ACTIVITY 1

Energy Diagrams --- Attraction

Goal
Changes in energy are a good way to describe an object's motion. Here you will construct energy diagrams for a toy car and learn how these diagrams can be useful. This technique will prepare you for similar uses of energy diagrams in quantum physics.

In general terms physics can be divided into two broad categories - classical physics and modern physics. When we use modern physics to explain a phenomenon, we are using concepts that trace their origin to the quantum revolution that began in the early part of the 20th century. Classical physics is everything else. These two branches of physics share many concepts such as energy, momentum, forces, and conservation laws. They differ fundamentally in the concepts and models, which are used to describe the very small.

To gain understanding of the processes taking place at atomic and subatomic levels, you need the help of quantum mechanics. The objective of the *Visual Quantum Mechanics* units is to introduce you to some aspects of this relatively new way of thinking and, thus, to learn how we know about very small objects such as atoms and molecules.

In quantum mechanics the concept of energy is frequently used to help us describe events and motion. Instead of describing changes in motion in terms of forces and accelerations, we use changes in energy. A convenient way to describe changes in energy is to sketch a graph of the value of an object's energy at various locations. When we create such a graph for energy, we call it an *energy diagram*.

Using energy to describe motion is somewhat different from the typical approach. However, it is a very powerful technique that can be used for both small and large objects.

To prepare you for learning about atoms and other small objects you will first describe the motion of a toy car using potential energy diagrams. You will see that you will be able to describe the motion of a moving object without actually seeing that object or its motion. All you need to know is the energy.

An example of a *potential energy diagram* is shown in Figure 1-1. On the horizontal axis is the location of the car while the vertical axis shows the value of the potential energy at each location. It shows us how the potential energy changes along the path of the car. The potential energy is highest for locations between 0 and 0.1 meters, is 0.1 joules, and rises to an intermediate value for 0.2 to 0.3 meters. We shall see we can learn a lot about the car's motion from this diagram.

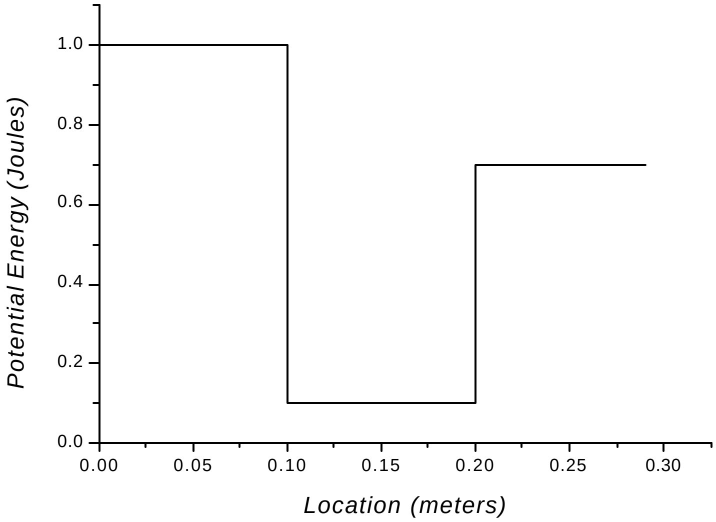


Figure 1-1: A potential energy diagram for a toy car.

The potential energy varies with the location of the object. This energy change can arise from a variety of interactions including elastic, gravitational, chemical, etc. In this unit, the potentials are generated with the help of magnets. However, the interactions between atoms and nuclei are of different origin. Therefore, the comparison with the atom that you will attempt later on will only be concerned with the shape of the potential energy curve, not with the origin of the interactions.

In these four activities you will arrange magnets along a track and observe the interaction between these magnets and a magnet on the car. By changing configurations of the magnets along the track you will obtain potential energy diagrams of various shapes. In this activity you will arrange the magnets in *attractive* mode.

The friction between the wheels of the car and the track is relatively high. If we were to account for that friction, it would have made the energy diagrams complicated. However, for the purposes of our qualitative analysis we will try to think about what would have happened if the friction acting on the car were very small.

In this activity we will frequently make approximate sketches of the energy of the toy car. As a first example, consider what happens when you push the car along the track with no magnets near the track or on the car. Try it now by giving the car a gentle push.

? Use your observation of the motion and sketch a graph of speed vs. location. Your graph should be just a rough sketch. We do not measure the values of the speed, so we can only approximate the shape of the graph.

? Now, sketch a rough graph of the kinetic energy vs. location. (Hint: The kinetic energy is proportional to speed^2.)

Again, we have not measured the kinetic energy, so we can not put values on the vertical axis, but we can learn a lot from the shape of the curve. For example, your curve probably shows that the kinetic energy decreases with distance. This result tells us that the car's energy decreases as it moves along the track. That is not a surprise, because the car has internal friction as well as friction with the track. Your graph gives you an idea about the rate at which the friction changes the speed.

The decrease in kinetic energy is caused by energy going into overcoming friction. If friction were not present, the sketch of kinetic energy vs. location would be a straight line as shown in Figure 1-2.

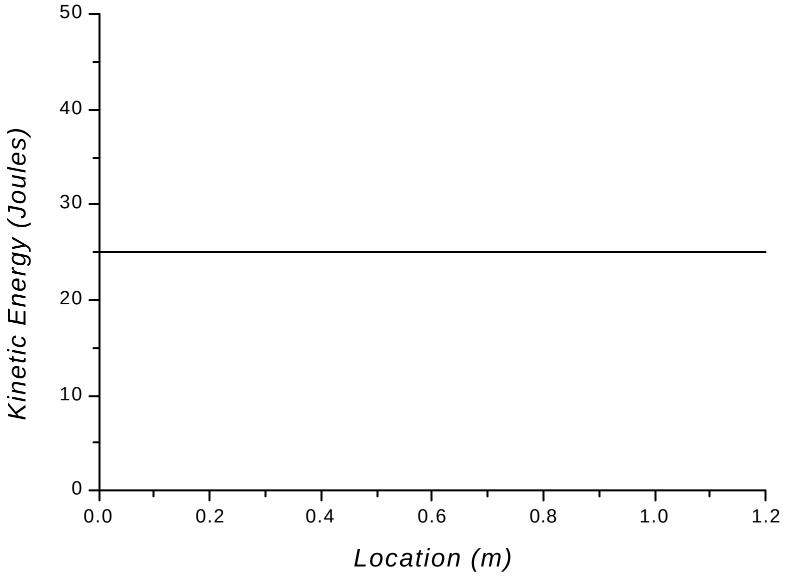


Figure 1-2: A graph of kinetic energy vs. locationfor a car that loses none of its energy to friction.

