Exploring Space & Time:
From Wormholes to Warp Drive

Supermassive Space Weekend

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(Royal Holloway UoL)

Southend Planetarium – 09.08.2025

Lecture Overview

- Classical Motion – Newton’s Laws & Thermodynamics
- Einsteinian Relativity - ***The Special Theory***
- Time Travel by High Speed
- Einsteinian Relativity - ***The General Theory***
- Time Travel by Black Hole
- Space Travel by Warp Drive
- Space-Time Travel by Wormhole
- Q&A (**Questions welcome throughout the talk!**)

Lecture Live Links (LLL)

Throughout the lecture, I will make a couple of references to previous talks, livestreams, and other online materials.

If you would like to check these out after the talk (or view recordings of previous lectures), please feel free to scan the QR code shown here.

Links and Resources: *Wormholes to Warp Drive* Lecture - 08.07.2025

[1] 'Time Travel 101 - Southend Museum Lecture' - R Clemenson
Previous lecture on special relativity from May 2025 given at the Beecroft Museum, with more details presented, and more historical context.

[2] 'Time Travel from Pythagoras' - R Clemenson
YouTube video from 2020, showing a full derivation of Einstein's time dilation formula using a 'light clock', and no more complicated mathematics than Pythagoras' theorem.

[3] 'Black Holes and Beyond - Southend Museum Lecture' - R Clemenson
Previous lecture with greater detail on general relativity from May 2025. See first 40 minutes for discussion of general relativity.

[4] 'Black Hole Basics - Saturday Spacewalk' - R Clemenson
Livestream from 2021 giving more technical details on general relativity, using some higher mathematics, and applying this to black holes. Don't let the title fool you… This is *far* from basic, and uses quite a lot of University level maths from the beginning!

[5] 'Mercury's Orbital Precession - Saturday Spacewalk' - R Clemenson
Livestream from 2021, deriving the perihelion shift in Mercury's orbit predicted by General Relativity.

Scan the QR code above, or simply click the QR code in the PDF of the lecture slides.

Part I - Space Travel via Classical Physics

Principles of Classical Motion

Thus far, every method our species has invented to travel from point A to B relies on two core branches of physics:

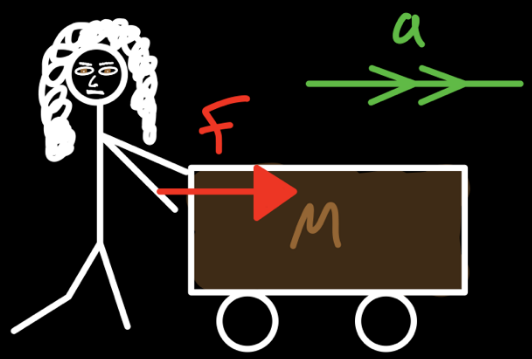
1. Newton's Laws of Motion

Laws describing how objects move when pushed a certain way.

2. The Laws of Thermodynamics

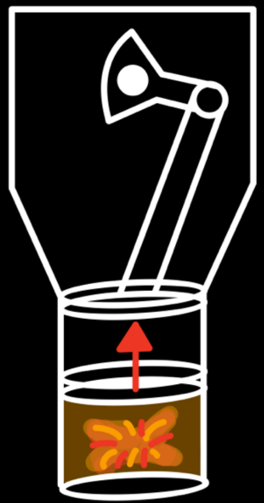
Laws describing how heat moves, and converts into motion.

Newton's Laws



$$F = ma$$

Thermodynamics



$$\Delta U = \Delta Q - W$$

Newton's Laws of Motion

Isaac Newton publishes his three laws of motion in his *Principia Mathematica*, in 1687.

By applying these three simple laws, we can describe how even the most complex mechanical systems behave.

Newton's Laws are what we use to launch rockets, design skyscrapers, and work out the motion of the planets.

Launch of the first Space Shuttle mission, 1981.

Isaac Newton, 1702.

Newton's Laws of Motion

<u>**Newton's First Law**</u>

Objects will not change their motion, unless acted on by a resultant force.

Things don't move unless you push them, and don't stop moving unless you pull them back.

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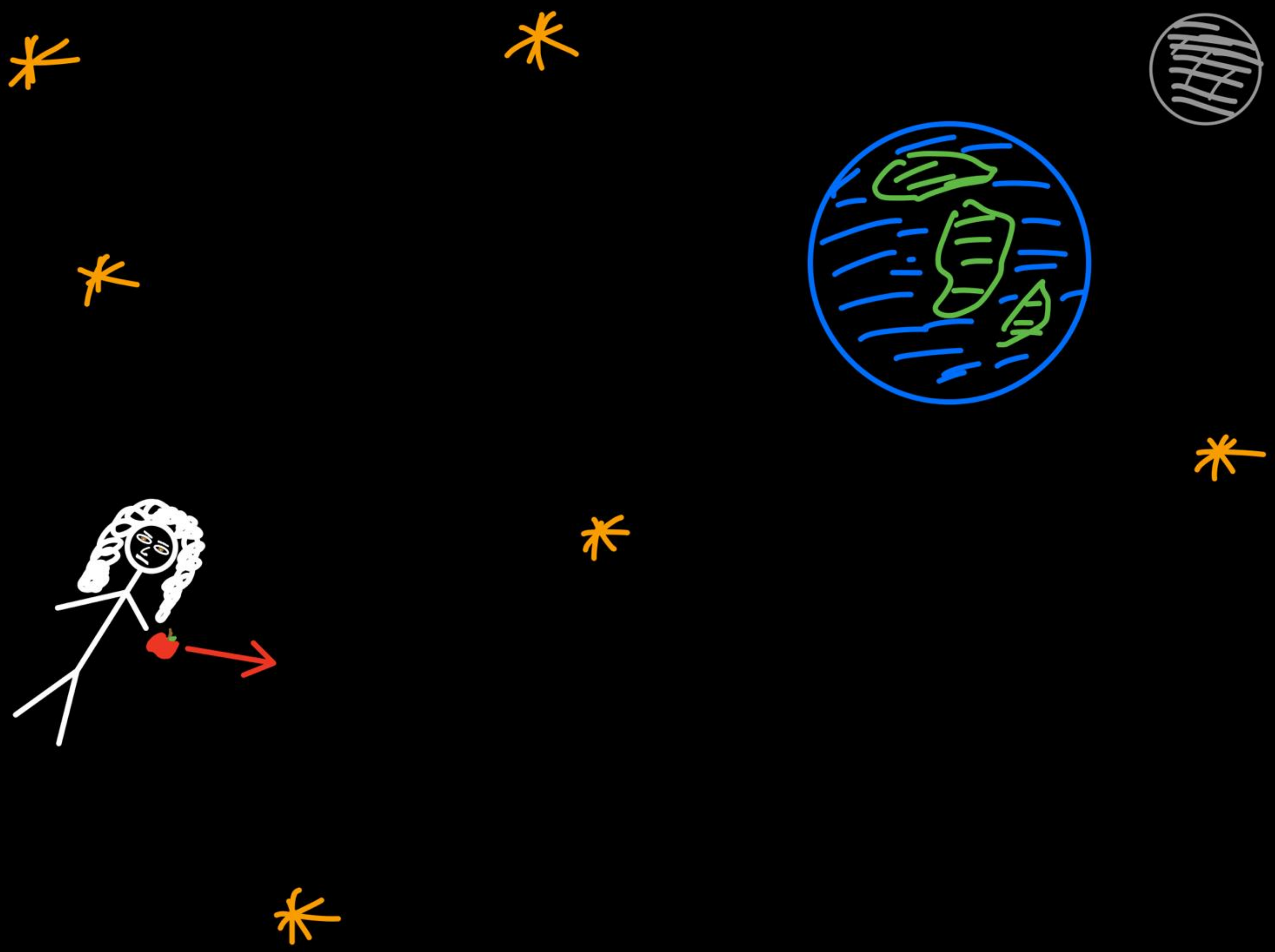

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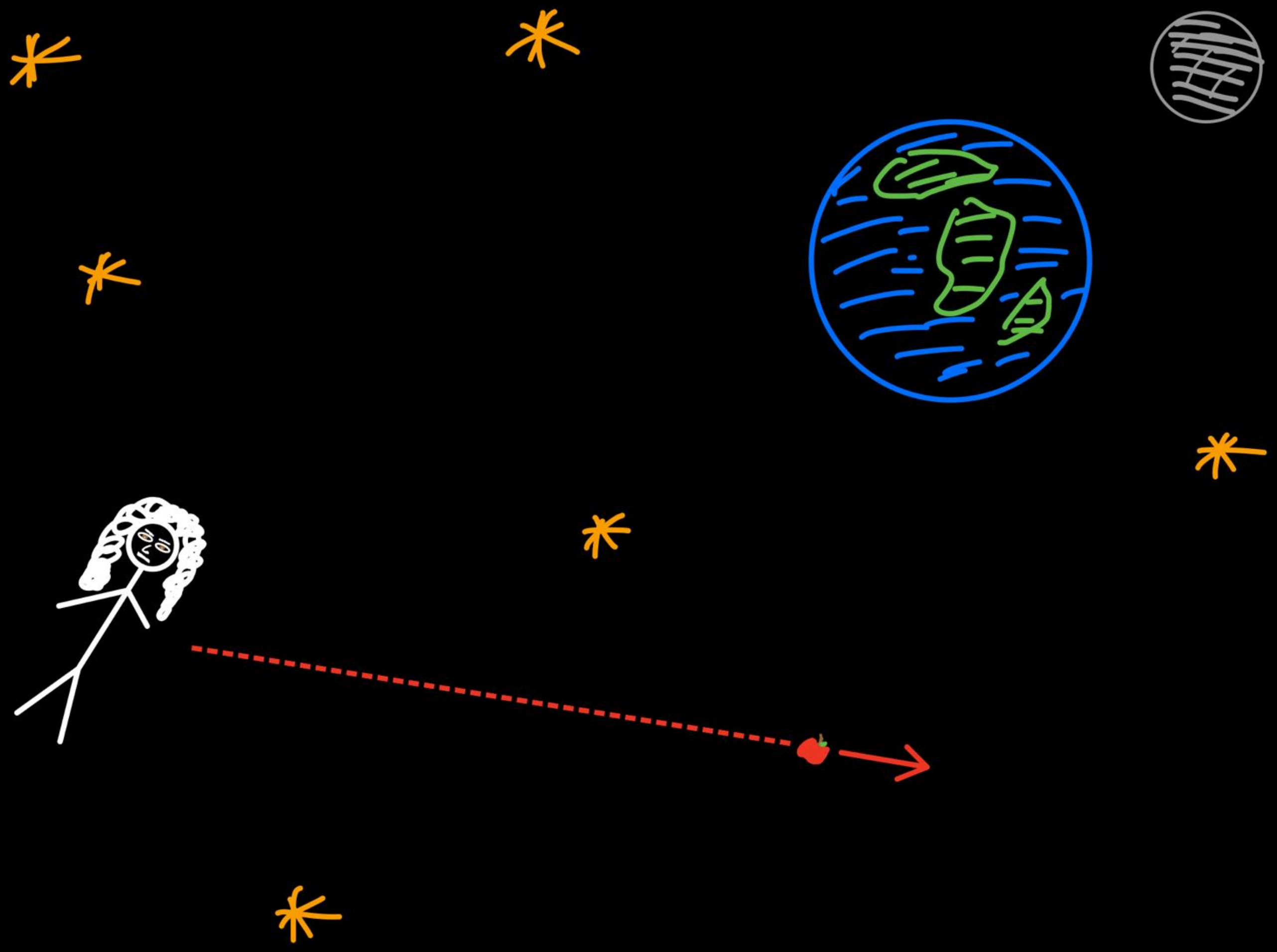

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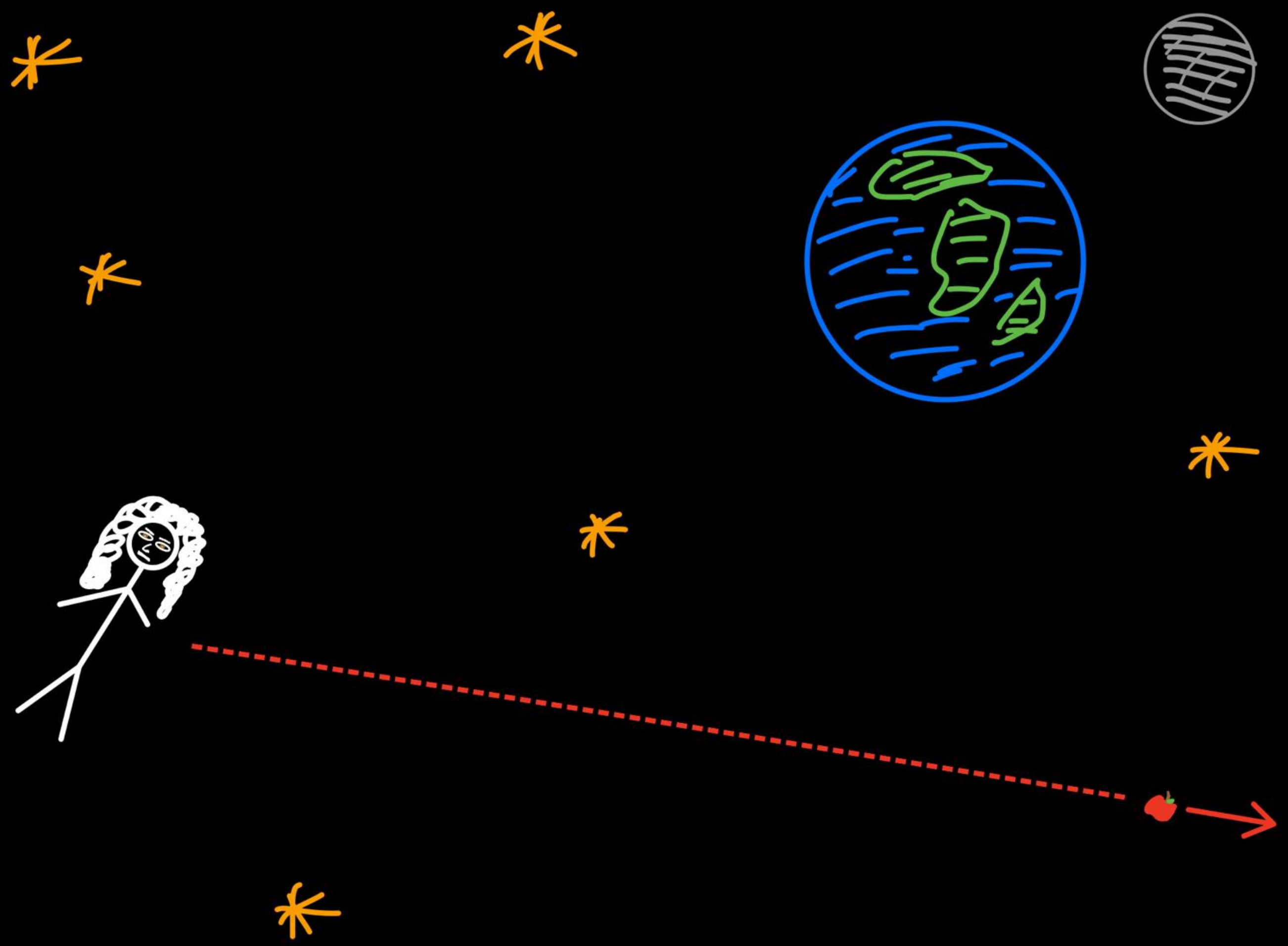

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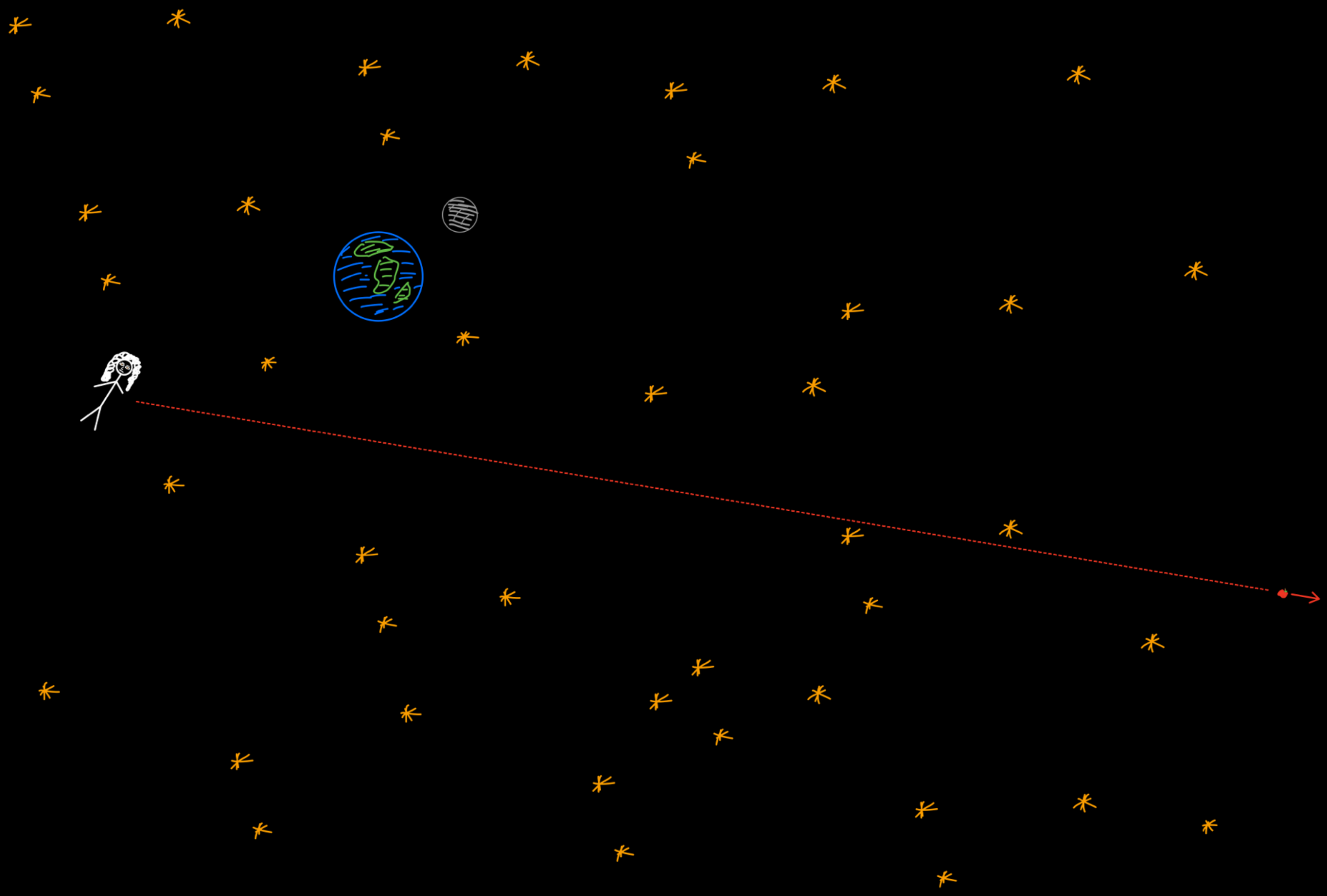
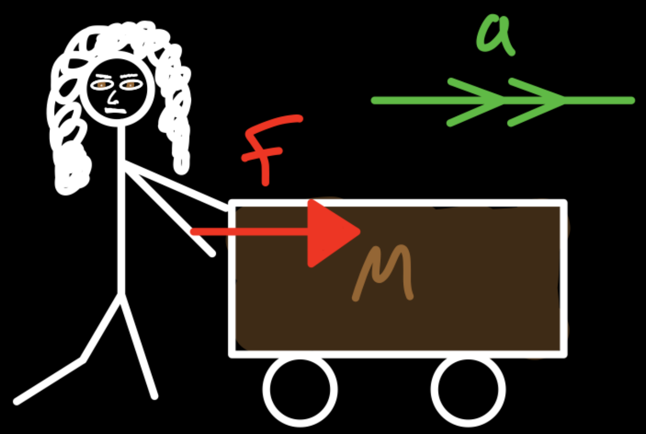


Newton's Laws of Motion

Newton's Second Law

The acceleration of an object is directly proportional to the force applied.

Objects accelerate faster, the harder you push them.



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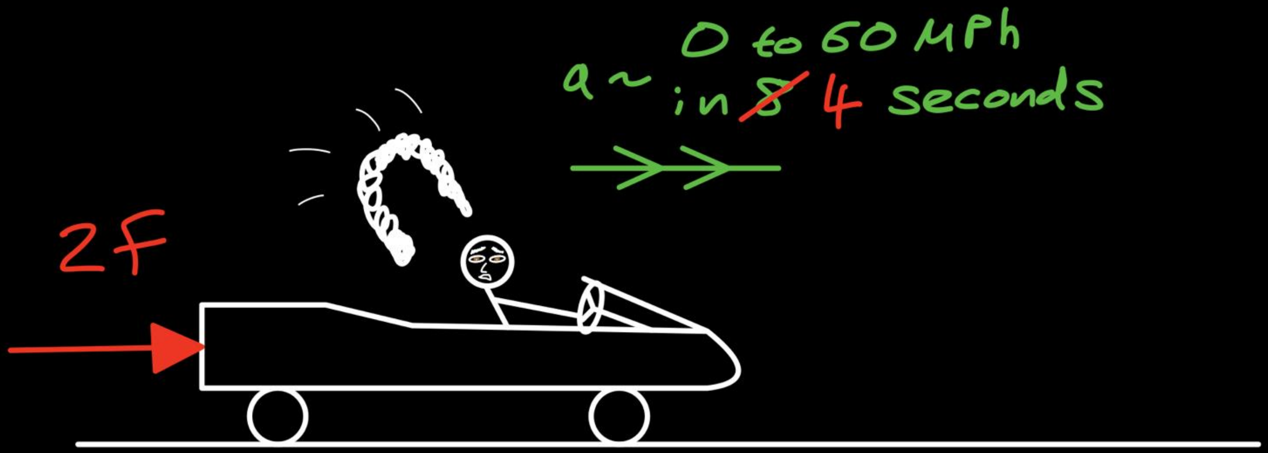

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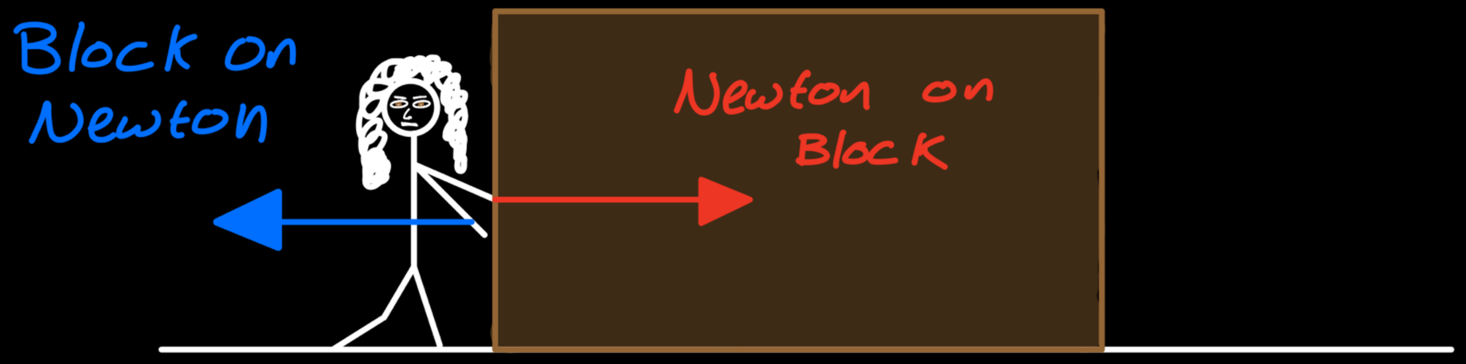

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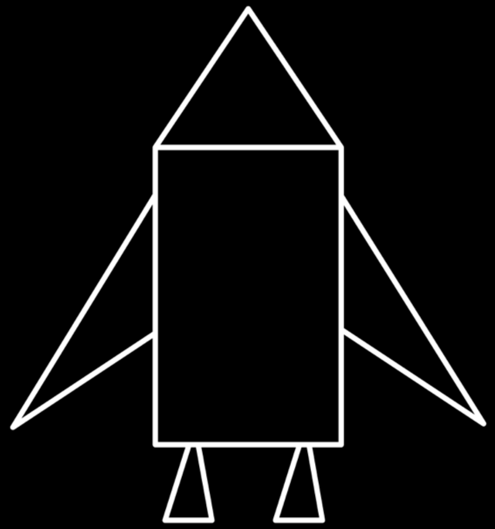

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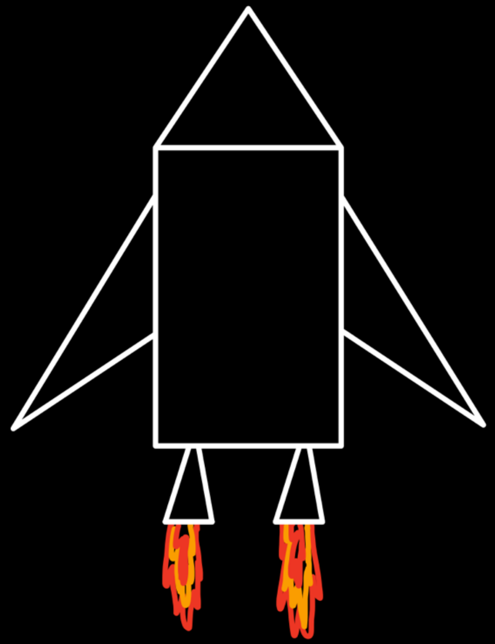

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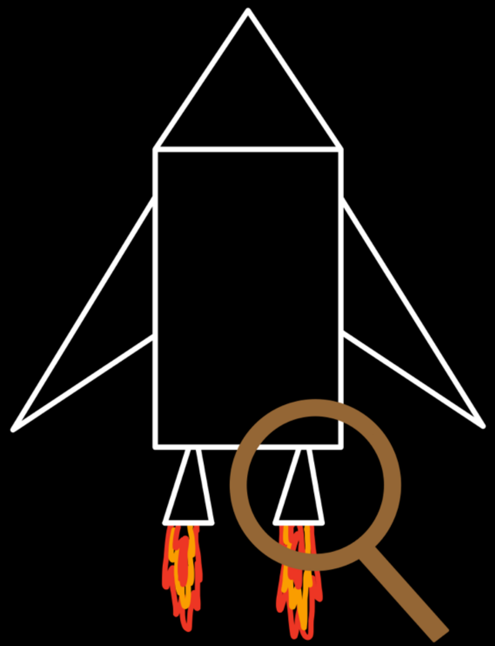

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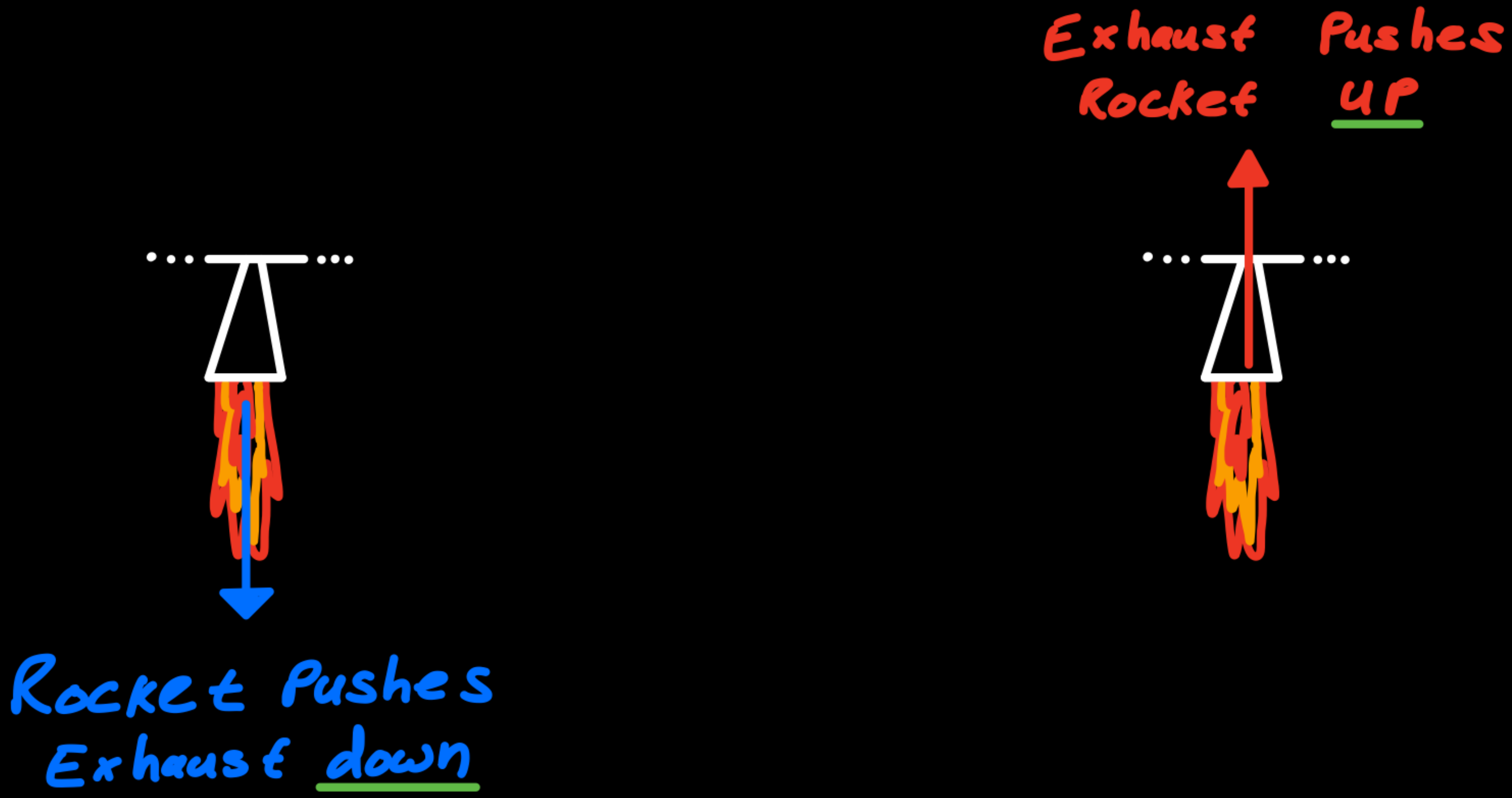
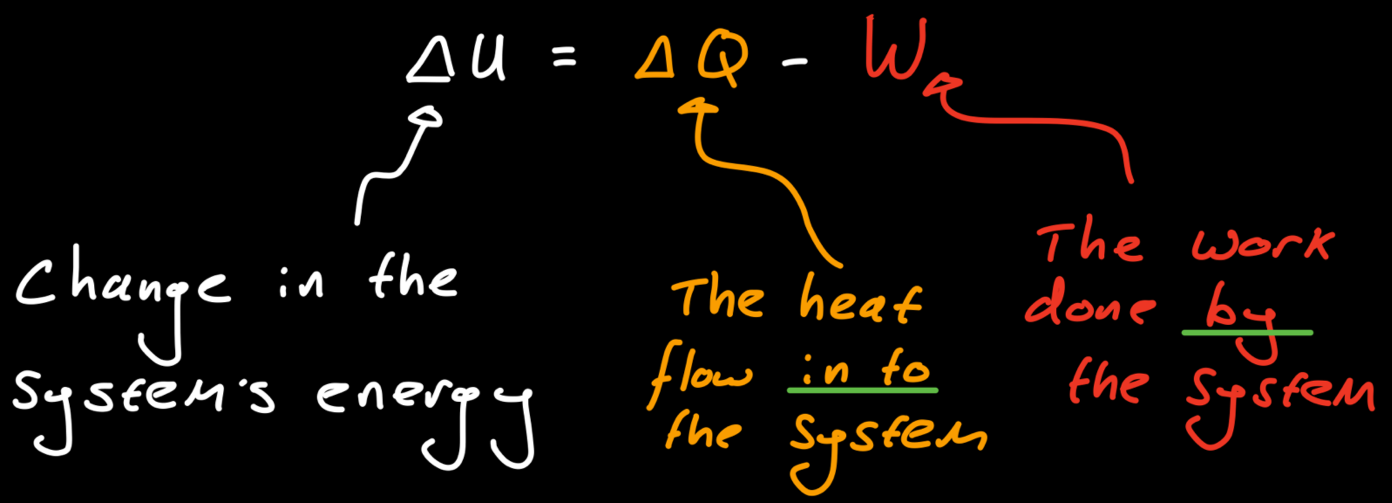


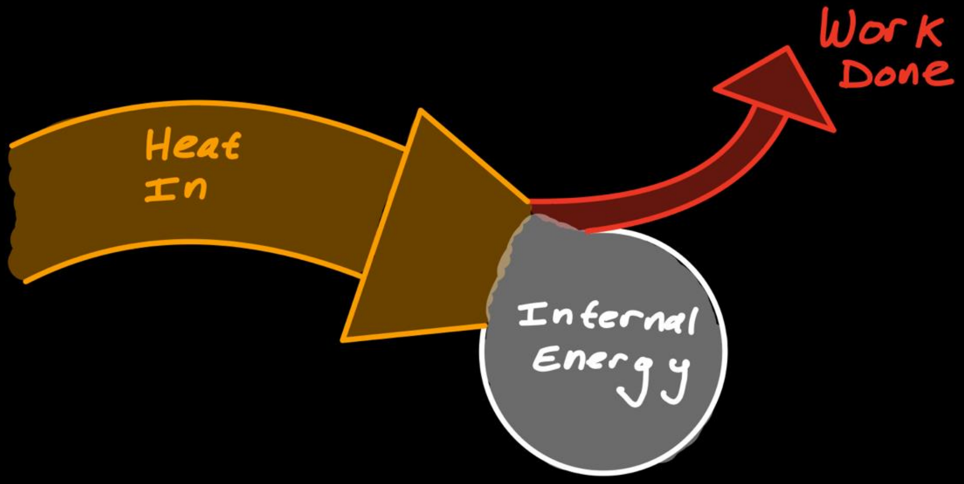
Thermodynamics

The First Law of Thermodynamics

The change in the internal energy of a system equals to the heat added to the system, minus the work done by the system.

Energy in, minus energy out equals the change in energy.





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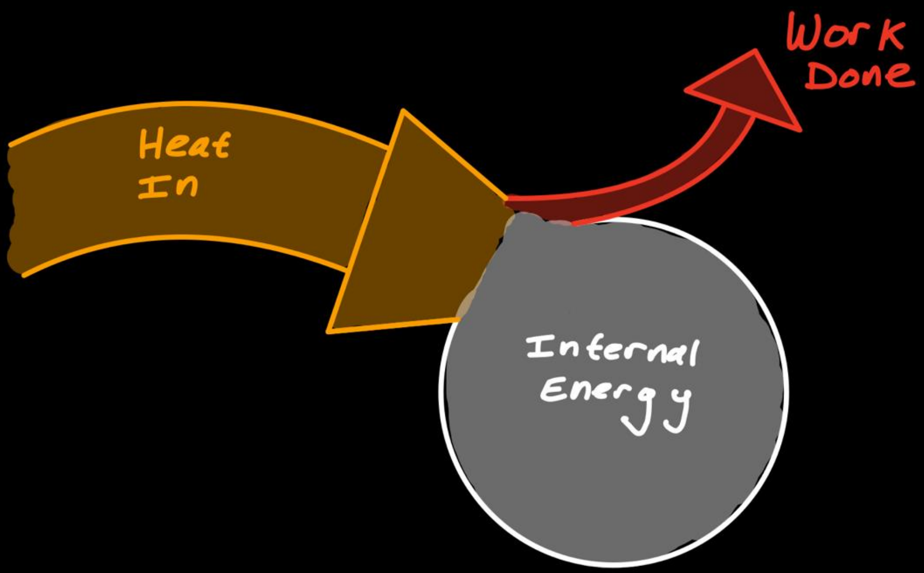
$$\Delta U = \Delta Q - W$$

Change in the system's energy (ΔU)

The heat flow into the system (ΔQ)

The work done by the system (W)



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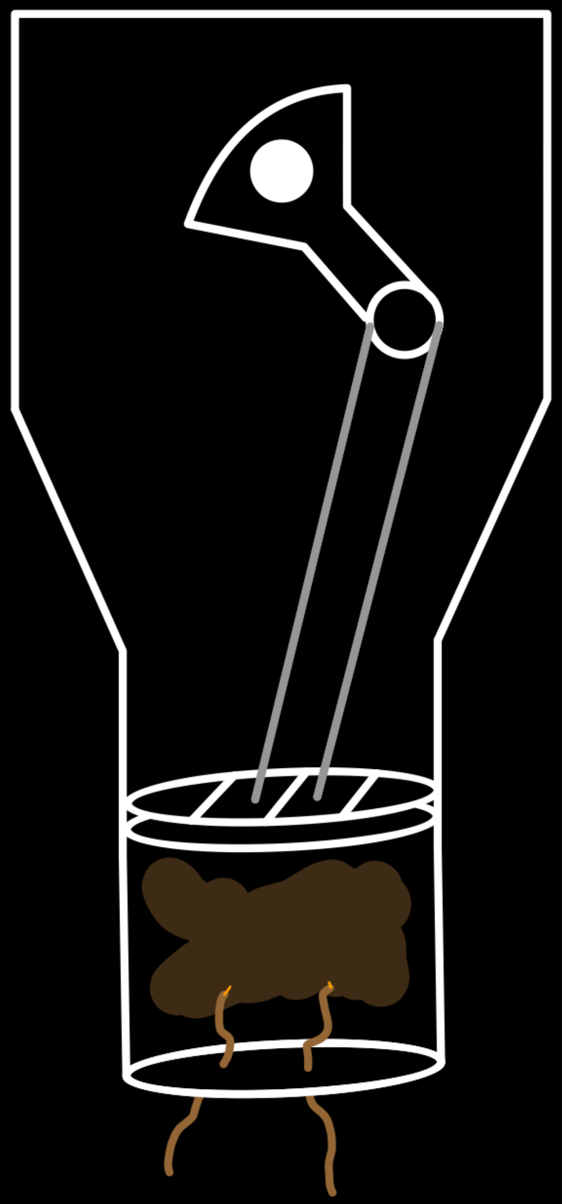

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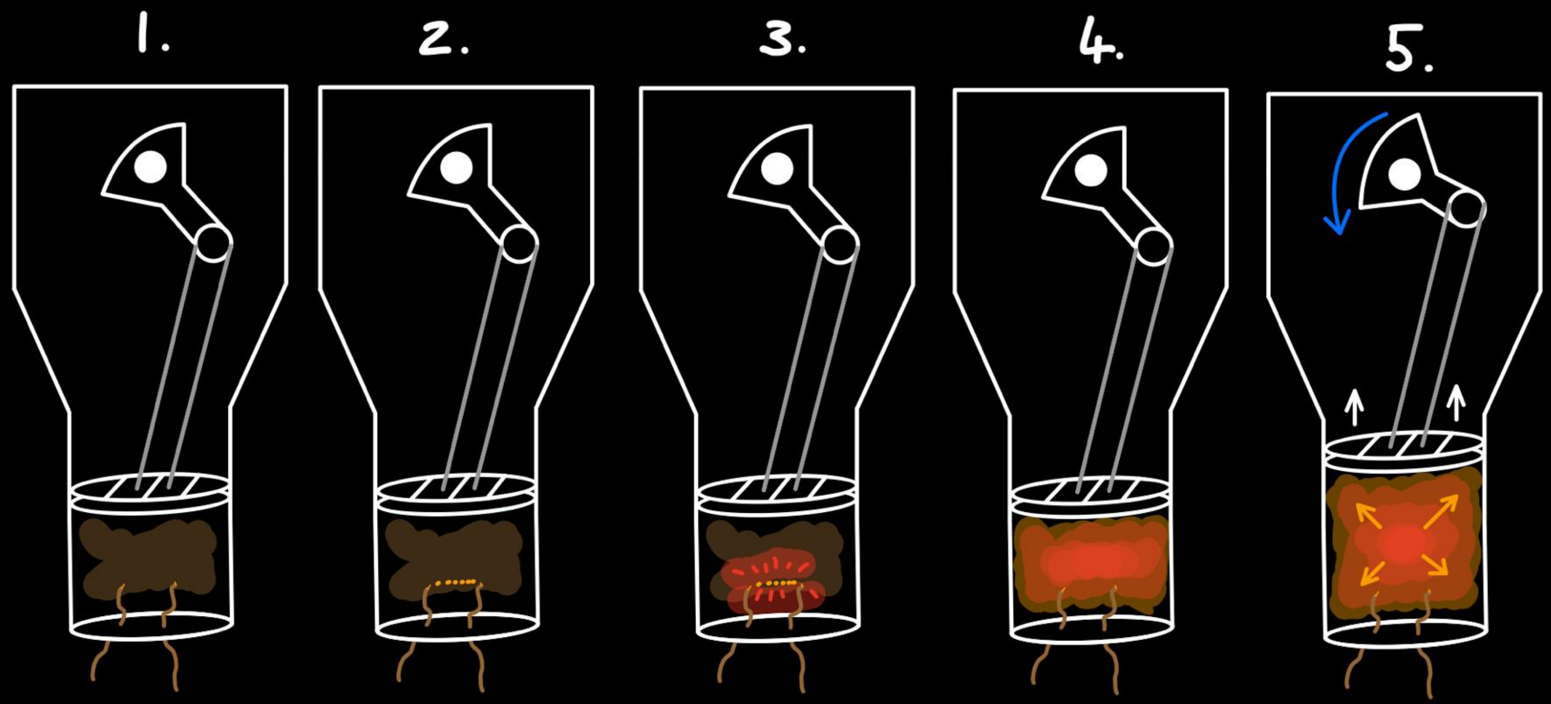

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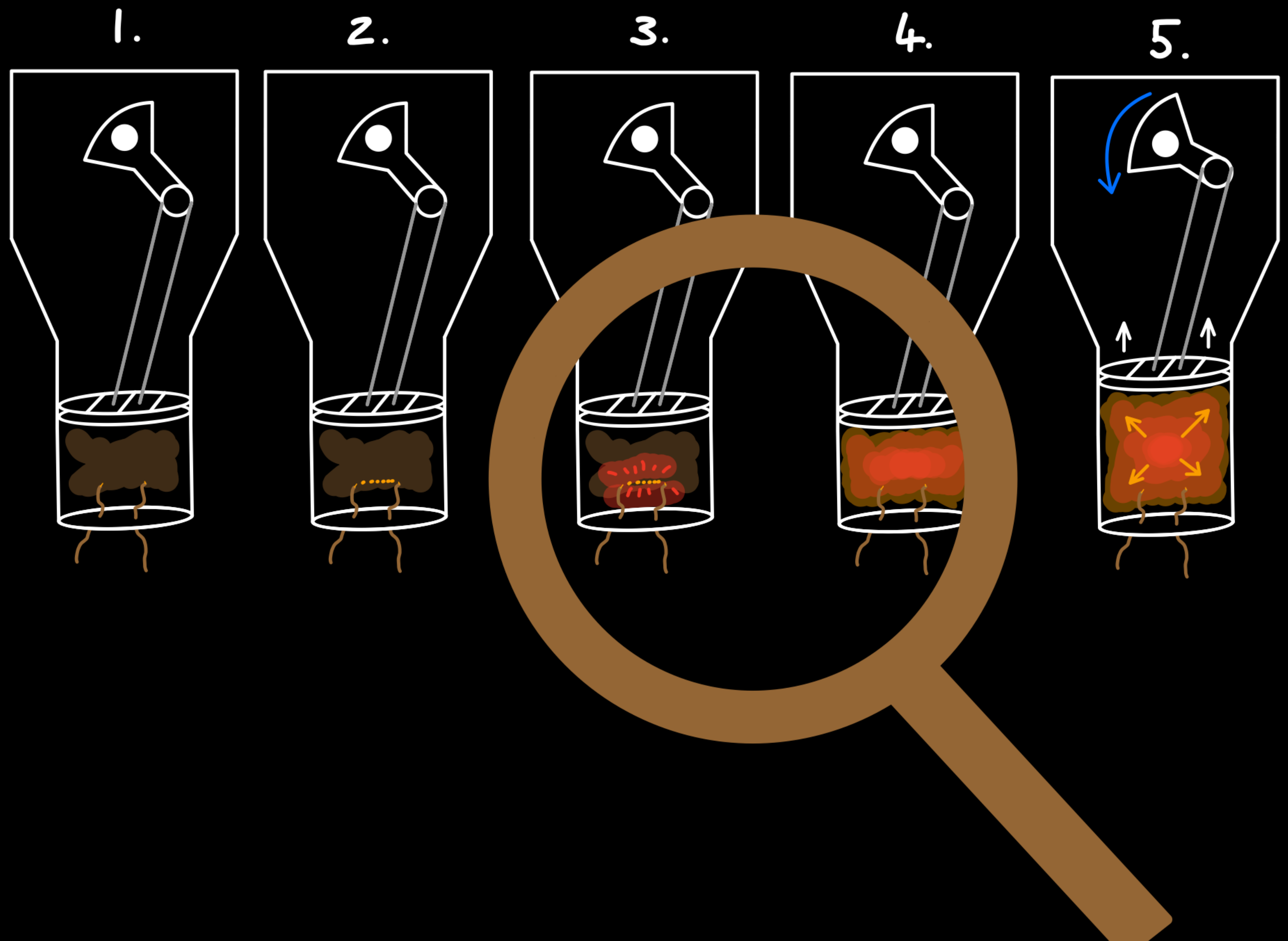

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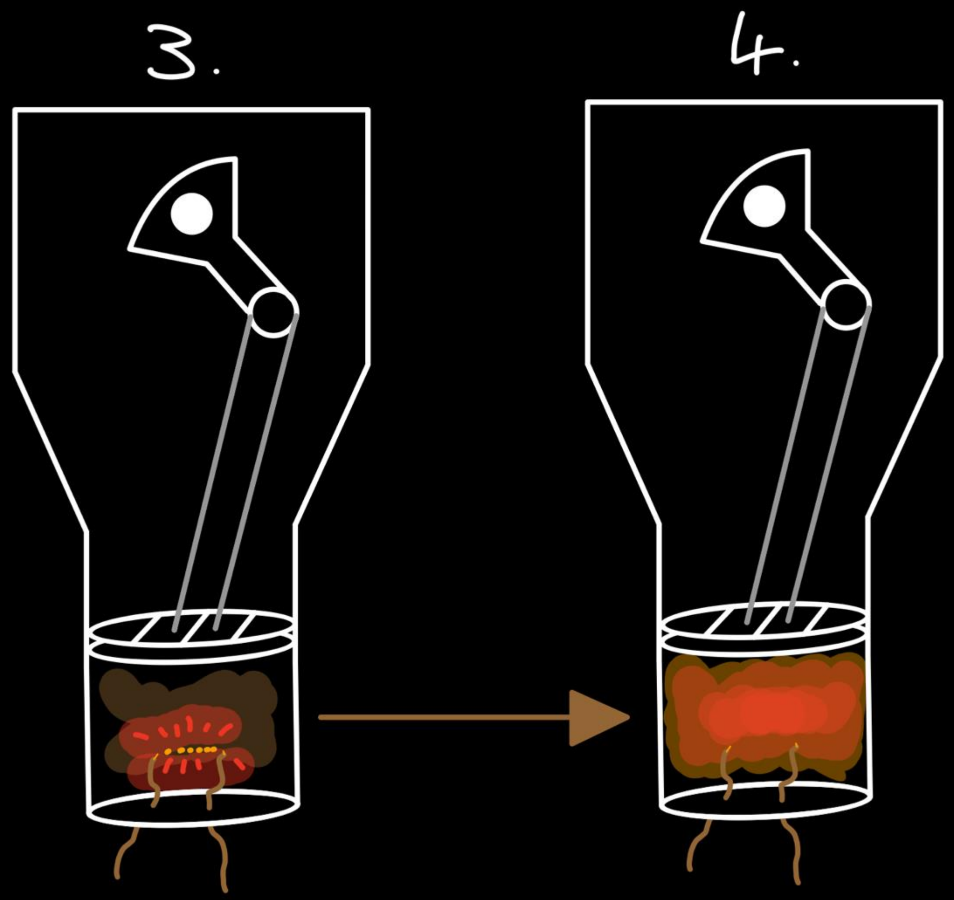

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$$C_3H_8 + 5\,O_2 \rightarrow 3CO_2 + 4H_2O$$

