

Unit 0 – An Integrated Approach to Energy

Thus far, the basic models described by Hestenes in *Modeling Methodology for Physics Teachers* are most fully developed in the areas of kinematics and dynamics. The concept of a force as an interaction between objects without internal structure is the backbone or theme of the analysis of mechanical systems.

In this energy unit, we propose the addition of the theme of energy interactions to this analysis. Energy is so fundamental that it is crucial to address it in a more cohesive manner than merely as another separate unit in the study of mechanics. If students begin early with qualitative energy interaction analysis, then when they encounter the quantitative treatment of work and energy, the ideas of energy transfer should be relatively straightforward. The transition to thermodynamics will be smoother if one builds on a model of energy as a form of interaction between particles that do have internal structure: one that describes energy transfers in terms of macroscopic and microscopic changes in the system and surroundings.

Even if you can't cover the field of thermodynamics in your class due to time limitations, this new approach will still provide a way for you to give your students a better overall picture of the role of energy interactions in mechanical systems.

This unit involves some ideas about work and energy that are different from the traditional approach. These new ideas are generally much clearer and simpler than the traditional thinking, but it does mean you might have to adapt or let go of some of your ways of thinking about energy and work. Your use of language is very important in this shift. For example, the difference between energy transformations or forms of energy (old) and energy transfer (new) is subtle but crucial, since energy transformations implies that there are different forms of energy - a misleading idea which can be partially avoided by the use of the term energy transfer, which stresses the universal nature of energy. (This will be elaborated on in the Teacher Notes.) It may be a matter of changing some deeply ingrained thinking and terminology. Be patient with yourself!

These materials should be considered a beta version ; they are relatively untested. Follow your own instincts, and do things in the way that feels most comfortable to you. The Teacher Notes which follow provide some options for different approaches you could take. Hopefully you will be able to incorporate some of these materials and ideas early into your study of mechanics. Enjoy!

Part 1 - INSTRUCTIONAL NOTES

Summary of the Main Themes and Concepts in this Unit

I. The Model:

- ☞ Energy is presented as a means of interaction between objects with internal structure. (Contrast this with the view of force interactions that occur between objects or point particles without internal structure.)
- ☞ The 1st Law of Thermodynamics/ Conservation of Energy are used as the underlying models of energy interaction.

II. Two Energy Themes: Energy transfer and energy storage

- ☞ focusing on modes of energy transfer and storage, not forms of energy

A. Energy Transfer: Energy is transferred across a system boundary by three modes:

Heating (Q) - due to difference in temperature

Radiation (R) - by photons/EM waves

Working (W) - by external forces

These are considered *macroscopic* processes. These modes are NOT properties of the system. They do not represent *changes* in the state of the system, hence we do not use the \sim notation to describe them. Since they are processes, and not intrinsic in the system, we feel it is better to use the gerunds; otherwise students may come to view Q, R and W as parts of the system (e.g., a system does not possess "heat").

B. Energy Storage: Energy is stored in a system as internal energy. This internal energy is a *property* or state variable of the system, due to the microscopic energies of the particles of the system. These particle energies cannot be measured directly. A *change* in internal energy is all that can be accounted for, since a change in internal energy results in a change in the state variables of the system (pressure, temperature, etc), so the internal energy is represented with \sim notation.

There are a variety of mechanisms of energy storage which can be accounted for as types of internal energy: *potential energies* (particle interaction energies-gravitational and elastic), *kinetic energy* (particle motion relative to the center of mass of the system), *chemical energy* (particle bond energies), and *thermal internal energies* (random particulate motion as a result of frictional effects), designated as $\sim E_g$, $\sim E_{el}$, $\sim E_k$, $\sim E_{chem}$, and $\sim E_{diss}$ respectively.

Together these make up $\sim E$, the change in internal energy.

$$\sim E = \sim E_g + \sim E_{el} + \sim E_k + \sim E_{chem} + \sim E_{diss} .$$

III. An Operational Definition of Energy:

Energy is a measure of the capability to produce change. By identifying the nature or source of the change (ie, change in motion, position, shape, temperature, etc.) one can identify the means of energy transfer or storage.

IV. The 1st Law of Thermodynamics, and Conservation of Energy

According to the Law of Conservation of Energy, the algebraic sum of changes in internal energy in the system must equal the energy transfers across the system boundary.

In this unit, we designate all processes that increase the energy of the system as positive: transferring energy into the system by heating it, working on the system (energy transferred in by forces), etc.

Energy that decreases the energy of the system is designated as negative;, such as energy leaving by cooling a system, or working done by a system (energy transferred out by forces).

So the 1st Law of Thermodynamics can be stated as:

$$\Delta E = Q + W + R$$

where ΔE is the sum of all the changes in internal energies, using the same sign designation as stated above.

To use the 1st Law in this form, one must identify the system first, and then determine the appropriate forms of internal energy storage mechanisms which undergo changes, and which modes of energy transfer are involved.

V. System Identification:

The identification of the system and its boundaries is arbitrary but critical for accurate energy interaction analysis. The larger the system designation, the more energy interactions will be classified as internal energies. rather than external energy transfers.

VI. Representational Tools:

This unit utilizes three representational tools, which are listed here according to their increasing levels of complexity. Their use will be explained in detail in a later section:

1. Energy Pie Charts:

- ☞ very qualitative, and relatively limited use - generally for introductory use, especially Modeling units, as post-lab discussion
- ☞ introduces the idea of internal energy as a *property* of a system
- ☞ introduces the concept of *changes* in internal energy of the system
- ☞ stresses the importance of system identification
- ☞ introduces the various mechanisms of energy storage, including ΔE_{therm} for frictionally dissipated energy
- ☞ does not represent energy transfers across system boundary, except for some simple examples of external forces
- ☞ represents Conservation of Energy and 1st Law of Thermodynamics
- ☞ introduces internal energy as a sum of energies:

$$\Delta E = \Delta E_g + \Delta E_{\text{el}} + \Delta E_k + \Delta E_{\text{chem}} + \Delta E_{\text{diss}}$$

