subject. Across different subjects, the word, "molecule", can have different meanings (Williams, 1999) in physics and chemistry. Within the same subject, the word, "power" in Optics and Mechanics can have completely different meaning. This challenge of defining a physics concept can be coined as "problem of context".

Lastly, we should be honest with students on our limited knowledge in physics, just like Feynman, on the definition of energy. This problem of definition is essentially due to the "incompleteness in knowledge" of current physics concepts. The concept of heat, for example, has been changed over the centuries, and it has been defined as sensation, motion, caloric, energy and process (de Berg, 2008). At this moment in time, we cannot be sure if heat will be later preferred to be defined as interaction or in terms of entropy. Besides, there is no agreement on the definition of entropy (Swendsen, 2011). Every definition on entropy can be considered to be an alternative conception when there are many different opinions on this definition as the knowledge on entropy is still far from complete.

A definition lacking important features of the concept by virtue of limited knowledge can be considered incomplete. This is an opportunity for students to learn about the tentative nature of science (Lederman & O'Malley, 1990), that is, scientific conclusions can be modified or replaced. According to Hecht (2006), there seems a prevalent belief within the physics community that the fundamental concepts in physics are well understood and adequately defined. The fact is, whoever carefully has studied the foundational literature in physics over the past centuries, will realize that none of these basic concepts have been satisfactorily defined because of the incompleteness in knowledge, either in theory or experiment. Our honesty with students on the problems of completeness may also generate interest or curiosity. This challenge of defining a physics concept can be coined as "problem of completeness in knowledge".

2. A Theoretical Framework on Alternative Conception

To understand the nature of alternative conception, Gyoungho Lee et al. (2005) have suggested a theoretical framework to describe the learning issues by synthesizing cognitive psychology and science education approaches (See Fig 1). Figure 1 shows the relationships among alternative conception, memory, and mental model in the structure and process of learning. Mental models are dynamic representations through integrating external information recognized and individual knowledge. This framework can be adapted to explain how students learn or interpret definitions and how they may develop alternative conception.

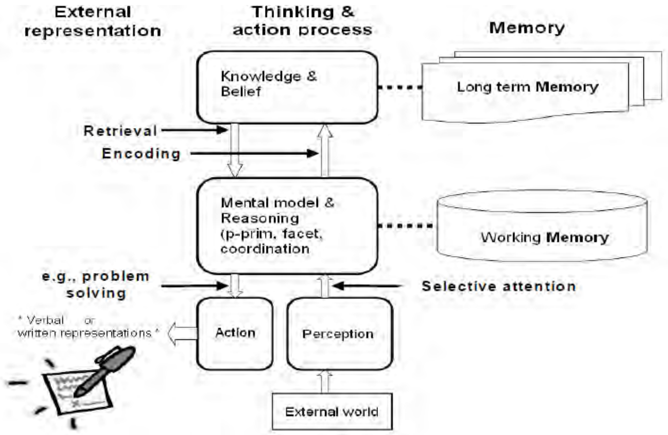

Fig 1. The relationships among alternative conceptions, memory, and mental models (Gyoungho Lee et al., 2005)

In this framework, perception and knowledge are generally recognized as the principal sources of mental models (Yates, 1985). Mental models are contingent on external information insofar as the incoming data as a cue to particular analytical or synthetical subprocesses (Rickheit & Sichelschmidt, 1999). Besides, knowledge on problems of definitions and belief on the tentative nature of science can affect the mental model and mark the other side of higher cognitive processes.

Mental models are defined by Johnson-Laird (1983) as structural analogues of the world; propositional representations are strings of symbols that correspond to natural language. In terms of memory, mental models are constructed in working memory, which involve mental representations of words, definitions or images themselves, as well as interactions between current sensory data and stored knowledge. We assume that definitions stored in the memory of students map propositional representations onto the mental models.

The understanding of definitions, concepts and principles by students implies the use of mental models. In this framework, the ability to remember definitions does not imply that students have interpreted them correctly and fully aware of their implication. Besides, when scientific laws, definitions, and knowledge are presented to students, they may interpret them according to their mental models or alternative conceptions that they have, which are not scientifically accepted.

Based on the discussion on the problems of definitions and framework on alternative conceptions, the following research question is proposed: How are alternative conceptions related to problems of definitions? In a sense, the hypothesis in this research study is similar to Itza-Ortiz's (2003) study, that is, *definition may not determine thought, but it certainly may influence thought*. Hence, we hope to establish that while definitions do not *necessarily* result in alternative conception, it may contribute to students' alternative conceptions because of the problems in definitions. In general, based on Gyoungho Lee's et al. (2005) framework, we propose that students' memory and knowledge of definitions, their belief on nature of science, as well as their perception can all contribute to alternative conceptions. In this paper, we only focus on the problems of definitions.

METHODOLOGY

In this study, qualitative meta-synthesis is employed to examine over hundreds of research papers on definitions in physics, problems in defining physics concepts and how they may result in alternative conceptions. These research papers are mainly selected from *peer-reviewed* journals such as *American Journal of Physics*, *International Journal of Science Education*, *Journal of Research in Science Teaching*, *Physics Education*, *Science & Education*, *The Physics Teachers*, and so on. There are also comparisons of definitions from research papers with selected definitions from textbooks, Dictionaries of Physics, and English Dictionaries to suggest how alternative conceptions can be resulted.

Rogers (1981) defines meta-research as *the synthesis of primary research results into more general conclusions at the theoretical level. The essence of meta-research is research on research, the analysis of analysis*. Literature reviews commonly cite Stern and Harris (1985) as the first to publish methods of qualitative meta-analysis in the nursing literature to document a meta-synthetic approach to qualitative findings. This technique has an interpretive, rather than aggregating, in contrast to meta-analysis of quantitative studies.

In this research study, systematic review of papers is selected with the help of databases such as Education Resources Information Center (ERIC). Search function is commonly used to locate the words, such as "definition", "semantics", and "language." For fundamental definitions such as mass, energy, heat, at least 40 journal papers were searched and studied. Analysis is carried out to refine the "problem" categories including the problems of circularity, precision, context and completeness in knowledge. Interestingly, the relationship between alternative conceptions and problems of definitions can be inferred by re-interpreting previous education research studies.

RESULTS AND DISCUSSIONS

To explain how problems of definitions may have implications to the mental models and result in alternative conceptions, the following discussions mainly utilize the definitions of concepts in physics. Note that these problems of definitions can also be found in other fields, such as biology and chemistry. We will explain how variants of alternative conceptions may result from these different problems of definitions, namely circularity, precision, context and completeness in knowledge.

1. The Problems of Circularity

One common conceptual definition of weight is the force the Earth exerts on an object. Note that the term, force, has problem of circularity because many use the same equation, $F = ma$ to define both force and mass. On the other hand, if we define weight operationally as "what the weighing scales read", it also has problem of circularity (Fig 2: Comparison of Conceptual and Operational definitions of Weight). By checking the dictionary, we would find that weighing scale is "a balance used for weighing." In general, defining a physical quantity by the measuring equipment may not help us to conceptualize the nature of this physical quantity. Circularity occurs in some definitions because this equipment is also defined by the same physical quantity which it is used to measure.

