Time Travel 101

The Science of Space:

‘A Physicists Guide to the Galaxy’

Robert Clemenson

(Sussex U & Royal Holloway UoL)

Southend Planetarium – 18.05.2025

Lecture Overview

- Newton’s Laws of Motion
- Galilean Relativity
- Maxwell’s Equations of Electromagnetism
- Einsteins Postulates
- Time Dilation
- Length Contraction
- The Tunnel Paradox
- Q&A (**Questions welcome throughout the talk!**)

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.

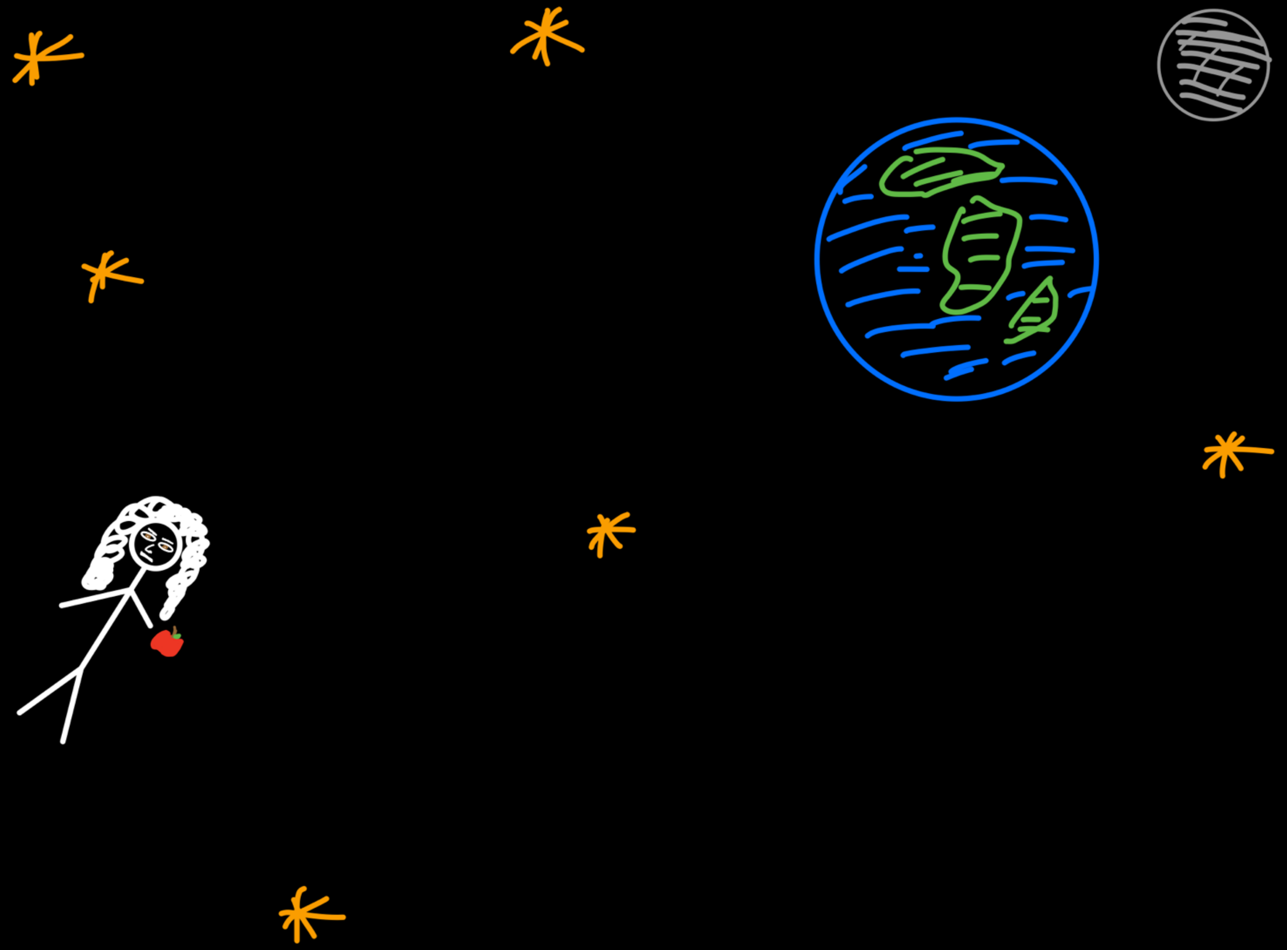
Isaac Newton, 1702.

Newton's Laws of Motion

Newton's First Law

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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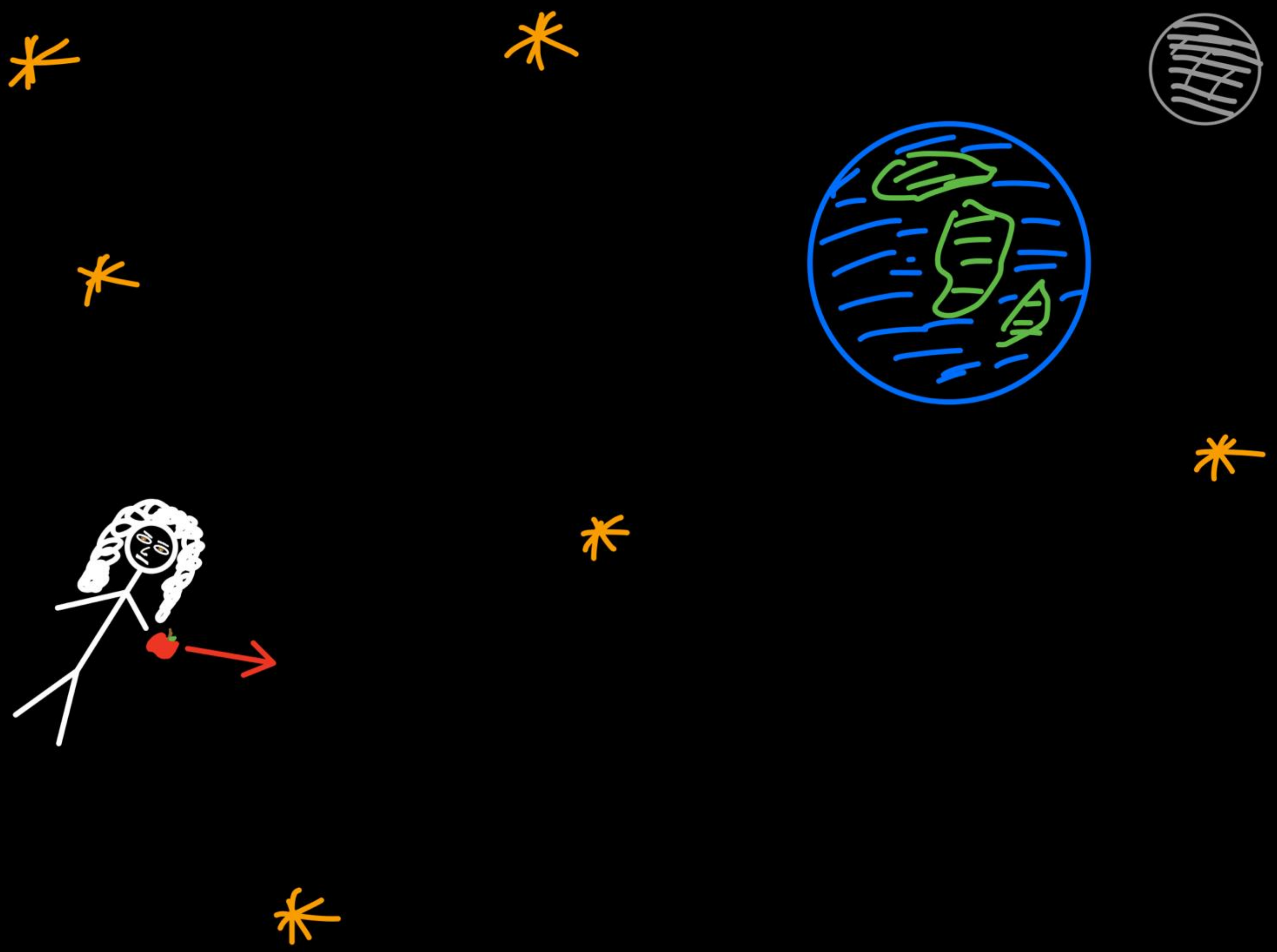

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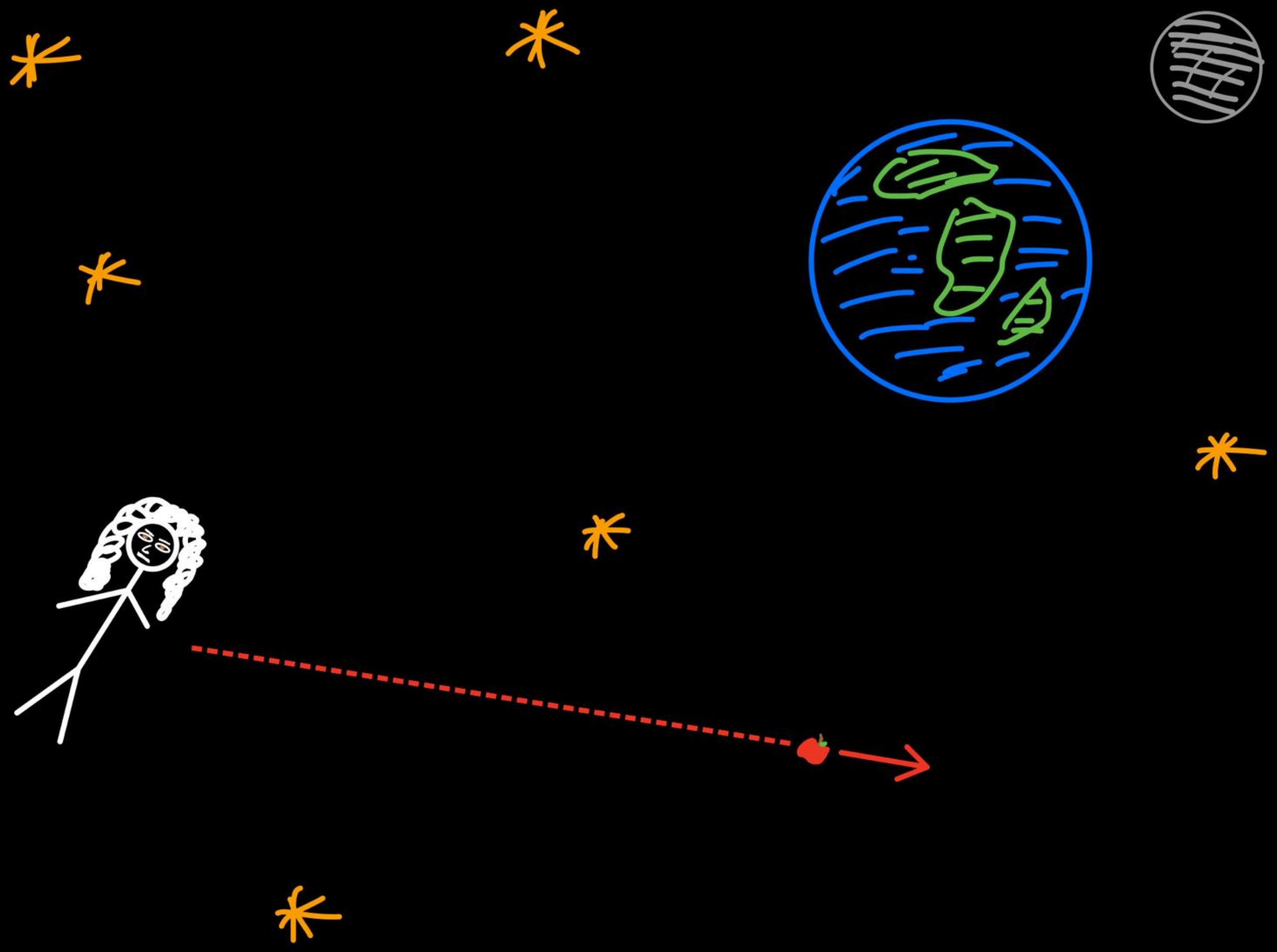

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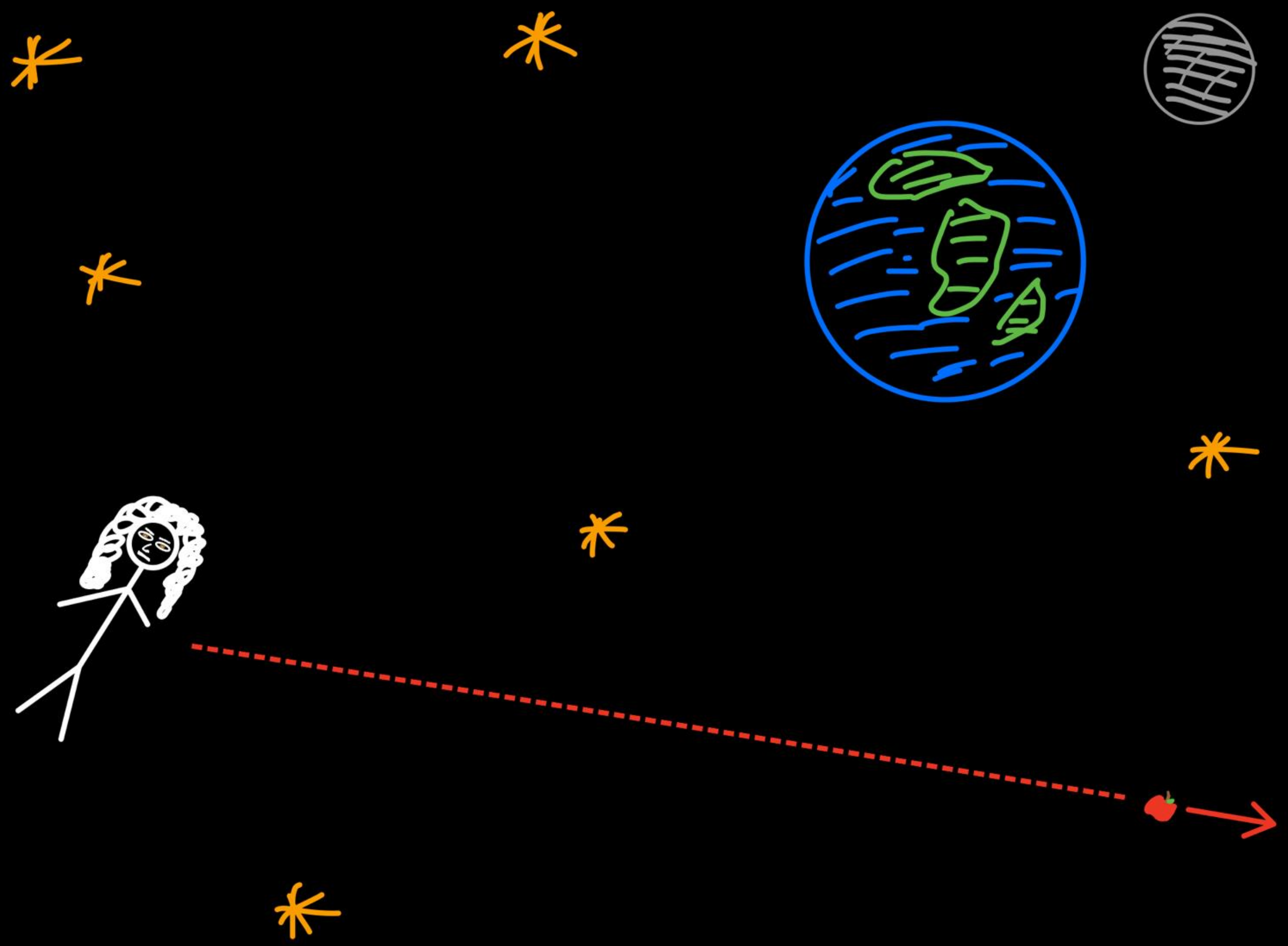

