January 2011

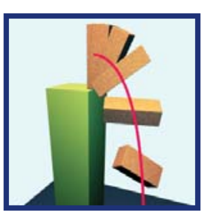
http://www.algarcia.org/AnimationPhysics/BalanceTutorial.pdf

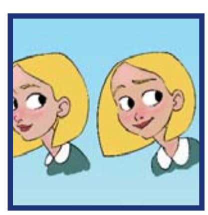
"We come into this world head first and go out feet first; in between it is all a matter of balance."

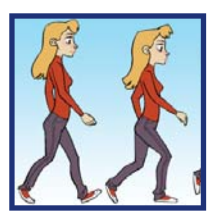
Paul Boese

Physics of Balance & Weight Shift

This tutorial helps you create realistic poses for your characters by showing you the basic principles of balance. You'll also see how weigh shift affects a pose and what makes an action pose dynamic.







Character Design

► Establishing balanced poses for your characters is an important stage in the design process. You don't want a standing character to look like it's about to tip over (unless it's supposed to).

So how do you know that a character's pose is in balance?

Consider these various poses; which ones are in balance and which ones are not. How can you tell the difference? Is the character's weight correctly reflected in the pose?

Understanding the principles of balance is equally important in visual development and for animation since stationary characters and objects in a scene need to be in balance.

Balance is not the same as symmetry and symmetry is not the same as balance.

The principles of balance also apply to moving characters, which need to be in or out of balance in a way that's consistent with how they're moving.

Center of Gravity

► The average position of an object's weight distribution is called the center of gravity (CG).

For simple, solid objects, such as a baseball or a brick, the center of gravity is located at the geometric center.

If an object does not have a uniform weight distribution then the center of gravity will be closer to where most of the weight is located.

For example, the center of gravity for a hammer is located close to where the head connects to the handle.

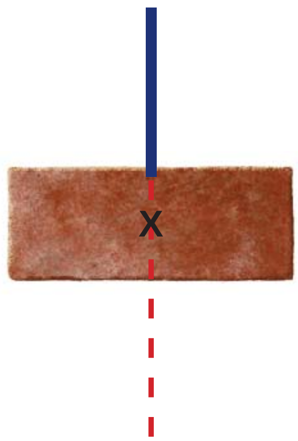
The center of gravity can be located at an empty point in space, such as the center of a hollow ball.

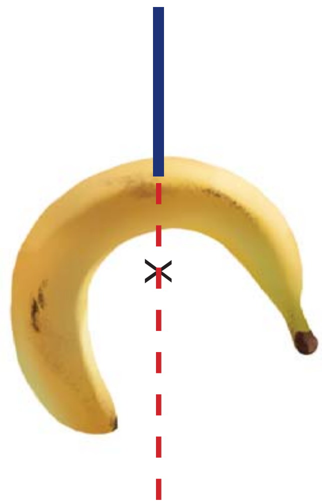
The center of gravity can even be completely outside of an object, such as for a donut or a curved banana.

Note: **Center of gravity is the same as the center of mass when the strength of gravity is constant, as it is on Earth.**

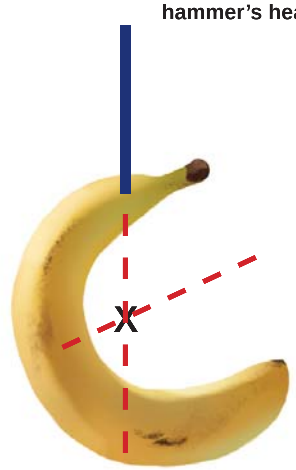
Locating the CG by Suspension

► One way to locate an object's center of gravity is by means of suspension. An object always hangs such that the CG is directly below the point of suspension.





The center of gravity of the hammer is located inside the handle close to the hammer's head.



Suspension from a single point is not enough to locate the center of gravity, it only tells you that the CG is somewhere below the point of suspension. But hanging the object from a second point lets you to find the CG by triangulation.

These photos show a doll, in various action poses, suspended from a variety of points. Notice how the position of the CG depends on the orientation of the arms and legs.

In this U-shaped pose the CG is located outside the body, at about the height of the pelvis.

With the arms raised the CG shifts higher in the body.

The doll has a hollow head so its CG is located a bit lower in the body than for a human.

Locating the CG by Support

Question: What's the easiest way to balance a donut on your finger?

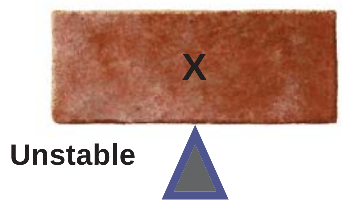
Answer: Put your finger through the hole so that the CG, located at the center of the donut, is below your finger.

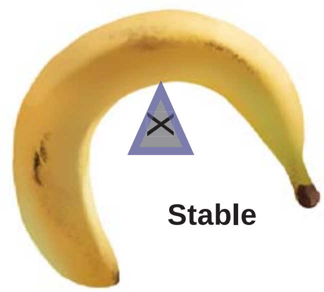
► Another way to locate an object's center of gravity is by means of support. An object will balance on a pivot point when the CG is exactly above or below that pivot point.

If the pivot is *below* the CG then the balance is *unstable*; any slight rotation causes the object to tip and fall off the pivot.

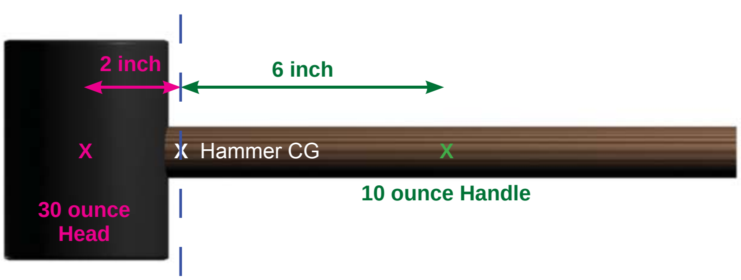
If the pivot is *above* the CG then the balance is *stable* and a slight rotation makes the object just swing back and forth.

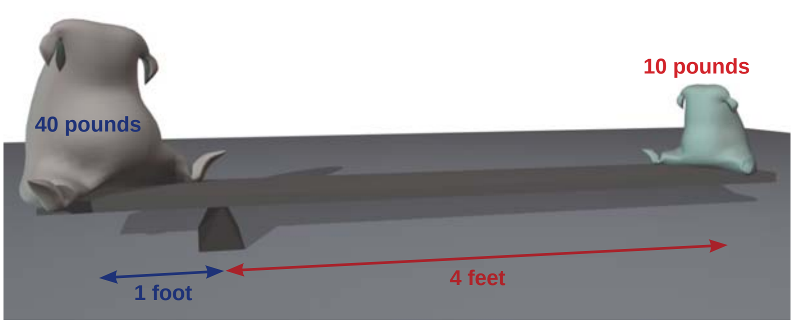
The toy bird above balances stabily on the tip of its beak. The wing tips are weighted so that the center of gravity is located just below the bird's beak.





The center of gravity is proportionally closer to where most of the weight is located, as in the hammer shown here.

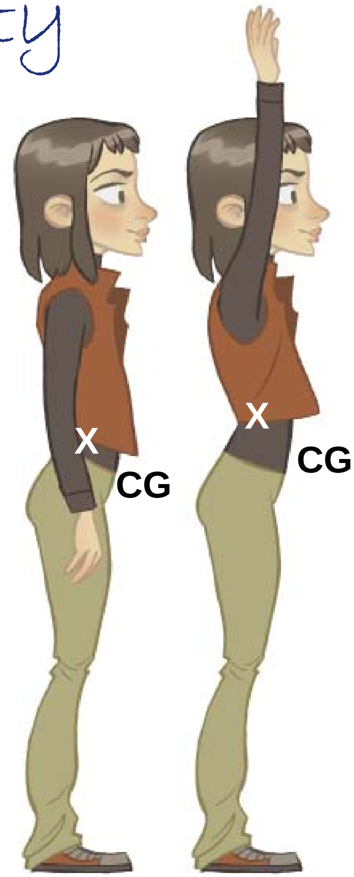




Locating the center of gravity by pivoting on a support is based on the same principle as a balance scale. The scale will balance when the leverage is the same on each side.