This graph represents a situation in which the kinetic energy never changes. Many times during this activity we will try to imagine how other graphs would appear if friction were not present.

Consider another example - the graph of the total energy of the car when it is moving on a level track. Because we ignore the effect of friction, the total energy (total energy = potential energy + kinetic energy) will not change. Thus, the graph will look like Figure 1-3.

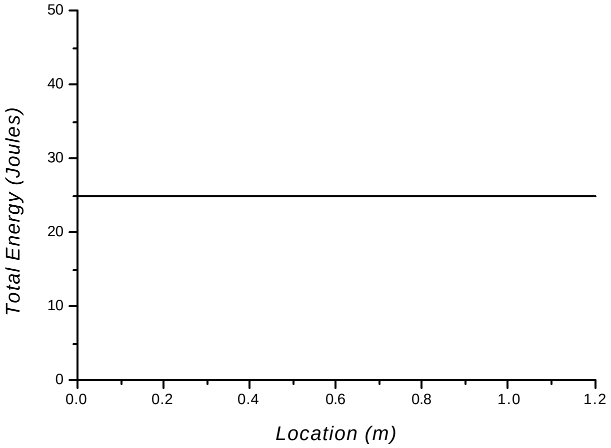


Figure 1-3: The total energy vs. location for a car that loses none of its energy to friction.

We can draw this graph because the total energy of the car at every point along the track is equal to its kinetic energy when no interactions are present. So far you constructed the energy diagram of the car, when no magnets are present.

Exploring interactions between attractive magnets

Now we will add interactions to our car. The interactions will occur between magnets on the car and magnets along the track.

The diagram below shows you how to set up the experiment:

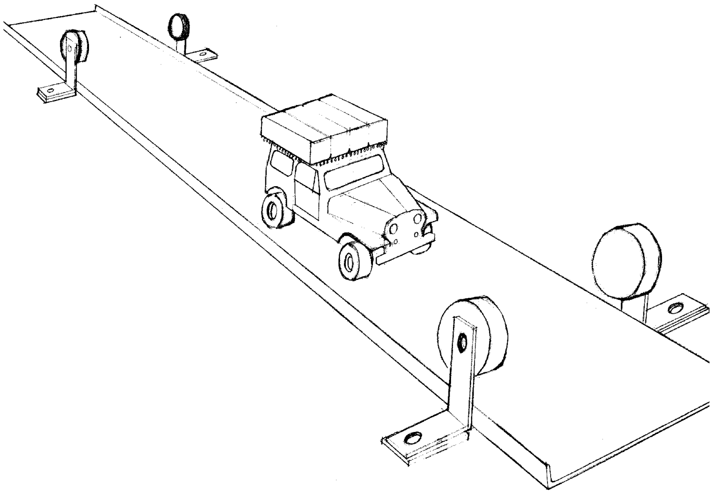
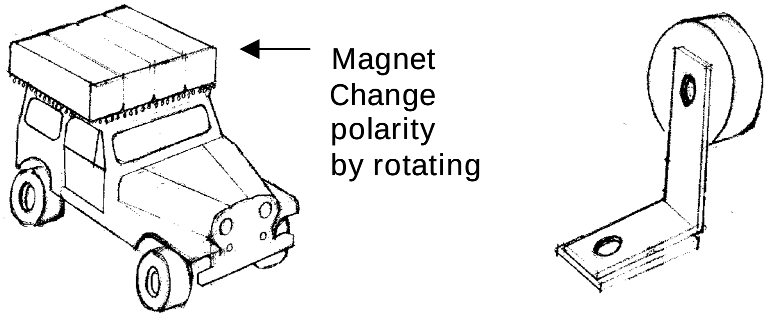


Figure 1-4: The experiment arrangement for the car interacting with magnets.



Magnet
Change
polarity
by rotating

Holder with magnet
Place at different
positions along the
track. Use in pairs
with one magnet
directly across the
track.

Figure 1-5: A car with a magnet and a magnet holder.

Push the car and watch carefully as it goes through the magnets. If the car does not go beyond the magnets, try again with a stronger push.

? How did the speed of the car change as it approached and then passed the magnets? Write down your observations about all speed changes.

? In the space below, draw a rough sketch of the speed changes vs. location and then kinetic energy vs. location.

? Indicate the location of the magnets on your diagram.

The graphs for the speed and kinetic energy have a large change in the neighborhood of the magnet. However, the diagrams should also show an overall decrease in value as the cars move along the track. As before, this decrease is due to interactions involving friction.

For the car with no magnetic interactions you had kinetic energy diagrams such as those in Figure 1-6.