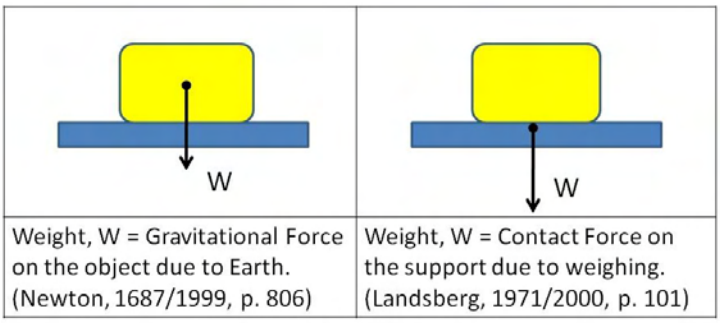

Fig 2: Comparison of Conceptual and Operational definitions of Weight

This problem of circularity is surprisingly rarely discussed in current literature. Although operational definition can be useful to physicists who have understood the physical concepts, it may not necessarily add value in learning for beginning students. (We do not deny the importance of operational definition.) To ensure everyone communicates and works with the same definition and mental image, we need to conceptualize and operationalize the terminology (Berg, 2009). While operational definitions may not enable student to conceptualize the physical meaning, it is useful to know how this concept is measurable by the appropriate equipment. For example, with the aid of an ammeter and voltmeter, the students may develop operational definitions for the concepts of currents, potential, potential difference and resistance (Shaffer & McDermott, 1992).

Some studies (Gunstone & White, 1981; Ruggiero *et al.*, 1985; Noce *et al.*, 1988; Kruger *et al.*, 1990) have shown that there is widespread confusion on the concepts of weight and gravity, in different ages of students and primary school teachers. However, the extent of confusion or alternative conception can be interpreted with different outcomes depending on whether we adopt conceptual (gravitational force) definition or operational (contact force) definition of weight (Galili, 1993). Besides, Galili (1996) argued that operational definition may develop operational knowledge, simplify weight–gravitation instruction and reduce learning difficulties for some students.

If students' memories on physics concepts are limited to the given operational definition, their conception of this physical quantity can be essentially operational knowledge with its content and structure. We may describe this kind of conception as "Operational Conception". Nevertheless, some may argue that operational definitions, with their problem of circularity, may not deepen our understanding of physical phenomena (Lindsay, 1937) or provide additional knowledge in learning or conceptualizing the physical quantity (See Table 1).

Table 1 Operational Conception

Operational Conception	
Definition of Physical quantity	**Definition of Measuring Equipment**
Weight *is what bathroom scales read.* (Bishop, 1999) **Weight** is the reading of a spring scale supporting the object, independent of any specification of how the spring scale is supported. (Iona, 1975)	**Scales**: a piece of equipment used for weighing people or things. (Macmillan English Dictionary, 2007) **Spring Balance**: The device is often used to measure the weight of a body approximately. (Oxford Dictionary of Physics, 2005)
Time: The *time of an event* is most naturally defined as the reading on a clock located at the event's position at the instant, at which the event occurs. (Scherr et al., 2001)	**Clock**: system for displaying or recording the passage of time. (Collins internet-linked dictionary of Physics, 2007)
Force: The force is measured by a dynamomter. (Coelho, 2011) The operational definition of **force** employs a spring scale calibrated in newtons. (Karplus, 2003 , p.285)	**Dynamometer**: an instrument used to measure a force, often a spring balance. (Dictionary of Physics, 2005) **Springs** can be used to measure forces. (Karplus, 2003 , p.285)
Temperature is the scale reading on a suitable thermometer. (Harris, 1969) **Temperature** is defined as the reading on a thermometer. (Keyes, 1973)	**Thermometer**: An instrument used for measuring the temperature of a substance. (Oxford Dictionary of Physics, 2005)
Electric Current is measured by the dial reading of a standard ammeter. (Karplus, 2003, p.315)	**Ammeter**: An instrument that measures electric current. (Oxford Dictionary of Physics, 2005)

The problem of circularity is not only restricted to operational definitions. Numerous studies seem to suggest that circularity in definitions can contribute to students' inability to distinguish heat and temperature, work and energy and so on. For example, temperature is defined in some textbooks in term of heat, and heat is commonly defined as transfer of energy by virtue of temperature difference. In a sense, heat and temperature are both defined from Zeroth Law of Thermodynamics or thermal equilibrium, that is, the concept of heat involves temperature, and the concept of temperature involves heat. Hence, it may explain why many students are unable to distinguish 'heat' and 'temperature' and the confusion can be attributed to their definitions (Warren, 1972; Bauman, 1992; Yeo & Zadnik, 2001).

In a similar way, work is sometimes defined as energy, and energy is defined in terms of work; they are defined from Work-Energy Theorem. Therefore, students may not be able to distinguish work with energy (Driver & Warrington, 1985; Kurnaz & Sağlam-Arslan, 2011) based on the proposed mental model. That is, students do not distinguish the meaning of definiendum (for example, work) and definiens (for example, energy); they may mix the meaning of work with the meaning of energy. This kind of alternative conception can be coined as Mixed Conception (definiendum and definiens) and sometimes, Indistinguishable Conception. Note that definiendum refers to the term to be defined and definiens refers to the terms used in the definitions. In addition, heat and temperature, for example, can both be interchangeably referred as definiendum and definiens.

It is often reported that students are confused with the concepts of mass and weight. The confusion may arise because we measure mass and weight with the same instrument, the balance (Parton, 1975). The definitions of mass and weight are also related to each other by the mathematical expression, weight, $W = mg$, m refers to mass and g refers to acceleration due to gravity. Hence, it is well established in engineering literature where the physicists' mass is often expressed as W/g (Iona, 1975).

Electric field has been reported as an abstract concept which students have difficulty (Ferguson-Hessler & de Jong, 1987). This could be attributed to the problem of circularity when the definitions of electric field, electric charge and electric force are defined in terms of each other, based on Coulomb's Law. Alternatively, some textbooks will avoid the definition of electric force, but it does not really help. Without defining electric force, student's conception on electric force is still limited and it affects the conception of electric field. Strictly speaking, all definitions in physics have problem of circularity when they are all words referring to some other words, and these words will eventually refer back to these initial words defined within the same dictionary (See Table 2).

Table 2: Mixed Conception (definiendum and definiens)

Mixed Conception (definiendum and definiens)	
Definiendum (The term to be defined**)**	**Definiens (**The terms used in the definitions**)**
Heat: "the process by which energy transfers occur as a result of a temperature difference." (Carlton, 2000) **Heat** is energy which is transferred from an object at a higher temperature to another at a lower temperature, until they reach the state of thermal equilibrium. (Thomaz et al., 1995)	**Temperature**: Temperature is a measure of the concentration of heat energy. (Carlton, 2000) **Temperature** of a system is a property that determines whether or not a system is in thermal equilibrium with other systems. (Balamuth, Wolfe & Zemansky, 1941)
Energy is defined as the ability to do work.	**Work** as an energy transfer between an agent and a recipient (Mungan, 2005) **Work** is the process of transferring energy to a system through the displacement of the system by an applied force. (Serway & Faughn, 2003, p.135)
Weight: Weight is the force of gravity acting on the mass and g is often called the acceleration due to gravity. (Johnson et al., 2000)	**Mass**: A common way of measuring an unknown mass is to use a balance to compare the weight of an unknown against the weight of a standard mass. (Beynon, 1994)
Charge (See *electric charged object*): Any object that can exert or feel the electric force. (Hobson, 2003)	**Electric Force** (See *electric force law*): Electrically charged objects exert forces on each other at a distance. (Hobson, 2003)
Electric Field: definition of electric field as electric force per unit charge. (Young & Freedman, 2004, p.806)	The **electric force** on a charged body is exerted by the electric field created by *other* charged bodies. (Young & Freedman, 2004, p.806)

2. The Problems of Precision

The definition of weight as *the force due to gravity* (Brown, 1999) is imprecise because it does not specify whether the force is gravitational or electromagnetic in nature (Bishop, 1999). Besides, the problem of precision may result in different conceptions on weight: students may conceive it as gravitational force or support force on the weighing scale (Galili, 1996). Some textbooks include that this force is downward in direction, however, it can be improved as "toward the centre of the Earth". Essentially speaking, more features or attributes, such as the ontology (Chi, Slotta, & de Leeuw, 1994) and cause (Piaget, 1974) can be added into the conceptual definition. On the other hand, operational definition of weight can be more precise by including the following features: measuring device (Robertson, 2008), nature of force (Bishop, 1999), direction (Iona, 1975) and reference frame (Iona, 1999).

