Kangaroo jumping video analysis: Day 2 of the Kangaroo Locomotion Case Study
(Teacher notes in blue, with sample student predictions and brief discussion of correct answers to analysis questions.)

Names:

Introduction

Animals use interchange between stored energy and kinetic energy in order to move in a controlled fashion. Today, we will explore how a kangaroo uses transformations of mechanical energy to hop long distances along the ground. Kangaroos are some of the only large mammals to use hopping as a form of long distance locomotion. Red kangaroos have powerful hind legs and can sustain hopping speeds of around 15m/s (34 miles per hour), although they usually travel more slowly [1]. In today's video analysis lab, we'll observe, track and describe the motion of a red kangaroo as it hops along flat terrain. By recording the position and velocity as a function of time, we can extract information about how the kangaroo's mechanical energy changes throughout its motion.

Some useful definitions:

- Kinetic energy: Energy associated with motion, described by $KE = \frac{1}{2}mv^2$
- Gravitational potential energy: Stored energy associated with location in a gravitational field, described by $PE_g = mgh$
- Elastic potential energy: Stored energy associated with stretching or compressing a spring or another spring-like material, described by $PE_s = \frac{1}{2}kx^2$
- Energy transformation: When the energy within a system changes from one form to another. Ex: If a rock is dropped from rest, its gravitational potential energy is transformed to kinetic energy as it loses elevation and gains speed.
- Energy transfer: When energy is transferred from one system to another. Example: If the rock hits the ground and comes to a stop, its kinetic energy is transferred to the environment in the form of heat, sound, and material deformation.

Objectives:

- Describe how the position vs. time and velocity vs. time graphs correspond to the observed motion in the video.
- Use data from the video to determine the kangaroo's kinetic energy and potential energy at different parts of its motion, in order to elucidate the relationship between kinetic and potential energy.
- Identify differences between energy exchanges that take place in living systems vs. inanimate objects.

Central questions:

- What forms of mechanical energy does the kangaroo have, and how does the total mechanical energy change, throughout the cycle of hopping motion?
- When does the kangaroo exchange energy with its environment?
- How is a kangaroo different from a bouncing ball, in terms of energy transformation and energy transfer with the environment?

Developing a testable hypothesis:

1. Download the "Hopping Maisy" movie from Canvas under > Files > Movies for video analysis.
2. After watching the movie, predict what the vertical position versus time (y vs. t) plot will look like for the kangaroo's center of mass while it is jumping. Sketch your prediction plot below.

Predicted motion plot:

Sample student prediction:

3. What forms of mechanical energy do you think the kangaroo has at each of the following points throughout a single jump? Explain your reasoning. You may want to refer to your findings for the bouncing ball yesterday as a starting place.
   a. Feet on the ground, starting to push off at the beginning of a jump:

Sample student prediction:

Elastic Potential energy – in the leg muscles

b. Feet have left the ground, kangaroo is moving upward:

Sample student prediction:

Kinetic energy – is moving
Gravitational Potential Energy – The jump

c. Kangaroo is at the very top of its jump before coming down:

Sample student prediction:

Gravitational Potential Energy

d. Feet on the ground, just after landing:

Sample student prediction:

Elastic potential energy

4. Do you think the kangaroo exchanges energy with its environment at any point throughout its motion? If so, when does this take place? Describe your reasoning.

Sample student prediction:

Yes, at the point it touches the ground due to friction.

Experimental design choice: We will collect motion data from the kangaroo in order to determine how the kangaroo's forms of mechanical energy change over time, similar to the ball bouncing lab yesterday. What point on the kangaroo's body will you track, in order to collect useful data? Options include the approximate center-of-mass, the nose, the eye, the foot, etc. Discuss the pros and cons of different options with your group in order to make a decision.

Note: This decision of which location on the kangaroo to track is impacted by a trade-off between precisely tracking a point from frame-to-frame in the video, while reducing confounding internal movements that were not related to the vertical hopping motion. For example, the tip of the kangaroo's tail would have the advantage of being easy to locate and track, but then the data would contain rotational motion of the tail with respect to the body, making it more difficult to analyze the kangaroo's overall movement. On the other hand, choosing a spot on the kangaroo torso corresponding to the approximate center of mass would avoid the unnecessary complication of limb movement; however, such a point would be difficult to identify and track from frame to frame. Some options that work well are the kangaroo's eye and the kangaroo's nose. In both cases, the object is easy to identify and track. Because the kangaroo's head does not move much with respect to the body while it is hopping, tracking either the eye or the nose gives a reasonable proxy for the center-of-mass movement of the animal. In our class, we allowed students to decide which point to track, while steering them away from options we knew expected would distract from the objects of the lesson.