2. Energy Bar Graphs and Flow Diagrams (essentially energy system schema)

- ☞ to be used in Modeling unit addenda, in post-lab discussions
- ☞ identifies internal energy changes, but also shows means of energy transfer across system boundary
- ☞ introduces concept of work as energy transfer across system boundary via external forces
- ☞ makes distinction between *changes* in internal energy and energy transfer as a *process*.
- ☞ shows how macroscopic energy transfer W , Q , R can affect microscopic energy storage ΔE (internal energy)
- ☞ introduces 1st law of Thermodynamics: $\Delta E = W$
- ☞ slightly more quantitative than pie charts
- ☞ represents Conservation of Energy and 1st Law of Thermodynamics

3. The Equation of Everything: $W + Q + R = \Delta E_k + \Delta E_i + \Delta E_p = \Delta E$

- ☞ comprehensive treatment of 1st Law of Thermodynamics
- ☞ quantitative treatment of Energy Bar Graph / Flow Diagrams

VII. Quantitative Development of Work and Energy

1. The spring labs

- ☞ paradigm labs develop quantitative definitions $E_{el} = 1/2kx^2$, $E_k = 1/2 mv^2$,
 $E_g = mgh$, $W = F\Delta x$.
But we will officially define "working" as simply another mode of energy transfer, via external forces.
- ☞ presents the work-energy theorem(center-of-mass calculations) as a relationship for particles with no internal structure:

$$F_{net}\Delta x = 1/2mv^2$$

2. Energy analysis misconceptions

- ☞ limitations of center-of-mass approach (work-energy, point particle) are shown with the presentation of the paradoxical, contradictory energy situations which require 1st Law of Thermo analysis of a system with internal structure in order to account for internal energy changes and be conceptually accurate:
 1. Frictional dissipation (sliding a block on a frictional surface)
 2. Deformable objects (inelastic collision, a jumping person)

VIII. Classical Thermodynamics as an Extension of Mechanics

3. Equation of Everything

The more formal treatment of thermodynamics begins, under the umbrella of the Equation of Everything:

$$W + Q + R = \Delta E_k + \Delta E_i + \Delta E_p$$

The Equation of Everything is a comprehensive statement (a working model) of the First Law of Thermodynamics that accounts for macroscopic energy transfer as heating, work, and radiation, and microscopic internal energy changes, as kinetic, interaction(potential), or particle(chemical) energy.

Part 2 - ENERGY TRANSFER AND STORAGE vs. ENERGY FORMS

Typically, energy is described as having different forms or types. Many different forms are presented: light energy, kinetic energy, electrical energy, and so on. Energy is described as coming in these different forms, and as being able to change forms via various transformation processes or mechanisms.

In this unit, we are proposing a shift from this emphasis on different forms of energy to a focus on what happens to energy, while treating energy as a single, conserved, fundamental quantity. Instead of exploring energy forms or transformations, the interest lies in the questions of energy transfer and storage.

The Problem with Energy Forms

Treating energy as having different *forms* (ie, heat energy vs. sound energy vs. light energy, etc.) implies that these quantities are fundamentally different in some way. One runs the risk of introducing an artificial level of complexity because questions naturally arise: what is different about the forms? Is it a difference in how the energy is stored? or exchanged? or how it flows? or all of the above? How does one distinguish among the different *forms* of energy?

It is much simpler instead to focus on two questions: how energy *flows* and how it is *stored*. Underlying this shift in focus is the critical understanding that all energy is the same conserved, substance-like stuff ; that there are not different *forms* or types of energy. Energy can be defined as the capability to produce change. The changes produced might be different - changes in position, changes in shape, etc, but the energy that produced those changes is fundamentally the same.

Energy As a Flowing, Substance-Like Quantity

A quantity can be called substance-like if a density can be assigned to it, and if it can flow through space. Some substance-like quantities include mass, electric charge, and amount of matter. It is generally agreed that a substance-like quantity is conserved, whereas the principle of conservation does not apply to a non-substance-like quantity such as temperature or velocity or electric field. Therefore, according to these qualifications, energy can be described as a conserved, substance-like quantity, because a density can be attributed to it, it flows through space, and it is conserved.

As a substance-like quantity, energy can be transported, exchanged, and stored. Energy flows, and can be stored, and can be transferred. But it is all the same "stuff." A helpful analogy is presented in Physics - A Contemporary Perspective by Randy

Knight.¹ in which energy is compared to money. Money can be stored in a variety of places - it can be in a money market account, or a checking account, in a wallet, or under the mattress. And money can be transferred by a variety of means - credit card, personal check, cash, an IOU, a savings bond. But ultimately, fundamentally, it is all the same thing: money. The means of *transferring* or *storing* the money varies; the fundamental nature of money does not. The same reasoning can be applied to energy: it can be stored by various mechanisms (internal energies, potential energies) and can be transferred by a number of modes (working, heating, radiation) but it is still all the same substance.

Consider also that we do not discuss different forms of other substance-like quantities. We do not distinguish between types of electric charge or types of momentum. We don't speak in terms of electron charge or positronic charge or ionic charge. If the substance-like nature of energy is to be taken just as seriously as the substance-like nature of electric charge, then speaking about different forms of energy is just as misleading as speaking about different forms of charge would be. ²

The main idea is to talk in terms of energy transfer modes instead of energy forms. For example, instead of saying *heat energy* flows from the table to the ice cube, one would say *energy* is transferred from the table to the ice cube by heating, due to a temperature difference. Instead of saying the gravitational potential energy of the ball is converted to kinetic energy, one would say the ball originally has energy stored due to gravity, which is then transferred to the energy of motion. Instead of saying work is done on the spring one would say energy is transferred to the spring by way of an external force, where it is stored by the spring.

The key distinction in these examples is that the source of the energy and the mode of transfer of the energy are stressed, and these sources or modes may change, but it's still just *energy* that is flowing.

Why bother? Pedagogical Justification

A shift of emphasis from energy *forms* to energy transfer and storage is advantageous because:

1. It provides a more accurate representation of the universal nature of energy. It avoids the misleading idea that there are different kinds of energies, and the ambiguities inherent in this outlook.
2. One can focus instead on the changes that are occurring in terms of energy transfer and storage instead of trying to identify the type of energy. Focus attention on energy interactions via these three questions:
Where does the energy come from?
Where does the energy go?
What does the energy do?