One common alternative conception of energy is that it is believed to be a kind of substance (Warren, 1983). This can be attributed to the imprecise definition, "Energy is the ability to perform work" which does not specify the ontology of energy. Hence, Aron (1999) explained using *The Feynman Lectures* that, "energy is *not* concrete; it is *not* a material substance; it is given meaning through the calculation of numbers." To be even more precise, one should state that not all energies are able to perform work based on Second Law of Thermodynamics (Sexl, 1981).

Newton's Third Law of motion is sometimes simply stated as "Action equals reaction". This suggests only two features, namely, there are two forces and they have the same magnitude. Note that Newton's Third Law may have five features (See Table 3). The features of definitions may include nature or ontology, which is sometimes not stated in the definition of heat, for example. This may result in different conception of heat, either as sensation, energy, process, or interactions, just to name a few examples. Some prefer the word, boundary, to be included in definition of heat too (Spalding & Cole, 1966, p. 92). Lastly, precision may refer to the value specified in the definition, such as the range of visible wavelength. The wavelength for violet, 390 nanometers is definitely more precise than 400 nanometers as found in some textbooks. This feature can be lacking in some definitions.

Table 3 Imprecise Conception I: (Lack of Important Features)

Imprecise Conception (Lack of Important Features)	
Less Precise Definitions	**More Precise Definitions**
Weight as a *result of weighing*. (Galili, 1993)	**Weight** implies a force exerted by something against support (or pivot) and equal to the contact, elastic, normal force exerted by the support (or pivot) on the object. (Galili, 1993)
Energy is the ability to perform work.	**Energy** is *not* concrete; it is *not* a material substance; it is given meaning through the calculation of numbers. (Arons, 1999)
Heat is energy that is being transferred from one system to another because of a difference in temperature. (Tipler, 2004)	**Heat** only has meaning when referred to the boundary of a system. It exists during the interaction only. (Spalding & Cole, 1966, p.92)
Newton's Third Law: Action equals reaction. To every action there is always an opposed equal reaction. (Hewitt, 2002, p.75)	Five Features of **Newton's Third Law** of Motion: 1. occur in pairs 2. are of the same kind (Electric or magnetic) 3. are of equal in magnitude 4. act along the same line, but in opposite directions 5. act on different objects. (Crundell, 2001)

Light. A form of electromagnetic radiation able to be detected by the human eye. Its wavelength range is between about 400 nm (far 'violet') and about 700 nm (far 'red'). (The Facts on File Dictionary of Physics, 2005)	**Light**: … It forms a narrow section of the electromagnetic spectrum, the wavelength range (for normal vision) being approximately 390 nanometers (violet) to 740 nanometers (red). (The Penguin Dictionary of Physics, 2000)

The definition of buoyant force as discussed in the Introduction (Hestenes et al., 1992), has a problem of precision. Teachers should include the *cause* of buoyant force or the *condition of applicability* in this definition. Archimedes principle applies for object which is partially floating, but it excludes the situation when there is no fluid below the object. The inclusion of these two features may improve the precision of the definition of buoyant force and affect how teachers and students will determine whether the book placed on a table, has buoyant force or not (See Fig 3). Hence, the precision of definition provided may help to achieve a more precise conception on the physics concept. That is, the problem of precision may result in a misconception or vague conception of a physical quantity when the definition in textbook is imprecise. We may name this kind of conception as "Imprecise Conception".

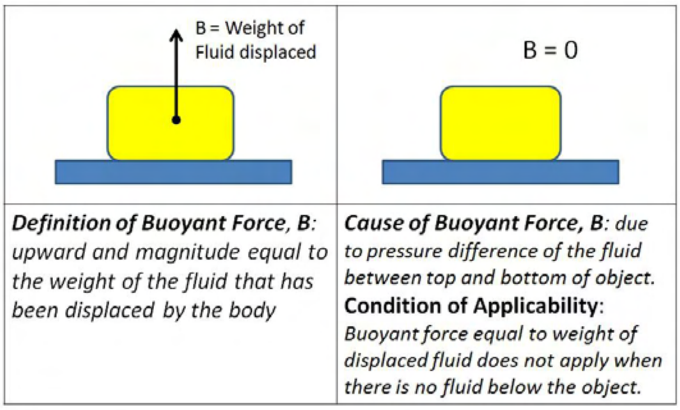

Fig 3: Definitions of Buoyant Force with/without cause and condition of applicability

Another kind of imprecise conception can be attributed to *undefined features* or *definiens* in the definitions. These features being stated in some definitions, should be further defined or explained on their meanings. That is, the effect to students is as if the features are not present in the working memory when we are not sure of their definitions or meanings. Similarly, the feature may adopt word which has multiple meanings, thereby misleading some students. To minimize this problem, we can avoid certain words with multiple meanings. For example, Newton's third law can be defined without the word, "action", by stating that "To every force acting on a body there exists a corresponding force that is equal in magnitude but opposite in direction, exerted by the body (Crew, 1929, p.76)."

There are more examples of words, ability, transfer, heat, random, or roundness which are commonly not defined within the same text (See Table 4). There can be disagreement on how these words should be defined, and their meanings can differ for some scientists. Temperature can be defined in term of heat, but heat could be defined as substance (Newburgh, 2009), motion (de Berg, 2008) and interaction (Moore, 1993) or others. The conception of temperature may vary with students if their conception of heat is different. If students do not have working memory of these words and their definitions, or they remember another definition different from the intended meaning, this problem of definition may also result in imprecise conception.

Table 4 Imprecise Conception II: (Undefined or ill-defined Features)

Imprecise Conception (Undefined or ill-defined Features)	
Imprecise Definition	**Undefined or ill-defined Features**
Energy is the **ability** to perform work.	The trouble is that **ability** is not defined, or depends on circumstances. (Swartz & Miner, 1996, p.160)
Heat: non-mechanical energy **transfer**. (Roche, 1971)	**Transfer** means complementary changes in the quantity of energy stored in interacting subsystems; it does not mean flow or any other form of transit. (Papadouris & Constantinou, 2010)
Temperature: Temperature is a measure of the concentration of **heat** energy. (Carlton, 2000)	**Heat** as a substance. (Newburgh, 2009) **Heat** is motion. (de Berg, 2008) **Heat** as an interaction. (Moore, 1993)
Entropy is a measure of the amount of disorder or **randomness** in a system. (Giordano, 2010)	**Random**: chosen or happening without any particular method, pattern or purpose. (Macmillan English Dictionary, 2007)
A **planet** is a celestial body that: 1. is in orbit around the Sun, 2. has sufficient mass to assume hydrostatic equilibrium (a nearly **round** shape), and 3. has "cleared the neighbourhood" around its orbit. (International Astronomical Union, 2006)	How are we to quantify the degree of **roundness** that distinguishes a planet? Does gravity dominate such a body if its shape deviates from a spheroid by 10 percent or by 1 percent? (Soter, 2007)

3. The Problems of Context

The definition on weight, for example, may vary according to daily or historical context and technical usage. It can be significantly different depending on the theoretical models adopted by geophysicists, metrologists or chemists. Although the mathematical definition of weight is commonly based on $W = mg$, geophysicists may focus on g, the gravity measurement and metrologists are concerned on m, the traceability to a prototype kilogram (Van Camp et al., 2003). Since weight can be defined in terms of mass and gravity, it is not a surprise when some students "equate weight with gravity" (Galili, 1993) or confuse weight with mass (Iona, 1975).

In some studies, it was found that the word, force, can be used as a verb or noun in different languages (Itza-Ortiz et al., 2003) or implied the meaning of energy (Grayson, 2004) and power (Gao, 1998; Suzuki, 2005). That is, force may refer to power or energy in daily life as defined in the dictionary, and its meaning is cultural dependent (Fig 4). The influence of daily meaning to the technical meaning can also be found on the words, momentum and impulse, in Itza-Ortiz et al.'s (2003) study.