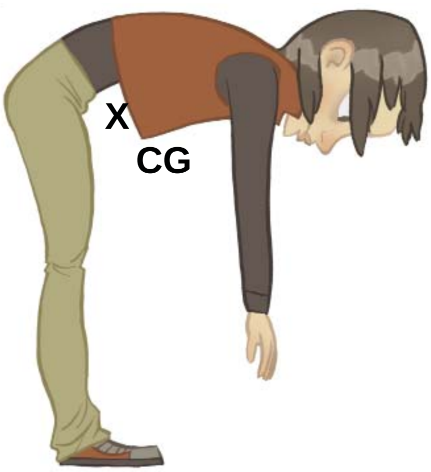
Human Center of Gravity

► Standing upright, an adult human's center of gravity is located roughly at the center of their torso at about the height of the belly button (at about 55% of the total height).

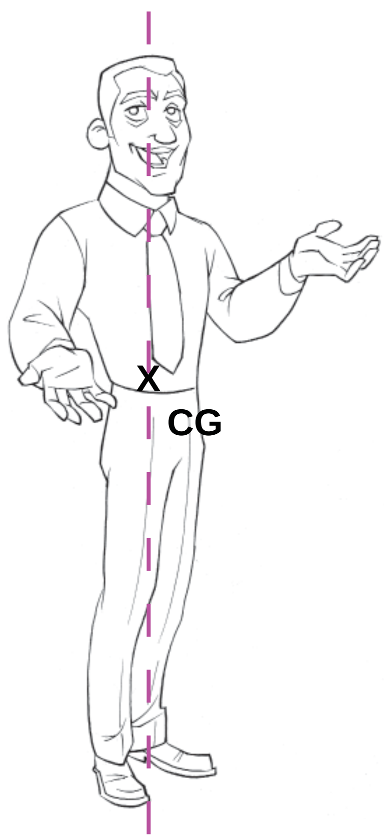


The exact location of a character's center of gravity will shift depending on the pose. For example, this character's CG rises a few inches when she raises her arms.

The center of gravity can even be at a point outside the body, such as when bent over in an inverted-U pose.

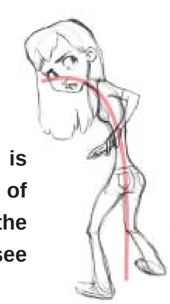


The *line of gravity* is an imaginary vertical line that extends upward and downward from an object's center of gravity.

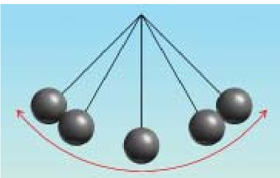


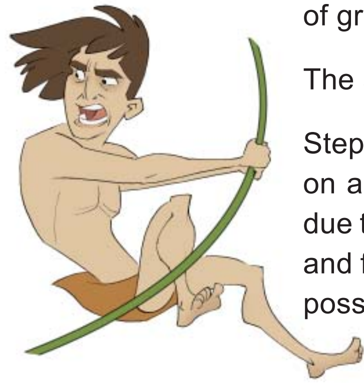
When a person is standing fairly straight, the line of gravity can be considered to be a plumb line that passes through the pit of the neck.

Note: **Line of gravity is *not* the same as the line of action, which indicates the dynamic, visual curvature of a pose (see the *Physics of Paths of Action* Tutorial).**



Falling & Tipping





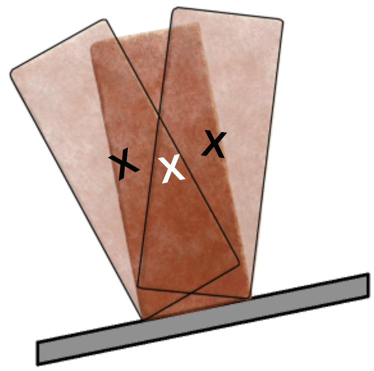
► One way to understand balance is from the fact that if nothing prevents a stationary object from lowering its center of gravity then it will move in order to do so.

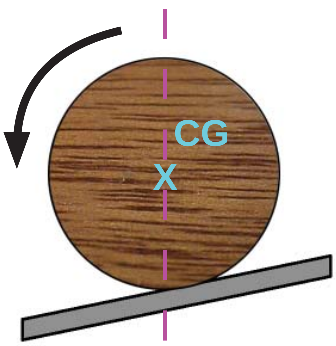
The simplest example is when you drop a ball, it falls.

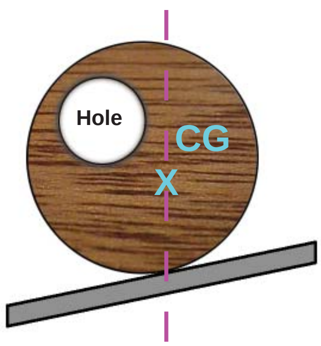
Stepping off of a high tree branch, Tarzan swings downward on a vine. The motion may continue past the lowest point, due to follow-through (inertia), but if he keeps swinging back and forth he'll eventually come to rest with the CG as low as possible (right under the point of suspension).

This simple principle, that an object will generally move so as to lower its center of gravity, helps you predict balance.

We know that this brick, sitting on a ramp, is in balance since a rotation to either side would raise the center of gravity.







A solid wheel goes downhill since rolling lowers its center of gravity.

On the other hand, this wheel with a hole that's off-center does not roll downhill since that rotation actually lifts the center of gravity.

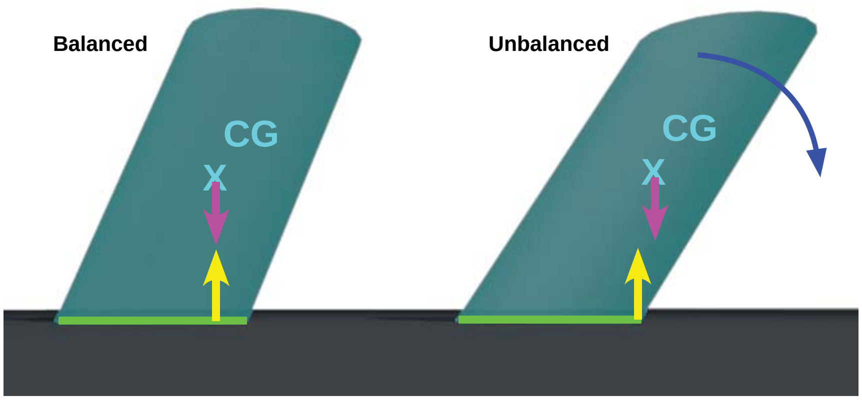
Question: **In these photos you see one of my favorite demonstrations in which a hammer is attached to a hinged board. The photo on the left looks normal but how is it that in the right photo we see the hinged board in the raised position (it even supports a small weight placed on top of the board)?!**

Answer: **The CG is located near the head of the hammer. On the left, the CG is at its lowest position with the board down. On the right, the CG is at its lowest position with the board up; in this case the CG gets lifted if the board angles downward.**

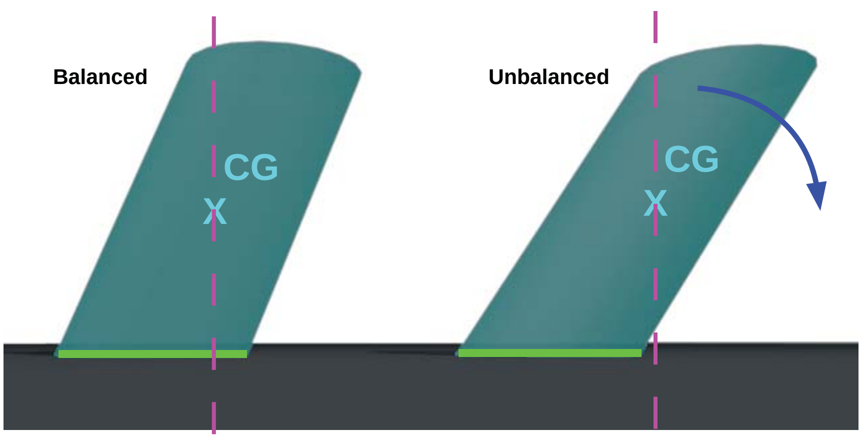
Base of Support

► An object is in balance if its center of gravity is above its base of support.

For the two cylinders below, the left cylinder's CG is above the base of support so the upward support force from the base is aligned with the downward force of gravity.



