Conceptual Energy: A Holistic Approach to Introducing Energy and Power to Freshmen

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Abstract

During the past few decades, a great deal of attention has been devoted to research dealing with how people learn. These studies have established three key characteristics of learning and transfer: initial learning is necessary for transfer; abstract representations of knowledge can help promote transfer; and all new learning involves transfer based on previous learning. In this paper, we present a holistic approach to teaching freshmen engineering students the concepts of work, energy, power, and efficiency. We will focus on the initial learning that is necessary for transfer by developing the students' understanding of energy using simple conceptual examples. Traditionally, in engineering programs, energy and power concepts are taught in parts, in courses such as dynamics, thermodynamics, applied thermodynamics, fluid mechanics, and heat transfer. Unfortunately, most engineering students by the time of their graduation do not have a good grasp of energy and power and do not see how all of these courses fit together. To prepare good engineers, the basic concepts of energy and power should be taught early in the freshman year and presented in a holistic way throughout the student's engineering education. In this paper, we show how these basic concepts could be taught in the freshman year without requiring mathematics and instead with focus on developing a better physical understanding of the concepts. We begin by explaining the fact that we need energy to build shelter, to cultivate and process food, to make goods, to transport goods and people, and to make our living places at comfortable settings. Next, students are taught that in order to quantify the requirements to make things, move or lift objects, or to heat or cool something, energy is defined and classified into different categories. Thermodynamics' Laws form the foundation of energy and analysis and design of many engineering problems and should be taught concurrently. The holistic approach presented in this paper can also benefit new engineering faculty and better prepare them to teach these important concepts.

1. Introduction

There are certain concepts that every engineer regardless of his or her area of specialization should know – among them are energy and power [1]. In this paper, we will discuss how to use the importance of energy and power in our everyday life to teach these ideas conceptually. The fact that we need energy to build structures, make goods, to mover or lift things, cultivate and process food, and heat or cool buildings should be stressed early in a student's engineering education. Whether a student is planning to pursue a civil engineering, mechanical engineering, or electrical engineering career, he or she needs to have a firm grasp of how we quantify the amount of energy we need to address our needs. It also is equally important for every engineer to know about energy sources, generation, and consumptions rates, and our own individual energy footprints. This is especially true today, when the world's growing demand for energy is among one of the most difficult challenges that we face. As educators, we all agree that future engineers are faced with two basic problems, energy sources and emissions, and the solutions to these problems require firm understanding of the energy concepts and innovative approaches. Moreover, the energy use per capita in the world has been increasing steadily as the economies of the world grow. The expected rise in the population of the world from the current 6.5 billion to about 9 billion people by mid-century will also add to the significance of the challenge.

Traditionally, engineering programs introduce students to the concepts of energy and power in parts in courses such as physics, dynamics, thermodynamics, fluid mechanics, and heat transfer. In a dynamics class students learn about potential, kinetic, and elastic energy forms. They are also introduced to the basic definition of power. Additional concepts such as internal energy, heat, and efficiency also are introduced in a thermodynamics class. Various power producing (e.g. steam and gas turbines) and power consuming machines (e.g. refrigerator, air conditioner, and heat pump) are introduced in a thermodynamics class. In a fluid mechanics class, turbomachinery is introduced. Students learn about power consuming and producing devices such as pumps and water and wind turbines. Energy and power requirements dealing with heating or cooling are discussed further in a heat transfer class. It is often said that if you could explain a difficult concept at a level that your grandmother would understand, then you yourself have fully understood the concept [2-3]. Unfortunately, many engineering graduates and new young faculty cannot pass this test. This paper is an attempt in explaining key energy and power concepts at a level understood by a freshman using simple daily examples. Moreover, the holistic conceptual approach presented in this paper is supported by learning theories such as expert-novice, conceptual understanding, and conceptual change [3-14]. These theories are discussed briefly by Moaveni and Chou [3] and repeated here for the sake of continuity of presentation. Bransford, et al. [12] discuss three key characteristics of learning and transfer: *initial learning is necessary for transfer; abstract representations of knowledge can help promote transfer; and all new learning involves transfer based on previous learning*. They also believe that the context in which one learns is also important for promoting transfer. Moreover, as Klausmeier [13] and Bransford, et al. [12] explain "*learners, especially in school settings, are often faced with tasks that do not have apparent meaning or logic. It can be difficult for them to learn with understanding at the start; they may need to take time to explore underlying concepts and to generate connections to other information they process.*" In this paper, we provide the initial learning that is necessary for transfer by developing the students' understanding of work, energy, and power using simple conceptual examples. We also show how to teach these concepts using examples that demonstrate wide application of what is being taught. According to Gick and Holyoak [14] when a subject is taught in multiple contexts and includes examples that demonstrate wide application of what is being taught, learners are more likely to abstract the relevant features of concepts and to develop a flexible representation of knowledge. Transfer is also enhanced by instruction that helps learners represent problems at higher levels of abstraction. Learners who were trained on specific task components without being provided with the principles underlying the problems could do the specific tasks well, but they can not apply their learning to new problems. As supported by these theories, the holistic conceptual approach presented here would better prepare the students for their future engineering courses such as dynamics, thermodynamics, fluid mechanics and heat transfer.