¹ Knight, R. *Physics - A Contemporary Perspective*, Addison-Wesley, 1996

² "Energy Carriers or Energy Forms?" Falk, Herrmann, and Schmid. *American Journal of Physics*. 51 (12) December 1983.

****** *An alternative treatment of energy transfer in terms of energy carriers is summarized briefly below. For more details, see Falk, et al.³*

Energy carriers

Instead of speaking in terms of different *forms* of energy, we can discuss energy transfer in terms of different energy carriers. An energy carrier is that other physical quantity that flows simultaneously as the energy is transferred. Again referring to the examples given earlier, the energy carrier for the circuit was electric charge, for the wagon the carrier was momentum, etc.

It is crucial to note that while a carrier flows *simultaneously* with the energy, the energy and its carrier do not necessarily occupy the same space or flow at the same rate. For example, in a circuit, electric charge flows at a very different rate than does the energy associated with it. A carrier is not a *mechanism* for transporting energy. To use the potato analogy, potatoes (energy) being moved by an inclined conveyor belt would roll down faster than the conveyor belt itself (the carrier) is moving. The energy is flowing at a different rate than the carrier. The relationship between energy and its carrier is more temporal than spatial. When energy flows, some kind of carrier does also, although not necessarily with a correspondence of position or velocity. A carrier *accompanies* energy as it flows, but does not *carry* energy.

What we have traditionally called a transformation of types of energies is really just energy changing carriers. Energy is transferred from one carrier to another. In a toaster, energy is transferred from the electric charge carrier to the entropy carrier (heat) - as opposed to electrical energy being converted into heat energy. In a thermocouple, energy is exchanged from the entropy carrier to the electric charge carrier.

Pedagogical Implications

An understanding of energy carriers is not necessary to be able to make this shift of emphasis from forms to transfers. Instructionally speaking, it may not be advisable to introduce the energy carrier idea to beginning students for the following reasons:

1. Few of us discuss entropy in our classes.
2. We probably would not have addressed any electrical concepts yet.
3. The idea of momentum flowing is tough to grasp.

The critical issue is not the idea of carriers, but the shift from forms of energy to energy transfer and storage modes.

Part 3 - Justification and Goals for the Approach in the Energy Unit- Energy Misconceptions

The shift from energy forms to an emphasis on energy transfer and storage may seem like merely a semantic change. The natural question is, what is the point of this shift? How will it change anything we teach in mechanics or energy or thermodynamics, ultimately? The answer is that the goal behind such a change in focus is to facilitate a more accurate method of analysis of mechanical systems. This approach will rely more on the 1st Law

³ "Energy Carriers or Energy Forms?" Falk, Herrmann, and Schmid. American Journal of Physics. 51 (12) December 1983.

of Thermodynamics and Conservation of Energy and less on the work-energy relationship that is usually so prevalent, but which has substantial conceptual shortcomings in a number of physical situations. These will be elaborated on later in the Paradoxes section.

The study of work and energy in mechanical systems typically utilizes the "work-energy theorem", stating that the work done on an object, $F_{\text{net}}\tilde{x}$, is equal to the change in kinetic energy of the object, $1/2m\tilde{v}^2$.

$$F_{\text{net}}\tilde{x} = 1/2m\tilde{v}^2$$

While this equation yields the correct *numerical* answer in simple situations, it can be very misleading. "Serious difficulties begin to enter, however, when [it is] uncautiously extended to systems of interacting particles or to objects that are treated as continuous but are deformable or have other internal degrees of freedom."¹ The work-energy equation is conceptually valid only when the system under consideration is taken to be a point particle with no internal structure, and all measurements are relative to the center of mass of the system. Therefore, any situations involving frictional forces or deformation of the system lead to energy paradoxes, since they involve internal structure issues which are not included in this work-energy, dynamical, point particle analysis.

In order to address/prevent/avoid these misconceptions, the 1st Law of Thermodynamics ($\tilde{E} = Q+W$) can readily be applied, either alone or in conjunction with the work-energy (center of mass) equation ($F\tilde{x} = 1/2m\tilde{v}^2$). By using the 1st Law and Conservation of Energy, the internal structure of the system can be taken into account, and a more valid model of the system can be used in the energy analysis.

The goal of this unit is to build a complete model of energy interactions under the umbrella of the Equation of Everything (a restatement of the 1st Law of Thermodynamics) using representational tools and paradigm labs to develop this model. The model will then be used to analyze mechanical systems accurately, taking into account the internal structure of the system. This will prevent the misconceptions that tend to develop when using exclusively dynamical interactions for analysis and ignoring internal structure and internal energy issues.

¹ A Arons, Teaching Introductory Physics, John Wiley & Sons, 1997

Three Situations Involving Misconceptions Regarding Work(ing)

The three situations below are examples of the inaccurate use of the work-energy theorem for analyzing a mechanical system. They show how using the 1st Law of Thermodynamics can clarify the energy interactions involved.

Dynamical Analysis: based on work-energy theorem and center of mass calculations, considering object as point particle

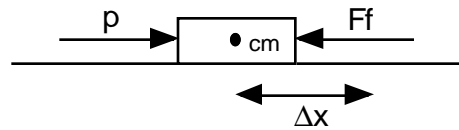
$$F_{\text{net}} \Delta x_{\text{cm}} = \frac{1}{2} m v_{\text{cm}}^2$$

Energy Analysis: based on 1st Law of Thermo and Conservation of Energy

$$\Delta E = Q + W$$

where Q = energy transferred by heating (due to temperature difference), and W = energy transferred by working (via external forces)

Misconception 1. Sliding a block along a frictional surface at constant velocity



Dynamical Analysis:

☞ $F_{\text{net}} = 0$ due to constant velocity ($\Delta v = 0$)

☞ $F_p = F_k$ and $\frac{1}{2} m v^2 = 0$

Therefore:

$$(F_p - F_k) \Delta x_{\text{cm}} = 0, \text{ so } W_{\text{net}} = 0$$

☞ Therefore, seemingly no work is done on the block. HOWEVER, the block heats up! Where does this new energy come from, if no work is done and no energy is added by heating? This is where the dynamical analysis breaks down, by not accounting for internal structure, and where a 1st Law energy analysis is needed.