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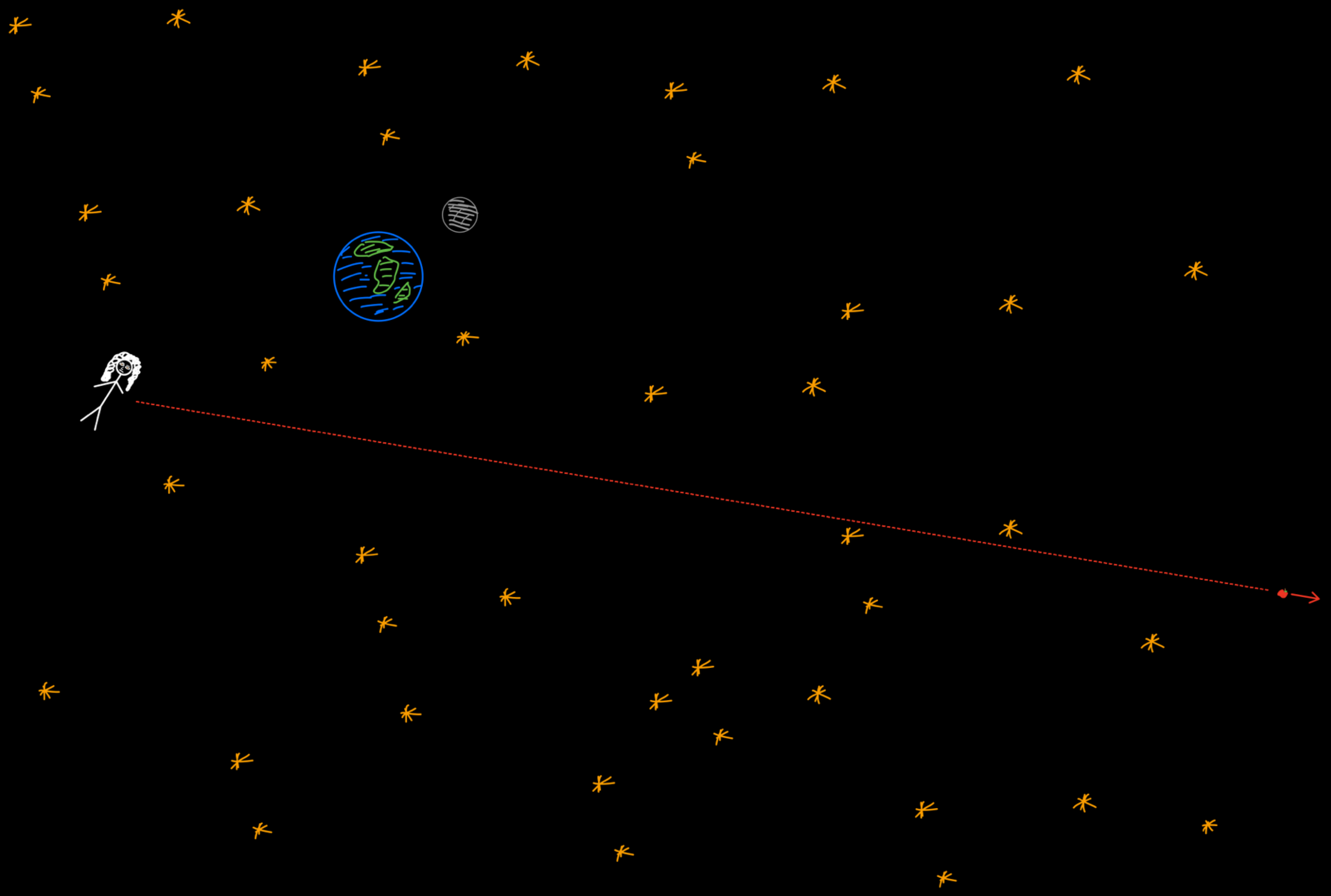
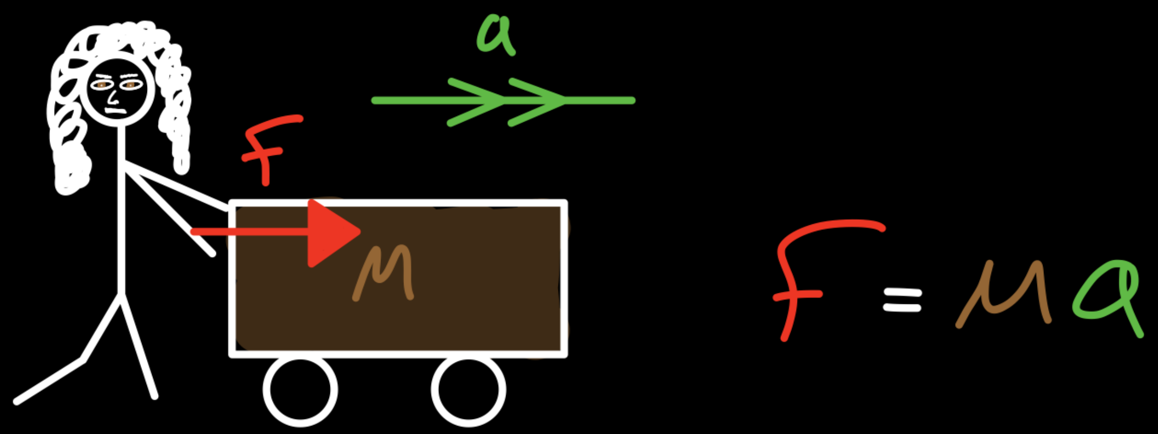


Newton's Laws of Motion

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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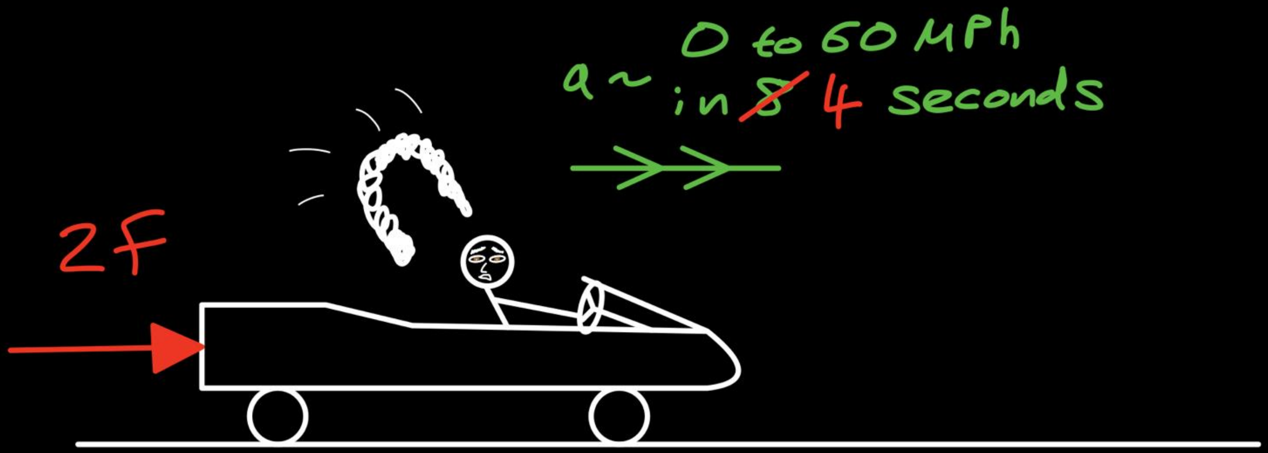

Newton’s Laws of Motion

Newton’s Third Law

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

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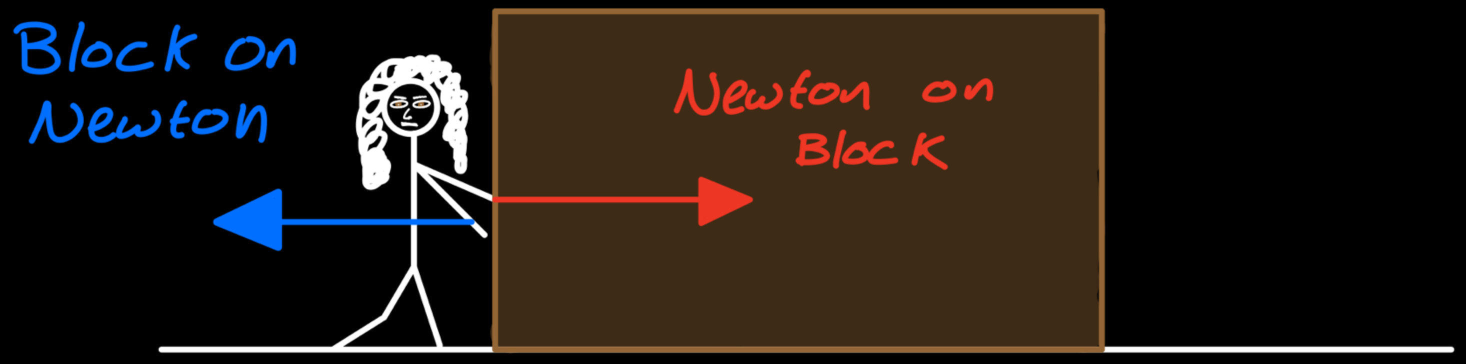
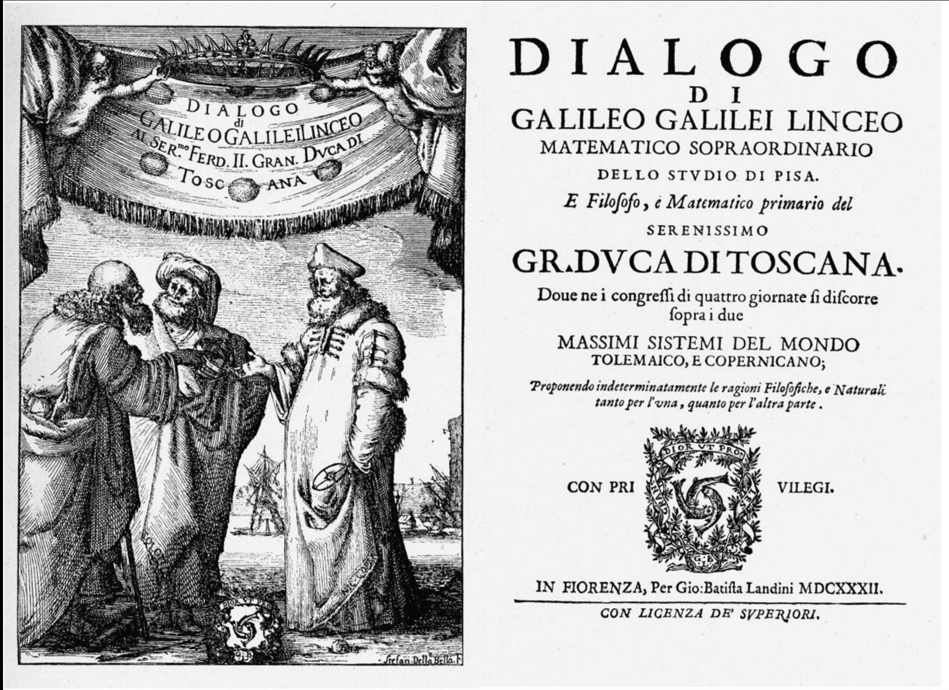


Galilean Relativity

In 1632 (ten years before Isaac Newton's birth), Galileo described his principle of relativity in his *Dialogo sopra i due massimi sistemi del mondo*.

It is this book that would see Galileo confined to house arrest for the last decade of his life, for challenging the Geocentric orthodoxy of the Catholic Church.


DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filosofo, e Matematico primario del
SERENISSIMO
GR. DVCA DI TOSCANA.
Doue ne i congressi di quattro giornate si discorre sopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
Proponendo indeterminatamente le ragioni Filosofiche, e Naturali tanto per l'una, quanto per l'altra parte.
CON PRI VILEGI.
IN FIORENZA, Per Gio: Batista Landini MDCXXXII.
CON LICENZA DE' SVPERIORI.

