Greg Kennedy
innovative juggler

Study Guide

Kinetics: The Physics of Juggling

Can anything be fun about the study of physics? Will we ever use these things in our real lives?

If you are juggler Greg Kennedy, the answer to both of these questions is emphatically yes. Greg, whose mind for logic and science led him first to a career in engineering, has discovered the pleasure and challenge of creating performance art using the fundamental concepts of physics. His juggling shows, which are as mind-boggling as they are entertaining, illustrate the principles of motion, light, energy and of course, gravity. But they also illustrate something else: that determination and imagination can turn an academic pursuit into a powerful art form.

Sit back and enjoy Greg's show, which includes pieces that have won him international awards and acclaim from his peers in the juggling community. And in this Study Guide, take in some of the concepts that have guided his work.

About Greg (the Bio)

In an effort to change people's preconceptions about juggling, Greg Kennedy fuses logic and creativity to synthesize new forms of juggling manipulation. In the early 1990's, Greg spent several years working as a professional engineer, in addition to his juggling career. His fascination with the geometry and physics of object manipulation led him to ground-breaking work with original apparatus, expanding the realm of juggling. "He is a visionary who can see the possibilities in props and movement that are obscure to the masses," writes Bill Giduz, Jugglers World magazine.

Twice Greg has entered the highest-level juggling competition, the International Jugglers Association Championships. On both occasions he received their highest honor, the Gold Medal. In 1996, his original presentation of "Hemisphere" won him first place in the Individuals competition, taking Gold. In 2002, he returned, combining efforts with partner Chris Ivey, and as the duo "Saccade" won Gold again in the Teams competition.

Greg continues to receive praise and recognition from his peers for his original contributions, broadening the fields of juggling and performance art. He presently balances his performing career with a pursuit of juggling innovation, experimenting with new shapes and surfaces as well as practicing traditional skills.

Physics and Juggling

While watching juggling, it's easy to be mesmerized by the movement and forget that the demonstration can be viewed as a lesson in physics. From the simplest throw and catch of one ball, a multitude of concepts of Newtonian mechanics can be derived. Once you add to that the inventive forms, surfaces and objects reacting together included within this show and a whole array of lessons is covered in brief. Here is a partial list of just some of the concepts utilized in the performance:

- Gravity
- Angle of Rebound
- Elliptical Movement
- Pendulum Movement
- Centripetal Acceleration
- Gyroscopic Stability
- Light Refraction
- Spectral Dispersion

As you can see this program touches on most concepts of a first year Physics course. The performance can simply be viewed as live demonstration of physical properties.

Gravity (of course!)

Definition

Gravity is the force of attraction between all masses in the universe; especially the attraction of the earth's mass for bodies near its surface. It is gravity that causes all objects to be pulled downward toward the ground (or more specifically towards the center of the earth).

Equation

Two bodies of matter attract each other proportionally to their masses and inversely proportional to the square of distance between them. If the mass of one body is designated as **M**, the mass of the other as **m**, the distance between them is **r**, and **G** is the universal gravitational constant, then the force of attraction between the two bodies is:

$$F = G \frac{Mm}{r^2}$$

What the universal gravity equation says is that as two objects are attracted and get closer together, the force increases and the acceleration between them also increases. Since the mass of the earth is so much greater than everyday objects, and the distance from the center to the surface of the earth is approximately the same anywhere on the earth's surface, differences in an object's mass and height become negligible.

Because of this, the acceleration of gravity on everyday objects here on earth is constant and predictable!

Wow, that seems really complex, no wonder it is so hard to juggle! Actually, all the math simply states the opposite. Although it may look really confusing, what all those numbers mean is that an object which is thrown acts in a predictable manner. What goes up, must come down!

How does this affect my juggling? I can predict the position time and speed of exactly how the balls will fall back down, and how they will travel in the air when I throw them. This enables me to track multiple objects in the air, creating many different types of juggling patterns.

Sometimes I juggle different objects of different masses, but they still all accelerate back down at the same rate. Do you know why?

Angle of Rebound

Definition

Rebound is the reversal in direction of an object upon encountering a barrier. The object approaches along an *angle of incidence* and rebounds along an *angle of reflection*. The angle of incidence, θ_i is the angle measured from the incoming direction of the object to a line drawn normal (90 degrees) from the surface. The angle of reflection, θ_r is the angle measured from the line drawn normal to the surface to the outgoing direction of the object.

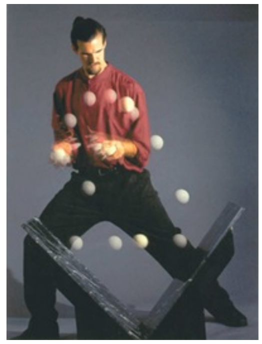
Equation

The law of reflection states that the angle of reflection and angle of incidence are equal.

$$\theta_r = \theta_i$$

Because of this, one can accurately predict how a ball will rebound from a surface based on the angle at which it approaches. To change where the ball will end up, you simply have to change the point which it starts.