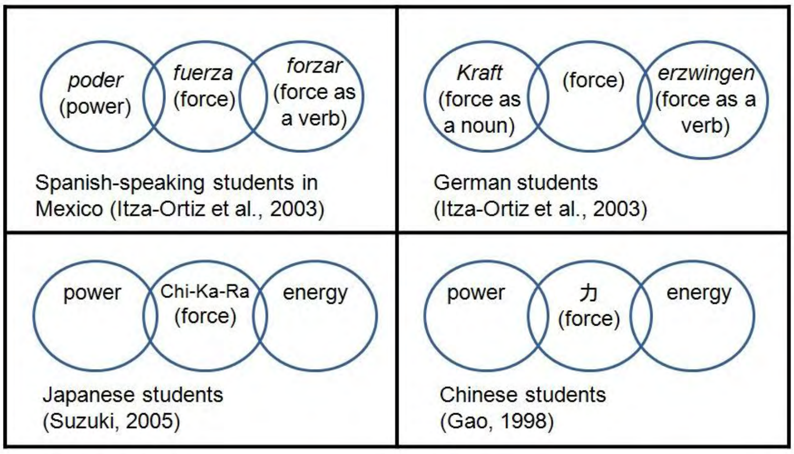

Fig 4. Cultural influence on the definitions of force

We may find the daily meanings of these words in the dictionary and several research studies (Williams, 1999, Itza-Ortiz et al., 2003, Suzuki, 2005) which students may have before lessons (Please refer to Table 5 for a comparison of dictionary definitions or daily meaning with technical meaning of some physics terms). Note that the meanings of words in the dictionary are also compiled by finding what various words have meant to some authors; it is not about providing authoritative statements on the "true meaning" of words (Hayakawa, S. I. & Hayakawa, A. R., 1990, p.34). Students may also learn the meanings of these words from the dictionary instead of physics textbooks.

In general, students may mix technical meaning of force, momentum, impulse, for example, with their meanings in everyday connotation (Williams, 1999; Itza-Ortiz et al., 2003). This kind of conception can be coined as "Mixed Conception" (Daily and Technical Context). In a sense, this is similar to intermediate conception (Grayson, 2004) which indicates a conception that may have elements of both alternative (incorrect) conception and technical ("correct") conception. That is, students may move back and forth between "old" conception (daily meaning) and "new" conception (technical meaning) depending on the context. However, if students can differentiate the daily and technical meaning of the words, they are likely to perform better in the assessments (Itza-Ortiz et al., 2003).

Table 5 Mixed Conception: Daily and Technical Context

Mixed Conception (Technical and Daily Context)	
Dictionary Definitions / Daily Meaning	**Technical Definitions**
CHI-KA-RA (**Force**) has nine meanings involving “physical strength”, “power”, “energy”, “ability”, “effort”. According to an English dictionary, the English word “force” has 12 meanings, including “violent action”, “physical strength”, “strong effect”, “power”… (Suzuki, 2005)	**Force**: We define the **force** F that an interaction exerts on a given object to be the *rate* at which momentum flows into the object because of that interaction. (Moore, 2003)
Momentum: the speed with which a moving object keeps moving or moves faster. (Itza-Ortiz et al., 2003)	**Momentum** is defined as the product of the mass of an object and its velocity. (Hewitt, 2002)
Impulse: One of the strong basic feelings that make people do things. (Itza-Ortiz et al., 2003)	**Impulse**: the amount of momentum that a specific interaction contributes to a particle’s momentum during a short time’s interval. (Moore, 2003)
Energy: 1. dynamic quantity; 2. vigorous exertion of power; 3. the capacity for doing work; 4. power. (Williams, 1999)	**Energy**: the numerical sum of the kinetic energies of all particles in the system plus the potential energies of all their internal interactions. (Moore, 2003)
Weight: 1. the amount that a thing weighs; 2. relative heaviness. (Williams, 1999)	**Weight**: the gravitational force exerted on an object. (Moore, 2003)

Students may mix technical meaning of the words with not only their daily meanings, but their historical meanings. For example, the alternative conception, “motion implies force”, can be attributed to Aristotle’s concept in physics (Clement, 1982). Aristotle recognized that motion was caused by inherent force of every object to seek its natural place. However, one may explain that this force was defined as *energy* (Grayson, 2004; Alvegard et al., 2010). (Students can be considered correct if they believe in “motion implies energy”.) Interestingly, electromotive force which was defined as a force, it is now preferred to be defined as “energy” (Fig 5). This has been a source of confusion to students for some time (Alexander, 1939).

Force	Electromotive Force
Agent involved in pulling or pushing. (Aristotle, 1934) Proportional to the quantity of matter and the speed. (Buridan, 14th Century) Rate of change of motion. (Newton, 1687) Forces are indestructible, convertible, imponderable objects. (Mayer, 1842)	Volta (1782) defined emf as “Prime mover of current”. (Source: Roche, 1989) Kirchhoff (1849) showed that Volta’s tension and Poisson’s potential function were numerically identical. (Source: Roche, 1989) Work done per unit charge. (Halliday, 2005)

Fig 5: The Evolution in the definitions of Force and Electromotive Force

The definition of heat has also evolved over time and it has been defined as substance (Newburgh, 2009), motion (de Berg, 2008) and interaction (Moore, 1993), just to name a few examples. There are also many different kinds of alternative conceptions depending on the research studies (Yeo & Zadnik, 2001; Chiou & Anderson, 2009), research sample, methodology, or interpretations of researchers (Refer to Fig 6: Alternative Conceptions of Heat). In addition, alternative conceptions can be interpreted differently depending on whether researchers define heat as energy transfer, "heat as noun," or transfer of energy, "heat as verb" (Romer, 2001).

Students' conceptions of heat (Yeo & Zadnik, 2001)	**Students' interpretative frameworks of heat (Chiou & Anderson, 2009)**
Heat is a substance. Heat is not energy. Heat and cold are different, rather than opposite ends of a continuum. Heat and temperature are the same thing. Heat is proportional to temperature. Heat is not a measurable, quantifiable concept.	Heat is treated as an intrinsic property of a substance. Heat is treated as a material substance Heat is treated as a nonmaterial entity, caloric flow. Heat refers to a transfer of thermal energy.

Fig 6: Alternative Conceptions of Heat

To summarize, students may mix technical meaning of these words with their definitions in historical context. If students are exposed only to historical meaning, one may describe them as having "Historic Conception". It is common that students mix technical meaning with historical meaning (Table 6), and we may describe this kind of conception as "Mixed Conception" (Technical and Historical Context). Interestingly, students may even use mixture of concepts on force from three theories, namely Aristotelian, Impetus and Newtonian theories (Halloun & Hestenes, 1985).

Table 6 Mixed Conception: Technical and Historical Context

Mixed Conception (Technical and Historical Context)	
Technical Definitions	**Historical Definitions**
Force: A **resultant force** is that *agent which changes the velocity* (*and momentum*) *of a body*. (Whelan & Hodgson, 1989)	Forces are indestructible, convertible and imponderable objects. (Mayer, 1842)
The **electromotive force** (e.m.f.) of a source is defined as the electrical energy produced per unit charge inside the source. (Breithaupt, 1995)	**Electromotive Force**: the force that separates positive from negative electricity, and avoids their reunion in the battery. (Gomez & Duran, 1998)
Heat: the energy in a substance as represented by molecular activities or configurations. (Stuart, 1938)	**Heat**: Thus heat is produced by motion. If it is matter, it must be admitted that the matter is created by motion. (Carnot, 1824, p. 68-9)

Mass is defined as Lorentz invariant, independent of velocity of the object. (Okun, 1989)	Transverse **mass** = $\mu\gamma$, Longitudinal **mass** = $\mu\gamma^3$ μ: mass of electron, γ: Lorentz factor **Mass** is velocity-dependent. (Einstein, 1905)
Displacement current: is not a flow of charge; nor is it a physical source of magnetic fields. (French, 2000)	**Displacement current:** a real flow of electricity across an insulating gap**.** (French, 2000)

There seems two different schools of thought on the alternative conception of force: Some explain that "motion implies force" is due to confusion of force with its daily meaning (Itza-Ortiz et al., 2003), and others explain with Aristotle's notion (historical meaning) of force (Clement, 1982). Note that these two explanations on alternative conceptions are not contradictory but complementary; the daily (dictionary) meaning of force, for example, can be influenced by their historical meaning. Hence, some students may not be able to distinguish the technical meaning of force with its daily meaning or historical meaning. To summarize, students may mix the technical concept of force, for example, with the concept of force in historical context or in daily context.

