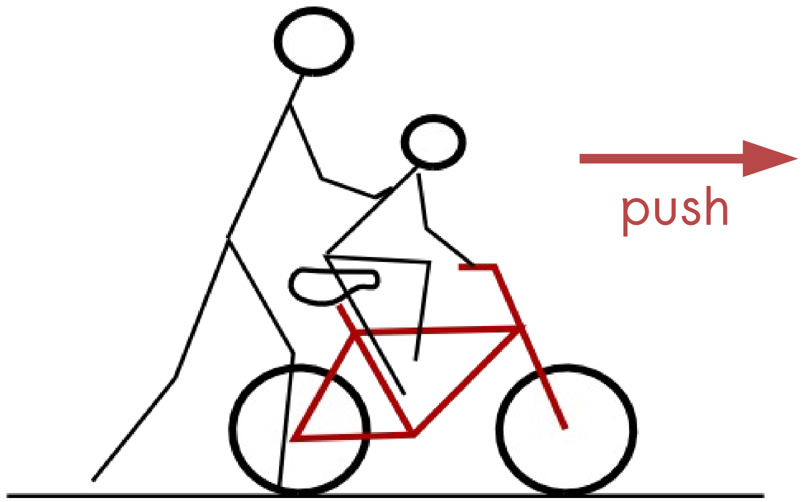
Newton's Laws of Motion

Generally, air masses move the way they do because of the forces that act upon them.

- *Definition:* A **force** is something that pushes or pulls on an object, causing it to **speed up**, **slow down**, and/or **change directions**.



A force can change an object's speed....

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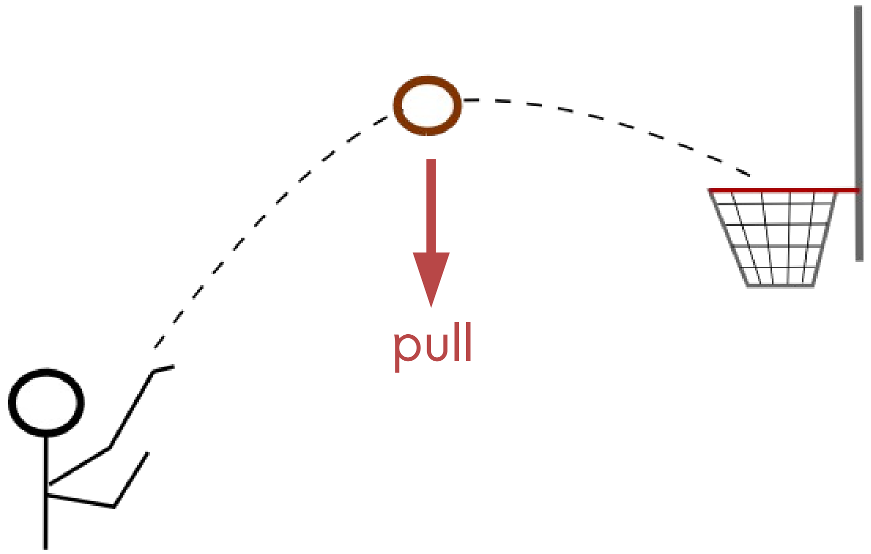

...or it can change the object's direction.

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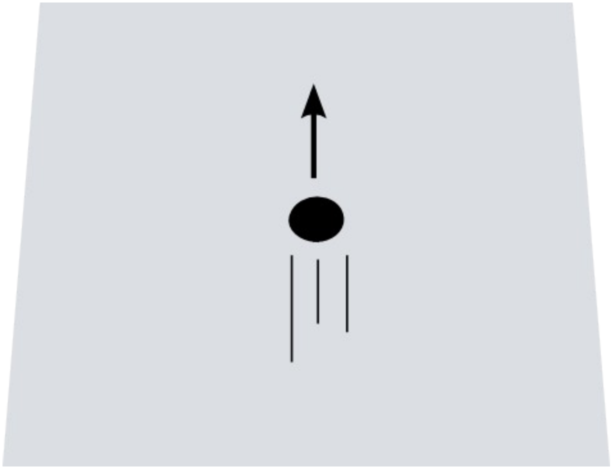

And of course, if no force acts, then the object moves in a straight line at constant speed forever.....think a hockey puck on the ice.

Newton's Laws of Motion

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- *Definition:* A force is something that pushes or pulls on an object, causing it to speed up, slow down, and/or change directions.

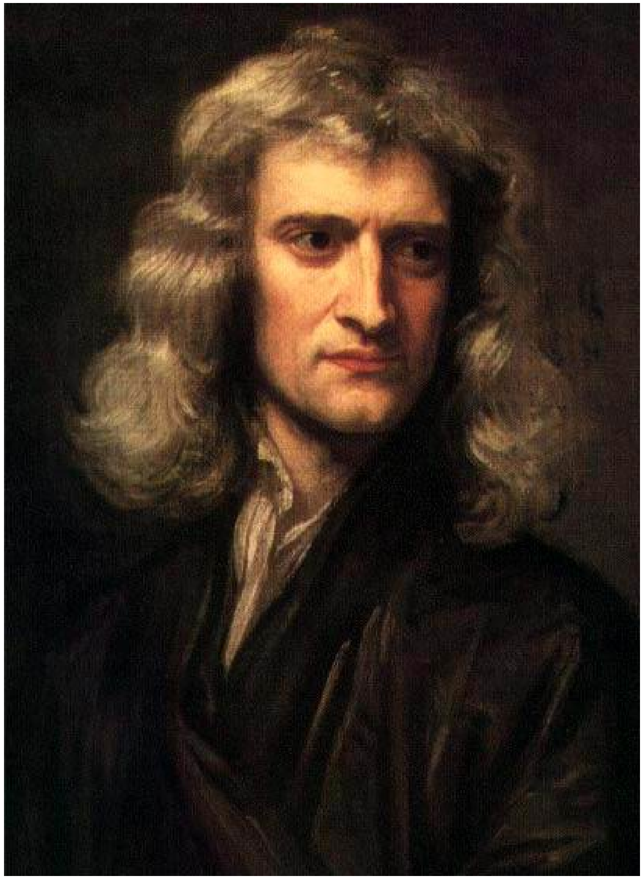
- *Definition:* The change in the speed and/or direction experienced by an object is called the object's **acceleration.**

    - The precise relationship looks something like

$$\text{acceleration} = \frac{\text{force}}{\text{mass}}$$

- To paraphrase Joe Biden, the development of Newton's laws was a big *(censored)* scientific deal!
  - Seen in the context of the time, Newton's laws of motion were perhaps the biggest single advance in the history of science
  - As never before, scientists could make quantitative, mathematical predictions for a wide range of physical systems
  - In meteorology, that meant predicting the weather. But of course that didn't happen overnight.....

A walk down memory lane....

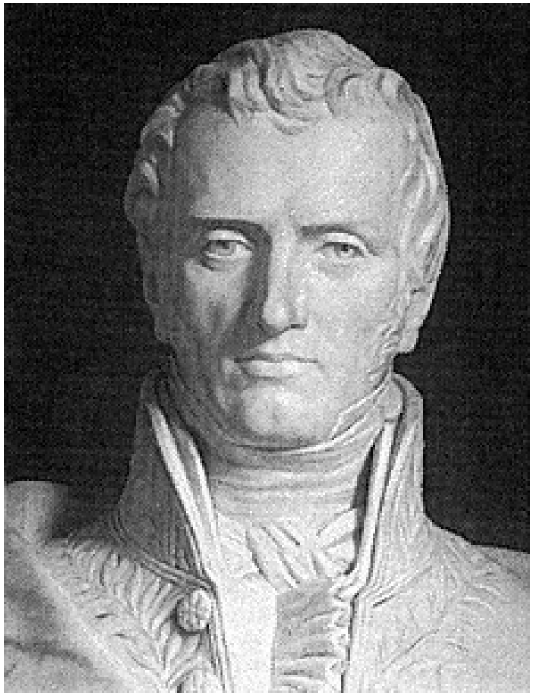


1680's: Motivated by planetary orbits, Newton develops his fundamental laws of motion, along with the basic ideas of differential calculus. Simultaneously (and independently), Leibniz develops calculus in a form closer to that used today.

A walk down memory lane....

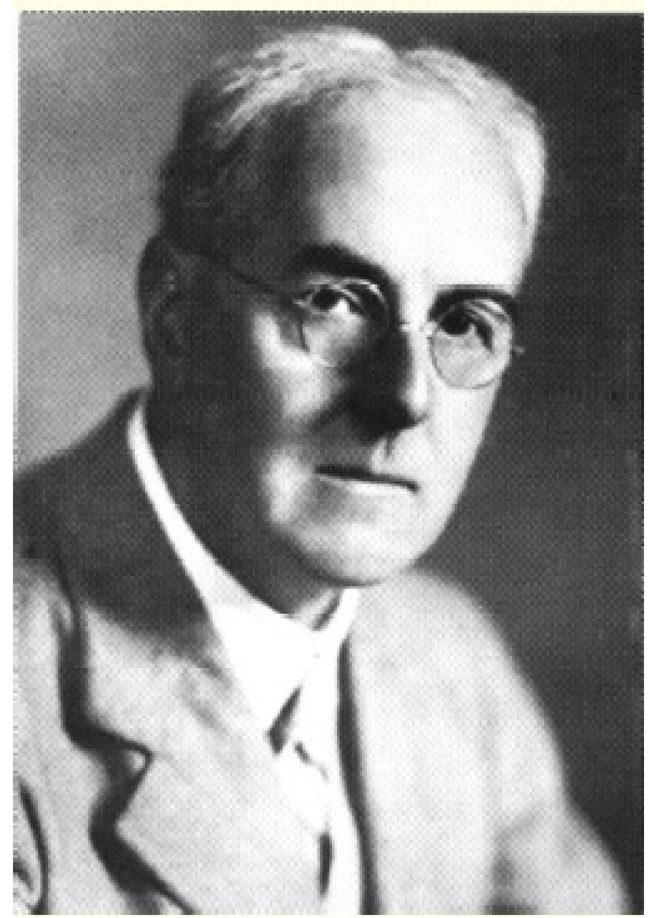
1750's: Leonard Euler develops a form of Newton's laws suitable for "perfect" (frictionless) fluids and gases.

A walk down memory lane....

1820's: Claude-Louis Navier and George Stokes extend Euler's equations to include the effects of friction. Essentially these same laws are used to predict the weather today.

A walk down memory lane....



1920's: Employing an army of people with calculators, Lewis Fry Richardson makes the first attempt (ultimately unsuccessful) to use Newton's laws to predict the weather.

A walk down memory lane....

Jon Von Neumann

1950's: The first modern electronic computer (the ENIAC) makes the first successful weather forecast using Newton's laws.

- So the key to understanding atmospheric motions is to understand the forces that produce these motions. And what, pray tell, are these forces you speak of?
- Well, for our purposes, the main ones are:

  (i) the pressure gradient force (PGF)