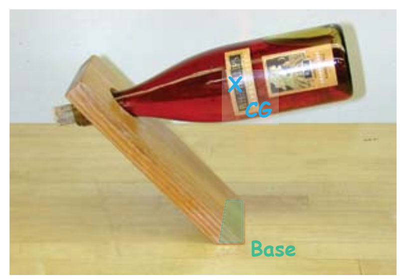
For the cylinder on the right the CG is not above the base of support so these two forces cannot align and instead create a torque that rotates the object, tipping it over.



The line of gravity helps you determine balance; if it passes through the base of support then the object is in balance.

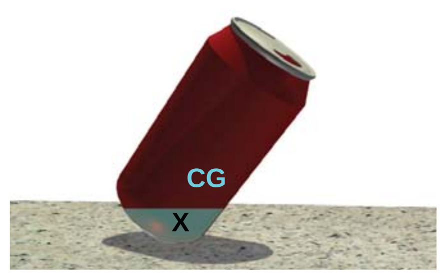
If the line of gravity touches the ground at a point outside the base of support then the object will tip over.

The base of support for these tilted cylinders is the area where they are in contact with the floor.

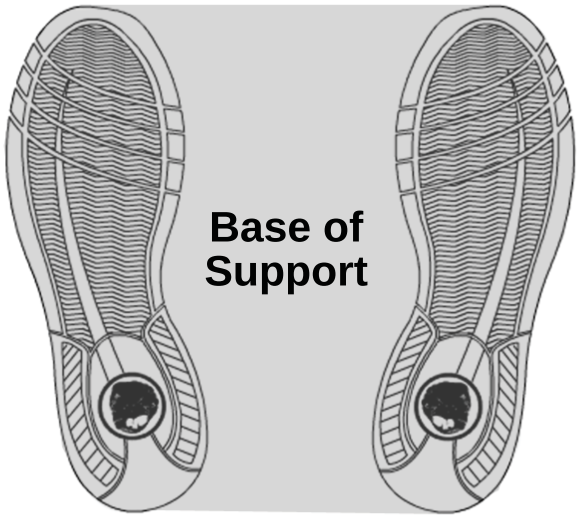


This wine bottle holder is stable because the CG is right over the base of support.

Pour a small amount of water into an empty soda can and you can stand it on its beveled edge.

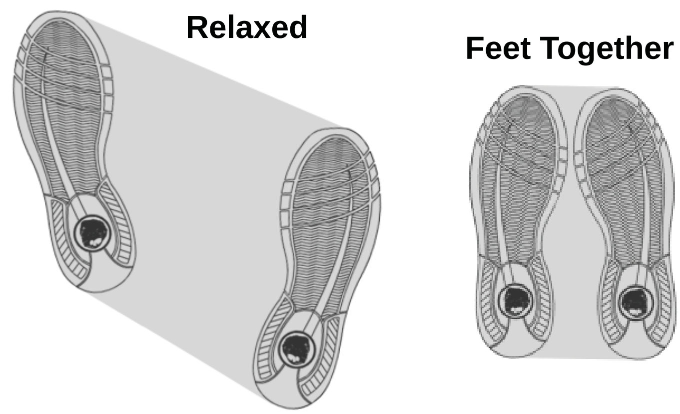


Human Base of Support

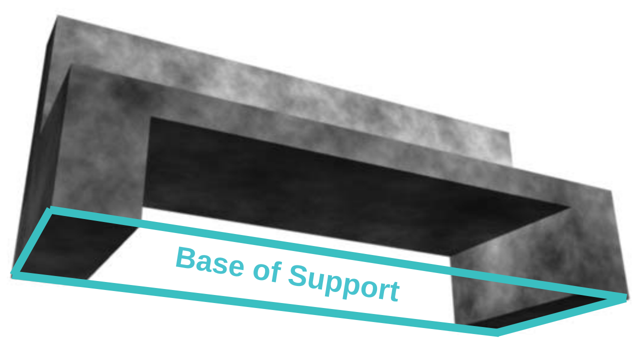


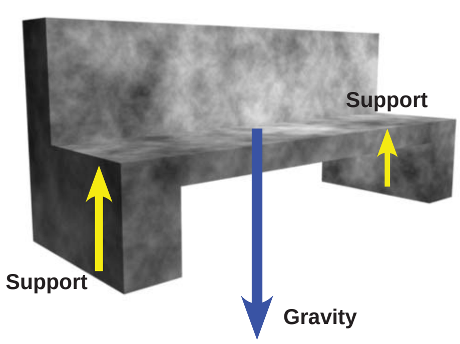
► Standing upright, your base of support is the area under your feet (or shoes) *including* the area between your feet. Roughly speaking, this area is traced from toe to toe and from heel to heel.

By moving your feet you can an increase or decrease the area of your base of support. The larger the base, the easier it is to keep center of gravity above it and stay in balance.



When an object has multiple bases of contact with the ground (e.g., two feet), the base of support is the entire area that surrounds all the points of contact.





The upward support forces from the two legs of the bench can balance the downward force of gravity (weight).

Balanced Character Poses

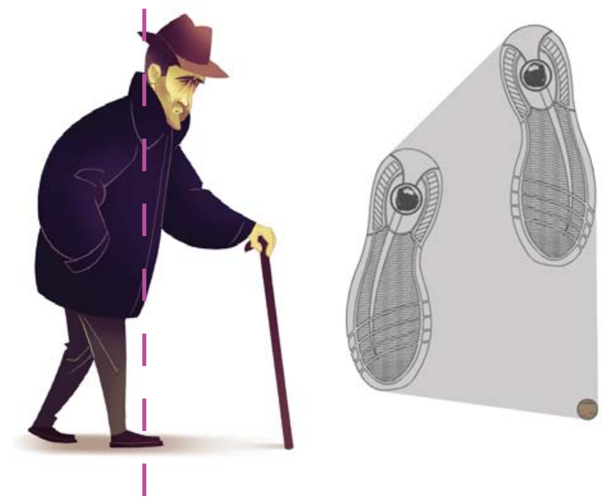
► To determine if a pose is in balance, first estimate the character's center of gravity. If the line of gravity (the vertical line extending down from the CG) passes through the base of support then the character is in balance.

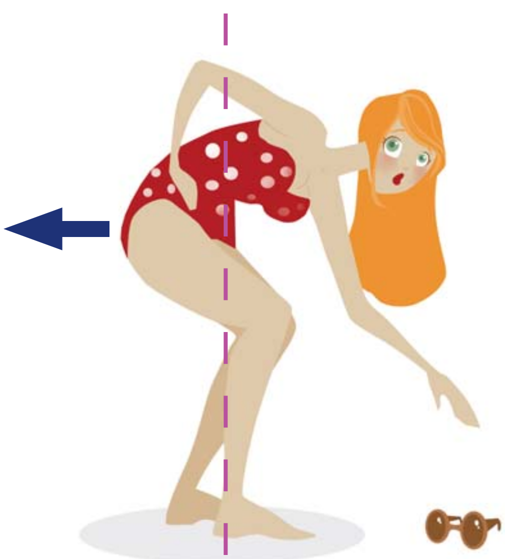
The lumberjack character is top-heavy; his CG is roughly in the center of his chest (and a bit forward since his large arm is extended forward).

The base of support is traced as the area from toe to toe and from heel to heel, and around the outer edge of each foot.

The pose on the left appears to be balance while the pose on the right seems unbalanced.

Although the old man on the right is leaning forward, the pose is in balance because the base of support is expanded due to the third base of contact, the cane.





As this character leans forward to pick up her sunglasses, in order to maintain her center of gravity above her feet she instinctively moves her lower torso backwards.