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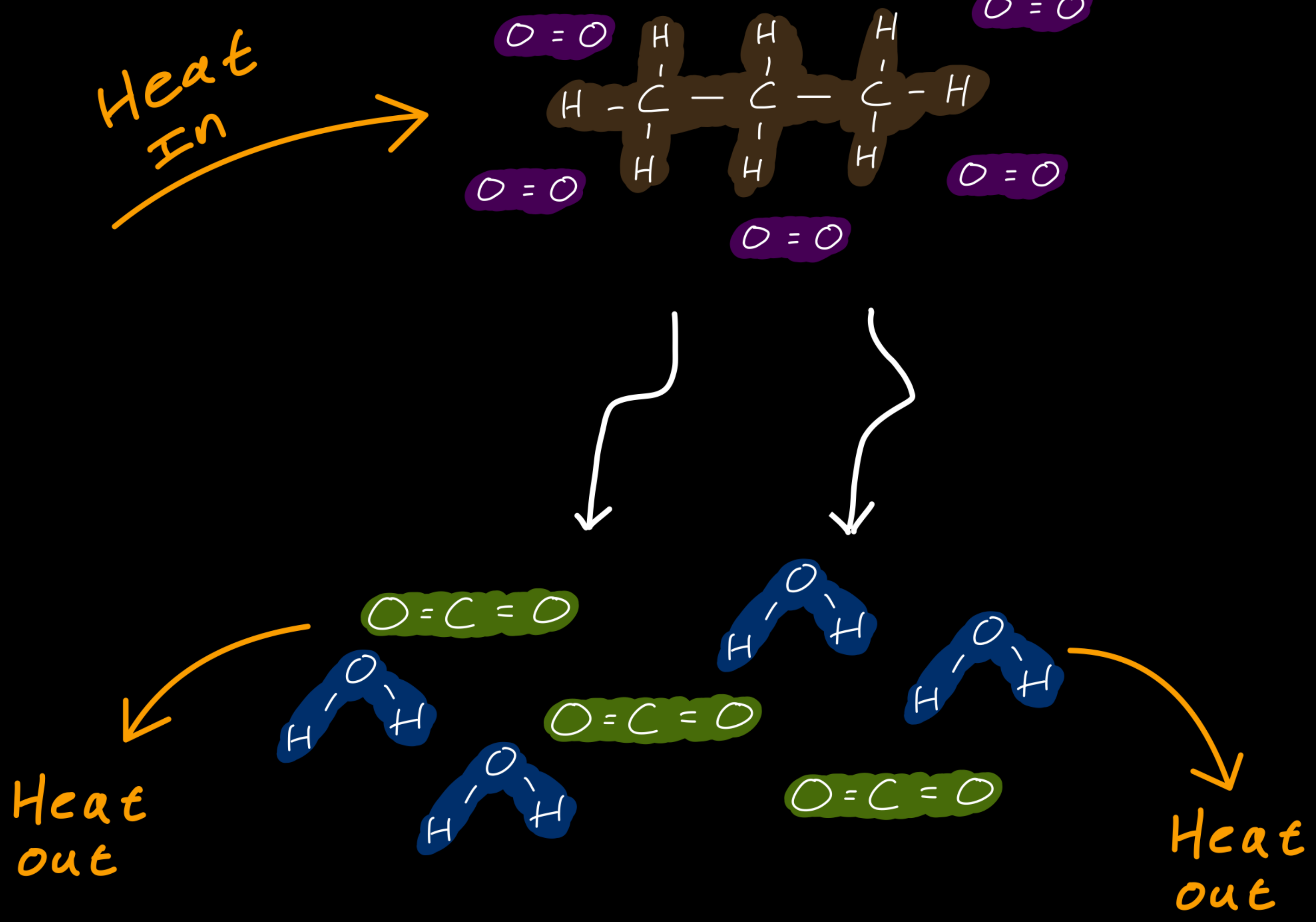

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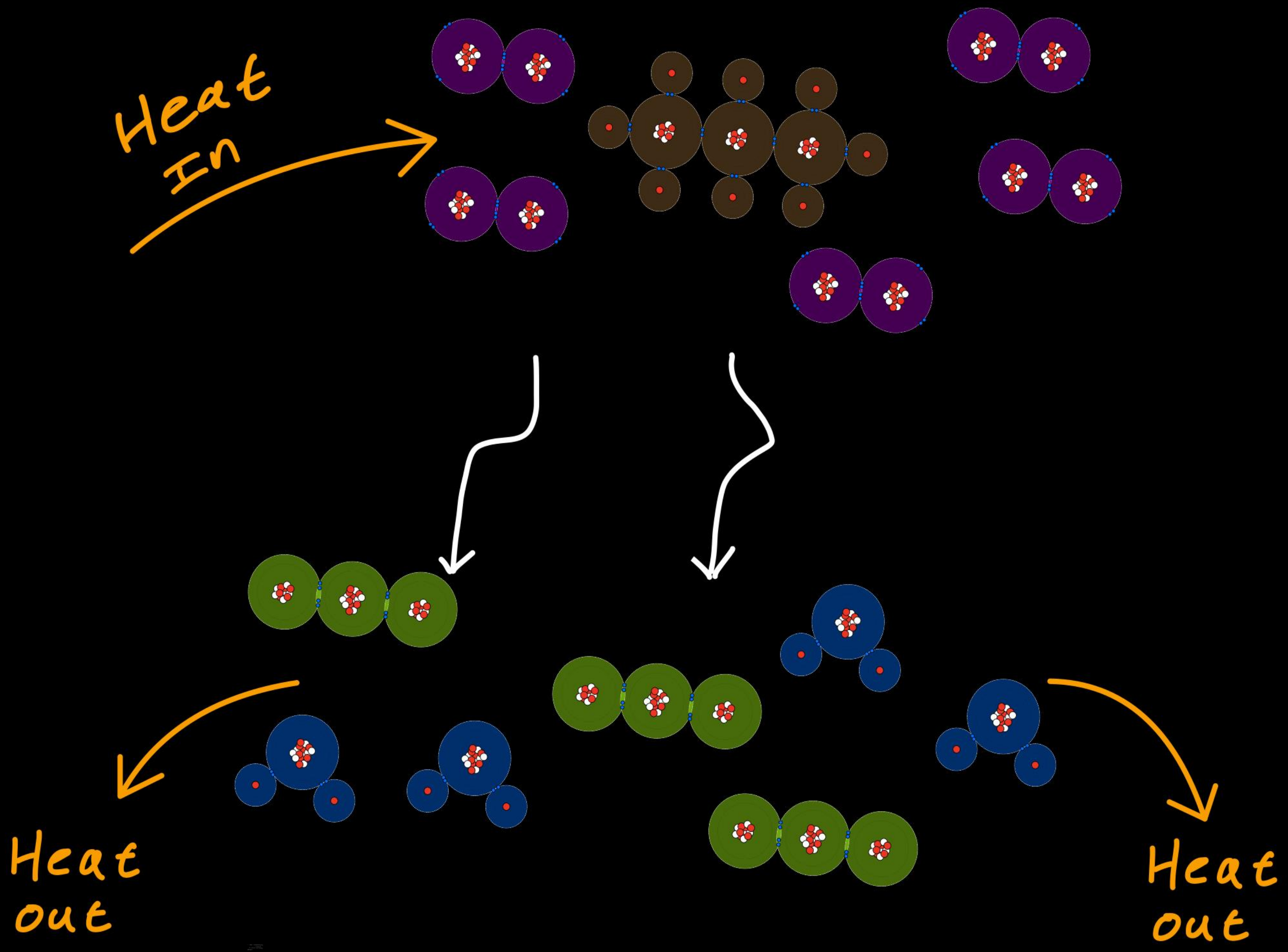

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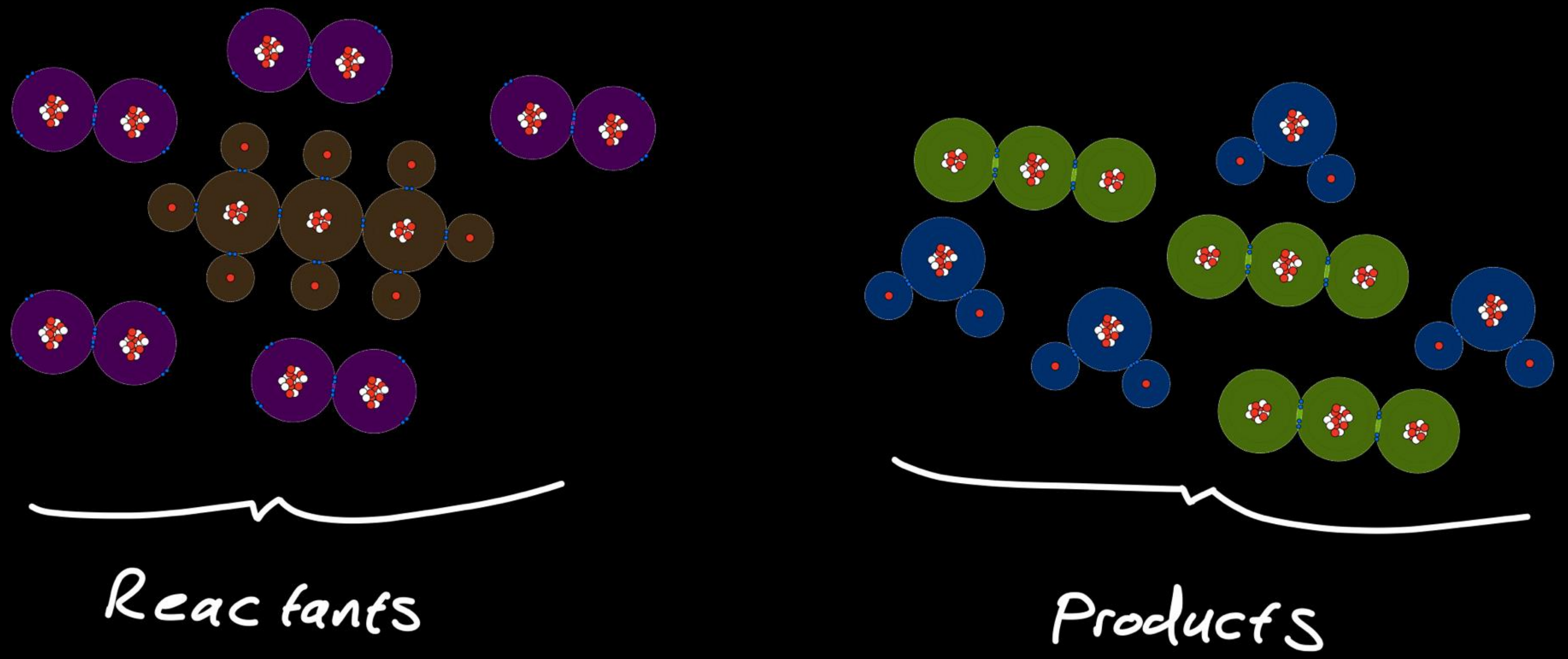

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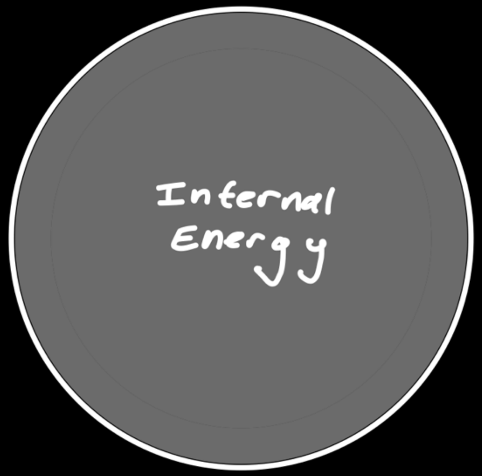

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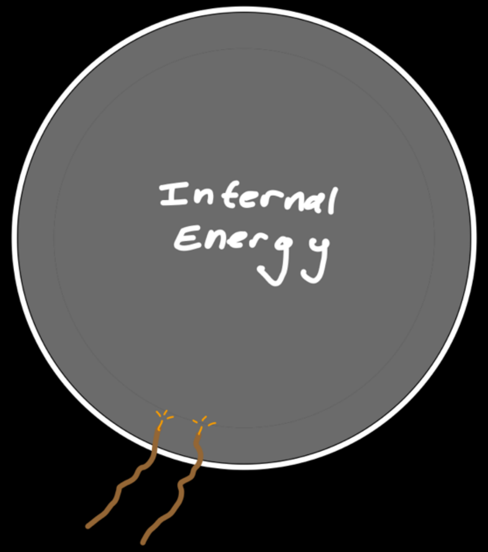

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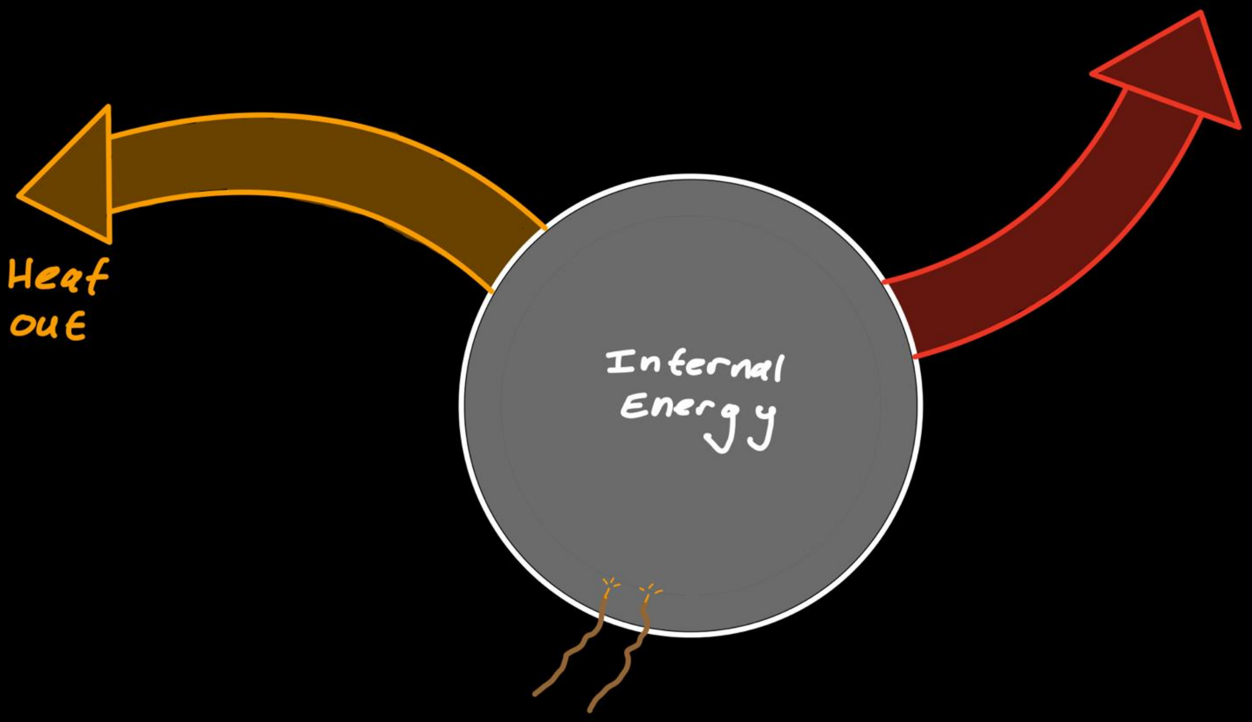

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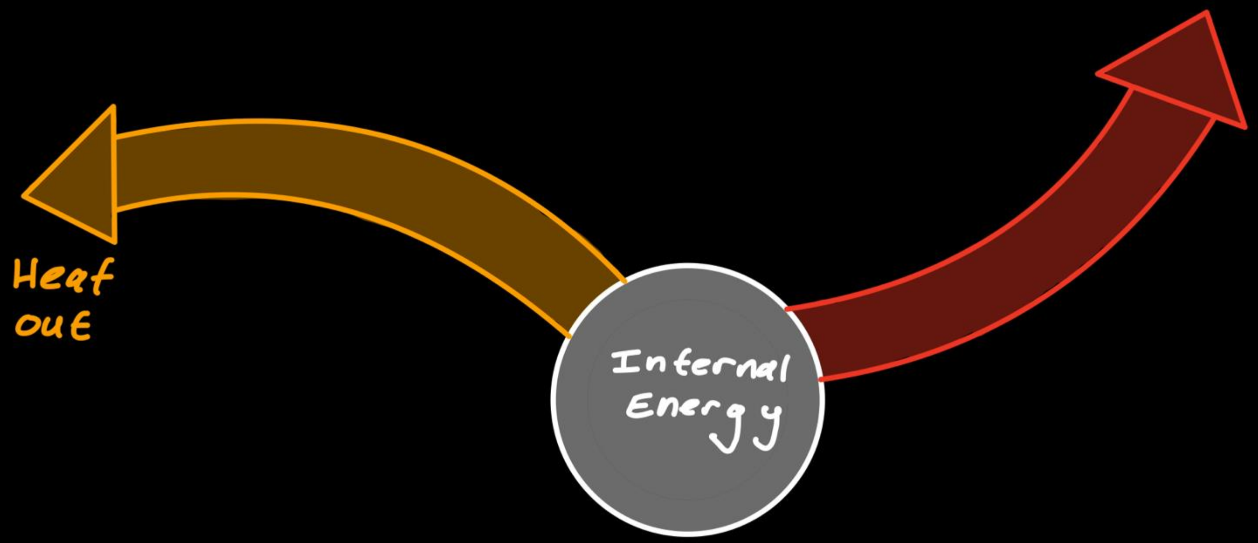

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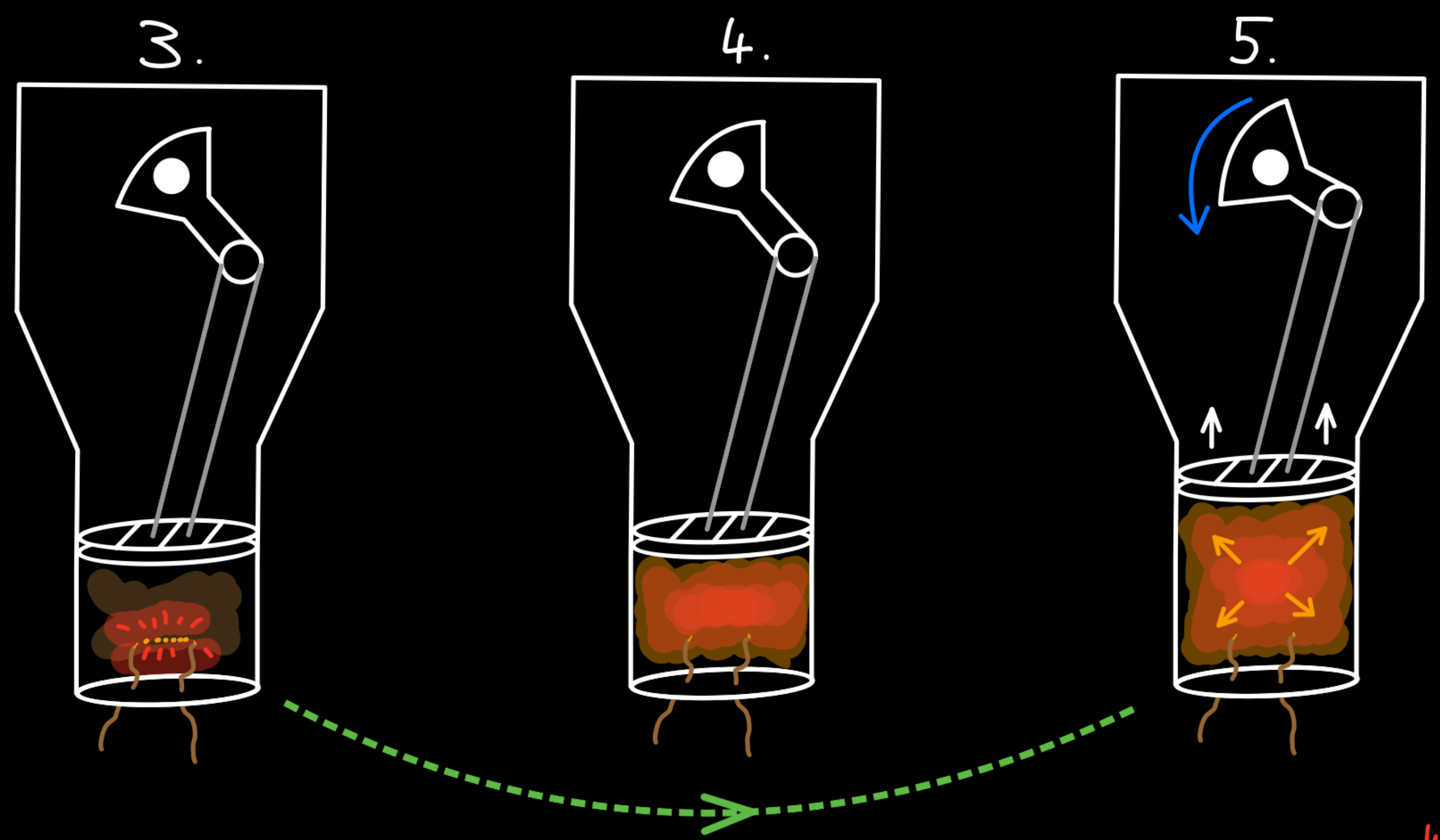
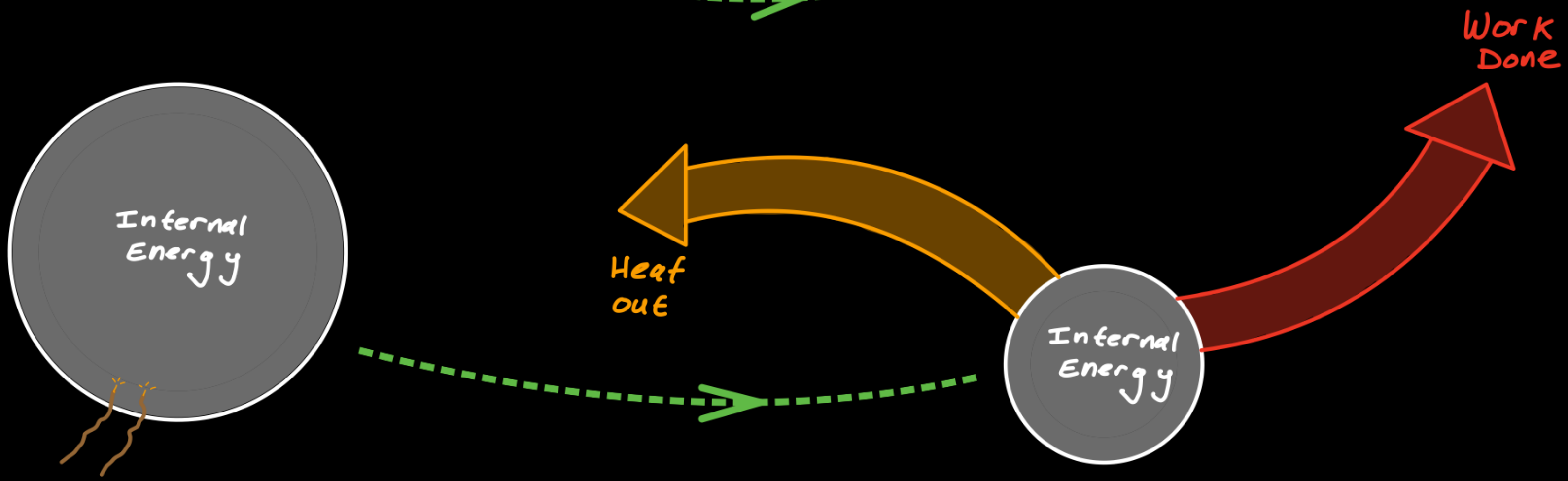




Part II - Time Travel via Sub-Luminal Velocity

Special Relativity

LLL [1]

Special Relativity is Einstein's 1905 theory of space and Time.

We will start with a lightening speed glance at Galileo Galilei's 1632 precursor to Einstein's Special Theory of Relativity.

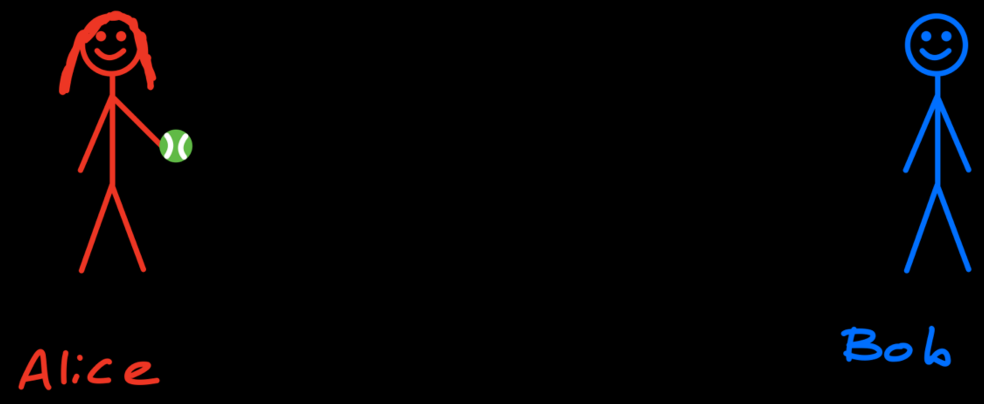
Galileo Galilei, 1640

Albert Einstein, 1905.

Galilean Relativity

Relativity is all about translating what one persons observed, to what another person would observe.

This second observer might be located at a different point in space relative to the first observer. They might also be moving relative to the first observer.



Throughout our discussion we will use two observers, Alice and Bob, and make comparisons of their observations of different events.

Let's consider what these two observers see when Alice throws a tennis ball at Bob.

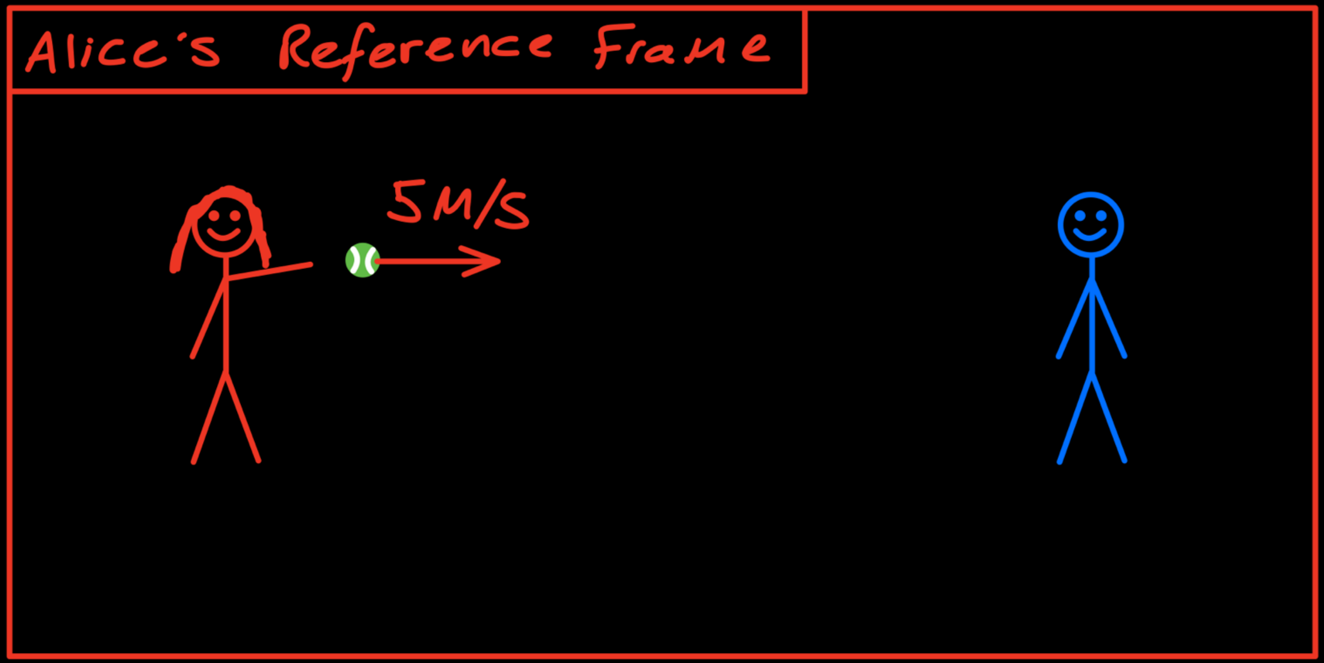
Galilean Relativity

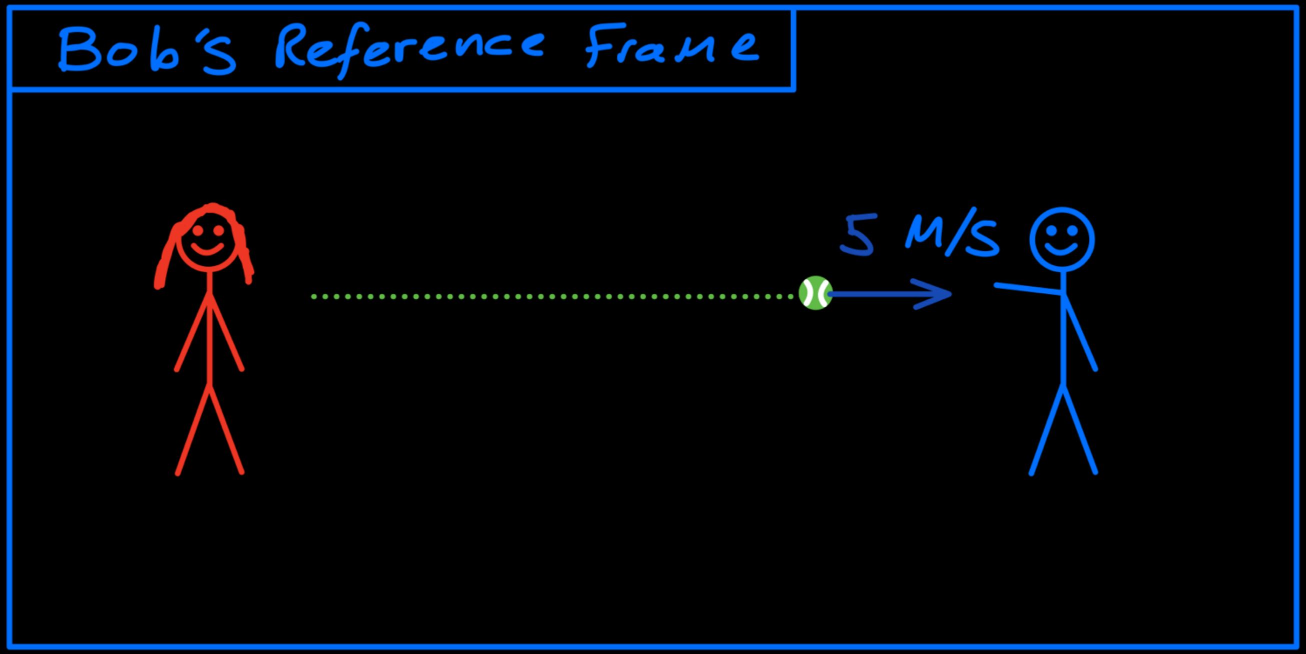
Alice throws the tennis ball towards Bob at a speed of **5 meters per second**.

This is the speed she perceives in her *reference frame*.

We will come back to the idea of a reference frame late. For now, we can think of this simply as *Alice's Point of View*.

In Bob's reference frame, the speed of the tennis ball when it reaches him is still **5 meters per second** (ignoring air resistance).



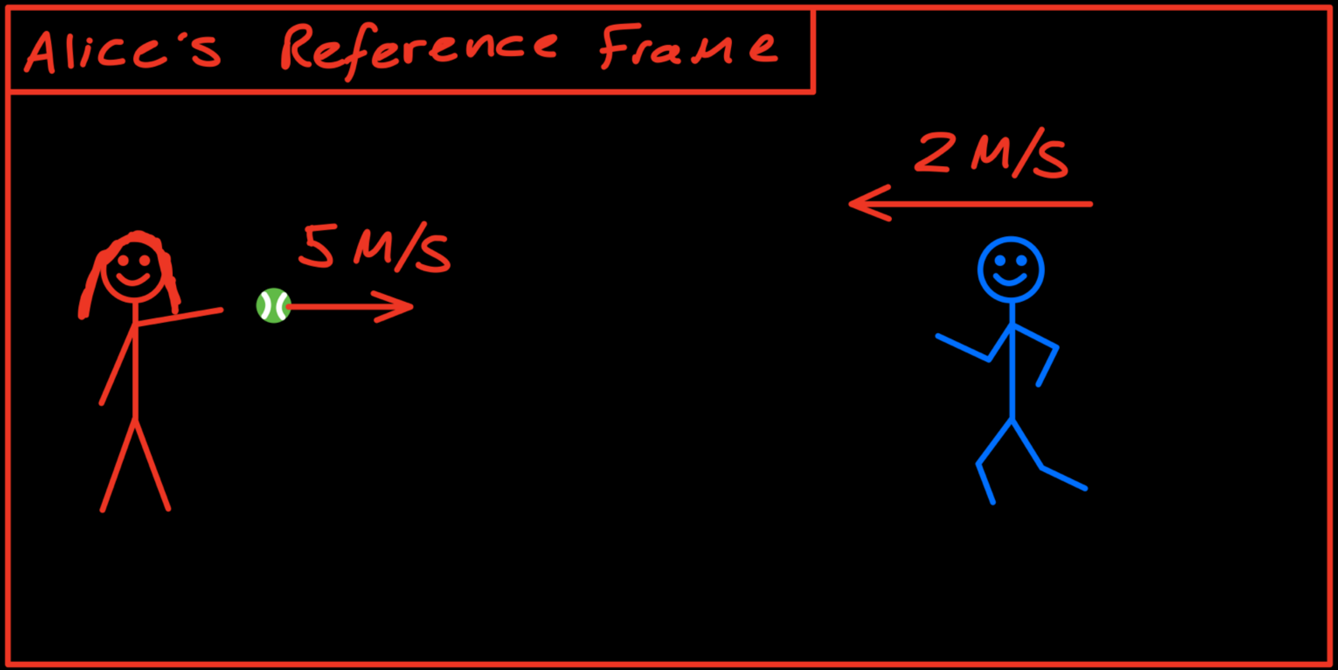


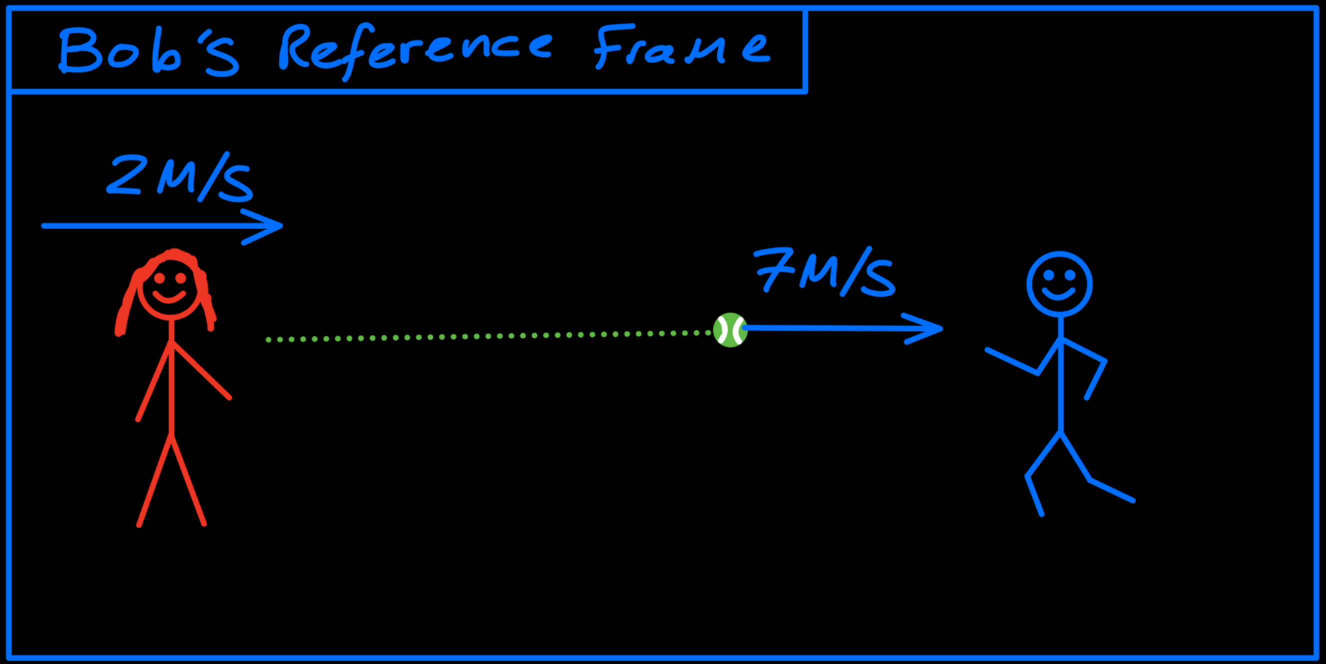
Galilean Relativity

How about if Bob is running towards Alice?

In Alice's reference frame, she see's Bob moving towards her at **2 meters per second**.

As a result, Bob measures the velocity of the ball to be **7 meters per second** in his reference frame.





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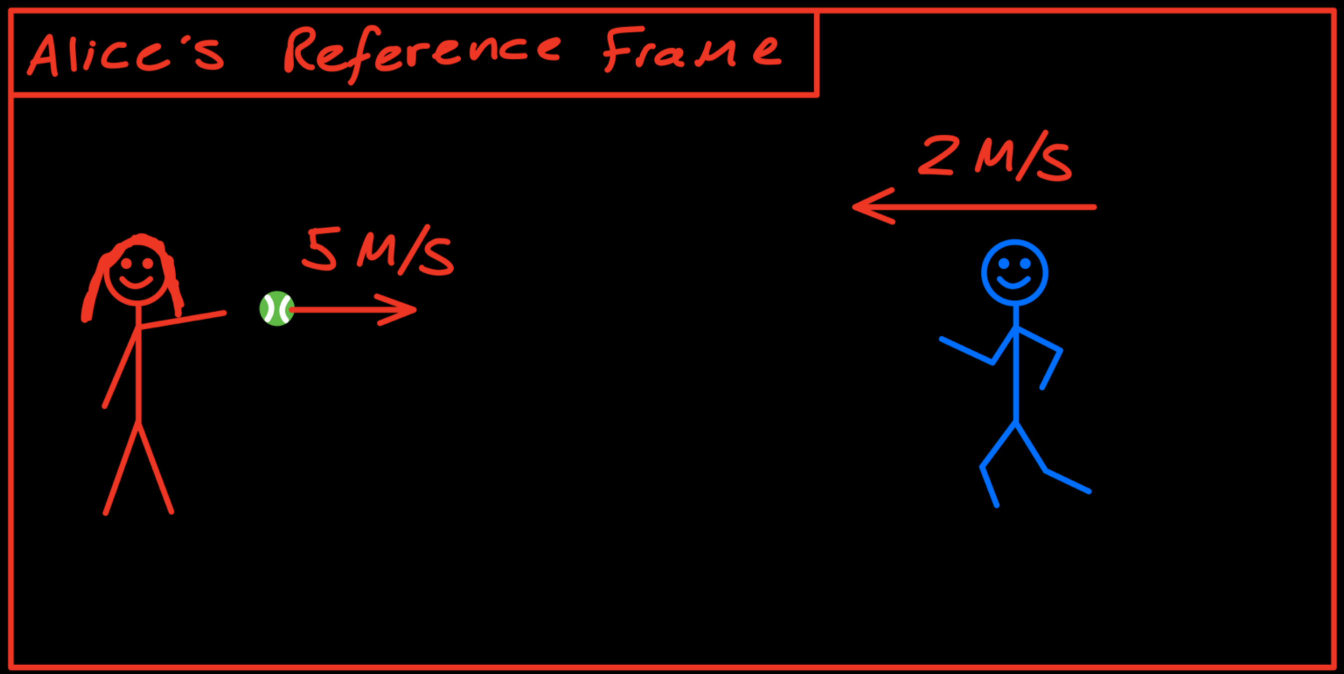
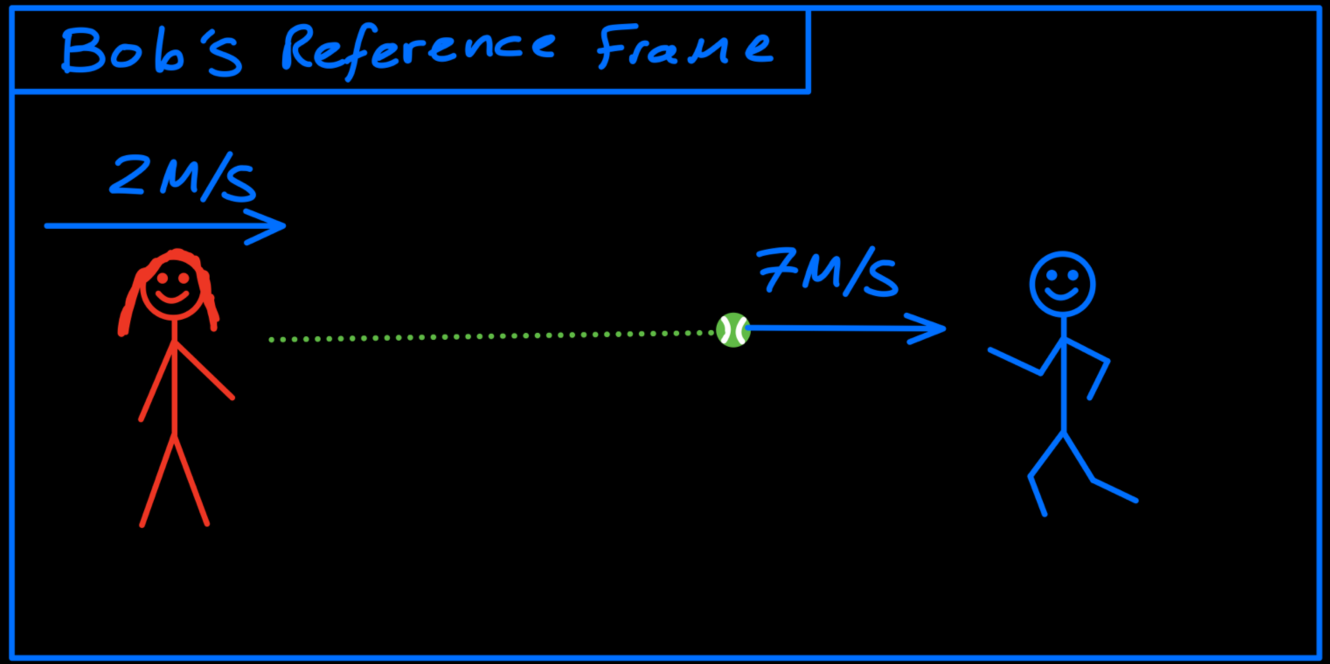
Who is correct?





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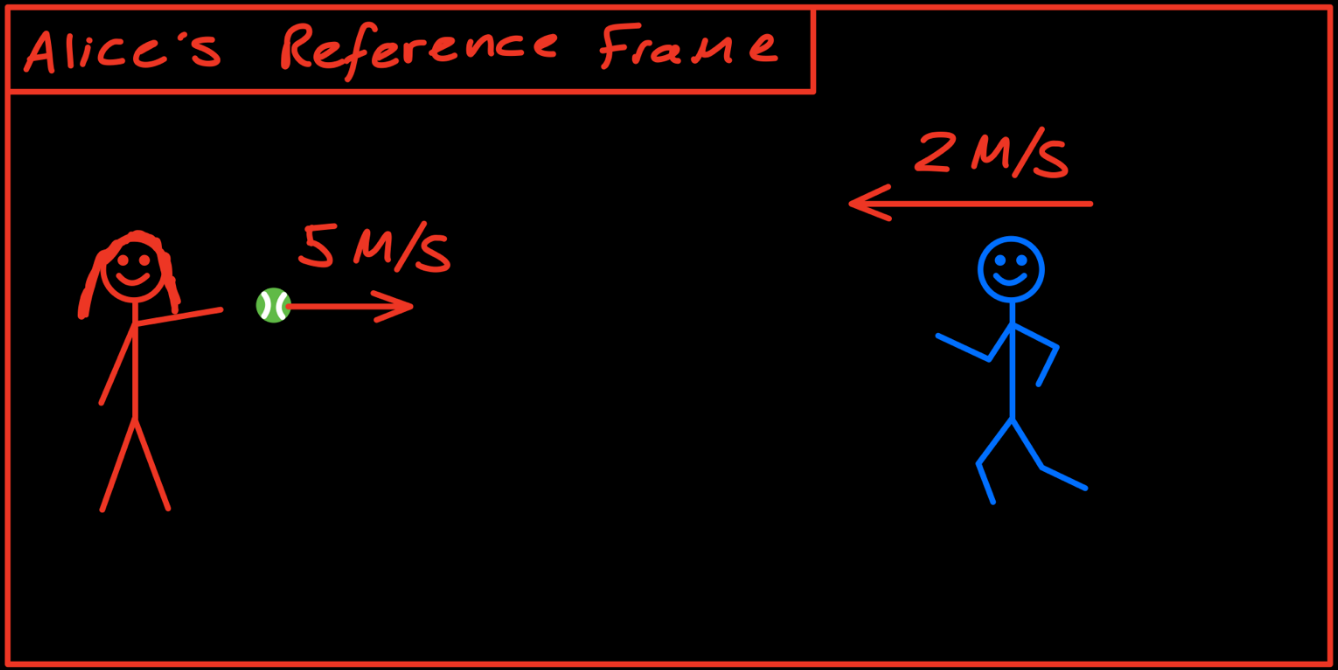
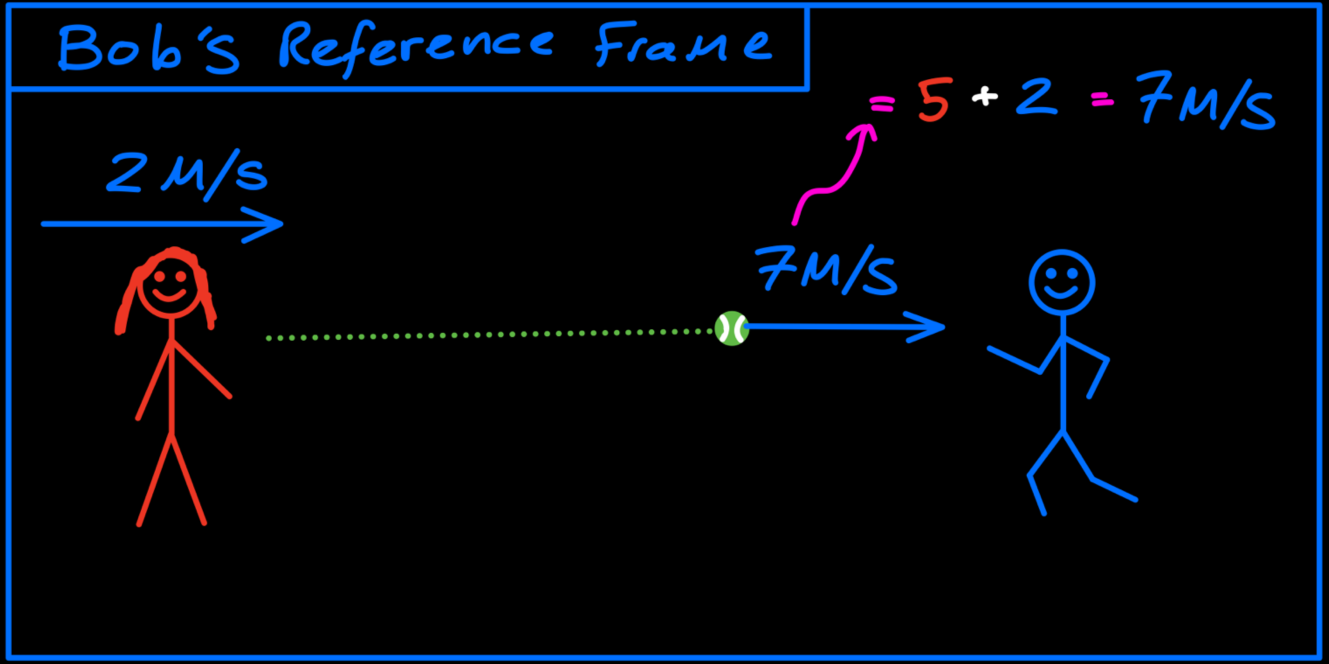
Who is correct?

Nobody is right or wrong! It's relative!

It depends who you ask.