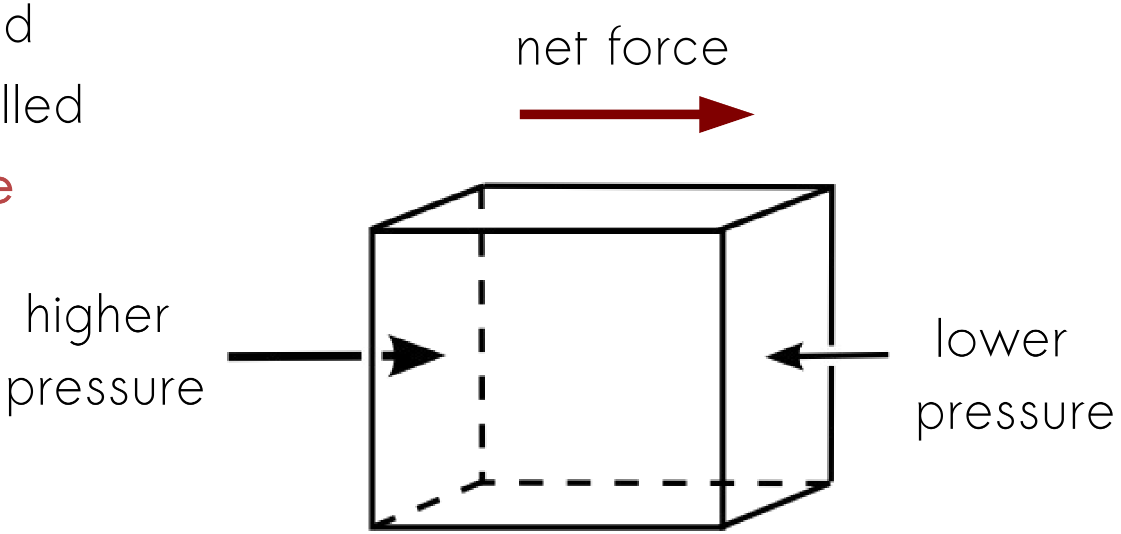
  (ii) the Coriolis force

  (iii) friction

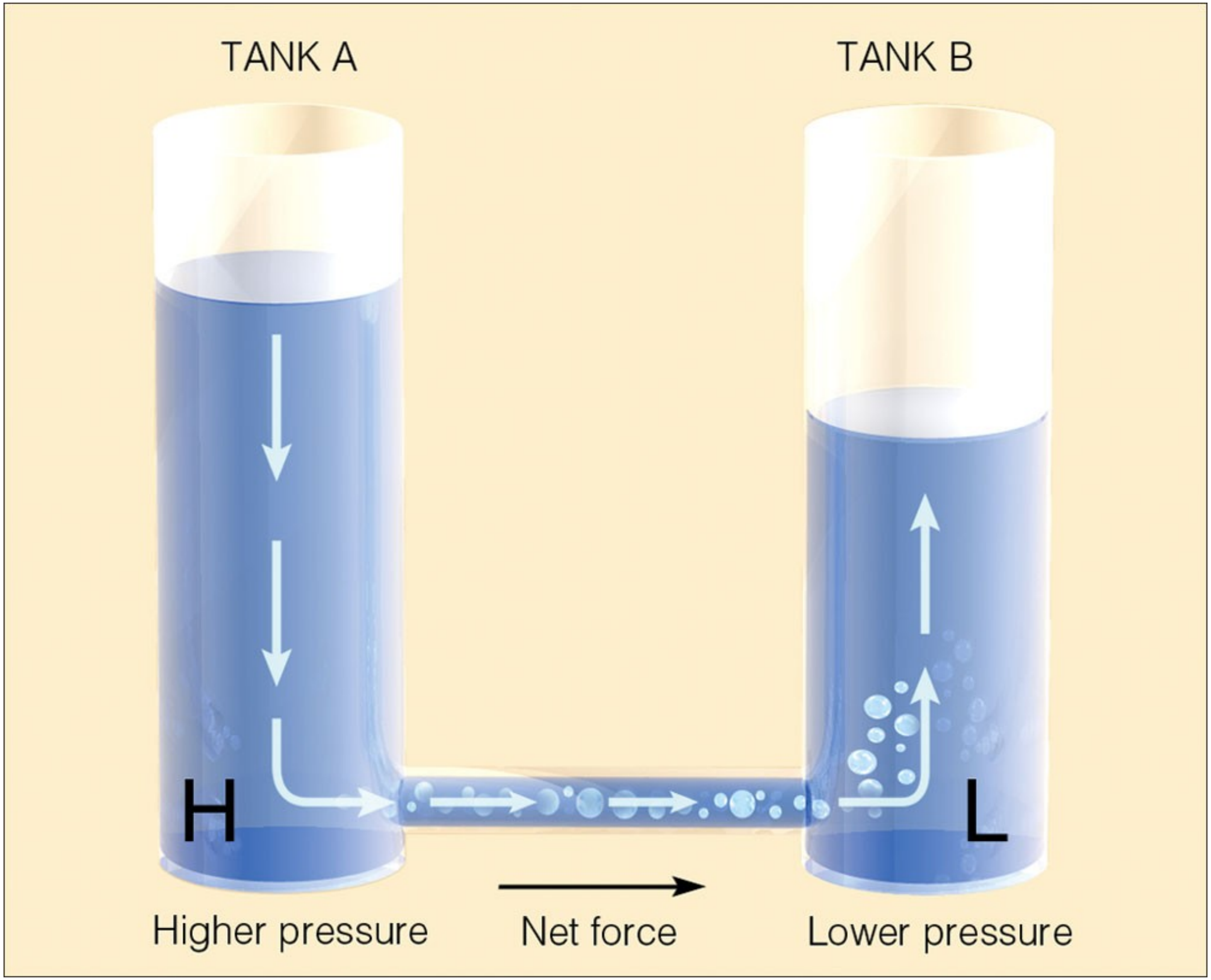
The Pressure Gradient Force (PGF)

For any given mass of air, the air surrounding it exerts pressure forces across each of its sides.

- The **net** pressure force exerted by the surrounding air is called the pressure gradient force (or PGF)

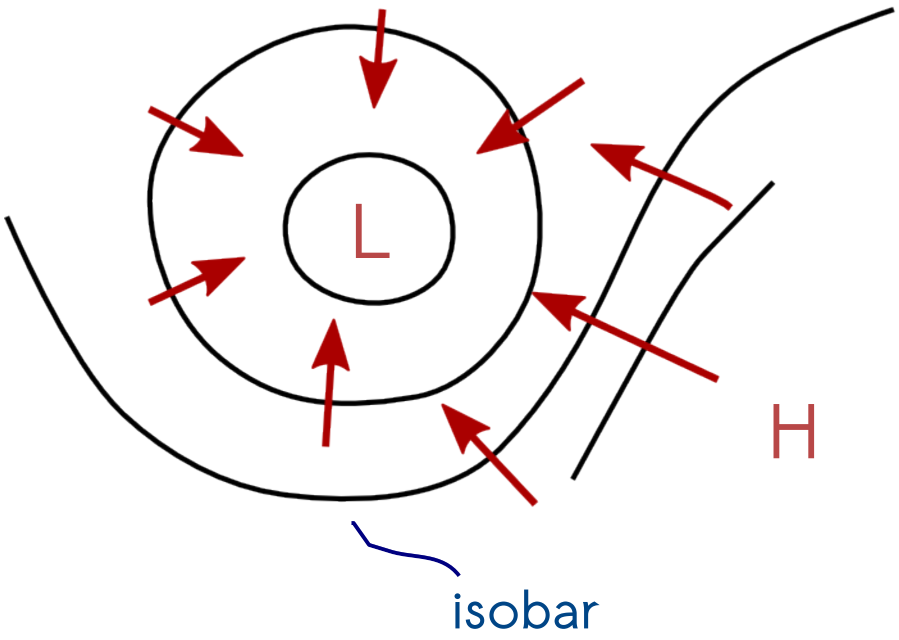


- The PGF always pushes from higher pressure towards lower pressure



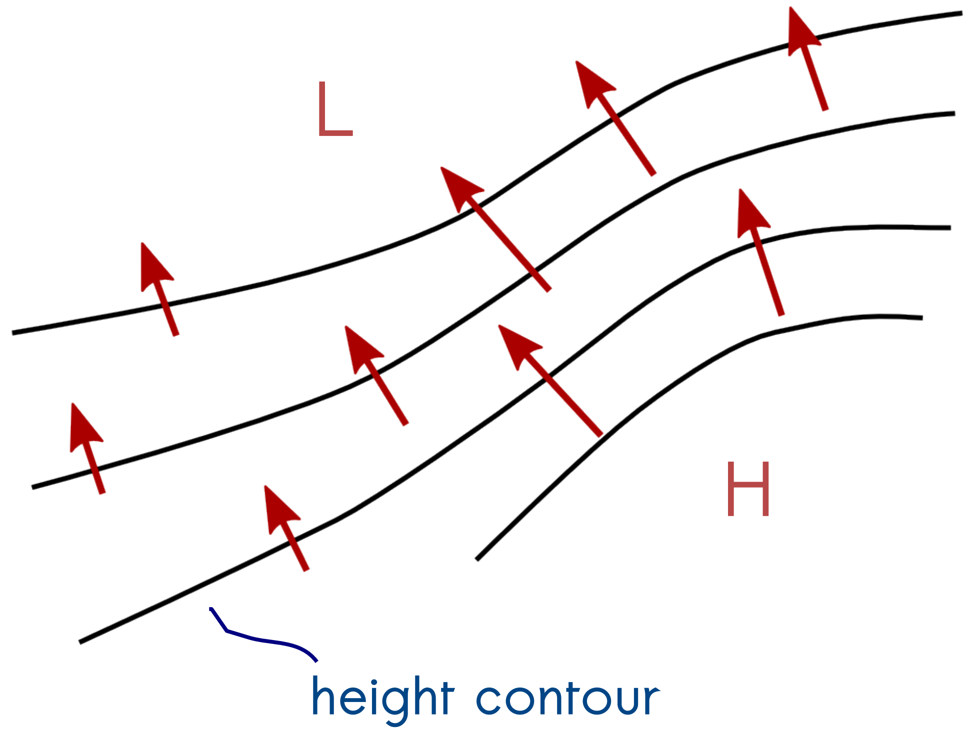
Higher pressure in Tank A causes water to flow towards Tank B

- On a surface map, the PGF is perpendicular to the isobars, pointing from higher pressure to lower pressure



- The strength of the PGF depends on the contour spacing:
  - More closely spaced contours imply a bigger PGF

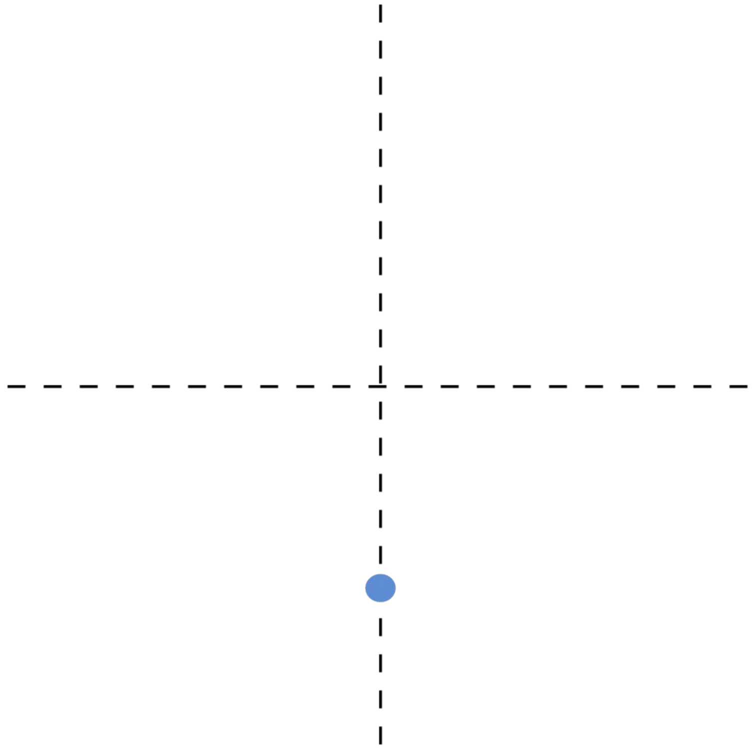
- On an upper-level chart, the PGF is perpendicular to height contours, pointing from higher to lower heights



- And as at the surface, the strength of the PGF depends on the contour spacing:
  - Again, tighter contours mean a stronger PGF

The Coriolis Force

- The Coriolis force is an **apparent force** (i.e., not a real force) that results from the Earth's rotation.
- To see how this works, consider an object moving in a straight line at constant speed, as seen from a coordinate system with fixed axes



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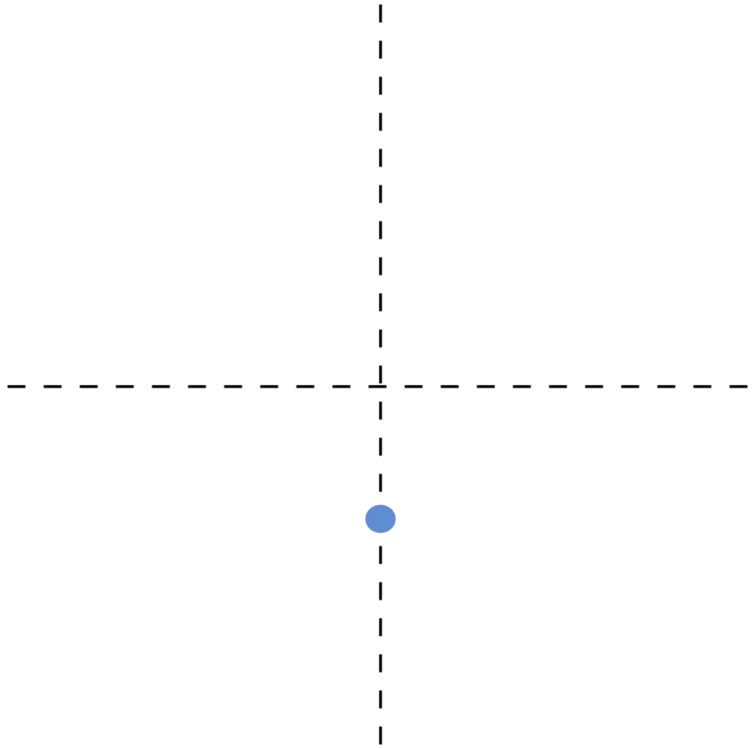

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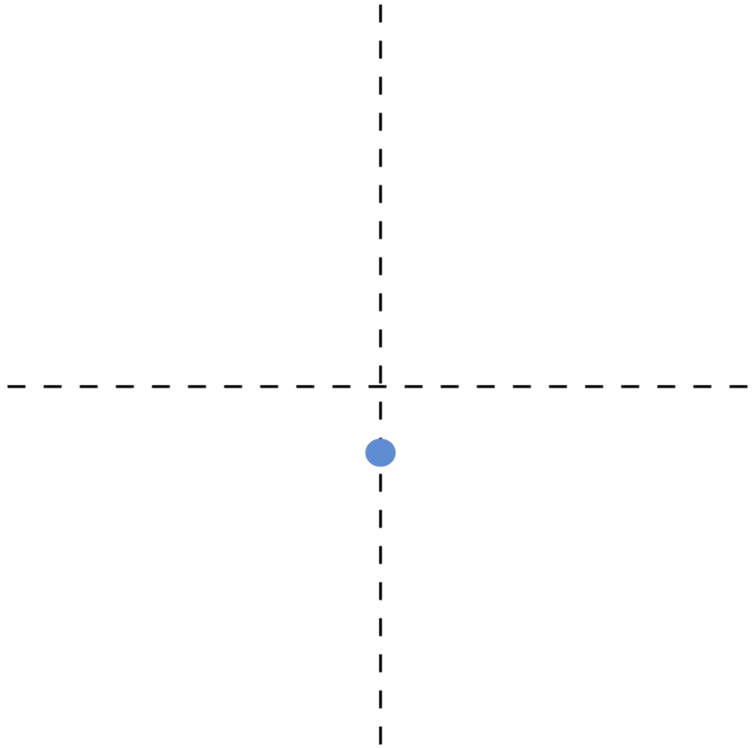

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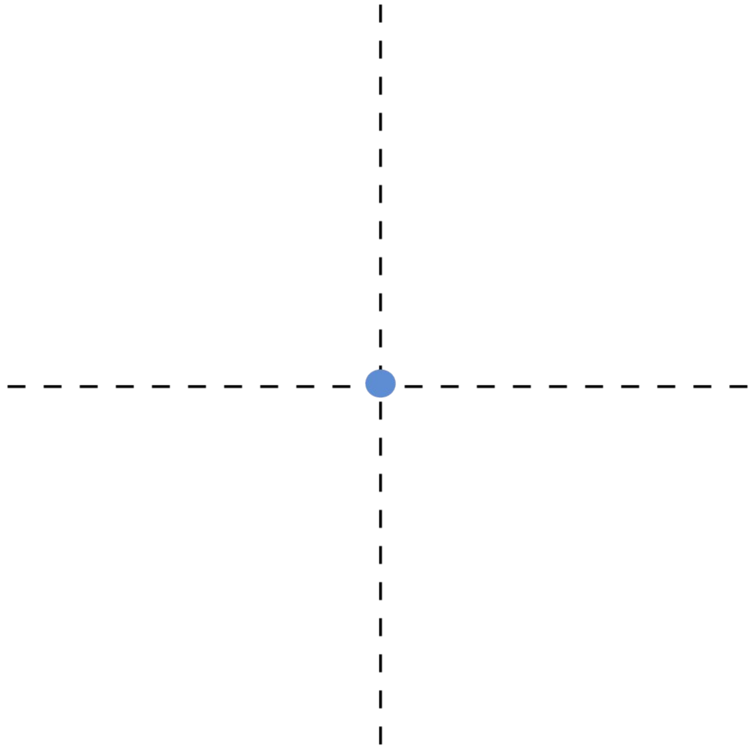