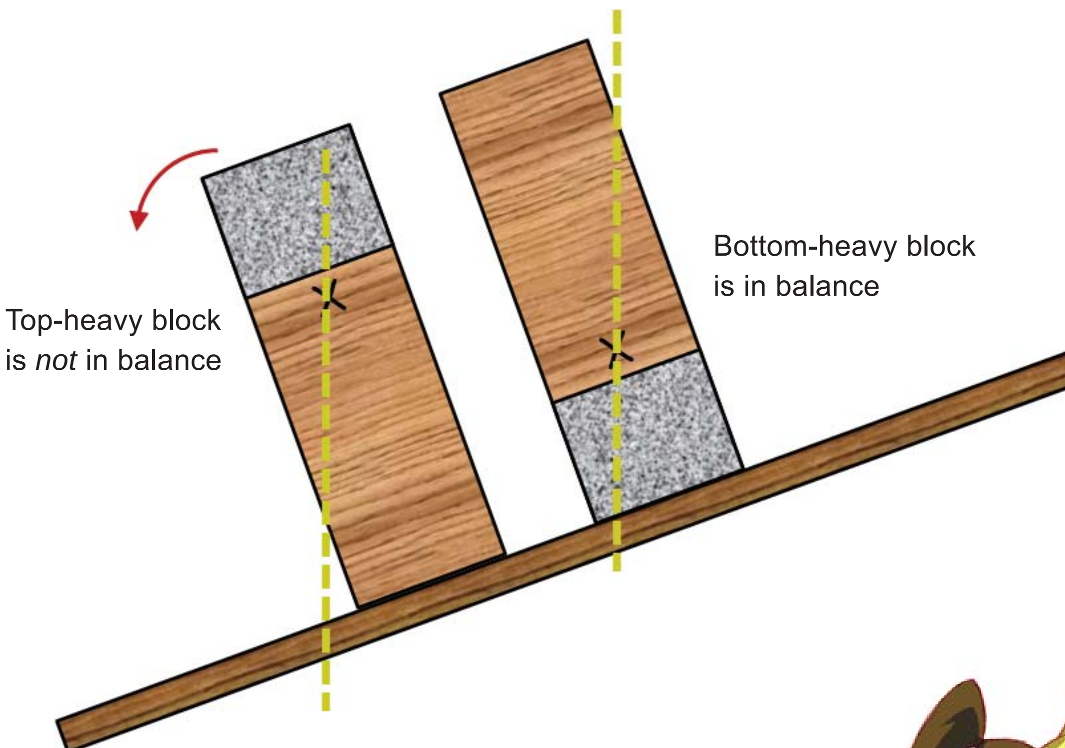
To understand this motion, try the following demonstration: Stand with your heels touching a wall and try to bend forward as if you were picking up an object from the floor. You probably won't be able to bend more than half-way down before you tip over.

Balance and Height

► The higher the center of gravity, the more likely that an object will be out of balance.

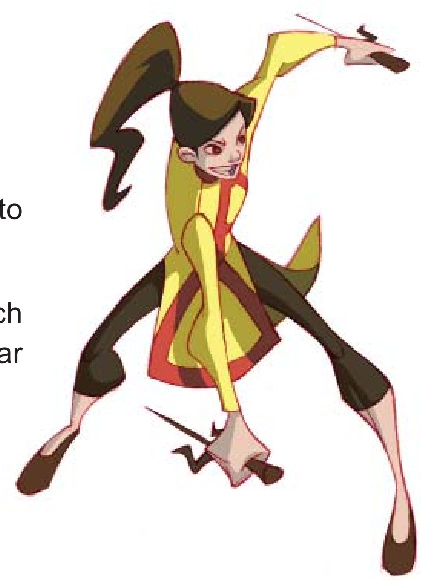
Take two similar blocks on an incline, as shown below. The first block is top-heavy so at the angle it's tilted the line of gravity is not over the base of support. That block tips over.

The other block is bottom-heavy, which positions the center of gravity over the base of support, making it stable.

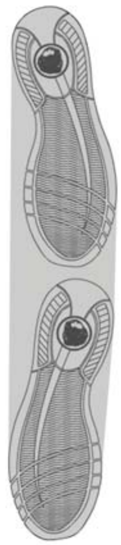


For maximum stability, this character's feet are wide apart to make her base of support as large as possible.

She is also crouching to lower her center of gravity, which makes her more stable because her CG doesn't move as far when she tilts from side to side.

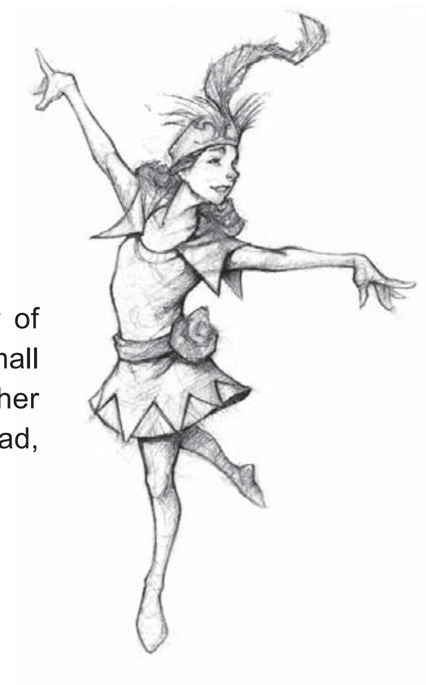


Staying in Balance

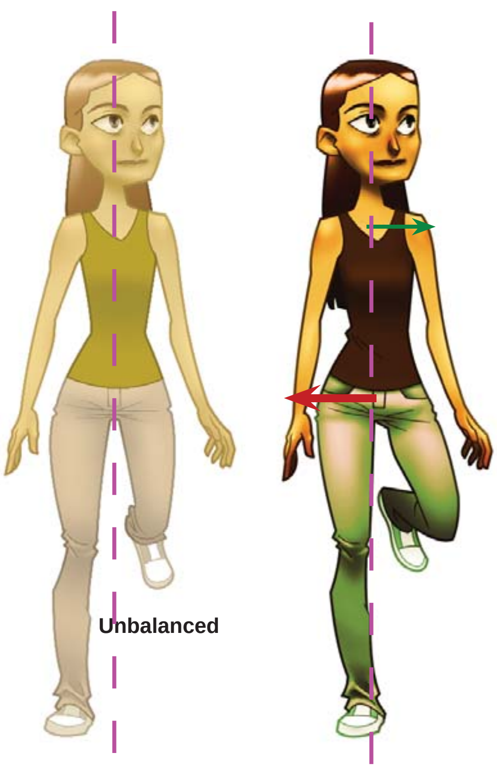


► Staying in balance is difficult when the base of support is small. In such cases you instinctively move the rest of your body to adjust the location of your center of gravity.

For example, balance is difficult with one foot in front of the other because the base of support is narrow. Holding your arms out lets you easily shift your center of gravity from side to side, keeping it over your base of support.



The ballerina needs to keep her center of gravity above her toe, which is a very small base of support. She can quickly shift her CG by moving her arms (as well as her head, torso, and back leg).



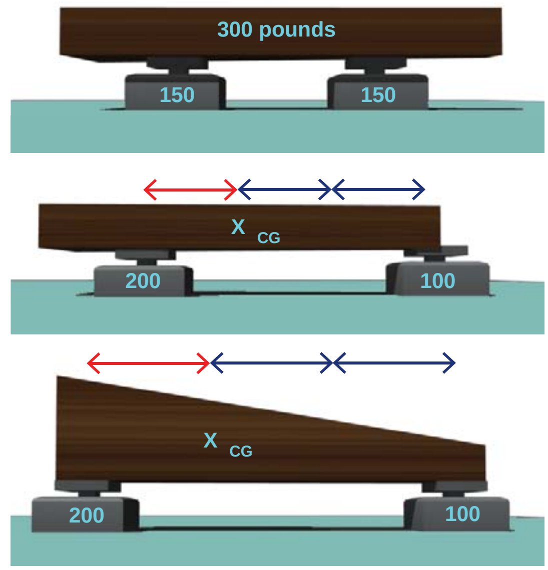
While standing on two feet, try quickly raising one leg. You'll lose balance since the center of gravity will not be above the base of support (the foot on the ground).

To balance on one foot you need to shift your center of gravity over that foot and this is most easily done by shifting your hip to that side.

However notice that as you shift your lower torso to one side your upper torso tends to shift a bit to the other side so that your momentum doesn't cause you to tip too far sideways.

Weight Shift

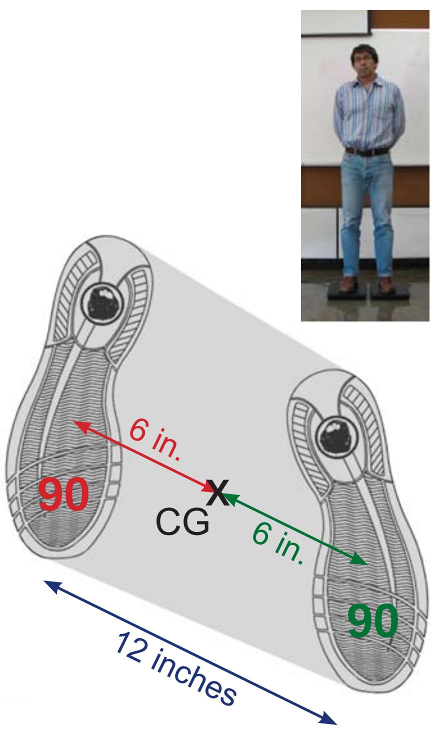
► Weight shift occurs if the center of gravity is positioned such that one leg bears more weight than the other. Weight shift is important since it affects a character's pose.