4. The Problems of Completeness in knowledge

Students may think that they have complete knowledge of the physics concept after reading their textbooks; this is a misconception. Students may not be aware of the tentative nature of science and they believe that laws and theories do not change. (Lederman & O'Malley, 1990). The fact is there are problems of completeness in knowledge even in the definition of weight. One criticism on conceptual definition of weight is that the theoretical concept of gravitational force between the Earth and the object, is inaccessible to measurement (Iona, 1987). That is, this ideal concept of weight does not really exist. The controversy is also contributed by Einstein's realization (Pais, 1982) that we are not able to distinguish the weight whether it is due to the gravitational field or accelerating elevator, sometimes known as the principle of equivalence. This has revolutionized the meaning of weight, in the early 20th century.

To be extremely precise, the weighing balance or spring scale does not always provide the correct weight, as the measured value is not linearly proportional to the mass of the body. That is, the weighing scale is unlikely to have perfect linearity throughout a wide range of application, and without error in measurement. The effect of environment due to pressure, temperature and humidity may increase the error of measurement too. Besides, practically every theoretical problem in physics is governed by nonlinear mathematical equation (Heisenberg, 1967). Hence, one may criticize the accuracy of operational definition of weight because of the problem of measurement in weighing scale.

Note that Einstein's replacement of Newton's gravitational force with a non-Euclidean space-time has considerably undermined the Newton's enduring definition on weight. While the theory of gravitation is continued to be researched, we may expect further redefinition on weight. (Astrophysicists are currently trying to understand the influence of dark matter and dark energy on gravitation.) The meaning of weight may change with new understanding on the nature of gravitational force. Hence, our knowledge on weight can be considered as incomplete! Our incomplete knowledge on physics concepts and their definitions can be coined as "Incomplete Conception". (See Table 7)

Table 7: Incomplete Conception

Incomplete Conception	
Definitions	**Problems of Incompleteness in Knowledge**
Weight: The weight of an object refers to the net gravitation force exerted on it by <u>all other objects</u>. (Hobson, 2003)	We know very little for sure about dark matter… We know even less about dark energy… (Wilczek, 2008, p.203)
Energy: The property of a system that enables it to do work. (Hewitt, 2002, p.125)	We have no knowledge of what energy is. (Feynman, 1964)
Each force in a Newton's third law pair: • has the same magnitude (size) • acts along the same line but in opposite directions, • acts for the same time, • acts on a *different* object, • is of the same type (e.g. two contact forces, or two gravitational forces) • can be identified by changing round the words. (Johnson et al., 2000)	The **<u>equality of action and reaction</u>** has almost no place in relativistic mechanics. It must essentially be a statement about the forces acting on two bodies, as a result of their mutual interaction at a given instant. And, because of the relativity of simultaneity, this phrase has no meaning. (French, 1968)
Mass: Mass as irreducible representations of the Poincaré group. (Wilczek, 2005)	We also don't really understand the masses of neutrinos… (Wilczek, 2008, p.202.)
Entropy: I have put forward 12 principles that have led me to conclude that Boltzmann's 1877 definition of the entropy in terms of the logarithm of the probability of macroscopic states of composite systems is superior to all other options. (Swendsen, 2011)	The issues I have discussed have been the subject of disagreements for well over a century. (Swendsen, 2011) "Nobody really knows what entropy really is." John von Neumann (Tribus & McIrvine, 1971)

Implications and Limitations

This paper suggests that the definitions that teachers adopt or the definitions that students are exposed to, may contribute to the alternative conceptions in students. Hence, teachers should develop pedagogy to help students in learning the definitions in physics. There seemed *very limited* physics education research papers on the pedagogy in definitions as compared to position papers on the correct definitions in physics. We may let students debate or discuss the preferred definitions (Carlton, 2000) with the help of these position papers. In addition, students should be aware of the problems in definitions which may impede their learning in physics concepts.

Students' ability to define a concept does not imply that they have fully understood the definition and its implication. For example, students may define acceleration in an acceptable manner, but they may not be able to apply the definition appropriately (Trowbridge & McDermott, 1981). Since memorization of the definition of a concept is relatively easier than the understanding its physical meaning; students may prefer this way of learning for assessment. Hence, "learning of a concept" and "learning of a definition of a concept" are not necessarily the same thing as noted by Smith and Ragan (1999, p. 179).

Teachers should also be aware that textbook authors may adopt definitions which have varied precisions. Students should not be penalized unnecessarily if there is no consensus opinion on some definitions, such as heat. Note that a few textbooks may provide more precise definitions, with more features, than most of the textbooks. It is not fair to assess students' knowledge on physics concepts by using those venerable textbooks which adopt uncommon "stricter" definitions. Hence, the definitions that we adopt in classroom may have implications in both learning and assessments.

We should realize that the concepts in physics are *closely* related to their definitions. The experts' definitions in physics concepts cannot perfectly represent the concepts they have in mind because of the challenges in defining or the problems of definition. Neither can all students comprehend the definitions fully because of their ability, attitude and the problems of interpretation. Hence, we may observe the following definitions, weight, energy, heat, for example, can be defined differently and they can result in four variants of alternative conceptions. To summarize, the problems of definitions may lead to at least four kinds of alternative conceptions, such as "operational conception," "imprecise conception," "mixed conception," and "incomplete conception" (See Appendix A).

The present classification of alternative conceptions (See Appendix B for additional selected papers and letters) can be further elaborated if we clarify the four problems of definition in more details. For circularity, we can divide it into direct circularity and indirect circularity. Indirect circularity may refer to slightly less direct circular definitions as in the example of electric force, electric charge and electric field, as compared to "direct circularity" which refers to two terminologies which are self-referencing. For problems of precision, we may use a more generic term, "problems of exactness". In general, problems of exactness can be divided into “problems of precision” and “problems of accuracy”. For example, it is more accurate to define heat as a process than caloric or sensation. Similar extensions can be applied to problems of context and problems of completeness in knowledge. They will be developed in future papers.

CONCLUSION

It is important to re-iterate that alternative conceptions are not mainly contributed by definitions available to students. We suggest coining the phrase “alternative definitions” to refer to the commonly available definitions of physical concepts adopted by physicists or textbook authors, which have problems of circularity, precision, context and completeness in knowledge. Alternative conceptions can be due to “alternative definitions” having the above fundamental definitional problems. That is, the problems of definitions may lead to at least four variants of alternative conceptions, namely, “operational conception,” “imprecise conception,” “mixed conception,” and “incomplete conception”.

In the contemporary world, students and teachers can access to more different definitions from internet or textbooks available all over the world. This may result in more variants of alternative conceptions on the fundamental concepts in physics. Besides, the classroom in this century may have more students from various parts of this globalized world. That is, students may come into the classroom with more varied background knowledge (more diversified definitions of physics concepts).

To conclude, with the awareness on the problems of definitions, circularity, precision, context and completeness, it may help to facilitate definitions of physics for deep understanding. Further development on this proposed framework on “Alternative Conception” can utilize the problems in definitions for improvement in textbook’s presentation and classroom teaching. Note that these four challenges in definitions cannot be easily resolved. Educators and students should be cognizant of the variants of alternative conceptions which can arise from alternative definitions. The concepts of alternative definitions can be useful and generalizable to science education and possibly beyond. The importance of definitions should deserve more attention from educators and students.