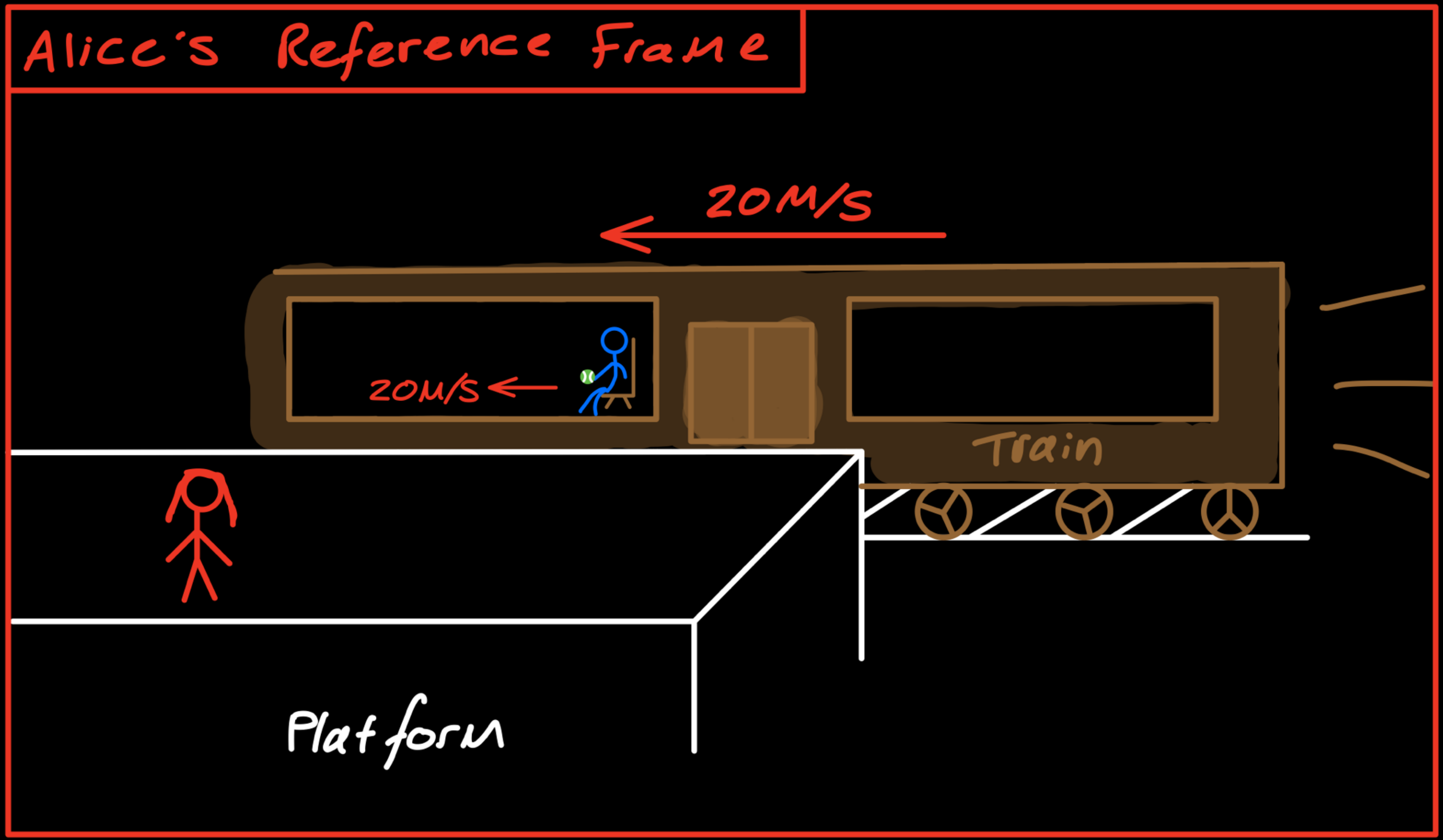




Galilean Relativity

Suppose Bob rides a train that passes Alice, standing on the station platform.

The train passes the station at a **constant speed** of **20 meters per second**.



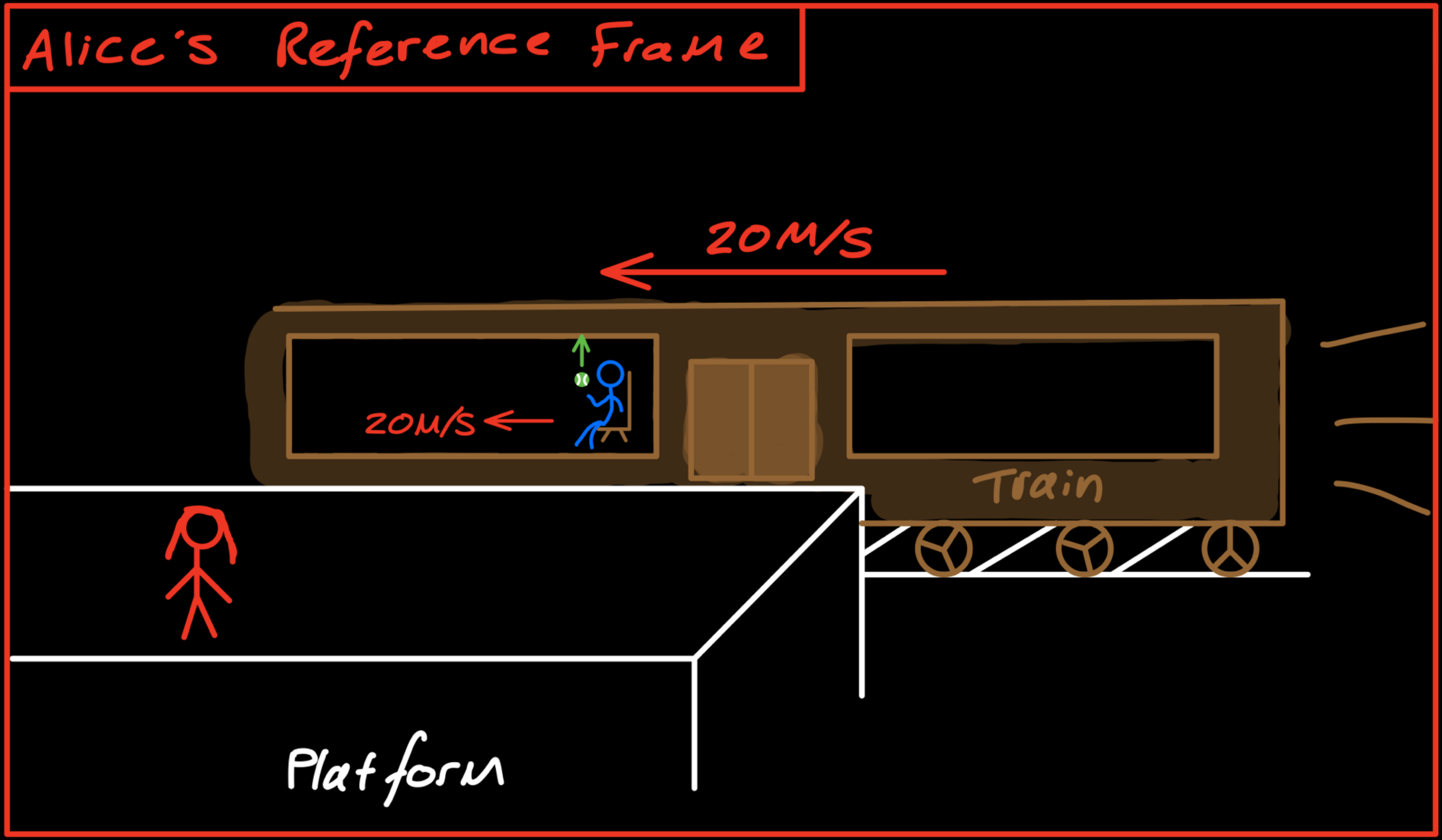
Galilean Relativity

Suppose Bob rides a train that passes Alice, standing on the station platform.

The train passes the station at a **constant speed** of **20 meters per second**.

Bob throws a tennis ball up in the air.

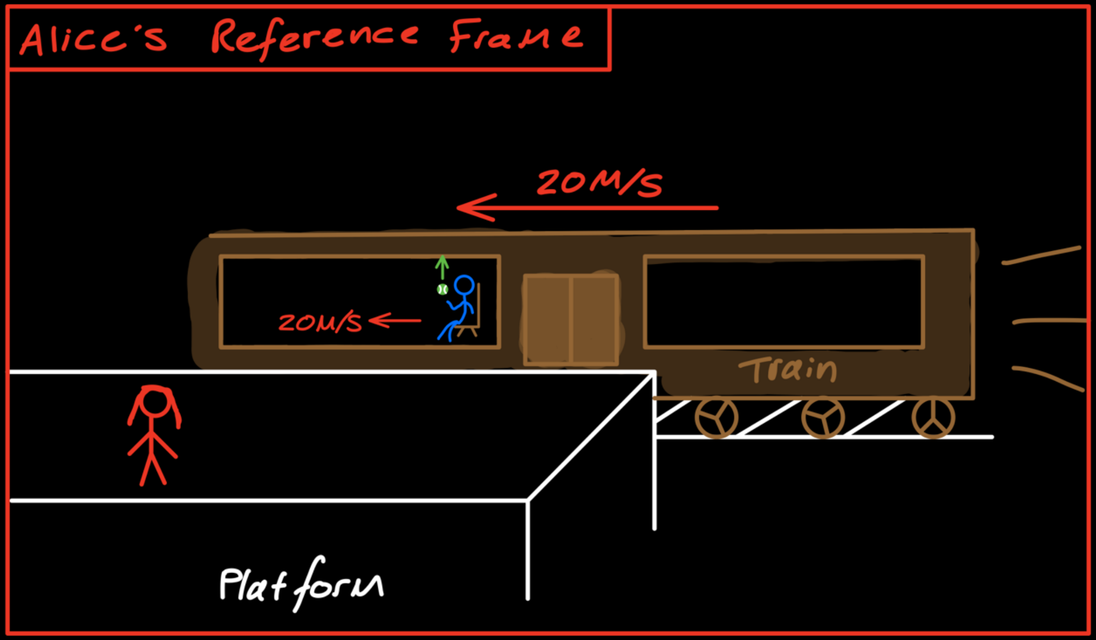
Let's consider how this appears to both observers.

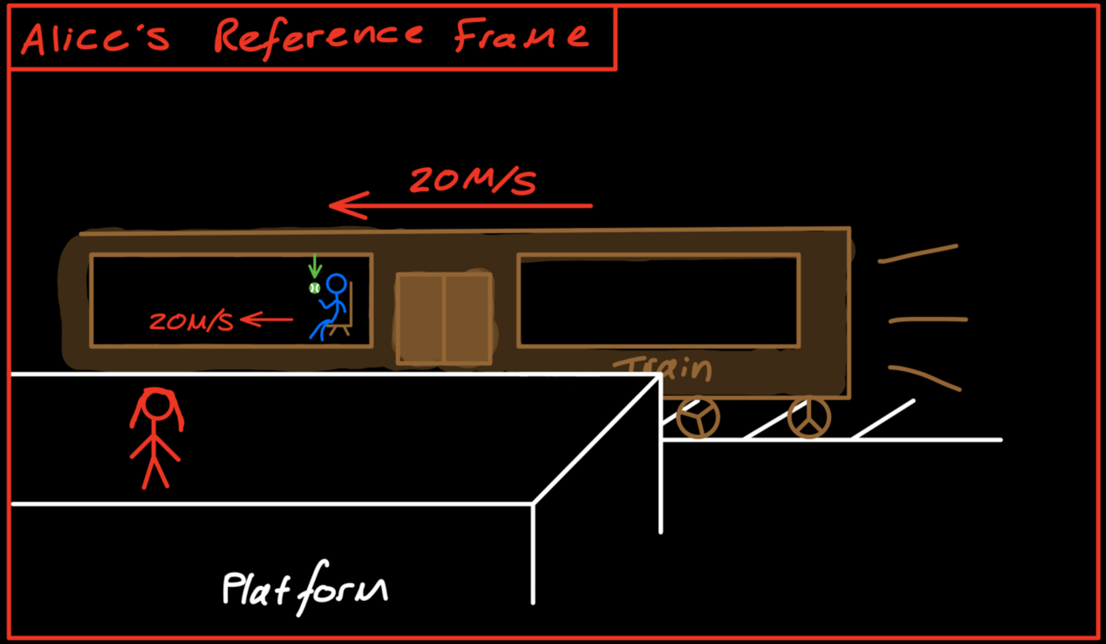


Galilean Relativity

In Alice's reference frame, she sees the tennis ball rise up in the air, and move along in a curved path before falling back into Bob's lap.

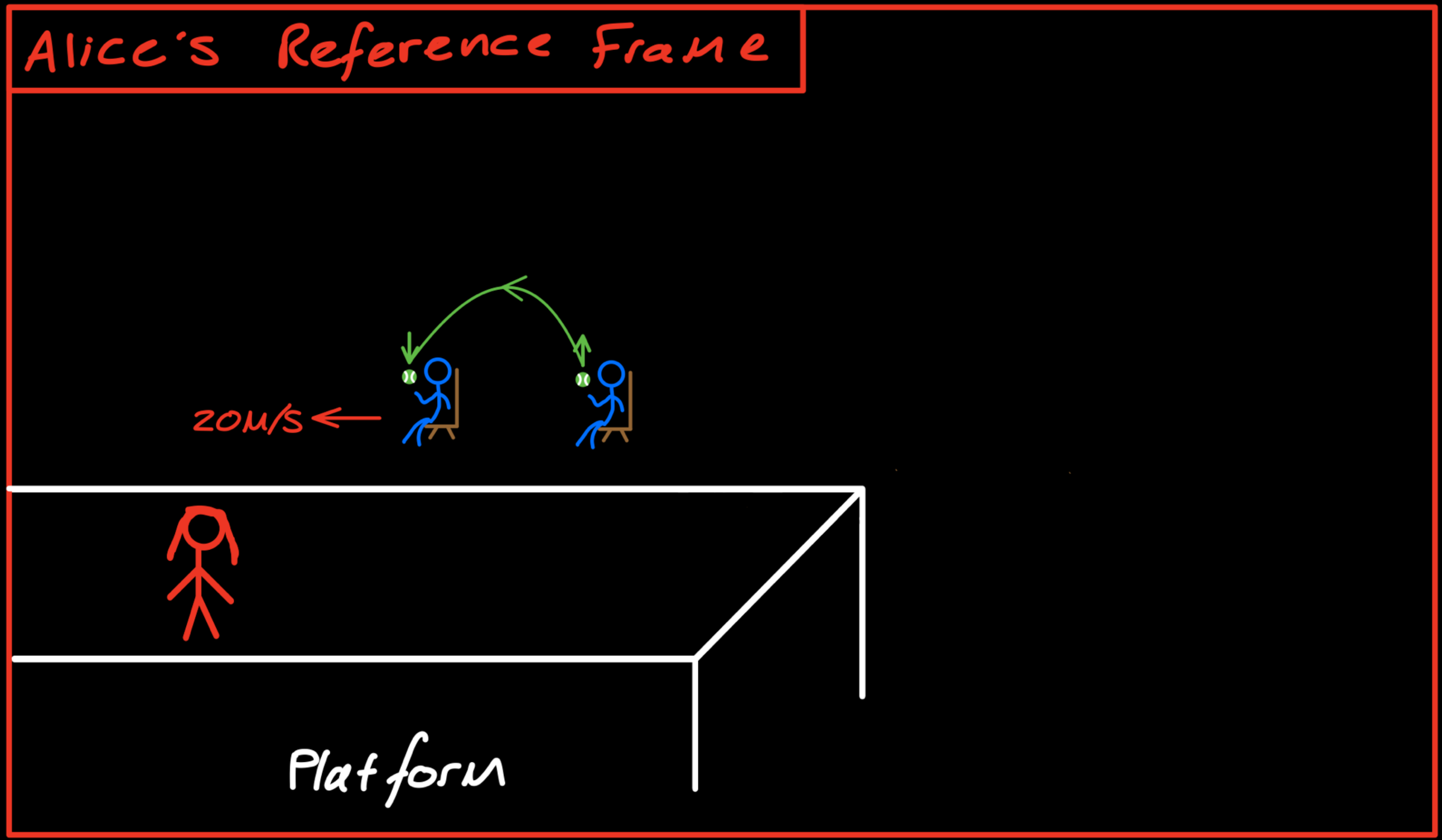
The tennis ball moves along with the train, across the platform.





Galilean Relativity

Removing the train from the figure, and looking at two snapshots of the tennis balls motion, we get a much clearer picture of what Alice sees.



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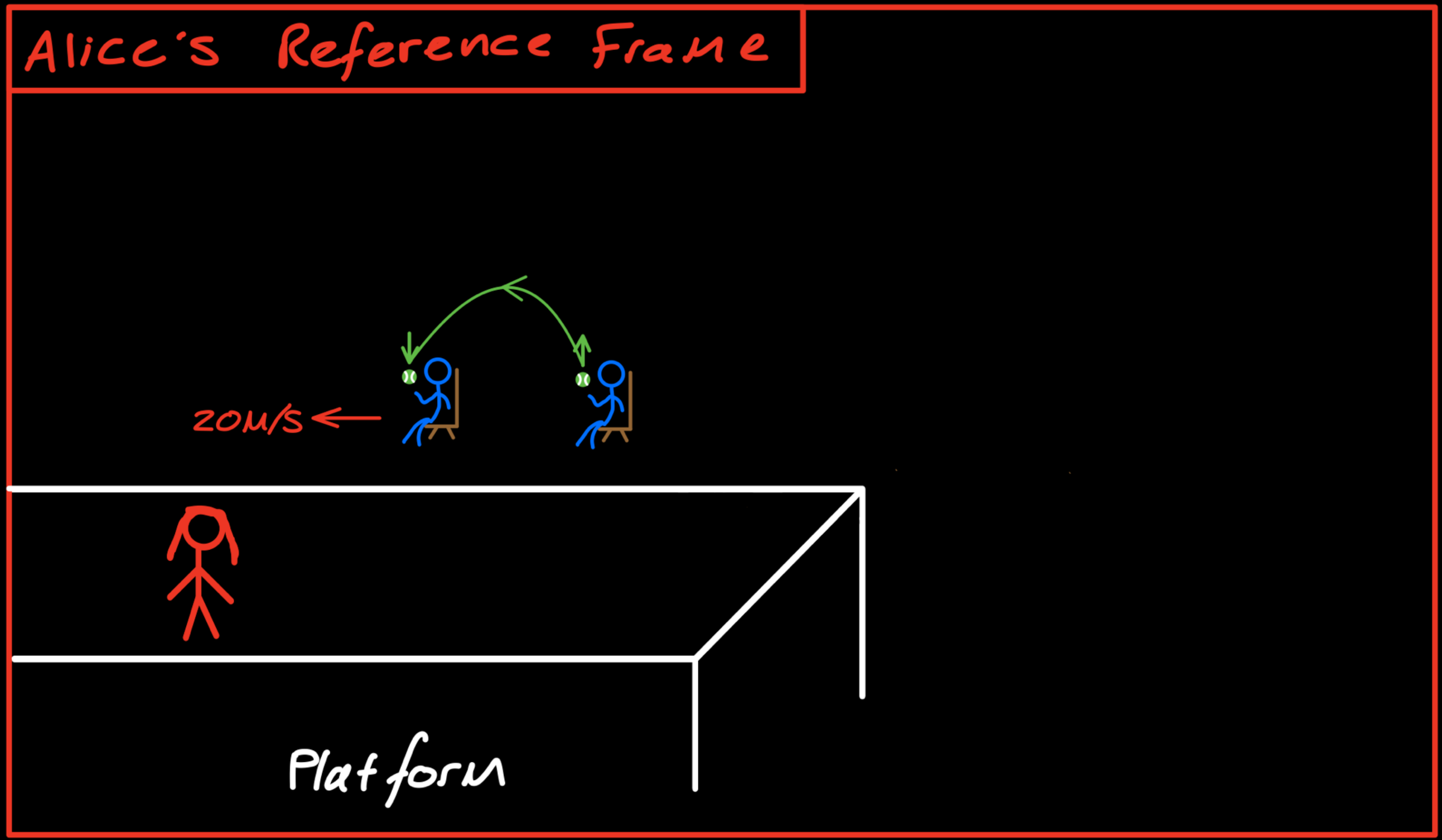
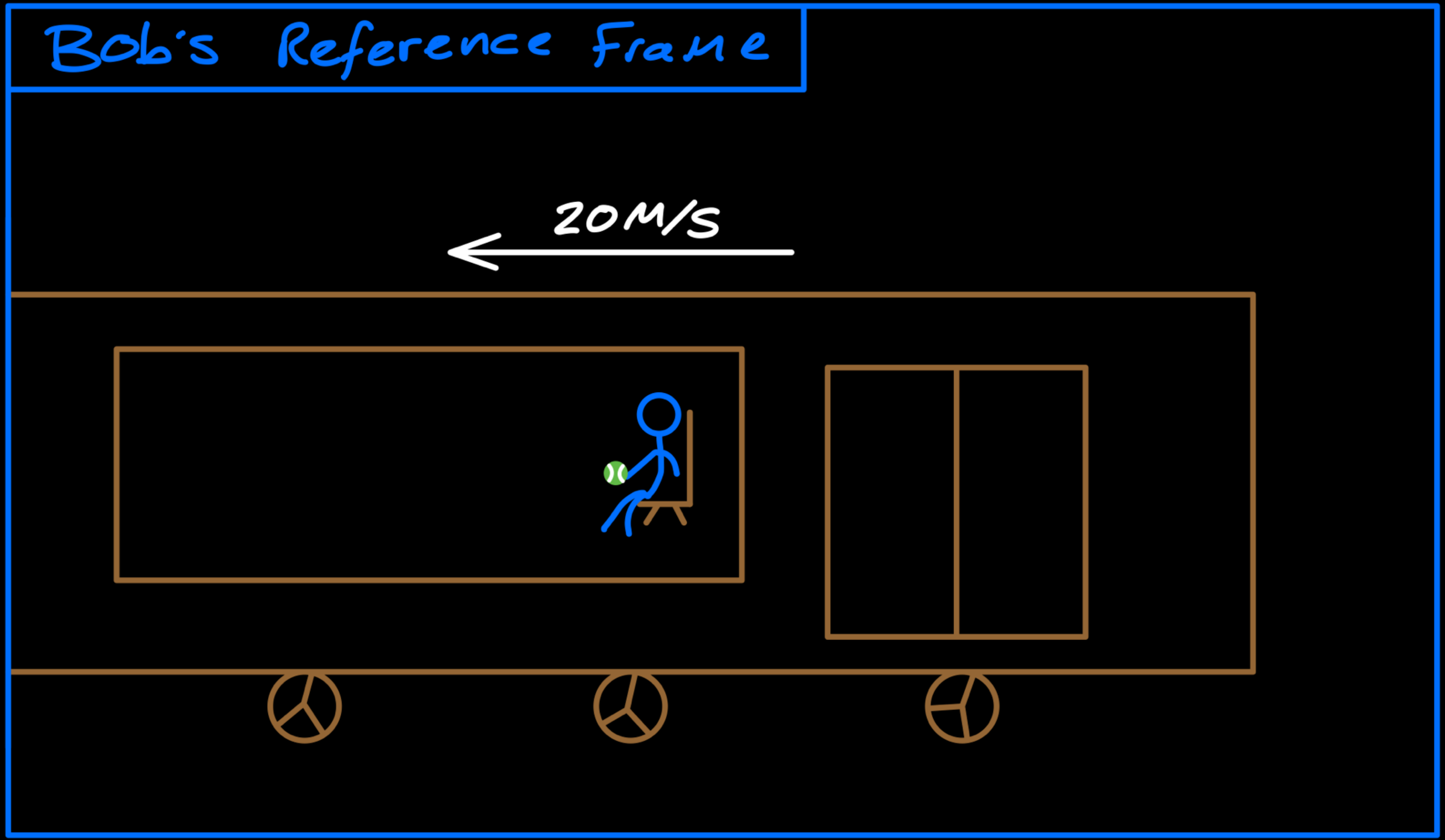
What does Bob see?



Galilean Relativity

Now consider Bob's point of view, sat on the train.

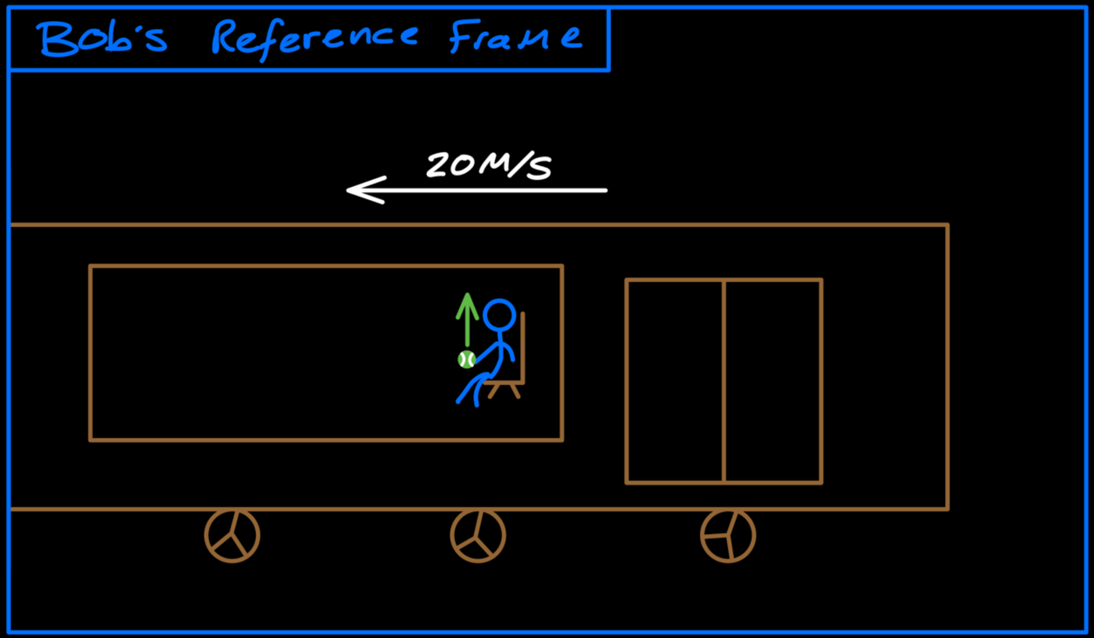


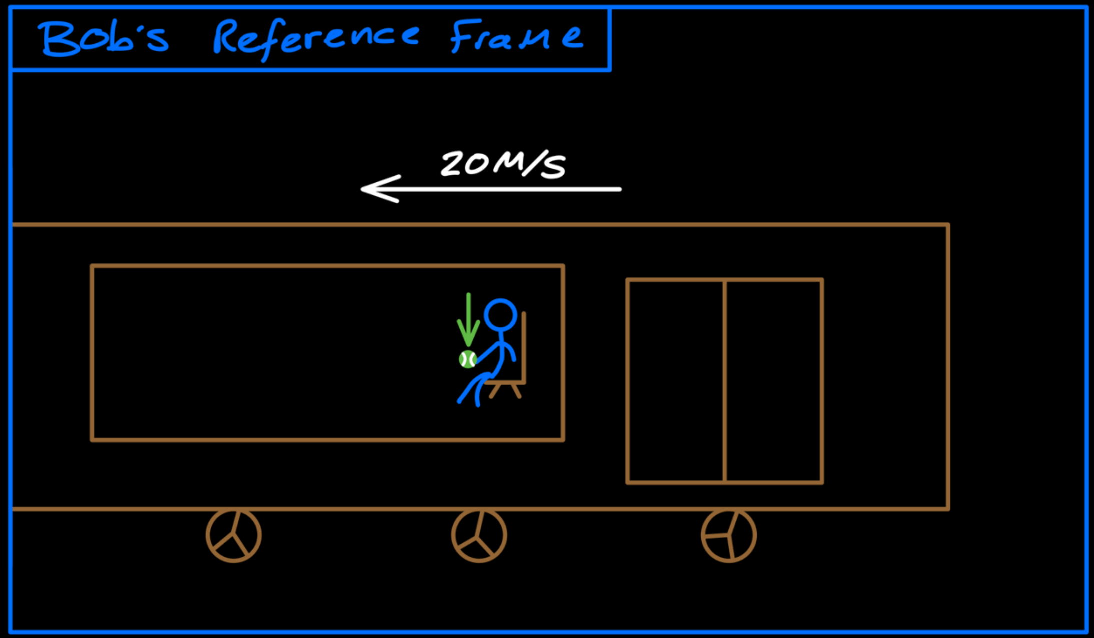
Galilean Relativity

In Bob's reference frame, the ball moves upwards in a straight line and falls back into his lap.

This is exactly what Bob would observe when the train is stationary at a station.

I.e. Newton's Laws of Motion appear to work the same way inside of a *stationary* train, as they do in a train moving at *constant speed*.





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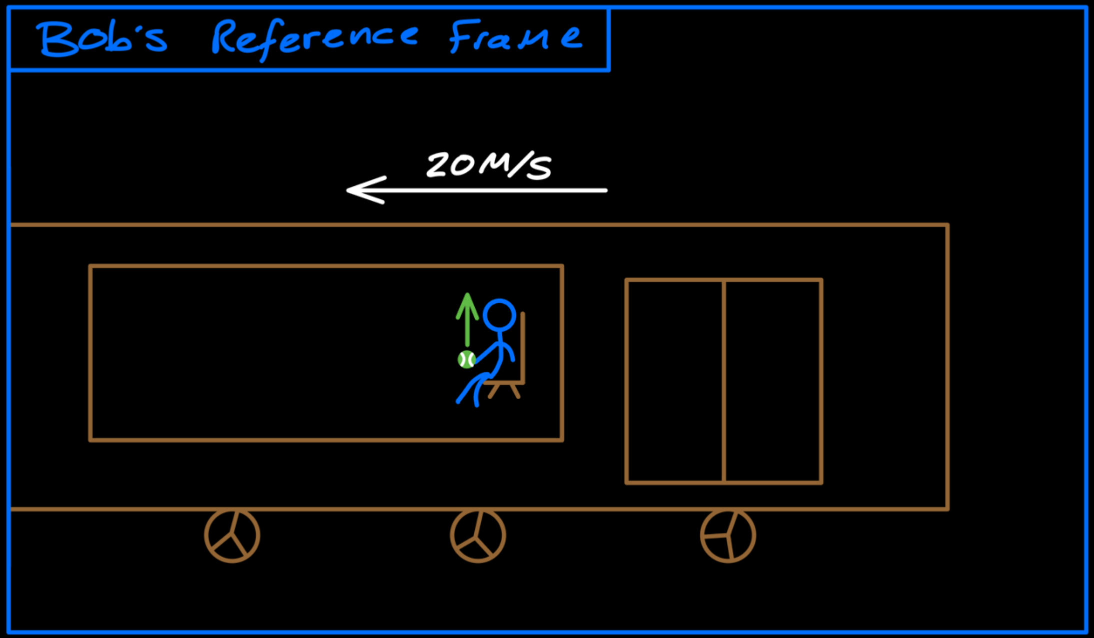
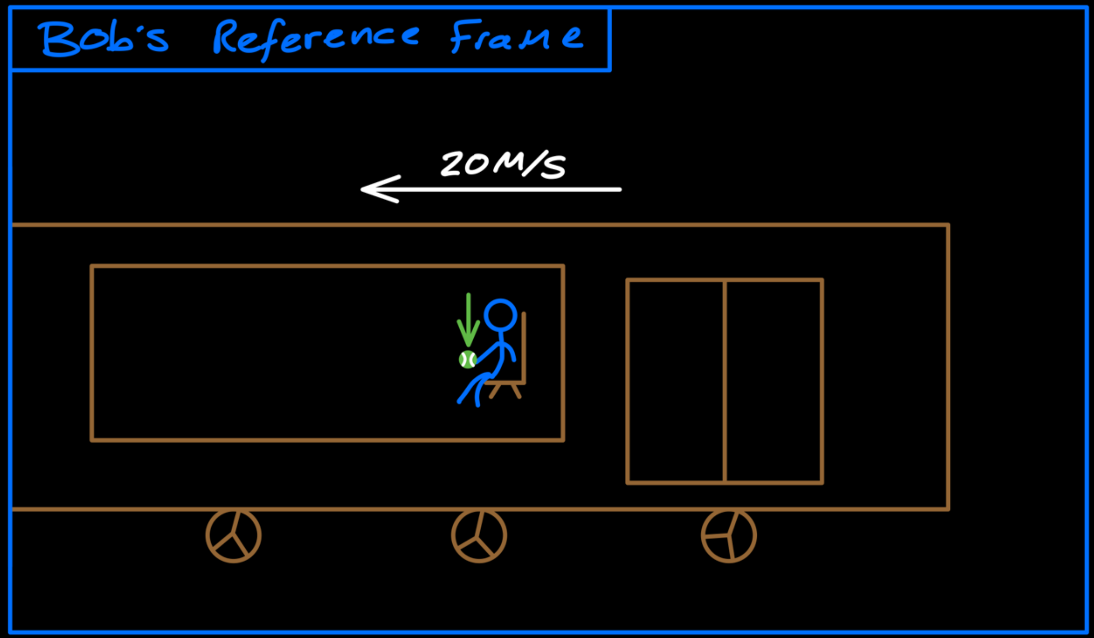
This is exactly what Bob would observe when the train is stationary at a station.

I.e. Newton's Laws of Motion appear to work the same way inside of a *stationary* train, as they do in a train moving at *constant speed*.

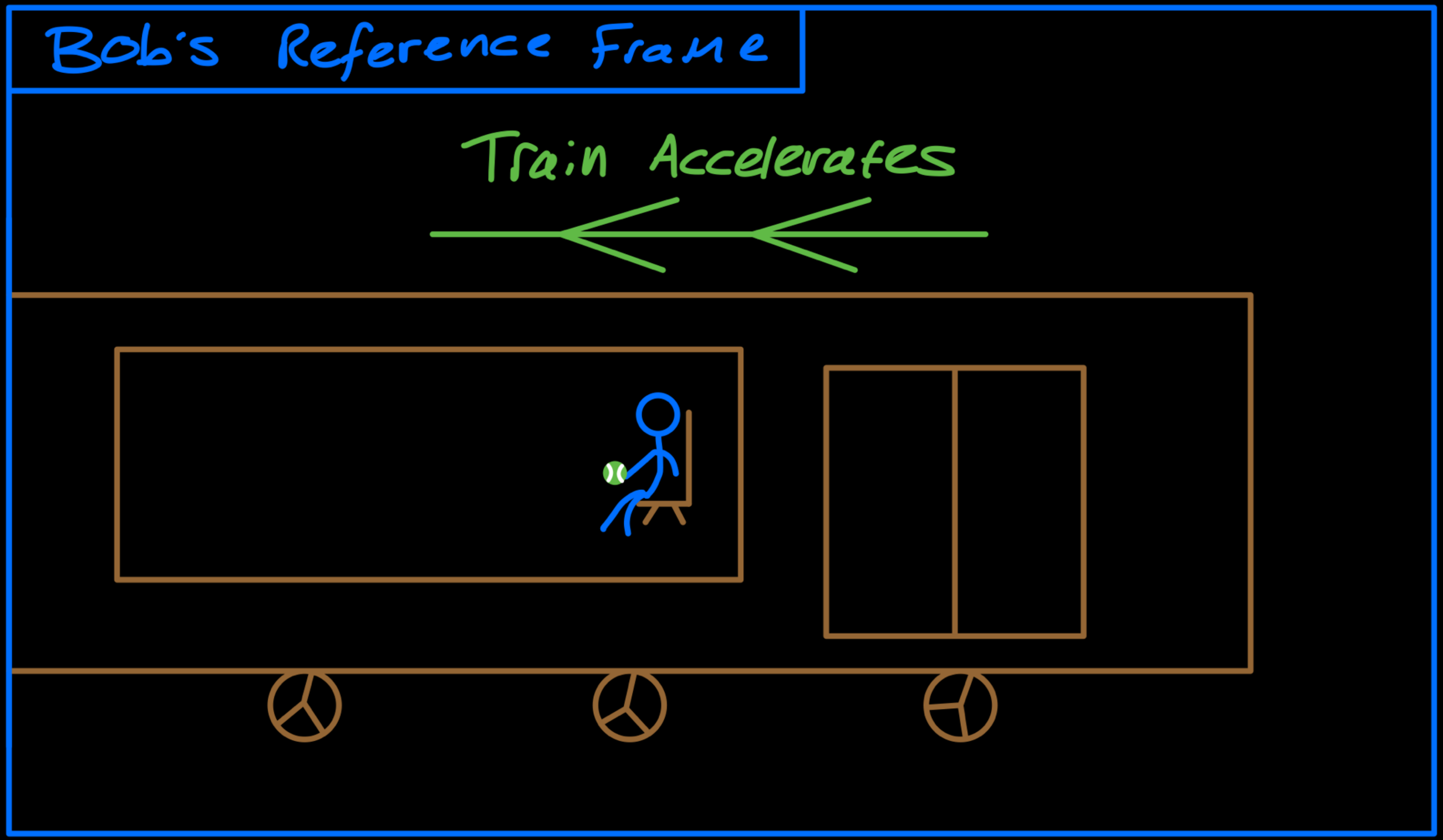
What about a train moving at a non-constant speed?





Galilean Relativity

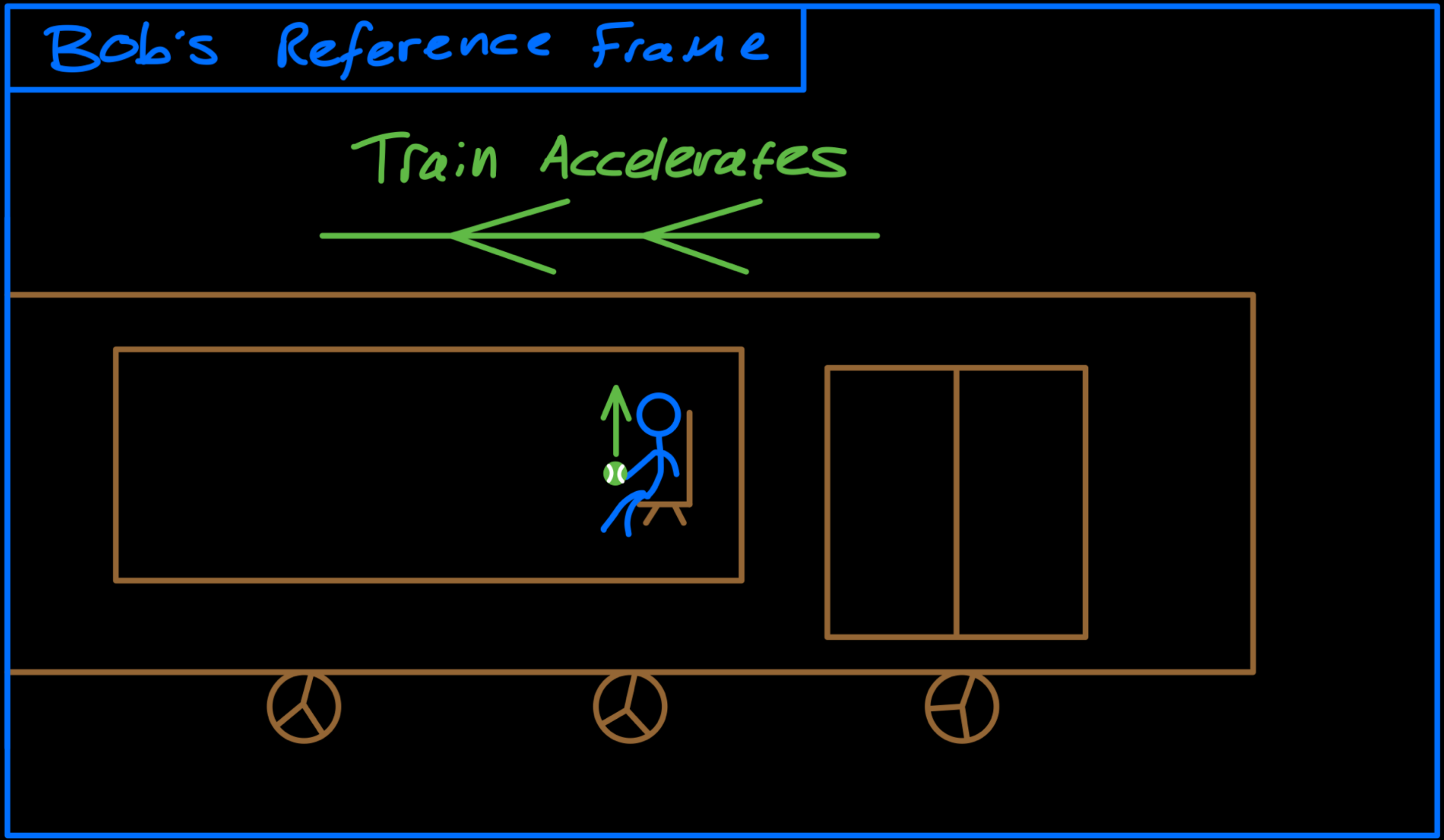
If the train accelerates (speeds up), Bob will observe something unusual.



Galilean Relativity

If the train accelerates (speeds up), Bob will observe something unusual.

He throws the ball upwards.



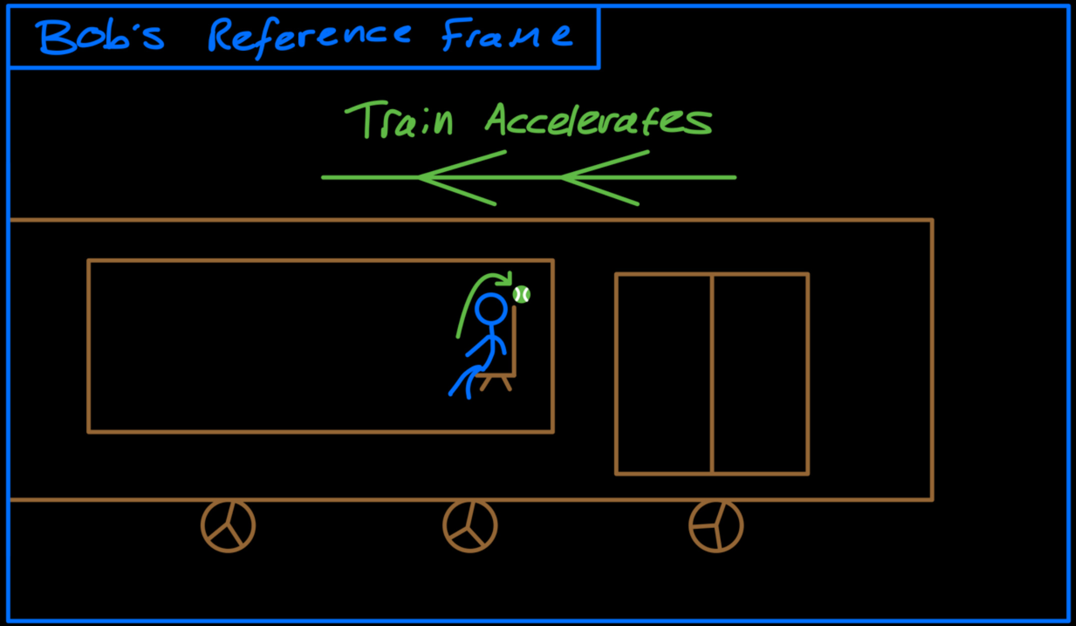
Galilean Relativity

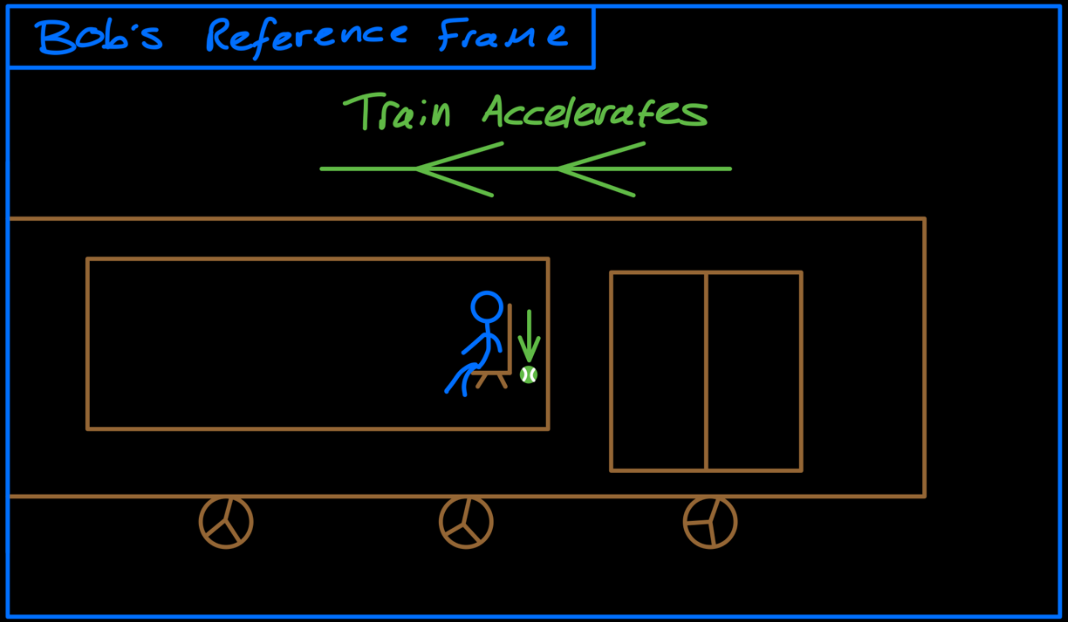
If the train accelerates (speeds up), Bob will observe something unusual.

He throws the ball upwards.

But the ball does not end up on his lap. It shoots over his head, and lands behind him.

This is different to what he would observer on a stationary train.

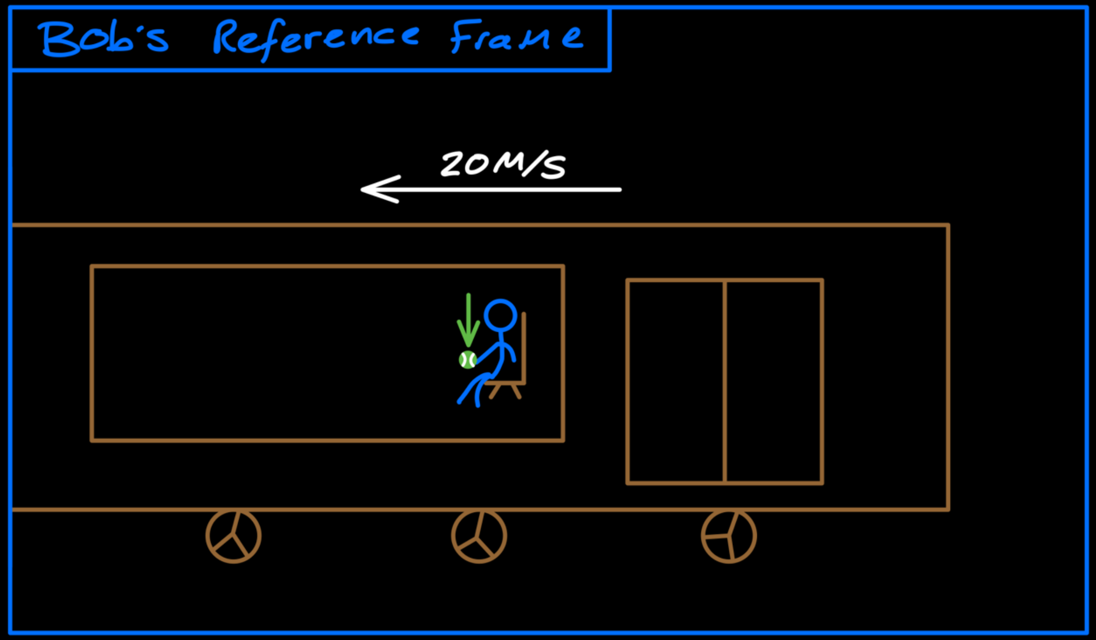


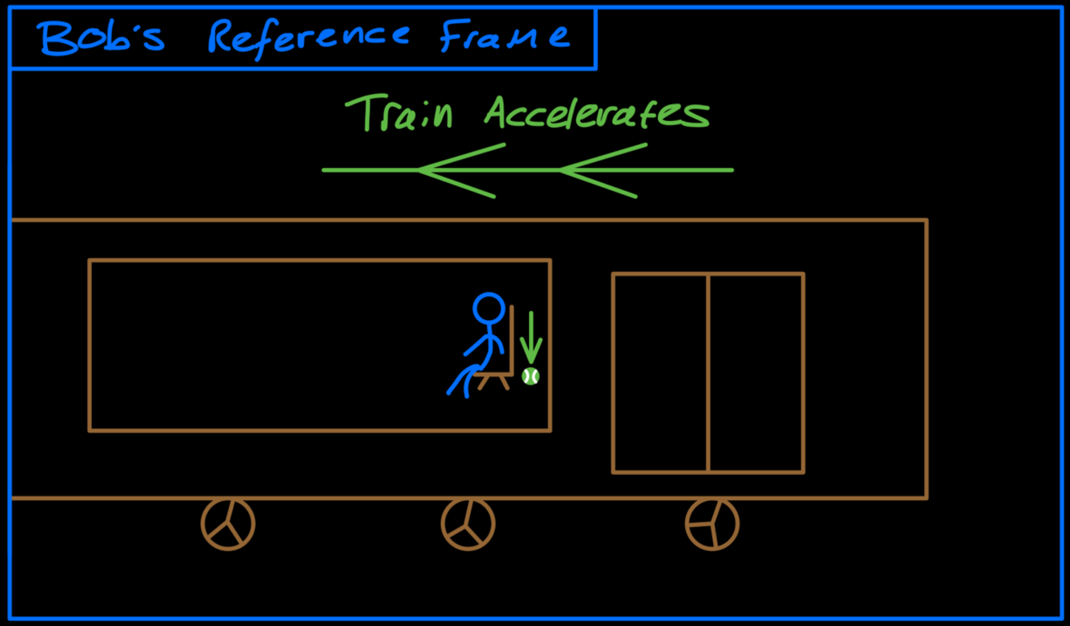


Galilean Relativity

This leads us to make a distinction between reference frames that move at a constant speed, and reference frames that are accelerating.

We call reference frames moving at a constant speed an **Inertial Reference Frame**.