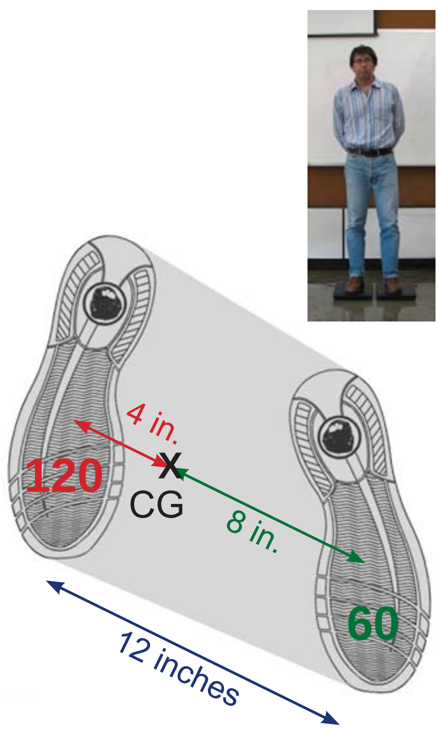
When the center of gravity is an equal distance between two supports then each support bears equal weight. However, if one support is closer to the CG then it supports proportionally more weight than the other.

Likewise, if the center of gravity is closer to one support than the other then the support closest to the CG bears greater weight in proportion to the ratio of the distances.

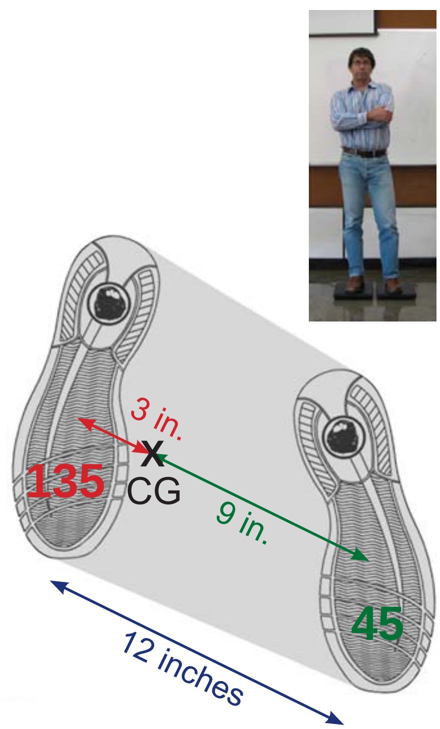
When a 180 pound person stands in a pose that positions the CG an equal distance between the feet then each foot bears 90 pounds of the character's weight. But a shift of the center of gravity to one side adds weight to that foot; even a small shift of the CG causes a significant weight shift.



Equal weight on each foot

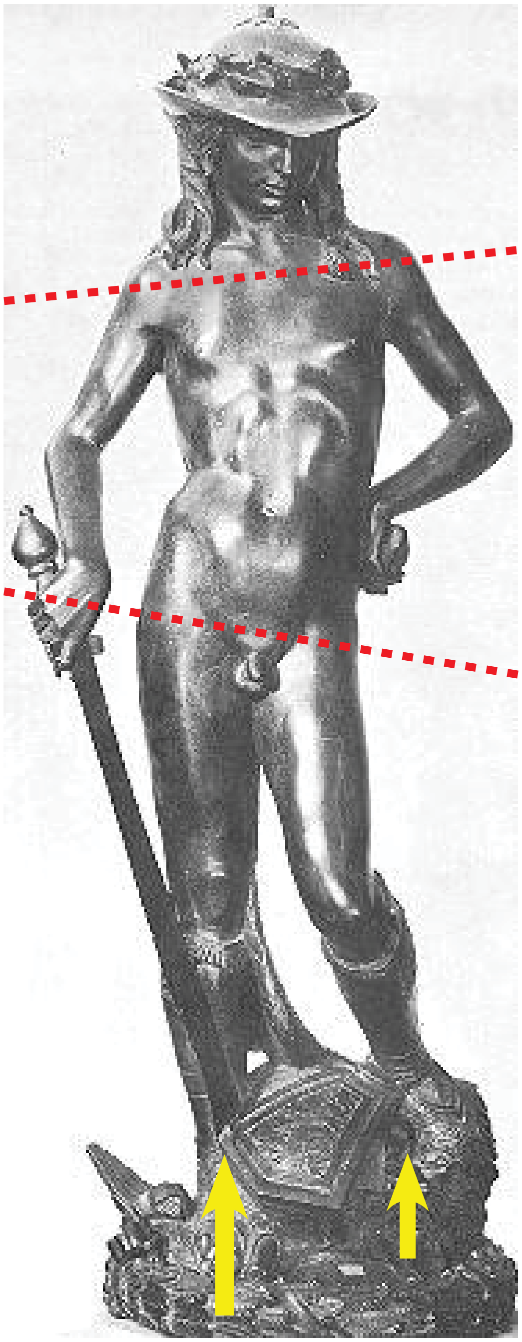


2-to-1 ratio of weights



3-to-1 ratio of weights

Contrapposto



Donatello's *David* (circa 1440s)

► Contrapposto is the term used to describe poses in which a character stands with most of its weight on one foot so that the shoulders and hips tilt toward that side.

Glenn Vilppu writes, "By simply shifting the weight to one leg, we automatically create a curve in the torso, as we generally shift the rest of the torso to compensate. This shifting doesn't stop there, but extends to the neck and head, going up, which tends to move in the opposite direction again."

The introduction of contrapposto dates back to the fourth century B.C. and is credited to the classical Greek sculptor Polykleitos. It is very prevalent in the work of Renaissance artists, such as Donatello and Michelangelo.

Standing on one foot is an extreme example of a contrapposto pose.

Standing versus Sitting

► The natural pose for a character will vary depending on whether the character is standing or sitting since the weight shifts are different.


Michelangelo's *David* (1504)

As seen in the photo on the right, weight shift in a contrapposto pose is evident even if only the upper body is visible.

So even if you are only drawing a character's upper body, be conscious of the entire body and how the pose varies due to weight shift.

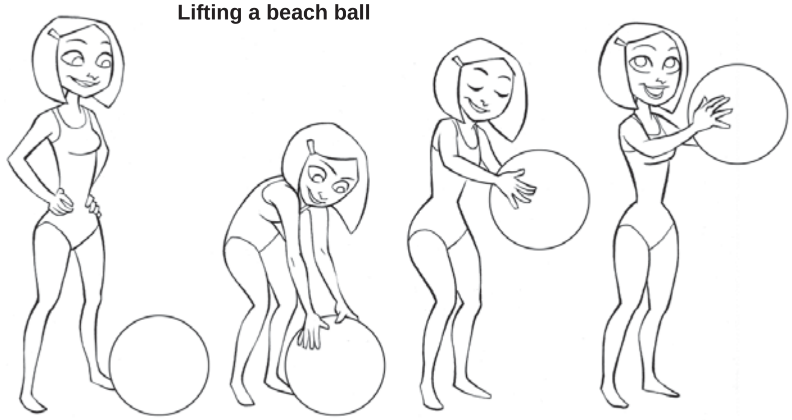
Likewise, when animating a medium shot in which only the characters' upper body is in frame you still need to be thinking about the whole body.

The characters shown here are highly stylized and cartoony yet they retain appeal because their poses look natural.

Lifting and Carrying a Weight

► Animating a believable lift requires poses that convey the weight of the object being lifted as well as the weight and strength of the character picking it up.

