Physics of Dance

* Basic physics definitions we'll need

* Balance

* Turns

* Jumps

* Why are dancers so slim? The physics behind the body size!

Basic physics definitions we'll need

* **Velocity** is how fast and in what direction an object is moving
  * It's basically rate = distance/time + direction
* **Momentum** is mass times velocity
  * If an object has a large momentum, it's hard to stop it!
* **Force** is basically a push or a pull
  * To change an object's momentum, you have to apply some kind of force for some time! So

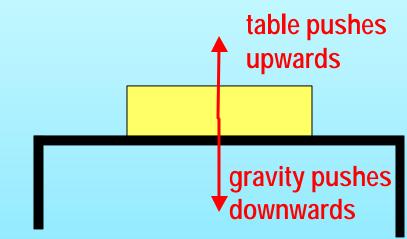**change in momentum = force x duration of time the force was applied**

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A force is a vector quantity

* A force is a <u>vector</u> quantity, meaning that it has both magnitude and direction.
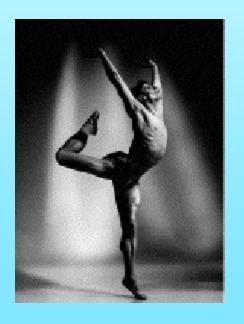 * This is why forces are often graphically represented as arrows

table pushes upwards

gravity pushes downwards

* Forces add! It's the **total** force that counts!
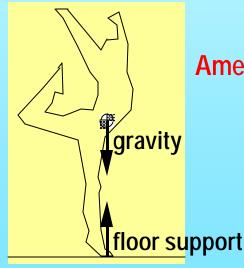
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What forces act on a dancer?

* Gravity (downwards)
* Support from floor (upwards)
* Friction from floor (sideways)
  * <u>Friction</u> is the force that resists relative motion between two bodies in contact
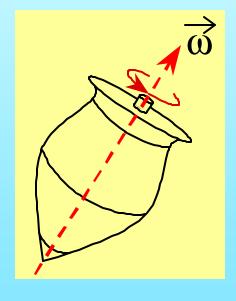

gravity

floor support

Keith Roberts
American Ballet Theatre principal
(photo by Roy Round)

Some more physics definitions: spins

* **Angular velocity** is how fast an object spins
  - It is also a vector, characterized not only by magnitude but also by the direction of the rotation axis.

* **Rotational inertia** is the inertia of a rotating object

  - <u>I</u>nertia in general is the tendency of an
  object to keep doing whatever it is doing

* **Angular momentum** is rotational inertia
times angular velocity

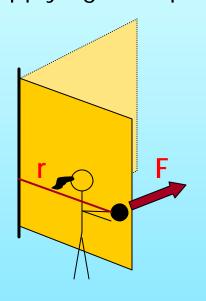 - If an object has a large angular momentum,
  it's hard to stop its spinning!

Torque

※ **Torque** is a measure of how much a force acting on an object causes that object to rotate.

※ You are applying a torque to doors every day of your life!

Torque = distance (r) times force (F)

change in angular momentum = torque x

duration of time the torque was applied

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Analogies

Motion without spins   Motion with spins

Velocity   ⟷   Angular velocity

Mass   ⟷   Rotational inertia

Momentum   ⟷   Angular momentum

Force   ⟷   Torque
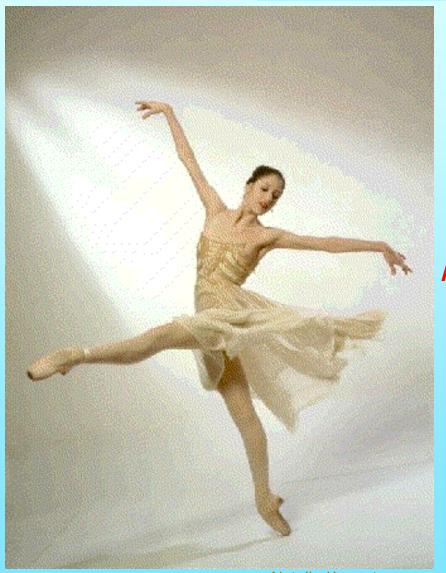
What's balance?

✳ No total force and no total torque

   ⌃ No total force is needed so that the momentum does not change

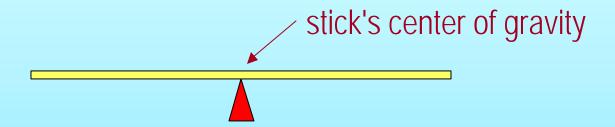   ⌃ No total torque is required so that the angular momentum does not change

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Amazing examples of balance…

Paloma Herrera
American Ballet Theatre principal
(photo by Roy Round)

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Center of gravity

✷ **The center of gravity** of an object is that point at which the object will balance.

stick's center of gravity

✷ The entire weight may be considered as concentrated at this point, hence the name.