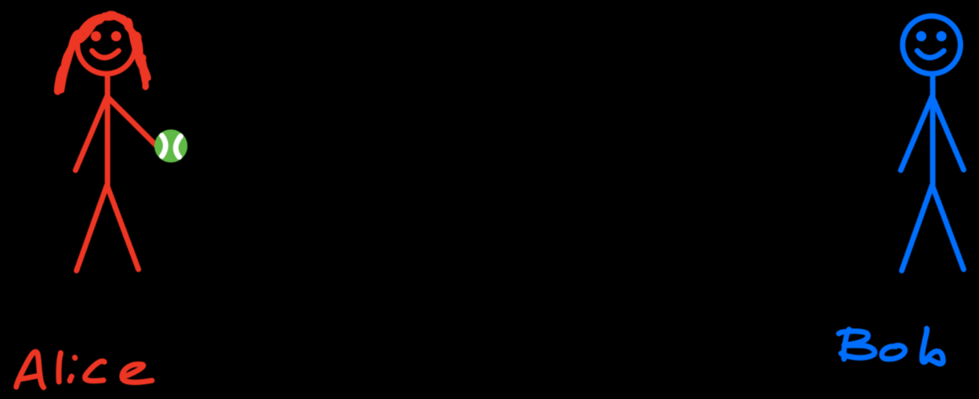
'Dialogue Concerning the Two Chief World Systems'

Galileo Galilei, 1640

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.

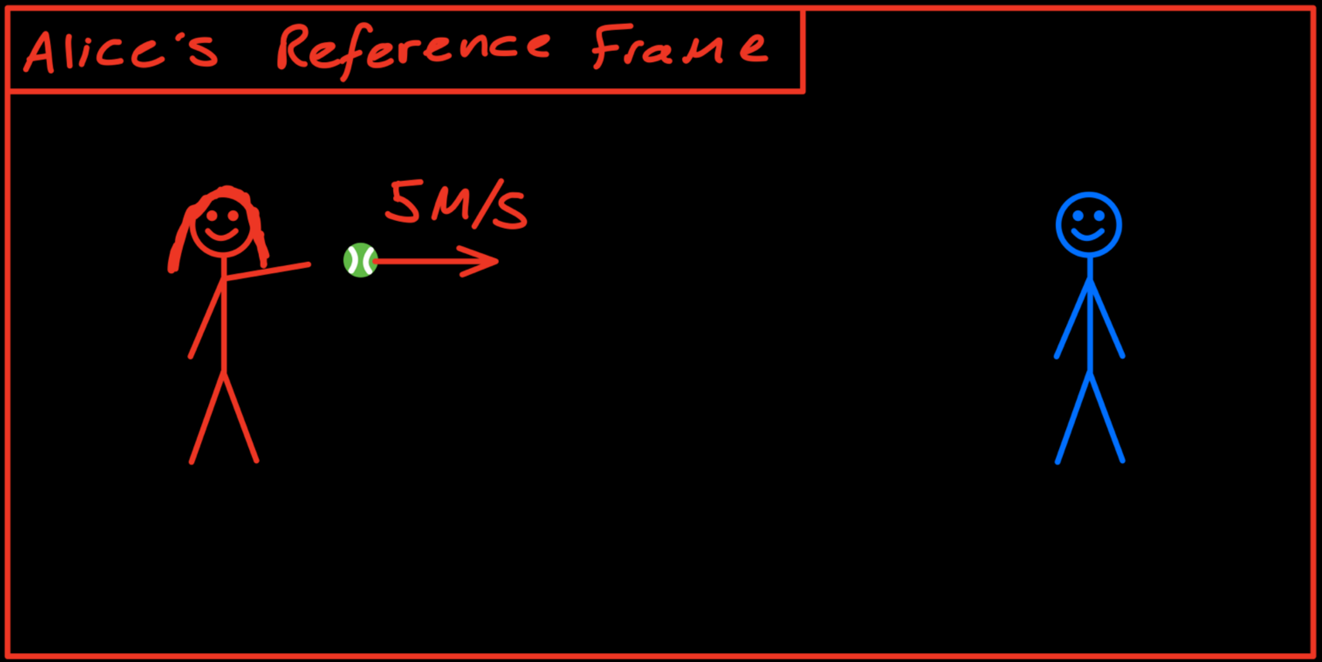
Galilean Relativity

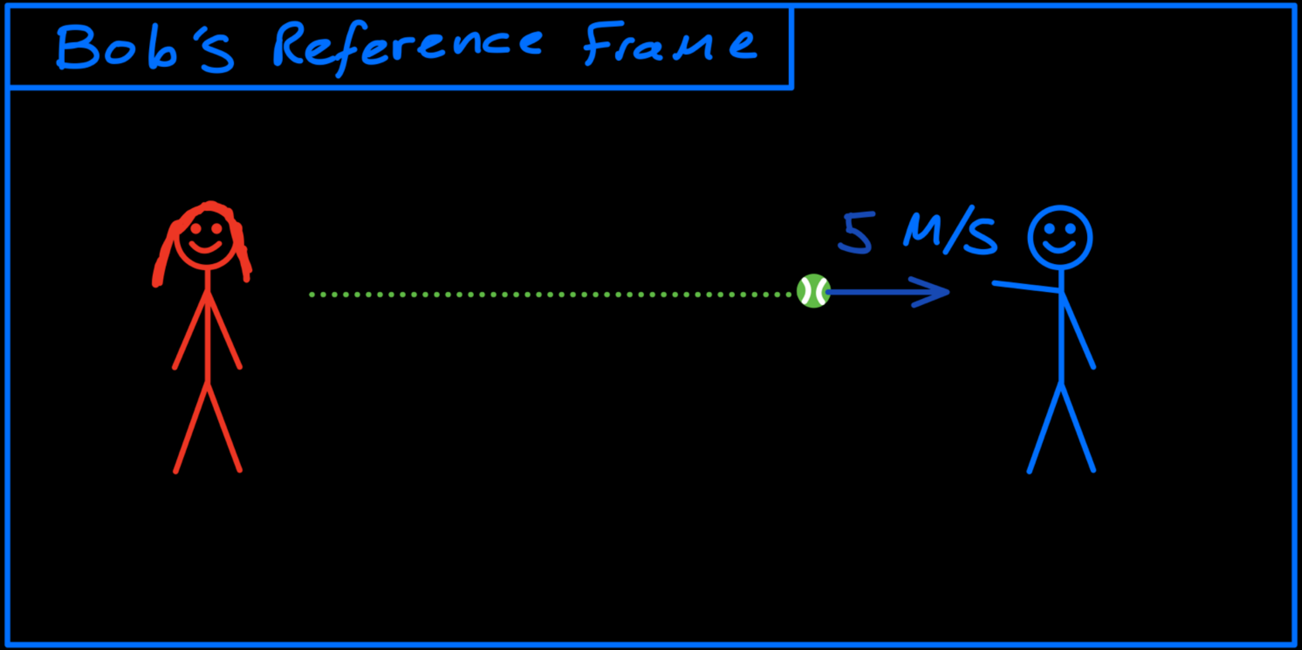
Alice throws the tennis ball towards Bob at a speed of **5 meters per second**.

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).