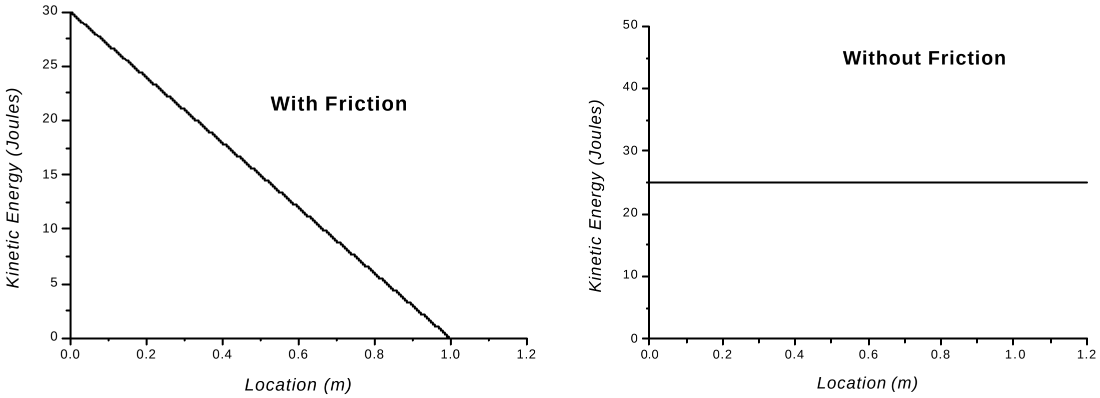


Figure 1-6: Kinetic energy diagrams for a car on a level track with friction (left) and no friction (right).

? The change from “without friction” to “with friction” in Figure 1-6 can help us think about how other graphs would look if friction were not present. Imagine the kinetic energy diagram that you drew for the car interacting with a pair of magnets. Draw it in the space below as if friction were not present.

On the “no friction” kinetic energy diagram in Figure 1-6, draw a line to represent the total energy of the car. Include the interactions with the magnets. Hint: Far from the magnets, the total energy equals the kinetic energy of the car.

The change in kinetic energy near the magnets shows that the kinetic energy becomes greater than the total energy. However, we know that energy is conserved. Thus, another form of energy must also change in the region near the magnets to keep the total energy constant. This other energy is the potential energy resulting from the magnetic interactions. We can use information about the kinetic and total energy of the car to construct a potential energy diagram of the car-magnet system. To construct a graph of a potential energy vs. location, use potential energy = total energy - kinetic energy. In the present case we must just approximate because we do not have exact values.

? Sketch the potential energy diagram of the car by subtracting the kinetic energy from total energy from the kinetic energy diagram.

To maintain conservation of energy the potential energy must be negative in the region near the magnet. In fact, the shape of the potential and kinetic energy diagrams turned out to be identical, although inverted. If we add the dip of the potential energy and the hump of the kinetic energy together, they will cancel out. The resulting diagram will be a straight line. This line represents the total energy of the car that does not change if friction is not present.

The graph of potential energy vs. location that you created are examples of *potential energy diagrams*. These diagrams can be useful in describing motion for all types of objects. Once you have the potential energy diagram for a situation, you can describe the motion of an object.

The usual method of using potential energy diagrams is to:

- start with the physical situation
- use the physics to draw the potential energy diagram
- describe the motion

In this way you can describe the motion even when you have never seen it. We can also describe other features in addition to speed and acceleration. In later activities we will look at some of those features.

The potential energy diagram provides an alternative way to describe motion of objects such as cars. They can also be used for analyzing the motion of very small objects — ones we cannot see. Thus, we need to first understand their value for objects we can see before using them with objects that are too small to see.

Homework Assignment

1. A friend of yours has set up a very low friction car and magnets and sketched the kinetic energy diagram in Figure 1-7.

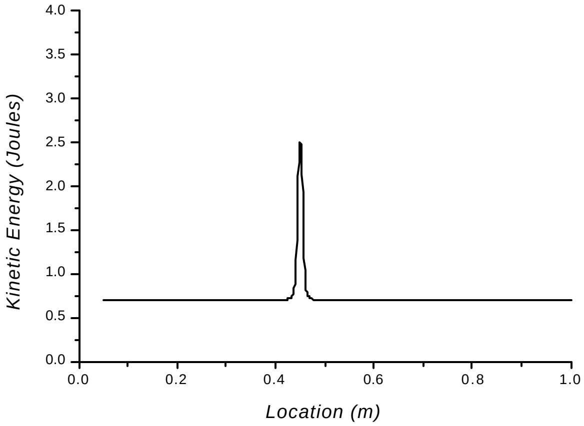


Figure 1-7: A kinetic energy diagram.

a) Indicate the location of the magnets in terms of meters along the track.

b) How is the speed of the car changing (increasing, constant, decreasing) as it moves from .3 m to .4 m, from .4 m to .5 m, and from .5 m to .6 m?

c) What is the value of the *potential* energy at point x = .35 m and at x = .45 m.?

d) Sketch the potential energy for this situation.

2. Figure 1-8 shows two potential energy diagrams for arrangements of cars and magnets.

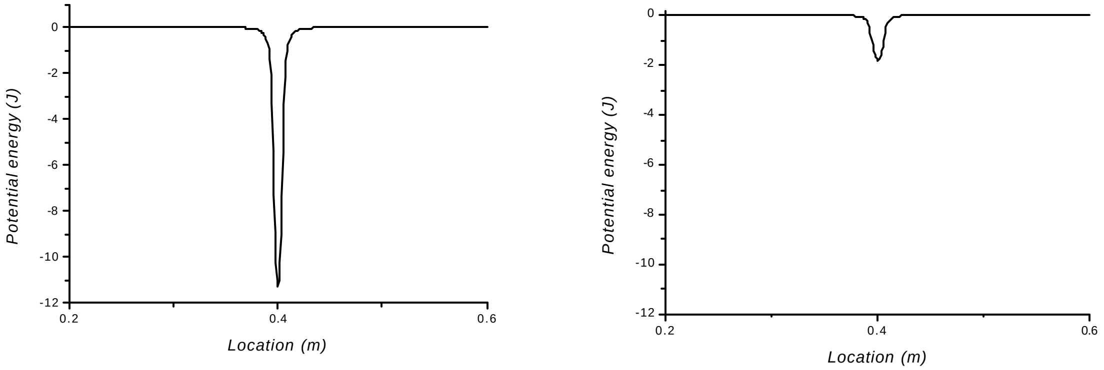


Figure 1-8: Two potential energy diagrams involving cars and magnets.