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A trick to know about center of gravity

※ In order to stay balanced, the center of gravity must remain directly above the area of contact with the floor!

- ➤ Then gravity's downward push and floor's upward push will go through the dancer's center of gravity and there is no total force and no total torque

- ➤ If this area is very small

  (e.g., a dancer is en pointe),

  it's harder to balance

Balancing *en pointe*...

Sylvie Guillem
Royal Ballet principal

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Area covered while *en pointe*
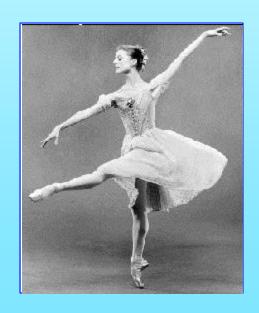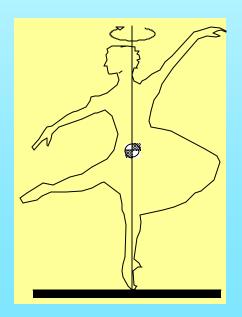
Demo with graph paper, etc.

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How can a dance keep a balance while turning?

* What's the trick that keeps the dancer balanced when she is turning?
  * The rotation axis shouldn't wobble around much!
* There's a lot of neat physics in turns!

What describes turns?

* The relevant quantities that describe turns are:
  * **Angular velocity** is how fast an object spins
  * **Rotational inertia** is the inertia of a rotating object
  * **Angular momentum** is rotational inertia times angular velocity
  * A change in angular momentum is equal to the **torque** exerted on an object times the duration of time the torque was acting
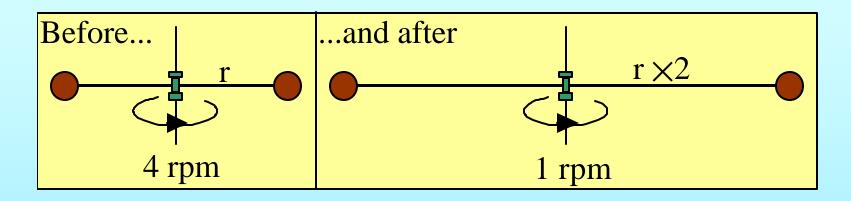
Rotational inertia

* Rotational inertia indicates how difficult it is to start an object spinning (or to stop it, if it's already spinning)
    * It depends on the mass of the object
        * The greater the mass, the greater the rotational inertia
    * It also depends on how far the mass of the object is placed from the rotation axis
        * If this distance is doubled, the rotational inertia gets quadrupled!
* If no torque is applied, the angular momentum stays the same
* So since angular momentum = rotational inertia times angular velocity, the greater the rotational inertia, the smaller the angular velocity!

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Rotational Inertia (2)

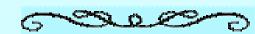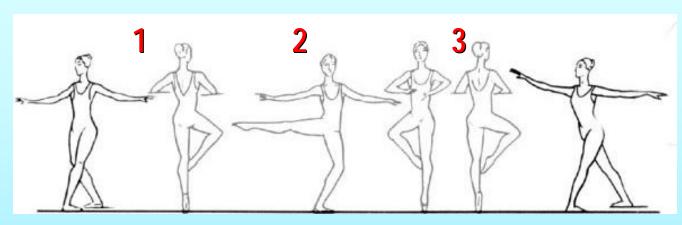| Before...	...and after
r	r ×2
4 rpm	1 rpm

* The masses were at a distance r from the rotation axis before
* Then the distance doubled => rotational inertia quadrupled, so the angular velocity became smaller by a factor of four.

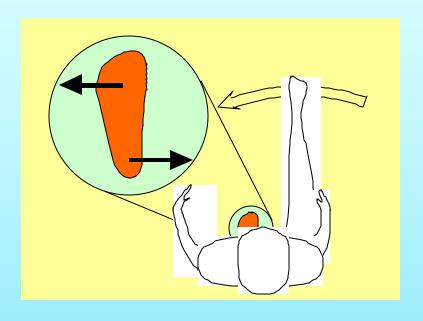* A number of ballet movements is based on this principle.

Fouette

1) Dancer starts turning -- arms brought together
   (r small, rotational inertia small, so large angular velocity)

2) Dancer stops for a moment by extending arms and leg
   (r large, rotational internal large, so small angular velocity)

3) Dancer continues turning -- arms brought togethe
   (r small, rotational inertia small, so large angular velocity)

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Friction can create torque, too!