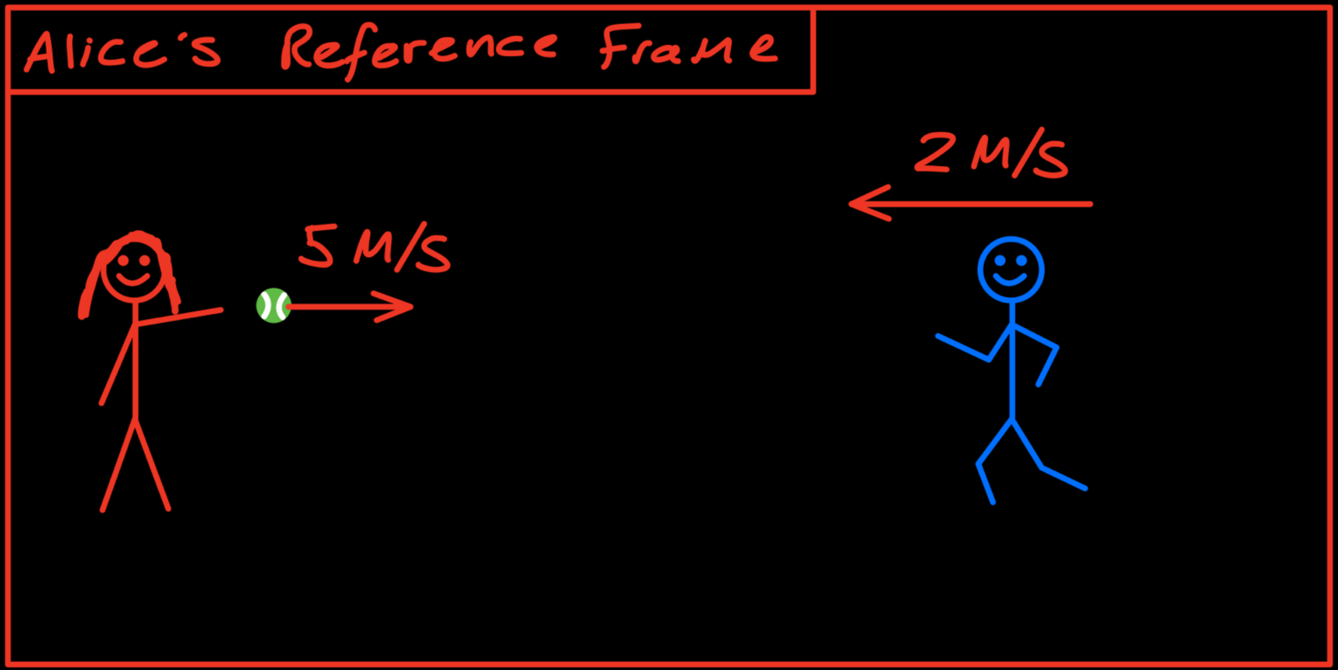


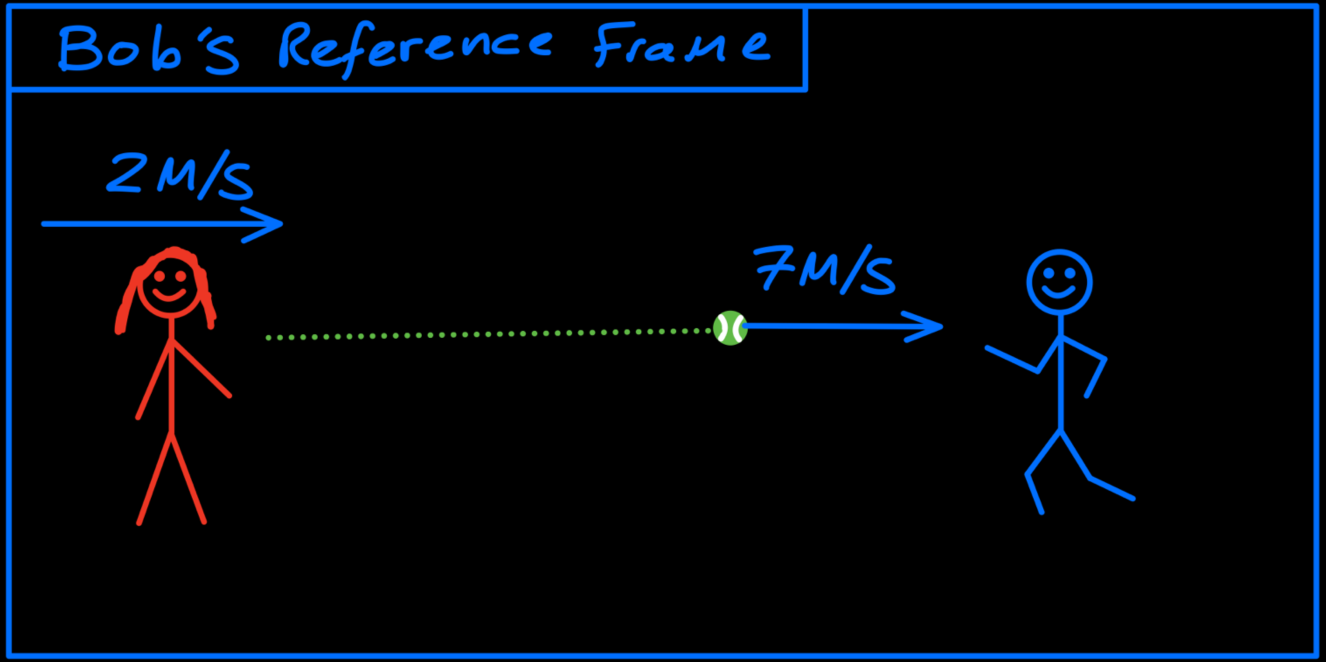
Galilean Relativity

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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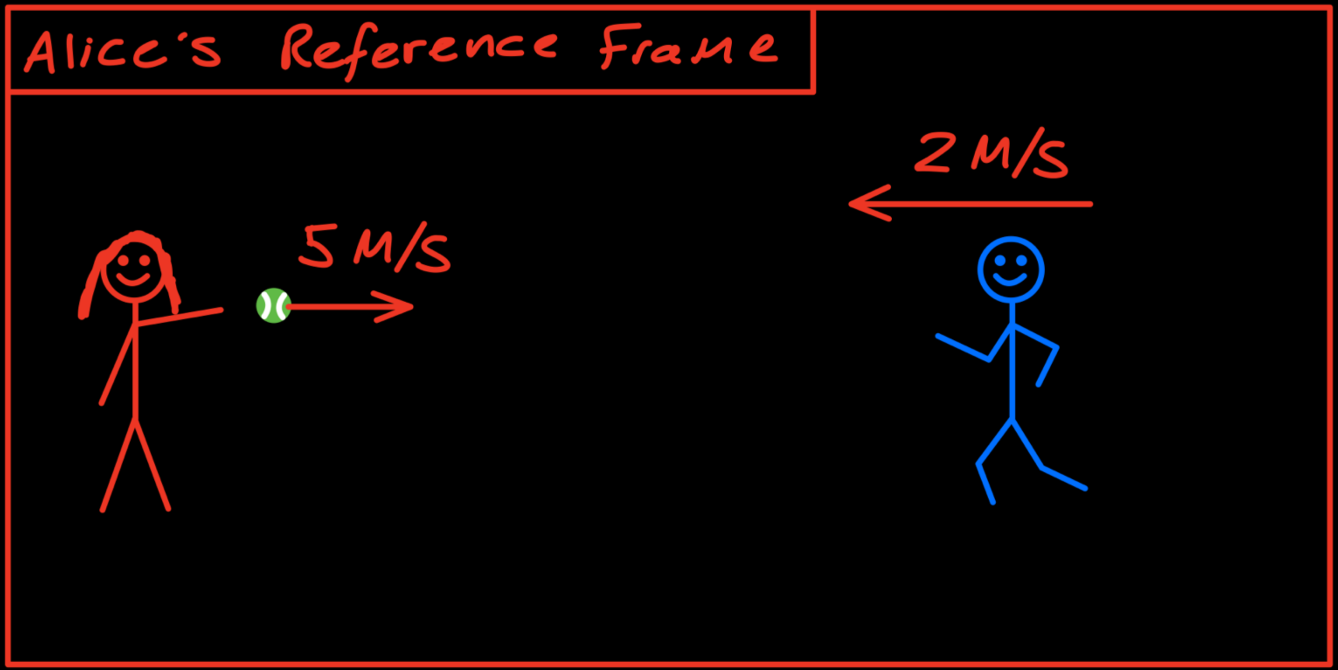
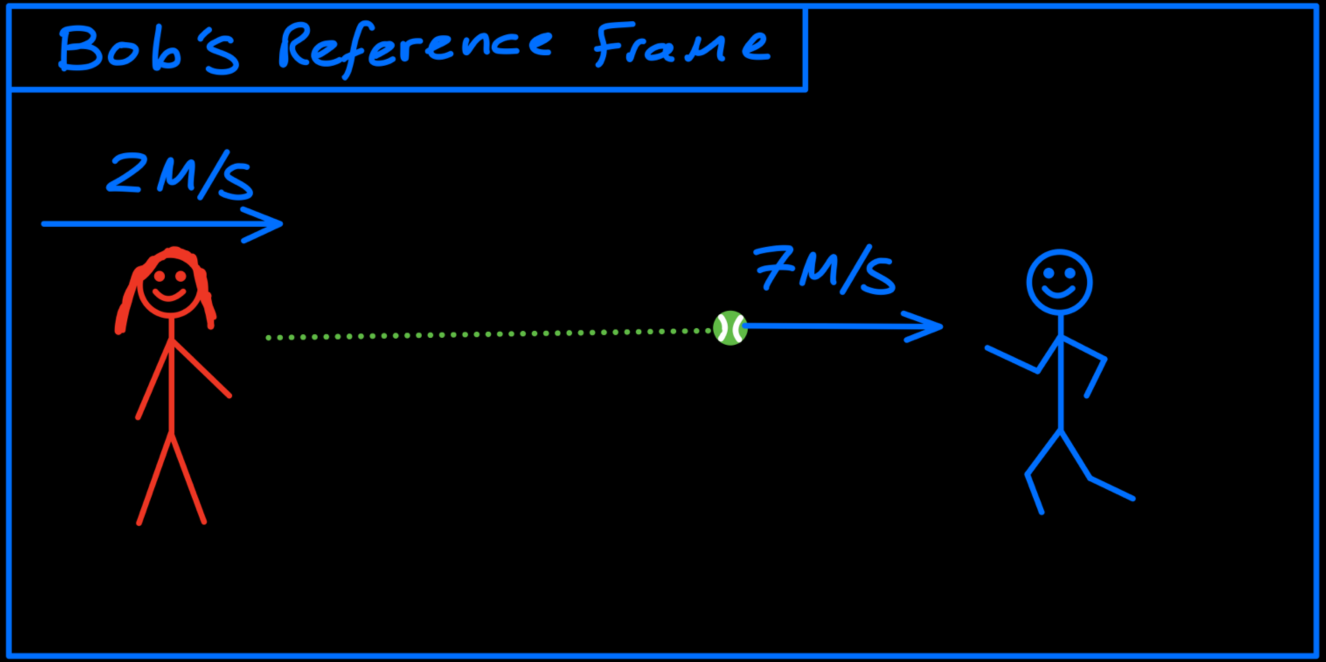
Who is correct?





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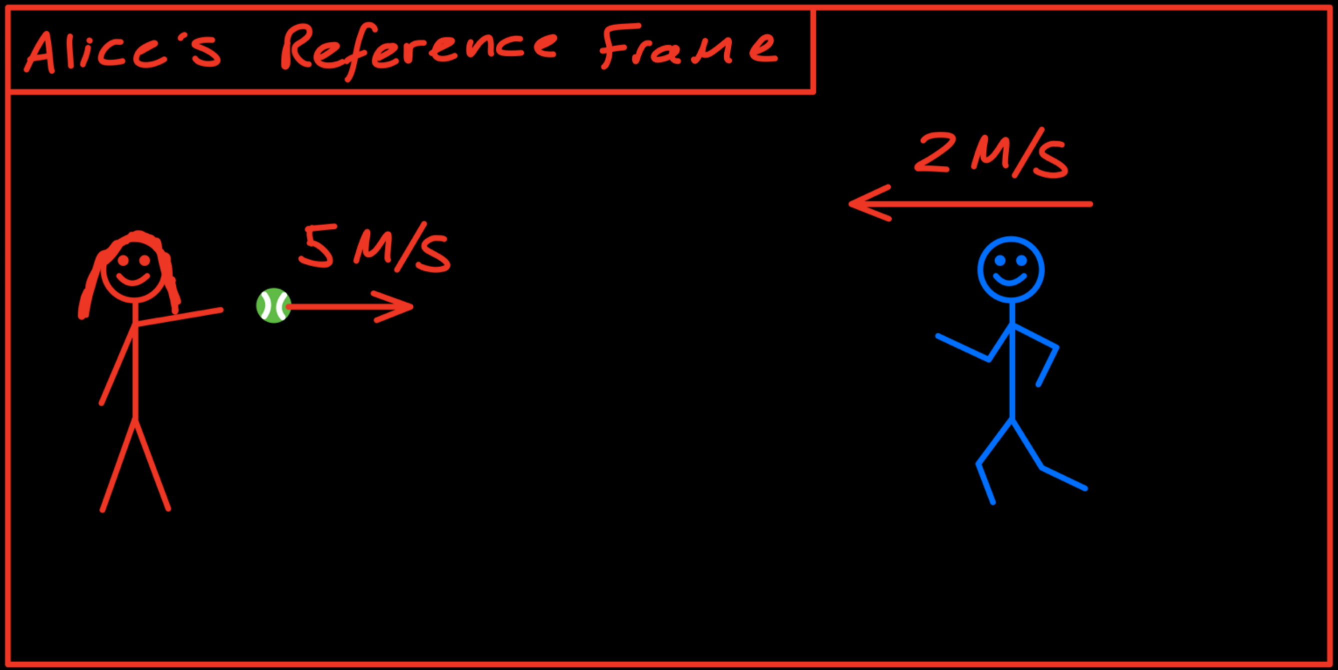
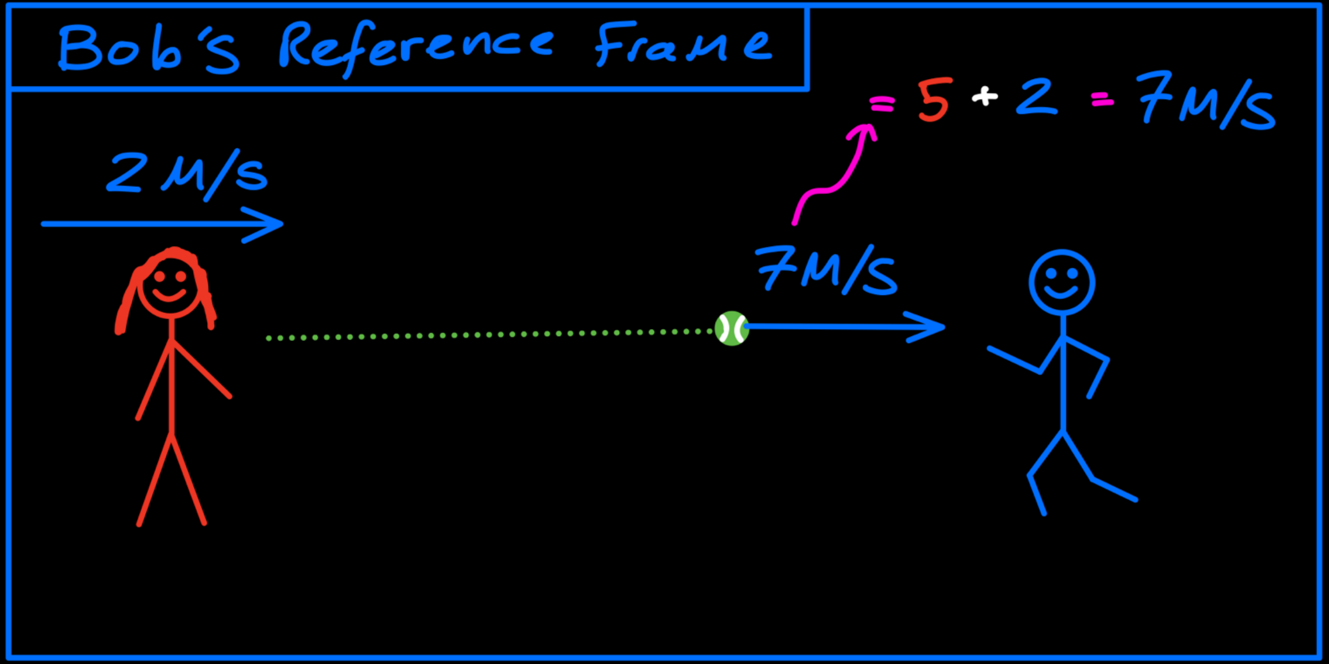
Who is correct?

Nobody is right or wrong! It's relative!

It depends who you ask.

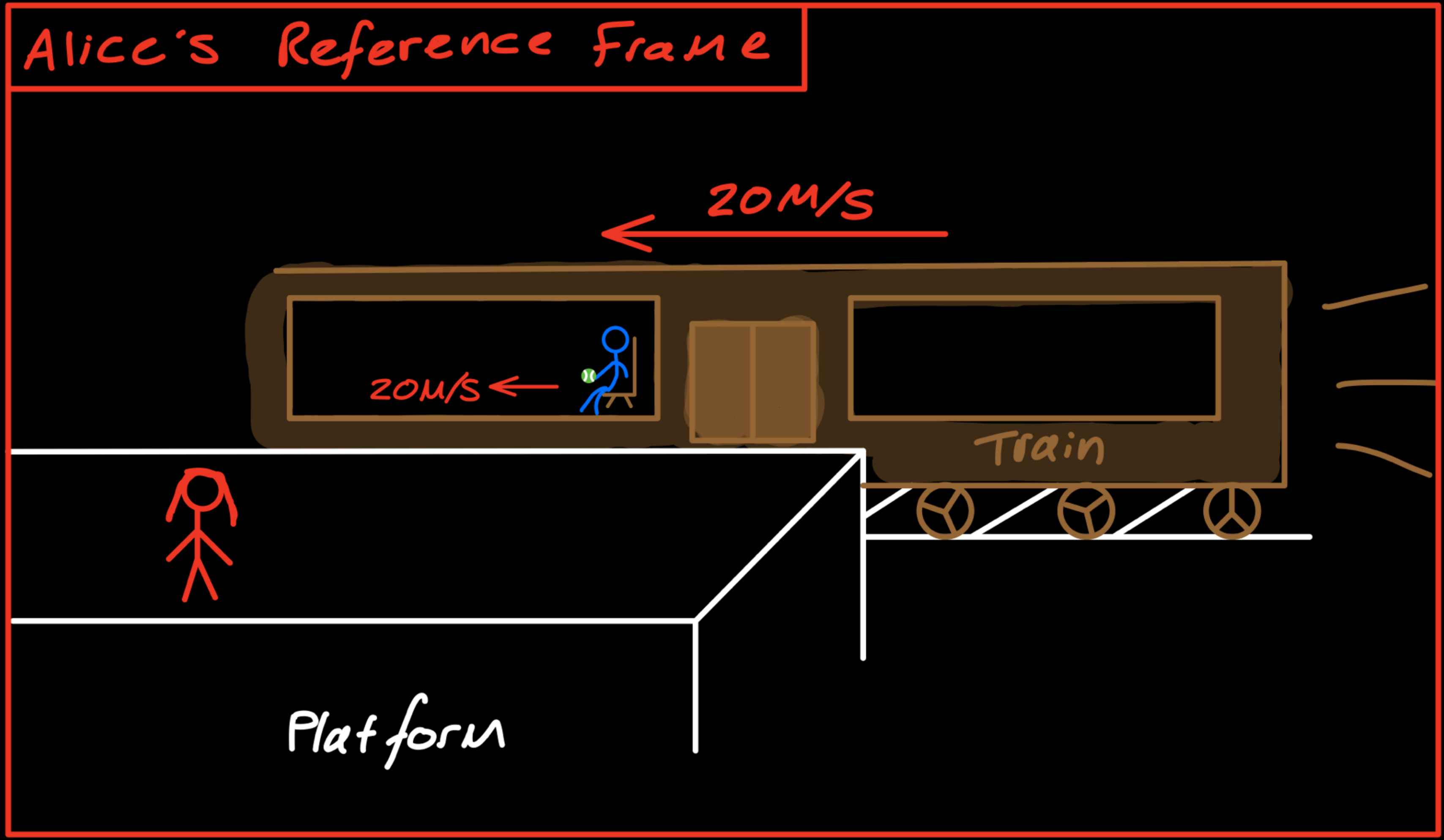




Galilean Relativity

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**.