Energy Analysis:

☞ What is the system?

--> block AND surface - this allows treatment of friction as an internal energy issue instead of an external force transferring energy

☞ ΔE = internal energies of system.

☞ What are the internal energies that change?

--> internal thermal energy, E_{therm} (E_{diss}), due to friction

--> notice that E_k does not change, so it is not included in ΔE accounting

☞ What is Q ?

--> 0, no external source of heating is present

☞ What is W ?

--> $W = F_p \Delta x$ due to external force imparting the push, adding energy

Therefore, the work done by the push is dissipated to internal thermal energy of the system: $W = F_p \Delta x = \Delta E_{\text{diss}}$

From there, what happens to that energy?

☞ $\Delta E_{\text{diss}} = Q$ because block increases in temperature, so energy is lost to surroundings through heating (due to temperature difference).

Misconception 2. Vertical Jumping

Dynamical Analysis:

$$\checkmark \quad \checkmark v = 0 - v_i$$

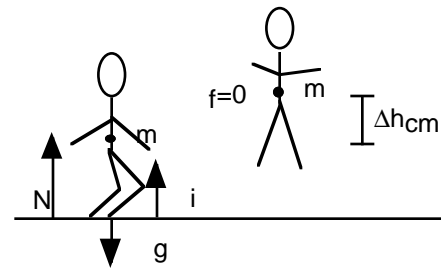
$$\checkmark \quad F_{\text{net}} = F_N - mg$$

Therefore:

$$(F_N - mg)\checkmark h = 1/2 mv_i^2$$

$$F_N\checkmark h - mg\checkmark h = 1/2 mv_i^2$$

$$\mathbf{F_N\checkmark h = mg\checkmark h + 1/2 mv_i^2}$$



- ✘ BUT, the normal force F_N does no work because there is no displacement where the force is applied. The quantity $F_N\checkmark h$ is "pseudowork".
- ✘ So where does the energy come from to propel the person upward, adding kinetic and gravitational potential energy?

Energy Analysis

✘ What is the system?

--> person + earth so that gravitational energy can be treated as internal energy

✘ What internal energies that change are involved?

$$\text{--> } \checkmark E = \checkmark E_{\text{grav pot}} + \checkmark E_{\text{kin}} - \checkmark E_{\text{chem(body)}}$$

✘ What work is involved?

--> none - no external forces are involved to transfer energy

✘ So, $\checkmark E_{\text{grav pot}} + \checkmark E_{\text{kin}} - \checkmark E_{\text{chem(body)}} = 0$

$$mg\checkmark h + 1/2 mv_i^2 - \checkmark E_{\text{chem(body)}} = 0$$

$$\mathbf{\checkmark E_{\text{chem(body)}} = mg\checkmark h + 1/2 mv_i^2}$$

- ✘ The energy producing the change in motion and height come from chemical energy of the body, NOT from work done by the normal force. The normal force does "pseudowork" - related to the displacement of the center of mass, yet not true work in the formal definition of displacement due to an applied force.
- ✘ The misconception arises from the deformation of the object, which can only be accounted for by acknowledging the object's internal structure.
 - ✘ If one considers the system to be only the jumper, then the COE equation yields:

$$F_N\checkmark h = \checkmark E_{\text{chem}}$$

Misconception 3. Collisions - Elastic and Inelastic

[diagram here of ball colliding w/wall]

Dynamical Analysis:

$$W_{\text{net}} = \Delta E_k$$
$$F_N \Delta x_{\text{cm}} = \frac{1}{2} m v^2 \quad (v = 0 - v_0)$$

However, F_N does no work, because the displacement is not occurring at the object boundary, where the force is applied. Thus, F_N is a zero-work force.

Energy Analysis:

system = ball + wall

$$\Delta E = W + Q$$

$$\Delta E = -\Delta E_k + \Delta E_{\text{el}} + \Delta E_{\text{diss}} = 0 \quad (\text{no work or heating, } W \text{ \& } Q = 0)$$

$$\Delta E_k = \Delta E_{\text{el}} + \Delta E_{\text{diss}}$$

$$\frac{1}{2} m v^2 = \Delta E_{\text{el}} + \Delta E_{\text{diss}}$$

$F_N \Delta x$ is numerically equivalent to $\frac{1}{2} m v^2$, but $F_N \Delta x$ is not doing real work, due to the deformation, and consequent change in internal energies.

Therefore:

If $E_{\text{el}} = 0$, (ie, clay ball = perfectly inelastic) all the E_k is dissipated to E_{diss} .

$$\Delta E_k = \Delta E_{\text{diss}}$$

If $E_{\text{diss}} = 0$ (ie, superball = perfectly elastic collision) all the E_k is stored as E_{el}

$$\Delta E_k = \Delta E_{\text{el}}$$

Part 4 - Energy Instruction Conceptual Plan/Storyline

The goal of this energy unit plan is to present energy as a theme throughout the study of mechanics in a clear, concise way that prevents misconceptions and is conceptually accurate.

Two major conceptual ideas are involved in this: 1) Energy storage and transfer are emphasized instead of energy forms and transformations, and 2) There is less emphasis on work and more emphasis on energy transfer modes.

The focus is on energy interactions of a system with internal structure, and a broader use of the 1st Law of Thermodynamics as a more accurate way to analyze a system.

The Plan

UNIT 0 - Energy Integration Preface

Sets the stage for energy integration into mechanics. Clarifies the distinction between energy transfer and storage vs. energy forms, emphasizes the focus on energy processes, elucidates the 1st Law of Thermodynamics

Contents

1. Instructional Notes: Energy transfer and storage justification, paradoxical energy analysis situations introduced, comparison of energy approaches - "old vs. new"
2. Representational Tools: Pie charts, bar graphs and flow diagrams, Equation of Everything presented - usage, notations, examples
3. Clarification of paradoxical work-energy analysis situations involving internal energies and deformable objects.
4. Unit Addenda Notes: Implementation options for how to integrate energy analysis into mechanics using the Unit addenda. An Energy Unit Addenda is included for each corresponding Modeling Unit (Units 2-8).

