ASTR 1P01

Brock University

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Lecture 6:
Newtonian physics

We will learn about…

- Some basic concepts in physics, such as mass, density, momentum, and rate of change.
- Newtonian mechanics and Newtonian gravity: the laws of physics that control the motion of most things in the universe, including stars and planets.

Nebula NGC 6357
Credits: NASA

Newton's first law of motion

- Isaac Newton, born in 1642, was an English mathematician, physicist, and astronomer.
- He is responsible for establishing the field of classical mechanics.
- In 1687, Newton published his book "Mathematical Principles of Natural Philosophy".
- There he introduced his three laws of motion and his law of universal gravitation.

Newton's first law of motion

- Before Newton, the motion of the planets was a mystery.
- Galileo, Kepler, and others described some properties of this motion, but the motion itself was only understood after Newton published his laws.
- With Newton's laws, it finally became possible to do a complete mathematical analysis of the motions of the planets.
- This was used to derive and explain Kepler's laws from fundamental principles.

Newton's first law of motion

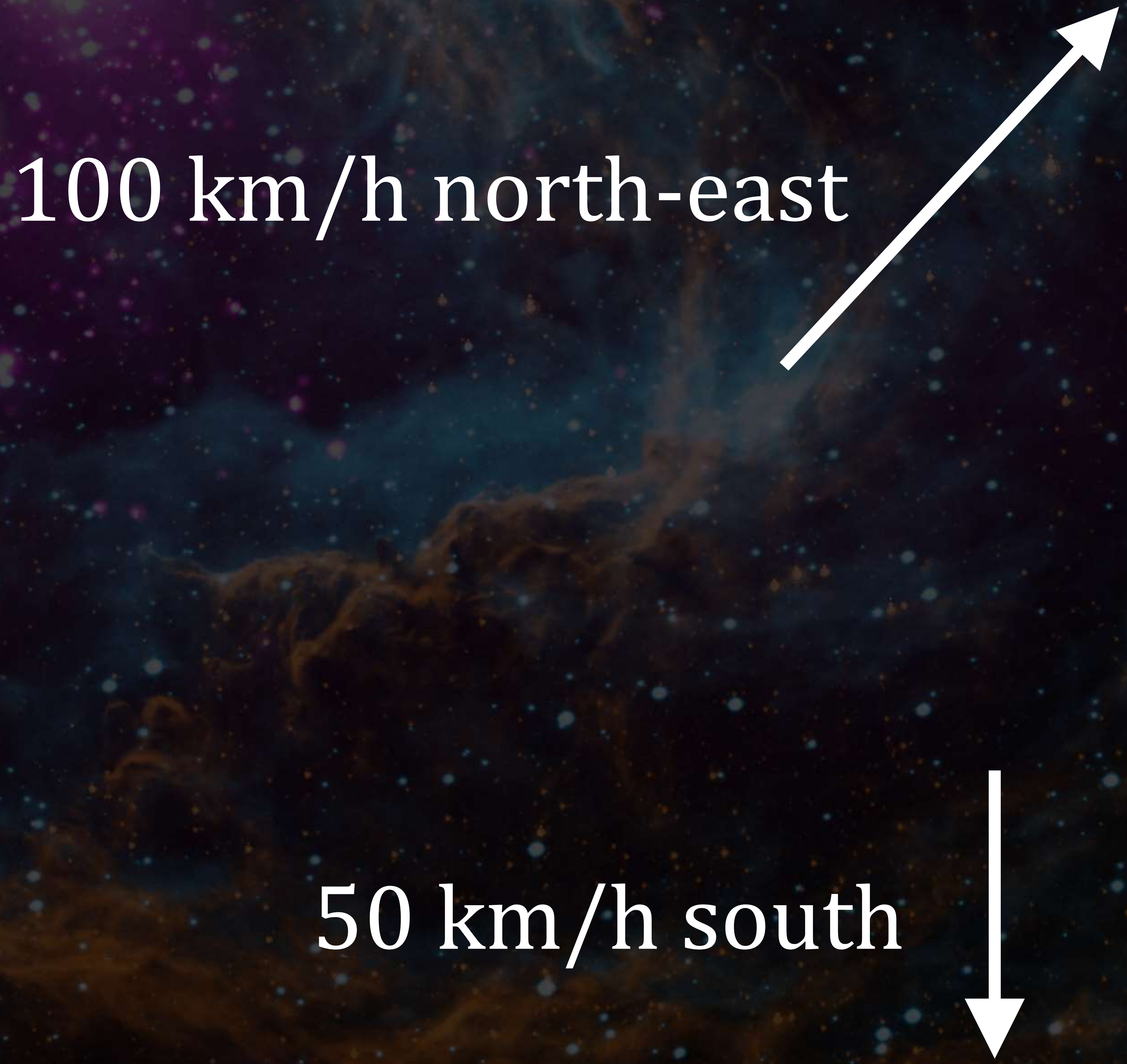
- Newton's laws apply not only to planets – they also apply to objects on Earth, and to Earth itself.
- And this is further evidence that the planets are made from the same matter as the Earth is.
- If I drop a ball on Earth, it follows the exact same laws as the Earth itself does when it orbits around the Sun.
- And if I drop a ball on Mars, or in the Andromeda galaxy, or anywhere else in the universe, it will still follow the same laws.

Newton's first law of motion

- To explain Newton's laws, we first need to clarify the difference between speed and velocity.
- In physics, speed means how fast you're moving, e.g. 100 km/h.
- Velocity has two components: a speed and a direction.
- So 100 km/h is a speed, while 100 km/h due north is a velocity.

Newton's first law of motion

- Mathematically, speed is just a number, while velocity is a vector.
- A vector is an arrow that has a length and a direction.
- The length, or magnitude, of the velocity vector is the speed.



100 km/h north-east

50 km/h south

Newton's first law of motion

- In the previous lecture, we learned that the inertia of an object is its natural tendency to keep moving at the same speed.
- Newton's first law of motion is basically a more precise version of Galileo's law of inertia.
- It states that an object moving at constant velocity will not change its speed unless acted on by a force.
- "Constant velocity" also includes being at rest – a constant velocity of zero.
- So Newton's first law also means that an object at rest will stay at rest unless acted on by a force.

Newton's first law of motion

- But what exactly is a force?
- Mathematically, force is a vector. Again, this means it has both a length and a direction.
- Physically, a force is an interaction or influence that pushes or pulls an object.
- The length of the force vector tells us how strong the force is.
- The direction of the force vector tells us the direction of the push or pull.

Newton's first law of motion

Force is measured in units of newton (N).

This force pushes the ball with 100 N to the north-east.

This force pulls the ball with 50 N to the south.

Newton's first law of motion

- Usually, we don’t really see Newton's first law in action.
- That's because moving objects generally touch surfaces, leading to friction; or the air, leading to air resistance.
- Both are types of forces, and these forces eventually reduce the object's speed to zero.
- Also, if you throw something in the air, the force of gravity will pull it back to the ground.
- So on Earth, objects never actually continue to move at constant velocity forever.

Newton's first law of motion

- But in space, there's an almost perfect vacuum, so stars, planets, and other objects can move forever without slowing down.
- If you throw a ball in space, far from the gravitational influence of any planet or star, the ball might keep moving at a constant speed in a straight line forever!

Some basic concepts in physics: mass

- Before we can understand Newton's second law, we need to understand some basic physics concepts.
- Intuitively, the mass of an object is a measure of how much matter is in that object.
- Mass is measured in units of kilograms (kg).

Some basic concepts in physics: weight

- The weight of the object is proportional to its mass, but the two quantities are not the same.
- The mass of an object is constant, it never changes.
- The weight of an object measures how much gravitational force attracts the object to the surface of a planet.
- So the object's weight will be larger on Earth than on the Moon, for example, since the Earth has more mass, so it exerts more gravity.
- In space, far from any sources of gravity, objects have no weight.

Pop quiz

- The gravity on the surface of Mars is about 1/3 of the gravity on the surface of Earth.
- If my mass is 60 kg on Earth, how much will my mass be on Mars?