2. What Do We Mean by Work and Energy?

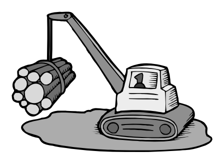
First, it is important that we define what we mean by the term "work." Mechanical work is performed when a force moves an object through a distance [1]. First, the concept of force should be thoroughly explained in such a way that students would develop a good grasp of what we mean by it. For example, it should be emphasized, the simplest form of a force that represents the interaction of two objects is a push or a pull. When one pushes or pulls on an object, that interaction between one's hand and the object is called force. When an automobile pulls a trailer, a force is exerted by the bumper hitch on the trailer [3]. Next, you should ask student what is energy? Energy is one of those abstract terms that students already have a good feel for. For instance, students already know that we need energy to create goods, to build shelter, to cultivate and process food, and to maintain our living places at comfortable temperature and humidity settings. But what they may not know is that energy can have different forms and is related to work (task). To explain quantitatively the requirements to move objects, to lift things, to heat or cool objects, or to stretch materials, energy is defined and classified into different categories. You can then begin with the definition of different forms of energy.

2.1 Kinetic Energy – What It Takes to Move Things

Students should be taught clearly that kinetic energy is a way by which we quantify how much energy is required to move something. Intuitively, students should understand that the amount of energy required depends on the mass of the object that you want to move and how fast you want to move it. How do you get something moved? You apply a force, as the result you do work, and when work is done on an object, it changes the kinetic energy of the object. The fact that when you perform mechanical work, it changes the kinetic of the object should be emphasized. Moreover, students need to understand that it is the change in kinetic energy, that is used in engineering analysis. Everyday examples should then be used to emphasis these concepts. For example, when you push on a lawn mower (applying a force to the lawnmower), which is initially at rest, and as you move it, you perform mechanical work on the lawn mower, consequently changing its kinetic energy from a zero value to some nonzero value. Next, it is important to move from conceptual phase to the quantitative phase. An object having a known mass and moving with a known speed has a kinetic energy, which is equal to one half its mass times the speed of the object squared. Again you should use everyday examples to demonstrate how one uses kinetic energy calculations.

Q: Estimate the work that must be performed to bring a car that is travelling at a certain speed to a full stop. With such an example, you also can introduce the SI or U.S. customary units for kinetic energy. Students should be reminded that they have been using system of units all their life. For example, when you ask a student: "how tall are you," he may say: "I am 180 cm." Or, when asked what is the expected outside air temperature today, you could answer with something like: “Today is going to be hot and reach 90 degrees Fahrenheit.” To quantify a dimension, the thermal state of air, or the amount of energy required to perform a task we use scales or a system of units.

2.2 Potential Energy – What It Takes to Lift Things



How do we quantify how much energy is needed to lift things? The work required to lift an object over a vertical distance is called potential energy. It is the mechanical work that must be performed to overcome the gravitational pull of the earth on the object. The change in the potential energy of the object when its elevation is changed could be quantified knowing the weight of the object and the change in the elevation.

Q: Estimate the energy required to lift an elevator and its occupant between floors. Again, this is a good point to introduce the SI and U.S. customary units for potential energy. Once again, it is important to emphasis the fact that as was the case with kinetic energy, students should keep in mind that it is the change in the potential energy that is of significance in engineering calculations. For example, the energy required to lift an elevator from the first floor to the second floor is the same as lifting the elevator from the third floor to the fourth floor, provided that the weight of the elevator and occupants and the distance between each floor is the same.