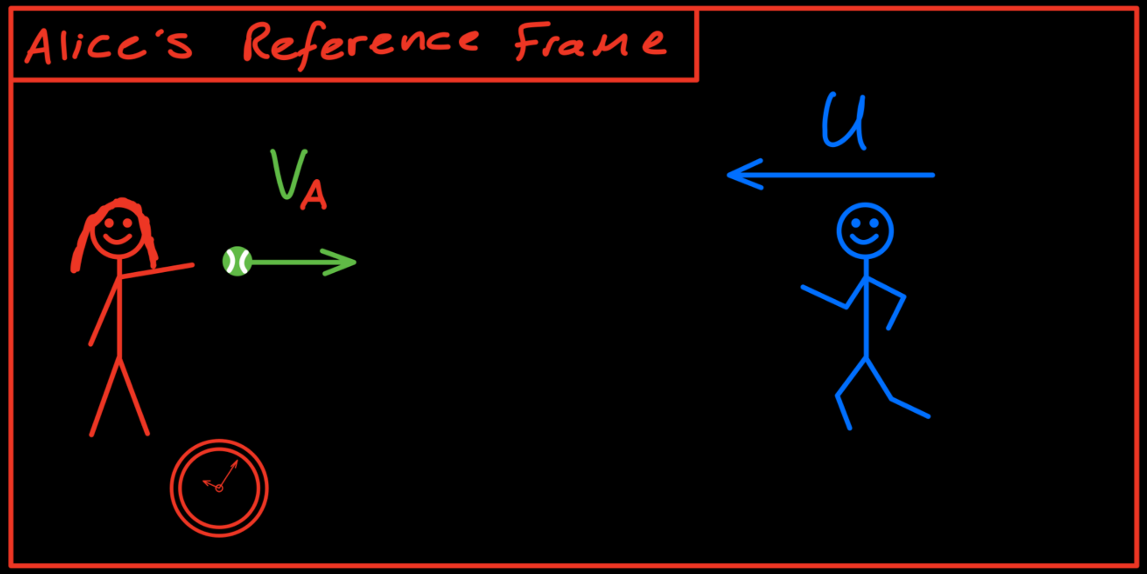
Galilean Relativity

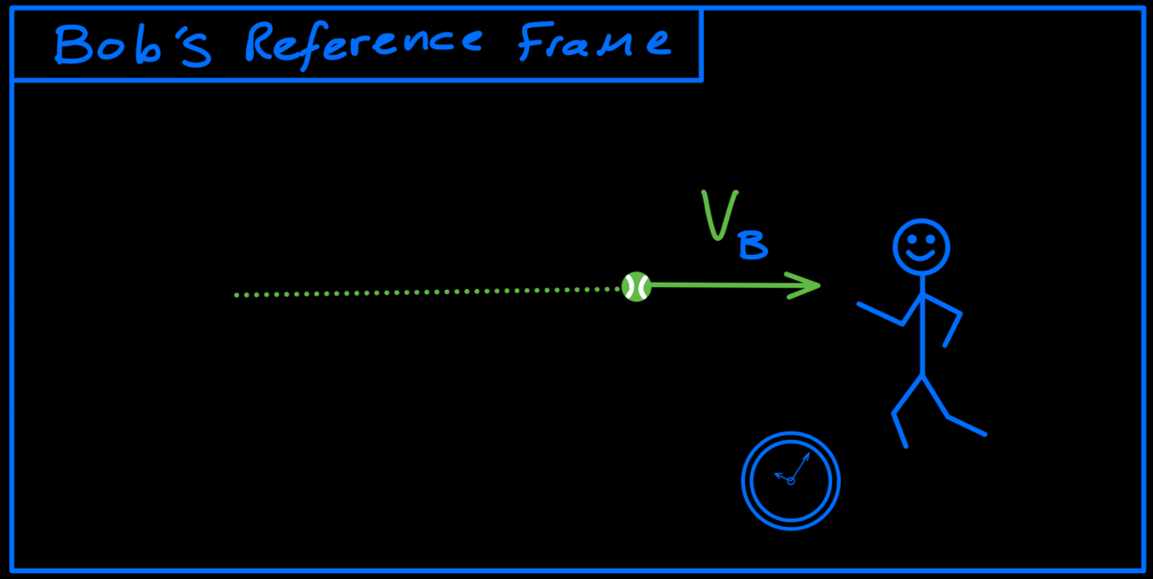
The Laws

1. Newton's Laws are obeyed in Inertial Reference Frames.

2. Velocity addition formula. $V_B = V_A + u$

3. Clocks tick at the same rate. 





Maxwell's Equations

In 1862, James Clerk Maxwell published the first form of his equations of electricity and magnetism.

These equations describe the ways that electric and magnetic fields are created, and how they interact.

They outline how a changing magnetic field can create a changing electric field, and vice versa.

Equations of Magnetic Force.

$$\left.\begin{aligned}\mu\alpha &= \frac{dH}{dy}-\frac{dG}{dz},\\ \mu\beta &= \frac{dF}{dz}-\frac{dH}{dx},\\ \mu\gamma &= \frac{dG}{dx}-\frac{dF}{dy}.\end{aligned}\right\}\ldots$$

Equations of Electromotive Force.

$$\left.\begin{aligned}P &= \mu\left(\gamma\frac{dy}{dt}-\beta\frac{dz}{dt}\right)-\frac{dF}{dt}-\frac{d\Psi}{dx},\\ Q &= \mu\left(\alpha\frac{dz}{dt}-\gamma\frac{dx}{dt}\right)-\frac{dG}{dt}-\frac{d\Psi}{dy},\\ R &= \mu\left(\beta\frac{dx}{dt}-\alpha\frac{dy}{dt}\right)-\frac{dH}{dt}-\frac{d\Psi}{dz}.\end{aligned}\right\}\ldots$$

For Electromagnetic Momentum	F	G	H
,, Magnetic Intensity	α	β	γ
,, Electromotive Force	P	Q	R
,, Current due to true conduction	p	q	r
,, Electric Displacement	f	g	h
,, Total Current (including variation of displacement)	p'	q'	r'
,, Quantity of free Electricity	e		
,, Electric Potential	Ψ		

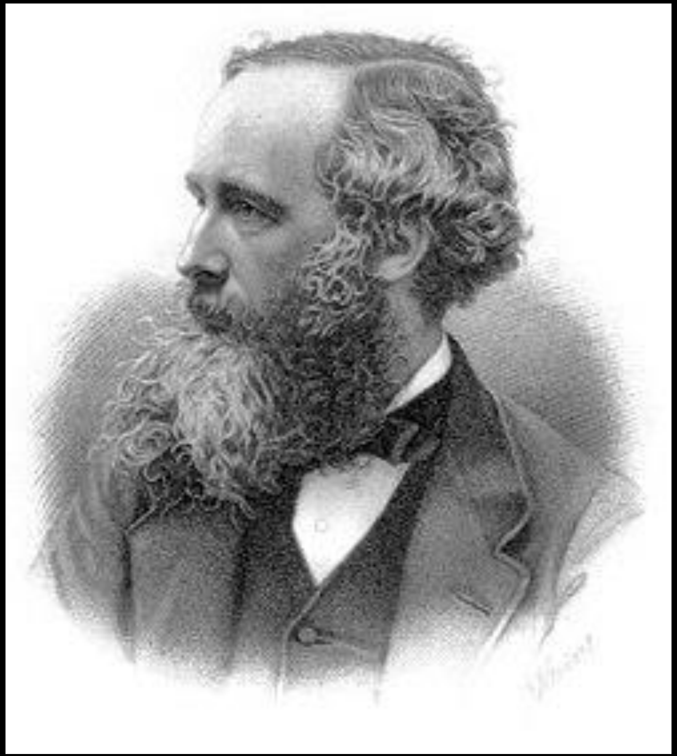
Between these twenty quantities we have found twenty equations, viz.

Three equations of Magnetic Force	(B)
,, Electric Currents	(C)
,, Electromotive Force	(D)
,, Electric Elasticity	(E)
,, Electric Resistance	(F)
,, Total Currents	(A)
One equation of Free Electricity	(G)
,, Continuity	(H)

Equation of Continuity,

$$\frac{de}{dt}+\frac{dp}{dx}+\frac{dq}{dy}+\frac{dr}{dz}=0.$$

Some of Maxwell's original **26 equations**, from his 1865 paper *A Dynamical Theory of the Electromagnetic Field*.



James Clerk Maxwell, approx 1870

Maxwell's Equations

Maxwell's original 26 Equations proved extremely hard to deal with.

In 1884 these were condensed to just four, by using a new mathematical language developed by Oliver Heaviside.

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \left(\vec{J} + \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \right)$$

Heaviside's simplified version of Maxwell's equations, written using the language of *vector calculus*.

Oliver Heaviside, 1900

Maxwell's Equations

In 1865, Maxwell showed that his equations predict the existence of an electromagnetic wave.

A self propagating, cycle of alternating electric and magnetic fields.

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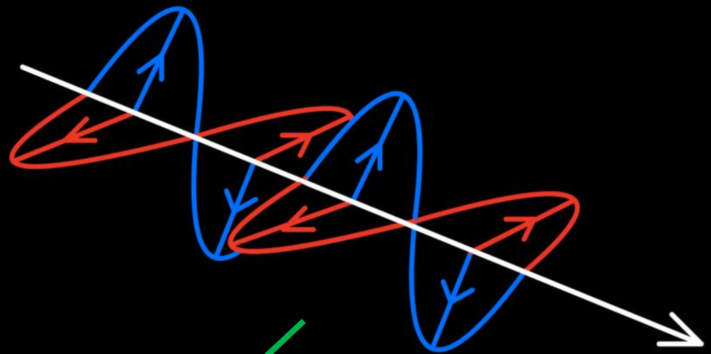

The equations even predicted the speed this electromagnetic wave should move with...

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = \frac{1}{\sqrt{8.85 \times 10^{-12} \times 4\pi \times 10^{-7}}}$$

$$= 3 \times 10^{8} \text{ m/s}$$

Maxwell's Equations

In 1865, Maxwell showed that his equations predict the existence of an electromagnetic wave.

A self propagating, cycle of alternating electric and magnetic fields.

The equations even predicted the speed this electromagnetic wave should move with...

THIS IS THE SPEED OF LIGHT

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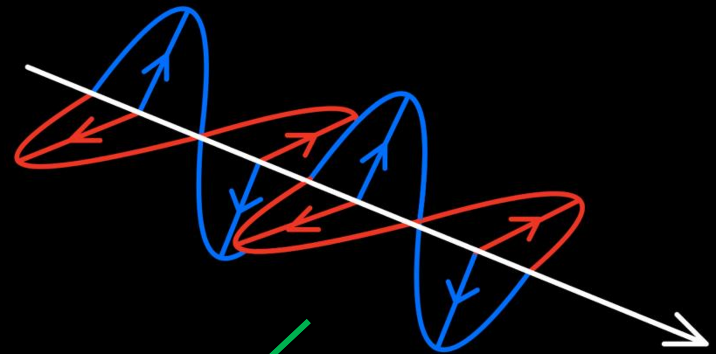

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The speed of light

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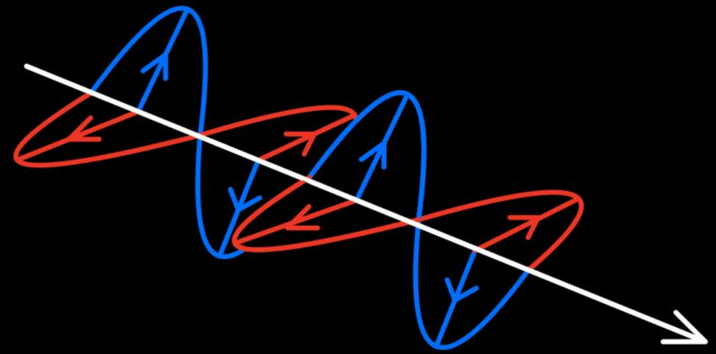

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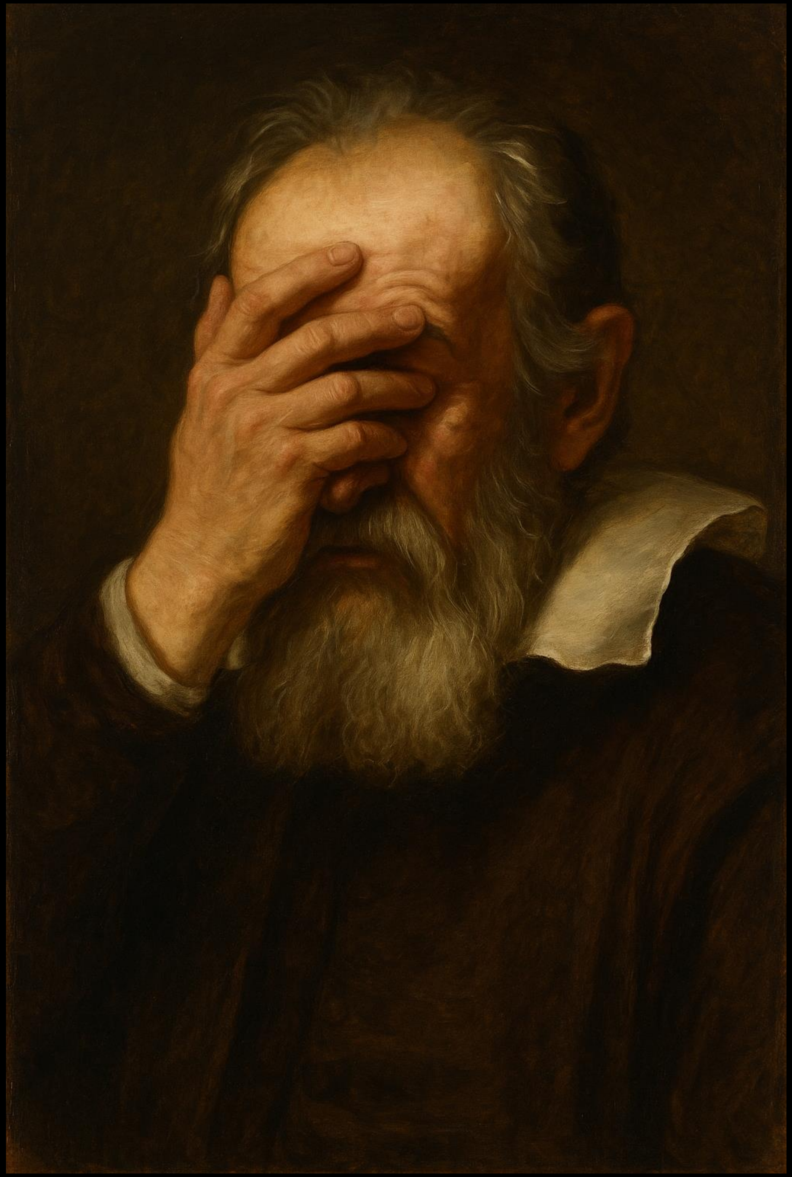
The speed of Light

Light is an "Electro-Magnetic wave".

A Problem for Galileo...

If we try to extend Galilean Relativity to Maxwell's equations, we run into a number of problems...

The equations become inconsistent, and predict things that we do not observe.



Note: This is an AI generated image.

A Problem for Galileo...

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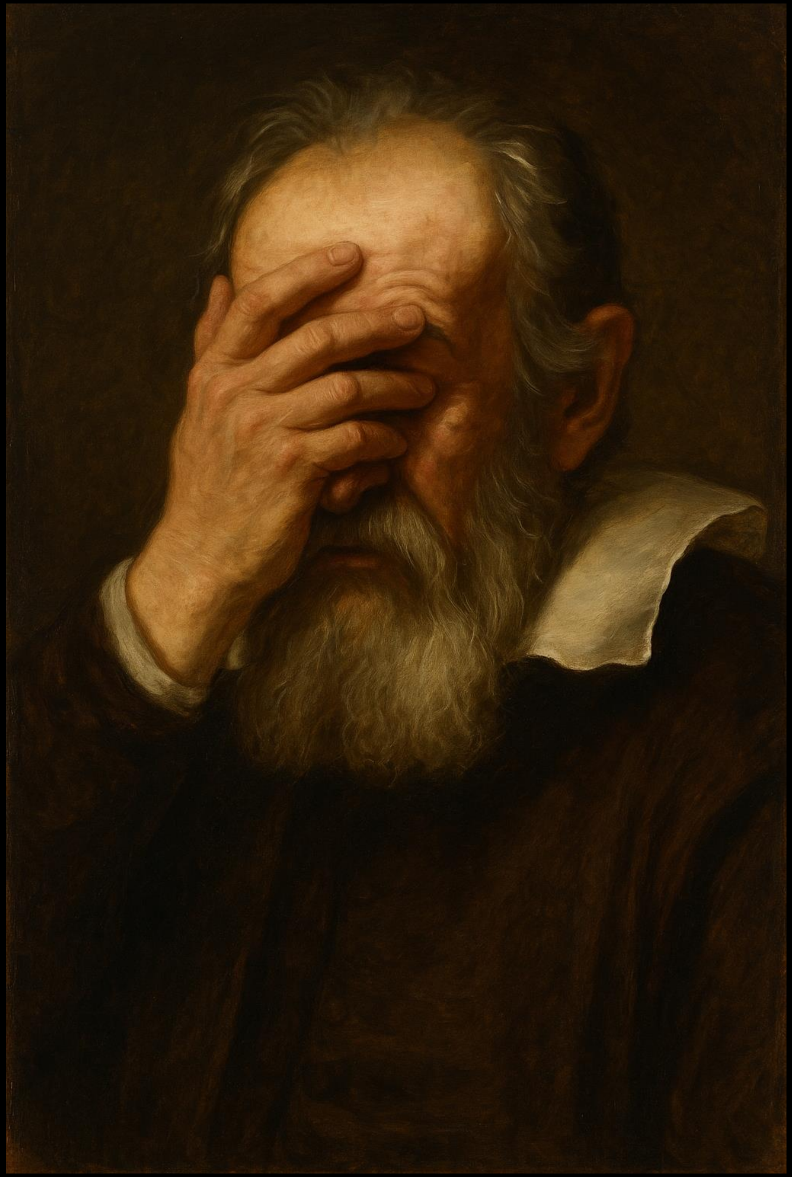
The equations become inconsistent, and predict things that we do not observe.

Recall Feynman's Golden Rule..



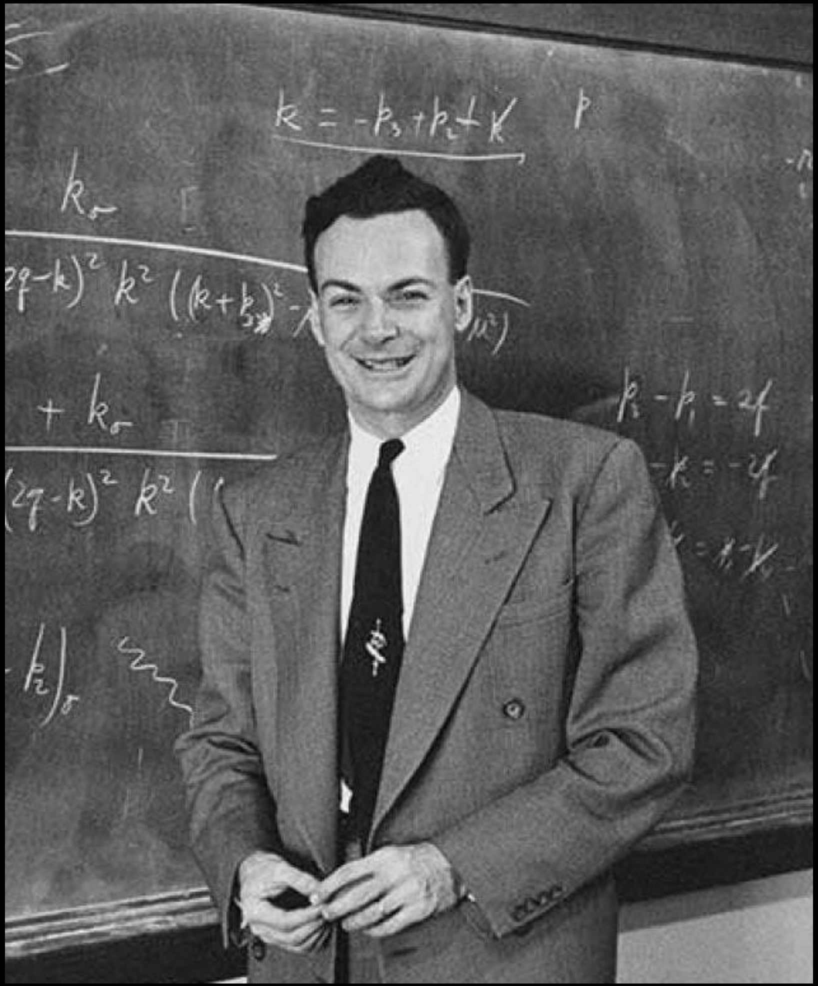
Note: This is an AI generated image.

Theory vs Experiment

"In general, we look for a new law by the following process: First we guess it; then we compute the consequences of the guess to see what would be implied if this law that we guessed is right; then we compare the result of the computation to nature, with experiment or experience, compare it directly with observation, to see if it works.

*If it disagrees with experiment, it is wrong. In that simple statement is the key to science. It does not make any difference how beautiful your guess is, it does not make any difference how smart you are, who made the guess, or what his name is — **if it disagrees with experiment, it is wrong**."*

Richard Feynman



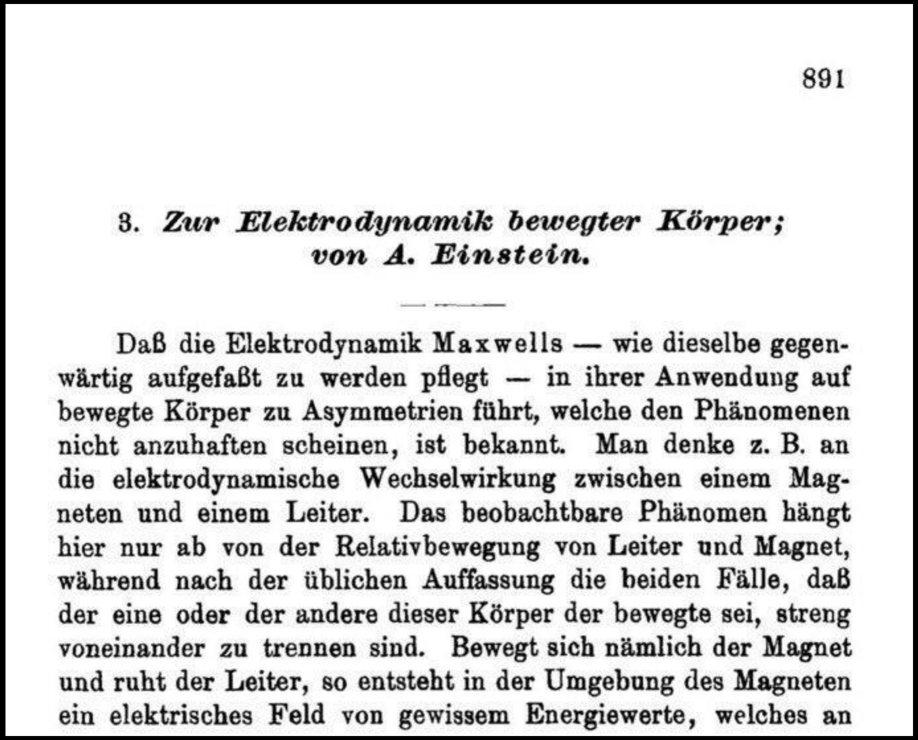
With insufficient theory to explain experimental observations, a **new theory is needed**.

Einsteinian Relativity

With Maxwell's Equations being the newer law, and the better tested law – It looks as if Galilean Relativity is for the chopping block.

In 1905, Einstein reconciles Maxwell's Equations with the concept of relativity.

He does this with only two postulates.



891

3. *Zur Elektrodynamik bewegter Körper;*
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an

On the Electrodynamics of Moving Bodies - 1905

Albert Einstein, 1905.

Einsteinian Relativity

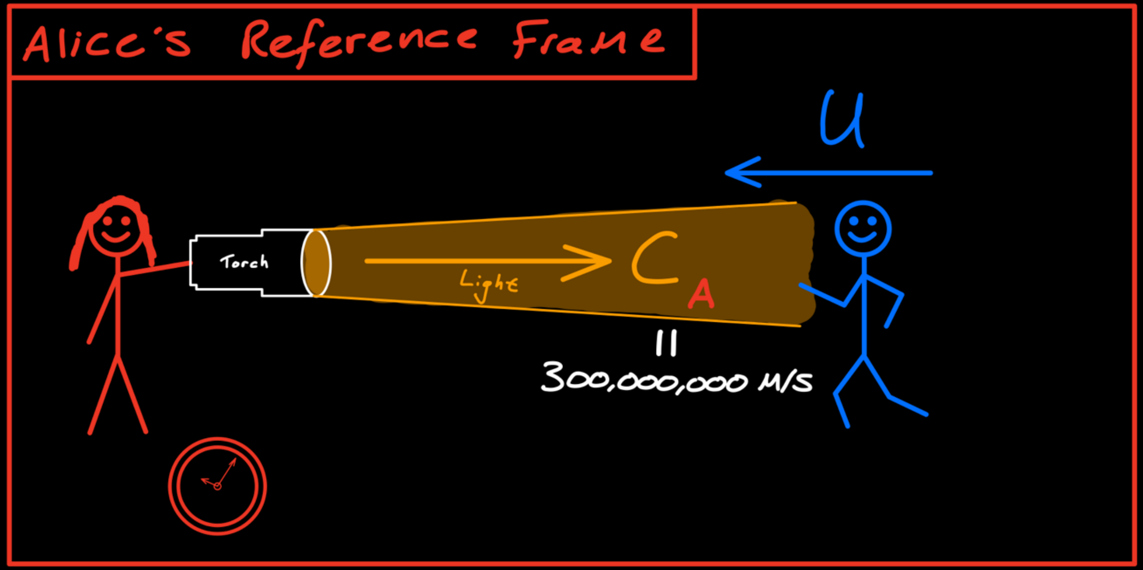
<u>The Laws</u>

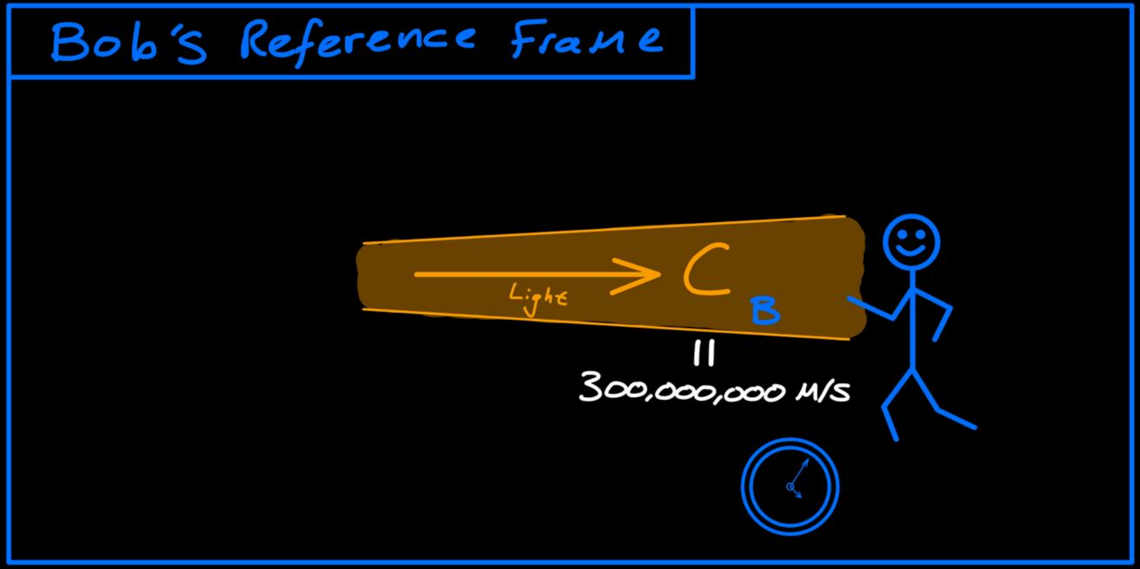
1. All Laws of Physics are obeyed in Inertial Reference Frames.

2. The Speed of Light is invariant. It is the same in all reference frames.

$$C_B = C_A$$

3. Clocks tick at different rates for different observers.





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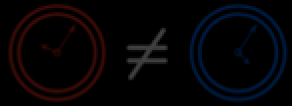

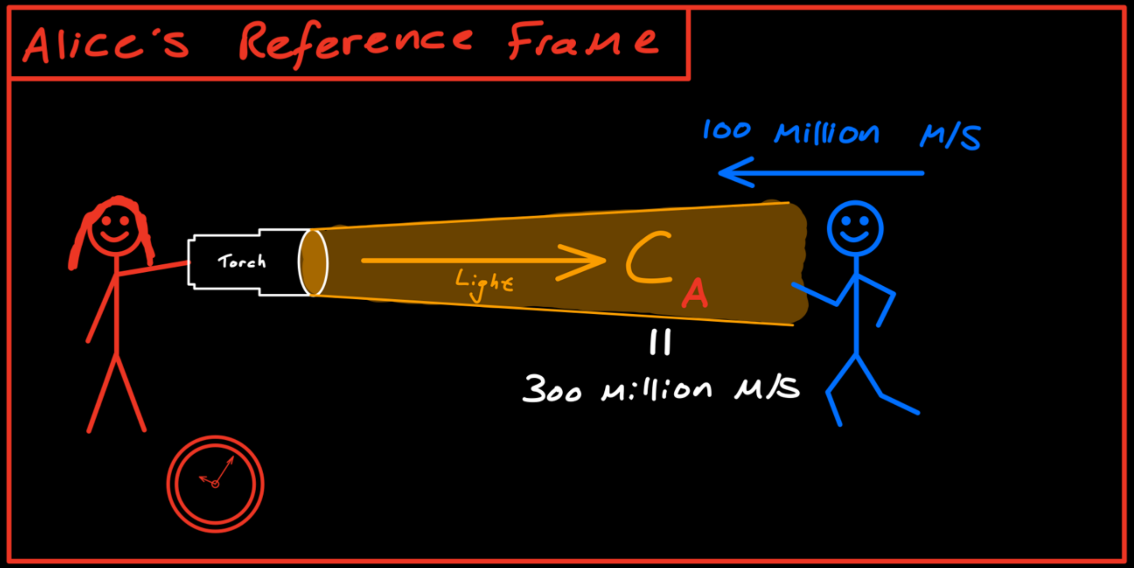

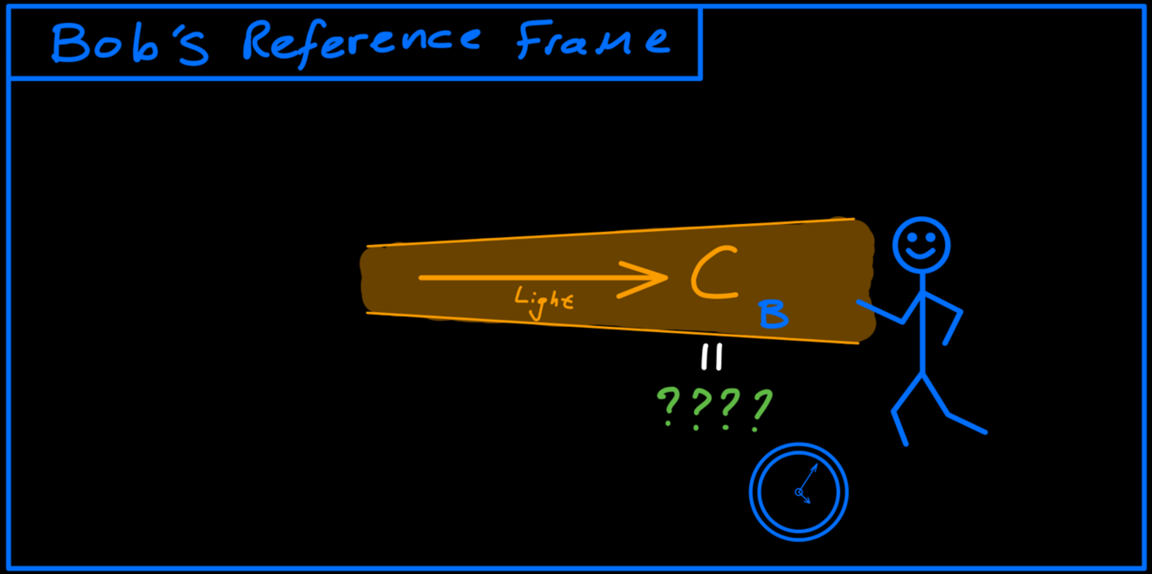

What do you think the speed of light seen by Bob should be?

Einsteinian Relativity

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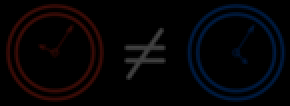
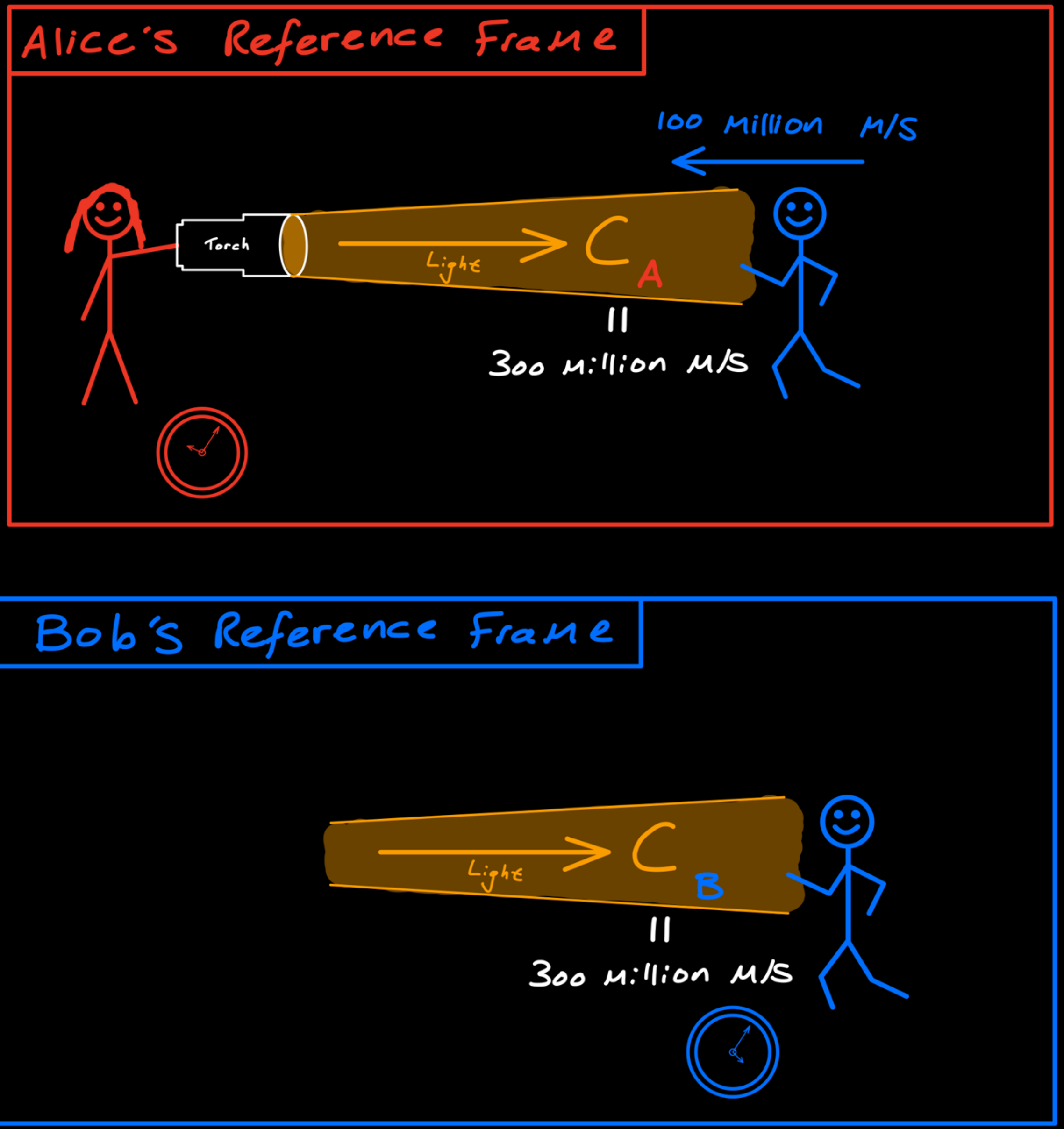
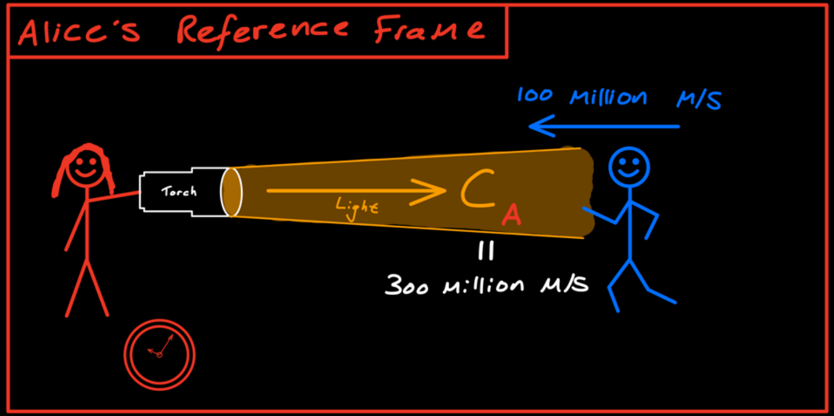


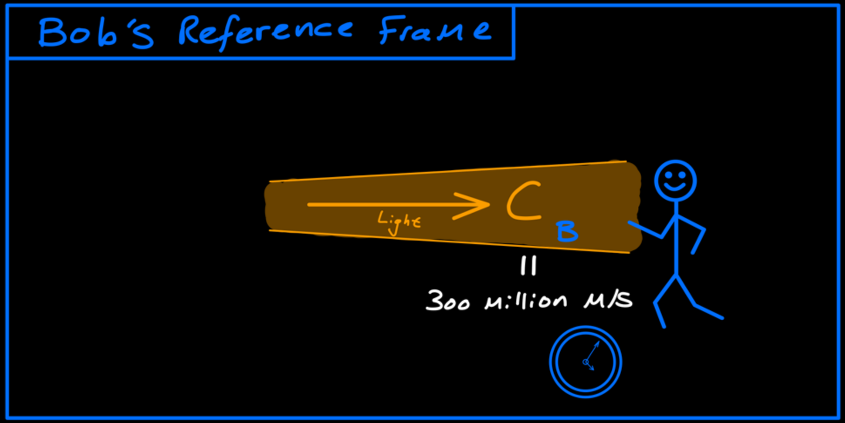


The Speed is unchanged! Light ALWAYS travels at the same speed, in any reference frame.

Einsteinian Relativity



The Laws



1. All Laws of Physics are obeyed in Inertial Reference Frames.

2. The Speed of Light is invariant. It is the same in all reference frames.

$$C_B = C_A$$

From the invariance of the speed of light, all of the bizarre consequences of Einstein's theory of Special Relativity can be worked out.

3. Clocks tick at different rates for different observers.

This is BY FAR, the most bizarre consequence of Einstein's postulates of relativity.

Einsteinian Relativity

The Laws

1. All Laws of Physics are obeyed in Inertial Reference Frames.

2. The Speed of Light is invariant. It is the same in all reference frames.

$$c_B = c_A$$

3. Clocks tick at different rates for different observers.

Why does the invariance of the speed of light mean moving clocks tick more slowly?

This makes some intuitive sense.

If you run at a light ray at head-on, something about your perception of time must shift for the speed of light to remain the same as if you were standing still.

But… It's deeper than just 'perception'. The passage of time ***really does*** change.

Plants growing on a highspeed rocket will germinate later than they would at rest on the Earth. Grey hairs will not appear as numerous, food will not spoil, clocks will not tick as far ahead.

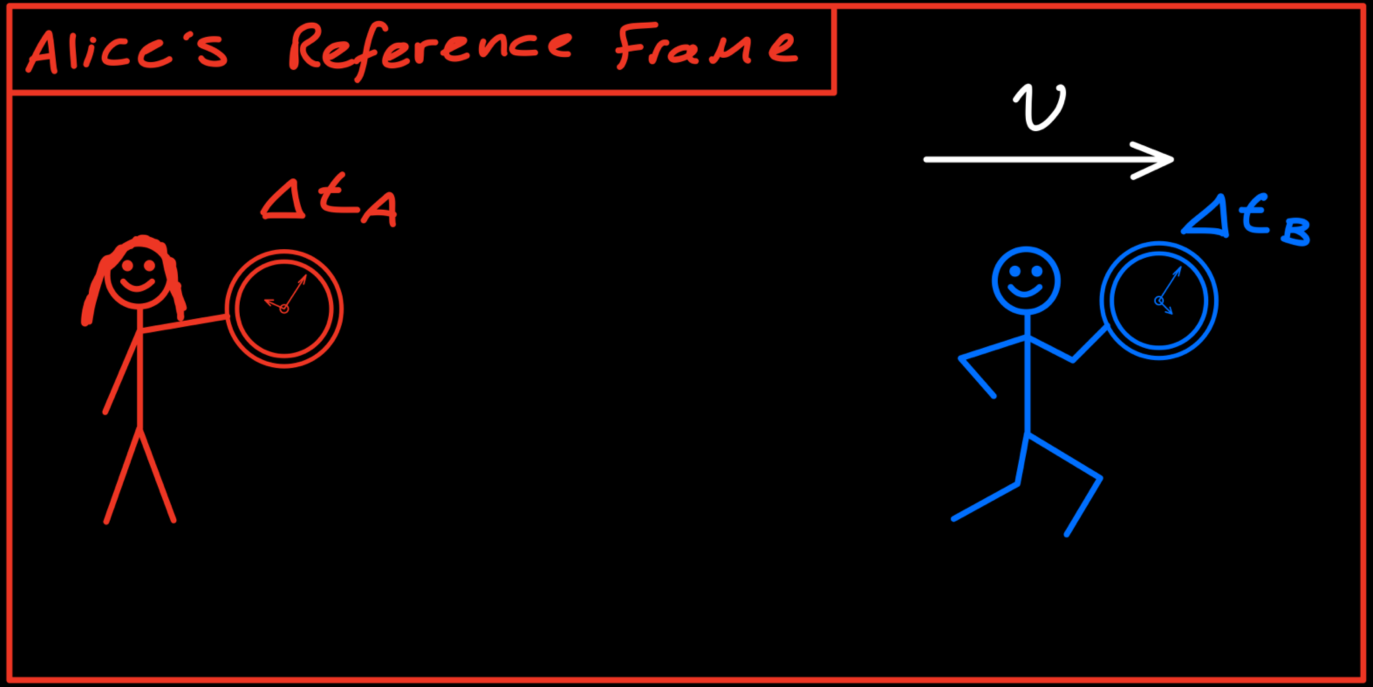
Time Dilation

LLL [2]

This phenomena is called *Time Dilation*.

Einstein derives a formula, describing exactly how much the passage of time changes depending on how fast someone is moving.

I derive this formula in full [here](#) LLL[2].

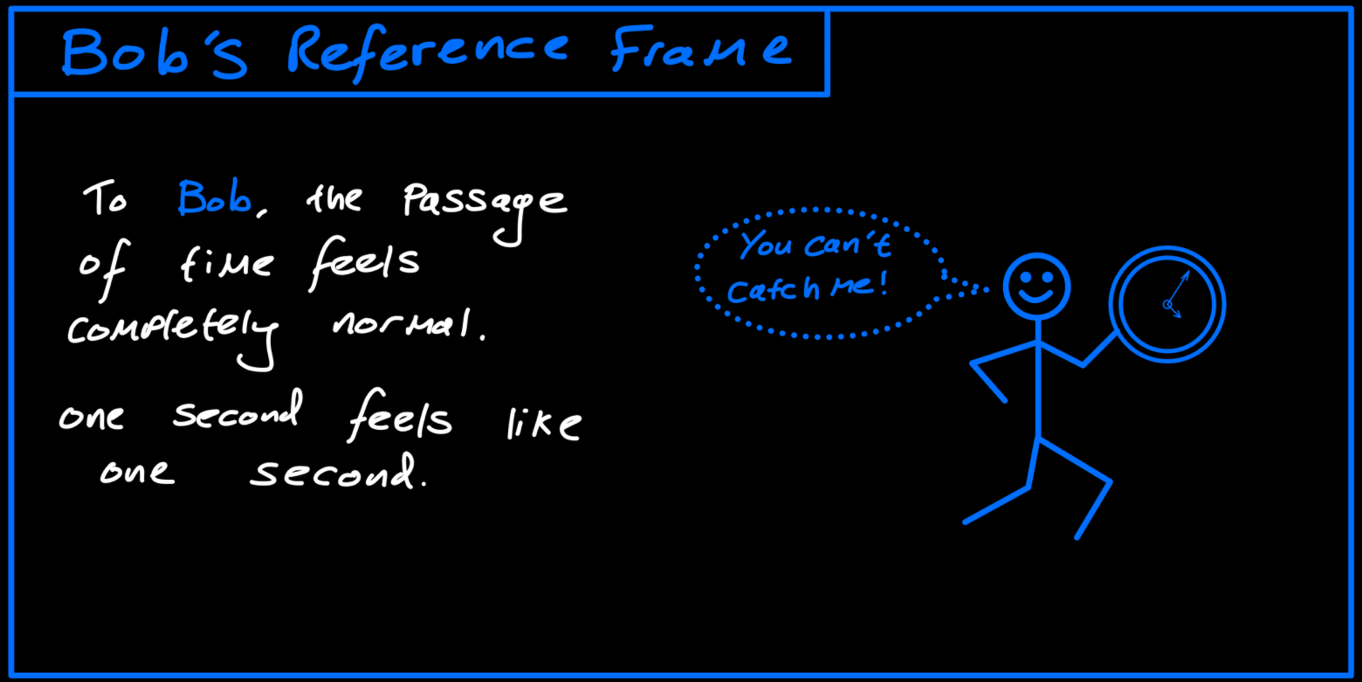


Time Dilation

First, let's think about how time passes for Bob while he runs away from Alice.

Bob's clock ticks once every second *from his point of view*, as expected.

What would Bob's clock look like, as seen by Alice?

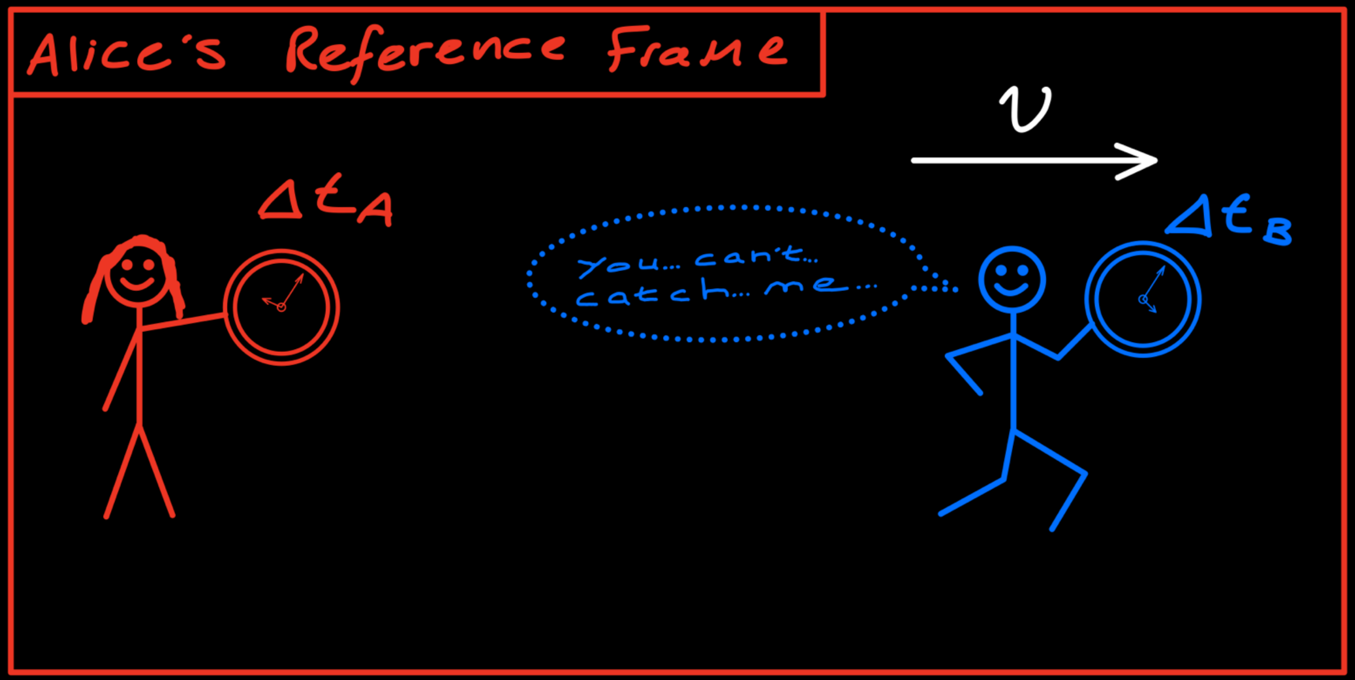


Time Dilation

When Alice looks at Bob's clock, it appears to tick more slowly than her own.