Lifting a beach ball



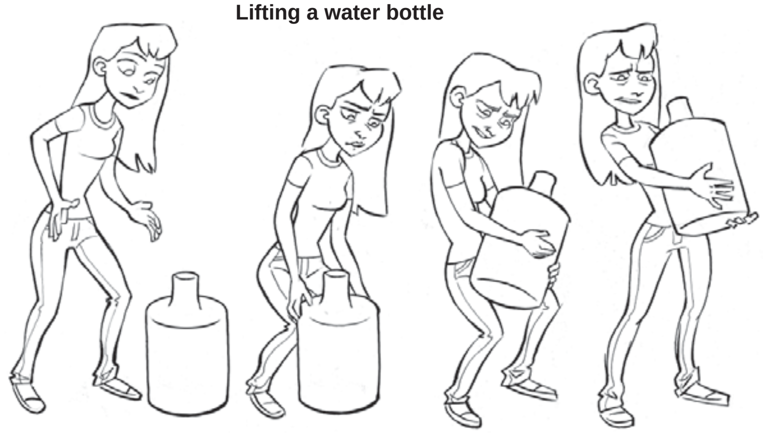
In this first example the object feels light as a beach ball. The lack of weight is indicated by how the character is posed holding the ball in her arms, away from her body.

If the ball was very heavy then the center of gravity of her plus the ball would be located in front of her toes. In that case, no matter how strong she is, she'd fall forward (imagine her as a statue holding a heavy, solid ball).

The lift shown on the right conveys that the water bottle is heavy. The character does not extend her arms away from her body and she also uses her legs to help lift.

Regardless of her strength, she needs to keep the heavy bottle close to her body so as to keep the total center of gravity (her plus the bottle) located over her base of support (her feet). She also leans backwards for the same reason.

Lifting a water bottle



The hiker's pose on the left suggests that his pack is light.

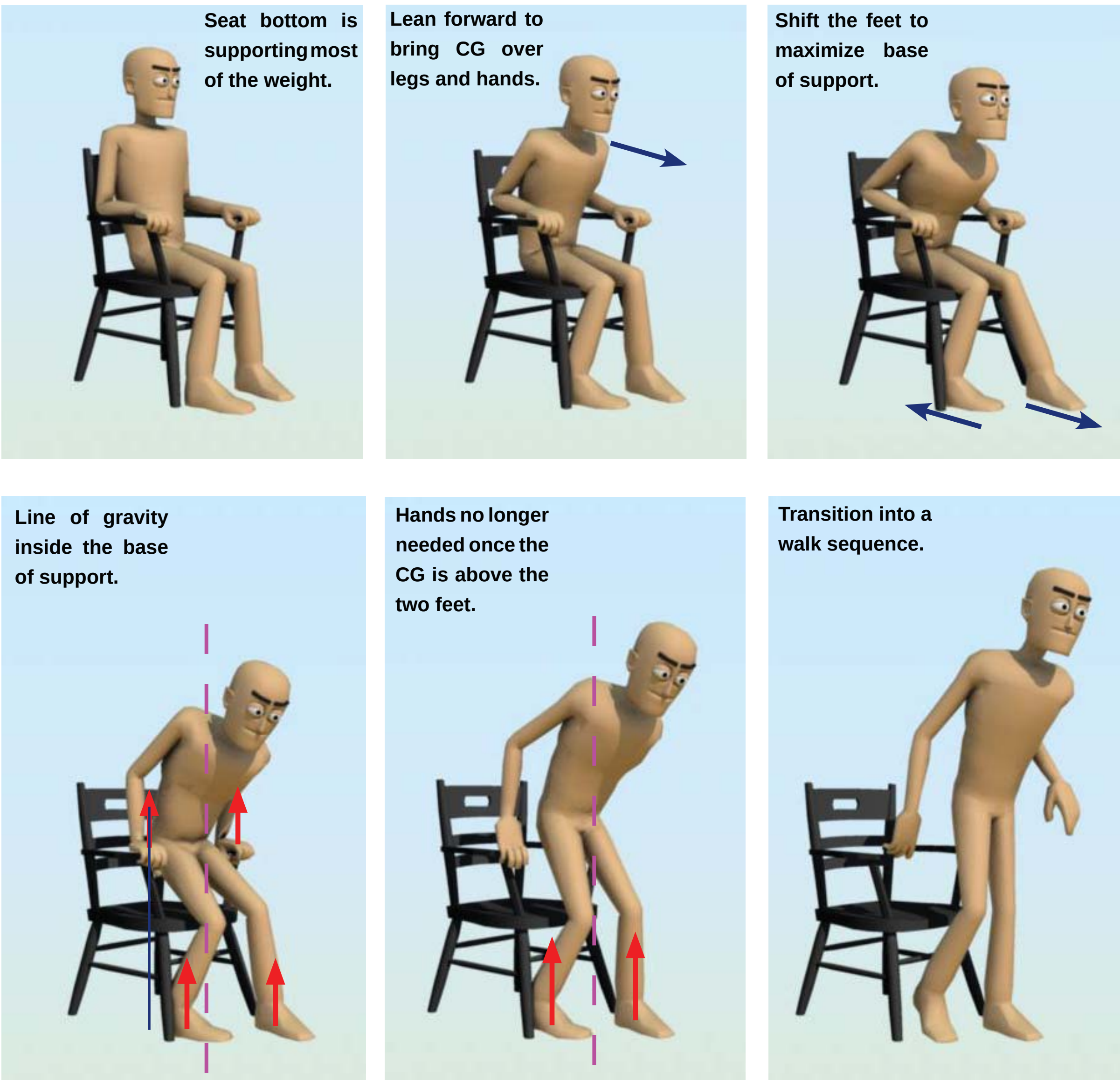
The pose on the right tells you that the pack is heavy because he has to lean forward to keep the total center of gravity over his base of support (his feet).

Note: **The weight of the pack is evident from the character's pose, even when we erase the backpack from the drawing.**

Rising from a Chair

► Your base of support changes as you rise from a seated position and this affects the poses. When rising slowly the center of gravity needs to remain above this base for the character to maintain balance at all times.

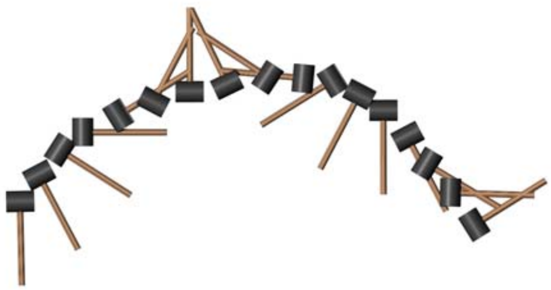
Notice that rising from a chair with arms is easier because the hands may be used to expand the base of support.



If the character stands up quickly then some of the poses may be out of balance. If so then the motion slows into the standing pose, much like a rising ball slows into its apex.

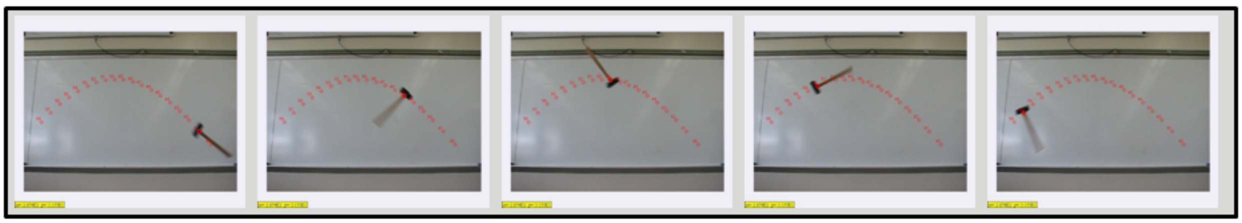
Throwing and Jumping

► The center of gravity helps you create realistic animated motion for thrown objects and jumping characters.



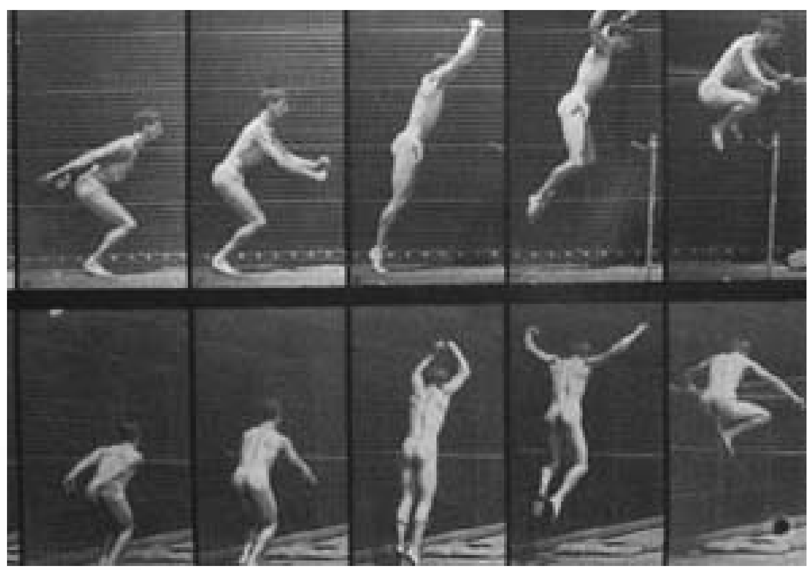
The motion of a thrown hammer, looks complicated but it's not once you identify the center of gravity.