It should be appropriate to end this paper with another insight from Feynman.

Test it this way: you say, "Without using the new word which you have just learned, try to rephrase what you have just learned in your own language." Without using the word "energy," tell me what you know now about the dog's motion." You cannot. So you learned nothing about science. That may be all right. You may not want to learn something about science right away. You have to learn definitions.

Feynman, 1969, p. 317

Appendix A: Alternative Conceptions on Weight

Table 8 Alternative Conceptions on Weight

Alternative Conceptions on Weight	
Alternative Definitions	**Variants of Alternative Conceptions**
Weight: *Weight is what bathroom* ***scales*** *read.* (Bishop, 1999) "the reading of a spring **scale** supporting the object, independent of any specification of how the spring scale is supported." (Iona, 1975) **Scales**: a piece of equipment used for **weighing** people or things. (Macmillan English Dictionary, 2007) **Spring Balance**: The device is often used to measure the weight of a body approximately. (Oxford Dictionary of Physics, 2005)	**Operational conception**
Weight: Weight is the force of gravity acting on the **mass** and g is often called the acceleration due to gravity. (Johnson et al., 2000) **Mass**: A common way of measuring an unknown mass is to use a balance to compare the **weight** of an unknown against the weight of a standard mass. (Beynon, 1994)	**Mixed Conception (definiendum and definiens)**
Weight as a *result of weighing*. (Galili, 1993) **Weight**: …those who define ***weight*** as a *result of weighing*, which implies a force exerted by something against support (or pivot) and equal to the contact, elastic, normal force exerted by the support (or pivot) on the object. (Galili, 1993)	**Imprecise Conception (Lack of Important Features)**
Weight: 1. the amount that a thing weighs; 2. relative heaviness. (Williams, 1999) **Weight**: the gravitational force exerted on an object. (Moore, 2003)	**Mixed Conception (Technical meaning with Daily Context)**
Weight: The weight of an object refers to the net gravitation force exerted on it by all other objects. (Hobson, 2003, p.99) We know very little for sure about dark matter… We know even less about dark energy… (Wilczek, 2008, p.203)	**Incomplete Conception**

Appendix B: Selected Papers & Letters related to Alternative Conceptions.

S/No	Alternative Conceptions	Research Studies/Papers/Letters
1	**Operational Conception**	Operational Definition of Mass (Galili, 1993; Galili & Kaplan, 1996)
2	**Mixed Conception (definiendum and definiens)**	Unable to distinguish heat and temperature. (Warren, 1972; Bauman, 1992; Yeo & Zadnik, 2001)
		Unable to distinguish work and energy. (Driver & Warrington, 1985; Kurnaz & Sağlam-Arslan, 2011)
		Unable to distinguish mass and weight. (Iona, 1975; Gonen, 2008)
3	**Imprecise Conception: Lack of Features**	Cause of Weight: Earth or All objects in Universe? (Gönen, 2008)
		Ontology: Heat as substance, energy, process or interaction? (Chi, Slotta & deLeeuw, 1994; Chiou & Anderson, 2009; Wiser & Amin, 2001)
		Condition of Applicability: Research Study on Buoyant Force (Hestenes et al., 1992) Paper and Letters on Buoyant Force (Hudson & Munley, 1996; Bierman & Kincanon, 2003; Harper, 2003)
4	**Imprecise Conception: Undefined or ill-defined Features**	Temperature: translational kinetic energy of its molecules. (Halliday, 2005, p.514) The chemists were critical of the physicists for their often imprecise use of the term 'molecule'. (Roberts & Watts, 1976)
5	**Mixed Conception: Technical and Daily Context**	Force as energy. (Gao, 1998; Grayson, 2004; Suzuki, 2005)
		Heat as sensation. (Leite, 1999; Wiser & Amin, 2001)
		Electricity as current, voltage, energy and power. (Grayson, 2004)
6	**Mixed Conception: Technical and Historical Context**	Force as energy. (Clement, 1982; Alvegard et al., 2010)
		Heat as caloric. (Carnot, 1824; de Berg, 2008)
		Velocity–dependent Mass: (Sandin, 1991; Gabrielse, 1995) Velocity–independent Mass: (Okun, 1989; Hecht, 2006)
7	**Incomplete Conception**	Energy as substance, substance-like, or abstract quantity. (Warren, 1983; Falk, Herrmann & Schmid, 1983; Arons, 1999)

References:

Alexander, L. M. (1939). Concepts and Definitions of Electromotive Force. *American Journal of Physics*, *7*(1), 23–28.

Alvegard, C., Anderberg, E., Svensson, L. & Johansson, T. (2010). The Interplay between Content, Expressions and Their Meaning when Expressing Understanding. *Science & Education*, *19*(3), 283–303.

Aristotle (1934). *Physics*. Cambridge: Harvard University Press.

Arons, A. B. (1999). Development of energy concepts in introductory physics courses. *American Journal of Physics*, *67*(12), 1063–1067.

Balamuth, L., Wolfe, H. C. & Zemansky, M. W. (1941). The temperature concept from the macroscopic point of view. *American Journal of Phys*ics, *9*(8), 199–203.

Bauman, R. P. (1992). Physics that textbook writers usually get wrong: II Heat and Energy. *The Physics Teacher*, *30*(9), 353–6.

Bazire, M., & Brézillon, P. (2005). Understanding Context Before Using It. (Dey, A., Kokinov B., Leake, D. & Turner, R. Eds.) *Modeling and Using Context*, *3554*, 29–40. Springer.

Berg, B. L. (2009). *Qualitative Research Methods for the Social Sciences* (7th ed.). Boston: Allyn & Bacon.

Beynon, J. (1994). A few thoughts on energy and mass. *Physics Education*, *29*(2), 86.

Bierman, J. & Kincanon, E. (2003). *The Physics Teacher*, *41*(6), 340–344.

Bishop, R. (1999). Weight – An Accurate, Up-to-Date, Layman's Definition. *The Physics Teacher*, *37*(4), 238–9.

Breithaupt, J. (2000). *Understanding Physics for Advanced Level* (4th ed.). Cheltenham: Stanley Thorne.

Brookes, D. & Etkina, E. (2009). Force, ontology and language. *Physical Review*, Special Topics, Physics Education Research, 5, 010110.

Brown, R. (1999). Weight – Don't use the word at all. *The Physics Teacher*, *37*(4), 241.

Carlton, K. (2000). Teaching about heat and temperature. *Physics Education*, *35*(5), 101–5.

Carnot, S. (1824/1988). *Reflections on the Motive Power of Fire.* edited E Mendoza. Mineola, New York: Dover.

Chi, M. T. H., Slotta, J. D. & deLeeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction*, *4*(1), 27–43.

Chiou, G. L. & Anderson, O. R. (2009). A Study of Undergraduate Physics Students' Understanding of Heat Conduction Based on Mental Model Theory and an Ontology–Process Analysis. *Science Education*, *94*(5), 825–854.

Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics*, *50*(1), 66–71.

Coelho, R. L. (2011). Conceptual Problems in the Foundations of Mechanics. *Science & Education*. (Online First).