2.3 Elastic Energy – What It Takes to Stretch or Compress Things

Most students have seen springs that are used in cars, locomotives, clothespins, and other things that we use in our everyday life. What students may not realize is that springs are also used in medical equipment, electronics equipment such as printers and copiers, and in many restoring mechanisms - a mechanism that returns a component to its original position. When a spring is stretched (by pulling on it and by doing work), elastic energy is stored in the spring, energy that will be released when the spring is allowed to return to its unstretched position. The elastic energy stored in a spring when stretched or compressed by a certain distance is given by one half of stiffness of the spring times its displacement squared.

Q: Estimate the energy required to open a clothespin. Again it is important to use an example to demonstrate how we quantify the amount of elastic energy needed to stretch a spring and then introduce the SI and U.S. customary units.

2.4 Thermal Energy – What It Takes to Heat or Cool Things

It should be emphasized that we also need energy to heat or cool our homes, to cook, or to heat water to shower. But what is "heat?" Before explaining what thermal energy means, the concept of internal energy should be explained. Internal energy is a measure of the molecular activity of a substance and is related to the temperature of the substance. The higher the temperature of an object, the higher its molecular activity and thus its internal energy. Thermal energy transfer occurs whenever there exists a temperature difference within an object, or between a body and its surroundings. So when we heat water, we transfer energy from a heating element that has a higher internal energy to water that has a lower internal energy. This form of energy transfer is called heat transfer.

Q: Estimate the amount of energy needed to heat up so many gallons of water from room temperature to an appropriate temperature level for shower. Using such an example is a good way to discuss three units that are commonly used to quantify thermal energy (1) the British thermal unit, (2) the calorie, and (3) the joule, and the relationship among them.

3. What do we mean by power?

Students commonly confuse energy with power. Power is the time rate of doing work, or the work (or energy), divided by the time required to perform the task. It should be made clear to students that the value of power required to perform a task represents how fast we want the task done. If we want a task done in a shorter time, then more power is required. Students should understand clearly that to perform the same task in a shorter period of time, more power is required. More power means more energy expenditure per second.

Q: Do you require more energy to walk up a flight of stairs or to run up the stairs?
Q: Which requires more power, to walk up a flight of stairs or to run up the stairs?

3.1 Watts and Horsepower

Good engineers have a "feel" for numbers. Most students exercise and lift weights. A simple way to provide a "feel" for how much power one horsepower represents is by using the following example. If you can bench press 220 pound force a vertical distance of 2.5 feet everyone second then you are producing one horsepower. How long can you keep that up? On the other hand, One Watt is approximately equal to lifting an object with a mass of 100 grams (~ weight of 1 N) a distance of one meter every second. Also, it is important for students to understand that 1 hp is slightly smaller than 1 kW. Another unit that is sometimes confused for the unit of power is kilowatt-hour, used in measuring the consumption of electricity by homes and the manufacturing sector. It should be emphasized that kilowatt-hour (kWh) is a unit of energy—not power. One kilowatt hour represents the amount of energy consumed during 1 hour by a device that uses one kilowatt (kW) [1]. In heating, ventilating, and air-conditioning applications, Btu per hour (Btu/h) is used to represent the heat loss from a building during cold months and the heat gained by the building during summer months. Another common unit used in the United States in air-conditioning and refrigeration systems is ton of refrigeration or cooling. One ton of refrigeration represents the capacity of a refrigeration system to freeze 2000 pound mass or 1 ton of liquid water at 32°F into 32°F ice in 24 hours. Therefore, 1 ton of refrigeration = 12,000 Btu/h. In the case of an air-conditioning unit, one ton of cooling represents the capacity of the air-conditioning system to remove 12,000 Btu thermal energy from a building in 1 hour. This is a good place to emphasize the fact that engineers are book keepers [1-3]. Whereas, in accounting practice, accountants keep track of dollars and cents, revenues, and expenditures, engineers keep track of forces, masses, energies, powers, displacements, accelerations, deformations, rotations, and stresses. That is why it is important to have a "feel" for numbers. Accounts have a feel for what one million dollar represents. As an engineering student do you have a feel for what one million kilowatt-hours represents?

Q: Estimate the horsepower and kilowatts required to move so many people, between two floors of a building.
Q: The energy requirement for this task is equivalent to providing electricity to how many 100-W light bulbs and for how long?
Q: Estimate the total amount of energy that could be saved if so many million people would take the stairs instead of taking the elevator to go up one floor daily during so many working days in a year.