Both diagrams are drawn to the same scale. Answer the following questions based on these diagrams:

a) Sketch kinetic energy diagrams for each situation.

b) For which situation is the attraction between the car and magnets greater?

c) For which situation does the interaction occur over a greater distance?

ACTIVITY 2

Constructing Potential Energy Diagrams

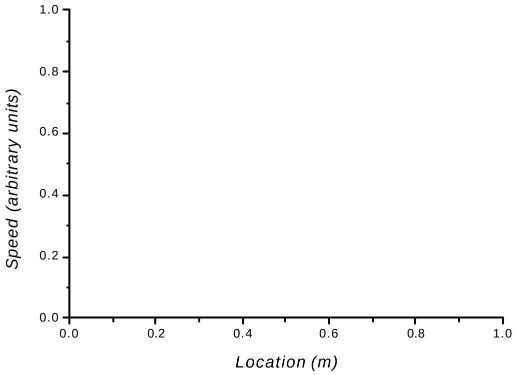
Goal
In this activity, you will explore energy diagrams for magnets in repulsive configurations. From these and the previous diagrams you will learn more about how to use these diagrams to describe motion.

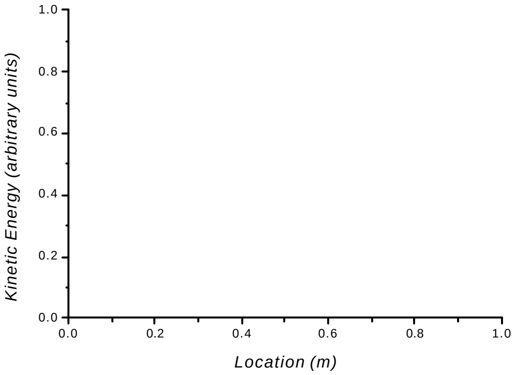
The experimental arrangement in this activity is similar to the previous one. The major difference is that we will arrange the magnets so that the ones along the track repel the one on the car. Again, we will try to imagine what the situation would be if the friction between the wheels of the car and the track was extremely small.

Use the same setup as in the previous activity and arrange the magnets so that the magnets along the track repel the magnets on the car. Push the car and watch carefully as it goes through the magnets. In the first observations we wish to consider a situation in which the car has enough energy to go past the magnets and continue along the track. If the car does not go beyond the magnets, try again with a stronger push.

? How did the speed of the car change as it went through the magnets? Record your observations below.

As you did in Activity 1, plot *approximate* graphs of speed vs. location and kinetic energy vs. location. You may create the graphs by laying a piece of paper along the track and sketching them there. Then, transfer the shape to the graphs below. Mark the position of the magnets on the location axis.

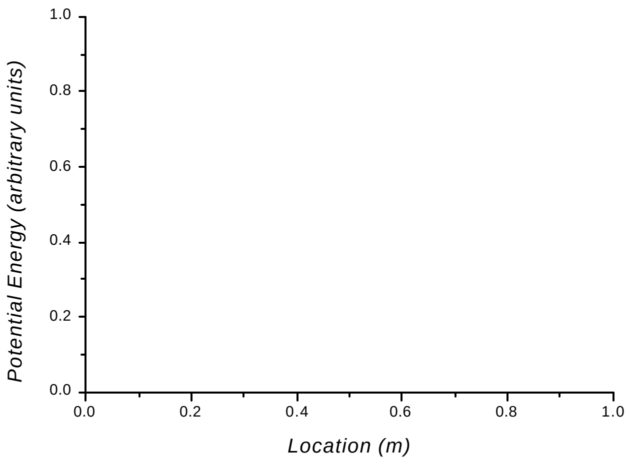




Now try to imagine both the kinetic energy and the total energy with very low friction. Draw a line which represents the total energy of the car if no friction were present.

Add to the graph above the kinetic energy as if there were no friction.

Sketch below the potential energy diagram of the car by applying the conservation of energy.



? How is this potential energy diagram different from the ones for the attractive situation?

? Explain the reason for this difference in terms of how the energy of the car changes.

So far we have tried to imagine the energy diagrams if friction could be removed. Because we cannot magically remove the friction from the toy cars, you will use a computer program to explore the frictionless case further.

Start the *Energy Diagrams Creator* program. With this program you can place a pair of magnets along the track and give the car a push. You can also change the amount of friction with the variable called the coefficient of friction. A coefficient of friction equal to zero means no friction.

Set up a computer version of the experiment that you just completed. Try it with a small amount of friction and describe your results below.

Now, set the coefficient of friction to zero. How do the results change?

Repeat this process for the experiment in Activity 1 — attraction. Describe your results below. If any of the results surprise you, discuss them with your instructor.

To check your partners' understanding of these ideas try a little game. While they are not looking at the computer screen, set up a configuration of magnets and a coefficient of friction. Run the car along the track to get the energy diagrams. Then cover the part of the screen that shows the car and magnets. Your partner(s) should look at the energy diagram and tell you

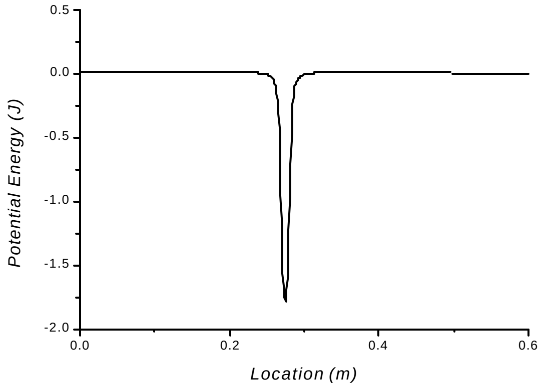
- the location(s) of the magnets,
- if each set is repulsive or attractive,
- the level of friction (zero, low, high), and
- how the speed changes as the cart moves along the track.