I use these concepts in a bounce ball routine. I created it after accidentally breaking a marble slab in half.



It uses two rigid surfaces placed in a V-shape 90 degrees from one another and each 45 degree angles from the ground. Multiple balls are bounced off the surfaces, creating different visual patterns.

I used the physics above to help me create my routine, predicting how the balls would travel upon collision with the surfaces. An interesting aspect of this shape is that when I throw a ball straight down one foot right of center, after two ricochets it will come straight up one foot left of center. Can you predict that with the equation above?

Elliptical Motion

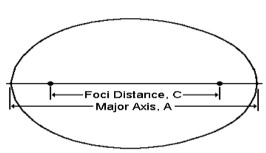
Definition

An ellipse is an oval. At any point on the arc, the sum of the distances to two distinct focus points is always the same. Johannes Kepler developed laws which described the motion of the planets across the sky. He showed that all planets move in elliptical orbits, with the sun at one focus.

Equation

Every ellipse has an *eccentricity,* ***e*** which describes how elongated it is and how far apart the two focus point are. The eccentricity of an ellipse (ranging from 0 to 1) can be defined as the ratio of the distance between the foci, ***C*** to the major axis of the ellipse, ***A***. The eccentricity is zero for a circle and near one for an elongated ellipse.

$$e = \frac{C}{A}$$



An ellipse can be approximated by rolling a ball on the inside surface of a sphere. Depending on the ball's initial speed and direction, the ellipse varies in eccentricity. A ball rolled quickly to one side at the rim will have a low eccentricity being very close to a circle. One rolled only slightly to the side will have a very high eccentricity and be oblong.

In 1995 I started experimenting with rolling patterns of multiple objects on the inside surface of a half sphere. I was very methodical about documenting different elliptical paths a single ball could travel and then using mathematics to derive different patterns which were possible with multiple balls, not all of which I was able to learn.

I spent hundreds of hours over the next year developing a routine. I found that using the surface gave me much more control than traditional toss juggling and enabled me to do many more objects (up to ten), but in such a small space collisions are common. Do you think it's easier to eliminate collisions with high eccen-tricity ellipses or low eccentricity ellipses? Why?

Simple Pendulums

Definition

A simple pendulum is a weight suspended from a string or rod of negligible mass. It has a single resonant frequency, which means it repeats its action after a set amount of time. It will swing out, then back, then repeat itself.

Equation

The period ***T***, the time it takes for the pendulum to repeat itself, of such a pendulum can be approximated in the equation:

$$T = 2\pi\sqrt{L/g}$$

where ***L*** is pendulum Length, ***g*** is the acceleration of gravity, and ***π*** is constant (3.1415). Notice that if the pendulum length is fixed, and gravity does not change, the period does not change. This means a pendulum which is swinging high will take the same amount of time to swing out and back as one that is swinging low.

Using this idea I can accurately predict the time for a set length pendulum to return to me after releasing it. It does not matter if I release it far from the suspension point or very near, it will still return after the same amount of time.

One of my performance pieces involves manipulating four pendulums from a single rigging point. By swinging the pendulums in different paths, and releasing them from different heights, I can create lots of interesting patterns.

One of the new challenges of this apparatus was finding patterns which would not tangle the strings.

The pendulums I use have 13' strings. Normally I release a pendulum once per second; for the 4 pendulums, each one completes its full swing in 4 seconds. Can you see why?

Centripetal Acceleration

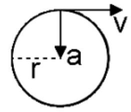
Definition

Centripetal acceleration describes objects which travel in circular paths. Newton's laws of motion and law of gravitation can be used to explain the circular motion of objects in our solar system. While moving in a circular path, an object is constantly being pulled "towards the center" of the circle away from its tangential path. The pulling force constantly redirects the object forming the circular path.

Equation

The centripetal acceleration, ***a*** is proportional to the a square function of the velocity of the object, ***v*** and inversely proportional to that of the radius of the circle, ***r***. It can be described in the following equation:

$$a = \frac{v^2}{r}$$



A simple analogy can be shown by a ball rolling inside a vertical circular track.

The ball wants to travel in a straight line fulfilling Newton's laws, but the surface of the track places an acceleration on the ball, causing it to travel in a circular path. For the ball to continue to travel in the track across the top of the circle, the centripetal acceleration must be greater than that of gravity.