UNIT VII-"More Energy with Less Work" - Quantitative Energy and Work Analysis

Uses paradigm spring lab(s) to quantitatively develop elastic potential energy, gravitational potential energy, and kinetic energy.

Also develops work as $W = F \cdot x$ in conjunction with the qualitative definition of work as a means of energy transfer via external forces.

The relationship between energy and work is made here (work-energy theorem) as a way to analyze systems with no internal structure. (center of mass calculations)

Then a situation will be presented where the work-energy analysis results in contradictions and paradoxes. The paradox cannot be conceptually resolved unless the system is analyzed using the 1st Law of Thermodynamics and is assumed to have internal structure. These situations include deformable objects and frictional forces dissipating energy. (inelastic collisions, jumping person, sliding a box on frictional surface,

among others) This will point out the limitations of the work-energy approach which neglects the internal structure of the system.

UNIT VIIB Thermodynamics as an Extension of Mechanics

The 1st Law of Thermodynamics is "fine-tuned" to become the Equation of Everything by defining \tilde{E} (energy storage mechanisms) as particle, interaction, or kinetic energy, and energy transfer modes as R, Q, and W.

A series of thermodynamics labs build the relationships among the macroscopic and microscopic quantities in the Equation, addressing the concepts and phenomena of temperature vs. heat, thermal equilibrium, phase changes, conduction and convection, etc. Deployment activities provide opportunities for students to pull all of these energy concepts together, making it a cohesive unit.

Summary of Conceptual Plan/Storyline

1. Mechanics units 2 - 6, 8 post-lab discussions:

pie chart energy analysis

☞introduces the idea of internal energy as a property of a system

☞introduces the concept of *changes* in internal energy

☞introduces the necessity of identifying a system

☞introduces the various mechanisms of energy storage, especially important to introduce Etherm as dissipated energy

☞presents the idea of Conservation of Energy

☞introduces internal energy as sum of energies: $\tilde{E} = \tilde{E}_{kin} + \tilde{E}_{pot} + \tilde{E}_{chem}...$

bar graphs and energy schema

☞introduces the concept of work as energy transfer across system boundary via external forces

☞shows how energy transfer can affect energy storage

☞makes distinction between *changes* in internal energy, and energy transfer as a *process*

☞introduces part of 1st Law of Thermo: $\tilde{E} = W$

☞continues to stress Conservation of Energy

2. Unit VII in Mechanics - "More Energy with Less Work"

spring lab

- ¥ presents the quantified treatment of elastic potential energy, kinetic energy, gravitational potential energy, and work as $F\tilde{x}$
- ¥ presents the work-energy theorem as a relationship for point particles-center of mass calculations

$$F_{\text{net}}\tilde{x} = 1/2 m \tilde{v}^2$$

paradoxical energy situations

- ¥ shows limitations of work-energy approach: friction, deformation, zero-work
- ¥ presents use of 1st Law analysis as more complete and accurate picture of energy interactions by including internal energy effects

3. Unit VIIB - Thermodynamics as an Extension of Mechanics

The Equation of Everything-restating the 1st Law

- ¥ additional terms (Q,R) are added to 1st Law to complete the Equation, and internal energies are categorized as kinetic, interaction, or particle energies
- ¥ thermodynamic processes are analyzed using bar graphs as well as quantified using the Equation
- ¥ thermodynamic concepts such as temperature, phase changes, specific heat, thermal equilibrium, conduction, convection, etc. are all treated under the umbrella structure of the Equation of Everything

Part 5 -Comparison of Energy Instructional Approaches Traditional Approach vs. *New Approach*

1. Instruction generally begins after completing kinematics and dynamics, with work and kinetic energy being addressed first by being quantitatively defined as $W=F\tilde{x}$ and $E_k = 1/2m\tilde{v}^2$.
 1. *Begin energy analysis virtually from the first day, tying in energy interactions with kinematics in Modeling units. Begin by identifying internal energy changes qualitatively, intuitively. ("What evidence is there for energy change?" Change in speed, temp, sound, etc.)*
 2. Energy comes in different forms, such as heat energy, electrical energy, light energy, etc.
 2. *Energy is a single, fundamental, substance-like, conserved quantity. There is only one "kind" of energy.*
 3. Energy can be converted or transformed from one kind to another.
 3. *Energy is not transformed since there are not different types of energies. Instead, energy is transferred via different modes, or stored via different storage mechanisms.*
- ¥ *Energy storage mechanisms are internal energies such as potential energy, kinetic energy, chemical energy...*

¥ Energy transfer modes include work (transfer via external forces), heating (transfer due to temperature difference), and radiation (transfer via EM waves)

4. Energy is seen as a general property or entity. Little distinction between energy as a property or a process.
4. *Internal energy is a property of a system, a state variable. It is accounted for by keeping track of the changes in internal energy, ΔE . Energy transfer is a process that can affect the internal energy of the system. Energy transfers are not accounted for as changes. They are NOT properties of the system.*
5. Energy is defined as the ability to do work.
5. *Energy is defined as the capability to produce change.*
6. Work is defined as $W \equiv F_{\parallel} \bullet \Delta x$, the product of a force and a parallel displacement.
6. *Work is defined as a mode of energy transfer across the system boundary via external forces.*
7. Less emphasis on identifying and distinguishing the system and surroundings.
7. *Identification of the system is arbitrary but crucial. The larger the system designation, the more the energy interactions will involve internal energy changes, as opposed to external energy transfers.*
8. Systems to be analyzed are generally particles or objects with no internal structure. Consequently, the work-energy theorem (center-of-mass calculation) is used as the primary means of energy analysis of mechanical systems. In situations involving frictional forces, zero-work forces, or deformable objects, contradictions arise when using this method, but these paradoxes are rarely addressed. Results are numerically correct, but conceptually inaccurate.
8. *Systems are treated as many-particle systems, with internal structure. This allows for an accurate accounting of energy interactions, especially in situations involving friction, zero-work forces, or deformation where changes in internal energy must be accounted for.*
9. Representational tools are generally algebraic ($W = Fx, E_k = 1/2 mv^2$, etc.) or graphical ($W = \text{area under } F \text{ vs } x \text{ curve}$). Some use of bar graphs, but energy designations are not clear.
9. *Representational tools include pie charts to represent changes in internal energy, (energy storage), bar graphs with schema to represent energy storage and energy transfers across the system boundary, and the Equation of Everything as a restatement of the 1st Law of Thermodynamics.*
10. The 1st Law of Thermodynamics: $\Delta E = Q - W$
sign notation: $+W = \text{work done by system}$
 $-W = \text{work done on system}$
10. *The 1st Law of Thermodynamics: $\Delta E = Q + W$*
sign notation: $+W = \text{work done on system}$
 $-W = \text{work done by system}$