A: 20 kg

B: 180 kg

C: 60 kg

Pop quiz

- The correct answer is:

C: 60 kg

- Mass is constant. If my mass is 60 kg on Earth, then it’s also 60 kg anywhere else. Only weight depends on the strength of gravity.

Some basic concepts in physics: density

- Imagine that you have 1 kg of bricks and 1 kg of feathers.
- Intuitively, the bricks “should” weigh more than the feathers, which means they should have more mass.
- But in reality, both the bricks and the feathers have the same mass of 1 kg!

1 Kilogram of Bricks vs. Feathers

Credits: OpenStax College Physics

Some basic concepts in physics: density

- So what's the difference? The bricks have a higher density.
- Density is defined as mass per unit volume.
- It is measured in units of kg per meter cubed (kg/m^3).
- If a material has a density of 1 kg/m^3:
  - 1 m^3 of this material will have a mass of 1 kg.
  - 2 m^3 of this material will have a mass of 2 kg.
  - And so on.

Some basic concepts in physics: density

- The average density of a brick is 2,000 kg/m^3.
- The average density of a feather is 2 kg/m^3, which is 1,000 times smaller.
- This means that to get 1 kg of feathers, we need a volume that is 1,000 times larger than the volume of 1 kg of bricks!

Pop quiz

- The density of the human body is approximately 1,000 kg/m^3. What is the volume of a 100 kg human?

A: $\frac{1}{10}\,\mathrm{m}^3$

B: $1\ \mathrm{m}^3$

C: $10\ \mathrm{m}^3$

Pop quiz

- The correct answer is:

$$\text{A: } \frac{1}{10}\,\text{m}^3$$

- If one 100 kg human has a volume of $\frac{1}{10}\,\text{m}^3$, then ten 100 kg humans will have:
  - Total mass: 1,000 kg.
  - Total volume: 1 m^3.
  - Density: 1,000 kg/m^3.

Some basic concepts in physics: momentum

- Momentum is the product of mass and velocity.
- You can think about momentum in terms of atoms.
- If a 1 kg brick is moving with a velocity of 1 m/s, each individual atom inside the brick moves with the same velocity.
- The mass is analogous to the number of atoms. So the momentum, mass × velocity, is like adding up the velocities of all the atoms.
- The momentum of this brick will be $1\text{ kg} \times 1\text{ m/s} = 1$.
  - The units of momentum are $\text{kg} \cdot \text{m/s}$, but that's not important right now.

Some basic concepts in physics: momentum

- Consider a brick with twice the mass, $2\ \mathrm{kg}$, moving at the same speed, $1\ \mathrm{m/s}$.
- Even though each individual atom is still moving at 1 m/s, there are now twice as many atoms, so the brick will have twice the momentum.
- The momentum will be $2\ \mathrm{kg} \times 1\ \mathrm{m/s} = 2$.

Some basic concepts in physics: momentum

- Now consider a $2\ \mathrm{kg}$ brick moving at twice the speed, $2\ \mathrm{m/s}$.
- Even though we have the same number of atoms as the previous brick, each individual atom is now moving at twice the speed, so the brick will have twice the momentum.
- The momentum will be $2\ \mathrm{kg} \times 2\ \mathrm{m/s} = 4$.
- In conclusion, we see that the momentum measures the “total movement” of all the atoms in an object.

Pop quiz

- What is the total momentum of two 3 kg bricks moving at 2 m/s?

A: 6

B: 12

C: 24

Pop quiz

- The correct answer is:

B: 12

- Two 3 kg bricks have a total mass of 6 kg. So the momentum is:

$$6\ \text{kg} \times 2\ \text{m/s} = 12$$

Some basic concepts in physics: rate of change

- Velocity is the rate of change of position. It tells us how fast the position changes.
- In other words, it tells us by how many meters the position changes every second.
- That's why it's measured in meters per second (m/s).

Some basic concepts in physics: rate of change

- If an object moves away at velocity 1 m/s:
  - After 1 second it will be 1 meter away.
  - After 2 seconds it will be 2 meters away.
  - And so on.
- If an object moves away at velocity 5 m/s:
  - After 1 second it will be 5 meters away.
  - After 2 seconds it will be 10 meters away.
  - And so on.

Some basic concepts in physics: rate of change

- Acceleration is the rate of change of velocity.
- It tells us how fast the velocity changes.
- In other words, it tells us by how many meters per second the velocity changes every second.
- That's why it's measured in meters per second per second or meters per second squared (m/s^2).

Some basic concepts in physics: rate of change

- If an object starts from rest and moves with acceleration $1\ \mathrm{m/s^2}$:
  - After 1 second it will be moving at 1 m/s.
  - After 2 seconds it will be moving at 2 m/s.
  - And so on.
- If an object starts from rest and moves with acceleration $5\ \mathrm{m/s^2}$:
  - After 1 second it will be moving at 5 m/s.
  - After 2 seconds it will be moving at 10 m/s.
  - And so on.

Pop quiz

- A ball starting from rest and falling on Earth has acceleration of approximately 10 m/s^2. What will be its velocity after 3 seconds?

A: 10 m/s

B: 20 m/s

C: 30 m/s

Pop quiz

- The correct answer is:

C: 30 m/s

- 10 m/s^2 means:
    - 10 m/s after 1 second.
    - 20 m/s after 2 seconds.
    - 30 m/s after 3 seconds.

Newton’s second law of motion

- Newton's second law of motion says that the force acting on a body is equal to the rate of change of the body’s momentum.
- If there's no force, there's also no change in momentum.
- But if we do apply a force, then it will cause the momentum to change over time. More force means more change in momentum.

Newton’s second law of motion

- Remember that momentum is mass times velocity.
- But in almost all cases, the mass stays constant.
- If there's a force, the momentum changes. But if the mass is constant, then changing the momentum only changes the velocity.
- In other words, if there's a force, then there's also acceleration: a change in velocity.

Newton's second law of motion

- So if the mass is constant, we can say that force equals mass times acceleration.
- Mathematically, you may be familiar with the equation $F = ma$:
  - F is the force,
  - m is the mass (assumed to be constant),
  - a is the acceleration.
- We measure force in newtons (N).
- 1 N is the force that gives a mass of 1 kg an acceleration of 1 $\mathrm{m/s^2}$.
- For example: if I push a mass of 1 kg with a force of 8 N, it will get an acceleration of $8\ \mathrm{m/s^2}$.

Newton’s second law of motion

- On the other hand, if there's no force, there's no acceleration, and the velocity doesn't change.
- But that's Newton's first law: the velocity stays the same unless we apply a force.
- So why do we need the first law? It seems redundant.

Newton’s second law of motion

- Well, not exactly: Newton's first law is needed because it defines the concept of inertial frames of reference.
- A frame of reference is a frame where an observer is at rest.
- An inertial frame of reference is one in which Newton’s first law holds.
- When you’re in a parked car, your frame is inertial.
- When you’re in a car moving at constant speed, your frame is also inertial.

Newton's second law of motion

- But when your car accelerates, the frame is not inertial any more.
- If you accelerate forward, the back of your chair pushes you forward.
- You are at rest in your own frame, even though a force is acting on you.
- So Newton's first law is not valid, and your frame is not inertial.
- In general, an accelerating frame is always a non-inertial frame.