I created a piece juggling on the inside surface of a vertical track. I spent a lot of time figuring out how to make the balls travel at a fast enough speed to stay in the track—and not too fast that I would lose control of them and they'd fly off. It was also important for me to keep the speed constant, so that I could work with different juggling patterns.

The ball stays in contact with the track until the velocity is low enough that the acceleration is lower than that of gravity. Then they fall out so that I can catch them. If the ball goes fast enough, it can continue around the circle multiple times before I catch it.

The track I use has a 2½ ft radius. A ball must have a minimum speed of 9 ft/sec to travel across the top of the circle. Can you predict that with the equation above?

Gyroscopic Stability

Definition

A gyroscope is a rotating object suspended in light supporting structure which isolates it from outside forces. At high speeds, the gyroscope exhibits extraordinary stability of balance and maintains its direction.

A gyroscope works because of *conservation of angular momentum*. The angular momentum of an isolated system remains constant in both magnitude and direction. What is angular momentum? A measure of the motion of a rotating object.

Equation

The *angular momentum,* ***L*** is defined as the product of the *moment of inertia,* ***I*** (the resistance of a physical object to angular acceleration) and the *angular velocity,* ***ώ*** (how fast it's spinning). Below is an equation that describes this.

$$L = I \times \acute{\omega}$$

If I increase the angular velocity of an object (which has a constant moment of inertia), the angular momentum will increase and thereby increase its stability.

The diabolo is a gyroscopic toy which was invented in China somewhere between the 4th and 3rd millennium B.C. It uses a string on sticks to support a spool which can be thrown and caught.

I first learned diabolo over 20 years ago. It still is one of my most dynamic routines and I frequently close my show with it.

The stability of the diabolo allows for a great range of movement, as long as you keep it spinning steadily. Some tricks speed the spool up. The faster it spins, the easier it is to keep in a straight path when it travels. This is especially important when I add the second diabolo.

A gyroscope has two parts: a rotating object and a light supporting structure. A diabolo also has two parts. The spool and a string on sticks. Do you see the similarities?

Light Refraction

Definition

Light will change direction when it crosses a boundary of two different substances, such as from air into glass. Snell's law gives the relationship between angles of incidence and refraction based on each substance's index of refraction.

Equation

When rays or beams strike a surface and are refracted through the surface they obey Snell's equation:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

where n_1 is the index of refraction of the first material, n_2 is the index of refraction of the second material, θ_1 is the angle of incidence, and θ_2 is angle of refraction (both measured from a line perpendicular to the boundary surface).

A glass sphere has a surface boundary with the outside air which is curved. Light rays approaching from one direction will enter the ball at different angles of incidence depending where on the sphere the light hits. For this reason the light entering from one direction will scatter to many different directions creating a sparkling effect.

I perform a slightly different form of juggling manipulation by rolling multiple glass spheres around in the palms of my hands.

The lighting effects of this piece are almost magical. A single tiny pool of light shines on my hands. As the crystal balls slide around, over, and through each other in my palms, a cascade of shimmering light is formed.

All the light comes from a single directed pin spot, yet the balls seem to be lit from within scattering light every which way. Do you know why?

Spectral Dispersion

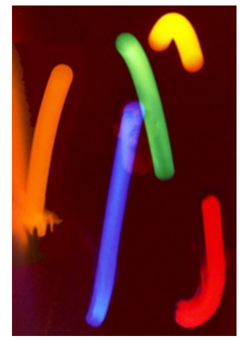
Definition

White light includes light of all colors. It may be separated into its spectral colors by dispersion in a prism. We then see the continuous range of spectral colors (the visible spectrum). Spectral diffusion is also seen in nature in the form of a rainbow. In this case it is water vapor in the air which causes the light to disperse.

A spectral color is composed of a single wavelength and can be correlated with wavelength as shown in the chart below.

White light also includes some types of light that are not visible to the human eye. Infrared light has a wavelength greater than 740 nm. Ultraviolet light has a wavelength below 380 nm. Neither of these can be seen without special instrumentation.

Recent technology improvements in LED's and lithium ion battery's have made it possible for me to illustrate spectral diffusion using juggling.



My routine starts with three white glowing spheres dancing about a darkened stage swirling and spinning creating trails of light. The three finally come together forming the triangular shape of a prism. The triangle explodes into different colors: red, yellow, orange, green, blue, violet; streaking together to form a continuous rainbow.

Each of the colored illuminated balls emits light of a specific wavelength. Using the chart above, can you find the range of wavelengths for each color?

Final Note From the Artist

The subject matter of this study guide may be used in conjunction with your present physics lesson plan or as a separated program to inspire future interest in physics. I feel one of the best ways to learn and generate interest is through live demonstrations of the concepts, as I provide in my program.

I hope this guide and show program helps your group in this pursuit of learning. Enjoy the show!