Crew, H. (1929). *General Physics*. Macmillan.
Crundell, M. (2001). *AS/A–Level Physics*. Oxfordshire: Philip Allan Updates.
Daintith, J. & Rennie, R. (2005). *The Facts on File Dictionary of Physics*. New York: Checkmark Books.
de Berg K. C. (2008). The Concepts of Heat and Temperature: The Problem of Determining the Content for the Construction of an Historical Case Study which is Sensitive to Nature of Science Issues and Teaching–Learning Issues. *Science & Education*, *17*(1), 75–114.
Deeson, E. (2007). *Collins internet-linked dictionary of Physics*. London: HarperCollins.
Dictionary of Physics (2005). London: Constable & Robinson.
Driver, R. & Warrington, L. (1985). Students use of the principle of energy conservation in problem situations. *Physics Education*, *20*(4), 171–176.
Einstein, A. (1905). On the Electrodynamics of Moving Bodies. *Annalen der Physik*, *17*(10), 891–921.
Ferguson-Hessler, M. G. M. & de Jong, T. (1987). On the quality of knowledge in the field of electricity and magnetism. *American Journal of Physics*, *55*(6), 492–497.
Feynman, R. P., Leighton, R. B. & Sands, M. L. (1964). *The Feynman Lectures on Physics, Vol 1*. Redwood City: Addison–Wesley.
Feynman, R. P. (1969). What is Science? *The Physics Teacher*, *7*(6), 313–320.
Feynman, R. P. (1998). *The Meaning of It All*. Massachusetts: Addison–Wesley.
French, A. P. (1968). *Special relativity*. New York: W W Norton.
French, A. P. (2000). Is Maxwell's Displacement Current a Current? *The Physics Teacher*, *38*(5), 274–6.
Gabrielse, G. (1995). Relativistic mass increase at slow speeds. *American Journal of Physics*, *63*(6), 568.
Galili, I. (1993). Weight and Gravity: teachers' ambiguity and students' confusion about the concepts. *International Journal of Science Education*, *15*(1), 149–162.
Galili, I. & Kaplan, D. (1996). Students' Operation with the Concept of Weight. *Science Education*, *80*(4), 457–487.
Galili, I. & Lehavi Y. (2006). Definitions of Physical Concepts: A study of physics teachers' knowledge and views. *International Journal of Science Education, 28*(5), 521–541.
Gao, L. B. (1998). Cultural Context of School Science Teaching and Learning in the People's Republic of China. *Science Education*, *82*(1), 1–13.
Giordano, N. J. (2010). *College Physics: Reasoning and Relationships*. Belmont, CA: Brooks/Cole Cengage Learning.
Gomez, E. J. & Duran, E. F. (1998). Didactic Problems in the Concept of Electric Potential Difference and an Analysis of its Philogenesis. *Science & Education*, *7*(2), 129–141.

Gonen, S. (2008). A Study on Student Teachers' Misconceptions and Scientifically Acceptable Conceptions About Mass and Gravity. *Journal of Science Education and Technology*, *17*(1), 70–81.

Grayson, D. J. (2004). Concept substitution: A teaching strategy for helping students disentangle related physics concepts. *American Journal of Physics*, *72*(8), 1126–1133.

Gunstone, R. F. & White, R. T. (1981). Understanding of gravity. *Science Education, 65*(3), 291–299.

Halliday, D., Resnick, R. & Walker, J. (2005). *Fundamentals of Physics* (7th ed.). New York: Wiley.

Halloun, I. A. & Hestenes, D. (1985). Common sense concepts about motion. *American Journal of Physics*, *53*(11), 1056–1065.

Harper, J. (2003). Archimedes' Principle and the FCI. *The Physics Teacher*, *41*(9), 510.

Harris, J. (1969). Temperature – its meaning and measurement. *Physics Education*, *4*(4), 204–6.

Hayakawa, S. I. & Hayakawa, A. R. (1990). *Language in thought and action,* 5th edition. Harcourt Brace.

Hecht, E. (2003). *Physics: Algebra/Trig* (3rd ed.). Pacific Grove: Thomson Learning.

Hecht, E. (2006). There is No Really Good Definition of Mass. *The Physics Teacher*, *44*(1), 40–45.

Heisenberg, W. (1967). Nonlinear problems in physics. *Physics Today*, *20*(5), 27–33.

Helsdon, R. M. (1976). Teaching thermodynamics. *Physics Education*, *11*(4), 261–2.

Hestenes, D., Wells, M. & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher*, *30*(3), 141–158.

Hewitt, P. (2002). *Conceptual Physics* (9th ed.). Massachusetts: Addison–Wesley.

Hobson, A. (2003). *Physics: Concepts and Connections* (3rd ed.). New Jersey: Prentice Hall.

Hobson, A. (2004). Energy and work. *The Physics Teacher*, *42*(5), 260.

Hudson, R. C. & Munley, F. (1996). Re-score the Force Concept Inventory! *The Physics Teacher*, *34*(5), 261.

Iona, M. (1975). The Meaning of Weight. *The Physics Teacher*, *13*(5), 263–274.

Iona, M. (1987). Weightlessness is Real. *The Physics Teacher, 25*(7), 418.

Iona, M. (1999). Weight – An Official Definition. *The Physics Teacher*, *37*(4), 238.

Itza-Ortiz, S. F., Rebello N. S., Zollman D. A. & Rodriguez-Achach M. (2003). The Vocabulary of Introductory Physics and its implications for learning physics. *The Physics Teacher*, *41*(9), 330–336.

Johnson K., Hewett S., Holt, S. & Miller, J. (2000). *Advanced Physics for You*. Cheltenham: Nelson Thornes.

Johnson-Laird, P. N. (1983). *Mental Models*. Cambridge: Harvard University Press.

Karplus, R. (2003). *Introductory Physics: A Model Approach* (2nd ed.). Buzzards Bay: Captain's Engineering Services.
Keyes, O. B. (1973). The concept of temperature–again. *Physics Education*, *8*(1), 60.
Kruger, C. J., Summers, M. K. & Palacio, D. J. (1990). An investigation of some English primary school teachers' understanding. *British Educational Research Journal, 16*(4), 383–397.
Kurnaz, M. A. & Sağlam-Arslan, A. (2011). A Thematic Review of Some Studies Investigating Students' Alternative Conceptions about Energy. *Eurasian Journal of Physics and Chemistry Education*, *3*(1), 51–74.
Langsberg, G. S. (1971/2000). *Textbook of Elementary Physics*, Volume 1. Honolulu, Hawaii: University Press of the Pacific.
Lederman, N. G. & O'Malley, M. (1990). Students' perceptions of tentativeness in science: Development, use, and sources of change. *Science Education*, *74*(2), 225–239.
Lee, G., Shin, J., Park, J., Song, S., Kim, Y. & Bao, L. (2005). Alternative conceptions, memory, & mental models in physics education. *2004 Physics Education Research Conference*. 1 ed. Sacramento, California (USA): AIP. 165–168.
Leite, L. (1999). Heat and Temperature: an analysis of how these concepts are dealt with in textbooks. *European journal of teacher education*, *22*(1), 75–88.
Lindsay, R. B. (1937). A Critique of Operationalism in Physics. *Philosophy of Science*, *4*(4), 456–470.
Mach, E. (1883/1989). *The science of mechanics.* La Salle, IL: Open Court. Mayer, J. R. (1842). Bemerkungen umber die Krafte der unbelebten Natur. Annalen der Chemie und Pharmacie. In J. R. Mayer (Ed.), Die Mechanik der Warme: Samtliche Schriften (Vol. 42, pp. 233–240). HP Munzenmayer, Stadtarchiv Heilbronn, Stadtarchiv Heilbronn, Heilbronn.
Moore, G. S. M. (1993). General, restricted and misleading forms of the First law of thermodynamics. *Physics Education*, *28*(4), 228–237.
Moore, T. A. (2003). *Six Ideas That Shaped Physics*. *Unit C: Conservation Laws Constrain Interactions* (2nd ed.). New York: McGraw-Hill.
Mungan, C. (2005). Work and Energy. *American Journal of Physics*, *73*(3), 197–198.
Newburgh, R. (2009). Carnot to Clausius: caloric to entropy. *Europe Journal of Physics*, *30*(4), 713–728.
Newton, I. (1687/1999). *Mathematical Principles of Natural Philosophy.* Berkeley, CA*:* University of California Press.
Noce, G., Torosantucci, G. & Vincentini, M. (1988). The floating of objects on the moon: prediction from a theory or experimental facts? *International Journal of Science Education, 10*(1), 61–70.
Okun, L. B. (1989). The concept of mass (Mass, Energy, Relativity). *Sov. Phys. Usp.*, *32*(7), 629–638.