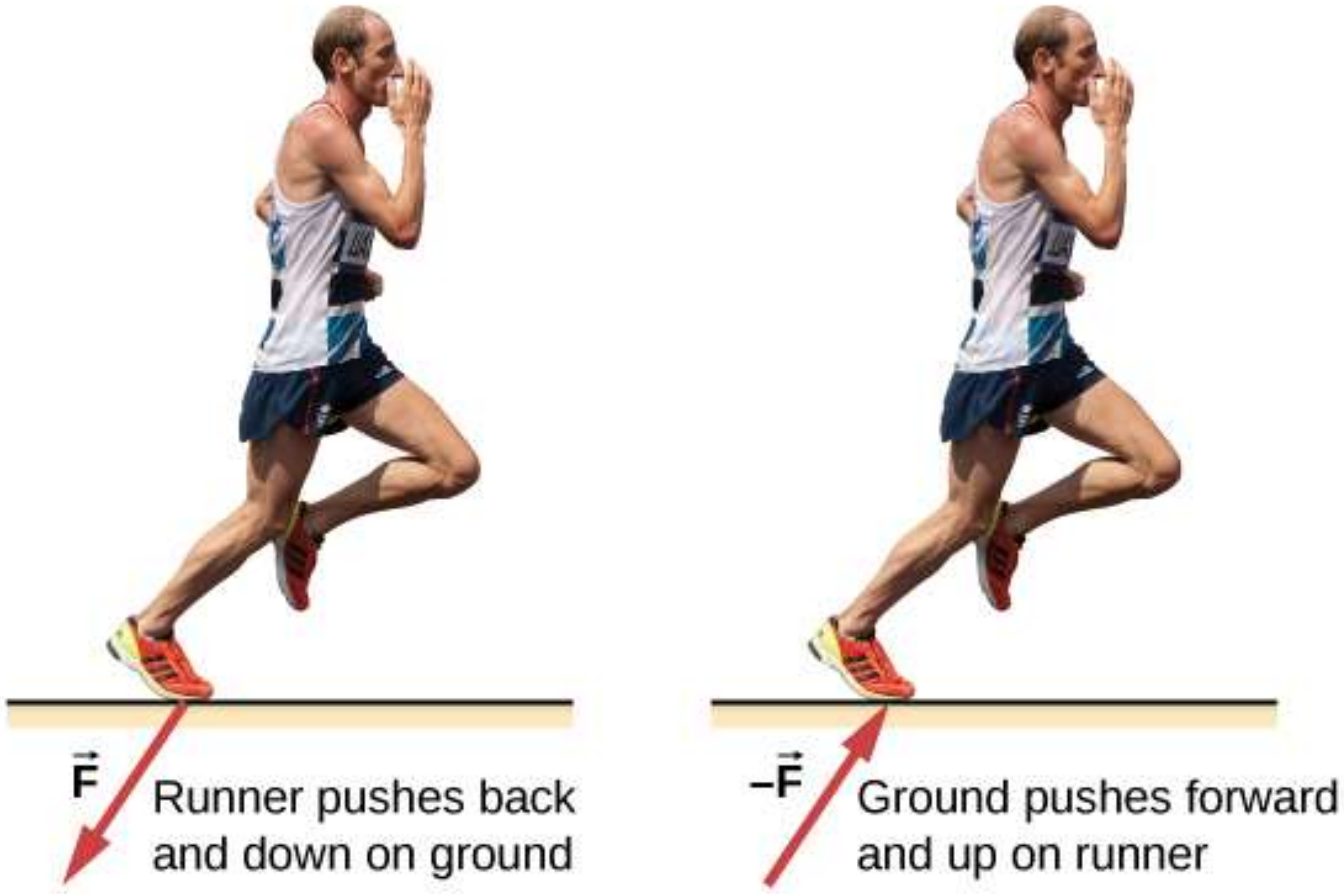
Newton’s second law of motion

- Remember that we can't feel the Earth moving because it's moving at a constant speed, and we can only feel acceleration, not constant speed.
- Newton's second law provides the reason: in an inertial frame, if you're moving at a constant speed, then there's no force acting on you, and therefore nothing to feel.
- But if you're accelerating, then there must be a force causing that acceleration. This force is what your body actually feels when you accelerate.

Newton’s third law of motion

- Newton's third law of motion says that if two objects exert forces on each other, these forces are equal in magnitude and opposite in direction.
- A simpler way of stating the third law is that "every action has an equal and opposite reaction".

- When you walk or run, you are using Newton’s third law.
- Your feet push against the ground (the action).
- The ground pushes back on your feet (the reaction).



A Runner Demonstrating Newton’s Third Law

Credits: OpenStax University Physics

- Rockets also operate using Newton’s third law.
- The rocket exhausts gas towards the back.
- Due to Newton’s third law, this action has an opposite reaction, pushing the rocket forward.
- Rockets don’t need to push on air! This actually works best in a vacuum.

A Rocket Launch Demonstrating Newton’s Third Law
Credits: SpaceX

Newton’s third law of motion

- The most important consequence of Newton's third law is conservation of momentum.
- This means that the total momentum of the two interacting objects never changes.
- The first object applies a force in one direction, causing a change in momentum in that direction.
- But the second object applies the same force in the opposite direction, causing an opposite change in momentum.
- The two changes cancel each other, so the total momentum stays the same.

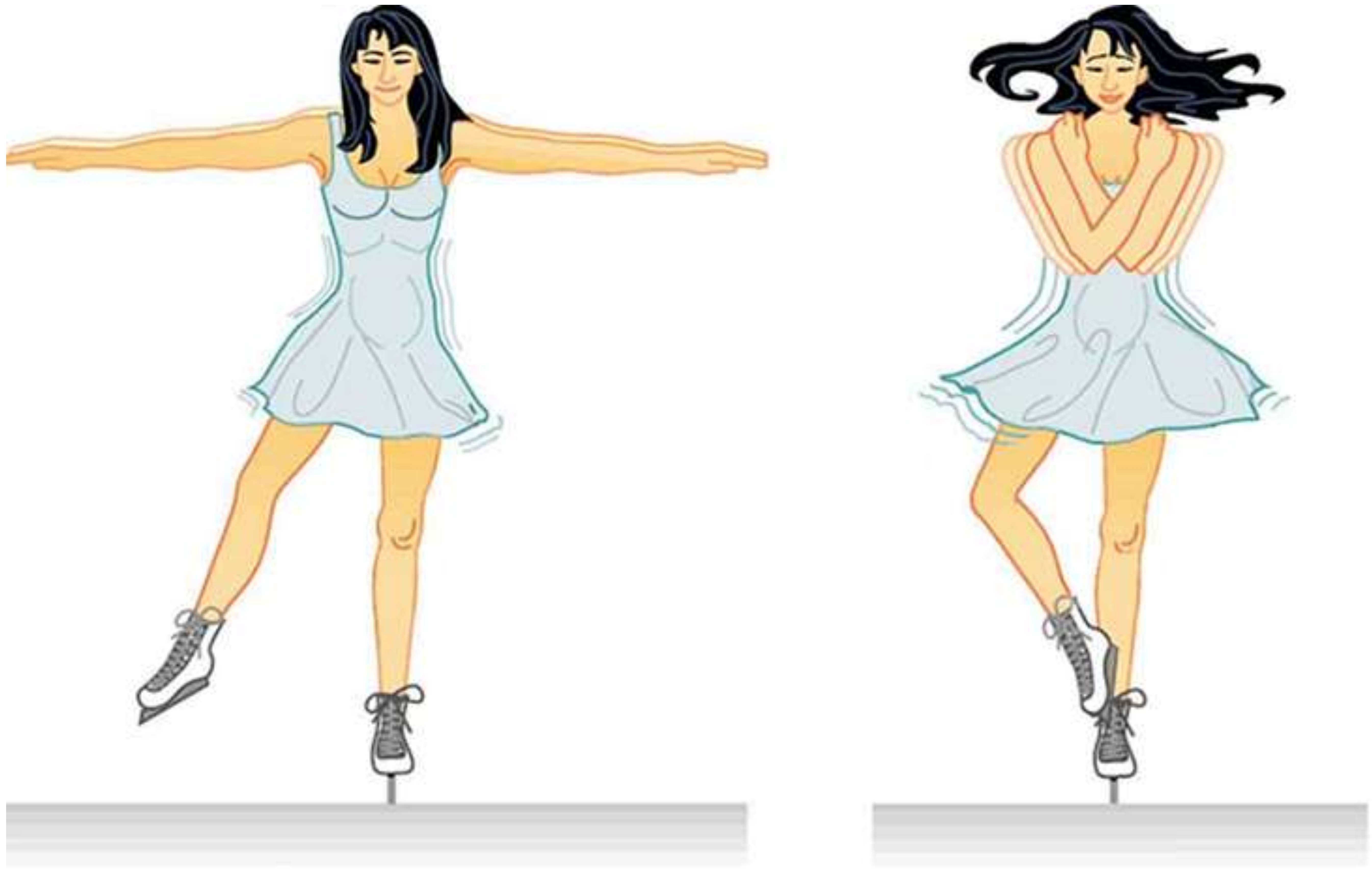
Newton’s third law of motion

- Mass is not conserved, and velocity is not conserved either.
- But momentum, the product of mass and velocity, is conserved.
- We can use the fact that momentum is conserved to simplify a lot of calculations.
- But more importantly, it gives us a better understanding of how our universe works at the most fundamental level.