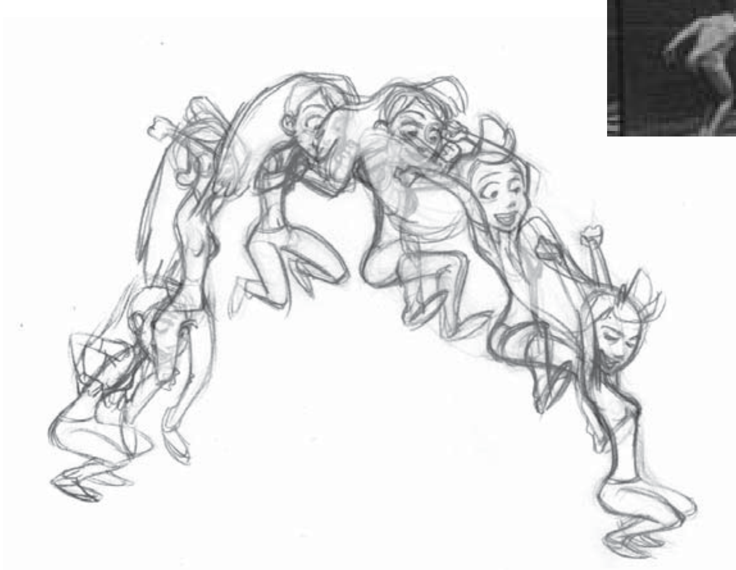
The center of gravity follows a path of action that is a parabolic arc (see *Physics of Paths of Action* tutorial) while the hammer rotates around the CG at a constant turning rate.



Notice how you swing your arms when you want to jump as high as possible. Lifting your arms raises your center of gravity and doing so as you rise out of your crouch makes you push off with greater force against the ground.

Once you're in the air, if you want to clear a hurdle then you naturally lower your arms. That lifts your torso by shifting your center of gravity to a lower point in your body.





In the "Fosbury Flop" the high jumper's pose lowers the center of gravity below the pelvis, allowing the jumper's body to clear the bar.

Dynamic Balance

► A pose that is out of balance for a stationary character may be in dynamic balance if the character is moving.

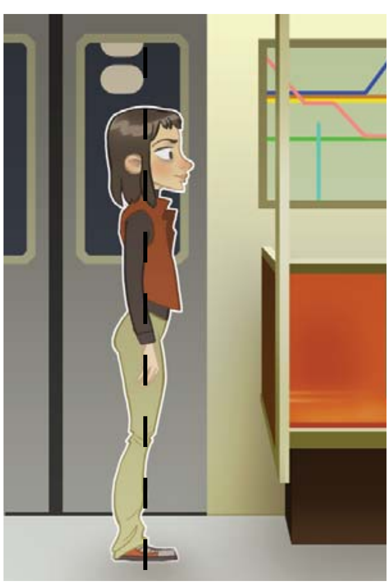
This runner leans into his turn so that the motion of falling over towards the side combined with his forward running motion results in a turning motion around the curve.

We see the same dynamic balance in the photos below.

Have you noticed how much easier it is to balance on your bicycle when it's moving? It's because the rotating wheels act like a gyroscopes, causing you tip over much more slowly.

"Life is like riding a bicycle. To keep your balance you must keep moving"

Albert Einstein



On the left our character stands in a subway train that's waiting at the station.

On the right, we have our character leaning forward to stay in balance because the train is accelerating forward.

A horizontal acceleration makes the line of gravity tilt at an angle. For example, when the acceleration is half that of gravity (or $^1/_2$ gee), the line of gravity tilts by 27 degrees.

The line of gravity tilts only while the train is accelerating; while travelling at a constant speed the line of gravity is again vertical.

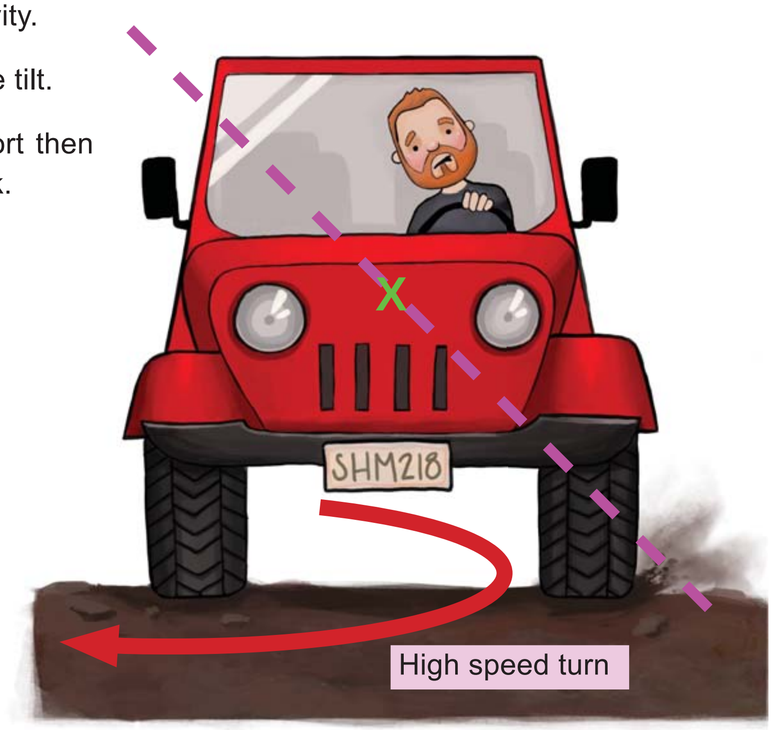
"Roll-Over" Loss of Balance

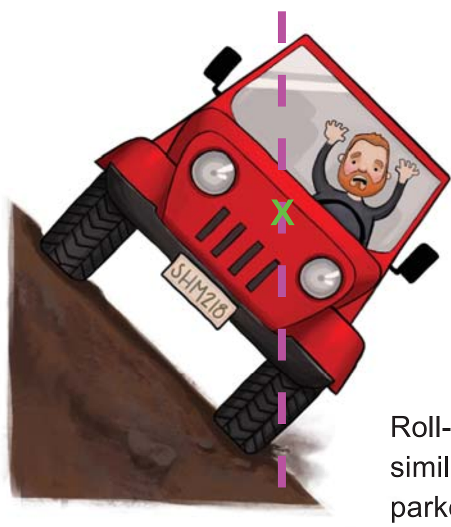
► During a sharp turn the line of gravity tilts inward towards the inside of the curve due to centripetal acceleration.

The sharper the curve (i.e., smaller the radius), the greater the acceleration, increasing the tilt of the line of gravity.

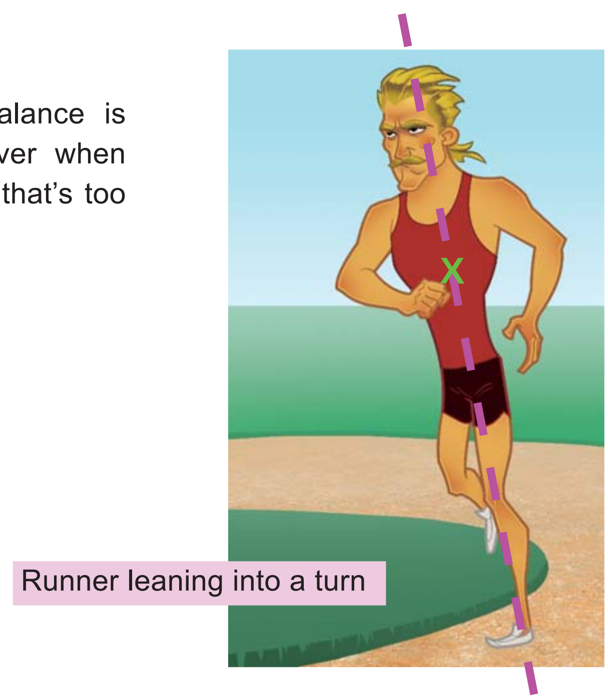
Similarly, the faster you take the turn, the greater the tilt.