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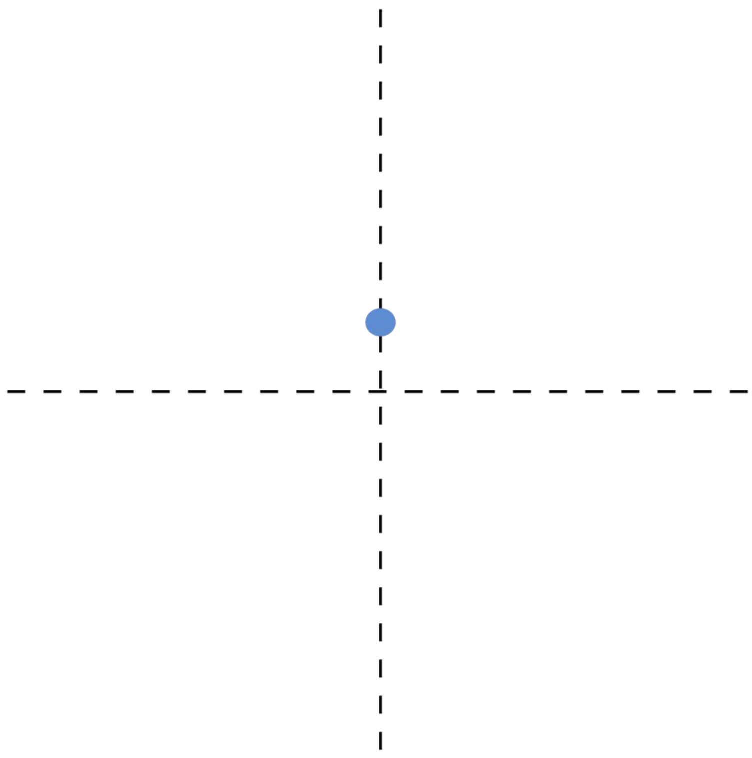

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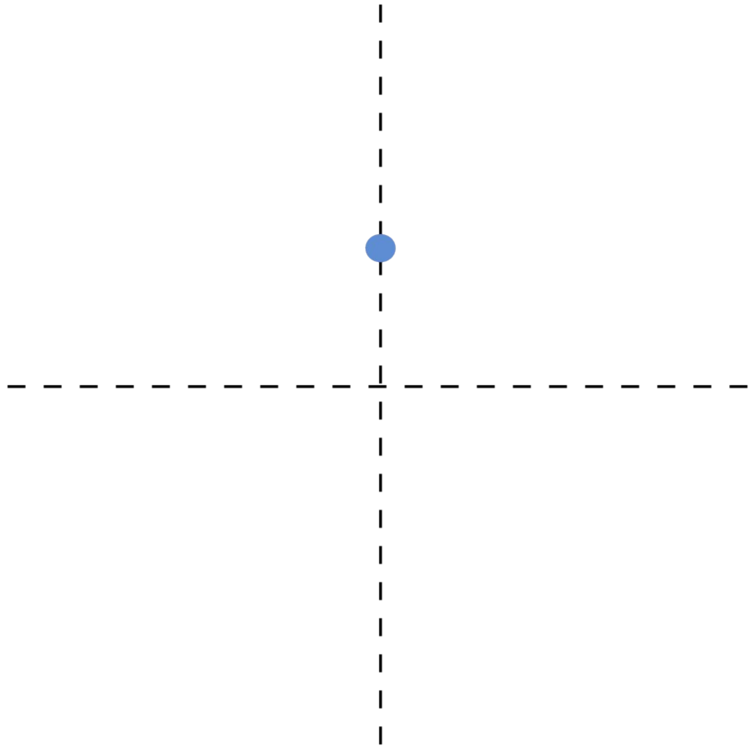

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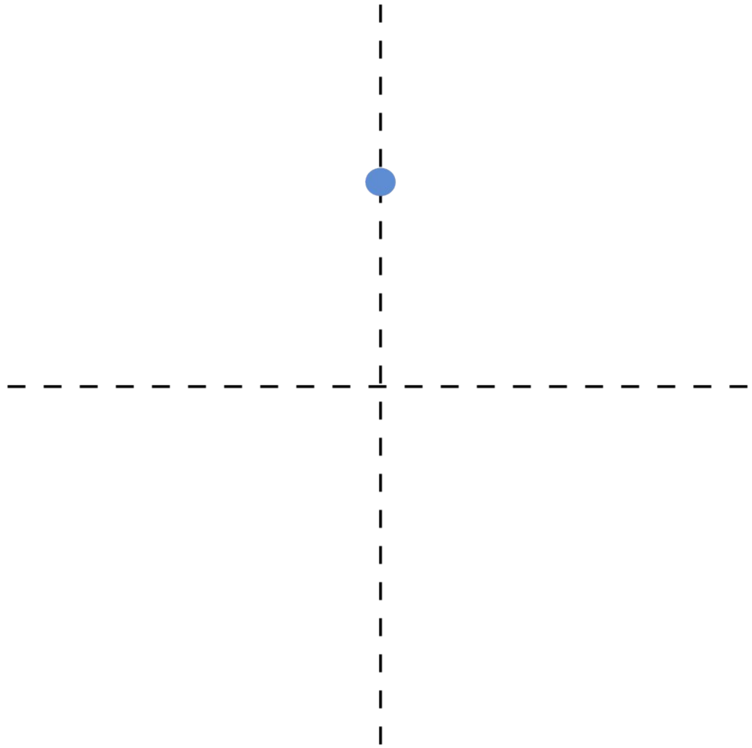

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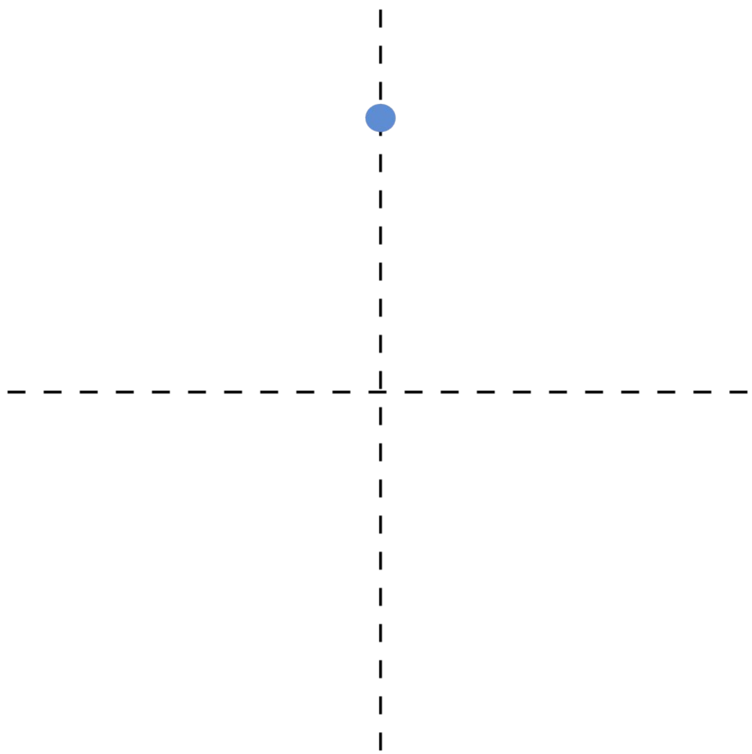

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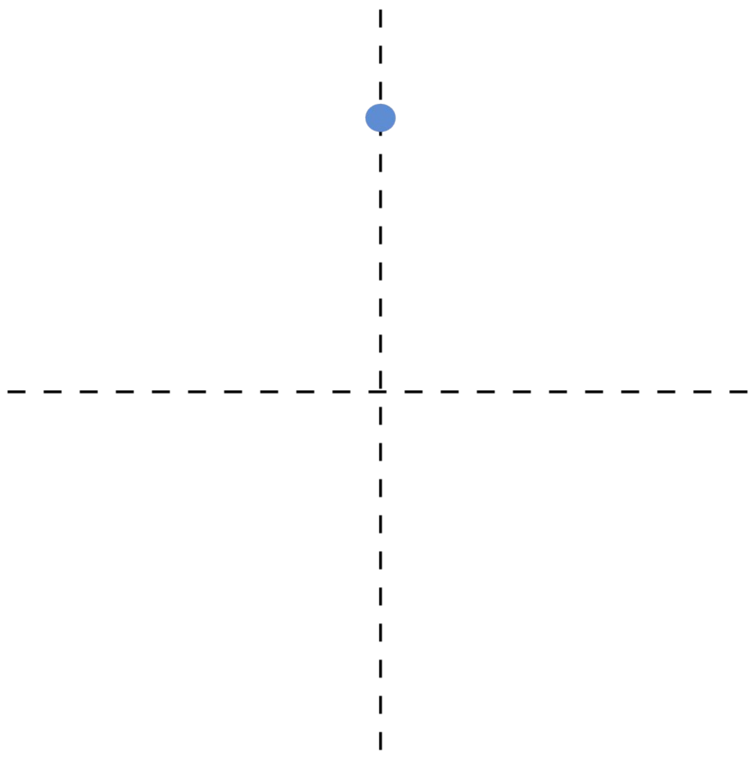
  (Note that there's no force on the object, since it doesn't change speed or direction.)



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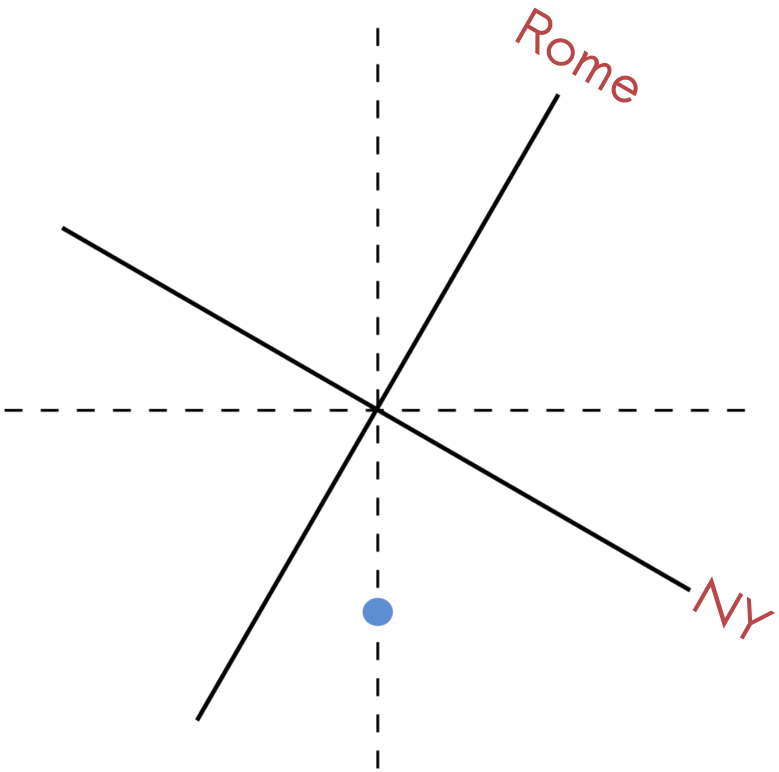

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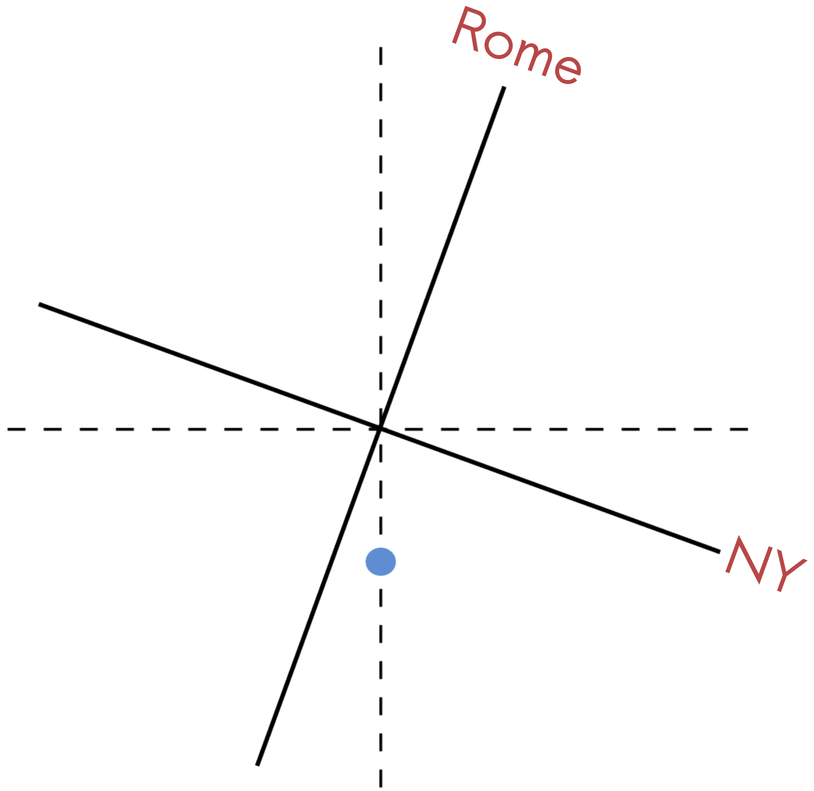