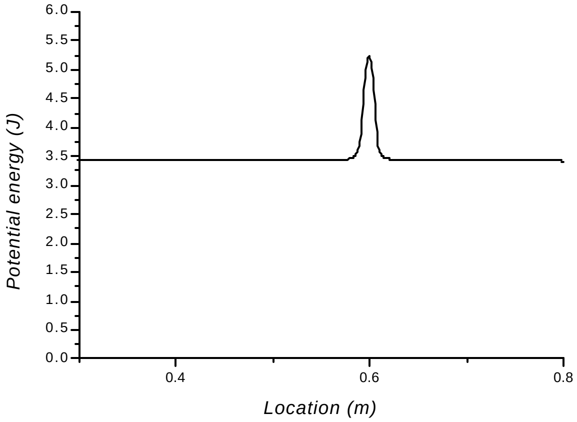
Don't make it too difficult. Your partners should set up a situation for you also. If any of the results surprise you, discuss them with your instructor.

The potential energy diagrams can provide information about many details of the motion other than increasing or decreasing of the speed of the object. Now that you are familiar with the two basic arrangements of magnets and their corresponding energy diagrams, you can use this knowledge to explore a new, more complex situation - an object trapped in a small region of space. In the next activity you will study the condition that allows the trapping and some other concepts such as *turning points* and *binding energy* associated with this type of motion.

Homework

1. The quiz show "Jeopardy" has opened a physics category. Below are two answers in the form of potential energy graphs. In this version of "Jeopardy" you need to give and explain the experimental arrangement and motion.





ACTIVITY 3

In a Trap

Goal

You will look at the motion of a car constrained to move in a small region of space and use diagrams to determine

- the range of energies for which the car will be trapped, and
- the energy needed to "break the car free" from its trap.

When you study properties of materials, you will find that many objects have their motion restricted to a small region of space. For example, electrons stay close to their atoms, and atoms in a solid are restricted in their motion by their interaction with other atoms. We say that these objects are *trapped* by their interactions with neighboring objects. When you study trapped electrons and atoms, you will use potential energy diagrams. To become prepared you will now consider with potential energy diagrams representing a car that is trapped by interactions with magnets.

You are already familiar with the attractive and repulsive situations, in which the car managed to escape the magnets and went all the way to the end of the track. In this activity, you will use conservation of energy and the total energy of the car to focus on another question: what conditions allow a car to be trapped in a region of space? You will start with a car initially repelled by one pair of magnets and later trapped between two pairs of magnets. Keep in mind that in your experiments you use the magnets as a convenient way of creating change in potential energy. However, these diagrams can be created with other objects as well.

For example, the interactions between electrons and nuclei are of non-magnetic origin. In this unit, you will be concerned only with the shape of the diagrams, not with the origin of interactions.

Car repelled by a pair of magnets

? Based on what you have learned from Activities 1 and 2, how would you arrange the magnets (as attractive or as repulsive) to create the following potential energy diagram?

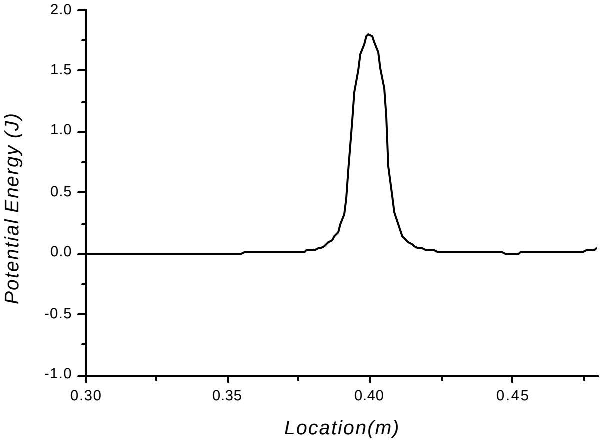


Figure 3-1: A potential energy diagram.

In general, when we work on a certain task, we always prefer to have as much information (data) available as possible. In the example with the car, to completely analyze its behavior, you will need an additional piece of information --- the total energy of the car. The total energy (*potential* + *kinetic*) is often represented by a horizontal line added either to the kinetic or potential energy diagrams. From now on we will draw the total energy as a line relative to the potential energy diagram, as shown in Figure 3-2.

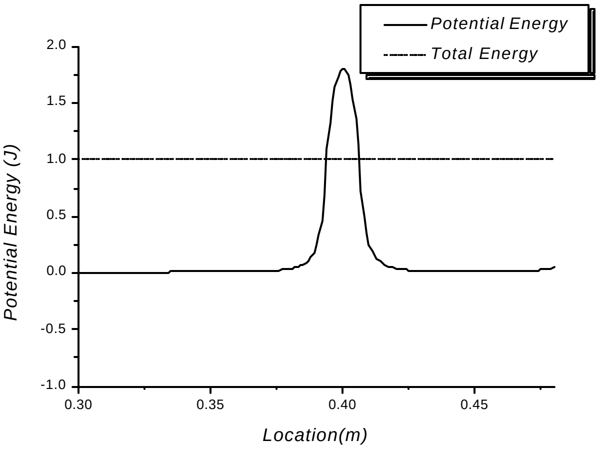


Figure 3-2: A potential and total energy diagram.

? Why should we draw the total energy as a flat line, while the potential energy changes in situations where we ignore friction?

Consider a car which has the total energy indicated in Figure 3-2. It is approaching a set of magnets from the right that have the potential energy represented by the solid curve. See Figure 3-3.