4. Power Production

After, the concepts of work and energy are introduced; some light should be shed on the energy sources, generation, and consumption. Start by asking questions such as: how is electricity generated in a conventional power? Where does the energy that makes a home warm during the cold winter months come from? The answers: fuels. In this paper, we will focus on U.S. data as a means to convey important information, however, students should be reminded that this is a global issue and should be understood at that level. The U.S. primary energy consumption by source and sector and its breakdown is shown in Figure 1. Next, students should be introduced to these major sources.

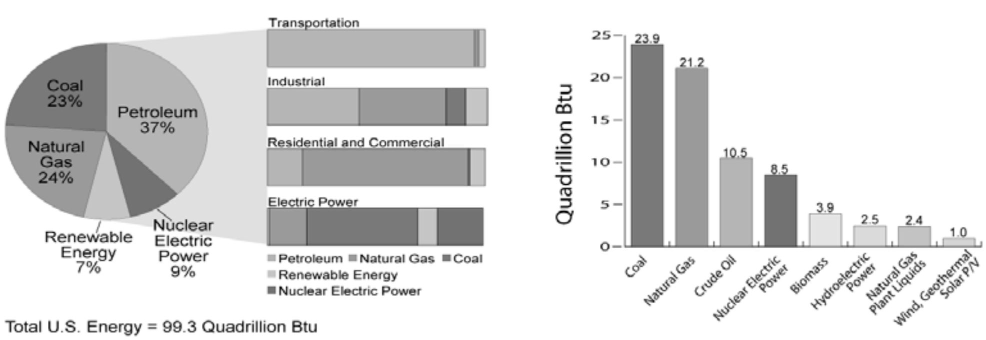
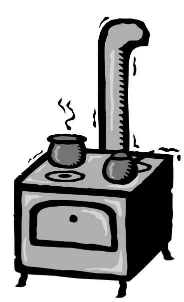


Figure 1: U.S. Energy Data. Source: U.S. Energy Information Administration, Annual Energy Review (2008).

4.1 Heating Values of Fuels



To generate power, we use fuels such as coal, natural gas, fuel oil, or gasoline. When a fuel is burned thermal energy is released. The heating value of a fuel quantifies the amount of energy that is released when a unit mass (kilogram or pound) or a unit volume (cubic meter or cubic foot) of a fuel is burned. It also is important for students to understand that different fuels have different heating values.

Q: How much thermal energy is released when so many pounds or kilogram of coal from certain location is burned?
Q: How much thermal energy is released when so many cubic feet or meter of natural gas from a certain location is burned inside a gas furnace.

Coal – In 2007, the U.S. electric power industry generated nearly 4,157 billion killowatthours. Coal, natural gas, petroleum, nuclear, and renewable sources were used to generate electricity. Almost half (48.5%) of all electricity generated in the United States was created from coal. Coal-fired power plants burn coal in boilers to make steam. The steam then turns turbines that are connected to generators to create electricity.

Natural Gas – The U.S. natural gas transportation network consists of nearly 1.5 million miles of mainline and secondary pipelines. These pipelines connect production areas and markets, and in 2008 delivered more than 23 trillion cubic feet of natural gas to about 70 million customers.

Heating Oil – Heating oil is a petroleum product used to heat homes in America, especially in the Northeast. Students should understand that at refineries, crude oil is refined into lubricating oil and different types of fuels including gasoline, diesel, heating oil, jet fuel/kerosene, and heating oil. Heating oil and diesel fuel are similar in composition; the main difference between the two fuels is sulfur content. Heating oil has more sulfur than diesel fuel.

Ethanol and Biodiesel – Ethanol is an alcohol based fuel that is made from the sugars found in corn, barley, rice, and sugar cane. Another renewable fuel is Biodiesel. Biodiesel is a fuel that is commonly made from vegetable oils or recycled restaurant grease, and could be in diesel engines.

4.2 A Conventional Power Plant

All freshmen engineering students should know how electricity is generated in a power plant. Water is used in all steam power-generating plants to produce electricity. A simple schematic of a power plant is shown in Figure 2. Fuel is burned in a boiler to generate heat, which in turn is added to liquid water to change its phase to steam; steam passes through turbine blades, turning the blades, which in effect runs the generator connected to the turbine, creating electricity. The low-pressure steam liquefies in a condenser and is pumped through the boiler again, completing a cycle, as shown in Figure 2. Students should also understand that there is always some loss associated with a dynamic system such as a power plant. In engineering, when we wish to show how well a system is functioning, we express its efficiency. In general, the overall efficiency of a system is defined as: **efficiency = actual output/required input**.