Angular momentum

- Remember that momentum can be thought of as the “total movement” of all the atoms in an object.
  - Mass is analogous to the number of atoms.
  - Momentum = mass × velocity = adding up the velocities of all the atoms.
- Angular momentum can be thought of as the “total rotation” of an object around a point.
- It is defined as mass × velocity × distance from the point.
- Angular momentum is also conserved.

- A figure skater is spinning with her arms out.
- The angular momentum of the arms is mass × velocity × distance from the axis of rotation.
- When she brings her arms in, the distance becomes smaller.
- The angular momentum and mass stay constant.
- If the distance is smaller, the velocity must increase so that the product stays the same.
- So the skater rotates faster when bringing her arms in.



A Figure Skater Demonstrating Conservation of Angular Momentum

Credits: OpenStax Astronomy

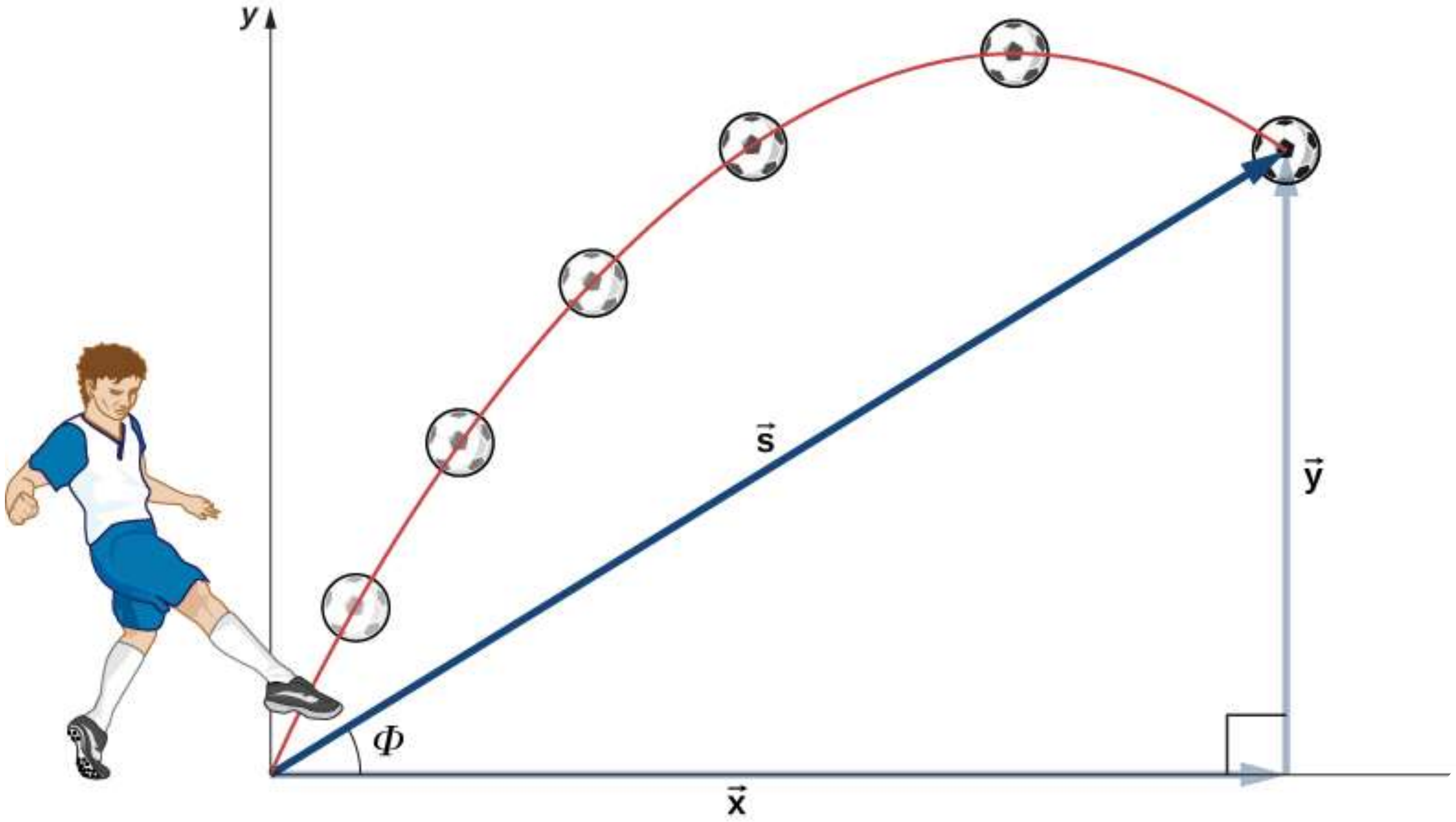
Angular momentum

- Remember Kepler’s second law: a planet's speed in its orbit is inversely proportional to its distance from the Sun.
- Now we know that this is a consequence of conservation of angular momentum.
- This works just like the skater! When the planet is closer to the Sun, the distance decreases, so the speed must increase.

Newton’s universal law of gravitation

- According to Newton’s first law, an object will keep moving in a constant speed in a straight line unless acted on by a force.
- But the planets are not moving in straight lines. According to Kepler’s first law, their orbits are ellipses.
- Therefore, there must be some force bending the paths of the planets.

- On Earth, gravity bends the paths of objects.
- When you kick a ball, it will not continue in a straight line.
- The path of the ball will bend due to gravity.
- Could the same force apply to planets?