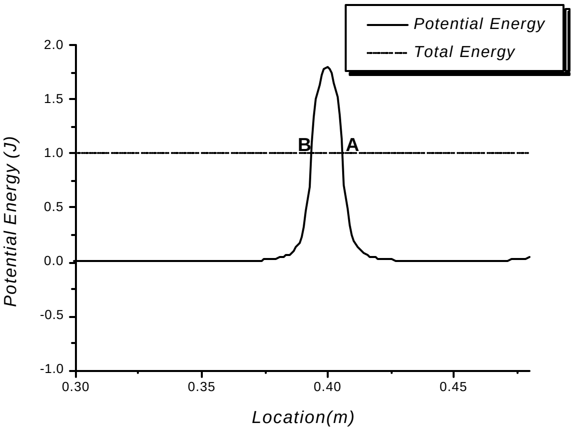


Figure 3-3: The magnets repel and the total energy is less than the maximum potential energy.

? What is the value of the kinetic energy:

- a) at .44 m;
- b) at point A, where the potential energy and total energy are equal;
- c) at .40 m;

Notice that in the region between points A and B the kinetic energy *that we calculate* is negative. This result is a difficulty. The mass of the car is always positive and so is the square of its velocity. Thus, kinetic energy can not be negative. A negative kinetic energy has no physical meaning! For a negative kinetic energy to exist, it has to be associated with negative mass or negative $(\text{velocity})^2$. Neither of these is physically possible. The car cannot have a negative kinetic energy, so it does not go into regions where we would calculate a negative kinetic energy.

Therefore, it is not physically possible for the car to get to the *left* of point A. When the car approaches point A from the right, it will stop at point A and turn back in the opposite direction.

Arrange the magnets so that you have a situation represented by the potential energy diagram in Figure 3-3.

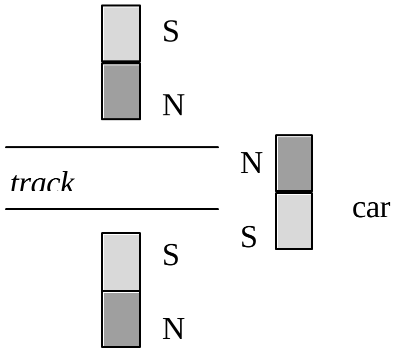


Figure 3-4: A situation in which the car is repelled by a pair of magnets.

Push the car, so that it turns around near the magnets. Then, sketch the approximate values of the total energy and the potential energy on the diagram in Figure 3-5. Mark the location at which the car turns around as point.

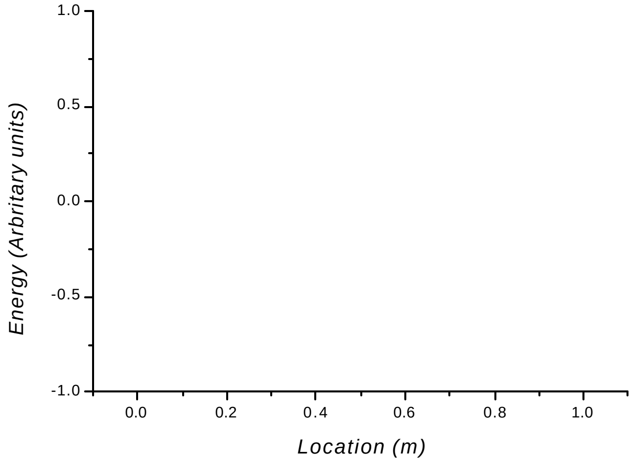


Figure 3-5: A potential energy diagram.

Now give the car a stronger push. What does the car do when it approaches point A (i.e. near the magnet)? Sketch in Figure 3-6 both the total energy level of this car and its potential energy. Indicate on this graph the approximate location of point C from the previous graph in Figure 3-5.

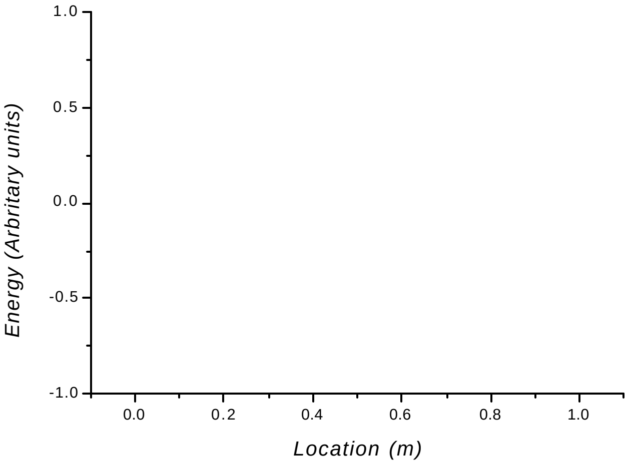


Figure 3-6: An energy diagram for a stronger push than in Figure 3-5.

Warning! The car is approaching a trap!

When we study atoms, we will look at several situations where two objects attract each other and, thus, stay close together. For example, an electron and a proton become a hydrogen atom because of their attraction. One way to learn about atoms is to consider the potential energy created by the attraction, then analyze the electron's total energy. To become prepared for that analysis we will now look at cars trapped by magnets.

We wish to establish a situation where the car is moving but it is trapped in a certain region of space. Arrange magnets (as many as you need) to create a situation where the car can be trapped in a region of space. Describe your arrangement of magnets.

? Draw the potential energy diagram for this situation.

? Use the potential energy diagram to explain why your arrangement will result in a trapped car.

? Now give the car a push that allows it to escape from the trap that you have created. Use energy to explain why the car can escape.

? Sketch your potential energy diagram again below. Then draw and label a possible total energy of the car when:

1. it is trapped in one region of space and
2. it escapes from the region.

? The potential energy diagram in Figure 3-7 shows one possibility for getting trapped car. On this diagram draw the maximum total energy level which the car can have and still remain trapped by two pairs of magnets. Explain your answer.