It also should be emphasized that all machines and engineering systems require more input than what they put out. The overall efficiency of a steam power plant should then be defined as: **power plant efficiency = net energy generated/energy input from fuel.** The efficiency of today's power plants where a fossil fuel (oil, gas, coal) is burned in the boiler is near 40%, and for the nuclear power plants the overall efficiency is nearly 34%.

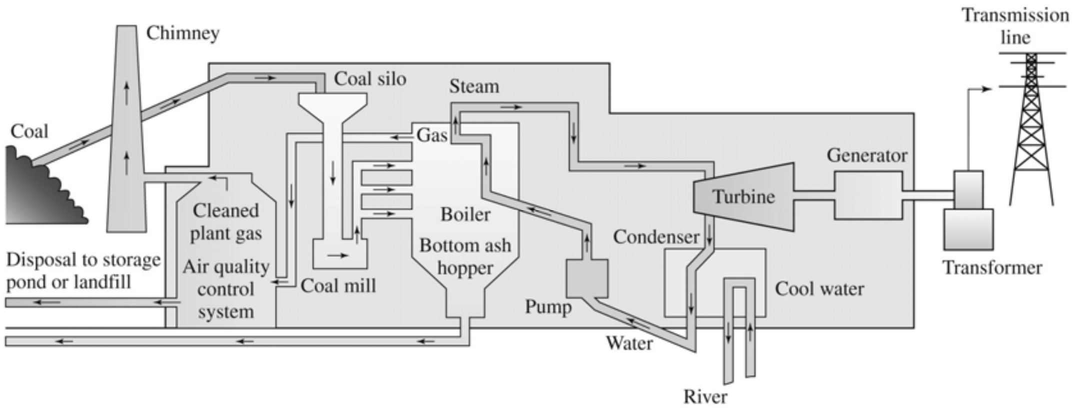
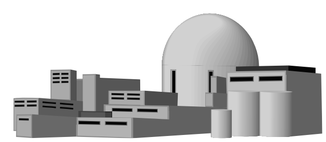


Figure 2: A schematic of a steam power plant [1].

Q: Estimate the amount of fuel needed in a power plant to provide the amount of energy that was estimated for so many million people to take an elevator between two floors of a building.

Next, we should explain the role of motors, pumps, internal combustion engine, refrigeration and air-conditioning systems and their efficiencies. For example, it should be emphasized that motors run many devices and equipment that make our lives comfortable. As an example, you can ask students to identify at least ten motors in various devices at home (e.g. motors that run the compressor of a refrigerator, garbage disposer, exhaust fan, tape player in a VCR, vacuum cleaner, turntable of a microwave, hair dryer, computer fan, and computer hard drive).

4.3 Nuclear Energy



As is the case with any new concepts, energy sector has its own terminology and students need to become aware of them. There are two processes by which nuclear energy is harnessed, nuclear fission and nuclear fusion. Nuclear power plants use nuclear fission to produce electricity. In a nuclear fission, to release energy, atoms of uranium are bombarded by a small particle called neutron. This process splits the atoms of uranium and releases more neutrons and energy in the form of heat and radiation. The additional neutrons go on to bombard other uranium atoms, and the process keeps repeating itself, leading to a chain reaction [1]. The fuel most widely used by nuclear power plants is Uranium 235 or simply U-235. Students need to understand that the U-235 is relatively rare and most be processed from the uranium that is mined. The energy in the nucleus or core of atoms can also be released by nuclear fusion. In nuclear fusion, energy is released when atoms are combined or fused together to form a larger atom. This process is called nuclear fusion and is the process by which the sun's energy is produced.

4.4 Solar Energy

Because of the current energy and sustainability concerns, there has been a renewal of interest in solar energy. Solar energy starts with the sun at an average distance of 93 million miles from earth. The sun is a nuclear fusion reactor, with its surface temperature at approximately 10,000^{0}F (5500^{o}C). Solar energy that reaches the earth is in the form of electromagnetic radiation consisting of a wide spectrum of wavelengths and energy intensities. The amount of radiation available at a location, on the surface of the earth, depends on many factors including geographical position, season, local landscape and weather, and time of day. As solar energy passes through the earth's atmosphere, some of it is absorbed, some of it is scattered, and some of it is reflected by clouds, dust, pollutants, forest fires, volcanoes, or water vapor in the atmosphere. Students need to understand that using various technologies, solar radiation can be converted into useful forms of energy, such as heating water or air, or generating electricity

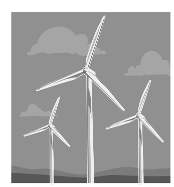
[1]. The economical feasibility of solar systems depends on the amount of solar radiation available at a location.