Bob shouts back at Alice as he runs away, and his speech appears drawn out, like slow motion…

These two observers experience the passage of time differently, due to their relative motion.



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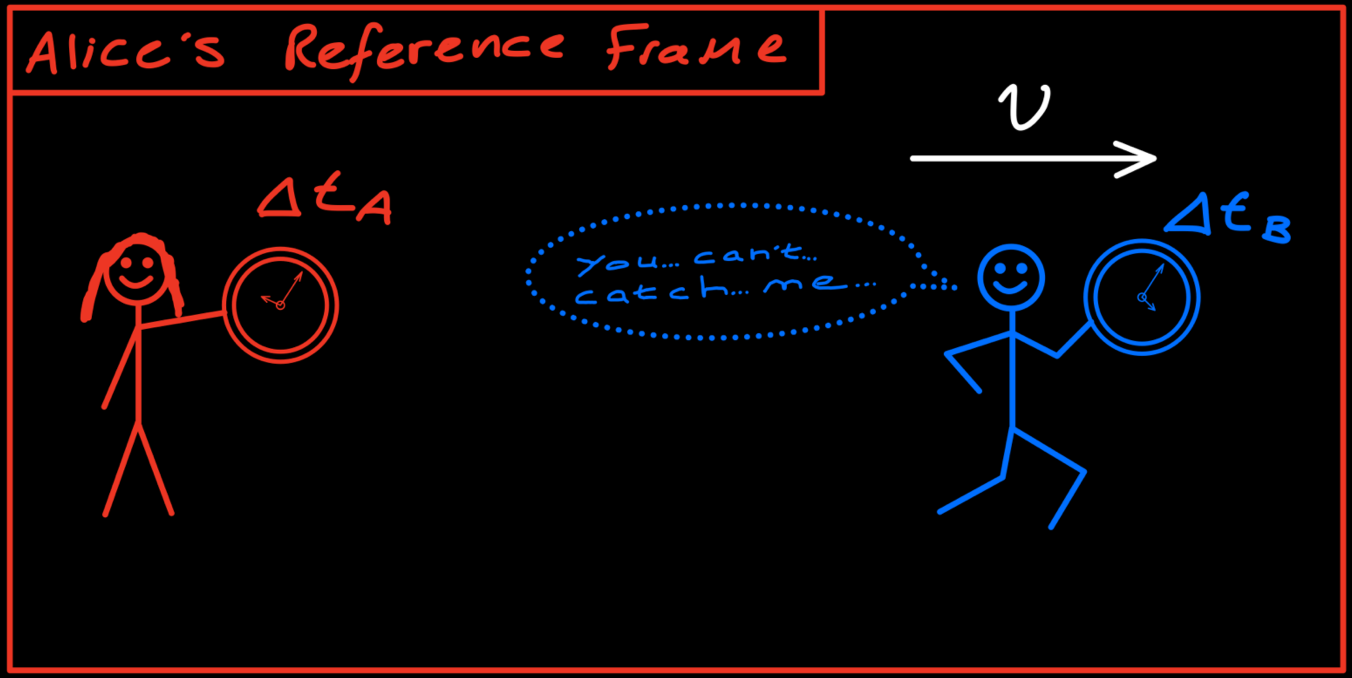


Hang on… Why do we not observe this phenomena in our every day lives?

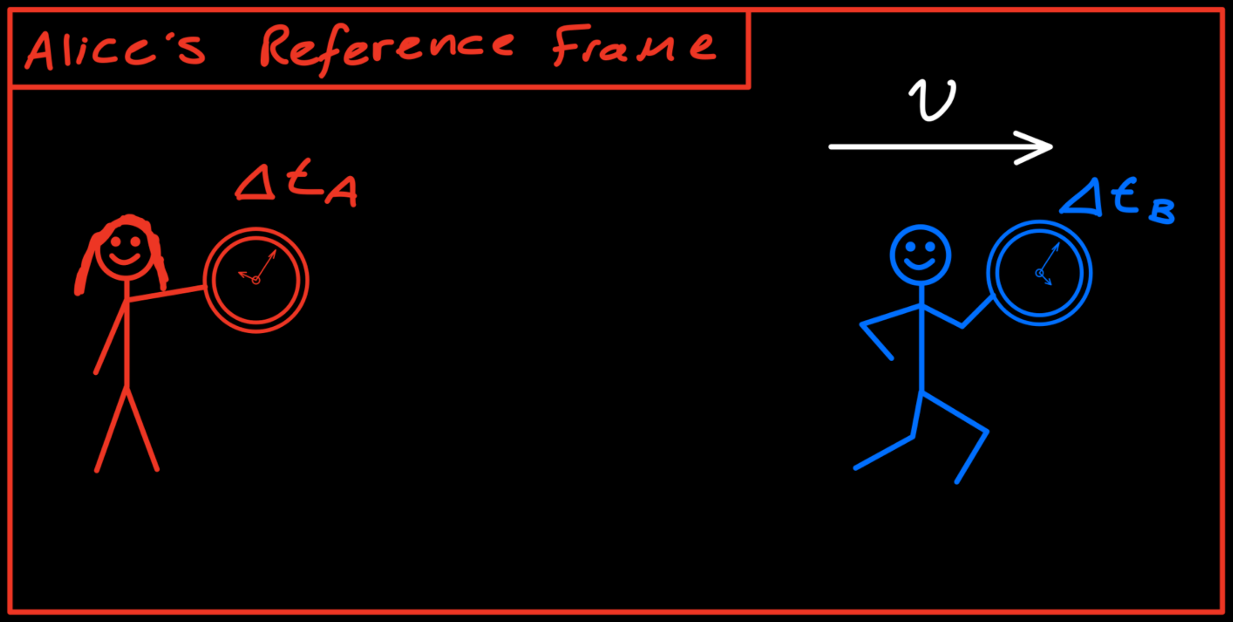
Not every jogger that runs past us moves in slow motion!

Time Dilation

Let's look at Einstein's Time Dilation formula…

Bob's velocity appears in the formula as a ratio of the speed of light.

This means the passage of time only changes significantly when moving at speeds close to the speed of light.



$$\Delta t_B = \frac{\Delta t_A}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Length of time recorded by Bob. (Δt_B)

Length of time recorded by Alice. (Δt_A)

Speed of Bob, seen by Alice. (v)

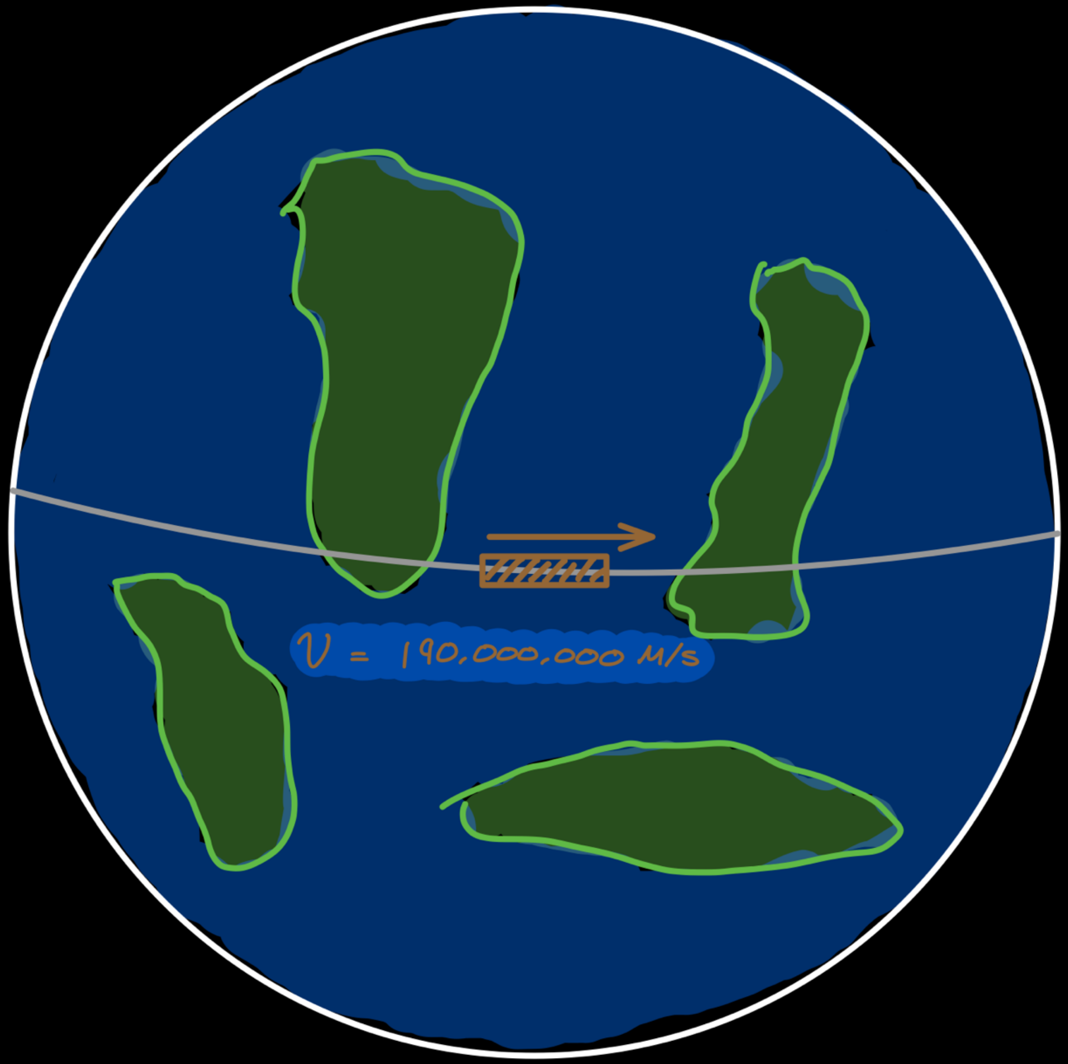
Speed of Light (300 million m/s). (c)

Forwards Time Travel

Suppose we could construct a trainline that spans the Earth's equator.

If a train could travel one thousand times faster than the Parker Solar Probe, the time dilation effects would become significant.

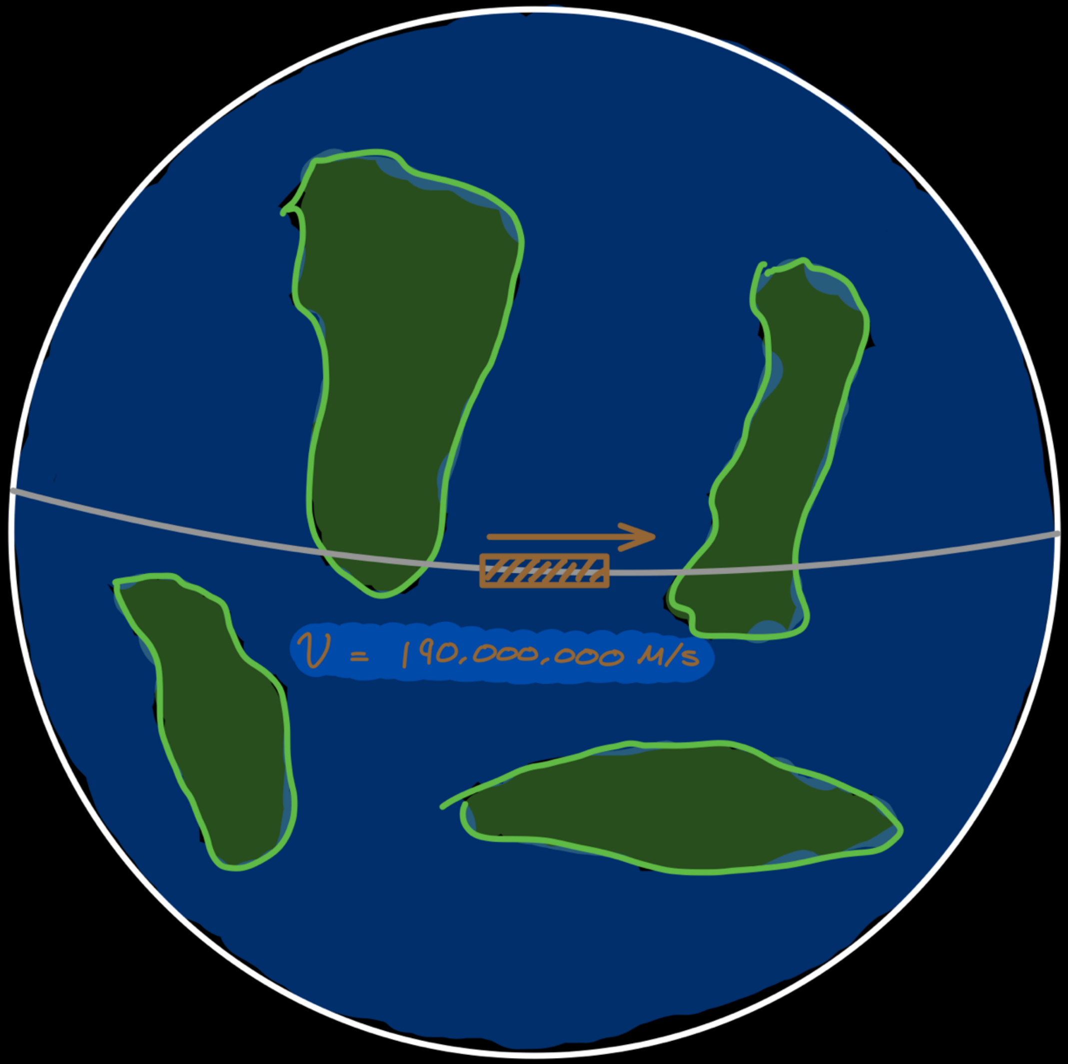
At this speed, the train moves at about **63%** of the speed of light.



Forwards Time Travel

At this speed, the train would make a full rotation around the Earth in just 0.2 seconds.

I.e. It would **make five full rotations** every single second.

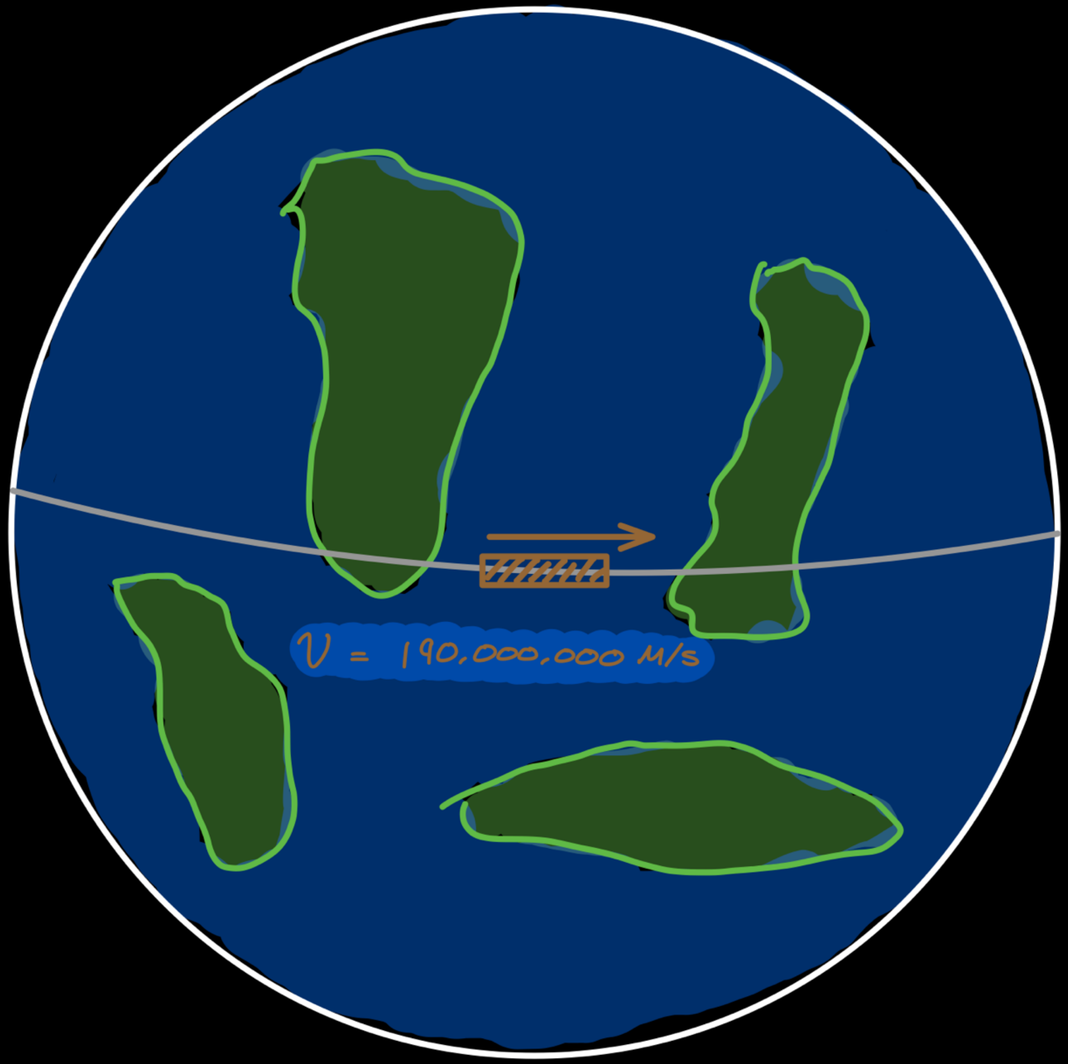


Forwards Time Travel

At this speed, the train would make a full rotation around the Earth in just 0.2 seconds.

I.e. It would **make five full rotations** every single second.

For each of these full rotations, the passengers on the train experience only 0.15 seconds.



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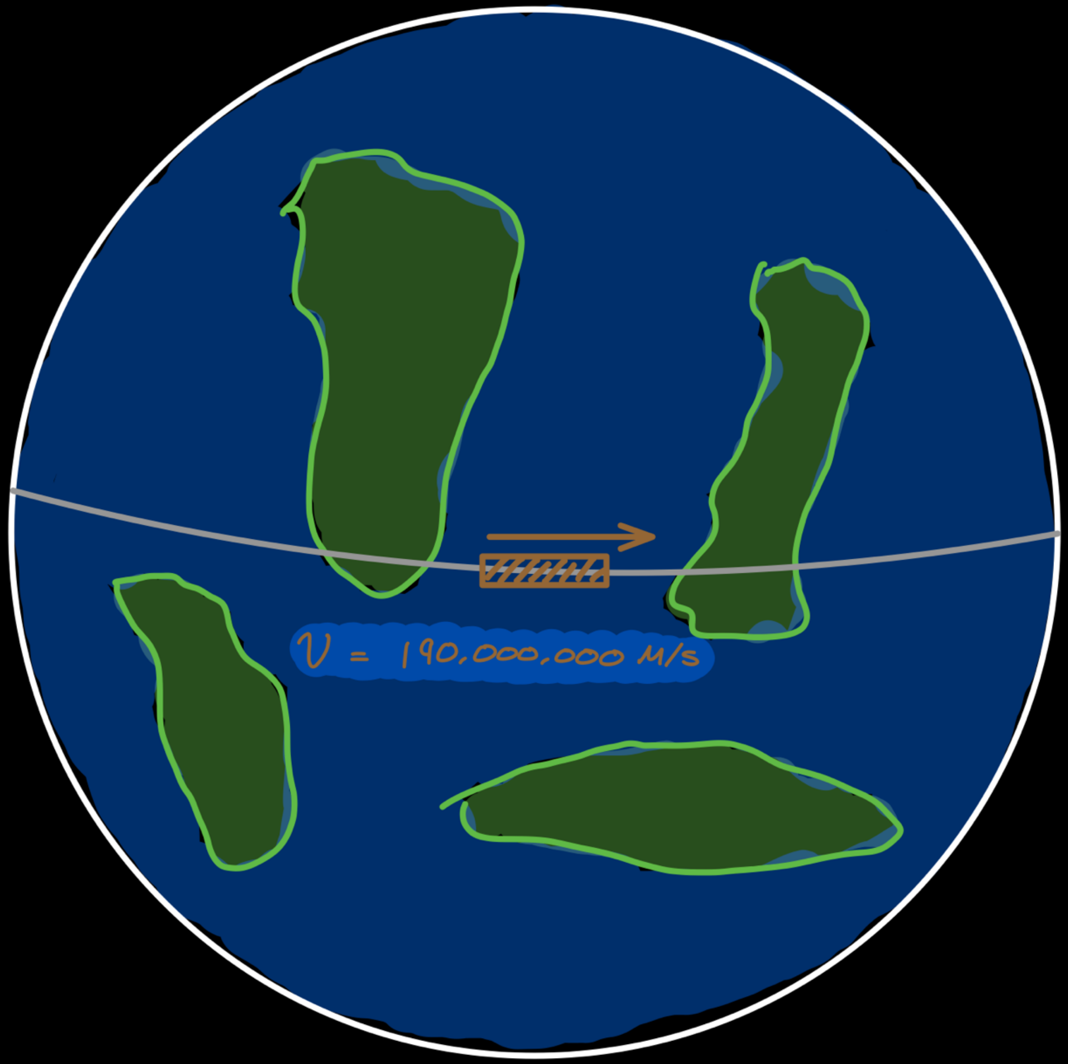
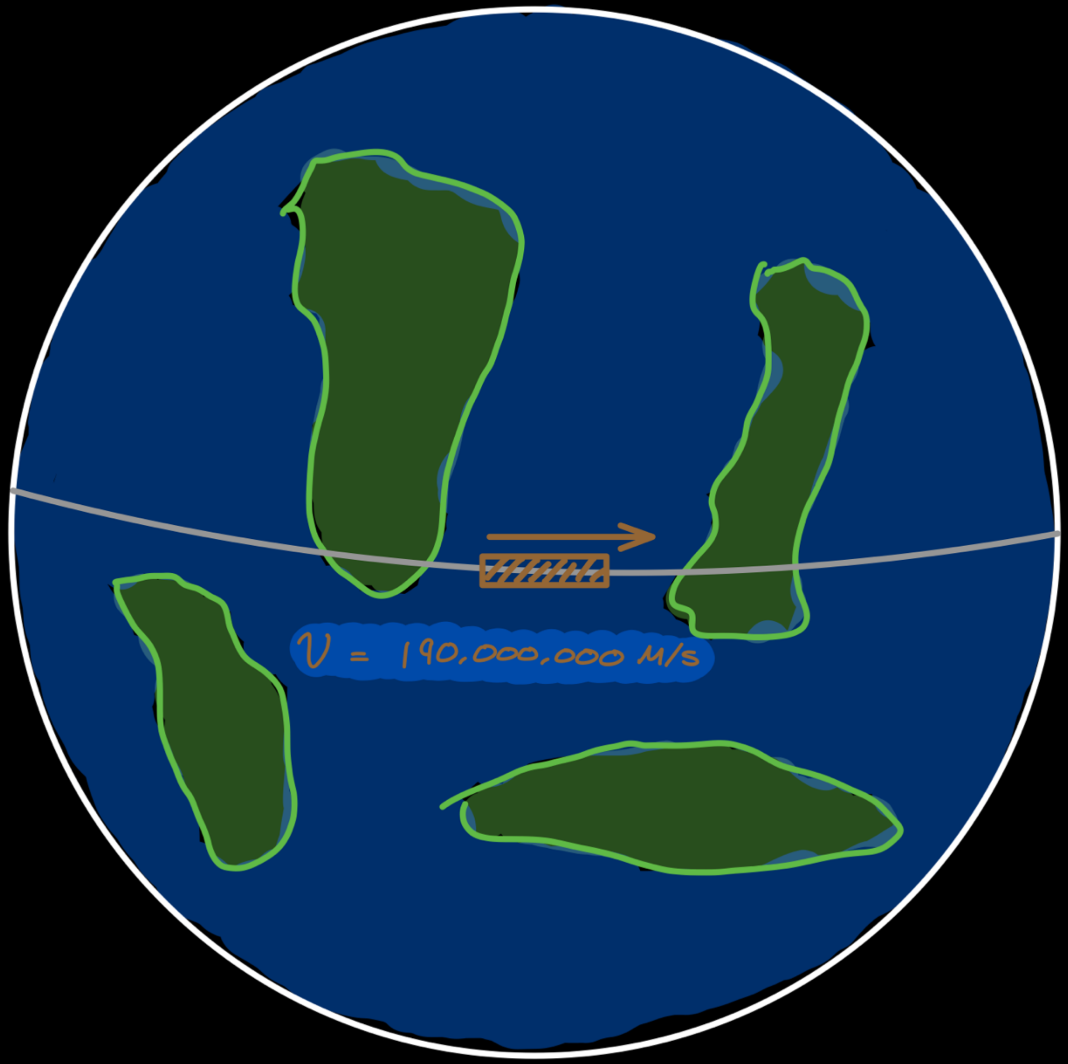


Forwards Time Travel

If the passengers remained on the train for ten years (recorded by everyone else on Earth), they would only experience about 7 years 9 months.

The passengers have therefore travelled forwards in time by about 2 years and 3 months.



Part III - Time Travel via Black Hole

Newton’s Law of Universal Gravitation

In 1687, Isaac Newtons published his breakthrough text, *Philosophiæ Naturalis Principia Mathematica*.

The Principia outlines his law of Universal Gravitation.

Universal – Gravity affects all objects with mass. Not only the heavenly bodies.

Newton’s apple tree in the grounds of Woolsthorpe Manor in Lincolnshire.

Isaac Newton, 1702.

Newton's Law of Universal Gravitation

"After dinner, the weather being warm, we went into the garden and drank thea, under the shade of some apple trees…he told me, he was just in the same situation, as when formerly, the notion of gravitation came into his mind. It was occasion'd by the fall of an apple, as he sat in contemplative mood. Why should that apple always descend perpendicularly to the ground, thought he to himself."

Taken from an early biography of Newtons, written by William Stukeley

Newton's apple tree in the grounds of Woolsthorpe Manor in Lincolnshire.

Newton’s Law of Universal Gravitation

At a more technical level, it was the insights from Kepler’s laws that allowed Newton to figure out his equation of gravity.

In order for the planets to move in elliptical paths, the force of gravity between two masses must go like the inverse square of the distance between the masses.

To come to this realization, Isaac Newtons had to invent the core mathematical field of *calculus* (**all before turning 23!**).

$$F = \frac{GMm}{d^2}$$

$$G = 6.67 \times 10^{-11} = 0.0000000000667$$

Newton's Law of Universal Gravitation

The Law instructs us on how to calculate the force of gravitational attraction between two masses.

The 'big G' constant at the front bears Newton's name (Newton's Gravitational Constant).

Note the small size of this constant, surprising the strength of the gravitational force.

The relative weakness of gravity, compared to the other fundamental forces remains an open problem in particle physics.

$$F = \frac{GMm}{d^2}$$

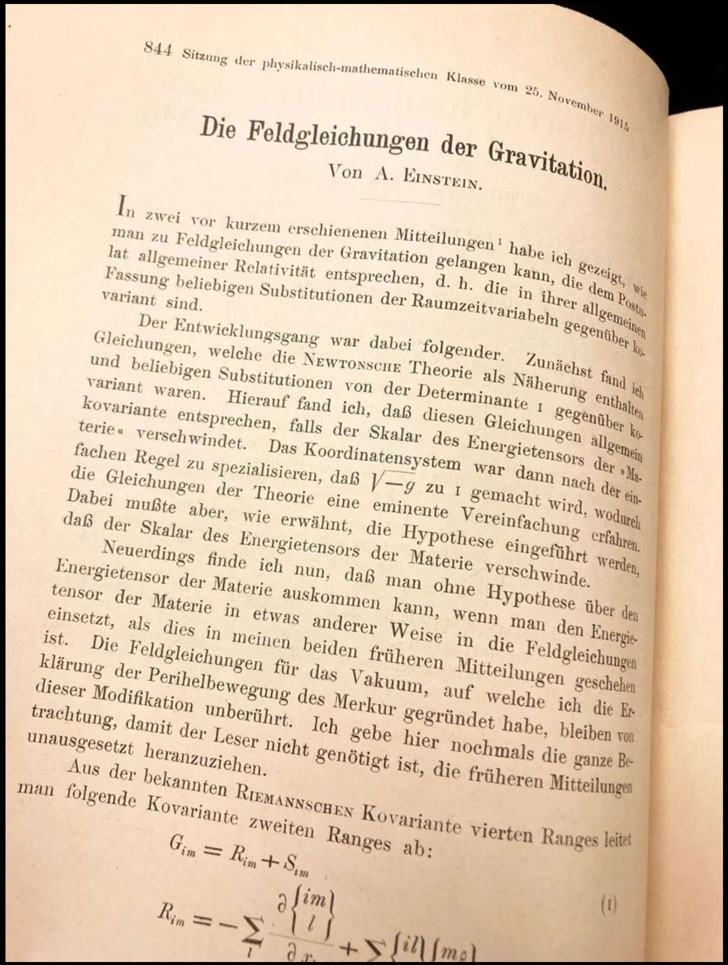
$$G = 6.67 \times 10^{-11} = 0.0000000000667$$

General Relativity

In November 1915, Albert Einstein publishes four papers, on four successive Thursdays.

The fourth of these papers, *The Field Equations of Gravitation*, sets out Einstein's new mathematical description of gravity.

The details of Einstein's theory are highly complex, but we will discuss some of the core ideas.



844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten und beliebigen Substitutionen von der Determinante 1 gegenüber kovariant waren. Hierauf fand ich, daß diesen Gleichungen allgemein kovariante entsprechen, falls der Skalar des Energietensors der »Materie« verschwindet. Das Koordinatensystem war dann nach der einfachen Regel zu spezialisieren, daß $\sqrt{-g}$ zu 1 gemacht wird, wodurch die Gleichungen der Theorie eine eminente Vereinfachung erfahren. Dabei mußte aber, wie erwähnt, die Hypothese eingeführt werden, daß der Skalar des Energietensors der Materie verschwinde.

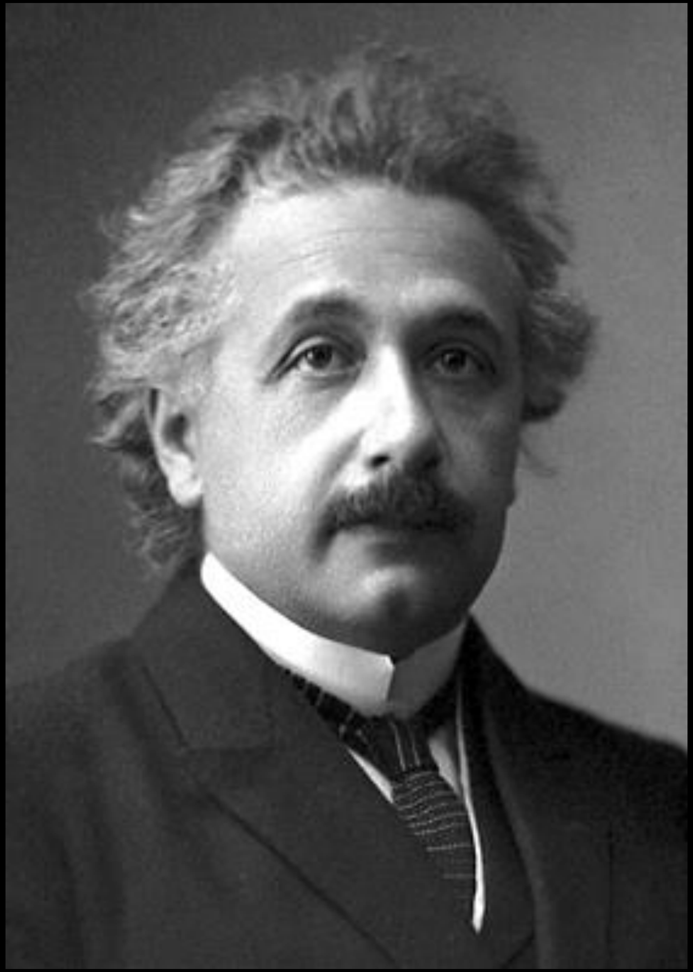
Neuerdings finde ich nun, daß man ohne Hypothese über den Energietensor der Materie auskommen kann, wenn man den Energietensor der Materie in etwas anderer Weise in die Feldgleichungen einsetzt, als dies in meinen beiden früheren Mitteilungen geschehen ist. Die Feldgleichungen für das Vakuum, auf welche ich die Erklärung der Perihelbewegung des Merkur gegründet habe, bleiben von dieser Modifikation unberührt. Ich gebe hier nochmals die ganze Betrachtung, damit der Leser nicht genötigt ist, die früheren Mitteilungen unausgesetzt heranzuziehen.

Aus der bekannten Riemannschen Kovariante vierten Ranges leitet man folgende Kovariante zweiten Ranges ab:

$$G_{im} = R_{im} + S_{im}$$

$$R_{im} = -\sum_l \frac{\partial \begin{Bmatrix} im \\ l \end{Bmatrix}}{\partial x_l} + \sum \ldots \qquad (1)$$

The Field Equations of Gravitation, published Nov 25th 1915.



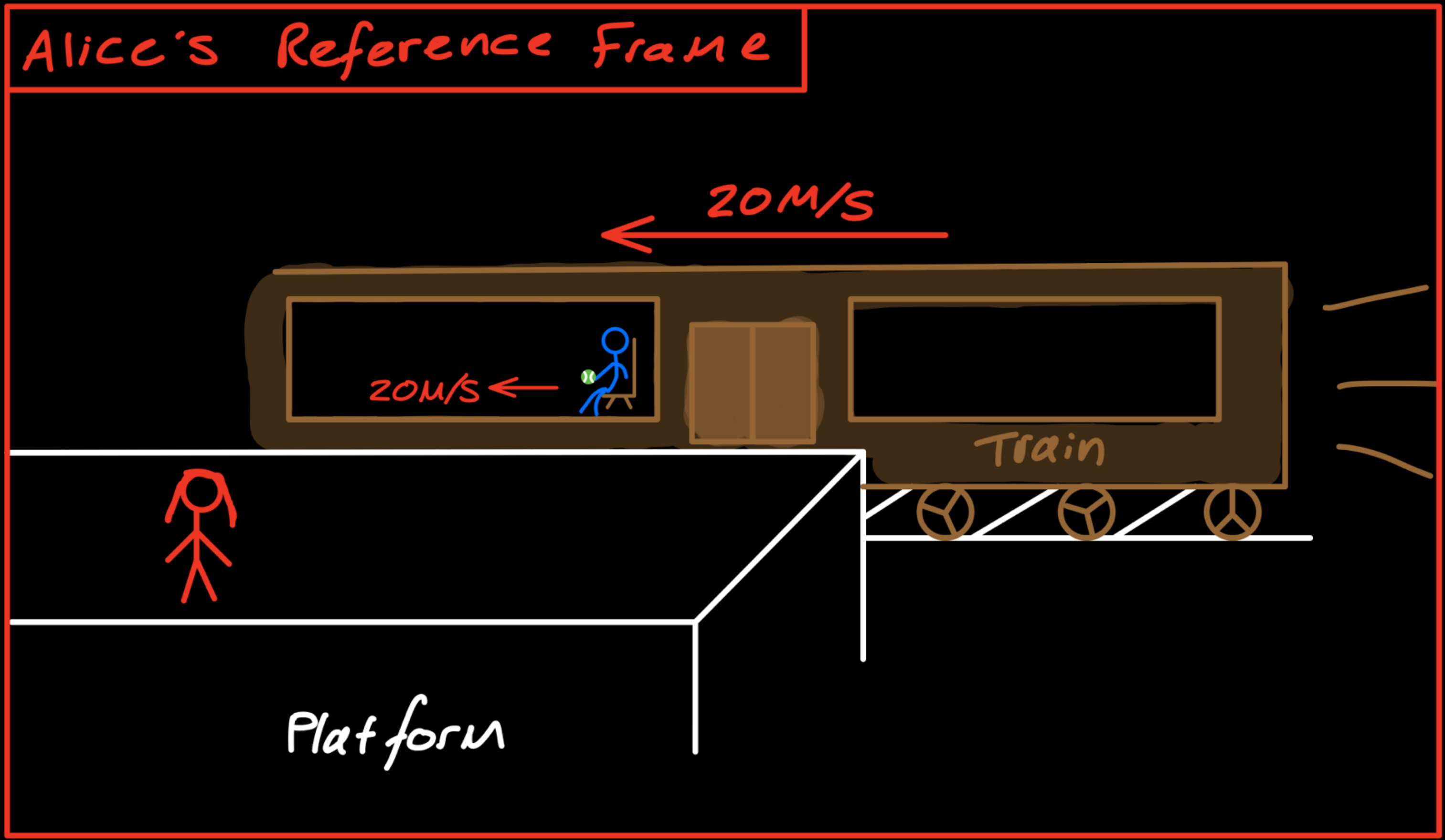
Albert Einstein, 1921.

General Relativity

Recall our discussion of trains and reference frames.

Suppose Bob rides a train, which passes Alice on a train platform at a constant speed of 20 meters per second.

Bob throws a tennis ball up in the air.



General Relativity

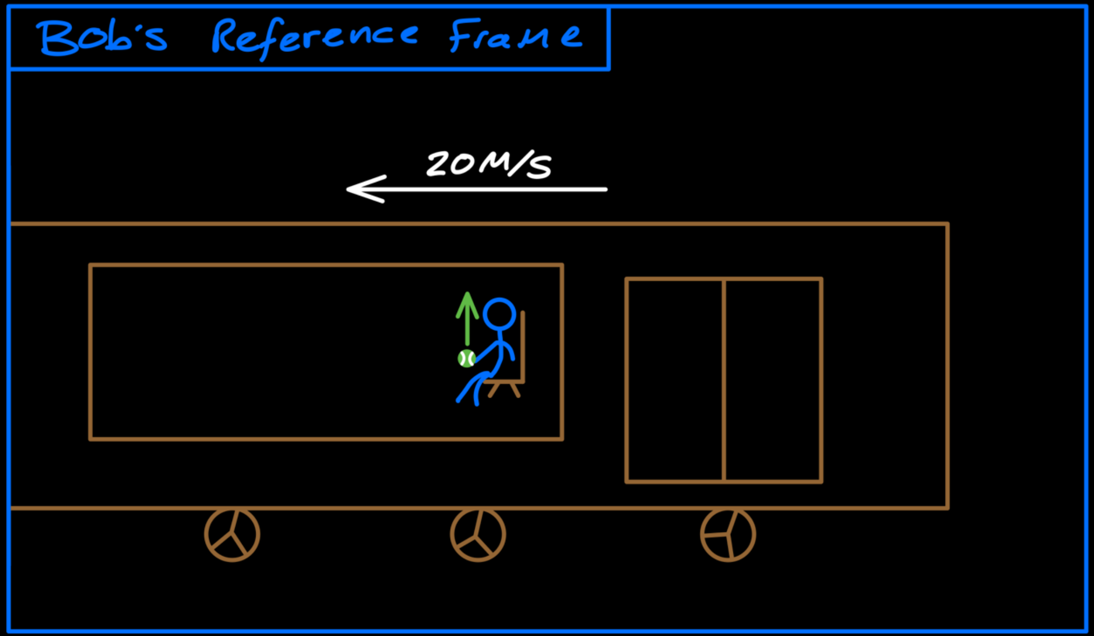
Recap: Inertial (Non-Accelerating) Reference Frames

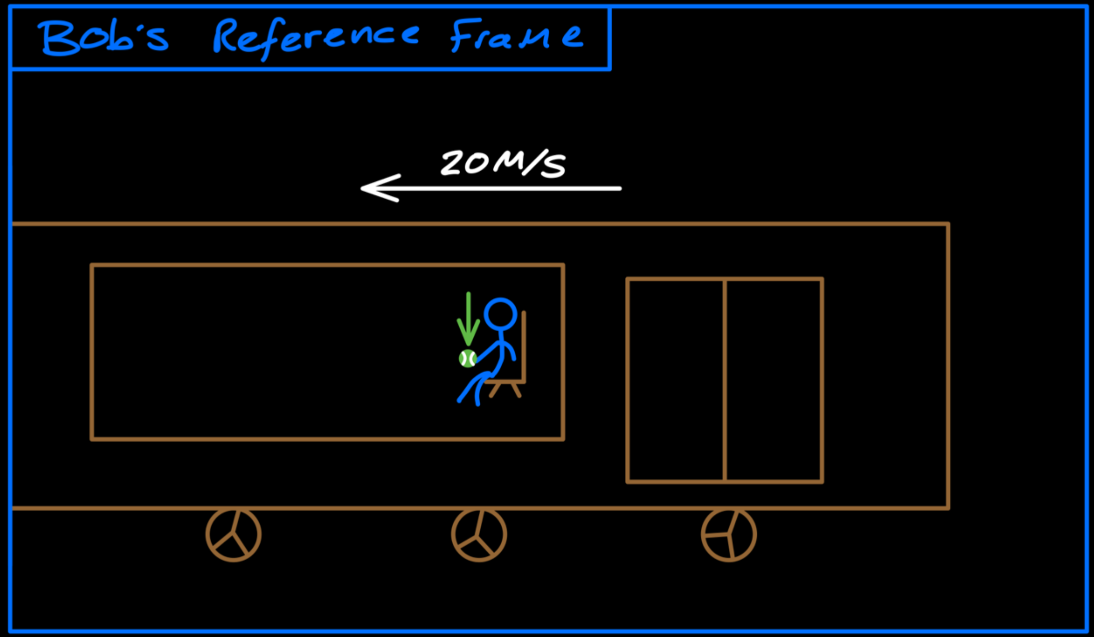
We call reference frames moving at a constant speed an **Inertial Reference Frame**.

In Bob's reference frame, the ball moves upwards in a straight line and falls back into his lap.

This is exactly what Bob would observe when the train is stationary at a station.

Bob *cannot* tell whether his train is at rest in the station, or moving at a constant speed away from the station.





General Relativity

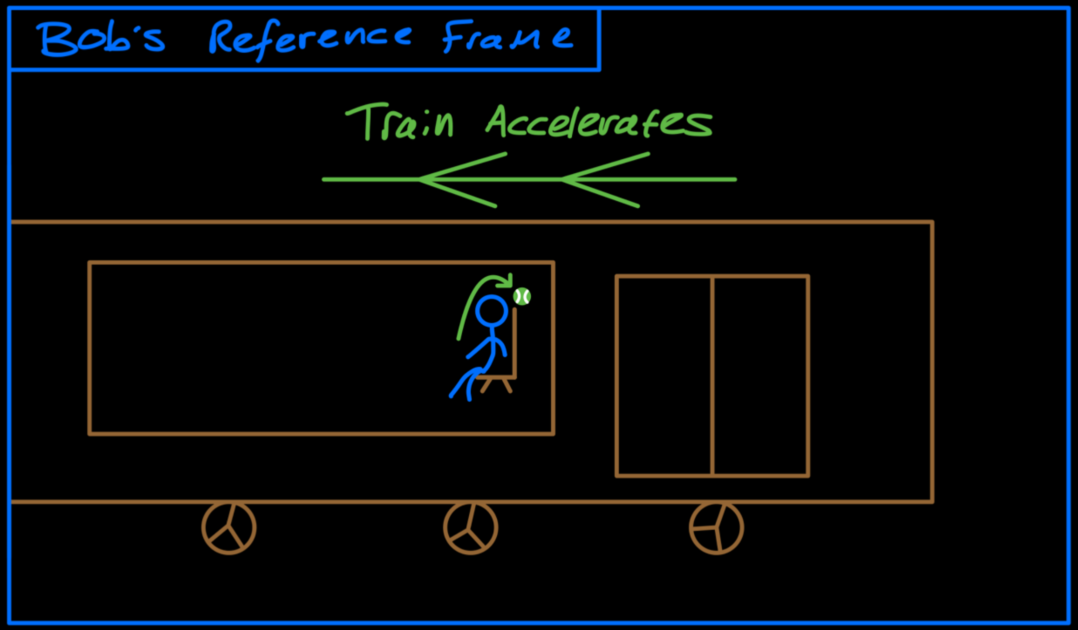
Recap: Accelerating Reference Frames

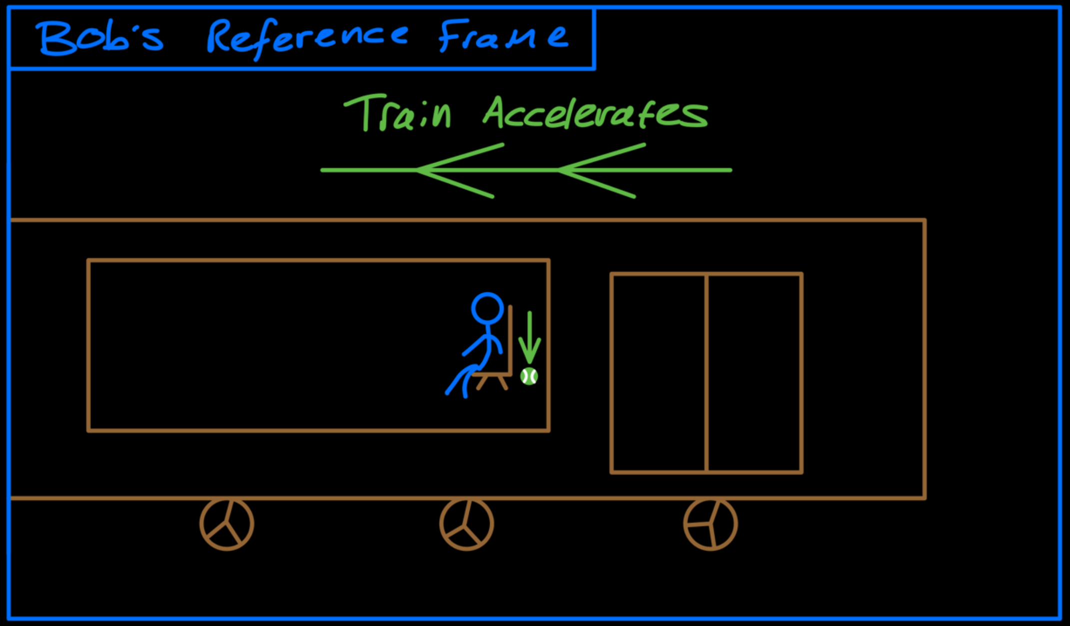
If the train accelerates (speeds up), Bob will observe something different.

He throws the ball upwards, but the ball does not end up on his lap. It shoots over his head, and lands behind him.

This is different to what he would observer on a stationary train.

Bob *can* tell that he is on an accelerating train, distinct from a stationary, or non-accelerating train.



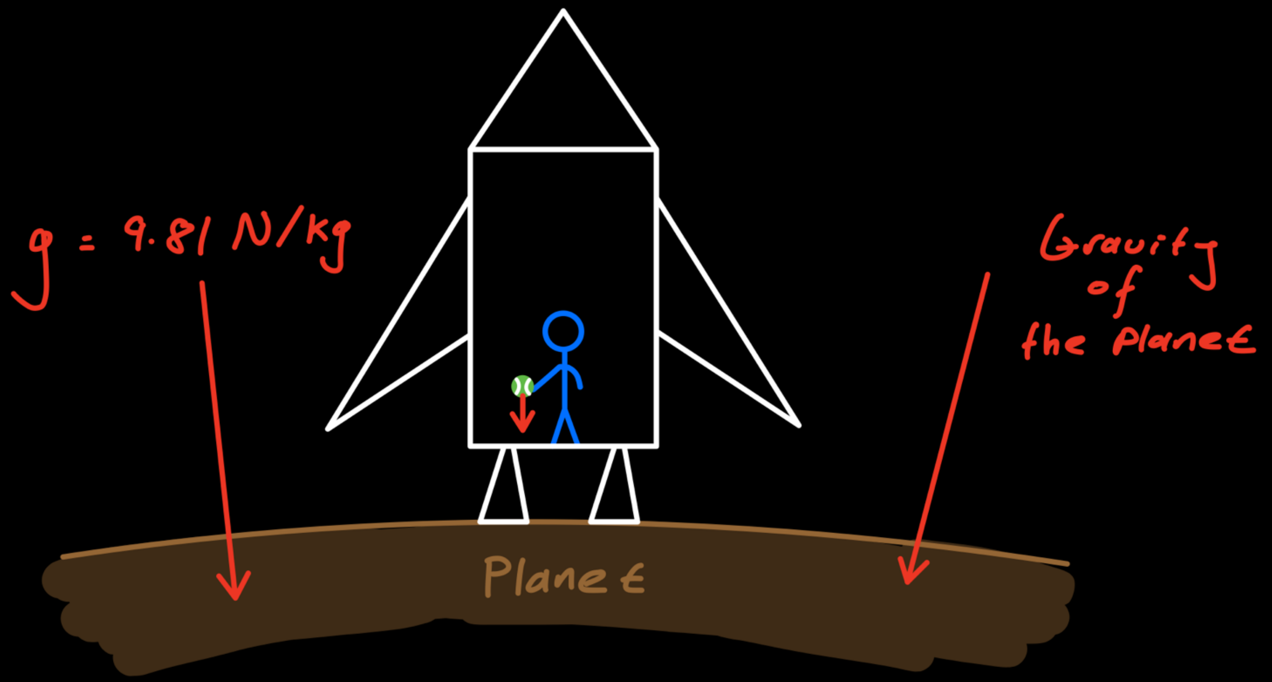


General Relativity

The Equivalence Principle

Suppose Bob is in a rocket, parked at rest on the surface of the Earth. The Earths surface gravity exerts a force of 9.81 Newton's per kilogram of mass.