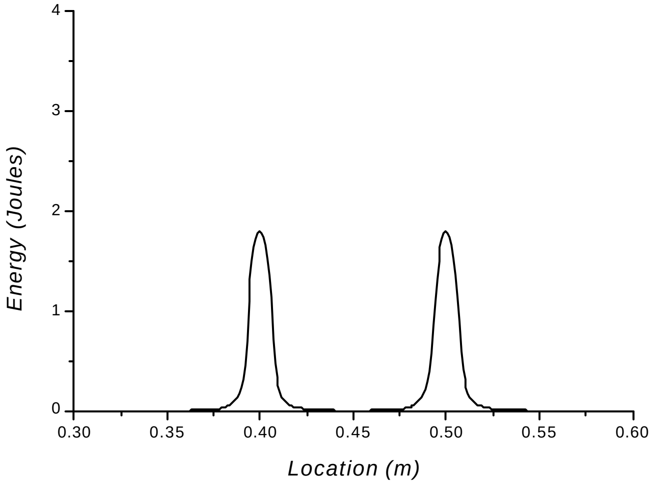


Figure 3-7: A potential energy diagram for a trapped car.

Notice that for some locations on the diagram the total energy of the car equals its potential energy. On one side the potential energy is greater than the total energy. This situation is equivalent to the kinetic energy having a negative value. Thus, the car will stay in the region where potential energy is equal to or less than the total energy. At the locations where the potential energy and total energy are equal, the car comes to a momentary stop, then changes direction. The locations where the car momentarily stops are called *turning points*.

The diagram in Figure 3-8 shows potential and total energies for a car. Indicate on the graph the car's turning points.

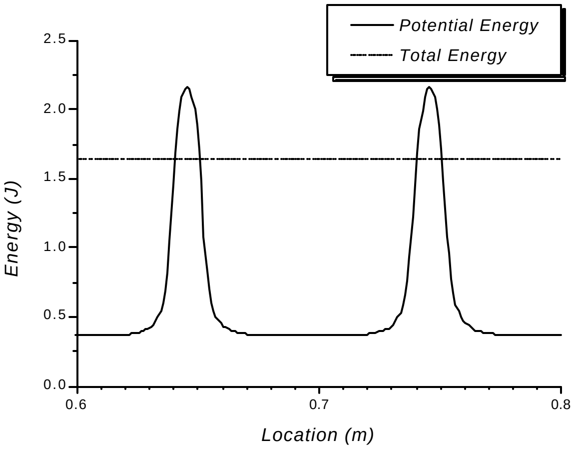


Figure 3-8: For this situation determine the turning points for a car that starts moving at 0.7 meters.

Identifying the turning points is a useful way of describing the region in which an object is restricted. Using potential and kinetic energy is an easy way to determine the turning points.

Once trapped, will the car stay there forever?

When an object is trapped in situations similar to the one represented by Figure 3-8, it must receive some energy if it is to get out of the trap. Suppose you wanted to help get this car out of its trap.

? How much energy would you need to give the car represented by Figure 3-8 so that it would no longer be trapped?

The energy needed to remove an object from a region in which it is trapped is called the *binding energy*. The binding energy is the *difference* between the maximum potential energy and the object's total energy.

Application — If friction were not present

Once again friction causes difficulty in seeing what happens when no energy leaves the car. To have a friction-free experience use the *Potential Energy Diagram Sketcher* program. Set up a situation that creates the potential energy diagram in Figure 3-7. Give the car the approximate total energy shown in Figure 3-8.

? Describe the car's motion with

- Large friction

- Small friction

- No friction

? Now, calculate the binding energy. Then, give the car that much energy. What happens?

Each member of the group should set the total energy of the car to a different value. Other group members should calculate the binding energy. Then, see if that amount of energy frees the car from its trap.

The attractive and repulsive diagrams that you have created were diagrams of simple shapes - representing an object being first accelerated and later decelerated (or vice versa). However, the motion of an object is often more complex. The next activity is an introduction to potential energy diagrams of complicated shapes and their application.

ACTIVITY 4

A Single Interaction and Other Things

Goal
We look at one more situation in which an object is trapped by an interaction, then complete a summary exercise to apply all that you have learned.

In the previous activity we trapped a car by placing it between two locations where repulsive interactions occur. We can also trap an object with one attractive interaction.

? Begin by setting up a situation so that the car is trapped by an attractive interaction. Describe below how you did it.

? You also used an attractive interaction in Activity 1. How is this situation different?

Remember the potential energy far from the magnets will be zero, and we define attractive potential energies to be negative. Sketch the potential energy diagram for the interaction that you have created. Again, assume that you can ignore friction. Draw only the potential energy due to the magnets.

Now, draw the total energy on this potential energy diagram as if friction were zero. To think about the value of the total energy, consider the turning points. For the object to be trapped, it must have two turning points. Thus, the total energy line must cross the potential energy curve twice. Use these concepts to draw the total energy line.

Based on our previous activities we must conclude that the total energy is negative when a single interaction traps an object. In this situation we have a negative potential energy and a negative total energy; only the kinetic energy is positive.

For many situations such as electrons in atoms, the object is trapped by one interaction. When objects are trapped in this way, we say they are in a *bound state*.

The binding energy for an object in a bound state can be determined as we did in Activity 3. It is the difference between the energy when the particle is *not* trapped and the energy when it is in the bound state.

In Figure 4-1 are energy diagrams which show the potential and total energies for an object. What is the binding energy for each object?