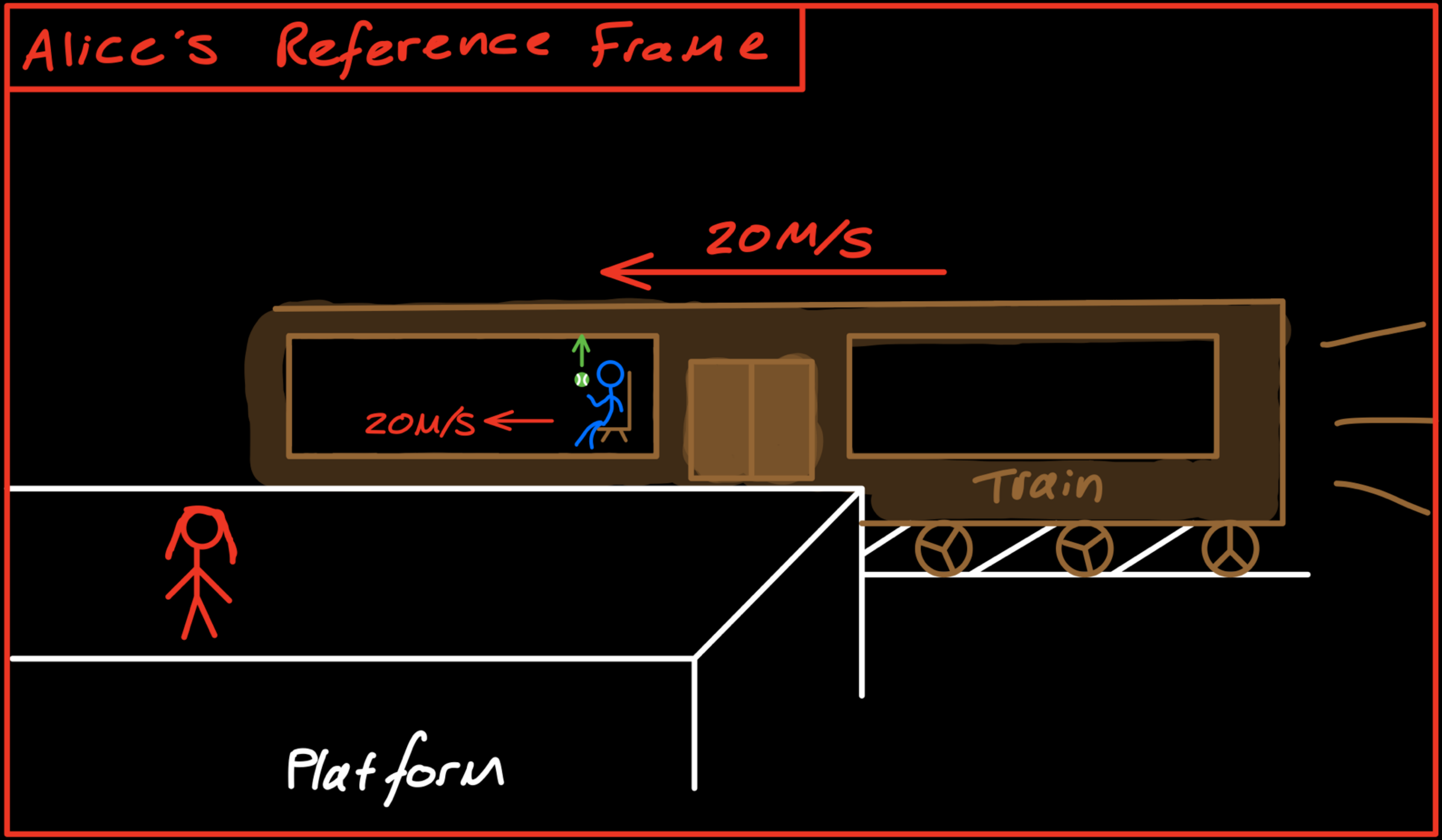
Galilean Relativity

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.

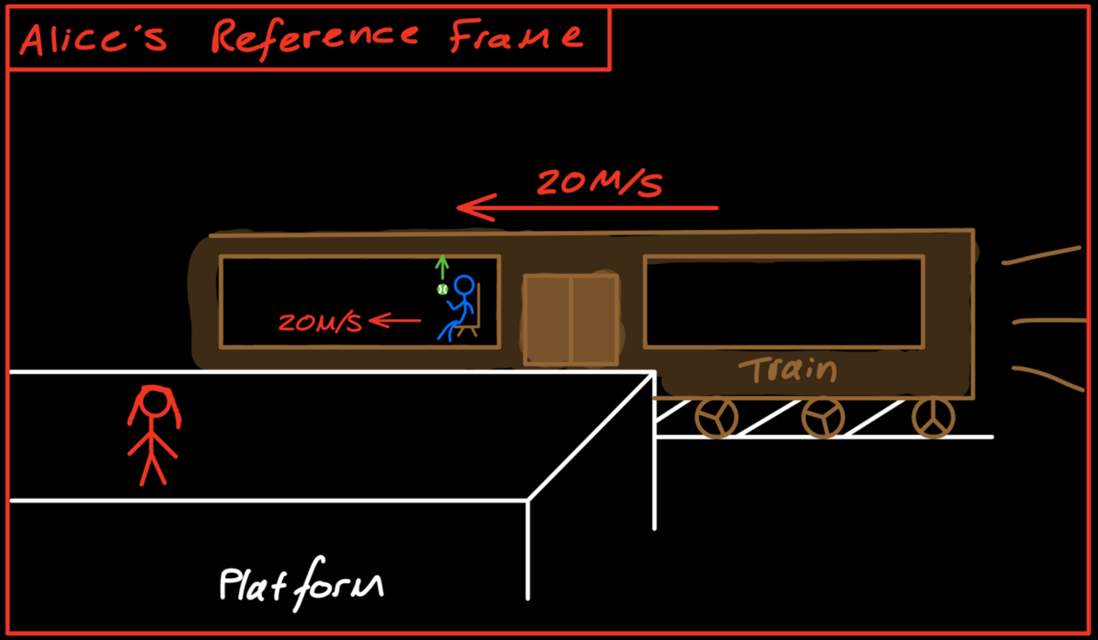
Let's consider how this appears to both observers.

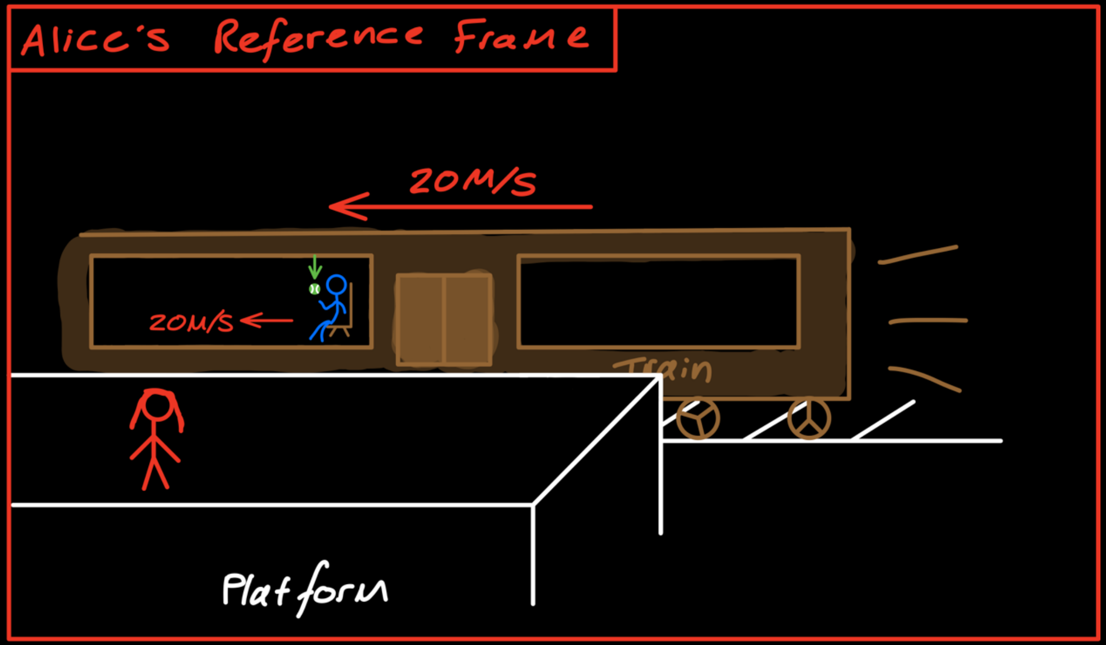


Galilean Relativity

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.

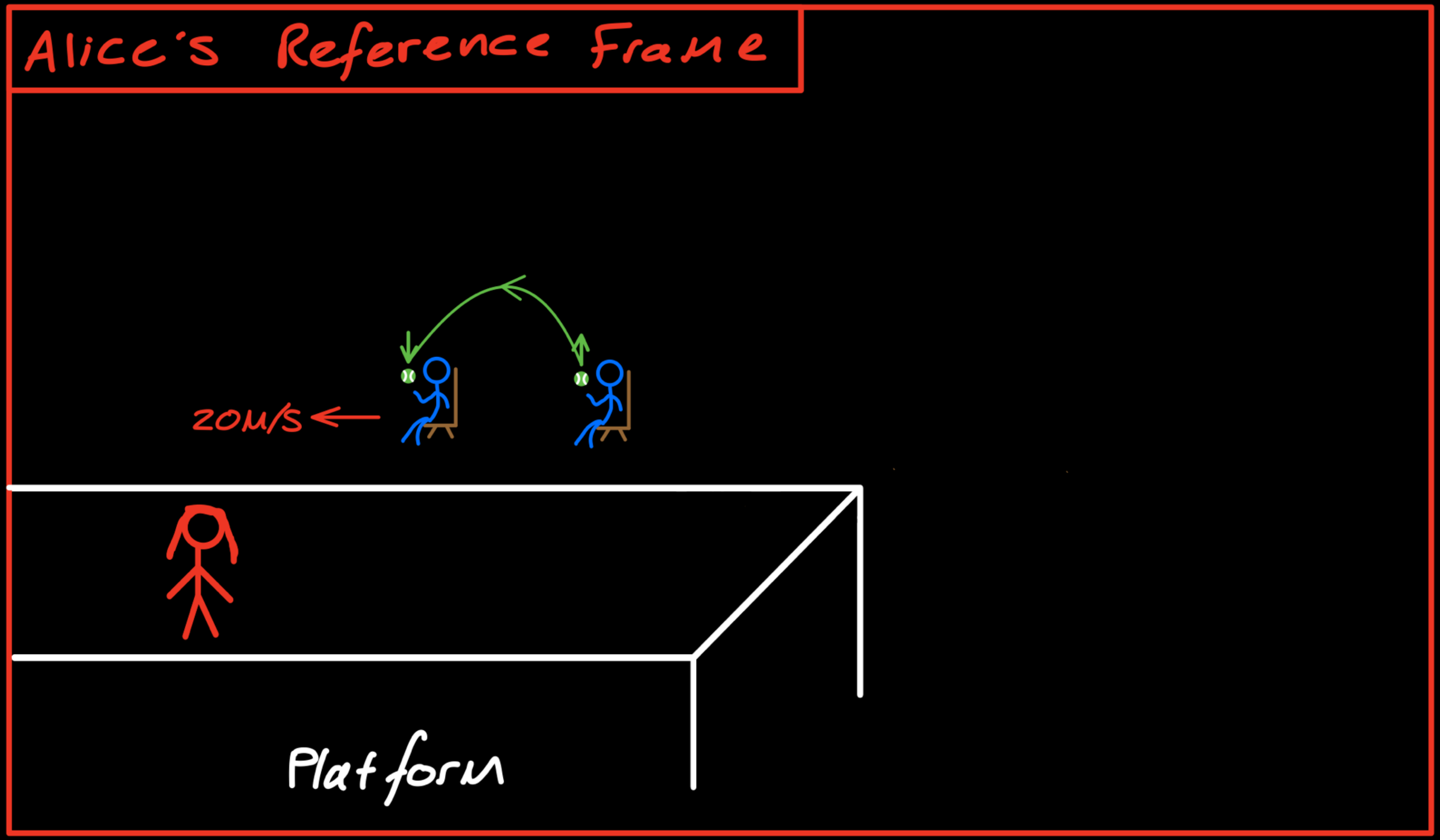
The tennis ball moves along with the train, across the platform.





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.