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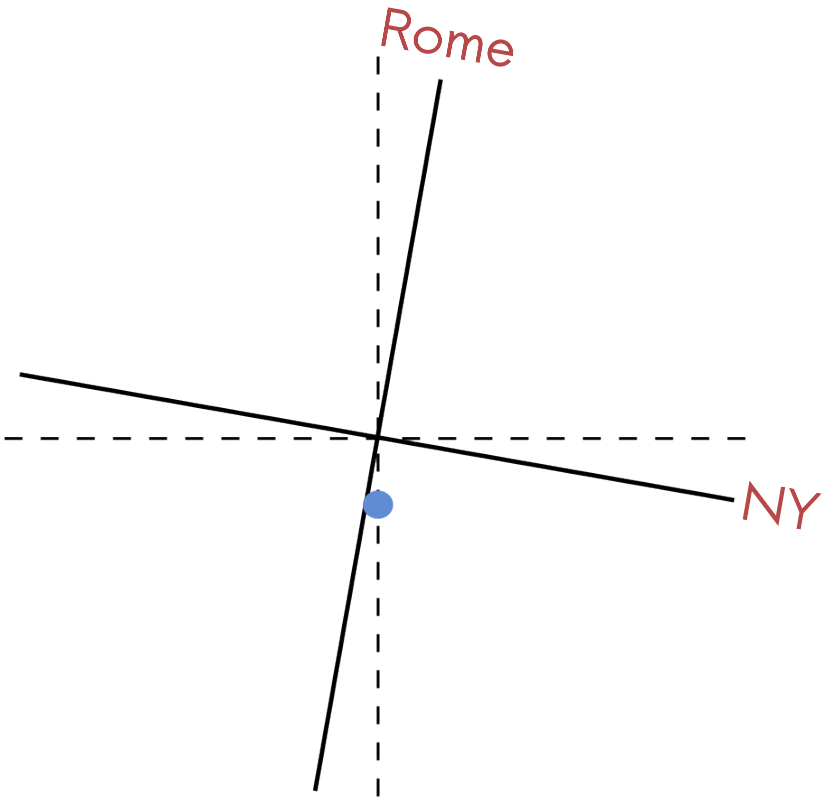

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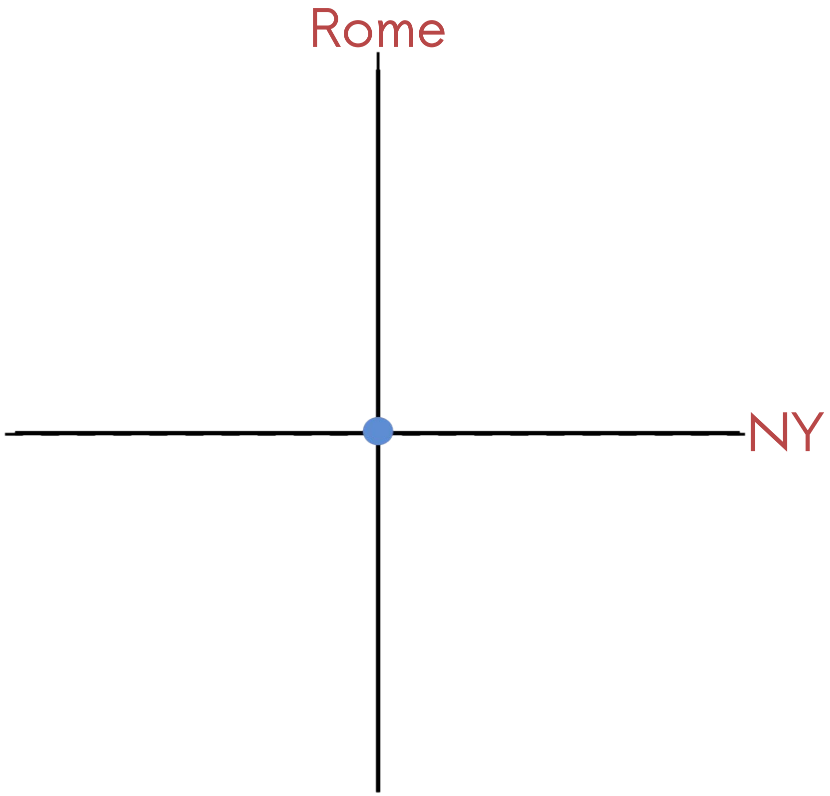

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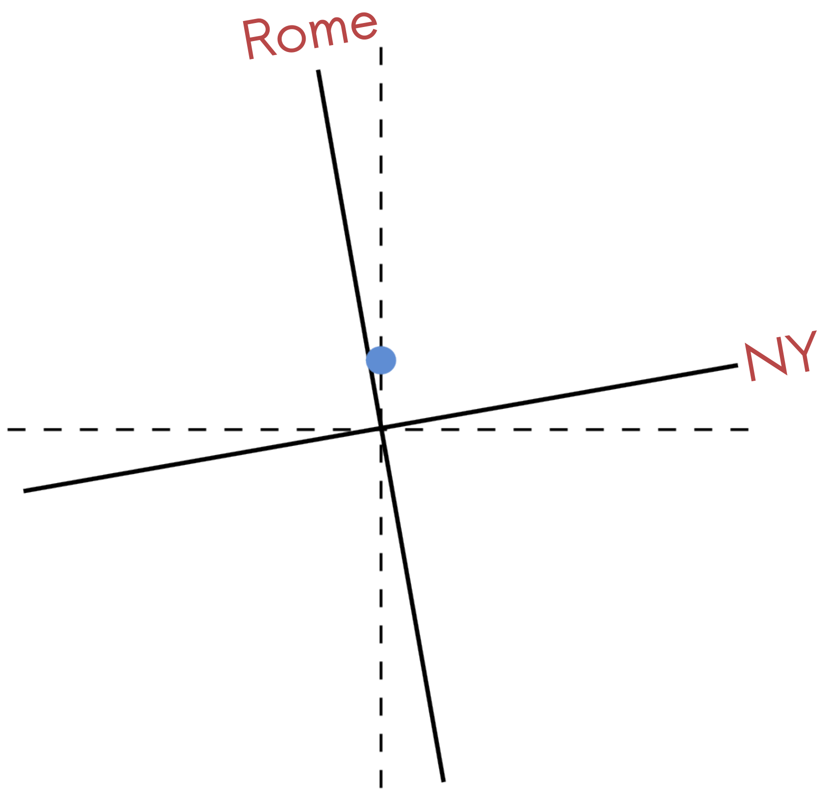

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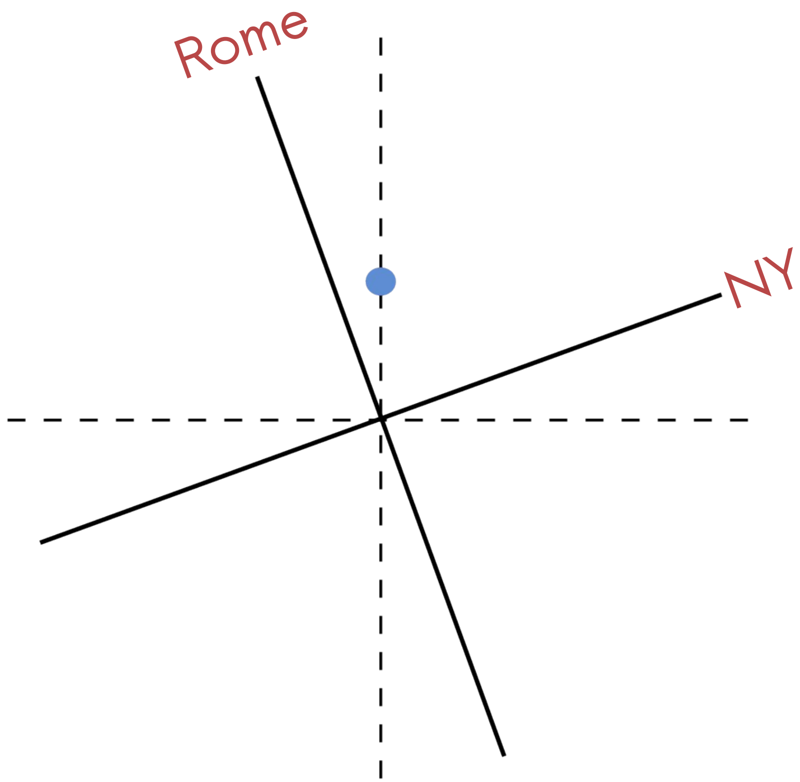

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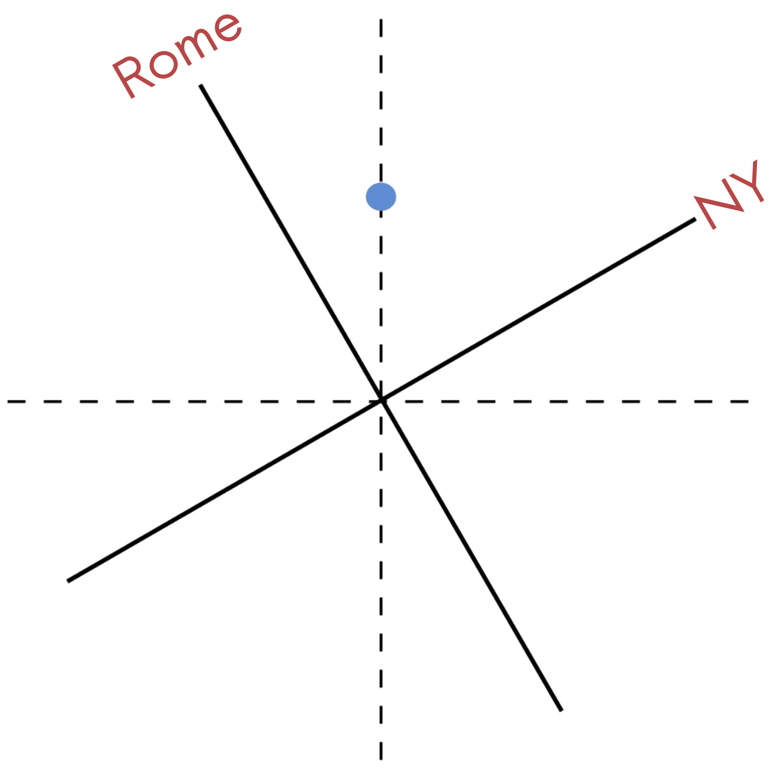

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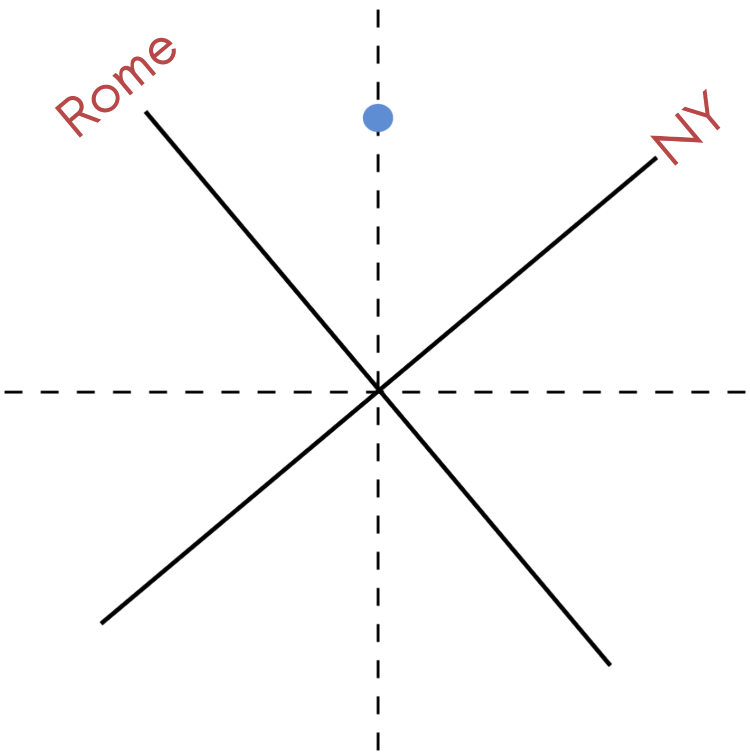

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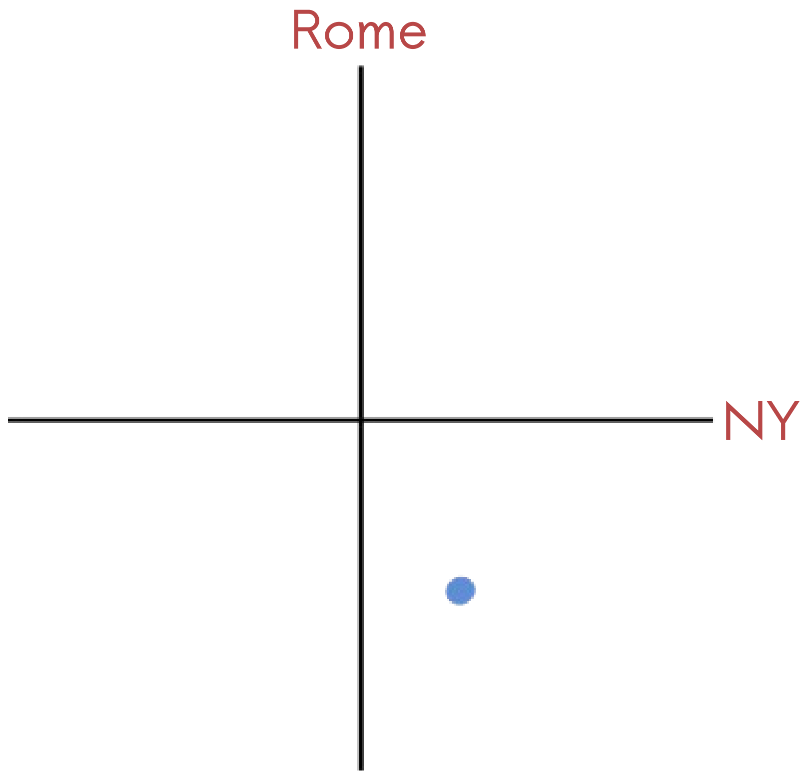
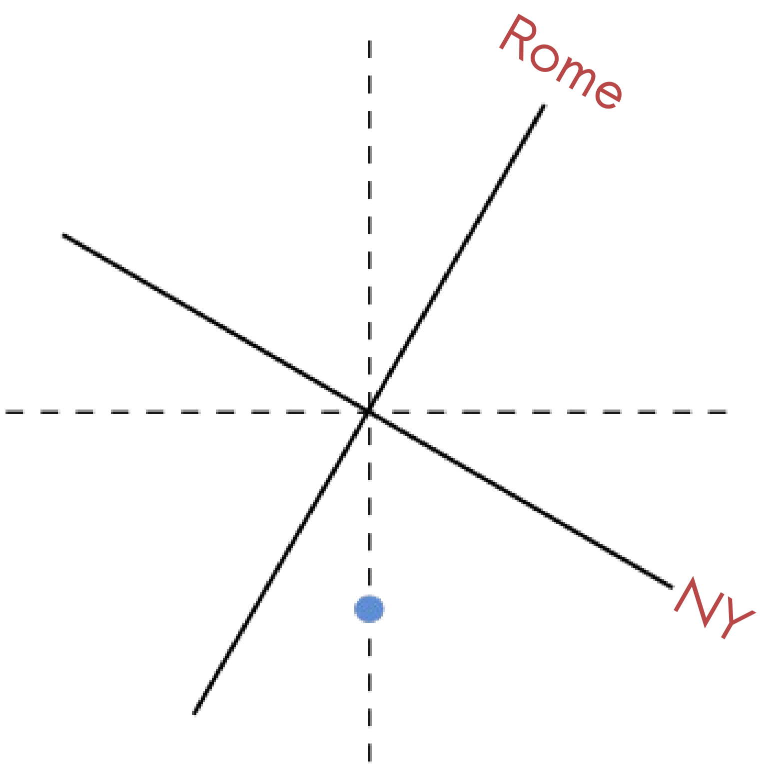