If the line of gravity falls outside the base of support then balance is lost and you roll towards the outside bank.





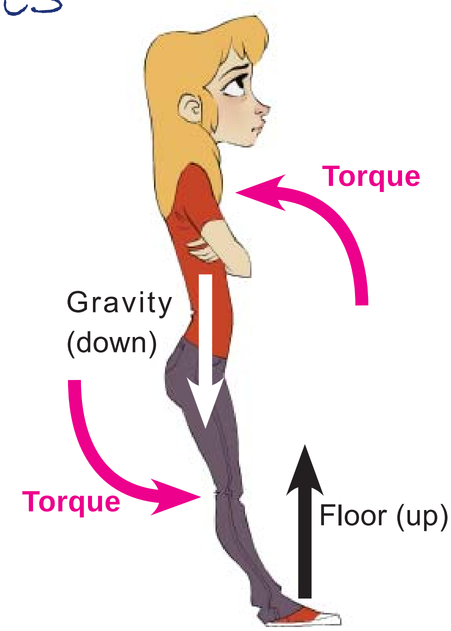
Roll-over loss of balance is similar to tipping over when parked on a hillside that's too steep (see page 11).

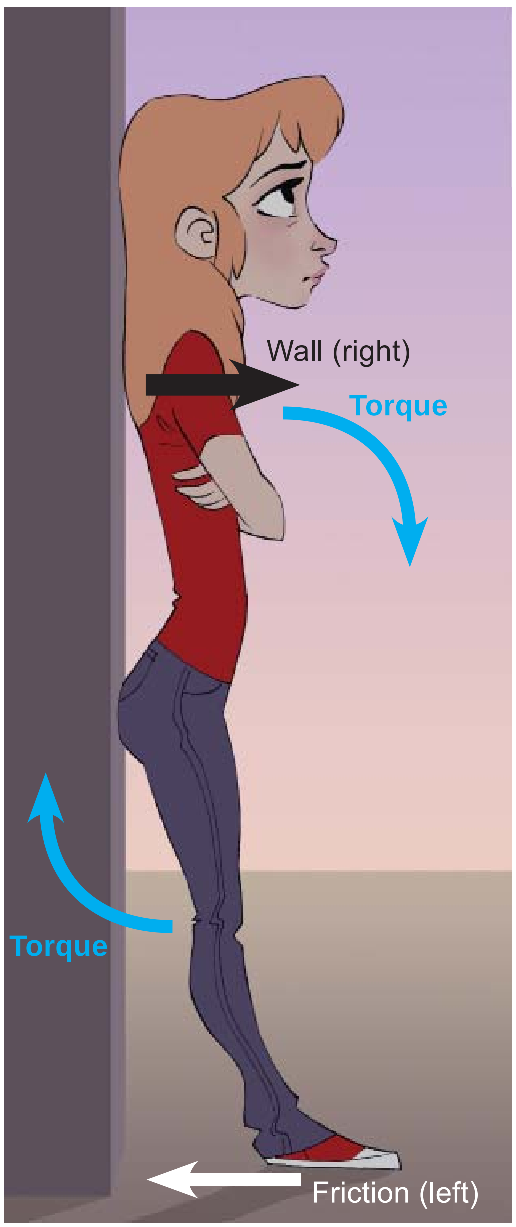


Horizontal Support Forces

► Balance may be achieved with support forces pushing or pulling in the horizontal direction when those forces exert a balancing counter-torque.

The character's pose on the right is obviously out of balance. The upward and downward forces are not aligned so they produce a torque that causes a rotation. The character tips backward and falls on her back.





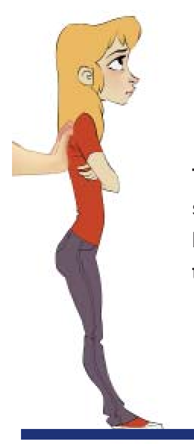
The same pose is in balance when the character leans against a wall since the rotation is prevented by horizontal support forces.

There are two horizontal forces that create the balancing counter-torque:

* The wall pushes the character towards the right.

* The frictional force of the ground pushes towards the left.

It's important to think about these forces because they affect the character's pose (e.g., the angle of the lower leg as it braces against the frictional force pushing on the foot).



The character's pose is the same if the force on her back were due to someone trying to push her forward.

Creating Action

► Balance is important but, for animation, motion is even more important. But what exactly causes action in nature and how can we create believable motion in animation?

That's the topic of this series' next tutorial, *Physics of Creating Action*.

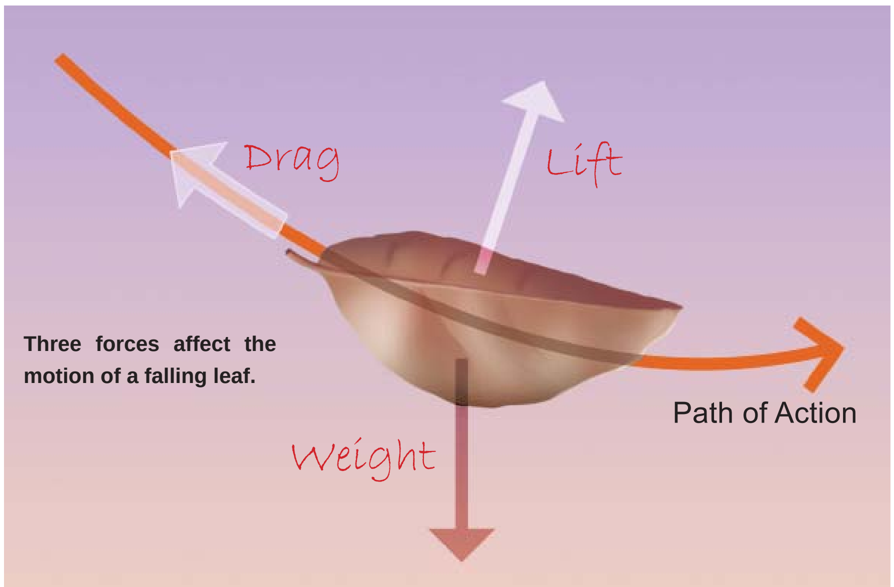


Image Credits

All illustrations not listed below are by Charlene Fleming and photos not listed are by the author.

Man-Bat, pg. 2, Cameron Chun.

Spaceman, pg. 2, Andrea Rhodes.

Stack of rocks, pg. 2, Corey Tom.

Hammer, pg. 3, Corey Tom.

Detective, pg. 3, Rebbaz Royee.

Flour Sack See-Saw, pg. 5, Corey Tom.

Soda Can, pg. 8, Corey Tom.

Bench, pg. 9, Corey Tom.

Shoe Prints, pg. 9-12, Corey Tom.

Woman in Swimsuit, pg. 10, Katie Corna.

Martial Artist, pg. 11, Lam Nguyen.

Balance on a Beam, pg. 12, Amy Seaver

Circus Ballerina, pg. 12, Lam Nguyen.

Weights on Scales, pg. 13, Corey Tom.

David (Donatello & Michelangelo), pg. 14-15, Wikimedia.

Two Women, pg. 15, Katie Corna.

Hiker, pg. 16, Rebbaz Royee.

Rising from a Chair, pg. 17, Corey Tom.

Thrown Mallet, pg. 18, Corey Tom.

Jumping Man, pg. 18, Eadweard Muybridge.

High Jump, pg. 18, Carl Blake, Flickr.

Bicycle Turning, pg. 19, Ethan Lofton, Flickr.

Skateboarder, pg. 19, Mike Baird, Flickr.

Roll-over Jeep, pg. 20, Stephanie Lew.

Special thanks to Alice Carter, Cassidy Curtis, David Chai, John Clapp, Courtney Granner, Lizz Greer, Rex Grignon, Martin McNamara, and the Shrunkenheadman Club at San Jose State.

***Physics of Animation* is a project supported, in part, by the National Science Foundation**