Galilean Relativity

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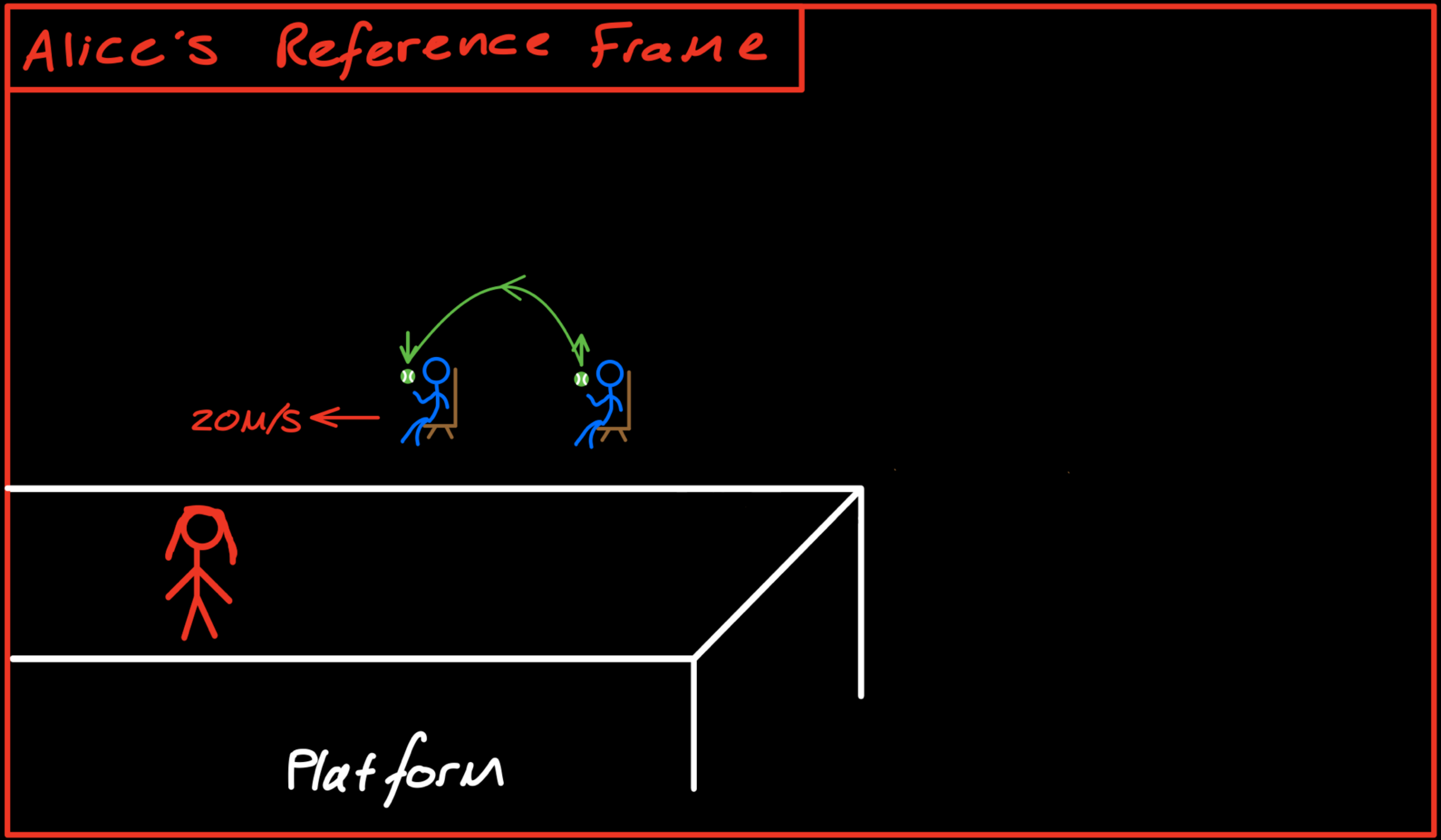
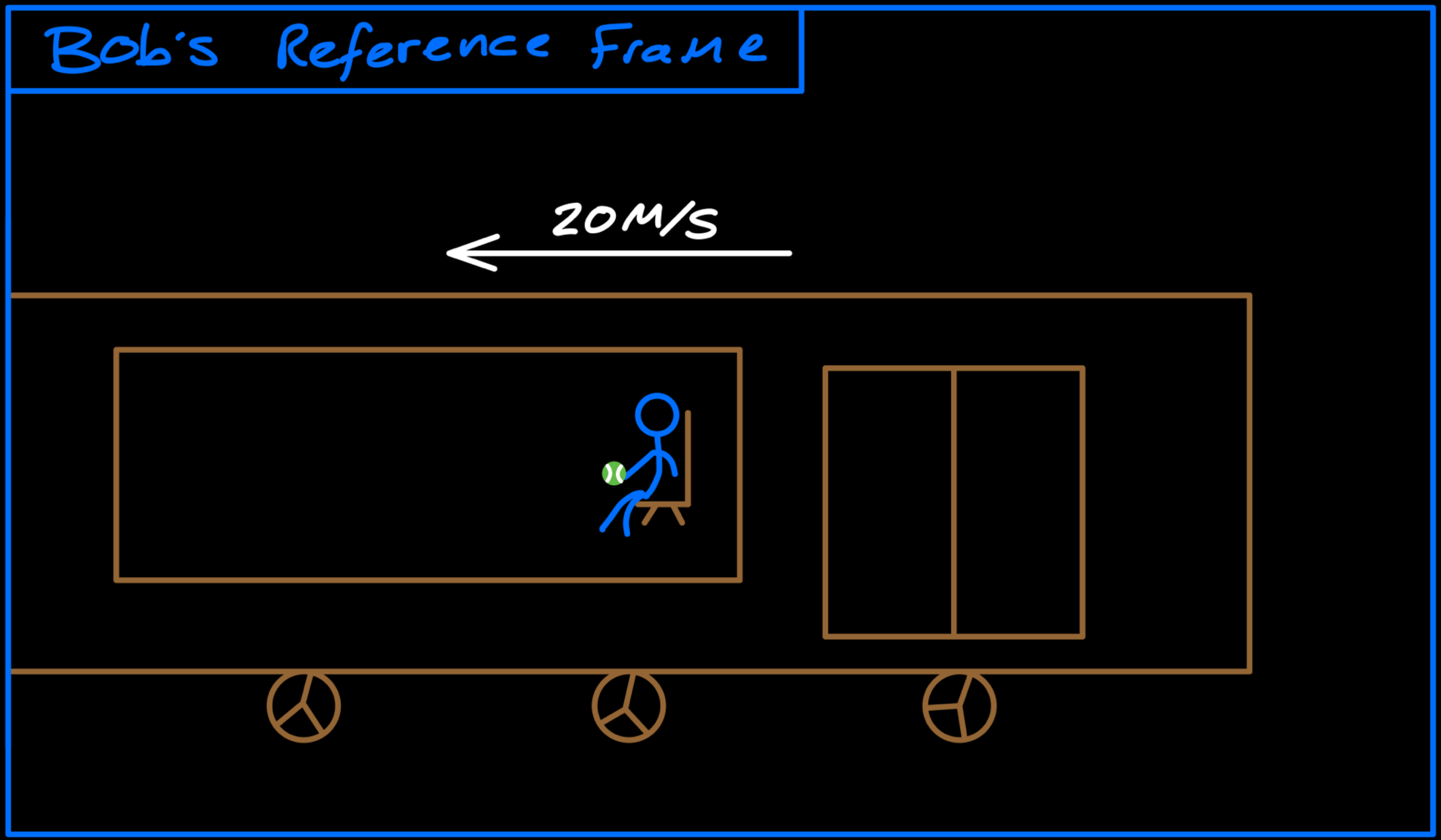
What does Bob see?



Galilean Relativity

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

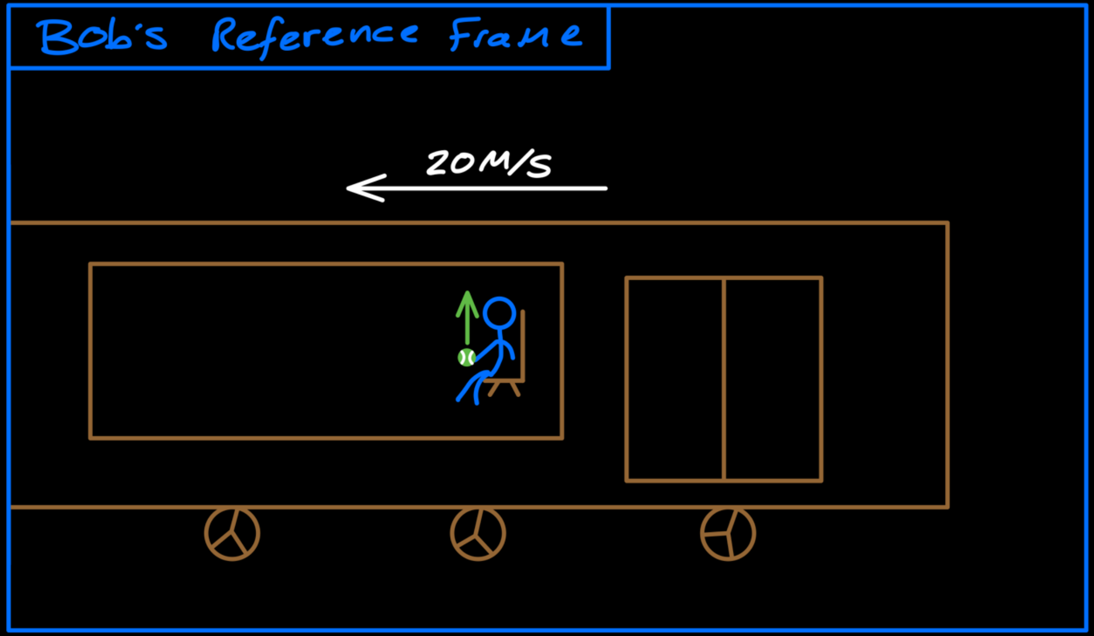


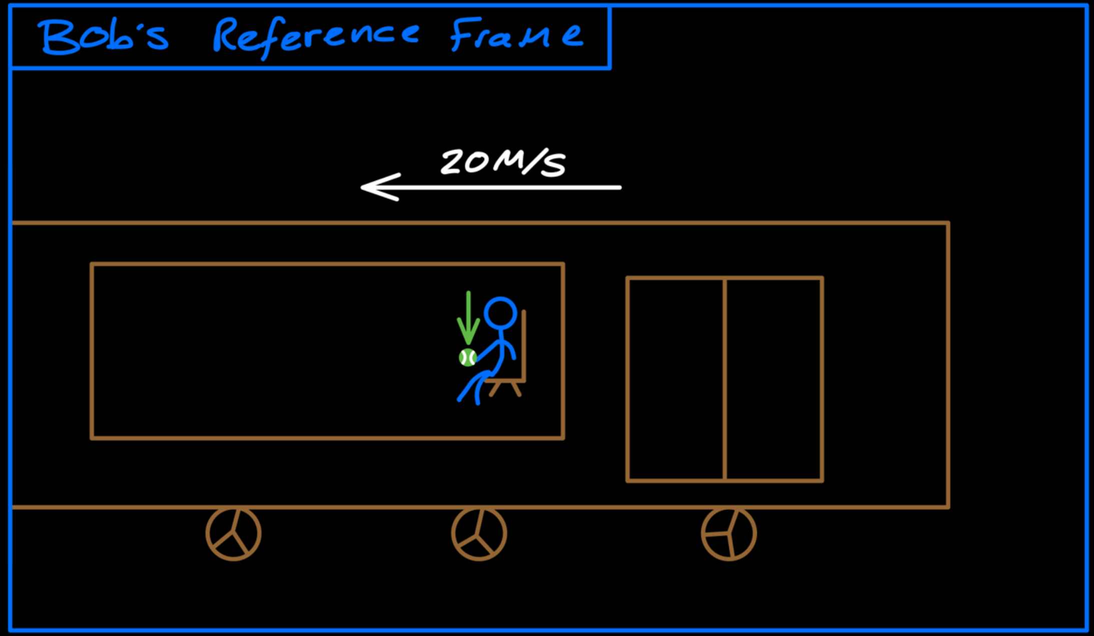
Galilean Relativity

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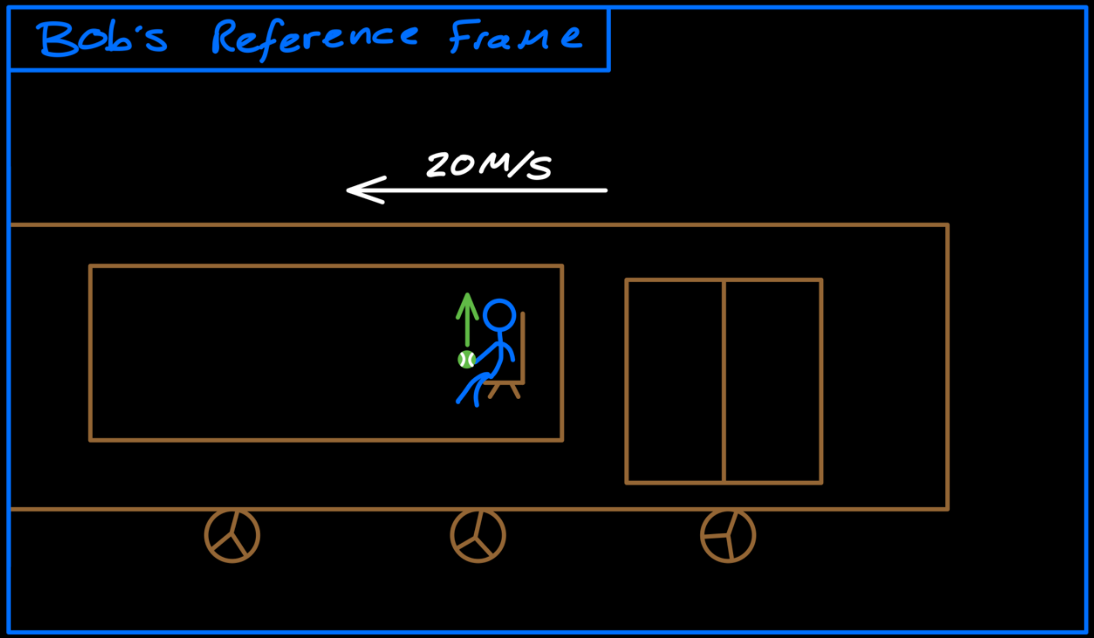
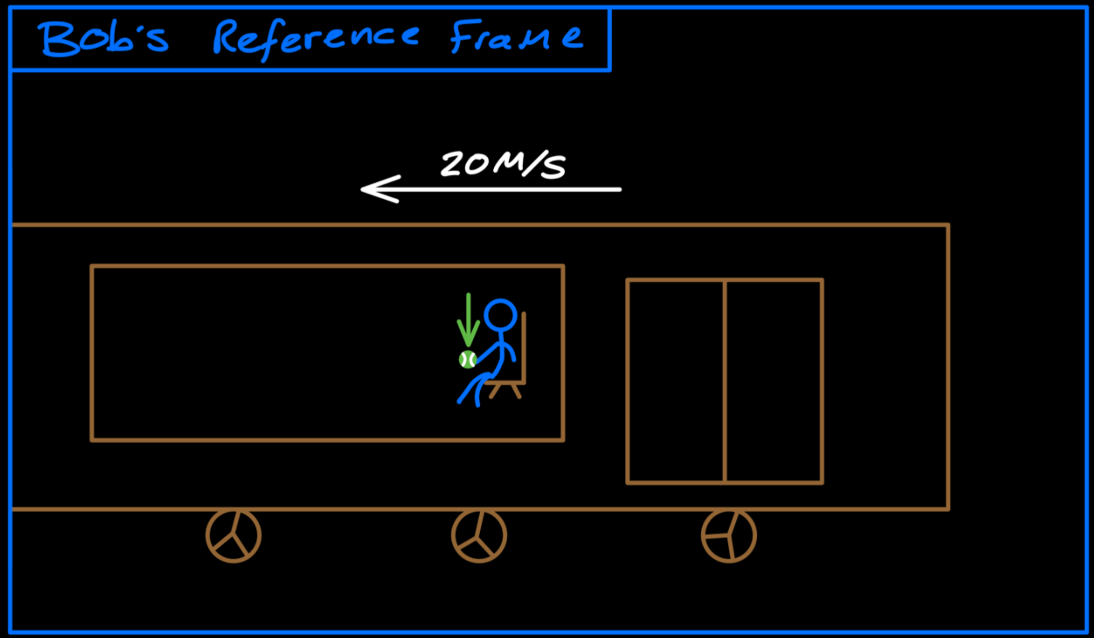
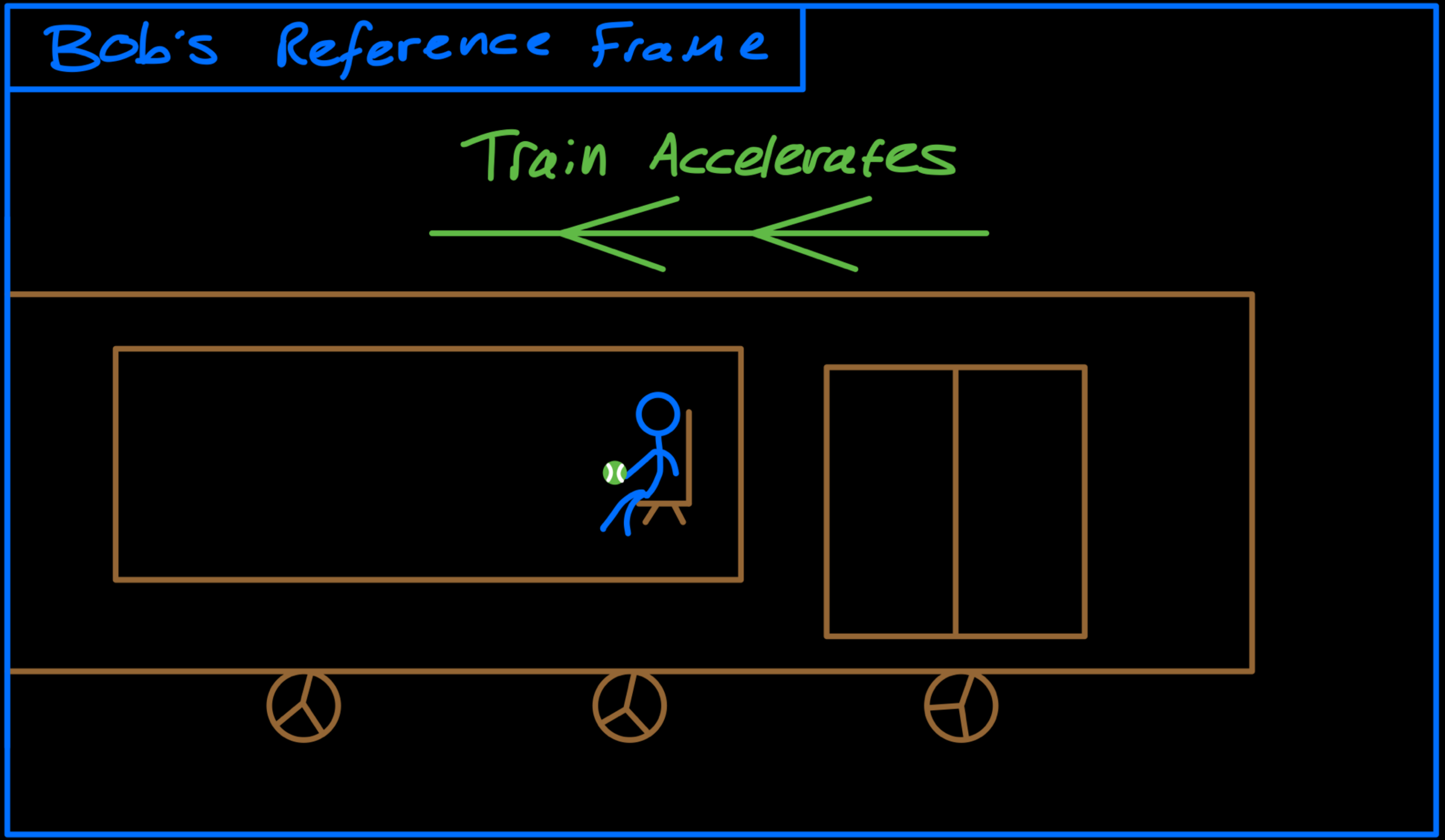
What about a train moving at a non-constant speed?