When the dancer pushes the floor one way, the friction between the leg and the floor creates the push the other way.
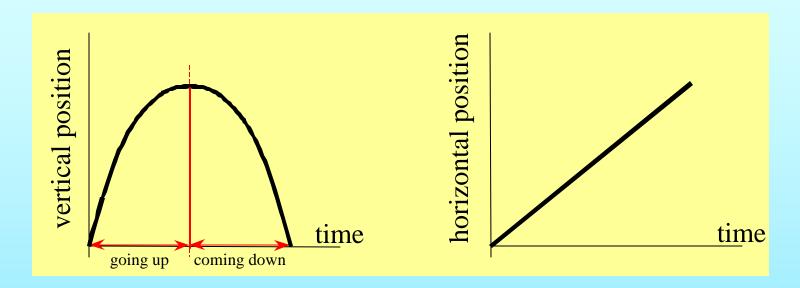
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The physics of jumps

* Gravitational force plays a major role in jumps
* The total effect of gravity is the same as if it were acting on the dancer's center of gravity only
* Gravity only affects vertical (not horizontal) motion
* Gravitational force is proportional to an object's mass
  * So double the mass, and the gravitational pull will double too!
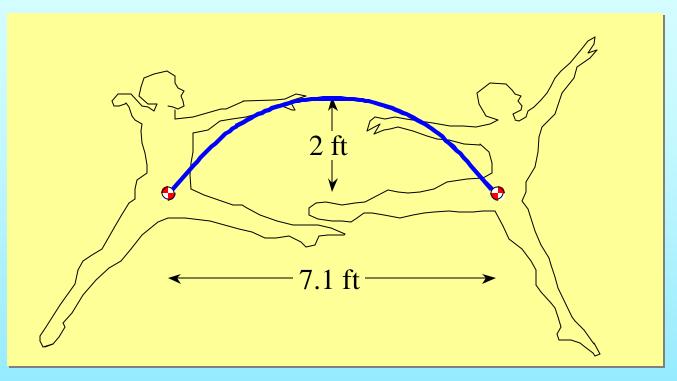
Horizontal vs. vertical motion

- The vertical position of the dancer's center of gravity vs. time describes a parabola
- There's no force in the horizontal direction, so the horizontal position is a straight line if we plot it vs. time
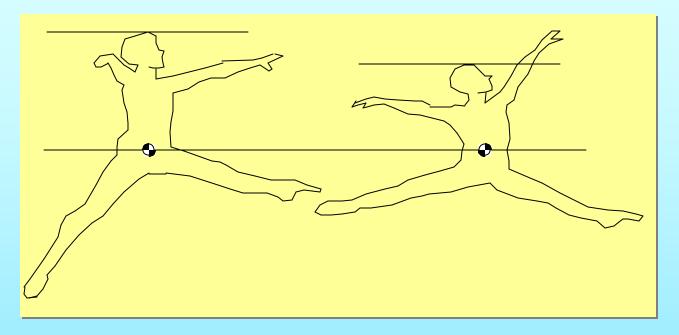
Trajectory in a jump

* If a dancer jumps so that their center of gravity rises by 2 feet, and the horizontal velocity is 10 ft/sec, this is what we would see.

Floating?

* While the trajectory is always the same, some dancers can create an illusion of floating in space.

* This is done by raising the legs, arms, adjusting the head
  * The vertical motion of the head is smaller than the vertical motion of the center of gravity

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Beautiful jumps

Yulia Makhalina
Farukh Ruzimatov
Kirov Ballet principals
(photo by Marc Haegeman)

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Body size effects

* Rotational inertia is proportional to the mass of an object and to the square of the distance from the rotation axis to the object's edge

* In order to rotate faster, need to decrease rotational inertia

* This can be done in two ways:
  * Decrease mass
  * Make sure most of the body is very close to the rotation axis
  * Most dancers go for both…

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A dancer's body evolution

* It is curious to see how the way dancers look changed over time
  * Increased technical demands required new body looks
  * And it's nothing but physics that's behind it!

Pierina Legnani (1863 - 1923).

Sylvie Guillem
Royal Ballet Principal

Never exaggerate!

※ Sometimes the demand for a perfect dancer's body leads to really ugly results…

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Conclusions and acknowledgements

* Physics does not "explain" dance, of course!
  * Dance is an art form, and as such is rather outside the realm of science

* However, it may help the dancer to know the physics behind the movements she is performing.

* I'd like to acknowledge George Gollin, UIUC

  http://www.uiuc.edu/ph/www/g-gollin/dance/dance_physics.html

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