If Bob drops the tennis ball, it will accelerate downwards at a rate of 9.81 meters per second per second, falling under the influence of gravity.



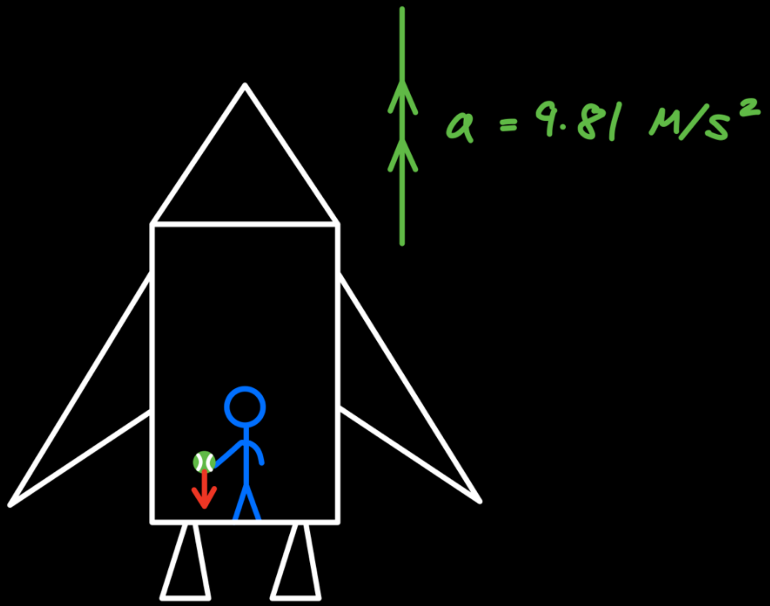
General Relativity

The Equivalence Principle

Suppose instead that Bob's rocket, accelerates upwards at precisely 9.81 meters per second per second.

Bob's feet would feel the floor of the rocket pushing up on him.

If Bob drops the tennis ball, it will appear to him to accelerate downwards at a rate of 9.81 meters per second per second.



General Relativity

Could Bob tell which situation he finds himself in? Both scenarios lead to the tennis ball accelerating down to the ground at a rate of 9.81 meters per second per second.

The indistinguishability of these situations is encapsulated in **Einstein's Equivalence Principle**.

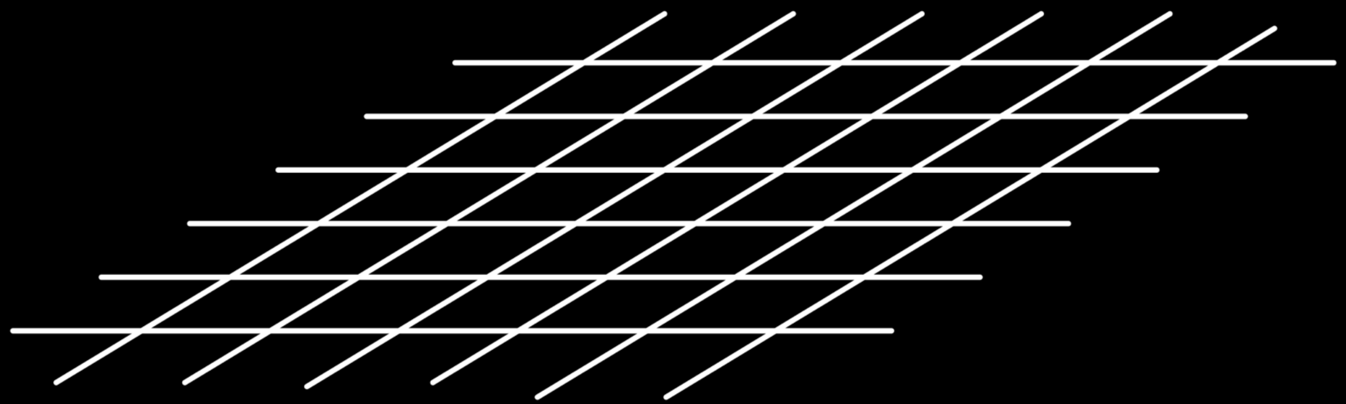
General Relativity

Einstein’s Equivalence Principle:

Gravity is indistinguishable from acceleration.

This is the insight that allows Einstein to conclude that gravity is a *geometric phenomena*.

Einstein’s earlier work on the theory of special relativity (1905) puts space and time into a single united framework, *four-dimensional space time*.



General Relativity

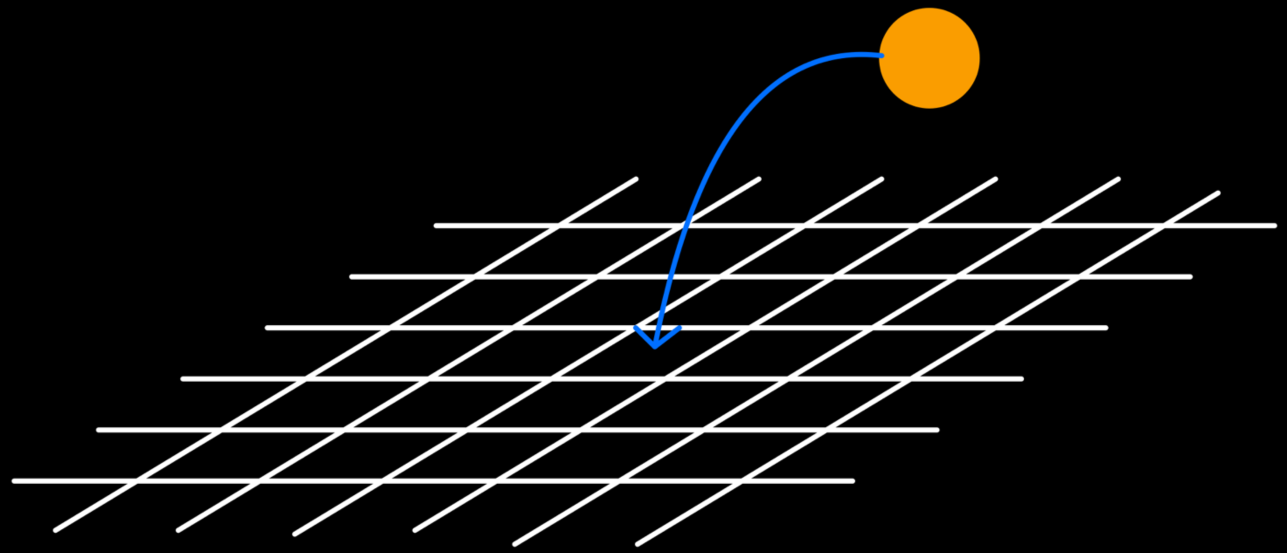
Einstein's Equivalence Principle:

Gravity is indistinguishable from acceleration.

This is the insight that allows Einstein to conclude that gravity is a *geometric phenomena*.

Einstein's earlier work on the theory of special relativity (1905) puts space and time into a single united framework, *four-dimensional space time*.

Space and time are more than just the stage on which physics happens, they are players.

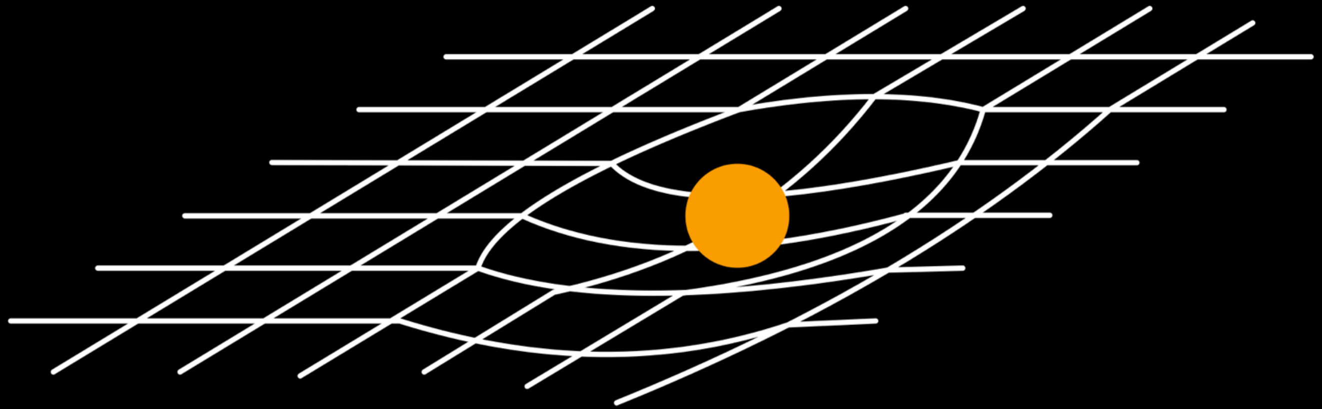


Let's add a piece of matter into this flat region of space.

General Relativity

The presence of matter, causes space-time to curves.

The curvature of space-time cases matter to experience the illusion of a gravitational force.



'Spacetime tells matter how to move; matter tells spacetime how to curve.' – John Wheeler

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space-time Curvature

Speed of Light

Matter

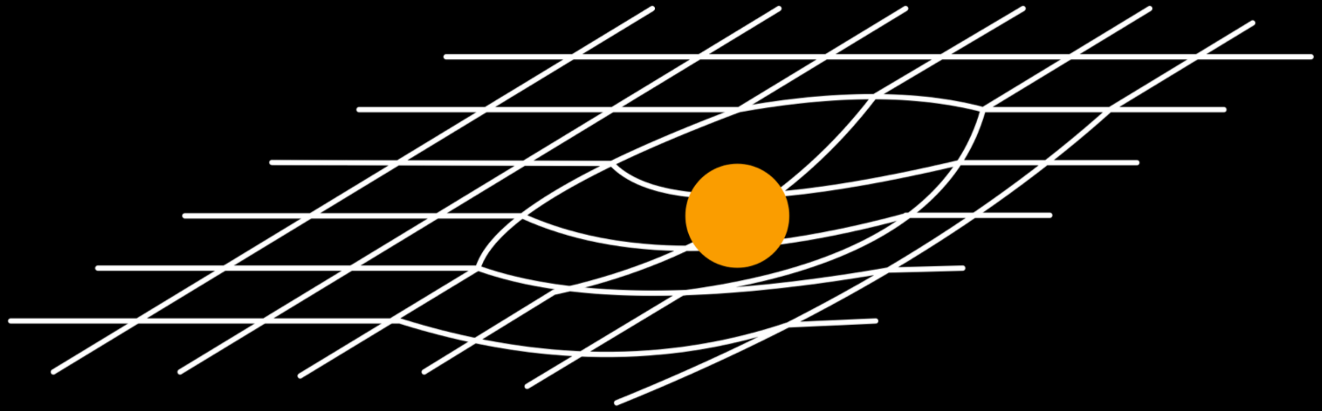
Space-time is more than just the stage on which physics happens, they are players too.

General Relativity

LLL [4]

More theory on General Relativity:

Not for the faint of heart!...



$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space-time Curvature ($G_{\mu\nu}$)

Speed of Light (c)

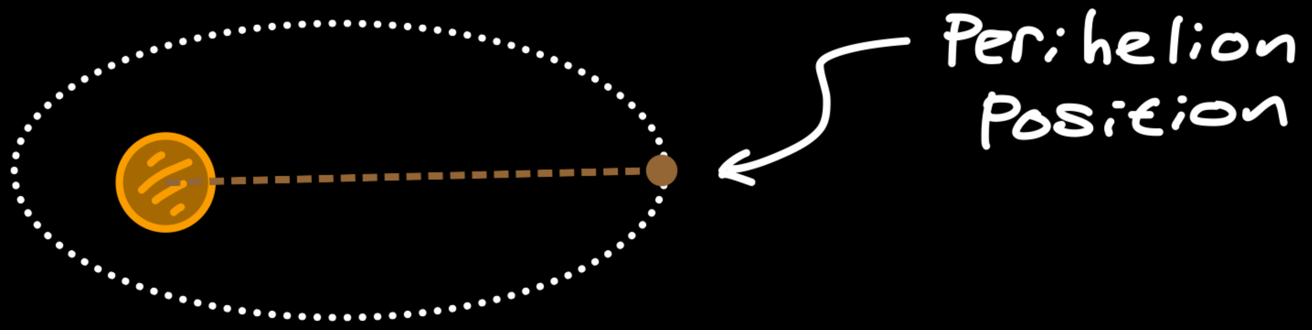
Matter ($T_{\mu\nu}$)

General Relativity

How do we know Einstein was right?

The abnormal precession of Mercury's perihelion was a longstanding problem in celestial mechanics (first pointed out in 1859 by Urbain La Verrier).

When physicists used Newton's Equation of Gravity to calculate the shape of Mercury's orbit, the calculated rate of advance of Mercury's perihelion is very far from the rate observed by astronomers.



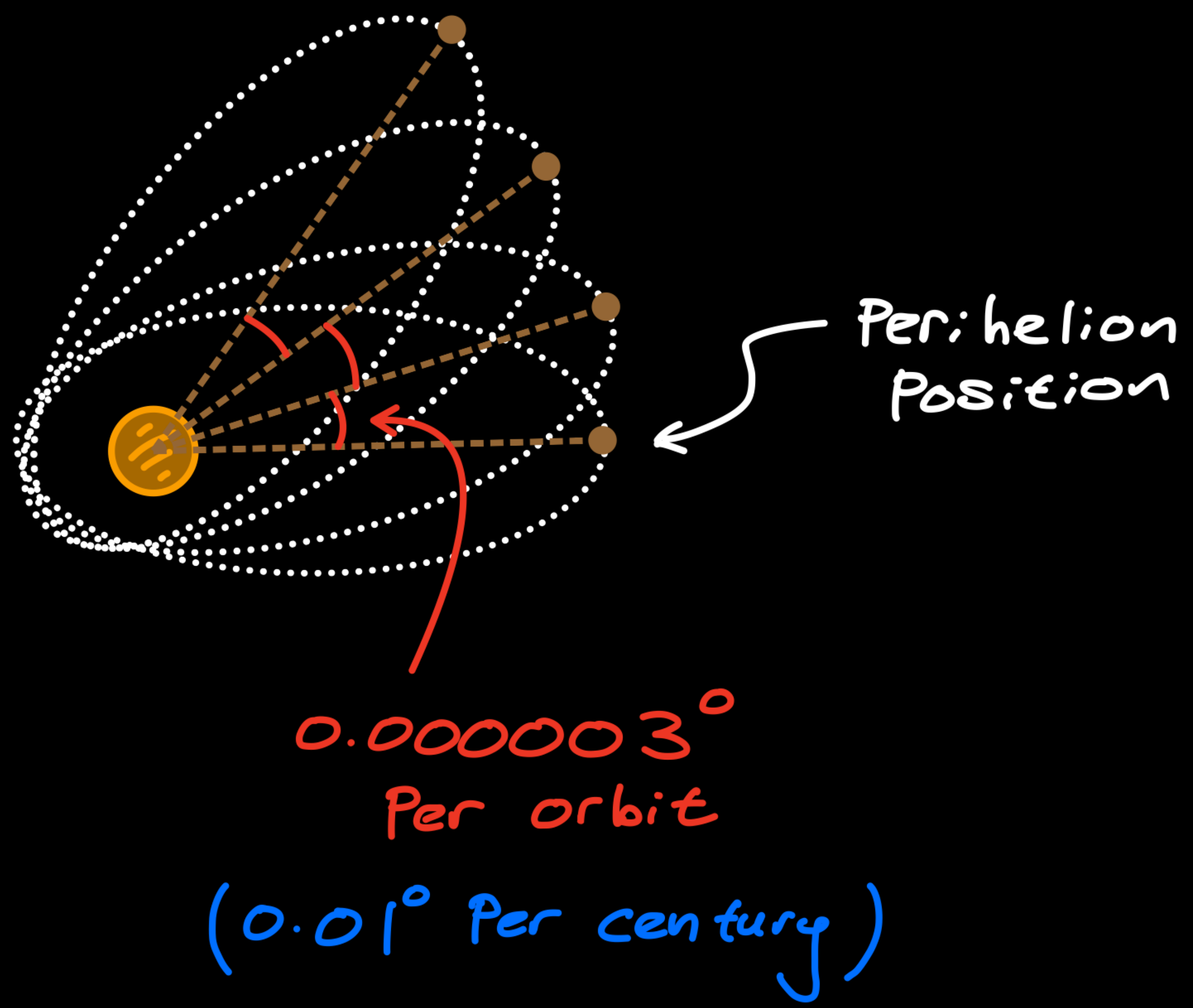
Perihelion – Point of greatest distance from the sun, in a planets elliptical orbit.

General Relativity

How do we know Einstein was right?

When we use Einstein's Equation of Gravity to perform the same calculation, the answer matches the observation made by astronomers to a very high degree of accuracy.

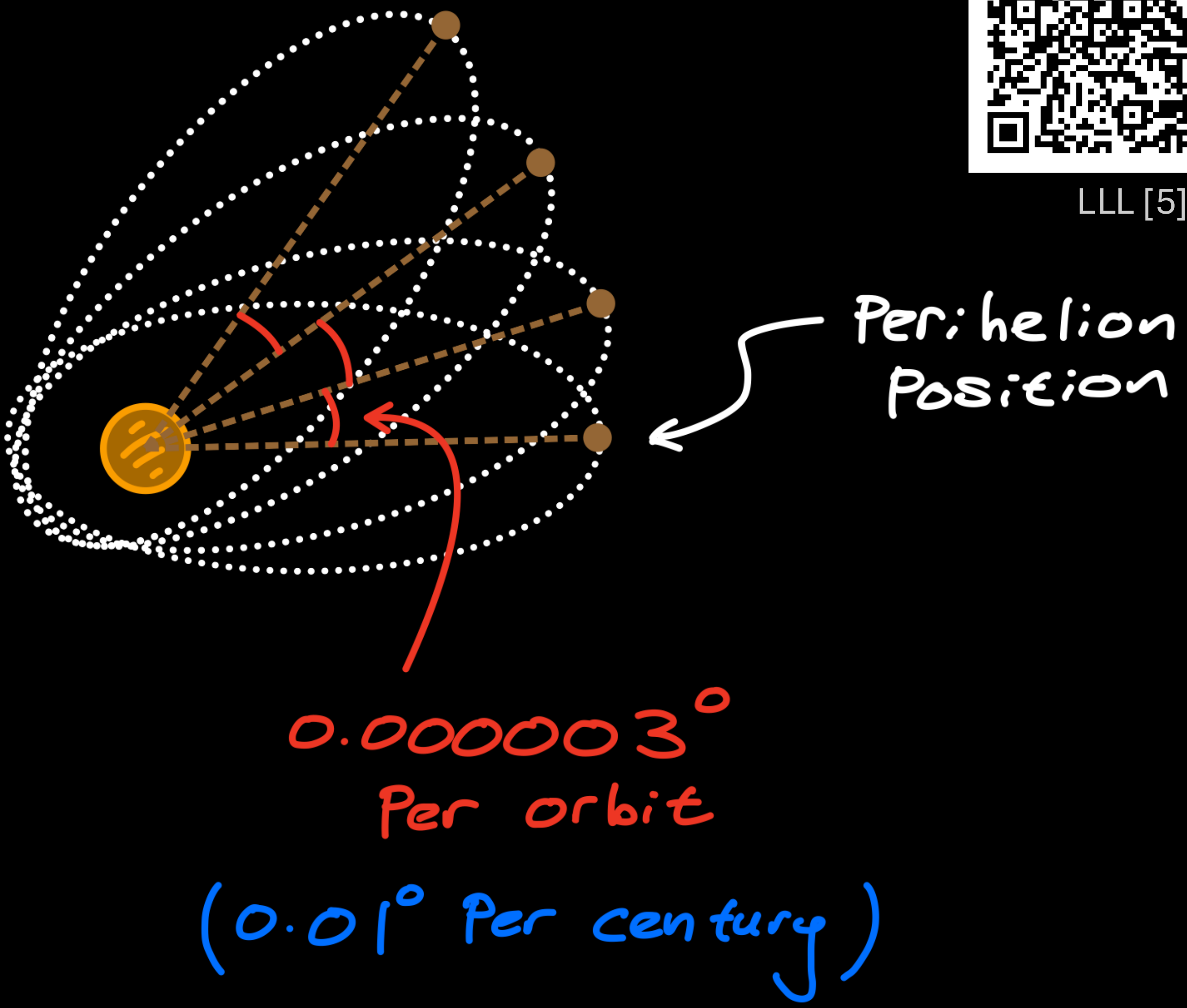
This is one feather in General Relativity's cap!



General Relativity

LLL [5]

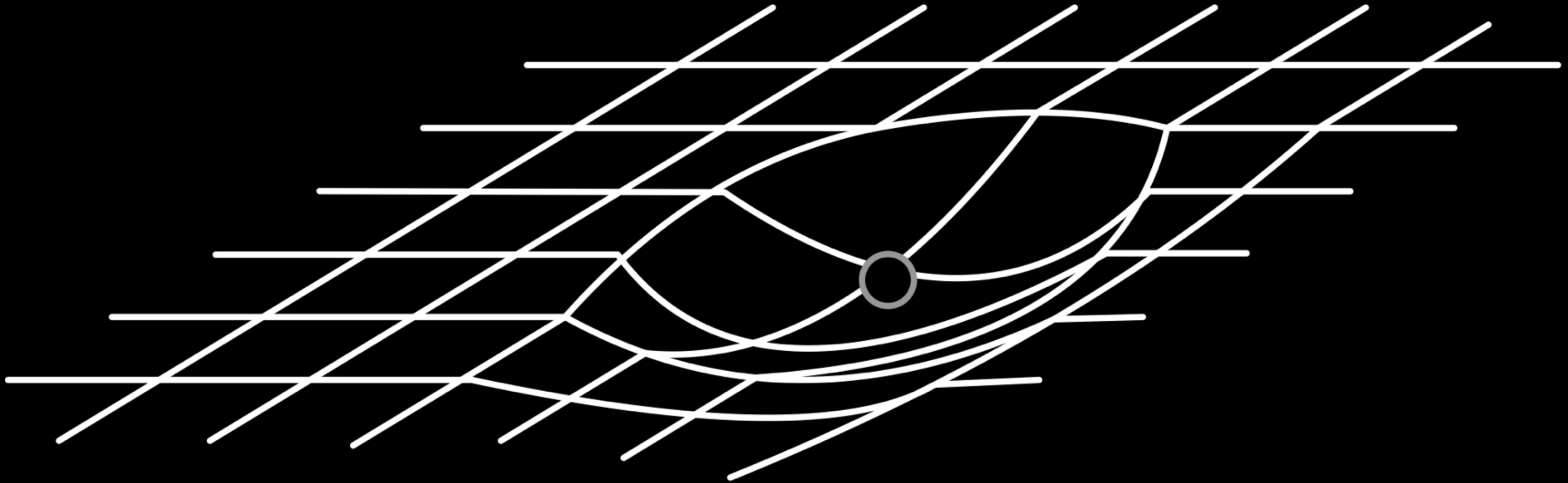
If you have a spare 1hr37min, you can watch me do this calculation in real time!



This is rough…

Don’t say I didn’t warn you!

The Monster Hidden in the Equations

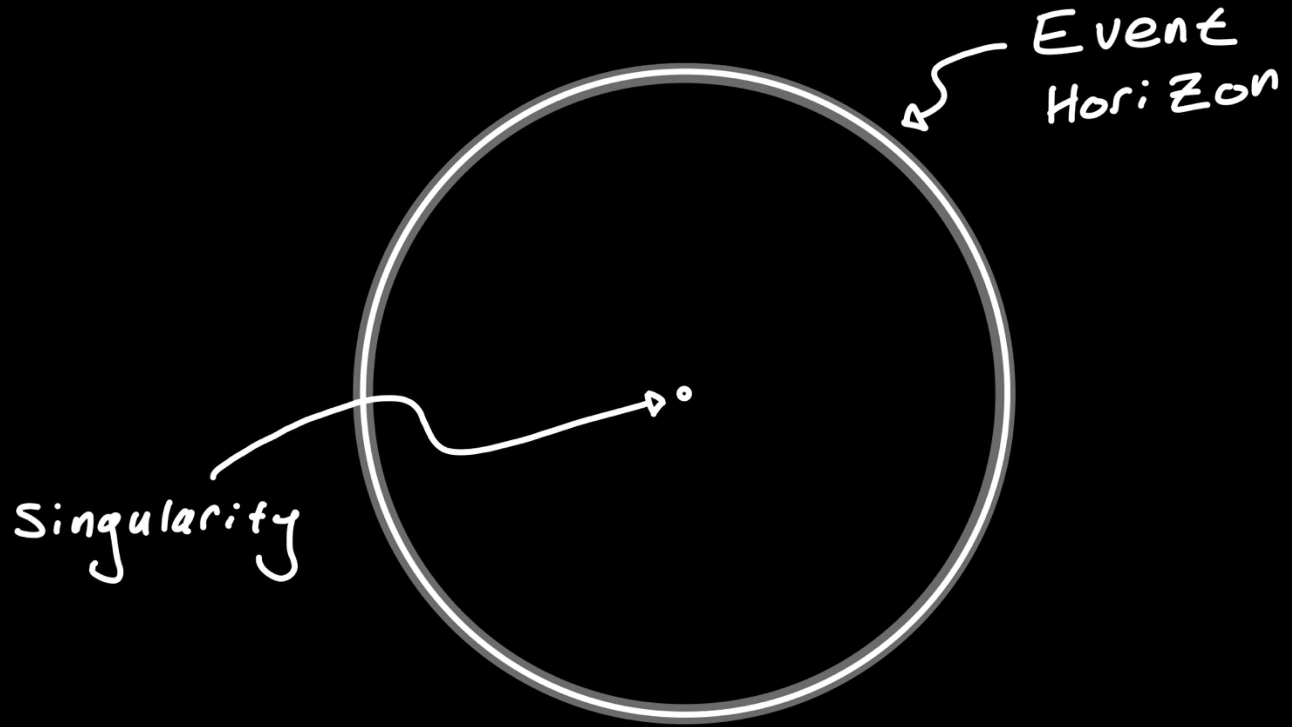


Karl Schwarzschild.

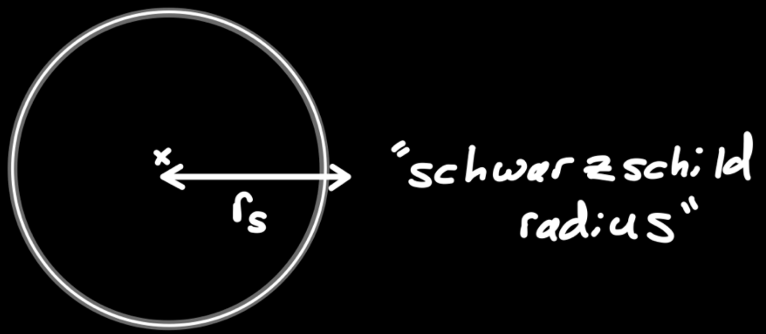
$$ds^2 = -\left(1 - \frac{2GM}{rc^2}\right)c^2dt^2 + \left(1 - \frac{2GM}{rc^2}\right)^{-1}dr^2 + r^2 d\Omega^2$$

Anatomy of a Black Hole

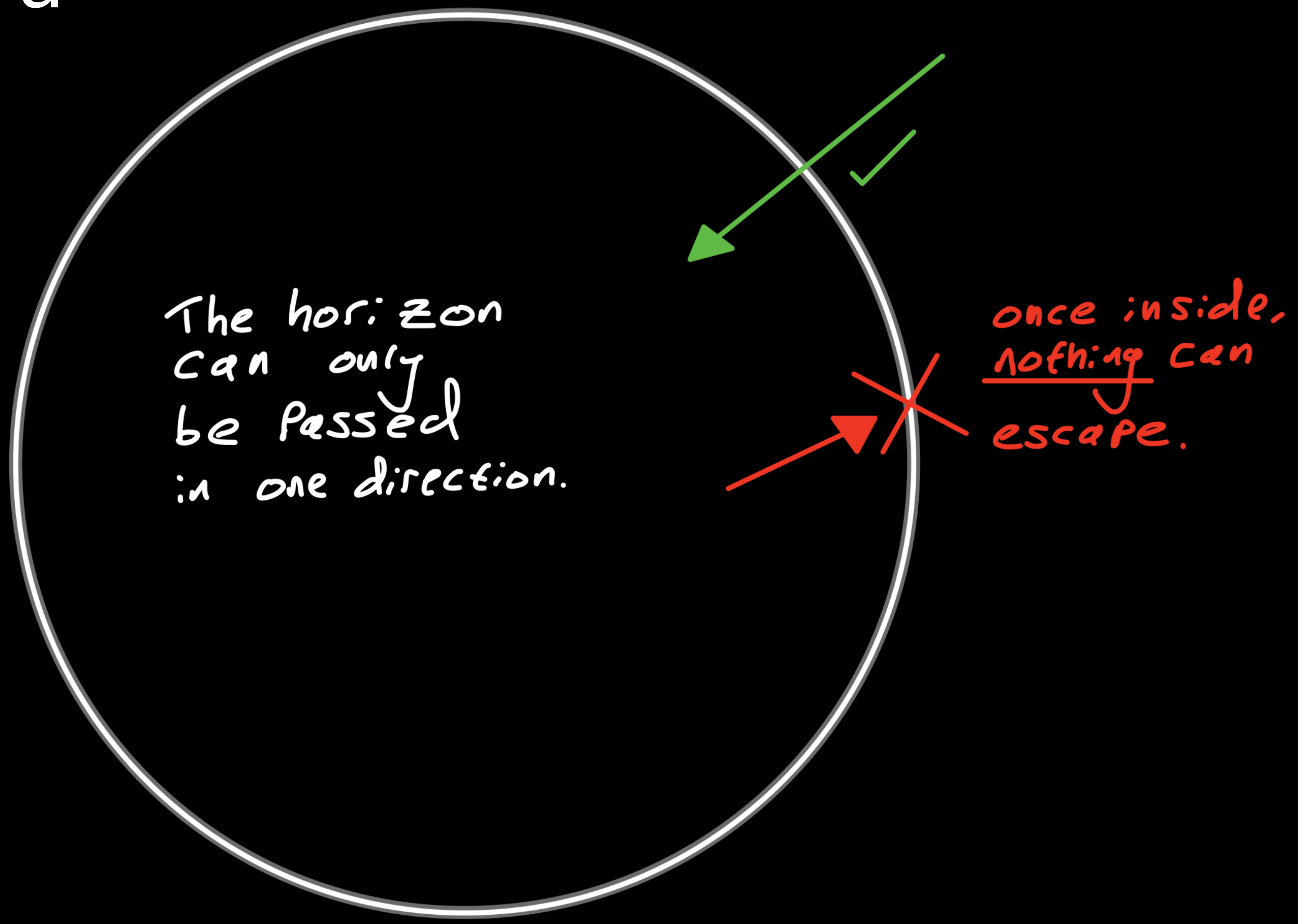
Describing a black hole is simple enough, as they have very few identifying features.



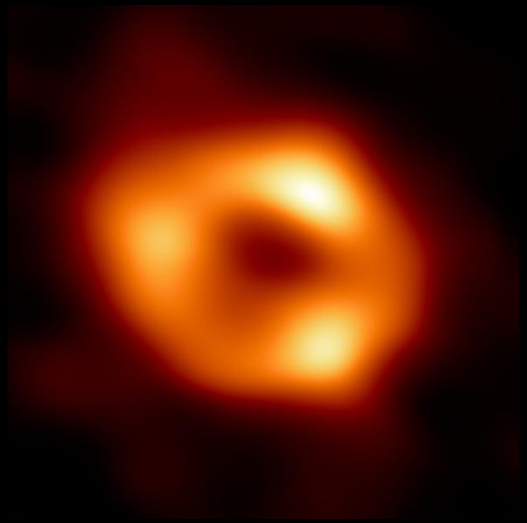
$$r_s = \frac{2GM}{c^2}$$



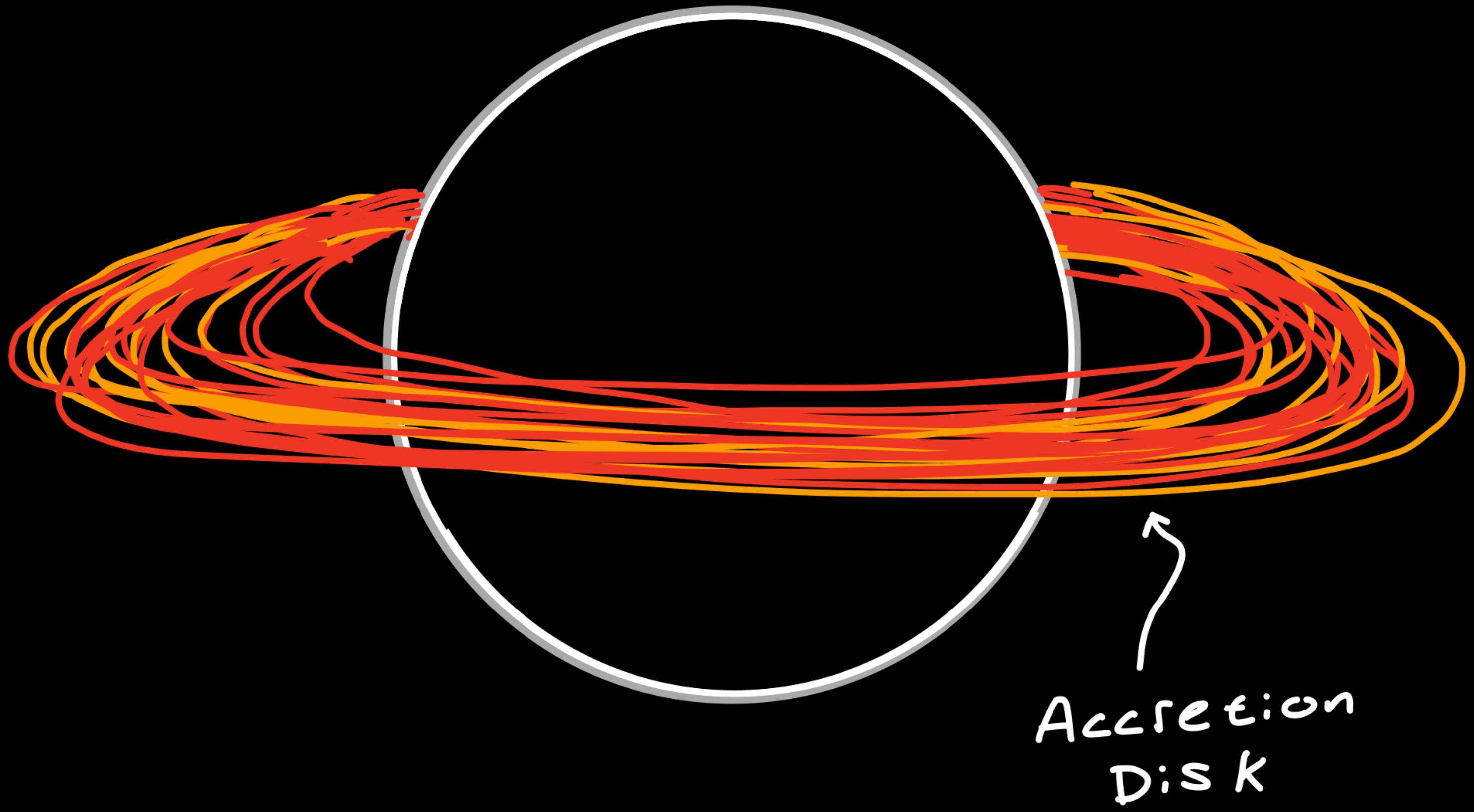
Anatomy of a Black Hole



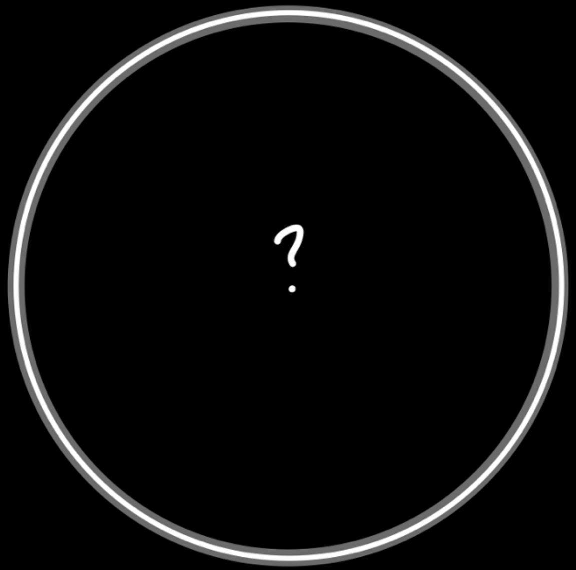
Anatomy of a Black Hole



Event Horizon Telescope image of Sagittarius A*.



Anatomy of a Black Hole

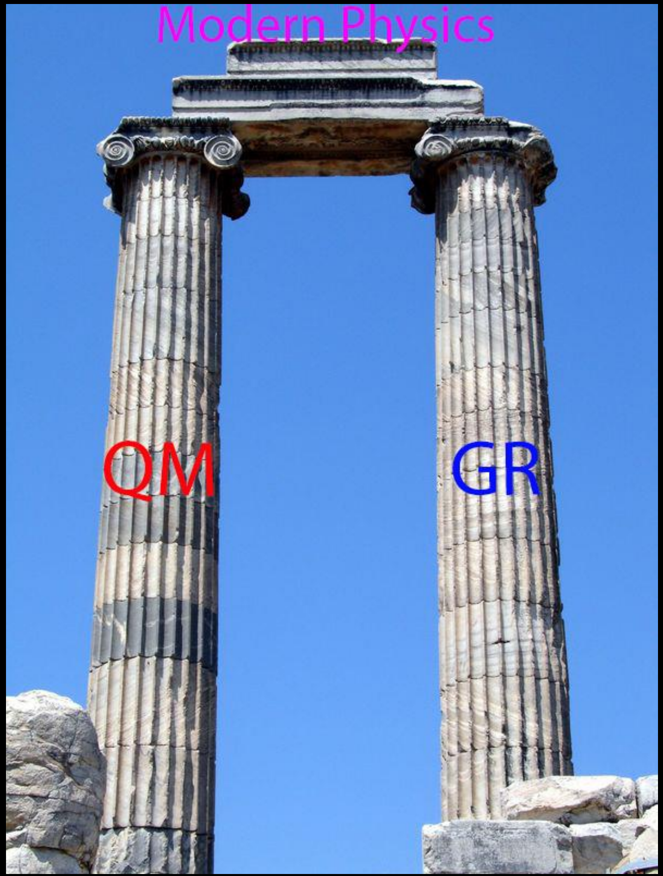


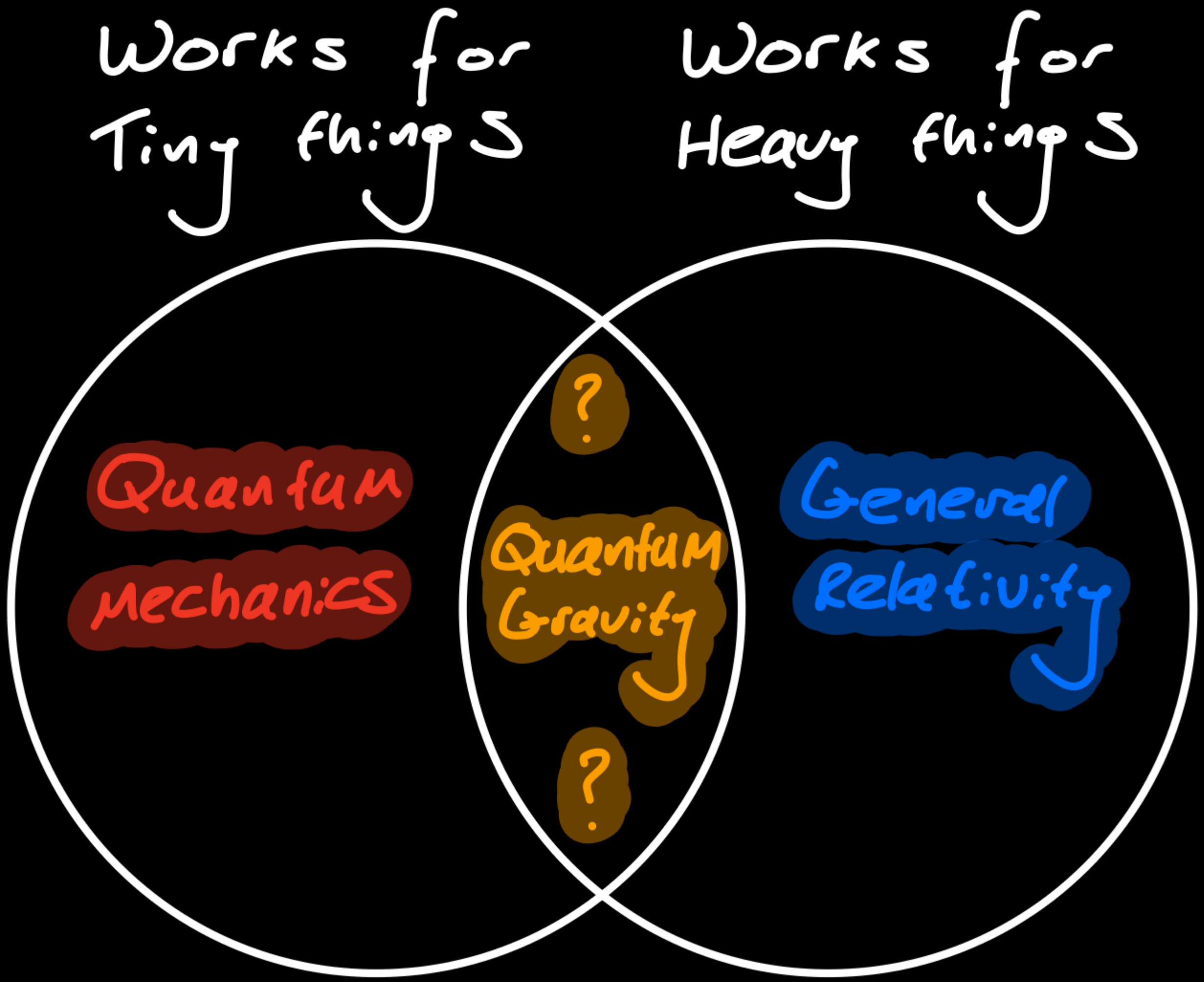
The Singularity:

- The point at the centre of a black hole.
- 'Infinitely Dense'.
- The laws of physics break down.

The Singularity

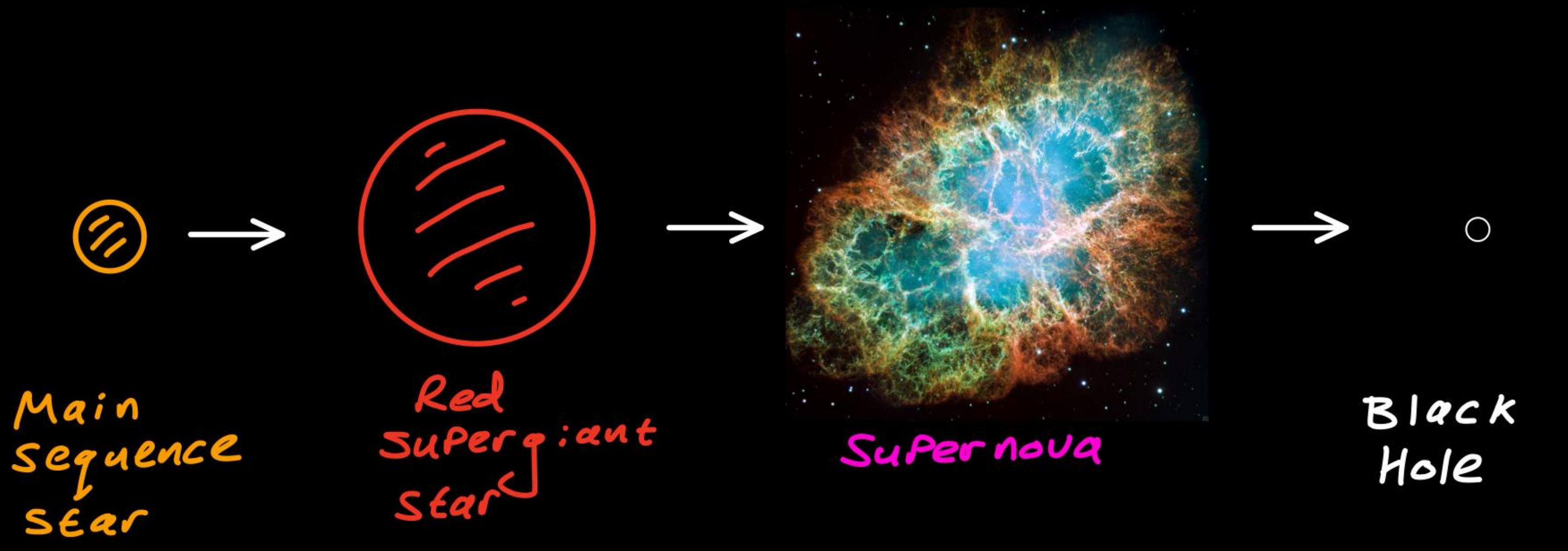
Why is the singularity so hard to understand?





Black Hole Formation

Black holes form when giant stars run out of fuel, and collapse under their own weight.

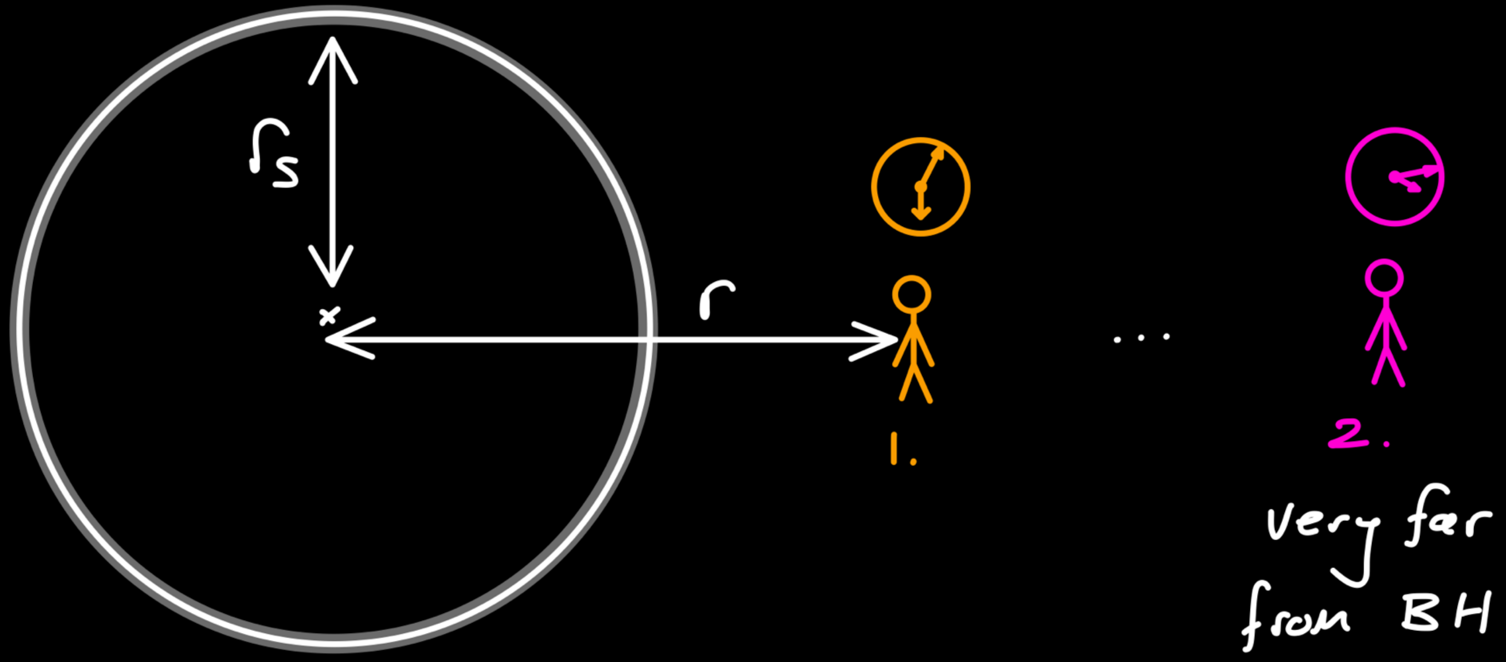


Roger Penrose and Stephen Hawking bridged the gap from Schwarzschild's theoretical solution of Einstein's equations, to show that black holes can form in real life (imperfect) conditions.

Natural Time Machines

Perhaps the strangest property of black holes, is how the bend and stretch time for those nearby...

$$\Delta t_{near} = \Delta t_{far}\sqrt{1 - \frac{r_s}{r}}$$



Person 2's clock will tick much faster than Person 1's.