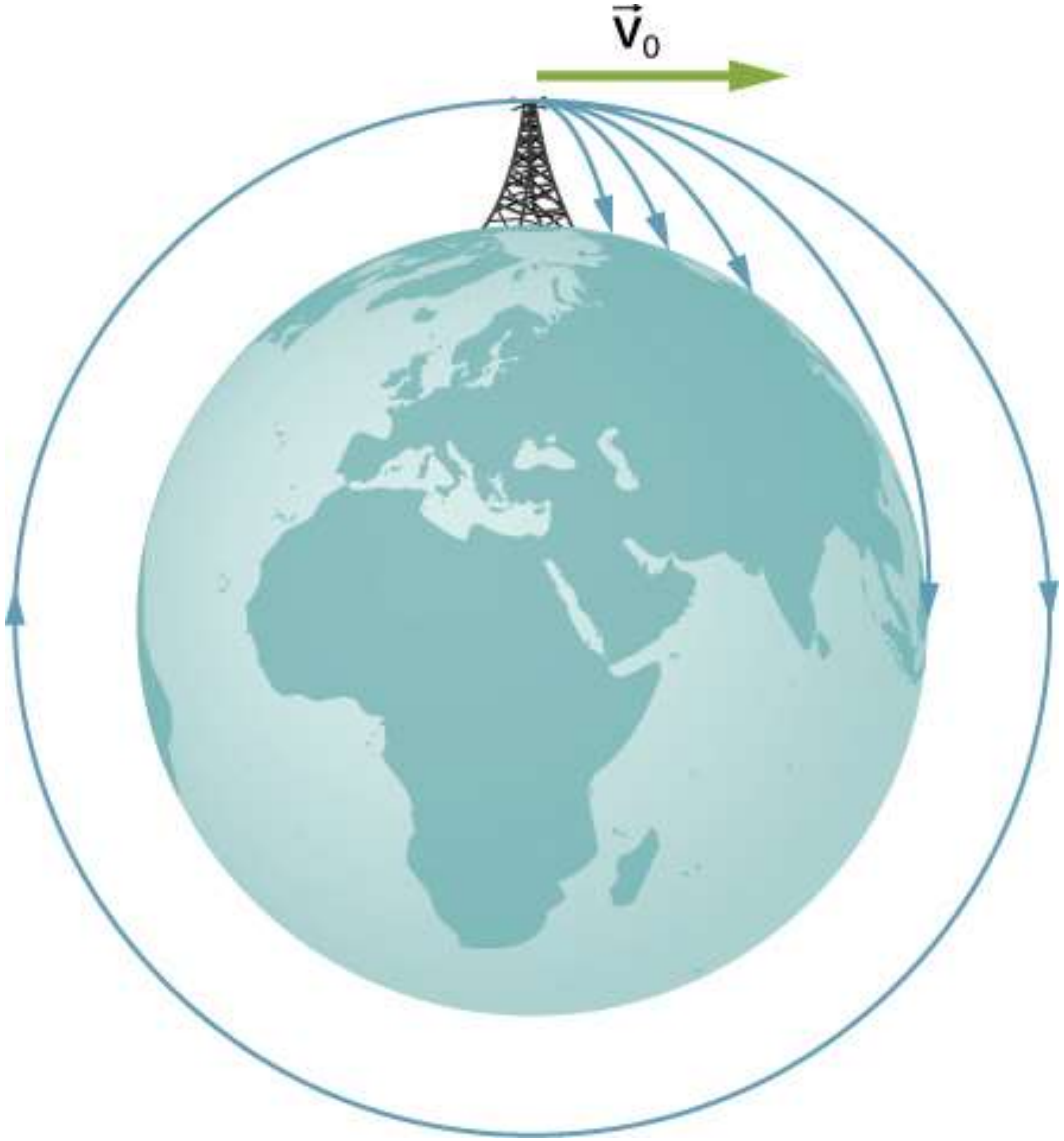
A Ball Following A Parabolic Path

Credits: OpenStax University Physics

Newton’s universal law of gravitation

- Until Newton, it was assumed that gravity works only on Earth.
- But where does it stop? At what distance away from Earth?
- For example, could gravity also pull the Moon, like it pulls a falling rock?
- If so, then this would explain why the Moon isn’t moving in a straight line. It keeps falling towards Earth, and this bends its path.

- Imagine throwing a ball from a high altitude.
- If the ball’s velocity is small, it will fall towards the ground.
- If you throw it fast enough, it will keep falling towards the Earth but never actually hit the ground.
- A similar things happens to the Moon. This explains the elliptical orbit of the Moon around the Earth.



A Ball In Orbit Around Earth

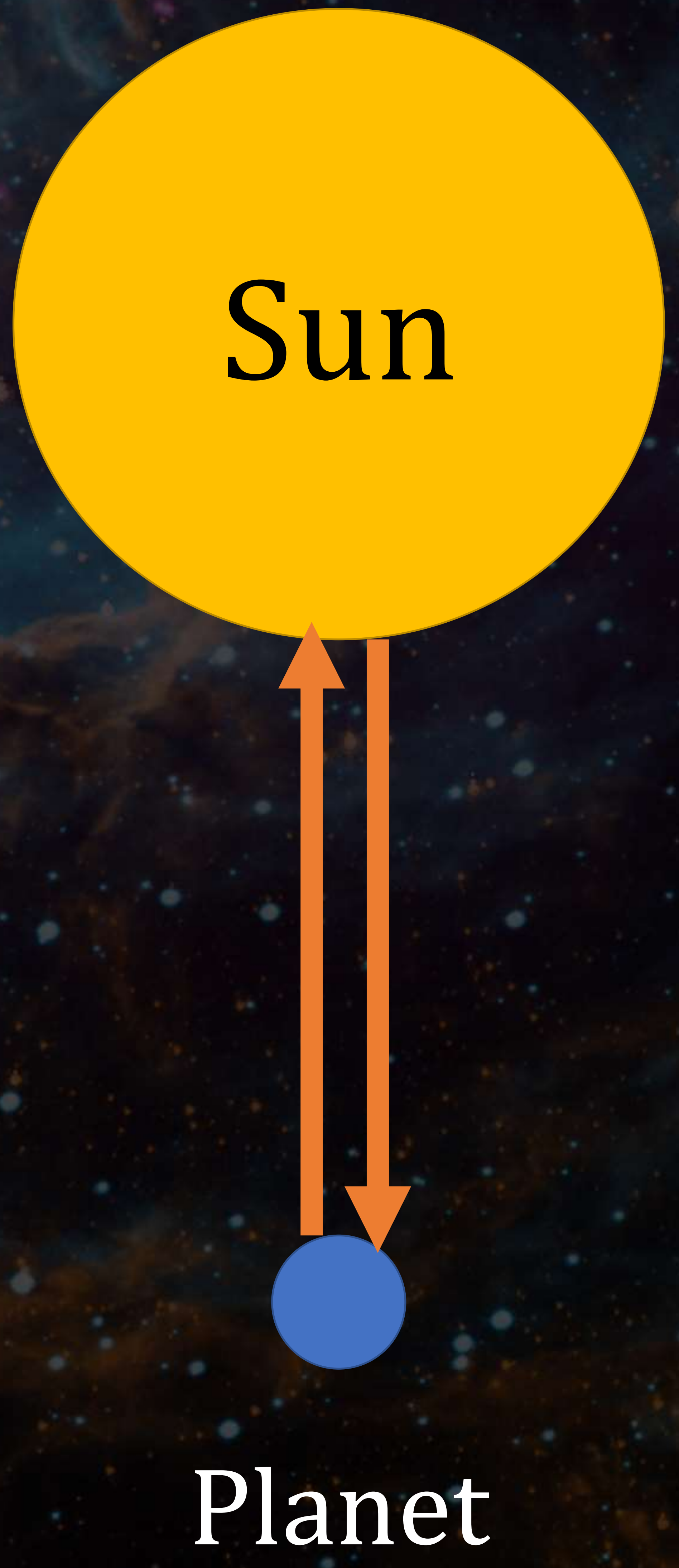
Credits: OpenStax University Physics

Newton’s universal law of gravitation

- If this works for the Moon, then it could also explain the elliptical orbits of the planets around the Sun.
- However, for this we must assume that Earth is not the only source of gravity, as was previously believed.
- The Sun is also a source of gravity, and all the planets “fall” in elliptical orbits around it.

Newton’s universal law of gravitation

- But why should the Earth and the Sun be special? The next logical step is to assume that every object in the universe has gravity.
- This is also consistent with Newton’s 3rd law: forces come in equal and opposite pairs.
- If the Sun applies a gravitational force on a planet, then by the 3rd law, the planet must apply the same force on the Sun.
- Therefore, the planets must also be a source of gravity.



Newton’s universal law of gravitation

- In fact, all objects that have mass attract each other.
  - At least, this is what Newtonian gravity says. General relativity provides a more precise definition of gravity, which we will learn later.
- This is why we call it the universal law of gravitation. It works on any object in the universe, not just on Earth.
- Since Newton was creating a new scientific theory, he had to make sure it’s consistent with the theories that came before it, such as Kepler’s laws.
- This is always the case when creating a new theory. If it’s inconsistent with what we already know, then it cannot be correct!

Newton’s universal law of gravitation

- Recall Kepler’s laws of planetary motion:
  - Kepler’s first law: The orbit of a planet is an ellipse, with the Sun at one of the two focal points.
  - Kepler's second law: A planet's speed in its orbit is inversely proportional to its distance from the Sun.
  - Kepler’s third law: The square of a planet's orbital period is proportional to the cube of the planet's average distance from the Sun.
- Newton was able to derive all three laws mathematically from his laws of motion and law of gravitation.
- Kepler’s laws described properties of the orbits, but did not explain what causes them. Newton’s laws provided the explanation.

The math of Newtonian gravity

- Just words are not enough to describe theories in physics and astronomy.
- To define a theory precisely, we must use mathematics.
- We can’t just say “massive objects attract each other”, because this statement is qualitative and doesn’t produce testable predictions.
- We need to express exact relationships between quantities, so that we can do precise calculations and compare them with data.
- To formulate and test his theory, Newton had to invent a new field of mathematics, calculus, which deals with change.