Galilean Relativity

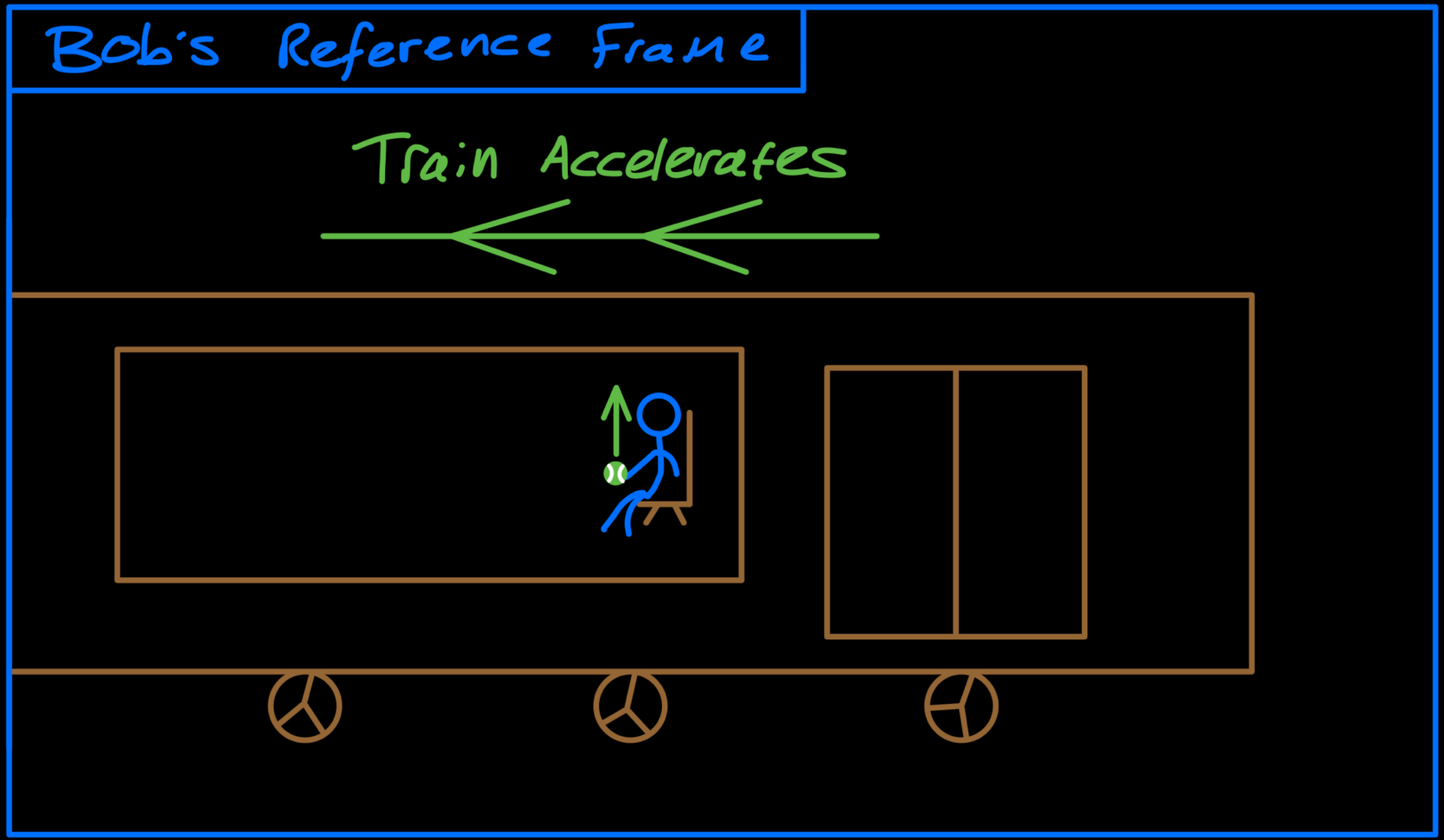
If the train accelerates (speeds up), Bob will observe something unusual.



Galilean Relativity

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

He throws the ball upwards.



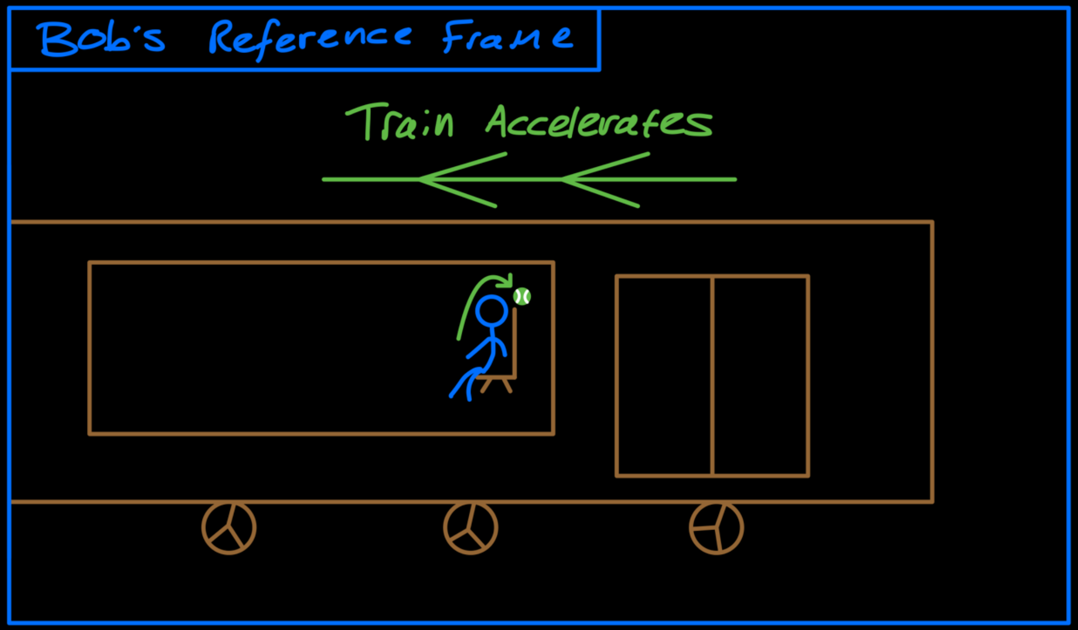
Galilean Relativity

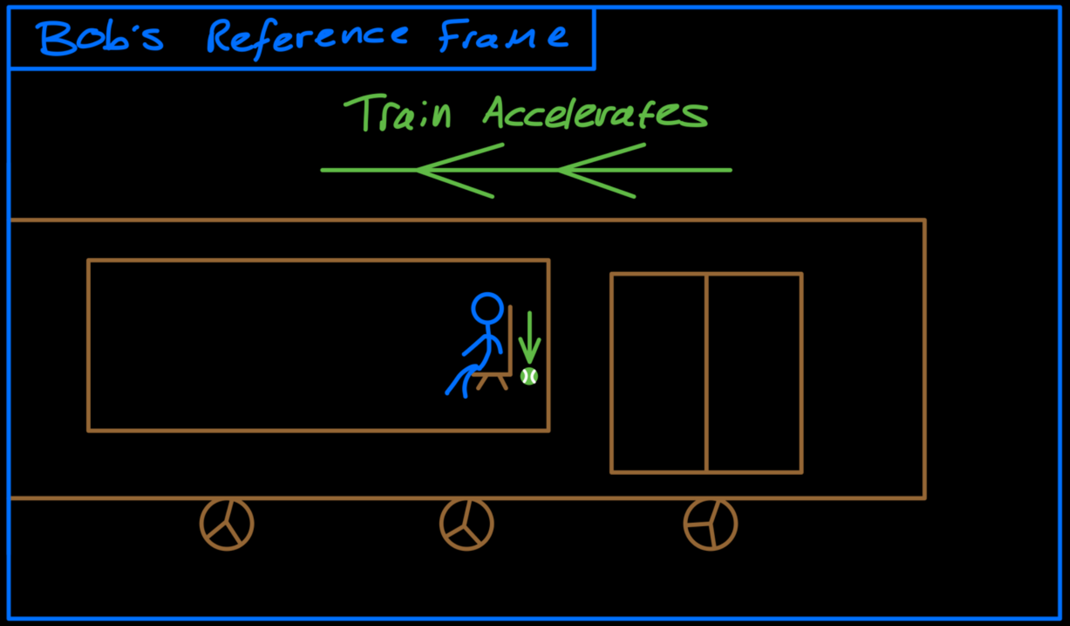
If the train accelerates (speeds up), Bob will observe something unusual.

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.