Part II. Data collection

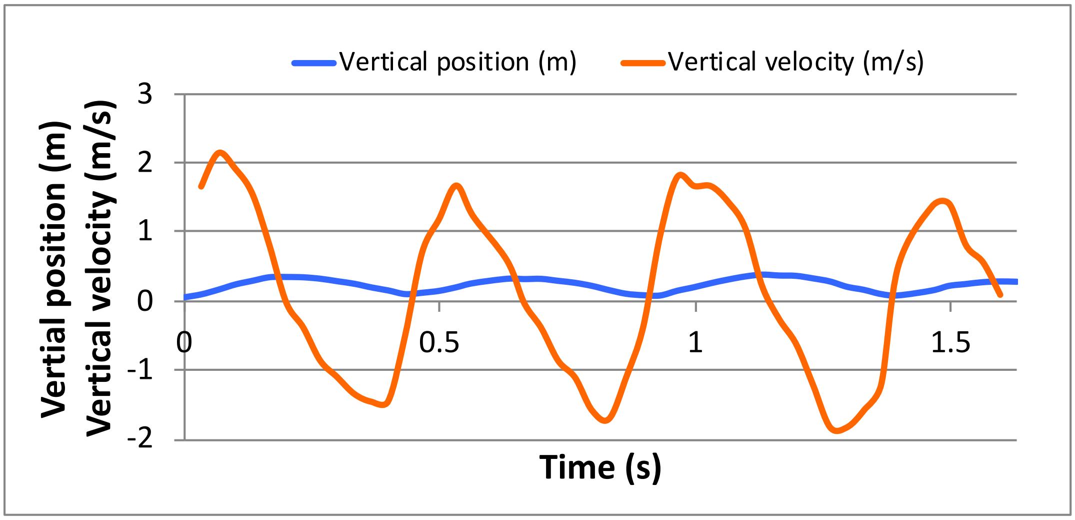
1. Open Tracker, go to "Insert", then "Movie", and navigate to where you have saved the movie. If you're not sure where it is saved, try looking in the "downloads" folder.

Note: There are a number of video analysis software packages available that can be used for this activity. Our figures were produced using Tracker, an Open Source Physics (OSP) package designed for physics educational purposes, which can be downloaded for free from this site: https://physlets.org/tracker/. Video analysis can also be performed using the educational software package Logger Pro. We recommend introducing students to the basics of video analysis using the associated tutorials for the selected software.

2. Following the directions in the video analysis tutorial for collecting data from a movie, obtain positional data for a point on the kangaroo's body while it is jumping. Collect data for at least 4-5 hopping cycles.
3. For calibration purposes, assume the fencepost in the background of the movie has a length of 1.5m and that the kangaroo has a mass of 50kg.
4. To prepare printable graphs, copy and paste your Time, Vertical Position (Y), Vertical Velocity (Vy), and Horizontal Velocity (Vx) into Excel. Leave an open row at the top, and add labels to each column to allow you to keep track of what quantity is in each column.
5. Prepare "scatter plot with smooth line" graphs of (Y vs. t) and Vertical velocity vs. time (V_y vs. t) in Excel, and add appropriate labels before printing.

6. Print your graph, cut it out and tape it into your lab here:

A sample plot prepared by obtaining positional data with Tracker video analysis, and plotting the data in Excel:



7. Examine the characteristics of these graphs, and discuss any similarities and differences with your position and velocity graphs for the bouncing ball lab yesterday. Can you explain what is happening in the kangaroo's motion during the times when the velocity is positive, negative, and zero, respectively?

Similarities between bouncing ball (yesterday) and kangaroo data:

- Velocity is positive and getting smaller in magnitude on the way up.
- Velocity is zero at the very top.
- Velocity is negative and getting larger in magnitude on the way down.

Difference between bouncing ball (yesterday) and kangaroo data:

- Unlike the ball, the kangaroo rebounds to a similar height every time.