The math of Newtonian gravity

- Remember: a scientific hypothesis can only be accepted as a theory if its predictions match experimental and/or observational data.
- The more precisely it matches the data, the more confident we can be in that theory.
- This happened before, with Ptolemy’s model. When it no longer matched the data, it had to be replaced with the heliocentric model, Kepler’s laws, and eventually Newtonian gravity.
    - In fact, 200 years after Newton, it was discovered that Newtonian gravity is not 100% precise either. It was replaced by general relativity, a much more precise theory. We will learn more about that later.

The math of Newtonian gravity

- Everything you are learning in this course can only be properly described using mathematical expressions.
- However, I stripped away the math so that I can at least explain the essence of the theories and concepts in words.
- This is often done in popular science articles and videos.
- It almost always results in oversimplification of the theories being explained, and creates misconceptions because the audience is not given the full details.
- In this course I try as much as possible to correct popular misconceptions, and avoid creating new ones.

The math of Newtonian gravity

- Newtonian gravity can be precisely described by this equation:

$$F = G\frac{m_1 m_2}{r^2}$$

  - m_1 is the mass of the first object.
  - m_2 is the mass of the second object.
  - F is the force of gravity between the objects.
  - r is the distance between the objects.
  - G is a constant of proportionality called the gravitational constant. Its value doesn't matter, it's just used to convert units.
- In words: "the force of gravity is proportional to the product of the masses of the two objects divided by the distance squared".

The math of Newtonian gravity

- Remember the comparison rule for fractions.
- If the numerator (top) gets larger, the fraction gets larger:

$$\frac{3}{5} < \frac{4}{5}$$

- If the denominator (bottom) gets larger, the fraction gets smaller:

$$\frac{3}{5} > \frac{3}{6}$$

The math of Newtonian gravity

- We can learn a lot about gravity from the fact that there’s a fraction on the right-hand side.

$$F = G\frac{m_1 m_2}{r^2}$$

- The force is larger if either of the masses in the numerator is larger.
- The force is smaller if the distance in the denominator is larger.

Pop quiz: $F = G\frac{m_1 m_2}{r^2}$

- Which object feels a larger force of gravity on Earth?
- m_1 = mass of Earth (constant), m_2 = mass of the object.

A: 10 kg object

B: 20 kg object

C: both feel the same force

Pop quiz: $F = G\frac{m_1 m_2}{r^2}$

- The correct answer is:

B: 20 kg object

- The force is larger when the mass is larger (because it’s in the numerator).

Pop quiz: $F = G\frac{m_1 m_2}{r^2}$

- By how much is the force of gravity on Earth on a 20 kg object stronger than the force on a 10 kg object?
- m_1 = mass of Earth (constant), m_2 = mass of the object.

A: twice as strong

B: 4 times as strong

C: 10 times as strong

Pop quiz: $F = G\frac{m_1 m_2}{r^2}$

- The correct answer is:

A: twice as strong

- When m_2 doubles, F also doubles, because they are proportional:

$$F \propto m_2$$

Pop quiz: $F = G\frac{m_1 m_2}{r^2}$

- At what distance is the force of gravity between two objects larger?
- $r =$ distance between the objects.

A: 10 meters

B: 20 meters

C: both feel the same force

Pop quiz: $F = G\frac{m_1 m_2}{r^2}$

- The correct answer is:

A: 10 meters

- The force is larger when the distance is smaller (because it’s in the denominator).

Pop quiz: $F = G\frac{m_1 m_2}{r^2}$

- By how much is the force of gravity between two objects at 10 meters separation larger than the force at 20 meters?
- $r =$ distance between the objects.

A: twice as strong

B: 4 times as strong

C: 10 times as strong

Pop quiz: $F = G\frac{m_1 m_2}{r^2}$

- The correct answer is:

B: 4 times as strong

- When r decreases by a factor of 2, F increases by a factor of $2^2 = 4$, because F is inversely proportional to the square of r:

$$F \propto \frac{1}{r^2}$$

Newtonian gravity at a distance

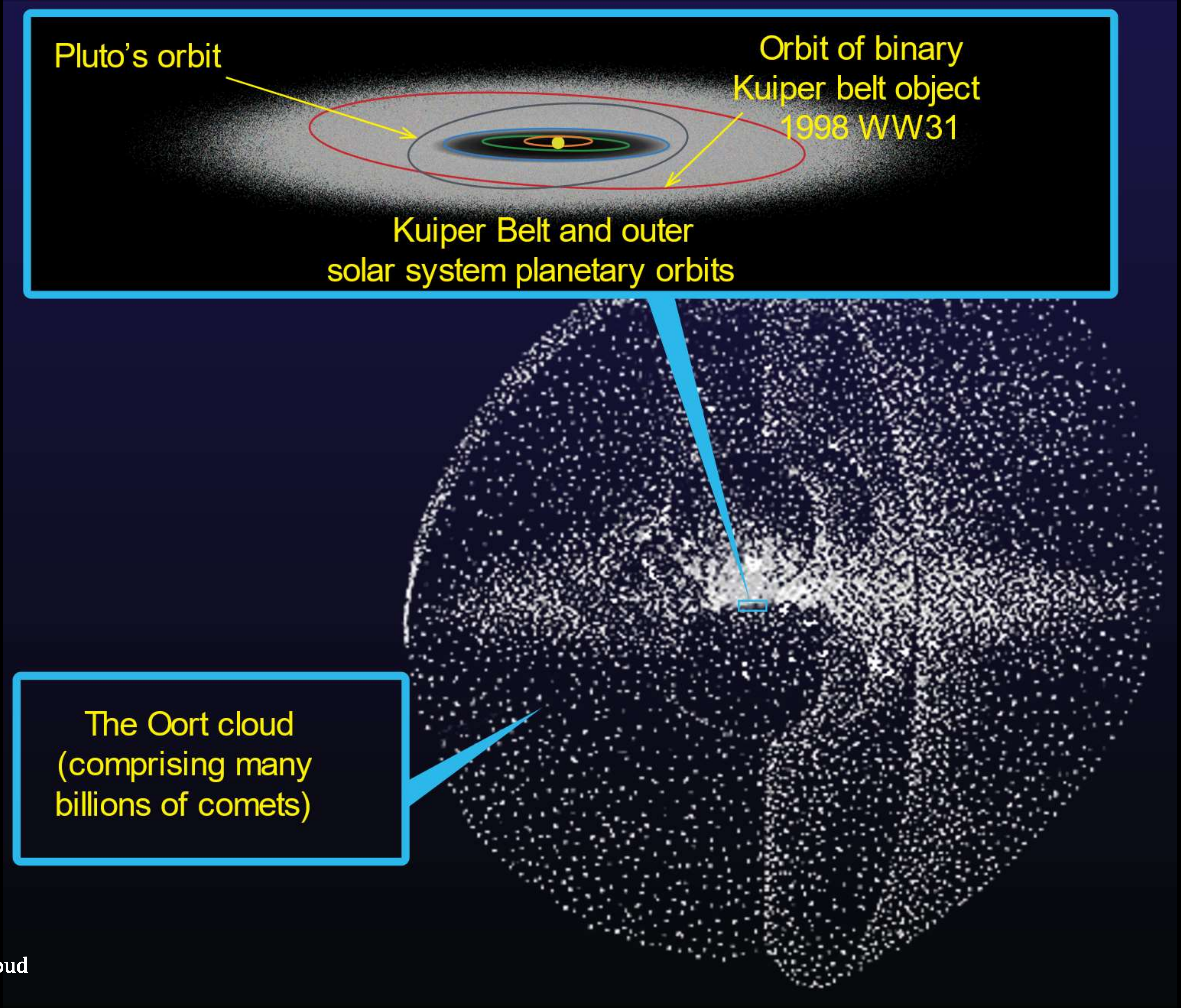
- Another thing we can learn from this equation is that gravity fades with distance but never disappears completely.

$$F = G\frac{m_1 m_2}{r^2}$$

- When r increases, F decreases. So planets farther away from the Sun feel a smaller force of gravity (if their masses are the same).
- But F never becomes zero, no matter how large r is.
- For F to be zero, r must be infinite.