Let's put this into perspective using Gaia BH1, the nearest known black hole to the Earth.

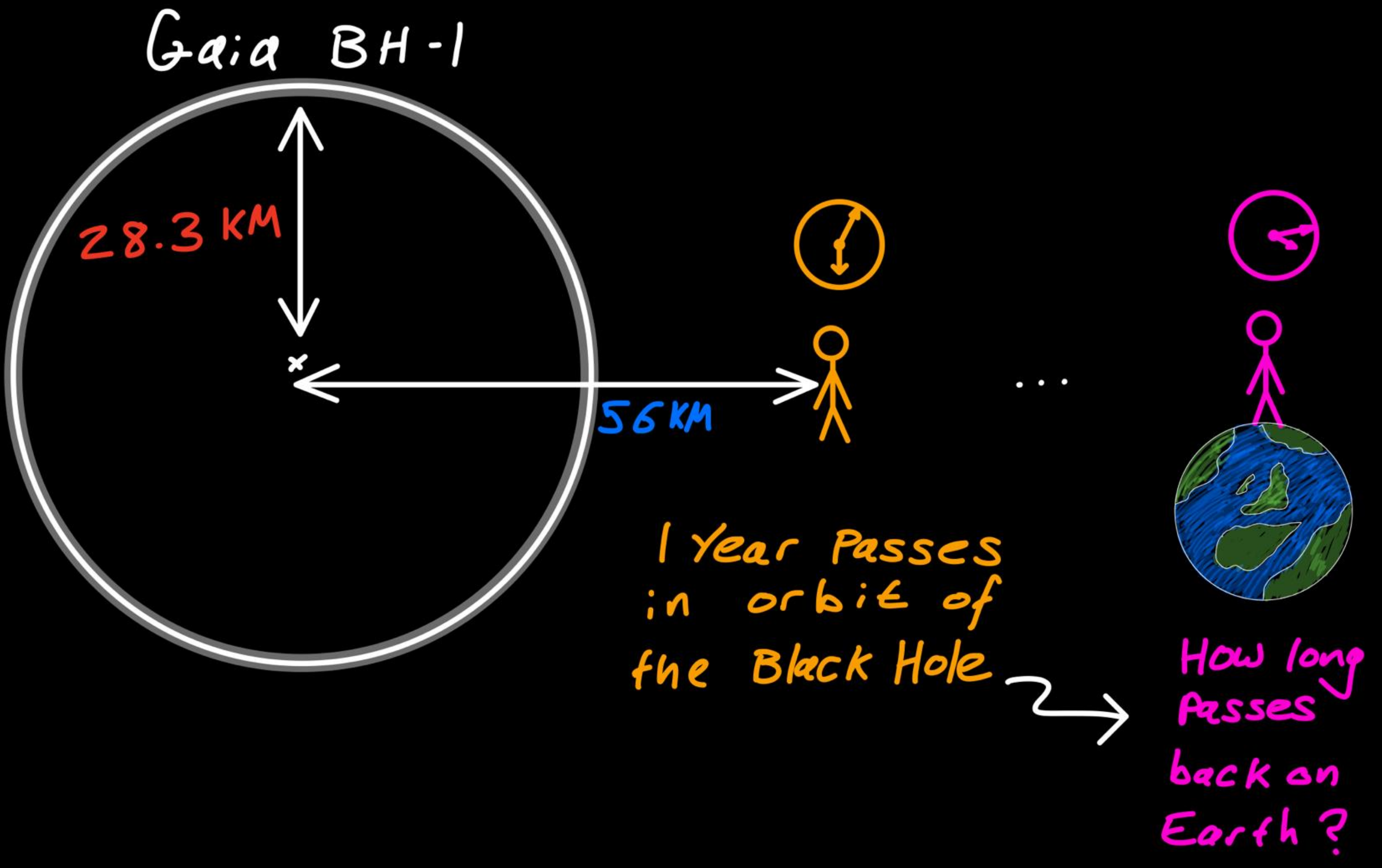
Natural Time Machines

Recall, Gaia BH1's radius stretched out to Dartford.

Suppose we get into an orbit that would stretch out to central London.

Natural Time Machines

Spend 1 year orbiting our nearest known black hole, and you will have travelled forwards in time by 5 months compared to everyone home on Earth.



$$\Delta t_{Earth} = \frac{1\,yr}{\sqrt{1 - \frac{28.3\,km}{56\,km}}} = 1\,yr + 5\,months$$

How do we know this?

“How can you possibly know this is correct? Given we’ve never been to a black hole!”

We (physicists) did the maths!

$$\mathcal{L} = -\left(1-\frac{2M}{r}\right)\dot{t}^2 + \left(1-\frac{2M}{r}\right)^{-1}\dot{r}^2 + r^2\dot{\theta}^2 + r^2\sin^2\theta\,\dot{\phi}^2$$

where $\dot{y} \equiv \frac{dy}{d\lambda}$

a)

(i) Euler Lagrange equations: $\frac{d}{d\lambda}\left(\frac{\partial \mathcal{L}}{\partial \dot{x}^\mu}\right) = \frac{\partial \mathcal{L}}{\partial x^\mu}$

- $\mathcal{L}$ is independant of time

$\Rightarrow \frac{\partial \mathcal{L}}{\partial t} = 0$

$\Rightarrow \frac{\partial \mathcal{L}}{\partial \dot{t}}$ is constant along geodesics

$\frac{\partial \mathcal{L}}{\partial \dot{t}} = -2\left(1-\frac{2M}{r}\right)\dot{t} = \text{constant}$

Let $E := \left(1-\frac{2M}{r}\right)\dot{t}$

This conserved quantity is associated with the particles energy.

- $\mathcal{L}$ is independant of ϕ.

$\Rightarrow \frac{\partial \mathcal{L}}{\partial \dot{\phi}} = \text{constant}$

$\frac{\partial \mathcal{L}}{\partial \dot{\phi}} = 2r^2\sin^2\theta\,\dot{\phi}$

Let $J := r^2\sin^2\theta\,\dot{\phi}$

J is associated with conserved angular momentum.

- $\mathcal{L}$ is itself conserved.

The interval,

$$ds^2 = -\left(1-\frac{2M}{r}\right)dt^2 + \left(1-\frac{2M}{r}\right)^{-1}dr^2 + r^2\left(d\theta^2 + \sin^2\theta\,d\phi^2\right)$$

is invariant, and has no dependance on the affine parameter λ. Therefore $\mathcal{L}$ is a constant along the geodesic.

$\mathcal{L} = -1$ for timelike geodesics parameterized by proper time τ, and $\mathcal{L} = 0$ for null geodesics.

(ii)

Consider the Euler Lagrange equation for θ:

$\frac{\partial \mathcal{L}}{\partial \theta} = 2\sin\theta\cos\theta(\dot{\phi})^2$

$\frac{\partial \mathcal{L}}{\partial \dot{\theta}} = 2r^2\dot{\theta}$

$\Rightarrow \frac{d}{d\lambda}(2r^2\dot{\theta}) = 2\sin\theta\cos\theta(\dot{\phi})^2$

We can orient our coord system initially at $\lambda = 0$, such that $\theta = \frac{\pi}{2}$ and $\left.\frac{d\theta}{d\lambda}\right|_{\lambda=0} = 0$ without loss of generality.

Making this choice

$\Rightarrow \frac{d}{d\lambda}(2r^2\dot{\theta}) = 0$ at $\lambda = 0$

$\frac{d}{d\lambda}(2r^2\dot{\theta}) = 4r\dot{r}\dot{\theta} + 2r^2\ddot{\theta}$

at $\lambda = 0$, this becomes

$2r^2\ddot{\theta} = 0$

$\Rightarrow \dot{\theta}$ will remain constant

So if initially $\dot{\theta} = 0$, and $\theta = \frac{\pi}{2}$, the geodesic will remain in the $\theta = \frac{\pi}{2}$ plane.

b) Along a radial geodesic:

$\dot{\phi} = \dot{\theta} = 0$

$\Rightarrow \mathcal{L} = -\left(1-\frac{2M}{r}\right)\dot{t}^2 + \left(1-\frac{2M}{r}\right)^{-1}\dot{r}^2$

Defining $K = -\mathcal{L}$, so $K = +1$ for timelike curves parameterized by τ, and $K = 0$ for null curves, and using $E = \left(1-\frac{2M}{r}\right)\dot{t}$,

we can write:

$-K = -\left(1-\frac{2M}{r}\right)^{-1}E^2 + \left(1-\frac{2M}{r}\right)^{-1}\dot{r}^2$

$\Rightarrow \dot{r}^2 = E^2 - K\left(1-\frac{2M}{r}\right)$

with $K = +1$ for timelike curves (with $\lambda = \tau$)

$K = 0$ for null curves

c)

M (Mass) — (Satellite) — $r = R \gg 2M$ Alice

(i)

$\dot{r}^2 = E^2 - K\left(1-\frac{2M}{r}\right)$

for Alice:

$\dot{r} = \frac{dr}{d\tau_A} = 0$

$\Rightarrow E^2 = \left(1-\frac{2M}{R}\right) \Rightarrow E = \left(1-\frac{2M}{R}\right)^{\frac{1}{2}}$

E is conserved along Alice's world line with $E = \left(1-\frac{2M}{R}\right)\dot{t}$

$\Rightarrow \frac{dt}{d\tau_A} = E\left(1-\frac{2M}{R}\right)^{-1} = \left(1-\frac{2M}{R}\right)^{-\frac{1}{2}}$

$\Rightarrow d\tau_A = \left(1-\frac{2M}{R}\right)^{\frac{1}{2}}dt$

$\tau_A = 0$ when $t = 0$

$\Rightarrow \tau_A = \left(1-\frac{2M}{R}\right)^{\frac{1}{2}}t$

$\Rightarrow \tau_A = t\left(1-\frac{M}{R}+O\left(\left(\frac{M}{R}\right)^2\right)\right)$ ← fine to do as $R \gg 2M$

$\Rightarrow \tau_A = t + O\left(\frac{M}{R}\right)$

(ii)

M (Mass) — (Satellite) $t = t_0$, $r = r_0$ — $r = R \gg 2M$ Alice

$\dot{r}^2 = E^2 - K\left(1-\frac{2M}{r}\right)$

Along null geodesic of signal, we now have:

$\left(\frac{dr}{d\lambda}\right)^2 = E^2$

$\frac{dr}{d\lambda} = E$ ← Taking +ve root as signal is outwards going

$\frac{dr}{d\lambda} = \left(1-\frac{2M}{r}\right)\frac{dt}{d\lambda}$

$\Rightarrow dt = \left(1-\frac{2M}{r}\right)^{-1}dr$

$\int_{t_0}^{t_1} dt = \int_{r_0}^{R}\left(\frac{r}{r-2M}\right)dr$

$t_1 - t_0 = \int_{r_0}^{R}\frac{r-2M+2M}{r-2M}\,dr$

$= \int_{r_0}^{R}\left[1 + 2M\frac{1}{r-2M}\right]dr$

$= R - r_0 + \left[2M\log(r-2M)\right]_{r_0}^{R}$

$= R - r_0 + 2M\log\left(\frac{R-2M}{r_0-2M}\right)$

$\log\left(1-\frac{2M}{R}\right) \sim -\frac{2M}{R} + O\left(\left(\frac{M}{R}\right)^2\right)$

$\Rightarrow 2M\log\left(\frac{R-2M}{r_0-2M}\right) \simeq 2M\log\left(\frac{R}{r_0-2M}\right)$

$\Rightarrow t_1 - t_0 = R - r_0 + 2M\log\left(\frac{R}{r_0+2M}\right)$

using: $\tau_A = t + O\left(\frac{M}{R}\right)$

$\tau_1 = t_1 + O\left(\frac{M}{R}\right)$

$\Rightarrow \tau_1 = t_0 + R - r_0 + 2M\log\left(\frac{R}{r_0-2M}\right) + O\left(\frac{M}{R}\right)$

d) $E \rightarrow$ Energy of satellite geodesic

$\Rightarrow E = \left(1-\frac{2M}{r}\right)\frac{dt}{d\tau_s}$

M (Mass) — (Satellite) $t = t_0$, $r = r_0$ — $r = R \gg 2M$ Alice

M (Mass) — (Satellite) $t = t_2$, $r = r_2$ — $r = R \gg 2M$ Alice

How do we know this?

“How can you possibly know this is correct? Given we’ve never been to a black hole!”

We (physicists) did the maths!

“But how do you know the maths works? You can’t test this in a lab.

There are many predictions we can test in the real world.

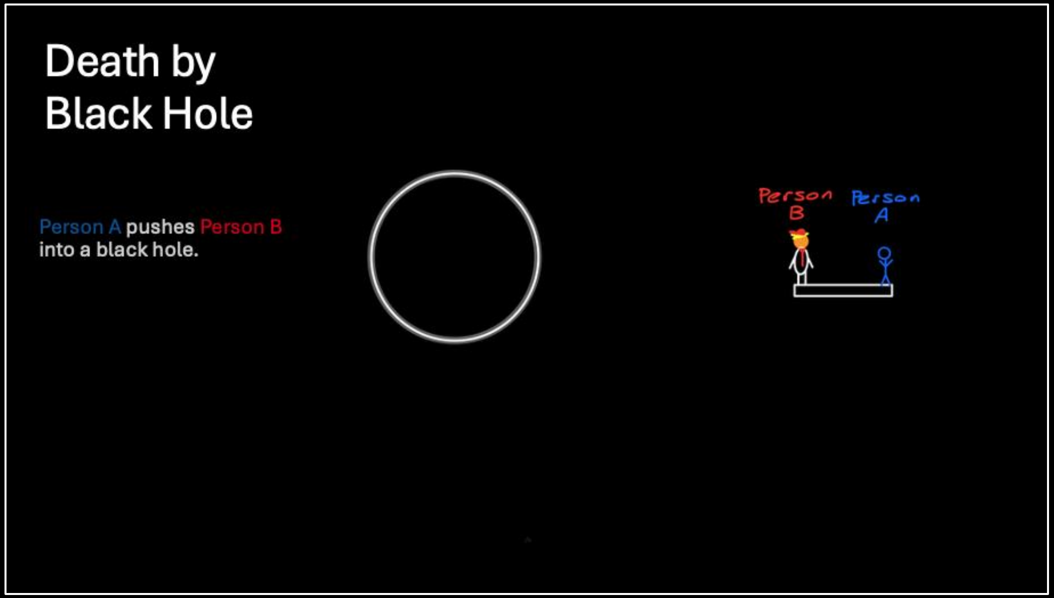
E.g. GPS

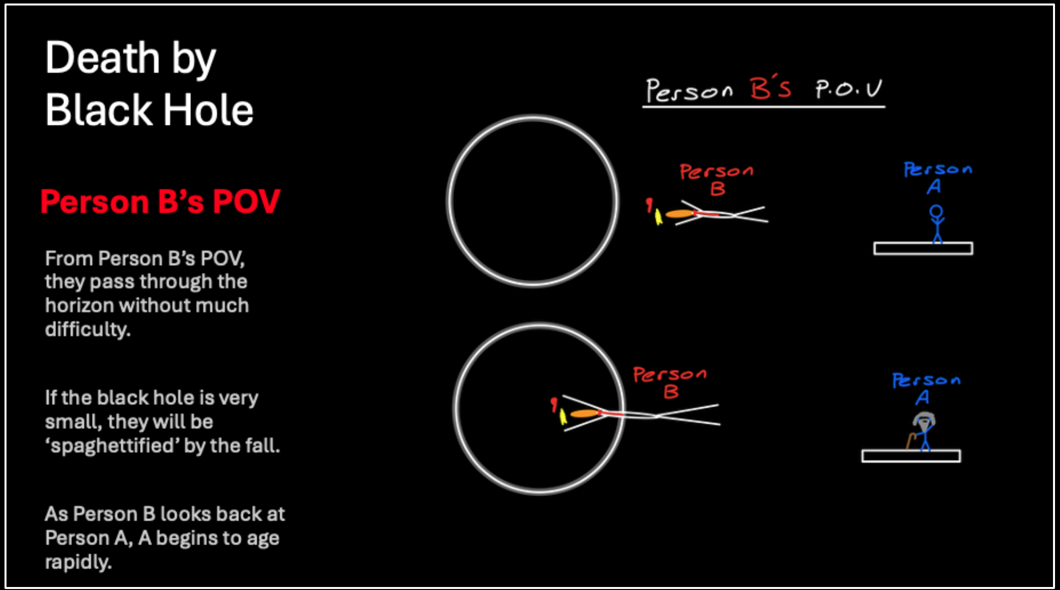
GPS satellites calculate location by pinging a signal between themselves and devices on the Earth. Extremely accurate clocks are needed to do this.

General relativity has to be accounted for in order for GPS to work.

Death by Black Hole…

See Lecture ‘Black Holes and Beyond’ for a discussion of what it would feel like to fall into a black hole…. LLL[3].





LLL [3]

Part IV - Space Travel via ‘*Warp Drive*’

The Universal Speed Limit

Not only is the speed of light constant, for everybody who measures it.

It is also the maximum speed anything can move at in the Universe.

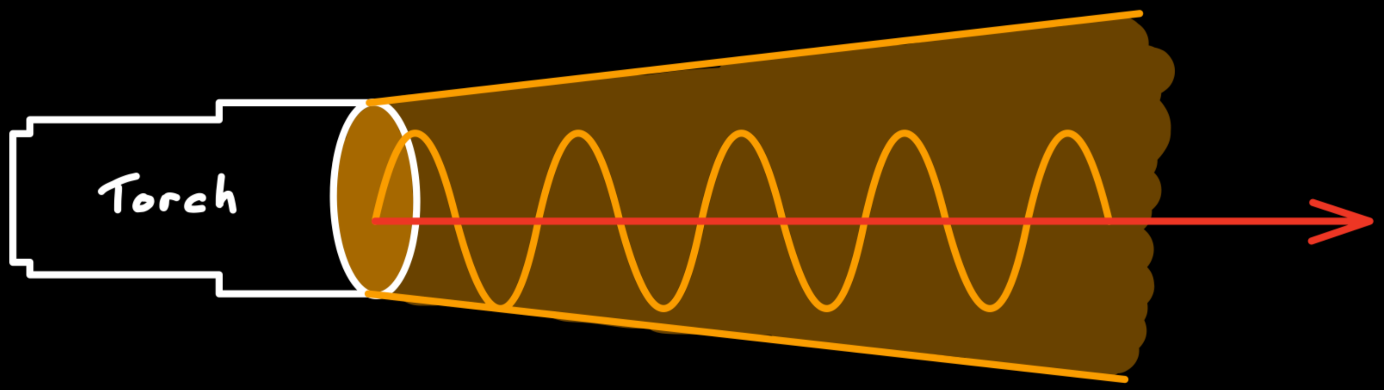
Note: This is an AI generated image.

‘Light Years’

Light is fast

A *light-year* is not a duration of time, but a unit of distance.

One light-year (abbreviated to LY) is the distance travelled by light moving through empty space in one year.



Speed = 300,000,000 Metres per second

or 670,000,000 Miles per hour

or 190,000 Miles per hour

'Light Years'

A *light-year* is not a duration of time, but a unit of distance.

One light-year (abbreviated to LY) is the distance travelled by light moving through empty space in one year.

1 LY = 300,000,000 × (365 × 24 × 60 × 60)

= 9,500,000,000,000,000 Metres

or 5,900,000,000,000 Miles

[590 Billion Miles]

‘Light Minutes’

A *light-year* is not a duration of time, but a unit of distance.

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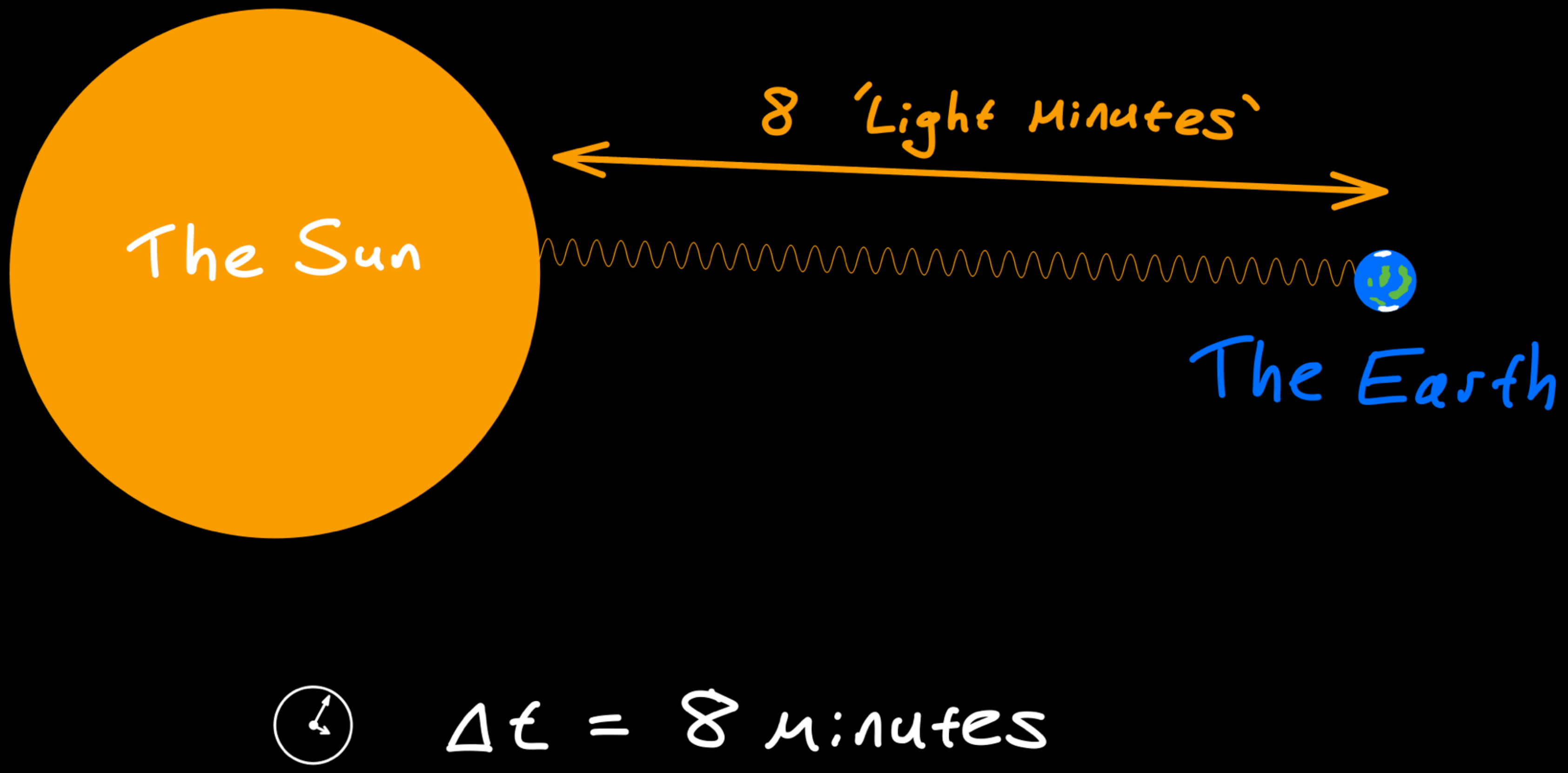


Though not a common unit, a *light-minute* can be defined as the distance travelled by light in a single minute.

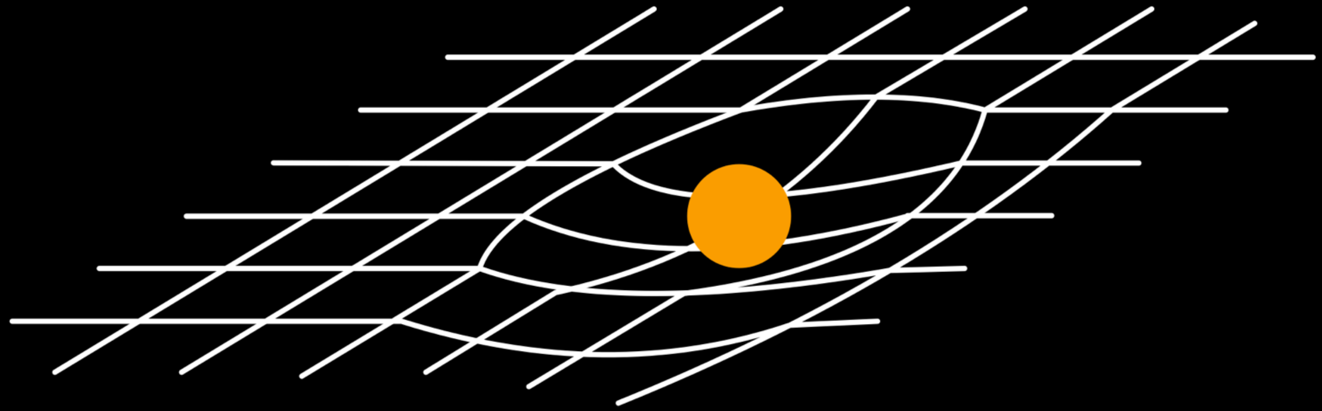
The Alcubierre ‘Warp Drive’

In 1994, Miguel Alcubierre allowed his imagination to wander while watching Star Trek, and laid the foundations for the serious scientific study of faster-than-light travel.

Miguel Alcubierre.

The Alcubierre ‘Warp Drive’

By imagining a configuration of space time, that would allow an observer to ‘surf’ the wake of a super-luminal bubble of space time, Alcubierre showed that faster than light travel is not explicitly forbidden by Einstein’s equations of gravity.

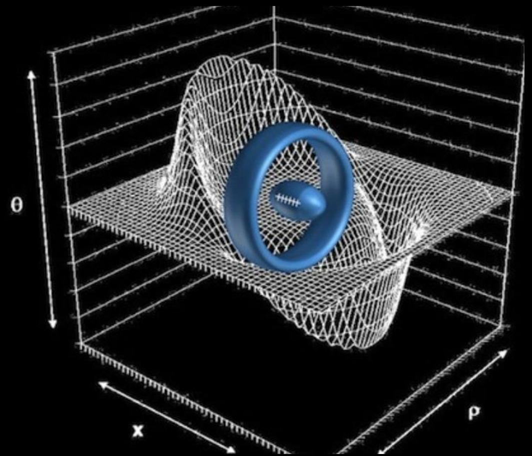


$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space-time Curvature

Speed of Light

Matter



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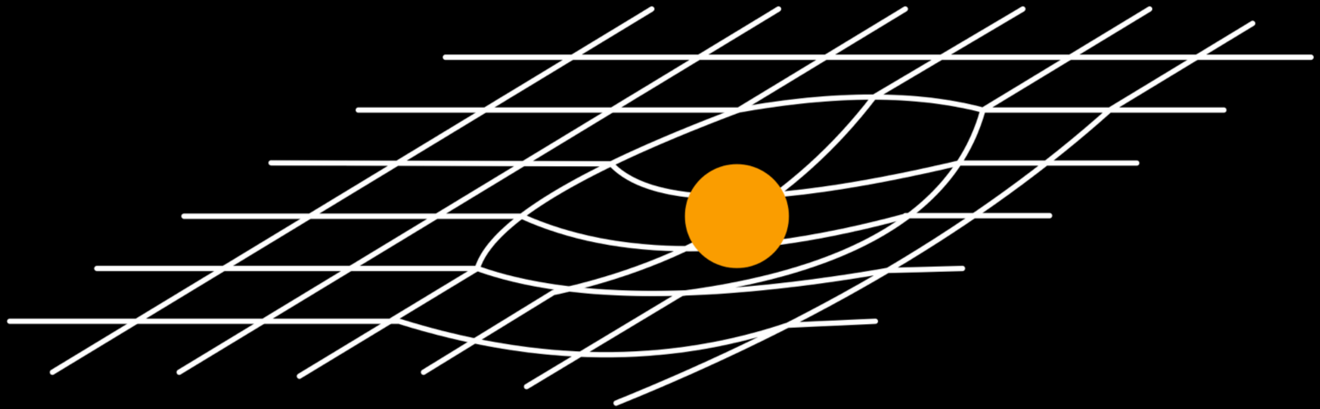

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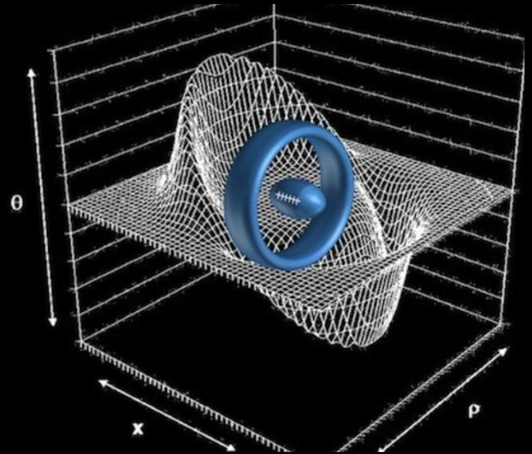
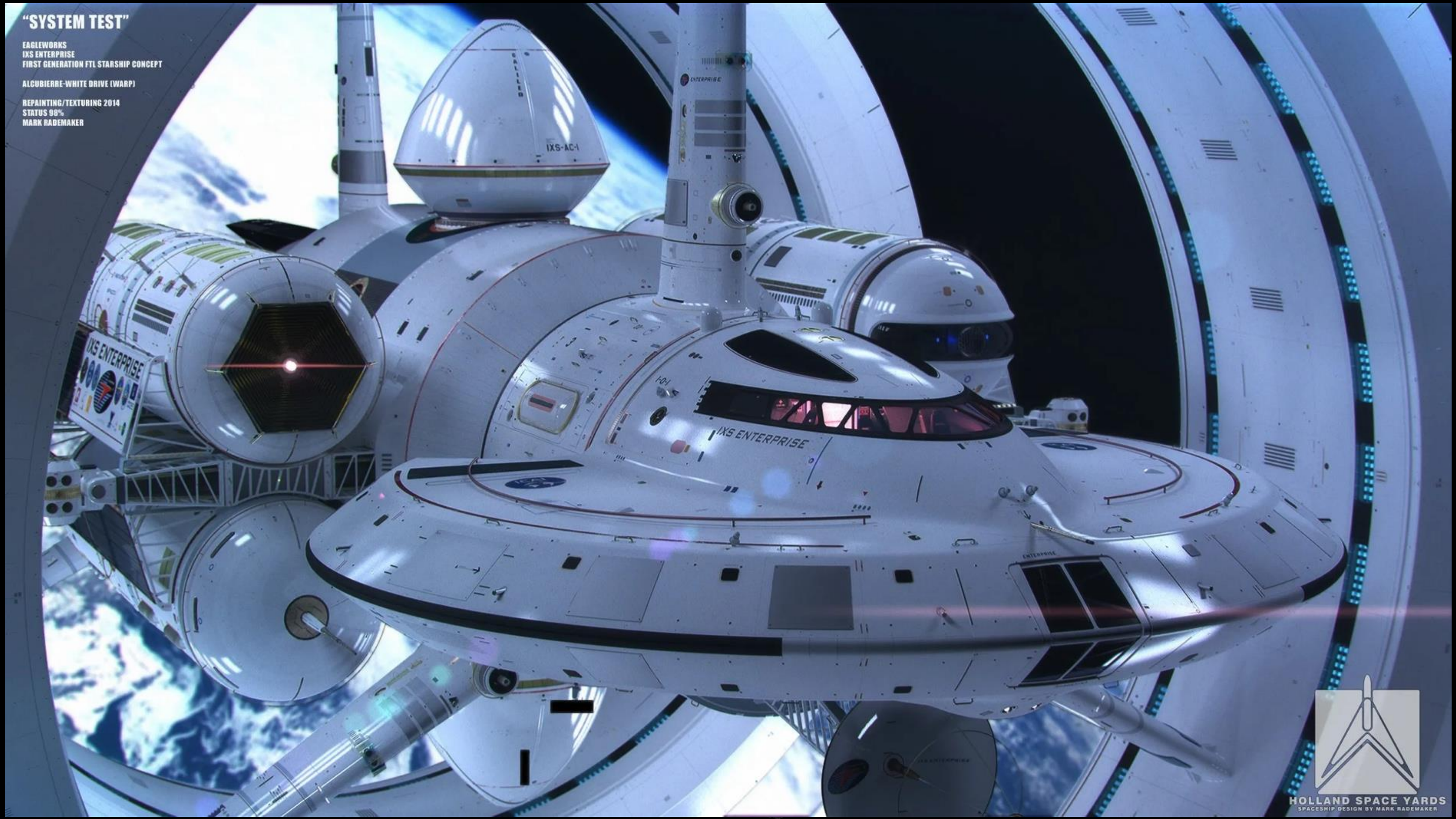


This does not mean other laws of physics won’t kill Alcubierre’s theory!

The Alcubierre ‘Warp Drive’

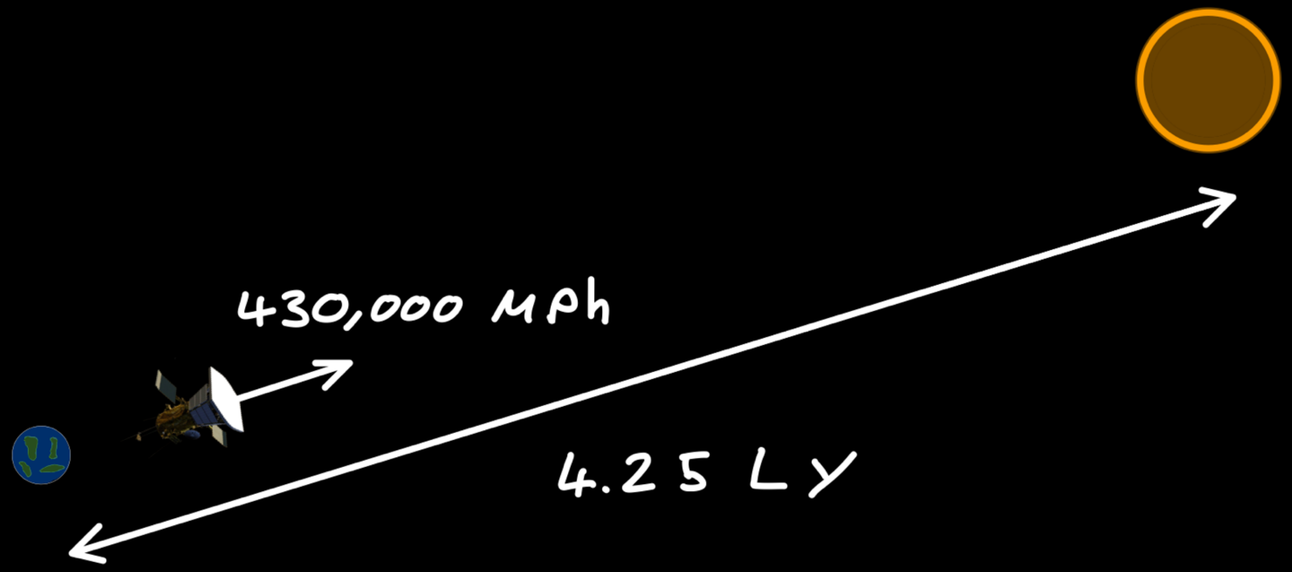


Artists impression of how a futuristic warp ship might look.

Proxima Centauri in a Week

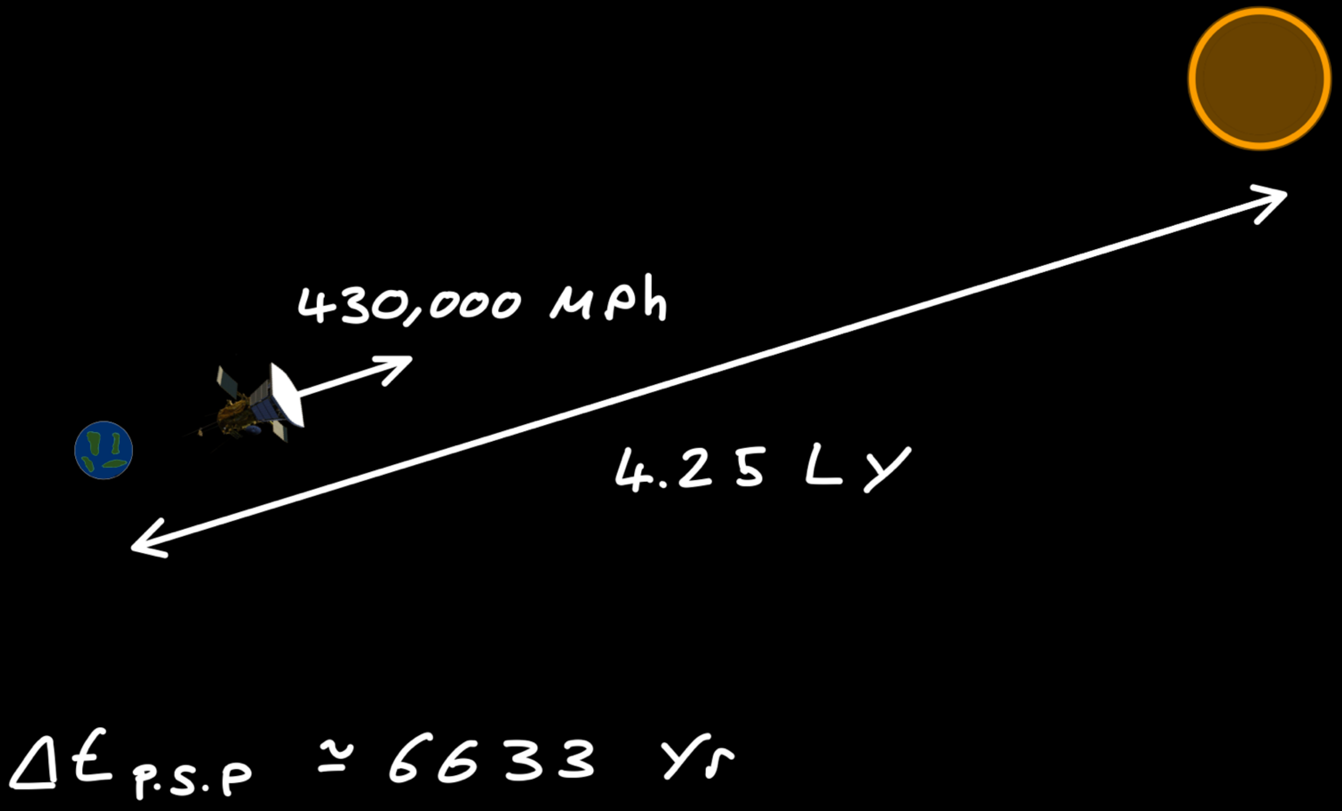
Proxima Centauri is the star closest to our own solar system.

It is a distance of 4.25Ly from the Earth (very close at the scale of the galaxy... very far by all other metrics!).



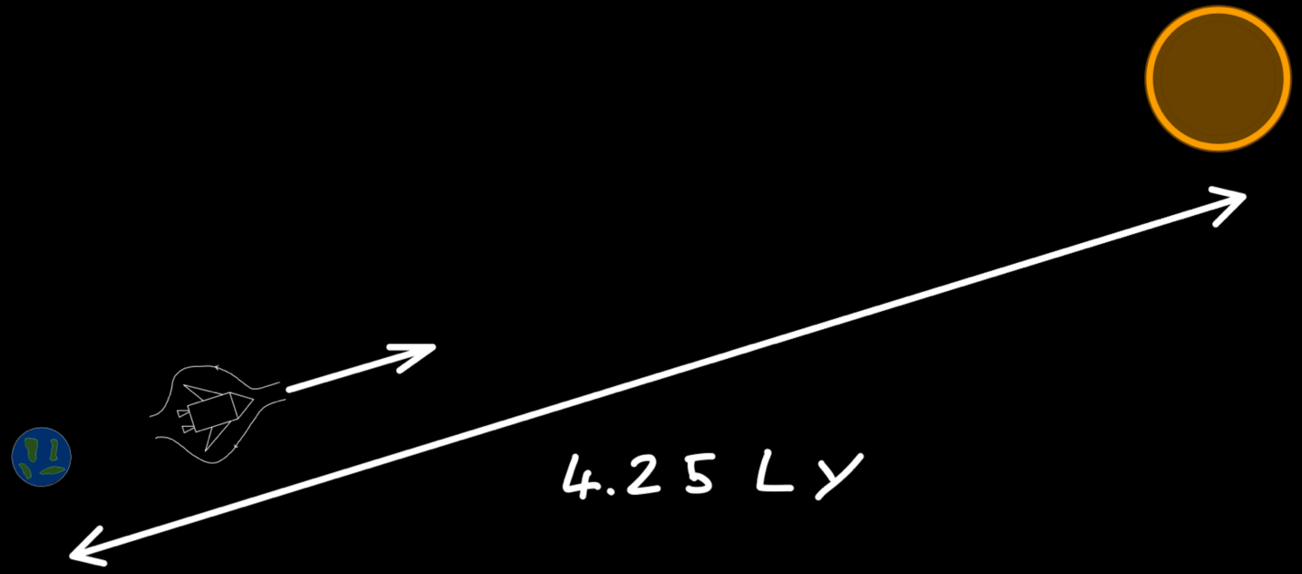
Proxima Centauri in a Week

Travelling at the fastest speed any human-made object has every moved (the Parker Solar Probe, during it's closest approach to the sun) it would still take about 6633 years to reach Proxima Centauri.



Proxima Centauri in a Week

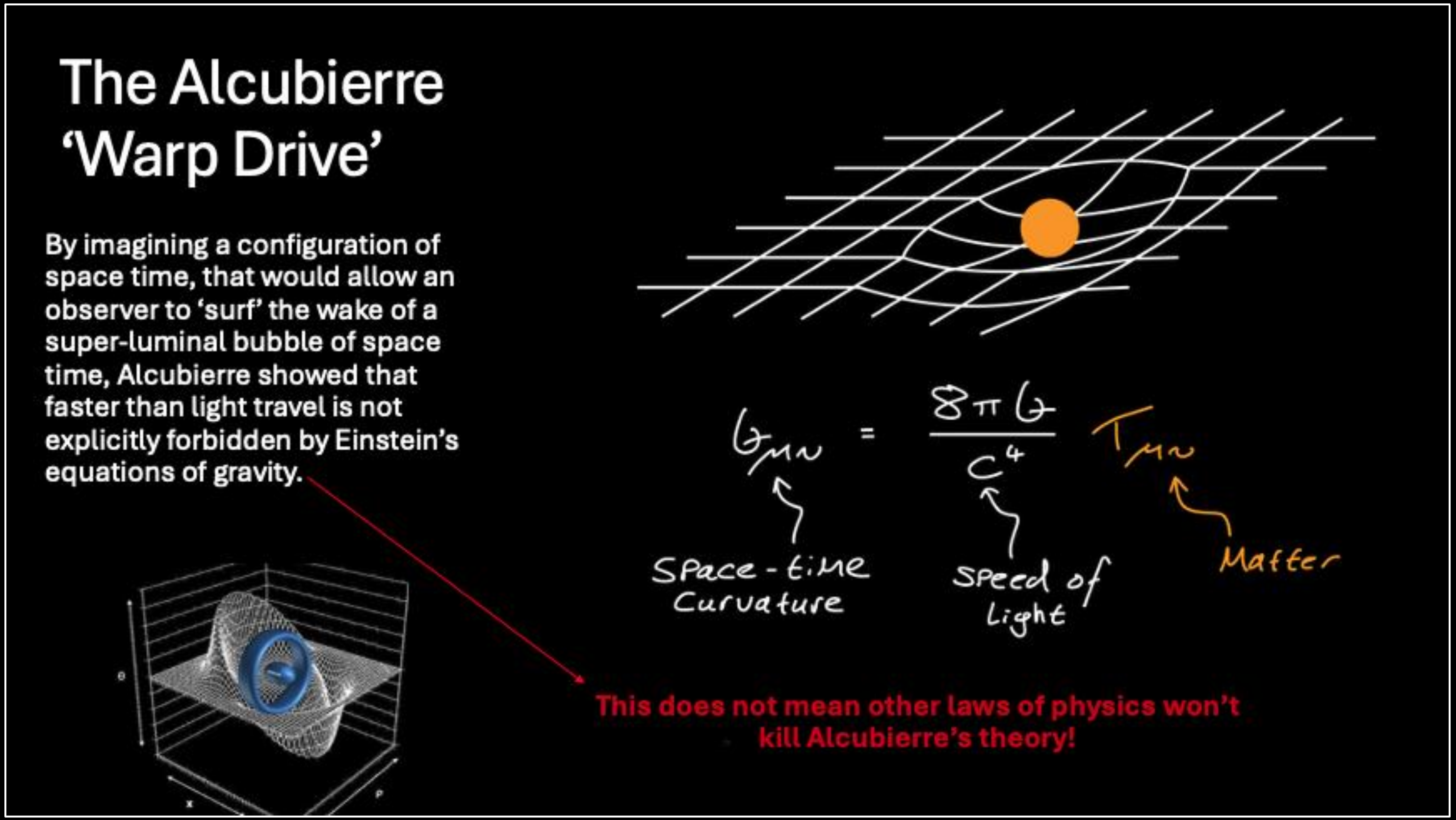
If FTL (faster than light) travel is possible, this journey could be completed in a matter of days.



Exotic Matter

On big problem with the Alcubierre Drive, is that it requires *exotic matter* to produce the distortion of space-time required to form and sustain such a ‘*Warp Bubble*’.

In this context *exotic matter* refers to substances with a negative mass, or a negative energy density.



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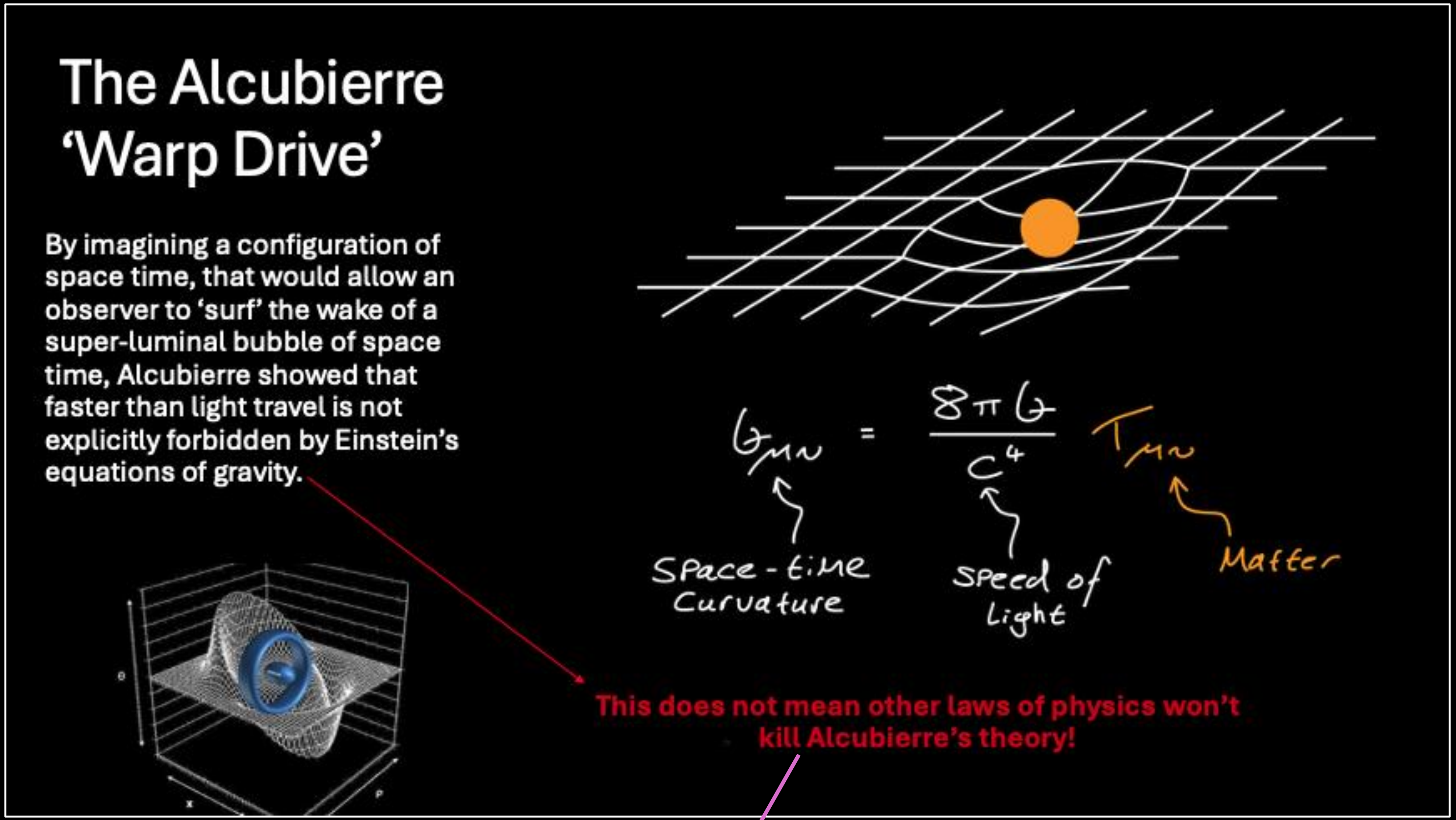

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But does *exotic matter* exist??