Part III: Results

1. You can calculate Gravitational potential energy and Kinetic energy directly from the raw data in the following way:
   a. Add a column in Excel labeled Gravitational Potential Energy (J). In the first cell, enter the formula "=m*g*h", where m is the kangaroo mass, g is the gravitational acceleration constant 9.8m/s^2, and *h* is the current vertical position. Enter numbers into the Excel cell corresponding to each quantity. For the vertical position, refer to the cell number for the current vertical position Y (e.g. B2 or C2, depending on

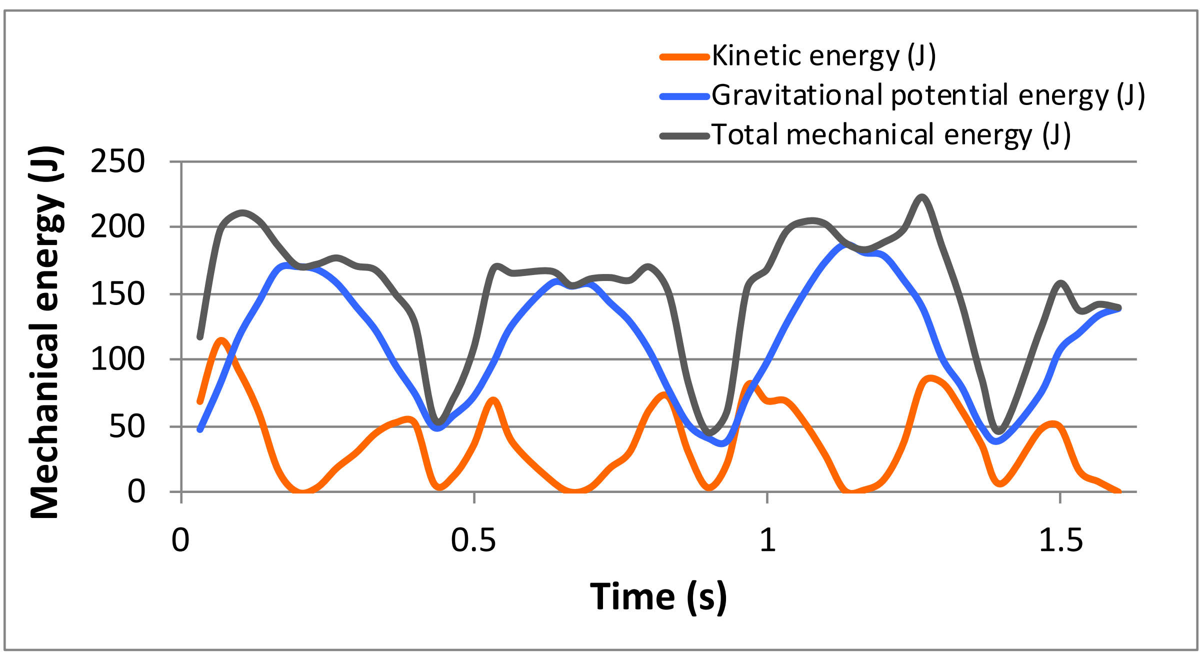
which column has your vertical position data). A reasonable estimate for the kangaroo's mass is 50kg. Ask for help if you're not sure how to enter the formula into Excel. Once you've entered this formula, select the bottom right corner of the cell with your mouse and drag it down to make the formula fill down through all the other cells in the column.

b. Add a column in Excel labeled Kinetic Energy (J). In the first cell, enter the formula "= 0.5*m*(Vx^2 + Vy^2)", where m is the kangaroo mass, Vx is the horizontal velocity and Vy is the vertical velocity. As before, enter an estimated number for the mass, and refer to the current values of Vx and Vy by identifying their cell numbers (e.g. C2 or D2, depending on which columns contain these data). As before, select the cell and drag down to fill in for other rows.

c. Add a column in Excel labeled "Sum of Gravitational Potential + Kinetic Energy (J)". In the first cell, enter a formula that adds the current values of Gravitational Potential Energy and Kinetic Energy from the adjacent columns. As before, select the cell and drag down to fill in the formula for other rows.