Newtonian gravity at a distance

- The Sun’s gravity attracts not only the planets in the solar system, but also icy bodies surrounding the solar system.
- These objects are located in:
  - The Kuiper (KIE-per) belt, at 30-50 AU (4-7 light hours), containing the orbits of Pluto and other dwarf planets.
  - The Oort (OR-t) cloud, much farther away, at 2,000 to 200,000 AU (0.03 to 3.2 light-years)
- The Sun’s gravity also affects nearby stars such as Alpha Centauri.



The Kuiper Belt and the Oort Cloud

Credits: NASA

Distances In the Solar System (Logarithmic)

Credits: NASA / JPL-Caltech

Newtonian gravity at a distance

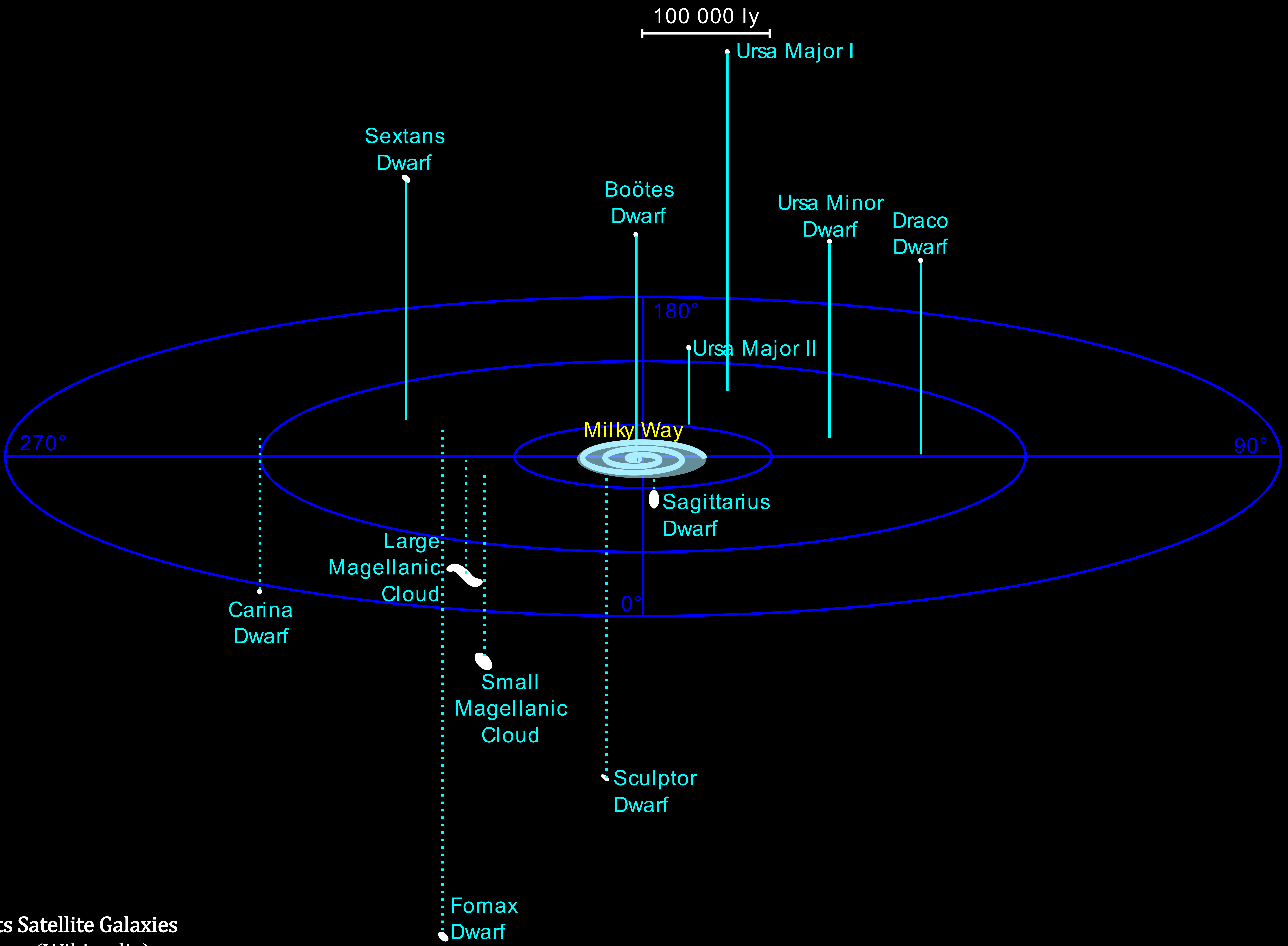
- Outside the Milky Way galaxy, the gravity of our Sun alone is so small that it has no effect on its own.
- However, the Sun’s gravity adds up with that of billions of other stars to create the gravitational pull of the entire Milky Way galaxy.
- If we zoom out, we can think of the Milky Way as a single source of mass, with the total mass of its billions of stars, including the Sun.

Newtonian gravity at a distance

- This means that other smaller galaxies orbit the Milky Way, just like planets orbit the Sun.
- These galaxies are called satellite galaxies, and they are located within 1.4 million light-years of the Milky Way.
- This includes the Large Magellanic Cloud and the Small Magellanic Cloud, which have been observed since prehistoric times.
- Other satellite galaxies were discovered more recently.

The Large and Small Magellanic Clouds

Credits: AndrewRT & Slashme (Wikipedia)



Map of the Milky Way and Its Satellite Galaxies

Credits: AndrewRT & Slashme (Wikipedia)

Newtonian gravity at a distance

- The mass of the Milky Way galaxy adds up with that of other galaxies to create the total gravitational pull of the Local Group.
- The mass of the Local Group adds up with other galaxy groups to create the total gravitational pull of the Virgo Supercluster.
- The mass of the Virgo Supercluster adds up with other superclusters to create the pull of the Laniakea Supercluster.
- And so on...
- Technically, the mass of your body participates in the gravitational pull that acts on entire galaxy superclusters!

The Laniakea (la-nee-uh-KEI-uh) Supercluster Contains 100,000 Galaxies

Credits: Andrew Z. Colvin

Free fall

- The Earth's gravity affects the Moon, which is ~384,000 km from Earth.
- It even affects the other planets in the solar system. In fact, to calculate the precise orbit of each planet, you must take into account the gravitational influence of all the other planets.
- So why do astronauts in space feel no gravity and can float in the air, even though they are only a few hundred km above the surface, much closer than the Moon?