object's position as seen from the rotating coordinates



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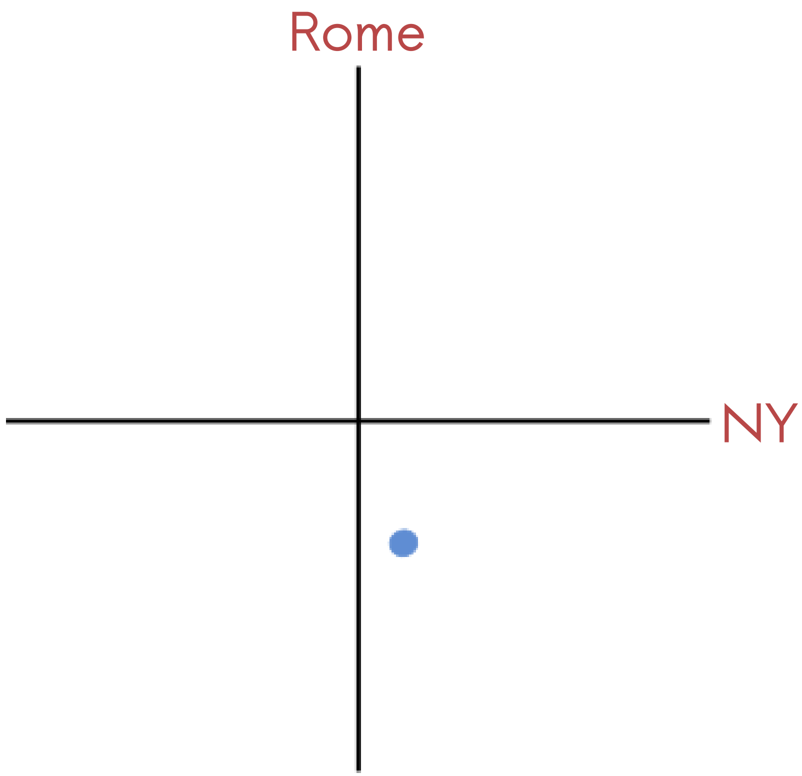

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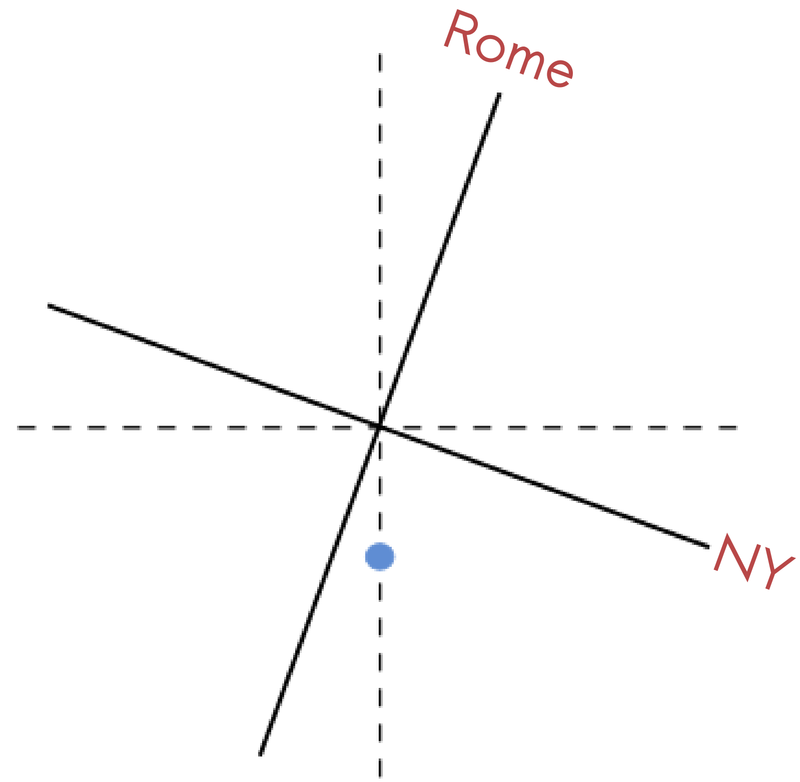

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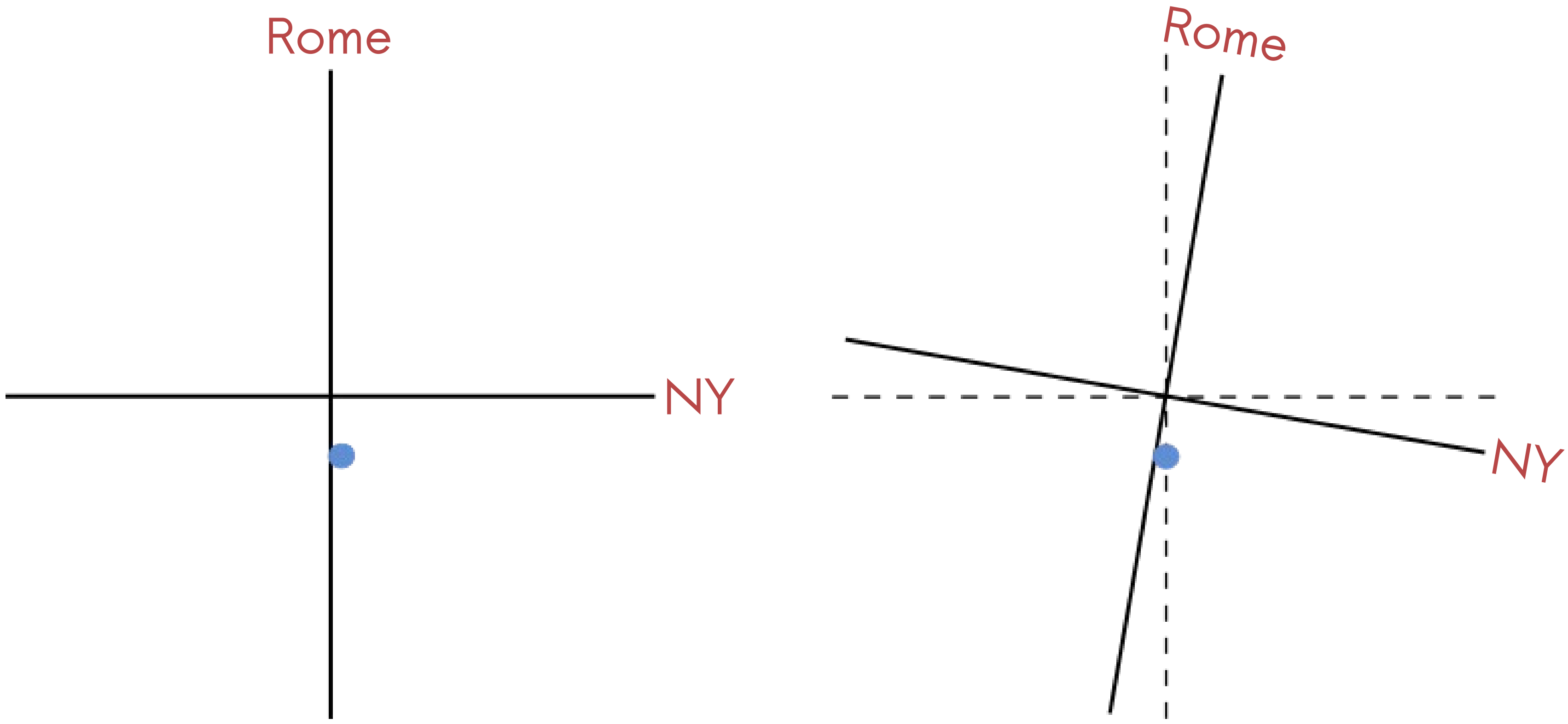

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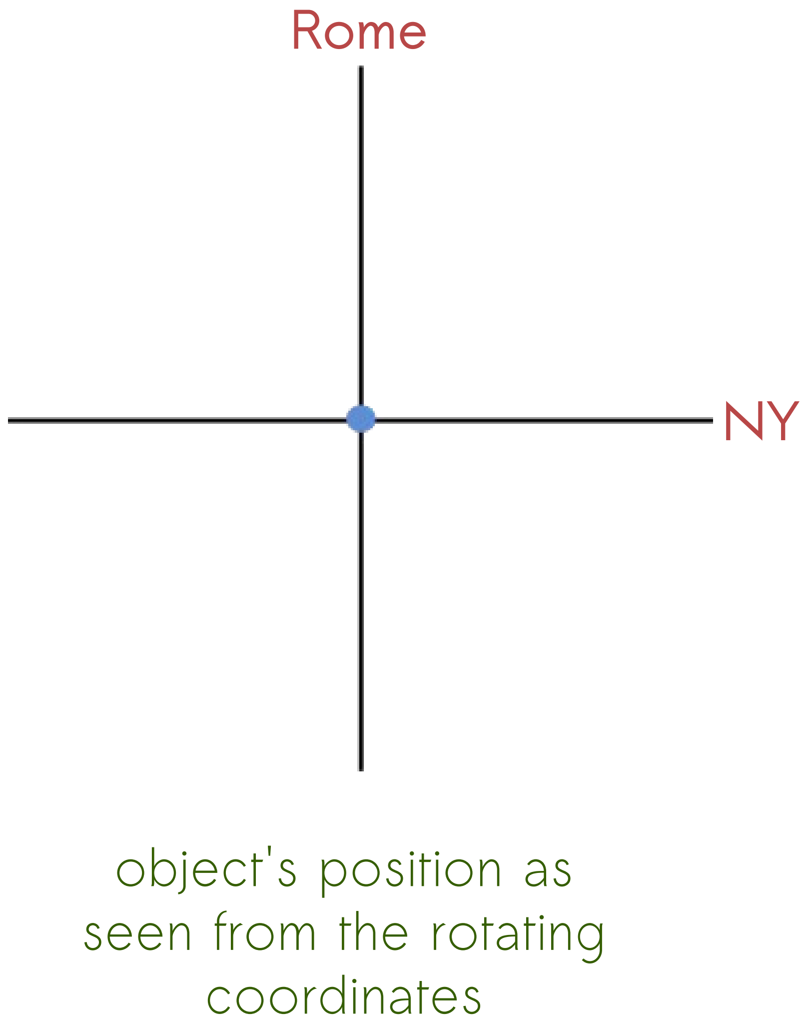

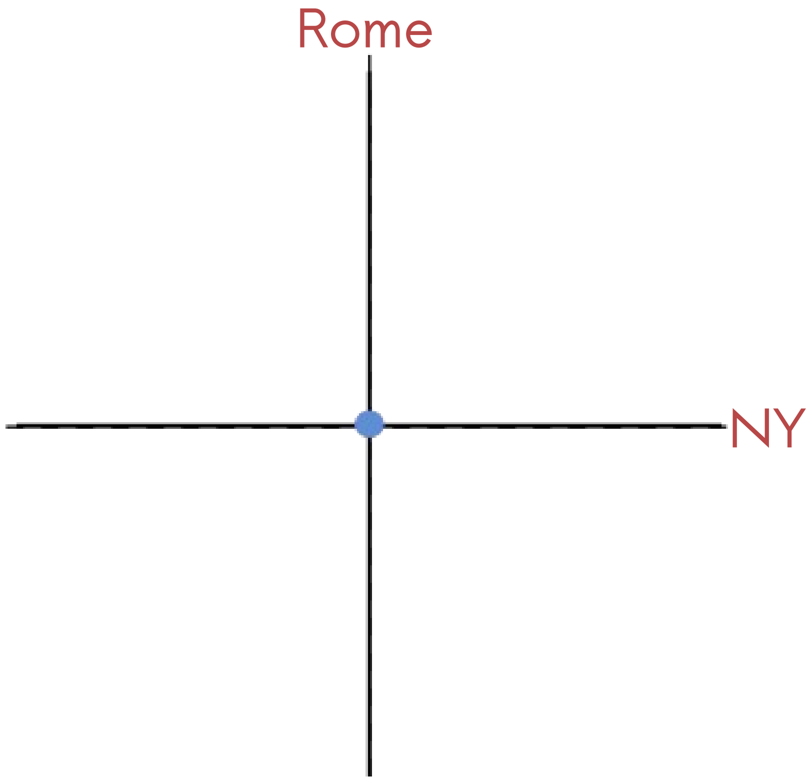

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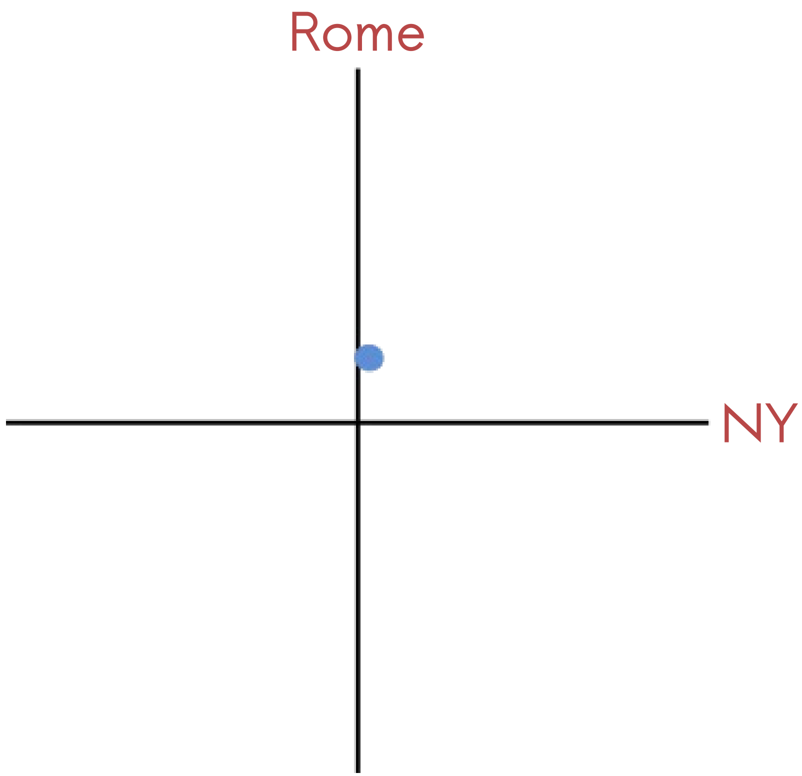