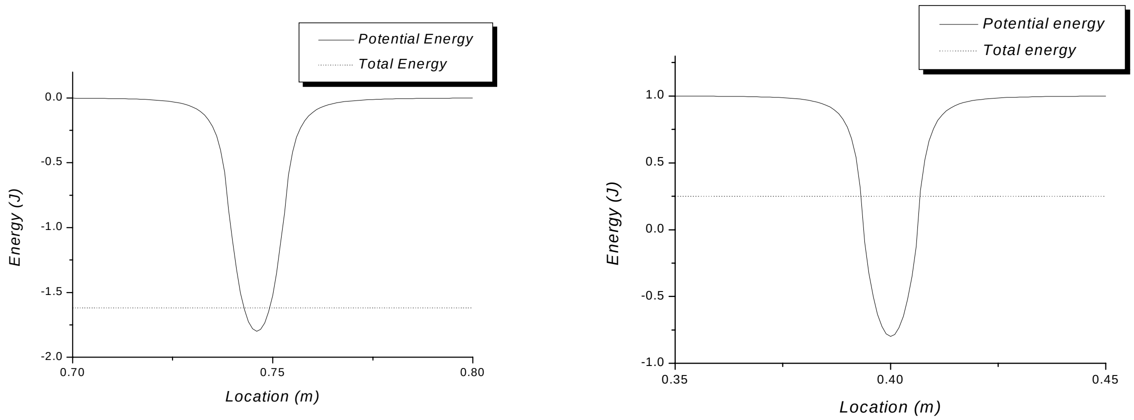


Figure 4-1: Energy diagrams for two situations.

This type of energy diagram is most useful when studying atoms. It will help us understand how energy changes in atoms and how light is created by atoms.

Catching a thief using potential energy diagrams

One of the advantages of the potential energy diagrams is that they provide many details of motion - one does not need to be present when a motion takes place in order to describe it. To provide you with a better understanding of the value of the potential energy diagrams and to prepare you for the study of atoms and nuclei, imagine the following situation:

As a secret agent you need to use your physics background to stop the theft of stolen paintings. The shipment of stolen art works is being moved by truck. Your partner has attached a large magnet underneath the truck. She needs to communicate to you where to place magnets along the road so the truck can be trapped and does not leave the country. However, she fears that any note could be intercepted. She knows that thieves usually sleep through physics class, so she draws a potential energy diagram and sends it to you. You receive the following drawing:

The horizontal dotted line on the diagram represents the total energy of the truck.

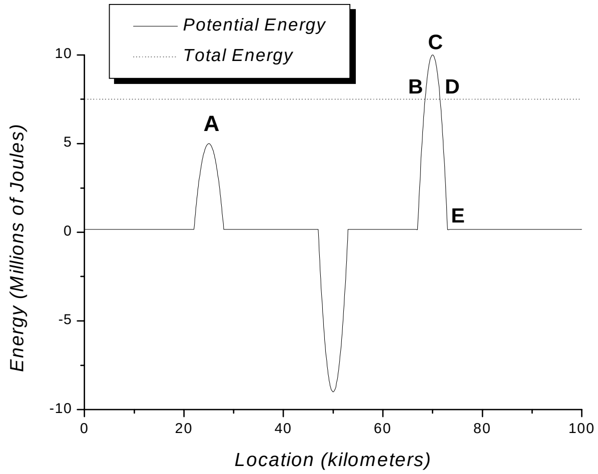


Figure 4-2: The energy diagram for the "catch a thief" scenario. The changes in potential energy shown here are larger and broader than are possible with real magnets. They were drawn this way so that they would be easy to see. After all, it's all fiction.

(This way of catching thieves may seem rather strange, but James Bond does even stranger things.)

? Which are the points reached by the truck when it moves from left to right with total energy as indicated on the diagram?

? Describe the motion of the truck at these points in terms of speed changes. The truck is moving from left to right.

? Describe the motion of the truck if it has twice as much total energy as indicated on the diagram and still moves from left to right.

? In terms of locations reached by the truck, what was different in the two situations?

? Explain how you used the potential energy diagram for your descriptions.

The final and most important step of your job is interpreting the drawing and helping to capture the thieves. The data that you need are available on your diagram. The truck is always on a flat road.

? Indicate where you would put magnets to create the potential energy diagram. Also state whether they would attract or repel the truck.

? List the points along the road (in km) which will result in a turning point for the truck.

? To accomplish your mission of trapping the truck, your colleague tells you to reverse a set of magnets just after the truck passes. Which set would result in trapping the truck? Explain your answer.

In this activity you have learned how the potential energy diagram can be used to predict and describe the motion of an object. The behavior of any object at a particular location in space can be determined by the potential energy diagram that represents the object's motion and object's total energy. In your assignment as a secret agent you applied your knowledge to macroscopic objects (the truck). When you study very small objects such as atoms and molecules, you will use energy diagrams and identical reasoning patterns. However, for one aspect — turning points — you will see that we must modify our ideas about what is possible.

Unit Summary

In these activities we have presented energy as a method of describing motion. To use this method you need to create a potential energy diagram from the physical situation, then use it and knowledge of the total energy to determine other variables of the motion such as speed and acceleration. Conservation of energy is crucial to understanding the energy diagrams. A decrease in potential energy means an increase in kinetic energy and vice versa. Thus, by looking at a potential energy diagram with the total energy marked on it, one can quickly use conservation of energy to describe the motion.

Inspection of energy diagrams quickly tells where an object such as a toy car can be. If a region exists where the potential energy is greater than the total energy, the object cannot enter that region.

Because the object cannot be in a region, it must turn around. The *turning point* is the location at which the object turns. At this point the potential energy is equal to the total energy.

If two turning points exist, the object is trapped in the region between them. By looking at an energy diagram you can easily determine the region in which the object is trapped.

When an object is trapped, it can become free of its trap only if it receives additional energy. We can determine this energy by calculating the difference between the total energy and the maximum value of the potential energy. This difference is the *binding energy*. When an object receives its binding energy, it is no longer trapped.

An object can be trapped or *bound* by an interaction with one other object. In this case the interaction must be attractive. We define the potential energy to be negative for these attractions. If the total energy is also negative, the result will be a *bound state*. Electrons in atoms are in bound states.

The energy diagram method enables us to determine quickly several features of an object's motion. It will be very helpful when we study electrons — and we will find that electrons do not behave quite the same way as toy cars.