Astronauts Floating Onboard the International Space Station

Credits: NASA

Free fall

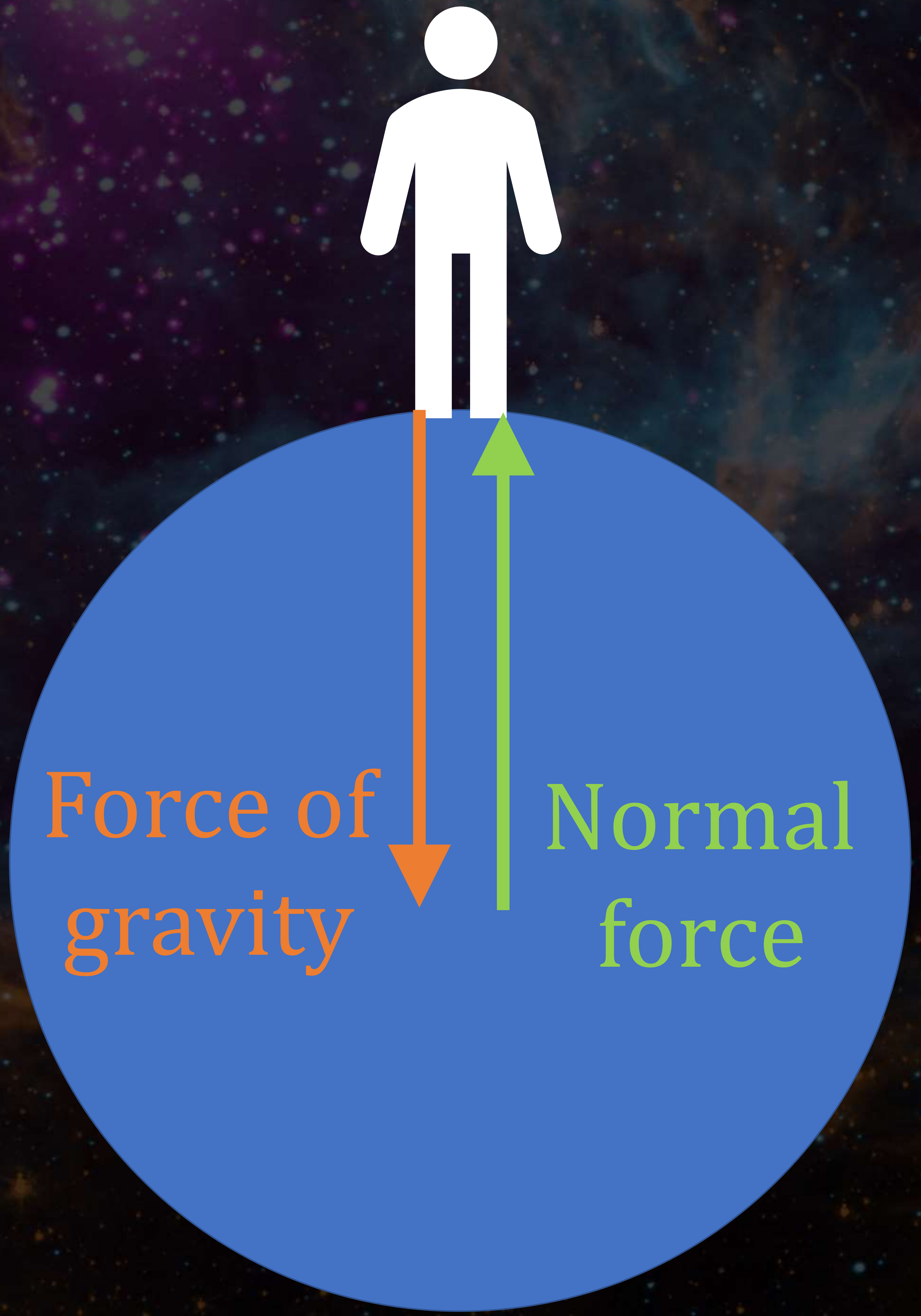
- In fact, the astronauts in orbit are in free fall. This means they're not floating, they're actually falling around the Earth!
- Just like a hammer and a feather fall at the same rate, the astronauts and the space station fall at the same rate.
- Since the astronauts fall at the same rate as the station, they appear to float.

Free fall

- Remember:
  - Weight is the gravitational force on the body.
  - Mass is the amount of matter in the body, and doesn’t depend on gravity.
- The astronauts feel “weightless” – they do not feel any gravity.
- But in fact, the gravity of the Earth is still acting on them.

Free fall

- We feel our weight when we are on Earth because the ground pushes up on us.
- This is called a normal force.
- It exists due to Newton’s 3rd law:
  - The force of gravity is the action.
  - The normal force is the equal and opposite reaction.

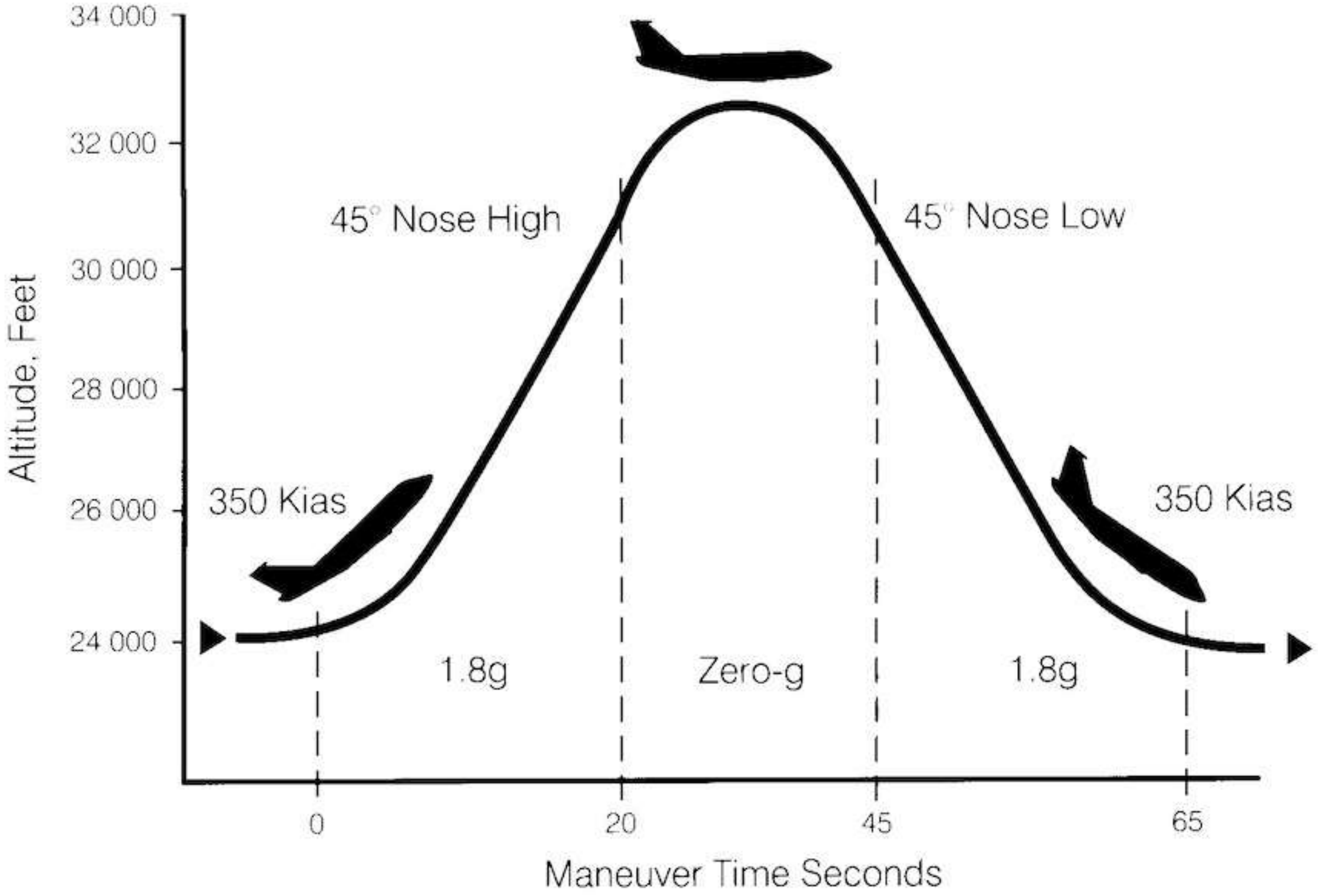


Free fall

- The astronauts don’t feel a normal force because they are falling at the same rate as everything around them.
- So nothing pushes up on them: not the air, not the walls of the space station, not anything else.
- They feel “weightless” because they don’t feel the force of gravity, even though it still acts on them.
- We know the force of gravity acts on them because otherwise they would continue flying in a straight line away from Earth.

Free fall

- You don’t need to go to outer space to feel weightless.
- It can also be achieved using a plane inside Earth’s atmosphere.
- In normal plane flight, the bottom of the plane exerts a normal force on us, so we don’t feel weightless.
- However, if a plane flies in a parabolic path, like an object thrown in the air, the passengers will experience weightlessness for a short time.



Parabolic Path for a Reduced-Gravity Aircraft

Credits: UCSD Physiology/NASA lab

Conclusions

- In this lecture, we learned about Newton’s laws of motion, Newton’s universal law of gravitation, and related physics concepts.
- We saw that Newton’s laws can explain Kepler’s laws, as well as many other types of motion.

- Reading: OpenStax Astronomy, sections 3.2-3.6.
- Exercises: Practice questions are available in the textbook and on the course website.