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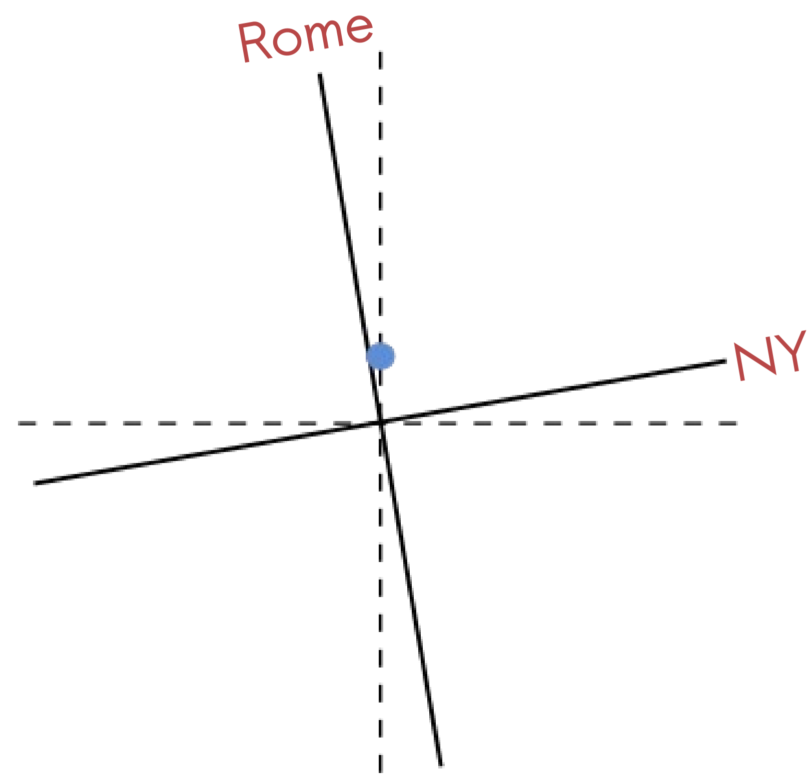

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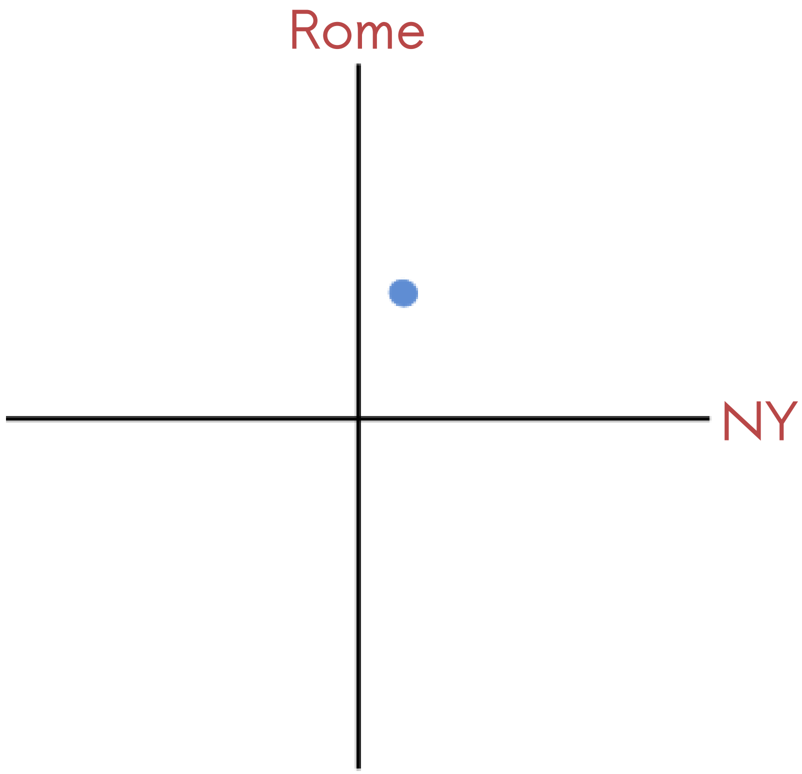

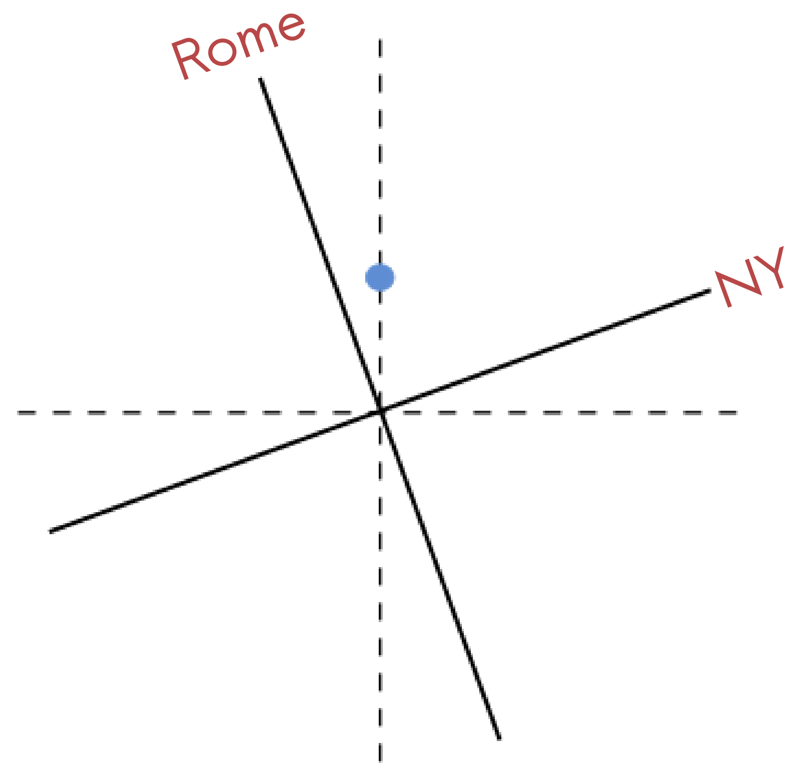

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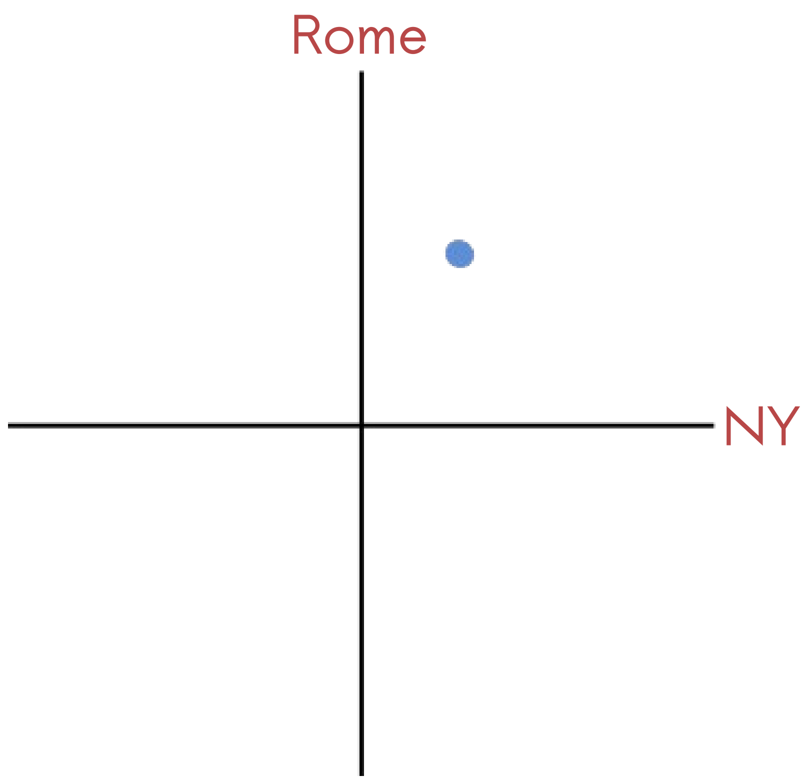

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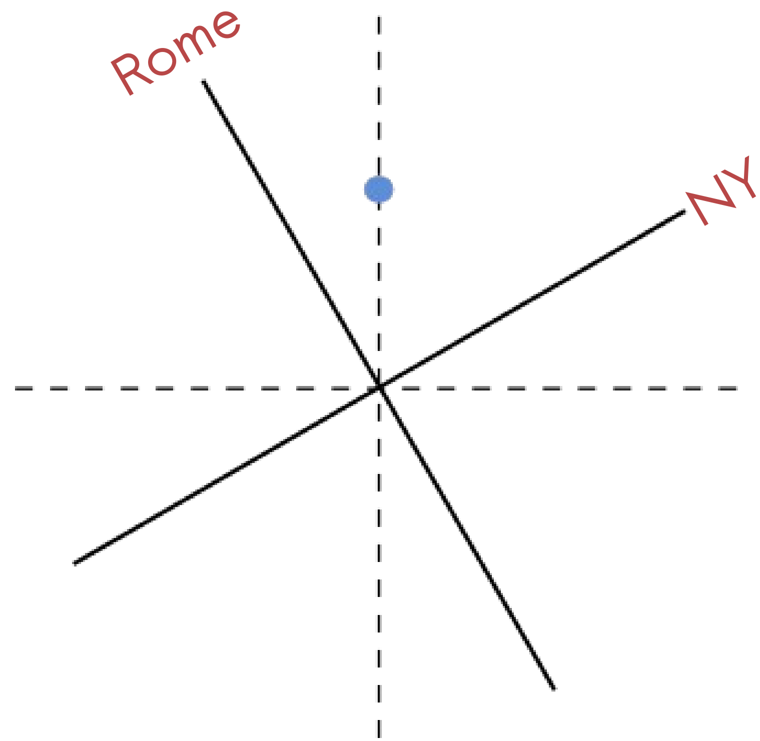

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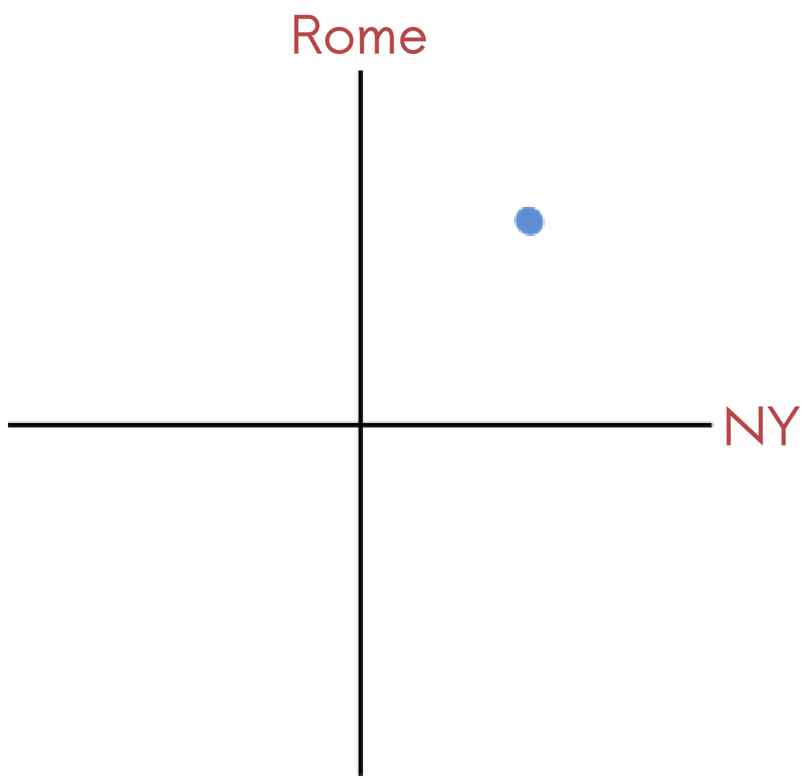