Pais, A. (1982). *Subtle is the Lord*… Oxford: Oxford University Press.
Palmer, D. (2001). Students' alternative conceptions and scientifically acceptable conceptions about gravity. *International Journal of Science Education*, *23*(7), 691–706.
Papadouris, N. & Constantinou, C. P. (2010). A Philosophically Informed Teaching Proposal on the Topic of Energy for Students Aged 11–14. *Science & Education*. (Online First)
Parton, C. G. (1975). Weight and mass. *Physics Education*, *10*(1), 58.
Piaget, J. (1974). *Understanding causality.* New York: Norton.
Redish, E. F. (2003). *Teaching Physics with the Physics Suite*. New Jersey: John Wiley & Sons.
Redish, E. F. (2004). A Theoretical Framework for Physics Education Research: Modeling student thinking, in *Proceedings of the International School of Physics, ―Enrico Fermi‖ Course CLVI*, Redish, E. F. & Vicentini, M. (eds.) Amsterdam: IOS.
Rickheit, G. & Sichelschmidt, L. (1999). "Mental Models: Some Answers, Some Questions, Some Suggestions" in *Mental Models in Discourse Processing and Reasoning*, edited by Rickheit G. & Habel C., North-Holland: Elsevier, pp. 9–40.
Roberts, I. F. & Watts, D. S. (1976). The teaching of thermodynamics at preuniversity level. *Physics Education*, *11*(4), 277–284.
Robertson, B. (2008). Science 101: Do balance and scales determine an object's mass or its weight? *Science and Children*, *45*(7), 68–71.
Roche, J. (1971). Teaching heat using the joule. *Physics Education*, *6*(2), 125.
Roche, J. (1989). Applying the history of electricity in the classroom: a reconstruction of the concept of 'Potential' In "*Teaching the History of Science ed Michael Shortland & Andrew Warwick*". Oxford: Blackwell, pp. 168–184.
Rogers, E. H. (1981). Methodology for meta-research. *Presidential address at the conference of the International Communication Association*.
Romer, R. H. (2001). Heat is not a noun. *American Journal of Physics*, *69*(2), 107–9.
Rossing, T. D. (1995). Magnetic forces and fields: A note on terminology, definitions, and pedagogy. *American Journal of Physics*, *63*(10), 957–958.
Ruggiero, S., Cartelli, A., Dupre, F. & Vincentini-Missoni, M. (1985). Weight, gravity and air pressure: mental representations by Italian middle school pupils. *European Journal of Science Education*, *7*(2), 181–194.
Sandin, T. R. (1991). In Defense of Relativistic Mass. *American Journal of Physics*, *59*(11), 1032–1036.
Scherr, R. E., Shaffer, P. S. & Vokos, S. (2001). Student understanding of time in special relativity: Simultaneity and reference frames. *American Journal of Physics*, *69*(7), S24–S35.
Sears, F. W. (1950). *Mechanics, Heat and Sound.* Addison-Wesley.
Serway, R. A. & Faughn J. S. (2006). *College physics* (6th ed.). California: Thomson Learning.

Sexl, R. U. (1981). Some observations concerning the teaching of energy concept. *European Journal of Science Education*, *3*(3), 285–289.
Shaffer, P. S. & McDermott, L. C. (1992). Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies. *American Journal of Physics*, *60*(11), 1003–1013.
Shaw, R. E. M. (1969). A question of heat. *Physics Education*, *4*(4), 251–2.
Slisko, J. J. & Dykstra D. I. (1997). The Role of Scientific Terminology in Research and Teaching: Is Something Important Missing? *Journal of Research in Science Teaching*, *34*(6), 655–660.
Smith, P. L. & Ragan, T. J. (1999). *Instructional design.* USA: John Wiley & Sons.
Soter, S. (2007). What is a Planet? *Scientific American*, *296*(1), 34–41.
Spalding, D. B. & Cole, E. H. (1966). *Engineering Thermodynamics*. London: Edward Arnold.
Stern, P. N. & Harris, C. C. (1985). Women's health and the self-care paradox: a model to guide self-care readiness. *Health Care for Women International*, *6*(1–3), 151–163.
Stuart, M. C. (1938). Use and Meaning of the Term Heat. *American Journal of Physics*, *6*(2), 40.
Suzuki, M. (2005). Social Metaphorical Mapping of the Concept of Force "CHI-KA-RA" in Japanese. *International Journal of Science Education*, *27*(15,16), 1773–1804.
Swartz, C. E. & Miner, T. (1996). *Teaching Introductory Physics: A Sourcebook*. New York: AIP Press.
Swendsen, R. H. (2011). How physicists disagree on the meaning of entropy. *American Journal of Physics*, *79*(4), 342–8.
Taber, K. S. (2000). Finding the optimum level of simplification: the case of teaching about heat and temperature. *Physics Education*, *35*(5), 320–5.
The Penguin Dictionary of Physics (2000). London: Penguin Books.
Thomaz, M. F., Malaquias, I. M., Valente, M. C. & Antunes, M. J. (1995). An attempt to overcome alternative conceptions related to heat and temperature. *Physics Education*, *30*(1), 19–26.
Tipler, P. A. & Mosca, G. (2004). *Physics for Scientists and Engineers* (5th ed.). New York: W.H. Freeman & Company.
Tribus, M. & McIrvine, E. C. (1971). Energy and information (thermodynamics and information theory). *Scientific American*, *225*(9), 179–188.
Trowbridge D. E. & McDermott, L. C. (1981). Investigation of student understanding of the concept of acceleration in one dimension. *American Journal of Physics*, *49*(3), 242–253.
Van Camp, M., Camelbeeck, T. & Richard, P. (2003). The FG5 absolute gravimeter: metrology and geophysics. *Physicalia Magazine*, Journal of the Belgian Society, *25*(3), 161–174.

Warren, J. W. (1972). The teaching of the concept of heat. *Physics Education*, *7*(1), 41–4.
Warren, J. W. (1983). Energy and its carriers: a critical analysis. *Physics Education*, *18*(5), 209–212.
Whelan, P. M. & Hodgson, M. J. (1989). *Essential Principles of Physics* (2nd ed.). John Murray.
Wilczek, F. (2005). Whence the Force of F = ma? 2: Rationalization. *Physics Today*, *58*(12), 10–11.
Wilczek, F. (2008). *The Lightness of Being*. New York: Basic Books.
Williams, H. T. (1999). Semantics in teaching introductory physics. *American Journal of Physics*, *67*(8), 670–680.
Wilson, J. D., Buffa, A. J. & Lou, B. (2001). *College Physics* (6th ed.). New Jersey: Pearson.
Wiser, M. & Amin, T. (2001). "Is heat hot?" Inducing conceptual change by integrating everyday and scientific perspectives on thermal phenomena. *Learning and Instruction*, *11*(4–5), 331–355.
Wong, C. L. & Yap, K. C. (2010). In Search of a Framework to facilitate Statements of Definitions in Physics: Is Feynman's Lectures on Physics a good Guide? *Global Chinese Conference on Science Education* 2010.
Yager, R. E. (1983). The importance of terminology in teaching K–12 Science. *Journal of Research in Science Teaching*, *20*(6), 577–588.
Yates, J. (1985). The content of awareness is a model of the world. *Psychological Review*, *92*(2), 249–284.
Yeo, S. & Zadnik, M. (2001). Introductory thermal concept evaluation: Assessing students' understanding. *The Physics Teacher*, *39*(8), 496–504.
Young, H. D. & Freedman (2004). *Sears and Zemansky's University Physics* (11th ed.). California: Addison Wesley.
Zemansky, M. W. (1970). The use and misuse of the word "heat" in physics teaching. *The Physics Teacher*, *8*(6), 295–300.