2. Make a "scatter plot with smooth line" graph that shows the <u>Gravitational Potential Energy vs. Time</u>, <u>Kinetic Energy vs. Time</u>, and <u>Sum of Gravitational + Kinetic vs. Time</u> all together in the same figure. Add appropriate vertical and horizontal axis labels, and include a legend that identifies each data set. Print this graph, and tape it here:

A sample plot prepared by obtaining positional data with Tracker video analysis, and plotting the data in Excel:



3. On your printed graph of mechanical energy, label by hand some time points corresponding to each of the situations described below (label as a, b, c, etc). For each one, describe here what is happening with the gravitational potential energy and the kinetic energy. (For example, "Gravitational potential energy is [increasing/decreasing/zero], Kinetic energy is [increasing/decreasing/zero]".
   a. Feet on the ground, starting to push off at the beginning of a jump:

   Gravitational potential energy and kinetic energy are both close to zero, but begin increasing as kangaroo pushes off.

   b. Feet have left the ground, kangaroo is moving upward:

      Gravitational potential energy is increasing. Kinetic energy is decreasing.

   c. Kangaroo is at the very top of its jump before coming down:

      Gravitational potential energy is at a local maximum. Kinetic energy is zero.

   d. Feet on the ground, just after landing:

   Gravitational potential energy and Kinetic energy are both approximately zero. The energy must have transformed into some other form at this point.

4. During which parts of the kangaroo's motion (if any) does the sum of gravitational potential energy and kinetic energy stay relatively constant? Why do you think this is the case?

   The sum of gravitational potential energy and kinetic energy stay relatively constant whenever the kangaroo is not in contact with the ground.

5. During which parts of the kangaroo's motion (if any) does the sum of gravitational and potential energy change significantly? Where do you think the energy is going during these times?

When the ball contacts the ground, the sum of gravitational potential energy and kinetic energy is close to zero. The energy must have transformed into some other form at this point.

We can speculate that some energy is stored as elastic potential energy in the kangaroo's muscles or tendons, and some energy has transferred to the environment through heat dissipation of the formation of sound waves. (Day 3 of our Kangaroo Locomotion case study will explore some of these possibilities in more detail through analysis of metabolic energy expenditure during kangaroo locomotion.)

6. How does the total mechanical energy (gravitational + potential) while the kangaroo is in the air change from one hop to the next? How does this compare with what you observed for a bouncing ball in the previous video analysis lab? (Compare with your graphs from the bouncing ball lab in your notebook and describe at least one similarities or differences you notice.)

In contrast to the bouncing ball, the total mechanical energy does not steadily diminish from one bounce to the next. Instead, it goes up and down a little bit, but remains fairly constant.

7. **Energetics and motion of living and nonliving systems.** Fill in the table below, describing your observations from video analysis of the bouncing ball and the kangaroo, in order to identify similarities and differences between the two. I've filled in one row as an example. Choose additional features of the motion or features of the mechanical energy to describe in the remaining rows.
   Sample responses included as an example:

Feature	**Bouncing ball**	**Hopping kangaroo**
Vertical motion while off the ground	Moves upward quickly at first, then slows down, and starts falling back toward the ground	Moves upward quickly at first, then slows down, and starts falling back toward the ground
Gravitational potential energy while off the ground	Increases on the way up, decreases on the way down	Increases on the way up, decreases on the way down
Kinetic energy while off the ground	Decreases on the way up, increases on the way down	Decreases on the way up, increases on the way down