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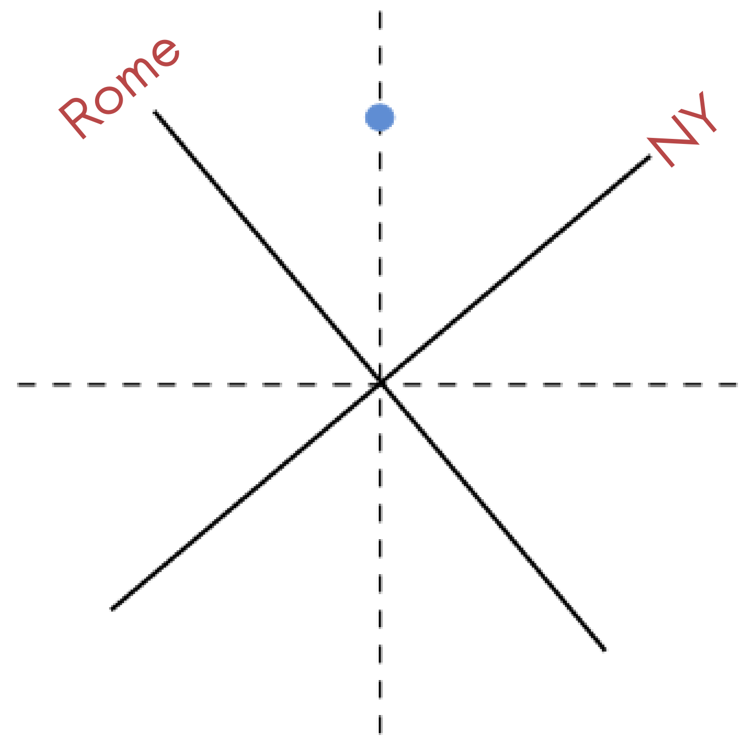
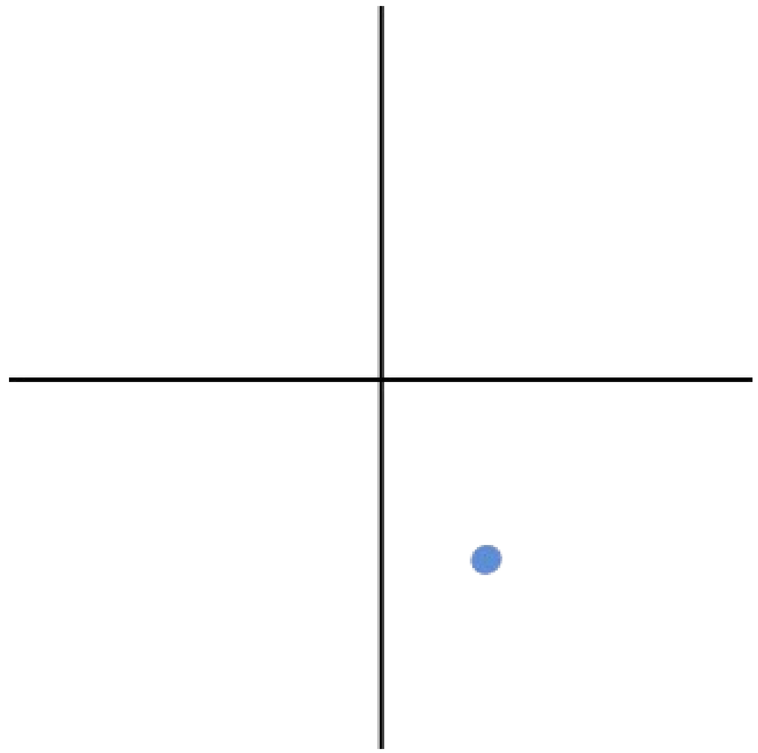


- This bending of the path as seen from the rotating coordinate system is called the **Coriolis effect**, and the associated apparent force is called the **Coriolis force (CF)**



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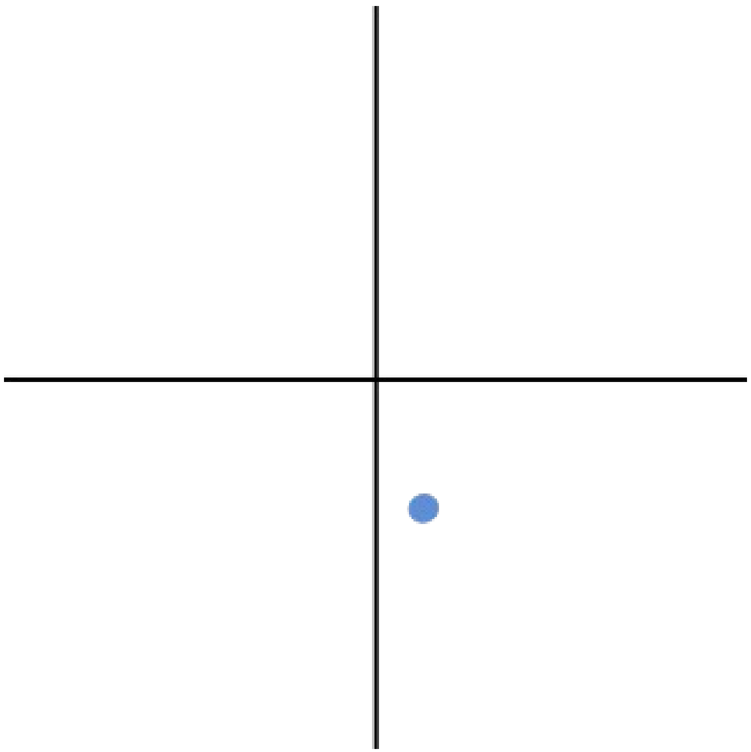

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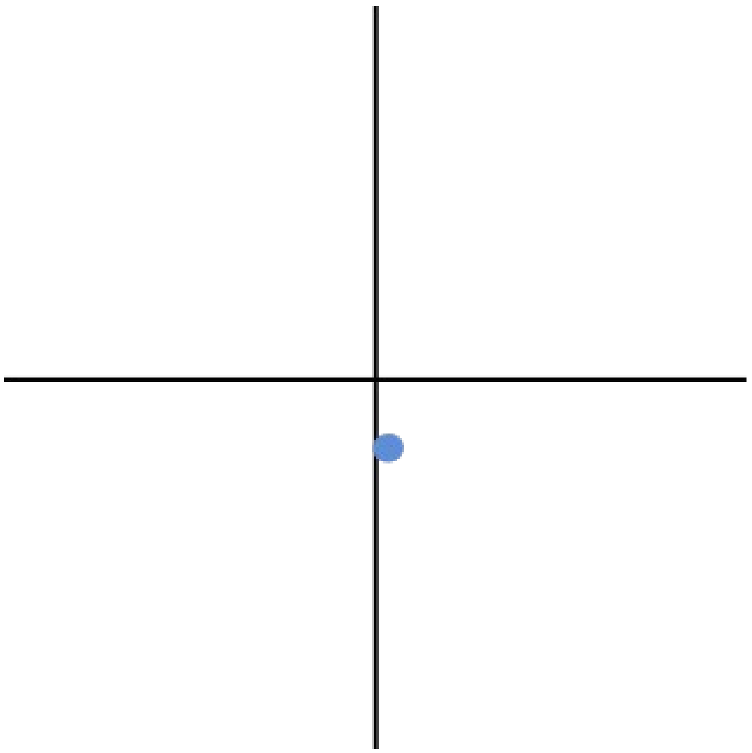

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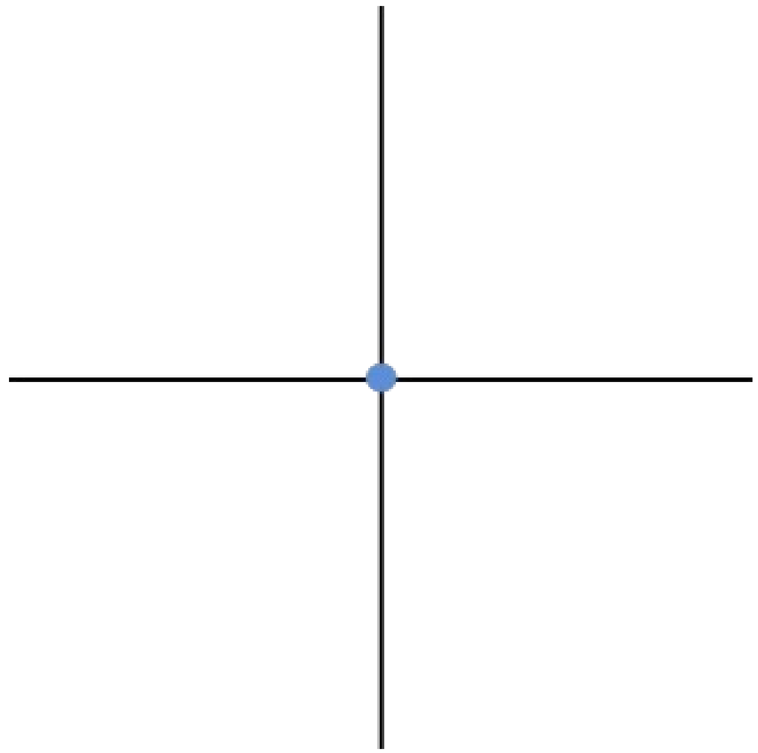

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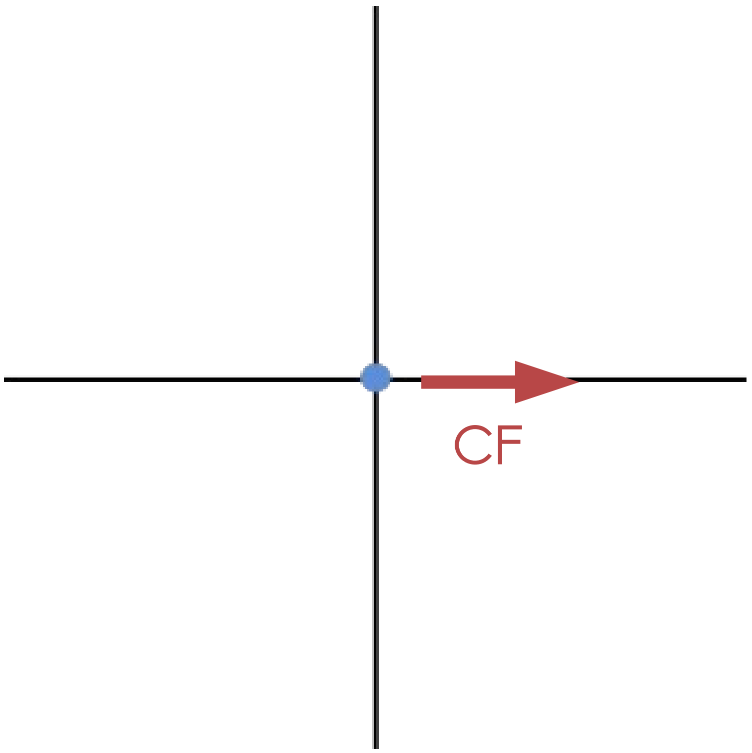

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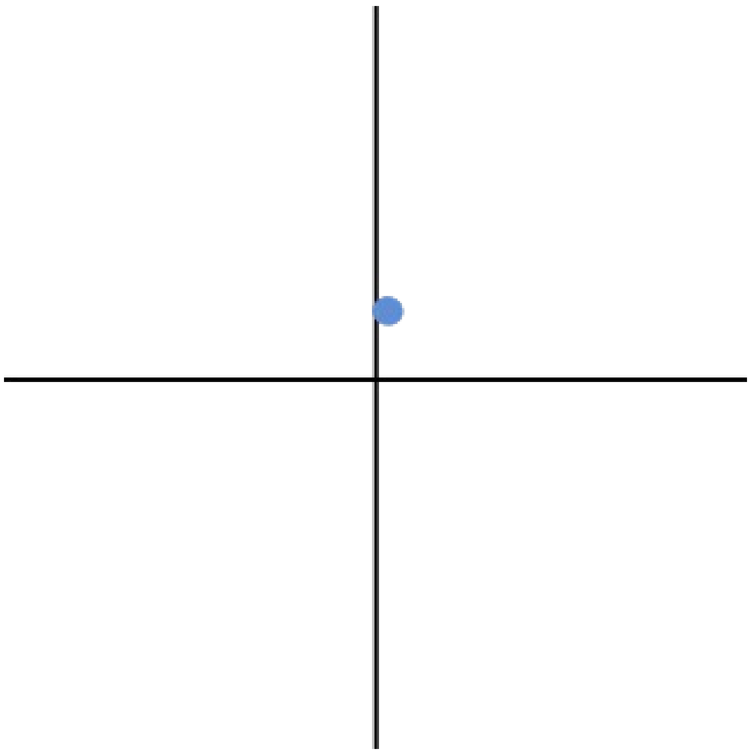

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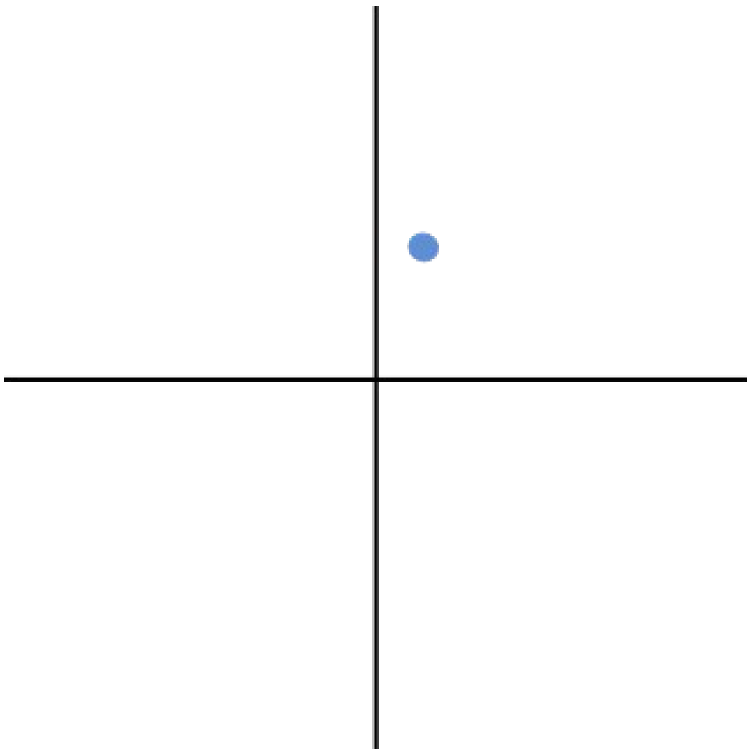