(+ = energy of system increases, - = energy of system decreases, consistent for all quantities)

Part 6 - REPRESENTATIONAL TOOLS - Examples, and Instructions for Use

1. These representational tools are designed to show energy status for a defined system in terms of transfer and/or storage at various stages in a process. These stages are generally before and after the event occurs, but it is often helpful to address intermediate stages as well.
2. The key to successful use of these tools is appropriate designation of the system to be analyzed - what components are to be included in the system, and what is to be relegated to the surroundings.

In general, the more components one includes in the system, the more one will focus on *internal* energies and energy storage. This simplifies situations involving friction. (*see Commentary on Dissipated Energy below.)

The fewer components included in the system, the more one will have to account for energy transfer across the system boundary. As a result, the larger the system, the simpler the analysis (generally).

By controlling the choice of the system to be analyzed, the teacher can guide the discussion to focus on the energy interactions that are most relevant at that time in that particular lesson.

Guiding questions may help in with energy analysis:

1. What is the system?
2. Where is the energy coming from? (Where is it stored?)
3. Where does the energy go, and/or what does it do? (How does it transfer or flow?)

***Commentary** : Dissipated Energy

In analyzing the situation of pulling a block along a surface at constant velocity, Arons⁴ designates the block and the surface together as the system. In this case, he says the work done by the pulling force is dissipated. This dissipated energy becomes thermal internal energy, which he then calls E_{therm} . E_{therm} is one kind of internal energy (others include chemical potential energy, elastic potential energy, etc.) and is the energy of the random molecular motion of the system. It is thermal internal energy due to internal (microscopic) interactions, which we perceive as a change in the temperature of the system. It is important to recognize that the change in temperature of the system is NOT due to the addition of energy by external heating, but is instead a result of the change in internal energy of the system.

To avoid the confusion and connotation with *heat* that the word *thermal* would probably cause (since at the initial, introductory level the issue of heating will not be addressed), we are using the term E_{diss} in the same sense that Arons uses E_{therm} . It

⁴ Arons, A.B. A Guide to Introductory Physics Teaching. Wiley and Sons, 1990.

seems likely that using the word *thermal* prematurely could lead to misconceptions about heat and temperature.

We will designate E_{diss} as the energy dissipated due to frictional forces. This is equivalent to Arons' E_{therm} . However, E_{diss} in this unit will also include other dissipative mechanisms such as sound and light. (Arons uses a separate term, E_{misc} to designate these other mechanisms.)

With proper use of the pie charts, it will be obvious that this dissipated energy is not lost, (ie, gone) but is still within the system. The difference is that the energy is no longer usable or easily measurable, or recoverable. This is a subtle distinction, and one that students may have to wrestle with and get a feel for. The reversibility or irreversibility of a process may be somewhat helpful in elucidating this idea of dissipation.

To tie E_{diss} in with the money analogy, dissipated energy is analogous to the service charges that the bank incurs for transactions - it is money that is still within the system, but is lost from our account, never to be recovered!

Representational Tool #1: ENERGY PIE CHARTS

Goals and Notations of Usage:

1. Goal: to qualitatively represent changes in internal energies/energy storage (including energy dissipated due to the effects of friction-see Commentary on Dissipated Energy above) as a system undergoes some process. Pie charts are NOT designed to address energy transfers across the system boundary, but they can be adapted to include this, and this will be done in some of the later unit addenda.
2. Goal: to qualitatively represent the Conservation of Energy and the First Law of Thermodynamics
3. The energy notation in the pie charts should be $E_{\text{__}}$, with subscripts indicating the source of the internal energy. These will generally be $E_{\mathbf{k}}$ (kinetic energy, defined as the energy of motion), $E_{\mathbf{g}}$ (gravitational potential energy, a type of interaction energy), $E_{\mathbf{el}}$ (elastic potential energy-again, interaction energy), and $E_{\mathbf{diss}}$ (energy dissipated to internal thermal energy due to friction, or other mechanisms such as sound and light)

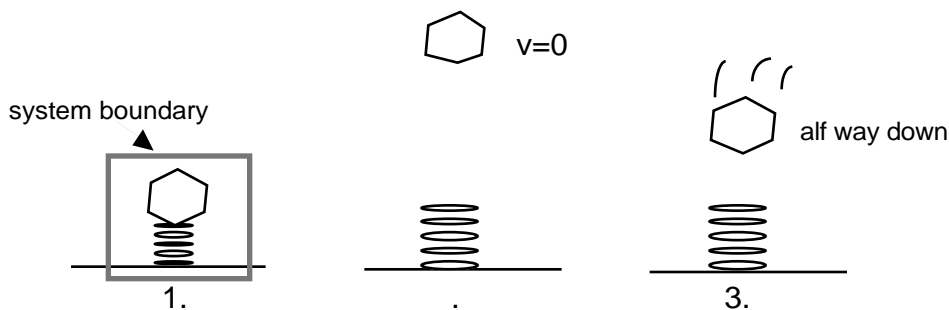
This $E_{\text{__}}$ notation, as opposed to KE, or GPE, or EPE is used for two reasons:

1. It stresses the universal nature of energy - it's all energy.
2. In this energy unit, we will use $E_{\text{__}}$ to indicate the mechanisms of energy storage involved in these various types of internal energy.