Or is this the nail in the coffin for Alcubierre's Drive?

Exotic Matter

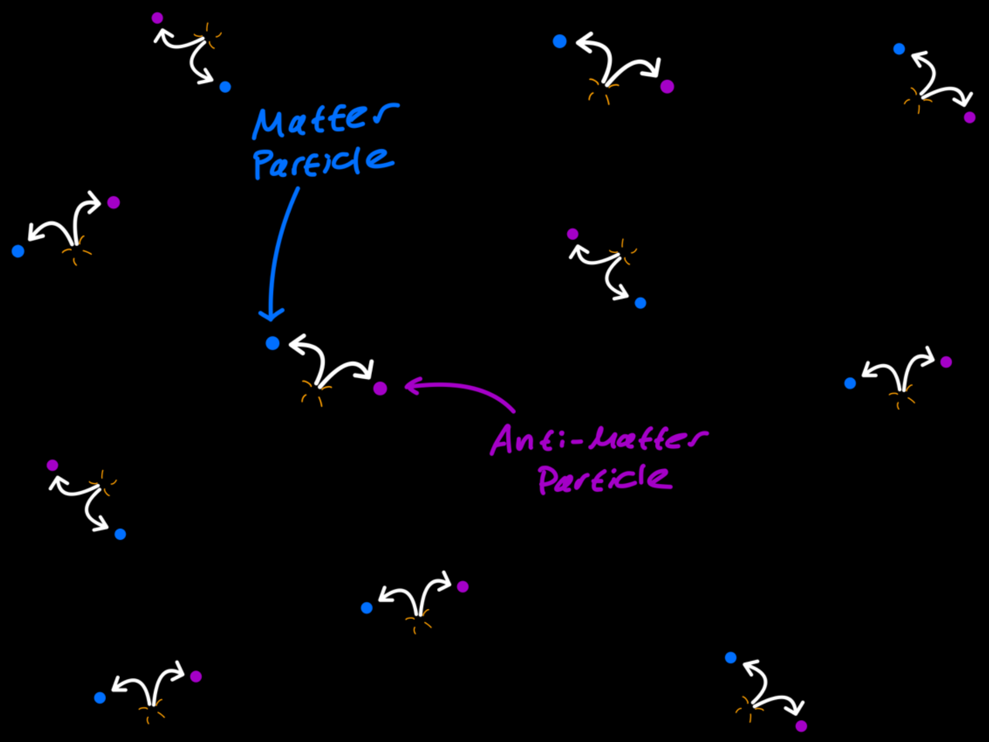
But does *exotic matter* exist??

Or is this the nail in the coffin for Alcubierre's Drive?

LLL [6]

Not in any useful sense, that we know of…

The closest phenomena we know of, which is a result of Quantum Mechanics, is the so called '*Casimir Energy*' present in the vacuum, detectable by measuring the force between two uncharged parallel plates.



Particles pop into existence and dissolve back into the vacuum a short time later.

This *fizz* of of creating and annihilating particles fills the entire Universe.

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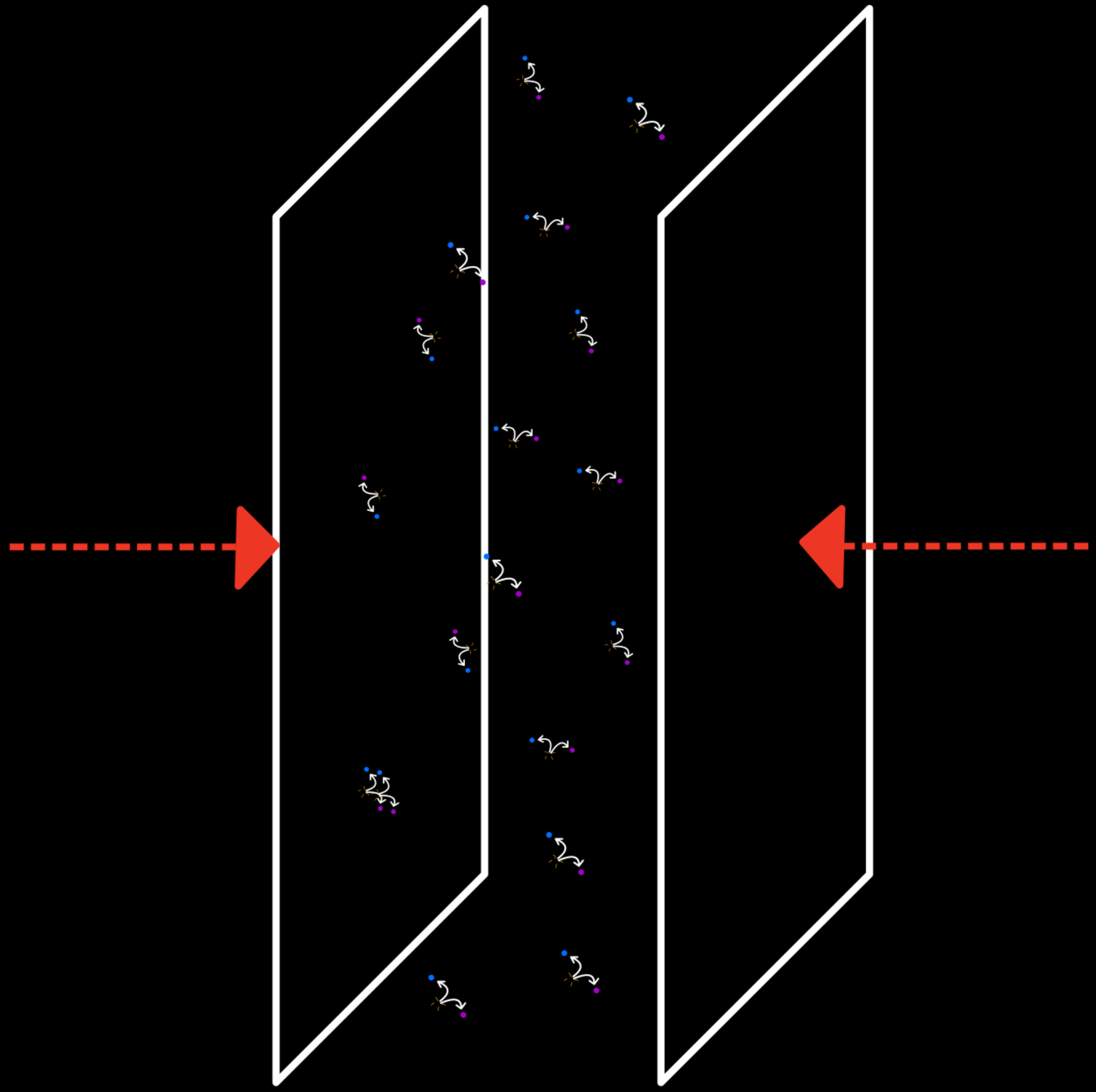

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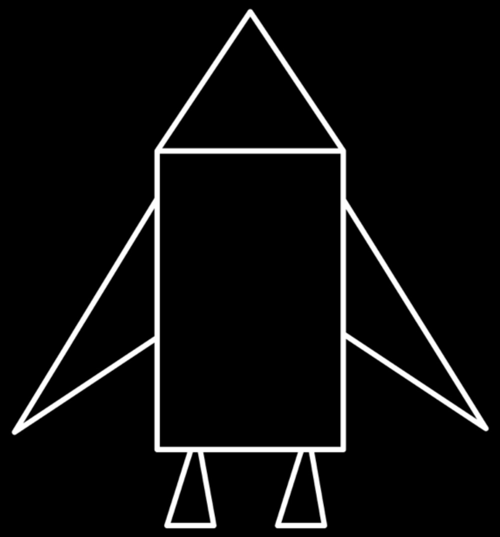
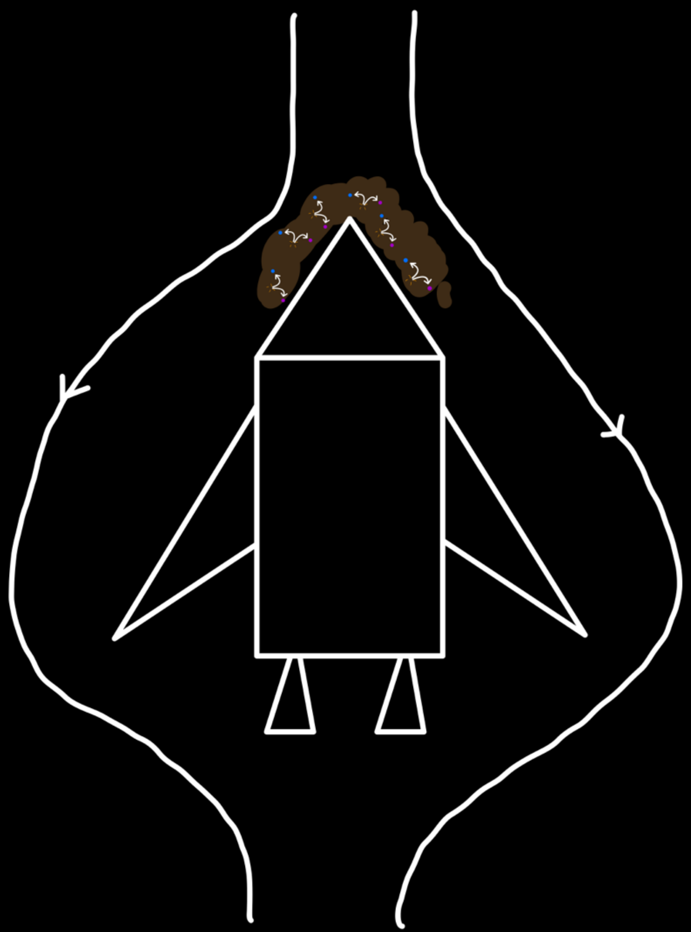
Other Problems…

Suppose we could build such a craft, there are some good reasons you might not want to do so!…



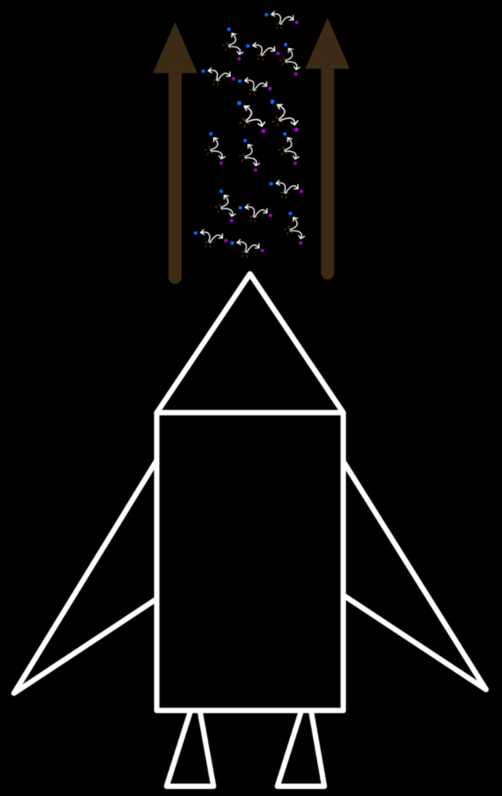
Other Problems…

Due to the super-relativistic speeds of the craft, a collection of very high energy particles would accumulate at the front of the ‘*warp bubble*’.



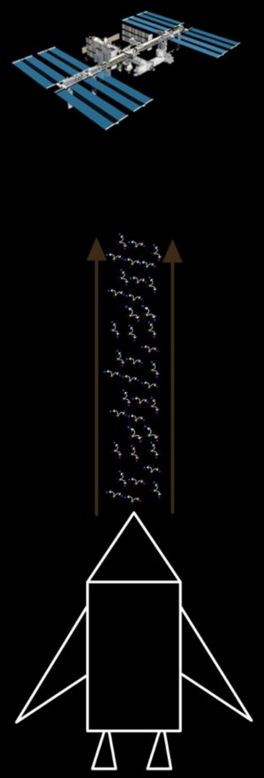
Other Problems…

When the craft decelerates, these high energy particles would continue to move…



Other Problems…

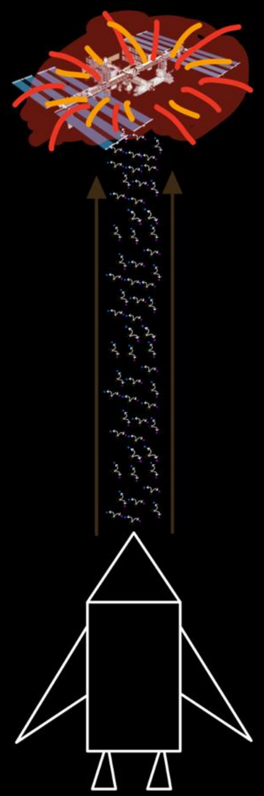
This deadly beam of paired matter & anti-matter particles would propagate forwards as a deadly beam of energy…



Other Problems…

Likely destroying what lay in its path….

Not the best introduction to other species!

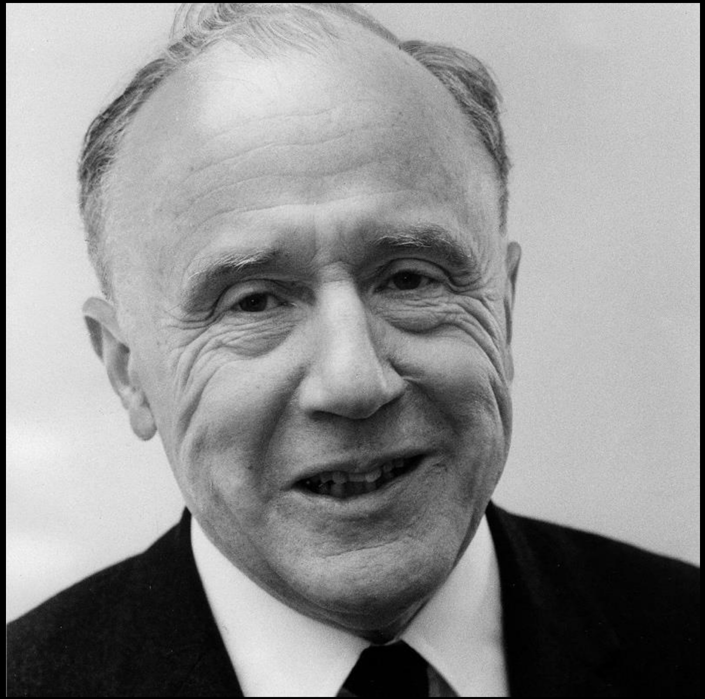


Part V – Space-Time Travel via Wormhole

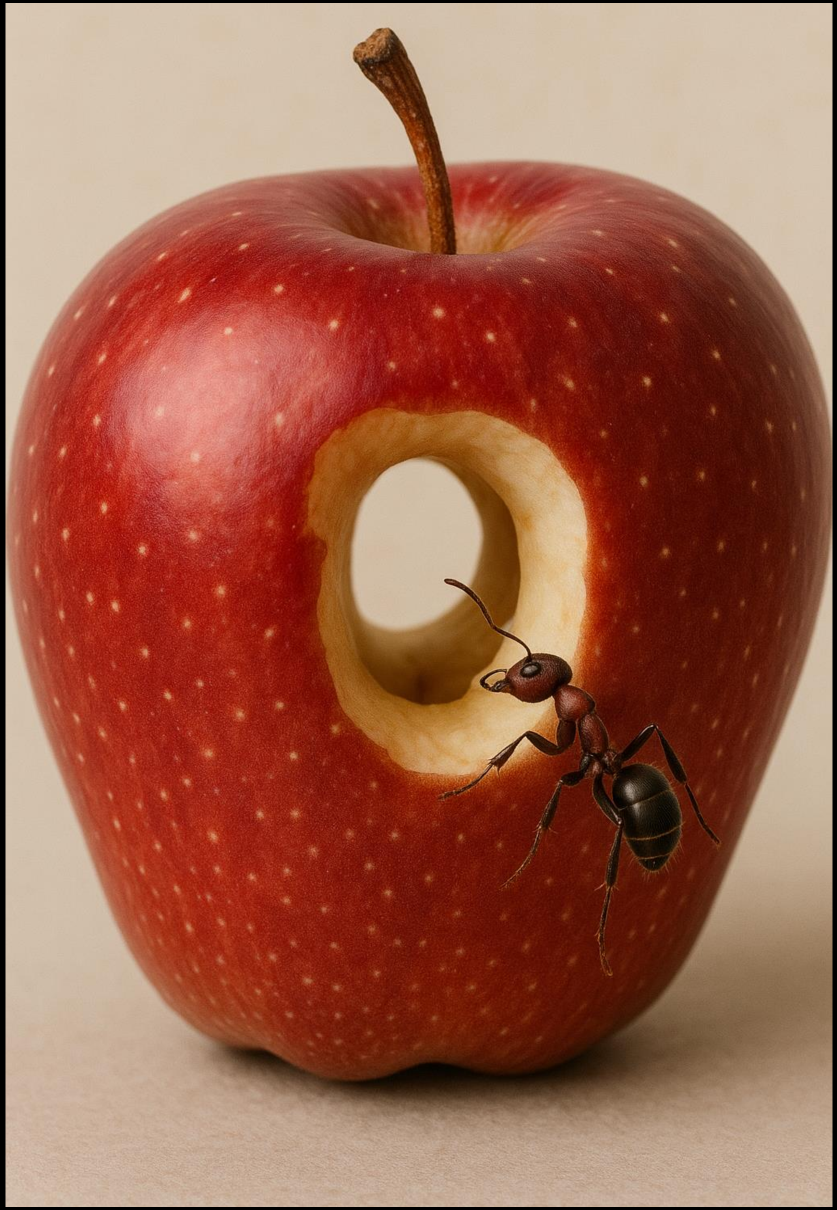
Wormholes

John Wheeler was the first to coin the term ‘*Wormhole*’.

The origin of this term comes from the analogy of an insect, wishing to cross from one side of an apple to the other. If there is a literal *worm hole* connecting the two sides, this provides a shorter path for the ant.

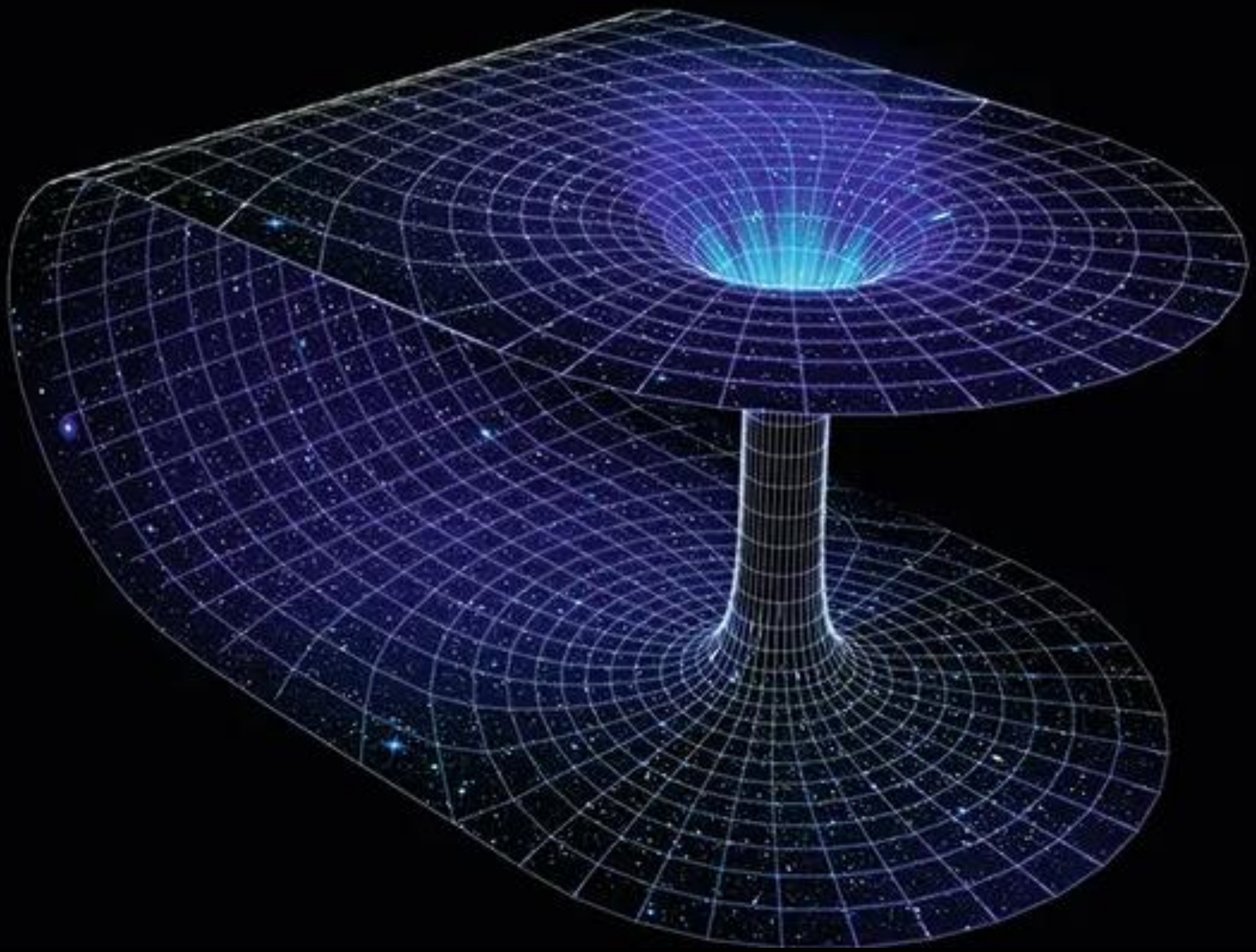


John Archibald Wheeler



Wormholes

In analogy to the literal *worm holes* found in apples (the most consequential fruit in the history of science), astrophysical wormholes would provide shortcuts from one point in 4D space time, to another point in 4D space time by ‘cutting through’ some higher dimensional bulk space.



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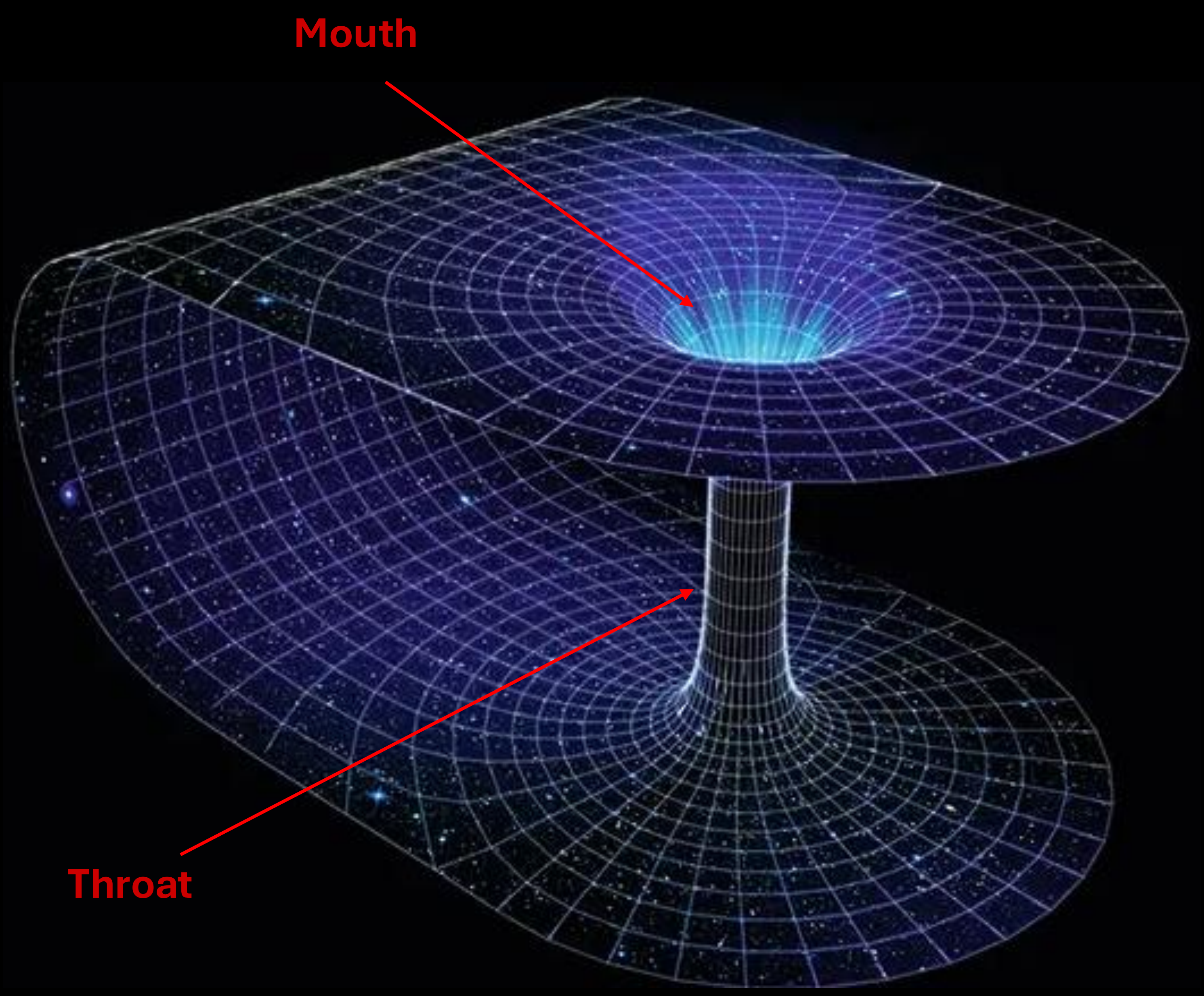


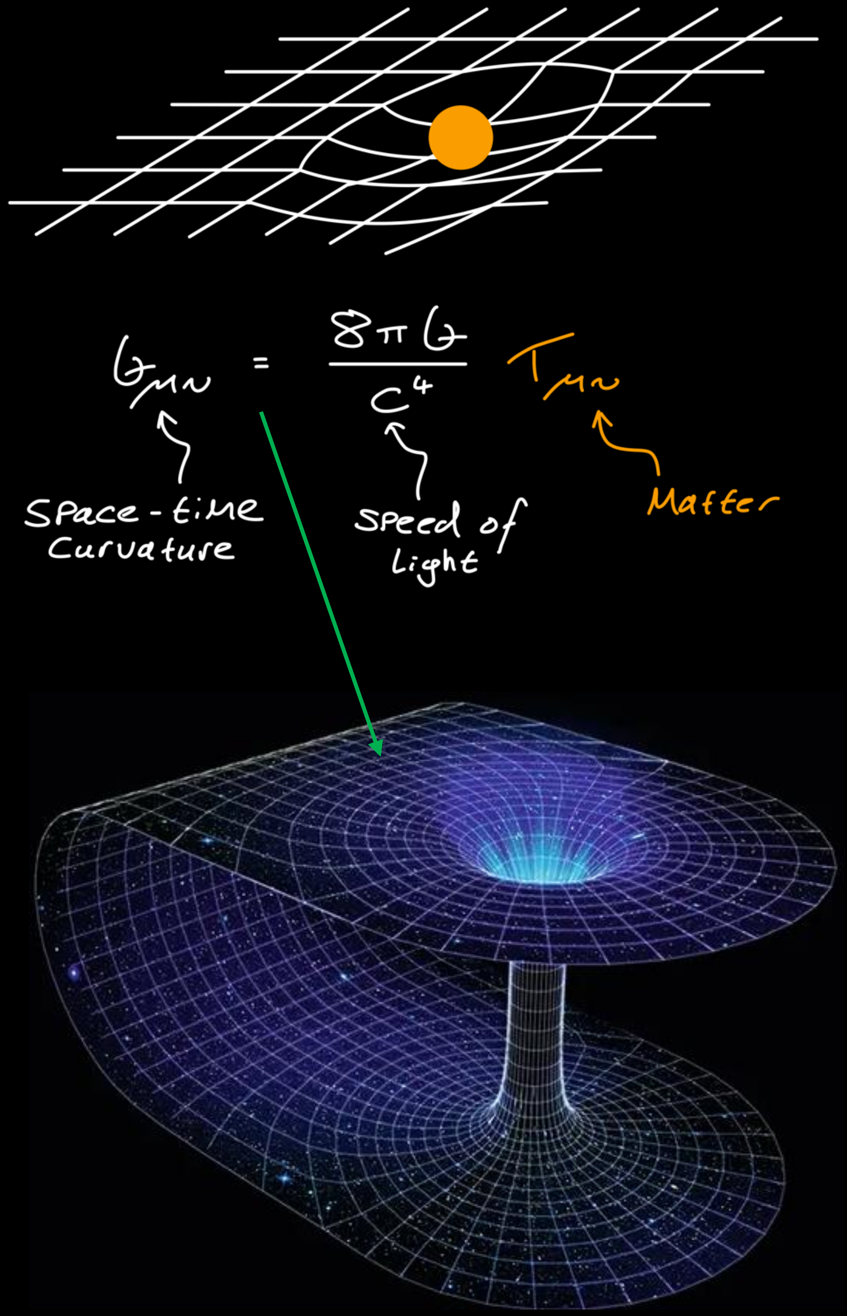
Wormholes

Wormholes aren't just based on a hunch...

They arise as natural solutions to Einstein's equation of gravity.

First noted in 1916 by Ludwig Flamm, they were picked up again in 1935 by Einstein and Nathan Rosen, who speculated about the physical meaning of this abstract mathematical solution.

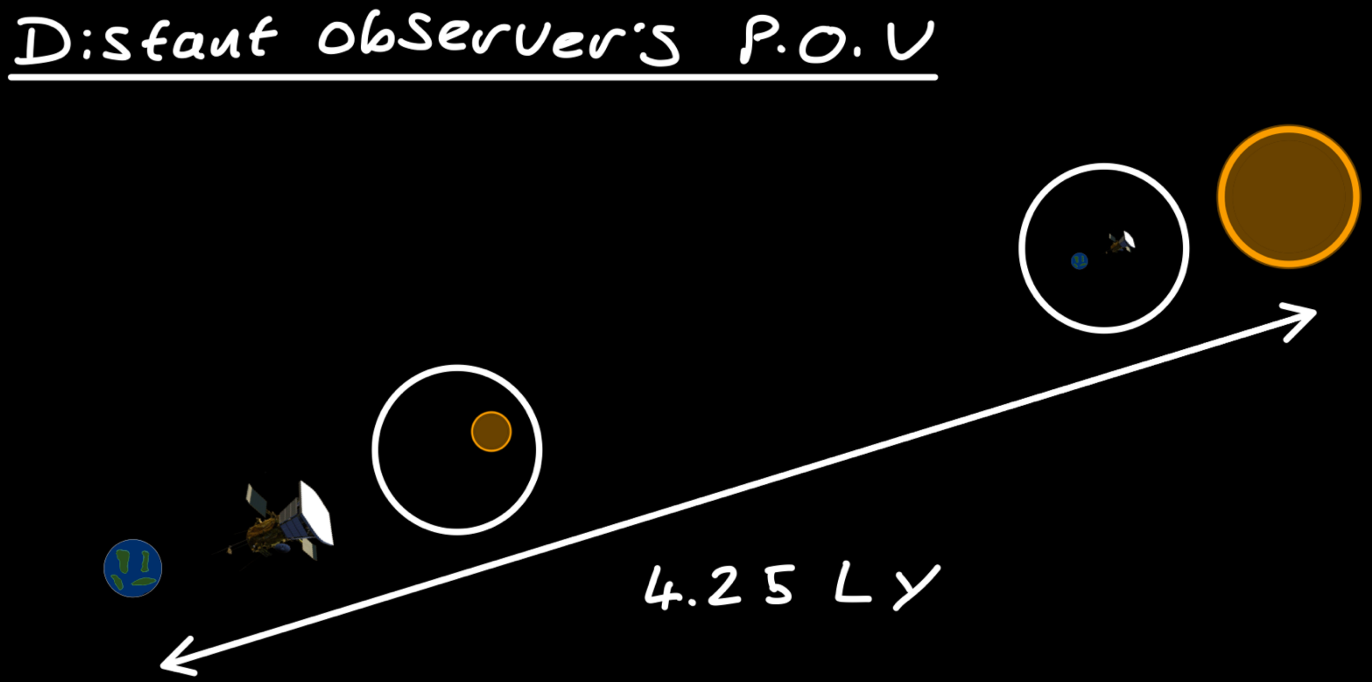
Ludwig Flamm



Wormholes

Returning to Proxima Centauri…

Wormholes might provide shortcuts between distantly connected regions of space.

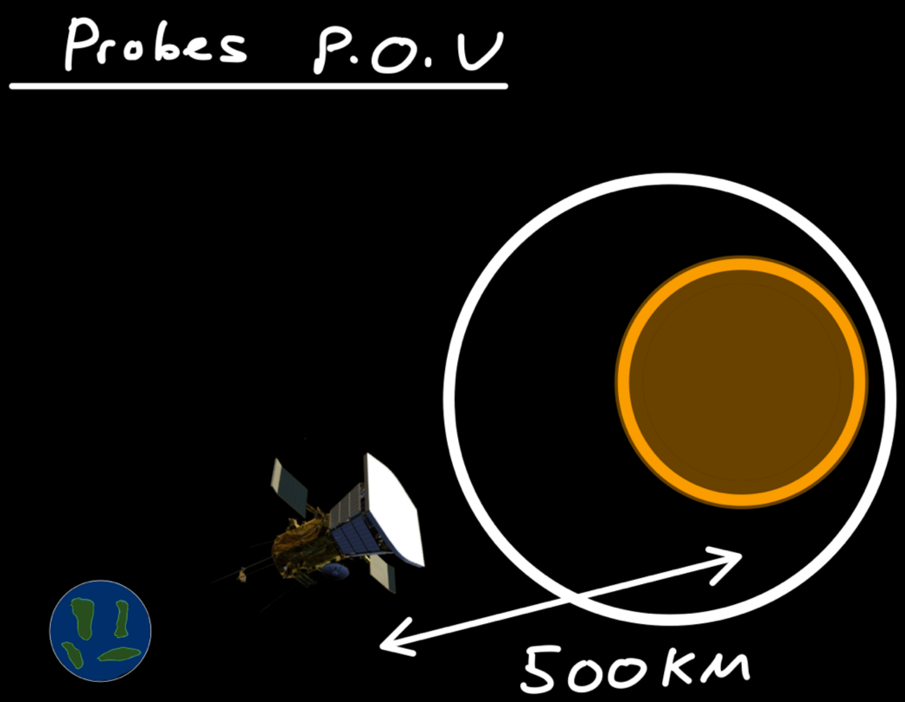


Wormholes

Returning to Proxima Centauri…

Wormholes might provide shortcuts between distantly connected regions of space.

Allowing great distances to be traversed more quickly, via the shortcut of a wormhole.



Exotic Matter Again…

Unfortunately… if wormholes exist, they cannot stay open for long enough for anything to pass through…

Creating a *Traversable Wormhole*, that could be passed through again requires negative energy densities!

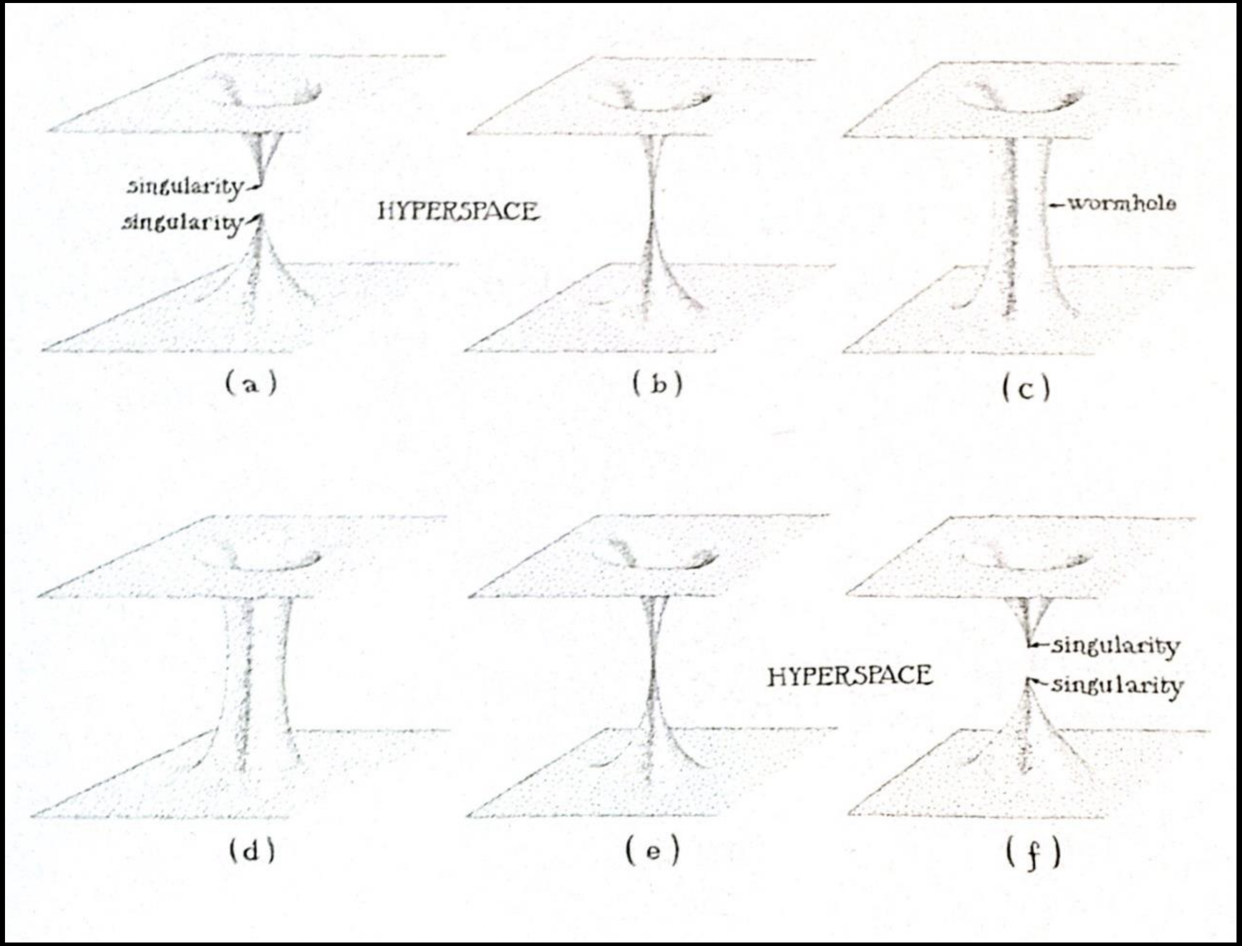


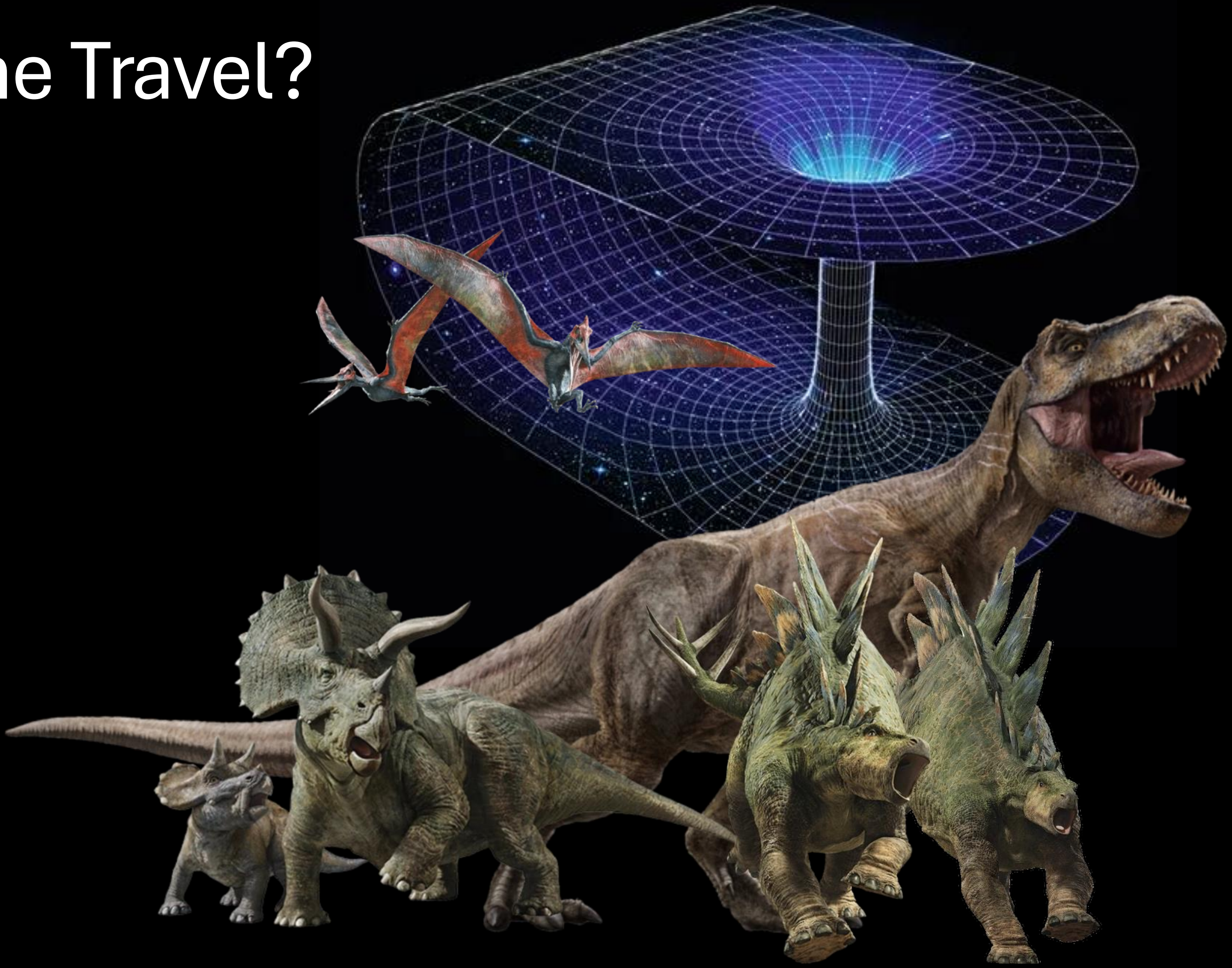
Figure from ‘Time Travel and Wormholes’ – Kip Thorne

Backwards Time Travel?

This probably isn't possible…

Einstein's theory of gravity (General Relativity) leaves open the possibility of Wormholes, which might connect different regions of space (and moments of time).

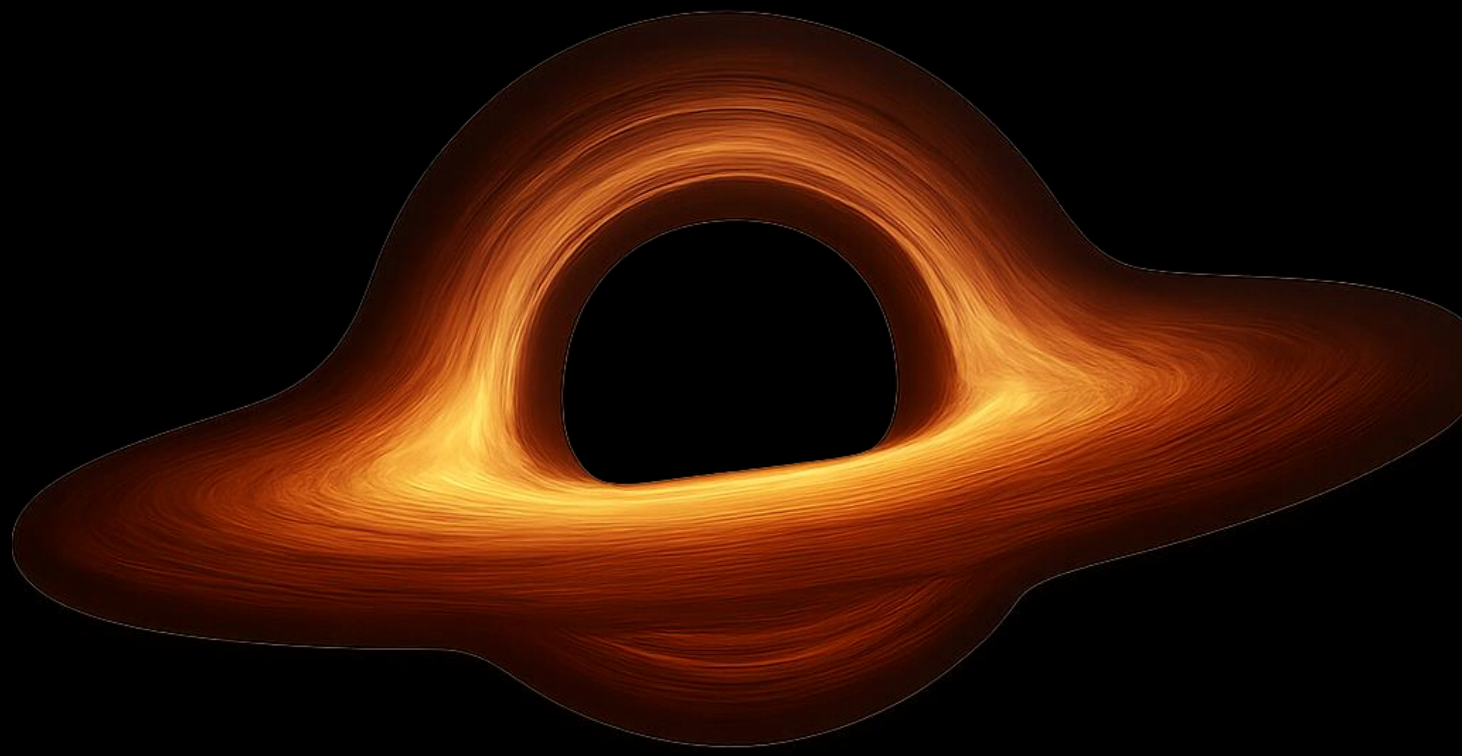
It's thought that when we find the complete theory of Quantum Gravity, something in this theory will rule out backwards time travel.



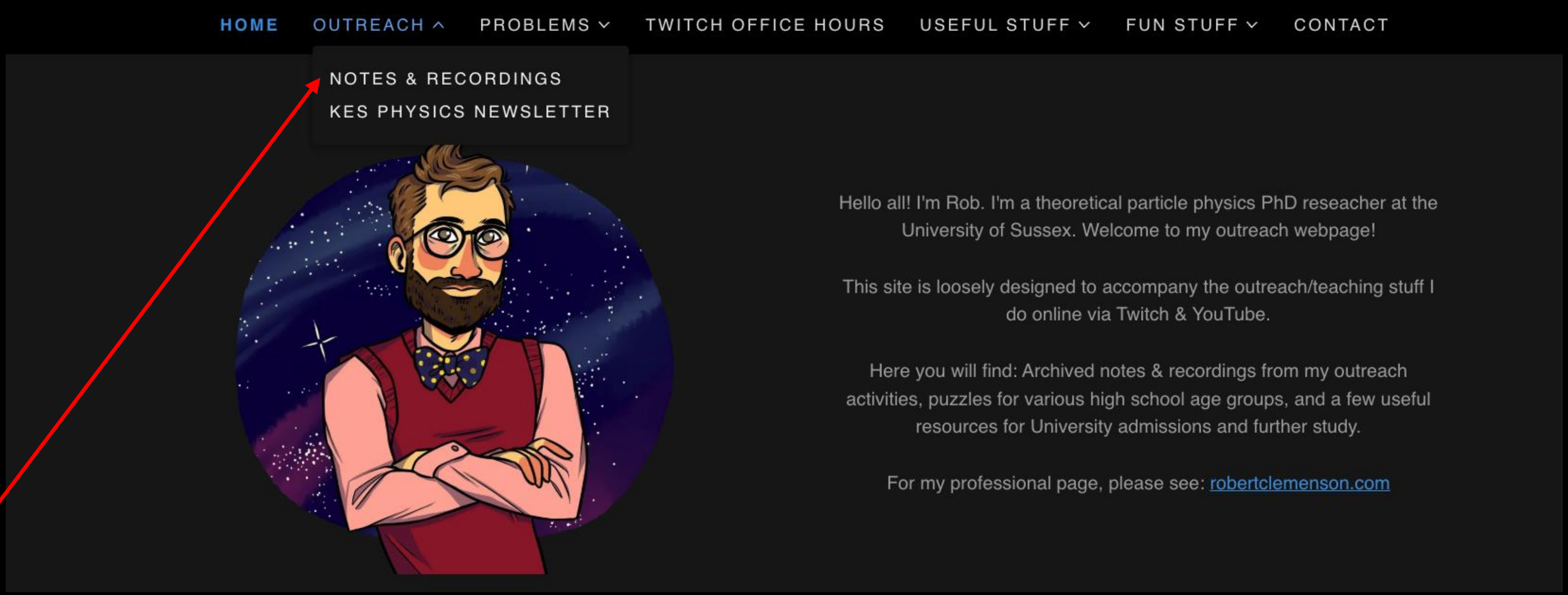
Questions!

Coming Up...

Watch this space!



Lecture Slides



These lecture slides are available on my outreach website:

CosmicConundra.com