Active Solar Systems – There are two basic types of active solar heating systems, liquid and air. The liquid systems make use of water or water-antifreeze mixture (in cold climates) to collect solar energy. In such systems, the liquid is heated in a solar collector and then transported via a pump to a storage system. In contract, in air systems, the air is heated in "air collectors" and is transported to storage or space using blowers. Most solar systems cannot provide adequate space or hot water heating, consequently, an auxiliary or back-up heating system is needed.

Passive Solar Systems – The passive solar systems do not make use of any mechanical components such as collectors, pumps, blowers, or fans to collect, transport or distribute solar heat to various parts of a building. Instead, a *direct passive solar system* uses large glass areas on the south wall of a building and a thermal mass to collect the solar energy. The solar energy is stored in interior thick masonry walls and floors during the day and is released at night. In cold climates, the passive systems also use insulated curtains at night to cover the glass areas at night to reduce the heat loss.

Photovoltaic Systems – A Photovoltaic system converts light energy directly into electricity. It consists of a photovoltaic array, batteries, charge controller, and an inverter (a device that converts direct current into alternating current). The backbone of any photovoltaic system is the cells. The photovoltaic cells are combined to form a module and modules are combined to form an array. The photovoltaic systems come in all sizes and shapes and are generally classified into stand-alone systems, hybrid systems, or grid-tied systems. The systems that are not connected to a utility grid are called stand alone. Hybrid systems are those which use combination of photovoltaic arrays and some other form of energy, such as diesel generation or wind. As the name implies, the grid-tied systems are connected to a utility grid.

4.5 Wind Energy



Wind energy is a form of solar energy. Students should realize that because of earth's tilt and orbit, sun heats the earth and its atmosphere at different rates. As air moves, it has kinetic energy. Part of this kinetic energy can be then converted into mechanical energy and into electricity. Two types of wind turbines are used to extract the energy from the wind, vertical axis turbine, and hoizontal axis turbine. The vertical axis turbine can accept wind from any angle and require light weight towers and are easy to service. The main disadvantage of this type of turbine is that because the rotors are near ground, where the wind speeds are relatively low, it has poor performance. Most of wind turbines in use in U.S. are of horizontal axis type. The wind turbines are typically classified as small (<100 kW), intermediate (<250 kW), and large (250 kW to 2 MW). It is also important for students to be familiar with the wind energy terminology such as hub, rotor, gear box, yaw motor, controller, and the brake and their functions.

4.6 Hydro Energy

Electricity is also generated by liquid water stored behind dams. The water is guided into water turbines located in hydroelectric power plants housed within the dam to generate electricity. The potential energy of the water stored behind the dam is converted to kinetic energy as the water flows through the turbine and consequently spins the turbine, which turns the generator. Hydropower accounts for 6% of total U.S. electricity generation. In 2008, it accounted for 67% of energy generation of all the renewable energy sources.

5. Concluding Remarks

Traditionally, in engineering programs, the concepts of energy and power are taught in parts, in courses such as thermodynamics, fluid Mechanics, and heat Transfer at sophomore and Junior levels. Unfortunately, most engineering students by the time of their graduation do not have a good grasp of energy and power and often confuse the two. To prepare good engineers, the basic concepts of energy and power should be taught conceptually early in the freshman year and followed by simple quantitative examples. It should be taught in a manner that develops a good physical understanding of basic concepts. Students should develop a good feel for what is meant by work, energy and its different forms and their magnitudes. They should clearly understand what it takes (quantify) to move, lift, or stretch things. Regardless of their areas of specialization pursuit, all freshmen should be comfortable with energy and power concepts. Having a good feel for these concepts, will allow students see how future classes such as dynamics, thermodynamics, fluid mechanics, and heat transfer fit together. To keep the number pages at a reasonable level we have only discussed a few concepts here. The ideas discussed here can be extended to introduce other concepts.

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