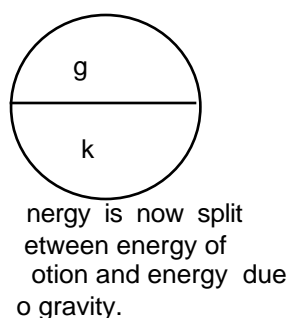
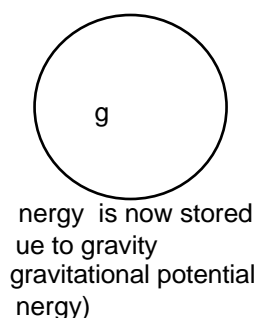
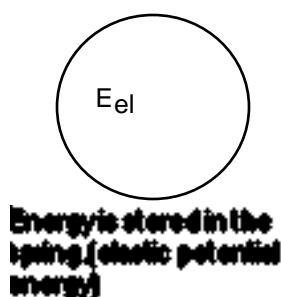
Symbols of energy transfer (across the system boundary) will be Q (heating as energy transfer due to temperature difference, R (radiating), and W (working as energy transfer by an external force). These terms (Q, W, and R) will not be used with the pie charts, since the pie charts focus on energy storage and internal energy changes.

Examples of Pie Chart Usage

Example 1: a spring-launched toy which is propelled into the air
system: spring and toy object



Corresponding Pie Charts:

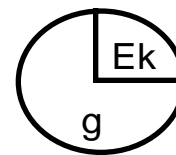


Analysis

1. It is critical to identify the system first. In this case, if the spring were NOT included in the system, the toy would initially have no energy, and the spring would then transfer energy to the toy by an external force across the system boundary (work). This is more complex, and is difficult to represent using the pie charts, which were designed only to address internal energy changes, not energy transfers across the system boundary.

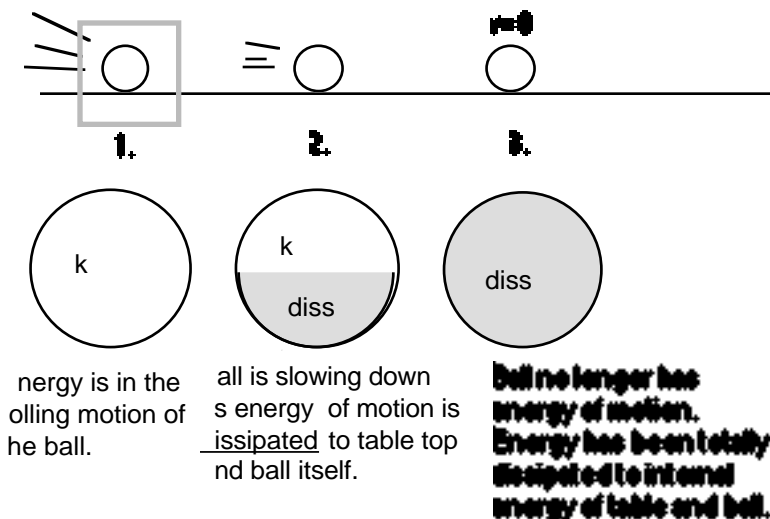
Try to identify the system so the energies are internal when using the pie charts. The goal is to focus on energy storage. The key is to make the system as inclusive as possible. It is recommended that the earth *always* be included in the system, so that E_g can always be considered an internal energy, rather than thinking in terms of the "work done by gravity."

2. Notice that the sizes of the circles are all the same. This is the implicit representation of the Conservation of Energy. If the toy were launched by a stronger spring, the circles would be larger.
3. The divisions in the pie show the relative amounts of the energies. For example, if point #3 had been when the toy was only 1/4 of the way down, then only 1/4 of the circle would be E_k , and 3/4 would be E_g .



The students need to be reminded that while these are qualitative, the *relative* sizes of the slices of the pies should be reasonable. For example, E_{diss} due to air resistance in most cases should probably be a small slice of the pie, not a large proportion.

Example 2: A ball rolling on the floor, coming to a stop due to friction
system: ball + floor



Analysis:

1. E_k includes both translational and rotational motion. It is the energy of motion.
2. E_{diss} = dissipated energy. It is a simple, qualitative way to account for the loss of energy of motion. It is shaded in to represent that the energy is no longer usable or accessible.
3. The system includes the table top in order to maintain the representation of conservation of energy. If the system were only the ball, the circles would have to get smaller as the energy of motion of the ball decreased and the dissipated energy left the system (the ball). Some of the dissipated energy does in fact go to the internal energy of the ball, but not all - some of it goes to the table top also. So if the table isn't included in the system, the circles would necessarily have to shrink as energy left the ball. This would be a confusing situation to reconcile with Conservation of Energy, and should be avoided!

Representational Tool #2: BAR GRAPHS AND ENERGY FLOW DIAGRAMS

These are more detailed and complex than the pie charts. The bar graphs are more quantified, and the energy schema diagrams provide a mechanism for accounting for energy transfers into and out of the system, across the system boundary.

The bar graphs represent the internal energies (energy storage). The system schema diagram shows the process occurring pictorially, representing the energy transfers into or out of the system using quantified arrows.

Again, the questions that will guide the proper use of these tools are:

1. What is the system?
2. Where does the energy come from?
3. Where does it go?

Steps in constructing a bar graph/energy flow representation

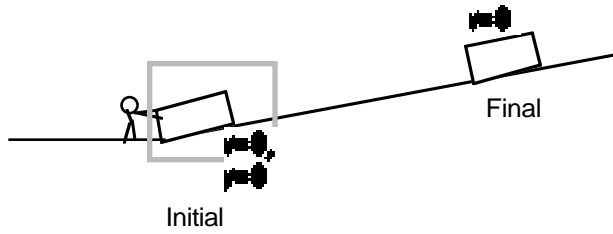
1. *Identify the system.* Now it will be much easier to deal with smaller, more isolated systems than when using the pie charts.
2. *Draw a pictorial representation* of the system inside the schema diagram.
3. *Identify the initial energy storage* (internal energies), and represent them with relative quantified bar graphs.
4. *Identify the resulting final internal energies* with final bar graphs.
5. *Identify the energy transfer(s)* that occur across the system boundary to cause the changes in the internal energies, and represent the transfer with quantified arrows pointing into or out of the system schema diagram.

In summary, you will use bar graphs to represent the Initial and Final energies, and the energy schema diagram to represent the During processes. The difference in the Initial and Final energies is the change in internal energy, ΔE , since $\Delta E = E_f - E_i$.