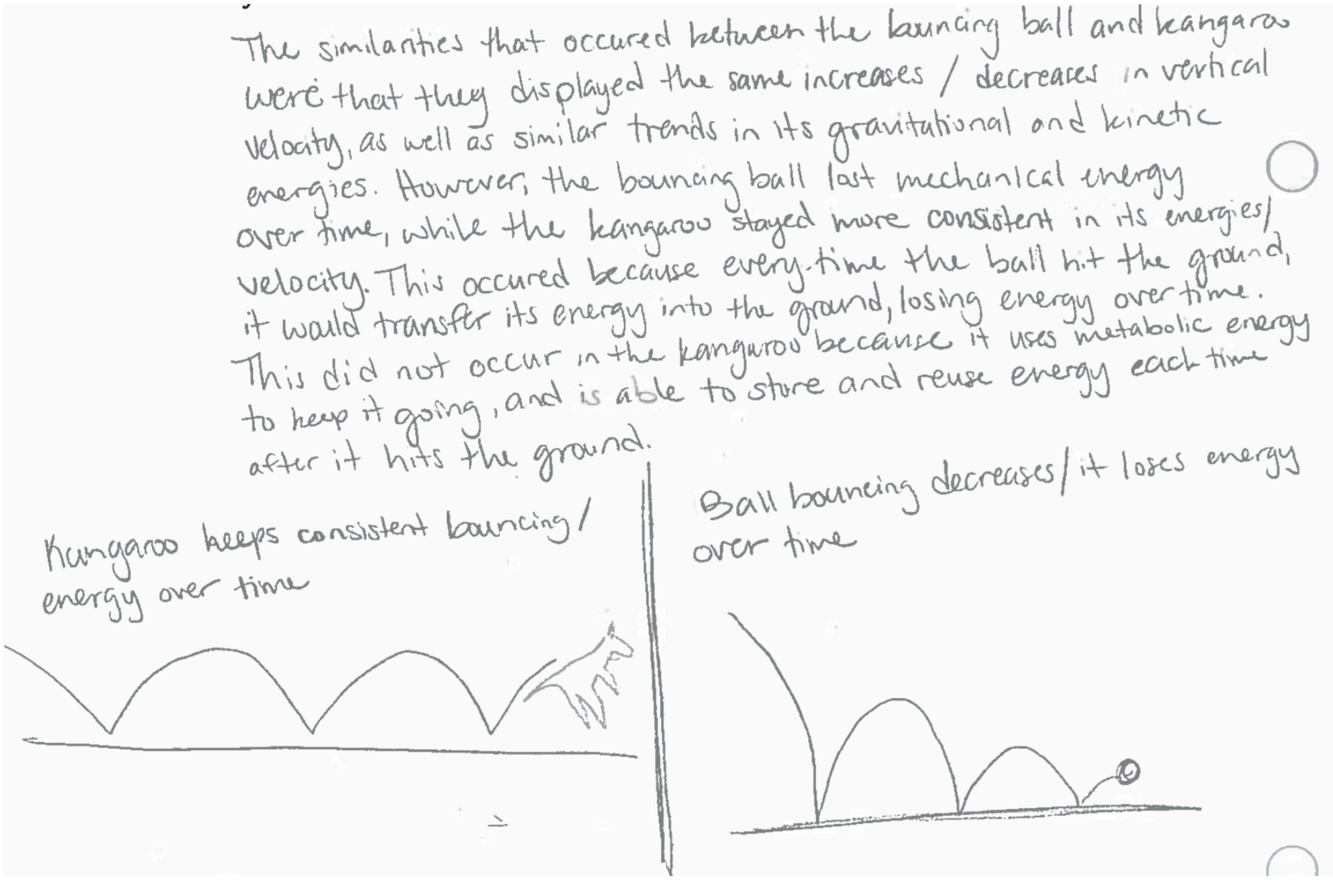
Total mechanical energy while off the ground	Changes forms between kinetic energy and gravitational potential energy, while the sum of the two stays fairly constant	Changes forms between kinetic energy and gravitational potential energy, while the sum of the two stays fairly constant
Total mechanical energy from one bounce to the next	The total mechanical energy gets smaller and smaller each time the ball rebounds.	The total mechanical energy stays fairly constant from one bounce to the next.

8. Based on the features described in your comparison table above, and your answers to the other discussion questions, write a short paragraph summarizing key similarities and differences in the energy transformations and energy transfers that take place for the bouncing ball and the hopping kangaroo. Can you think of any explanations that might account for these differences? You are encouraged to support your reasoning with words, sketches if applicable, and information from your data.

Sample student response:

Like the bouncing ball, the motion of the kangaroo maintains parabolic motion. Unlike the ball, however, the kangaroo maintains the level of total energy present in the system. This is because the kangaroo was able to store long-term energy in its leg tendons, giving the kangaroo incredible distance-hopping ability.

Another sample student response:


The similarities that occured between the bouncing ball and kangaroo were that they displayed the same increases / decreases in vertical velocity, as well as similar trends in its gravitational and kinetic energies. However, the bouncing ball lost mechanical energy over time, while the kangaroo stayed more consistent in its energies/velocity. This occured because every time the ball hit the ground, it would transfer its energy into the ground, losing energy over time. This did not occur in the kangaroo because it uses metabolic energy to keep it going, and is able to store and reuse energy each time after it hits the ground.

For analyzing student dialogue, teachers may choose to utilize a Quantitative Literacy Assessment Rubric (Boersma et. Al)

Boersma, S., Diefenderfer, C., Dingman, S. and Madison, B. 2011. Quantitative reasoning in the contemporary world, 3: Assessing Student Learning. Numeracy, 4 (2)., https://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=1080&context=numeracy (accessed February 28, 2020).

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