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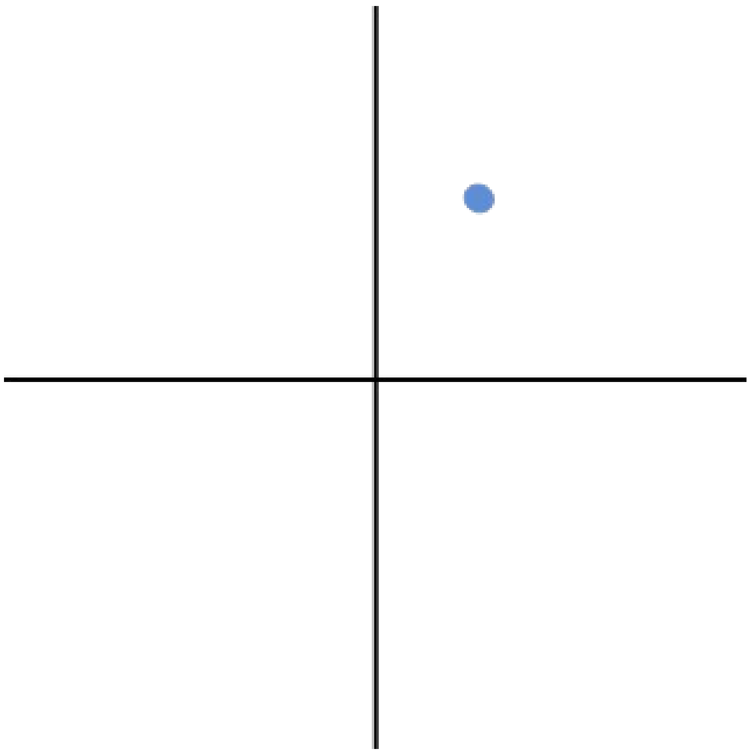

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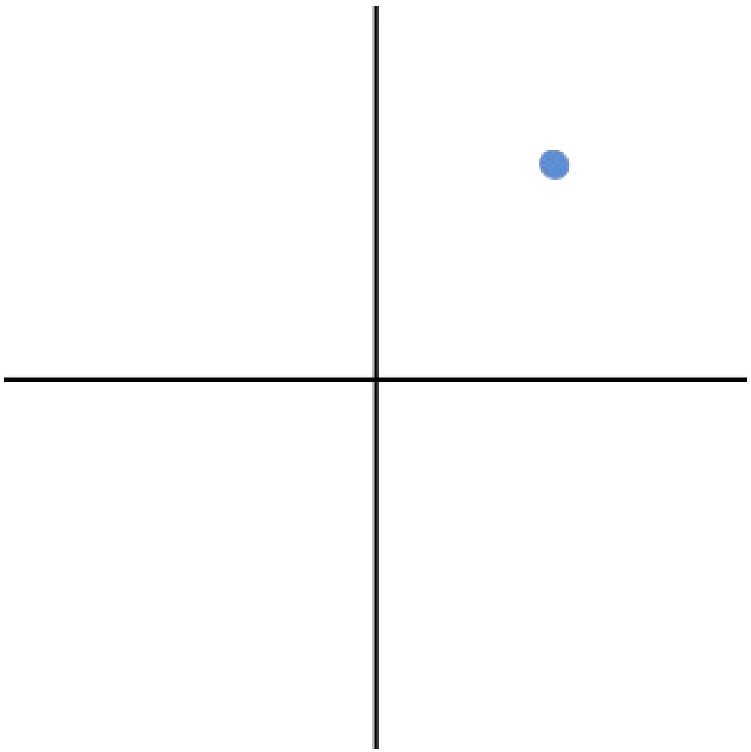

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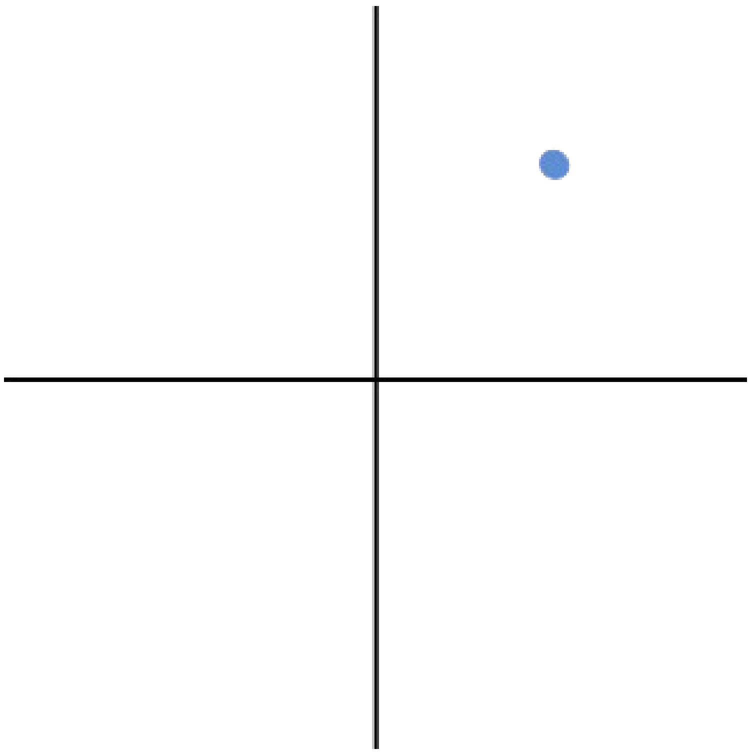
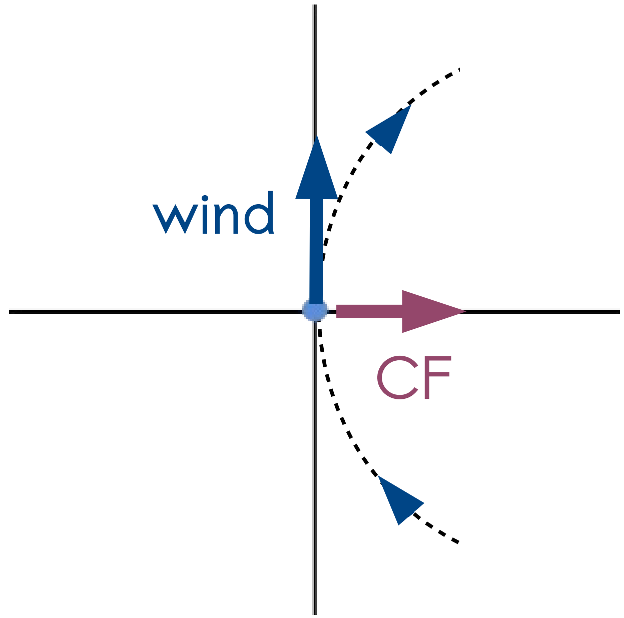
- In our case, the moving object is any small mass of air as it moves through the atmosphere. And because the Earth is rotating, this air will appear to be deflected by a Coriolis force, much like the example shown.

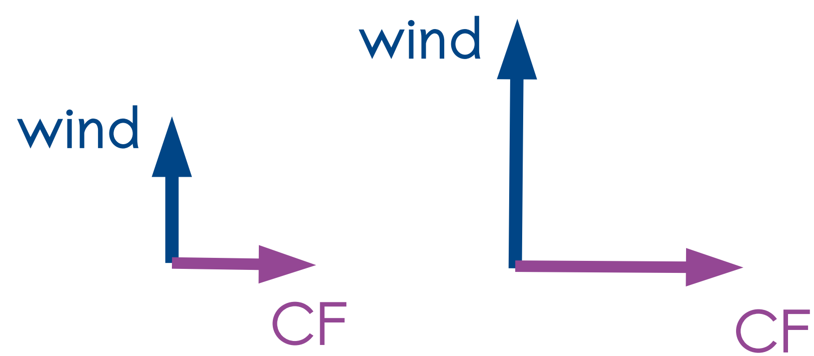


Two important properties of the Coriolis force:



- The *direction* of the force is always perpendicular to the air motion (i.e., perpendicular to the wind)

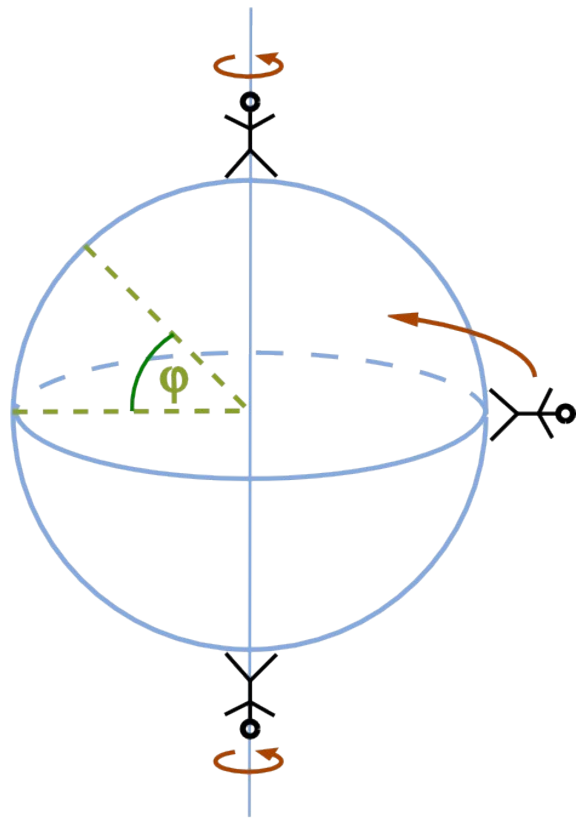
- The *strength* of the force is proportional to the wind speed (i.e., faster winds imply a bigger force)



The Coriolis Force on the Rotating Earth

An observer on the rotating Earth spins at different rates, depending on location:

- An observer at the North Pole spins counter-clockwise



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An observer on the rotating Earth spins at different rates, depending on location:

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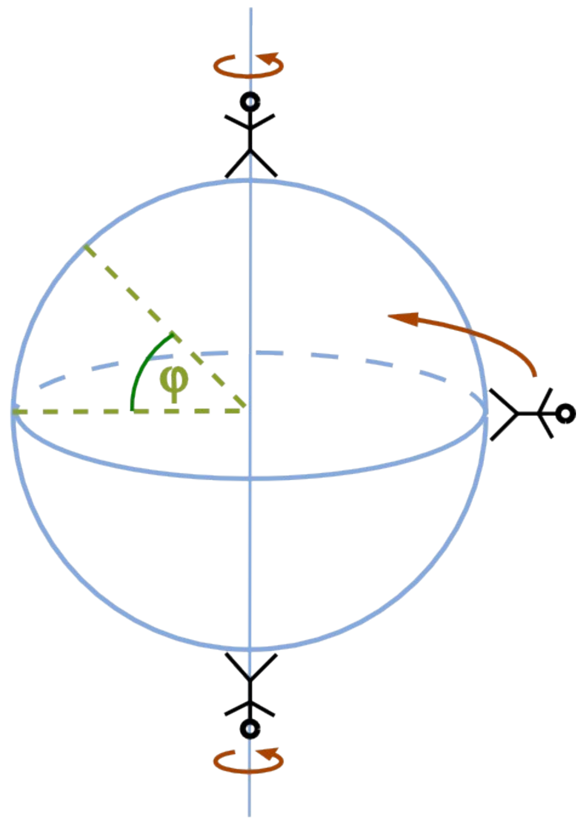
- At the equator, the observer doesn't spin at all (he just moves forward)



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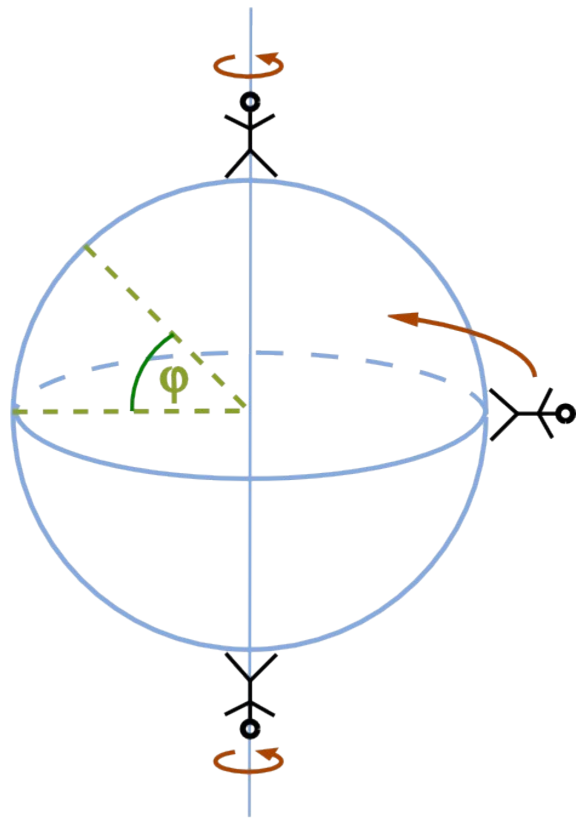
- At the South Pole, the observer spins clockwise



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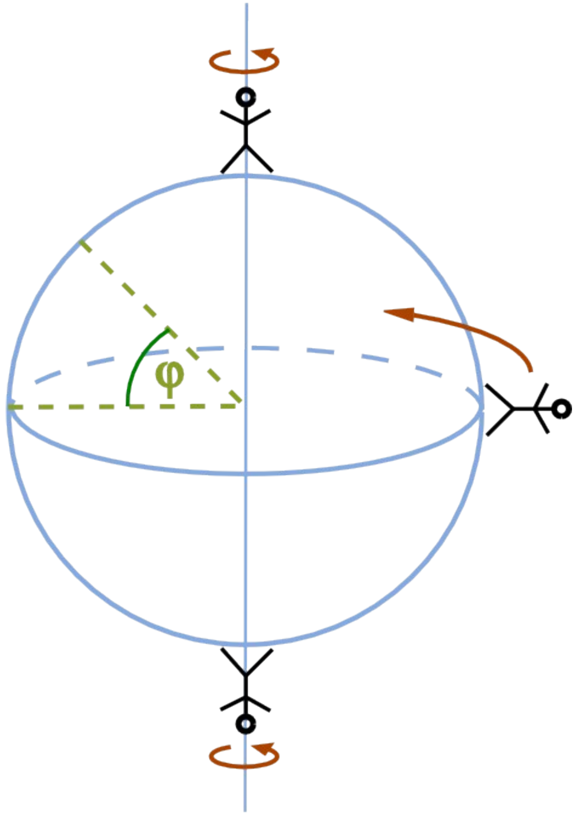

As a result, the Coriolis force varies with the latitude.....

Two things we can infer……

- The Coriolis force is strongest at the poles and zero at the equator
  - In between, the force varies with sin of the latitude ϕ; i.e.,

$$CF \sim \sin(\phi)$$

- The Coriolis force pulls in opposite directions for the Northern and Southern Hemispheres
  - In the Northern Hemisphere, the Coriolis force pulls to the right of the air motion
  - In the Southern Hemisphere, Coriolis pulls to the left