Thus the bar graphs and energy schema diagram represent the 1st Law of Thermodynamics, $W = \Delta E$

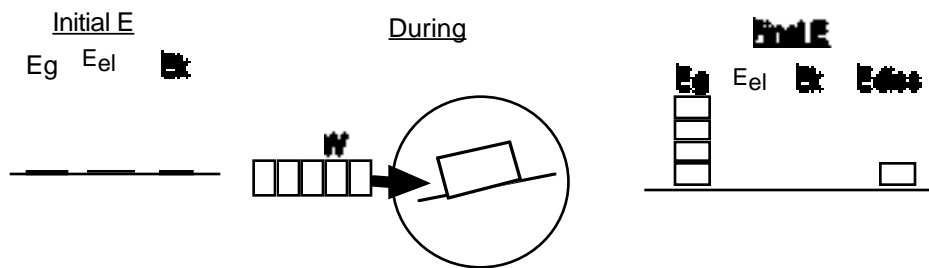
Examples of Bar Graph/Energy Flow Diagram Usage

Example 1 A person pushes a box from a 0 position up a ramp to a stop.



system = box + surface of ramp

Corresponding Bar Graphs and Energy Schema Diagram

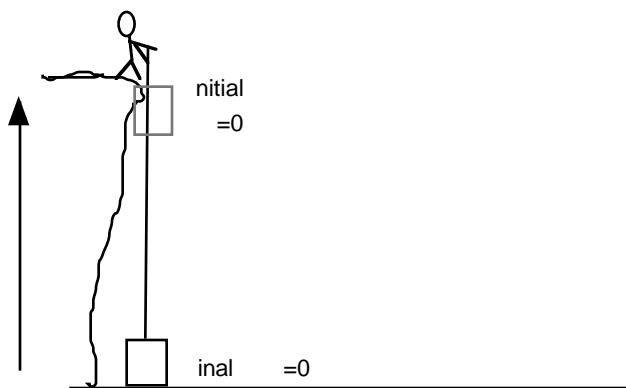


Analysis

1. Assuming the box starts at a 0 reference point, it has no initial energies.
2. Energy is transferred to the system via the external force provided by the person. This is defined as working. The work arrow is 5 blocks long.
3. At the final point, the energy transferred by working done has been stored as the energy of gravity, E_g , and some has been dissipated due to friction, E_{diss} .

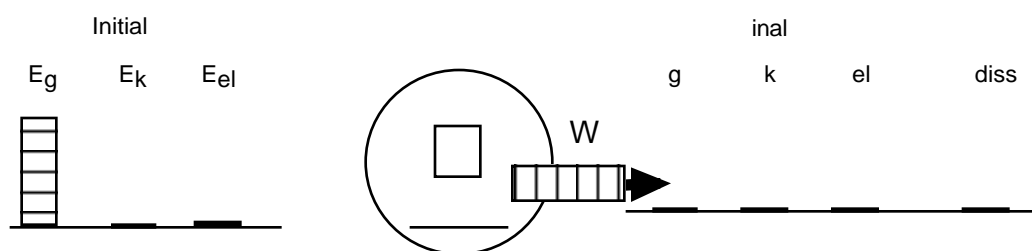
Notice that E_g and E_{diss} add up to 5 blocks also, in agreement with the Conservation of Energy.

Example 2: A person lowers a box to the ground.



system = box + earth

Corresponding Bar Graphs and Energy Schema Diagram

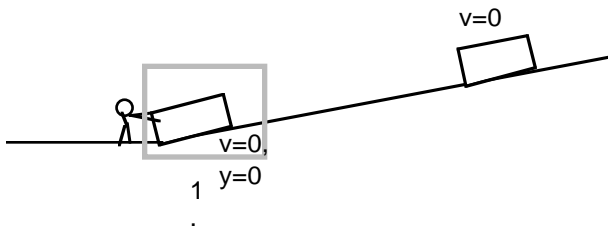


Analysis:

- Initially, the box only has gravitational potential energy, E_g , due to its position above the reference point where $y=0$.
- Afterwards, the box system has no energy - it is on the ground, not moving. It might be tempting to say that the energy E_g was lost to E_{diss} . However, what would it have been dissipated by? Friction is minimal, and we assume it was lowered gently so it doesn't slam into the ground. There is nothing internal to the system that would account for E_{diss} . Therefore, the energy was removed from the system by the external force of the rope acting on the box, which lowered the box to the ground. There was work done by the rope, and since the internal energy of the system decreased ($-\tilde{E}_g$) the work arrow must point OUT of the system, showing that $-\tilde{E}_g = -W$, since energy was transferred out of the system.

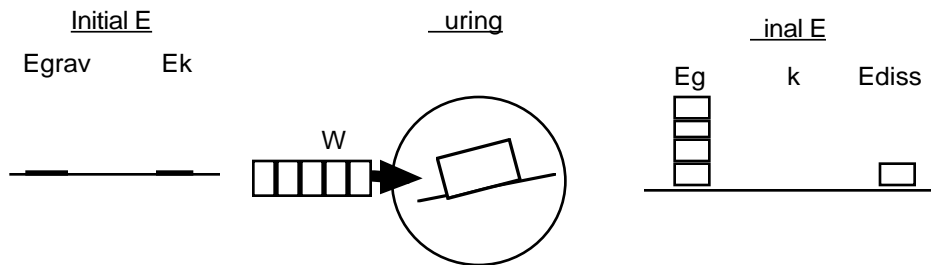
*Some students will probably want to account for E_{chem} of the person. They just need to be reminded that the person is not in the system. If he *was*, in the system, then yes, there would be a decrease in E_{chem} , as well as E_g and could be accounted for by an increase in E_{diss} , the person's metabolism.

Example 3 A person pushes a box from a 0 position up a ramp to a stop.



system = box + surface of ramp

Corresponding Bar Graphs and Energy Flow Diagram



Analysis

1. Assuming the box starts at a 0 reference point, it has no initial energies at point 1.
2. Energy is transferred to the system via the external force provided by the person. This is defined as work (work done on the system.) The work arrow is 5 blocks long.
3. At point #2, the energy from the work done has been transferred to the energy of gravity, E_g , and some has been dissipated due to friction, E_{diss} .

Notice that E_g and E_{diss} add up to 5 blocks also, in agreement with the Conservation of Energy.