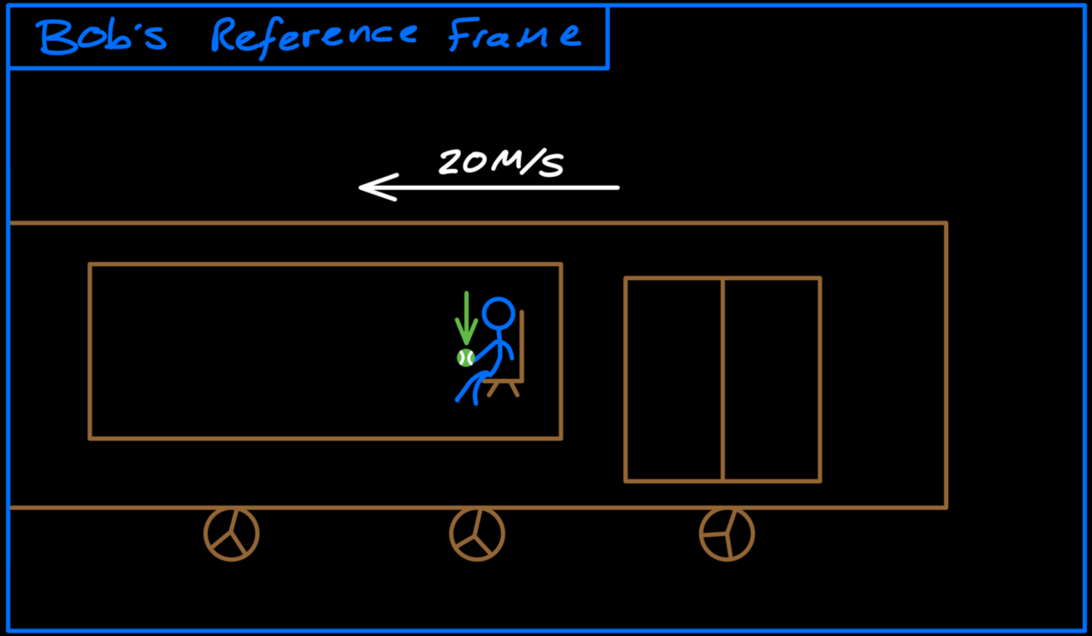


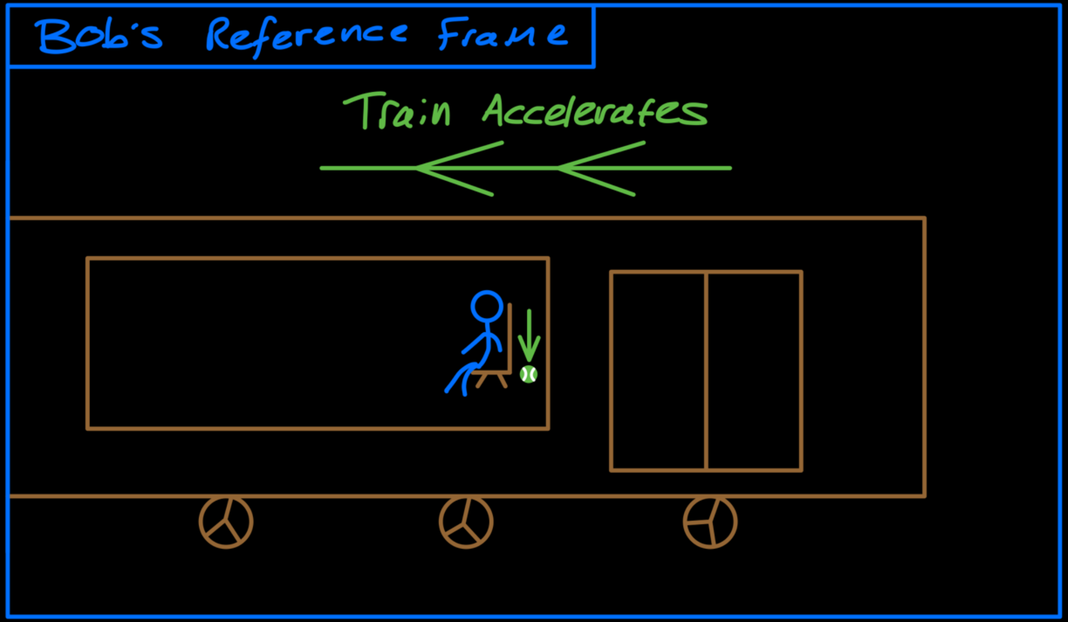


Galilean Relativity

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**.





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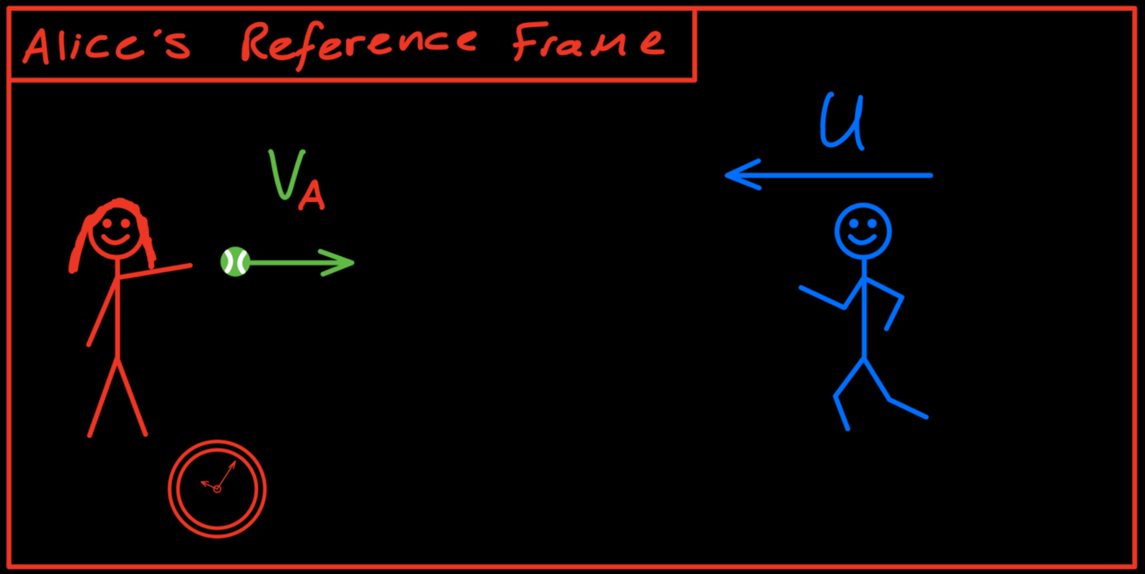
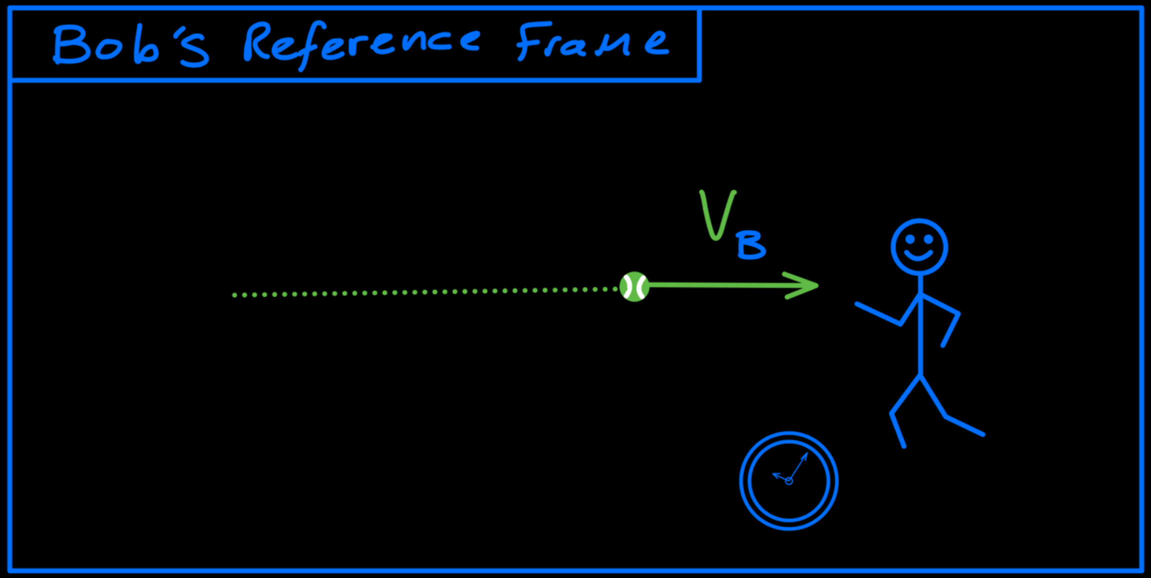




The Laws

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.

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

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		

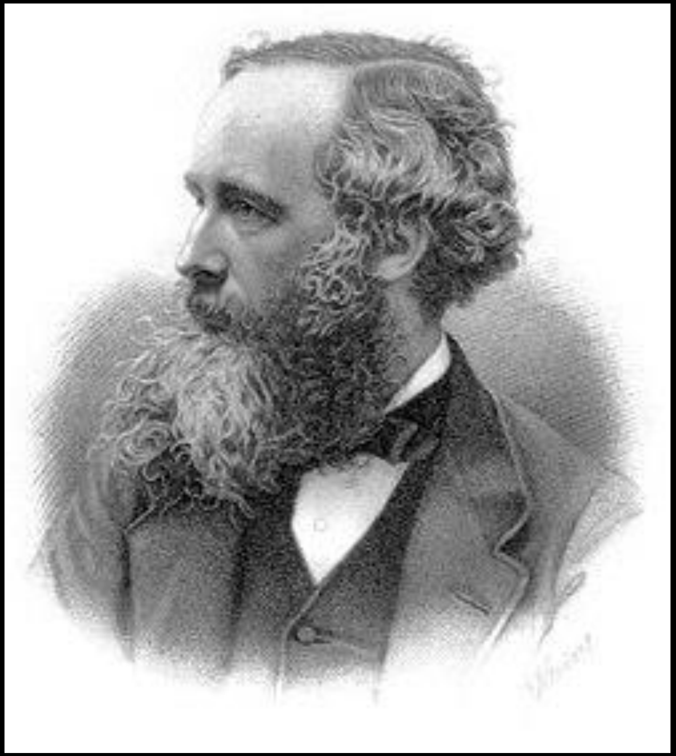
Between these twenty quantities we have found twenty equations, viz.

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

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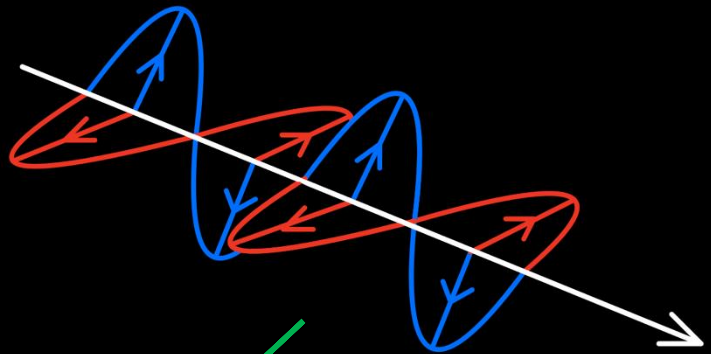

In 1865, Maxwell showed that his equations predict the existence of an electromagnetic wave.

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

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

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

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

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THIS IS THE SPEED OF LIGHT

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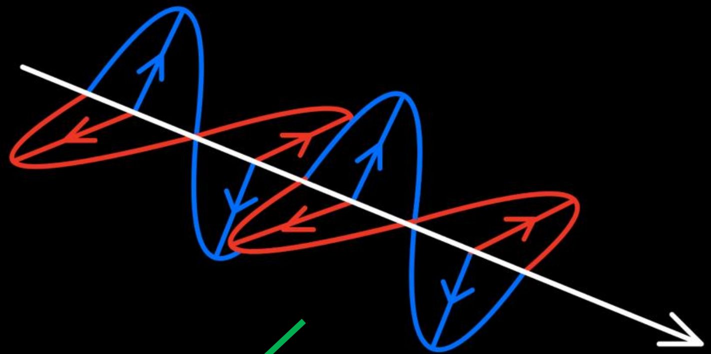

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The speed of light

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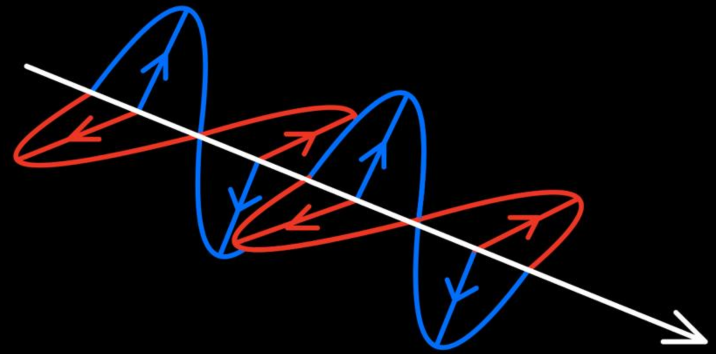

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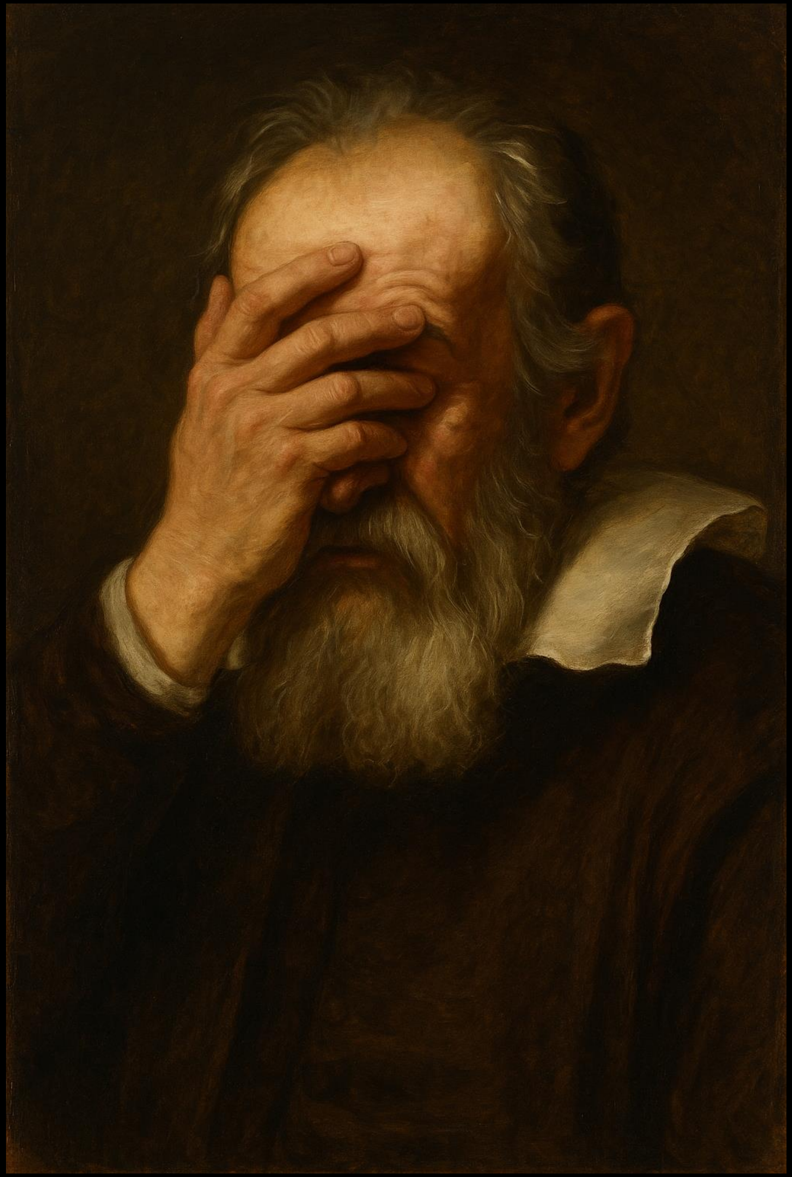
The speed of Light

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.

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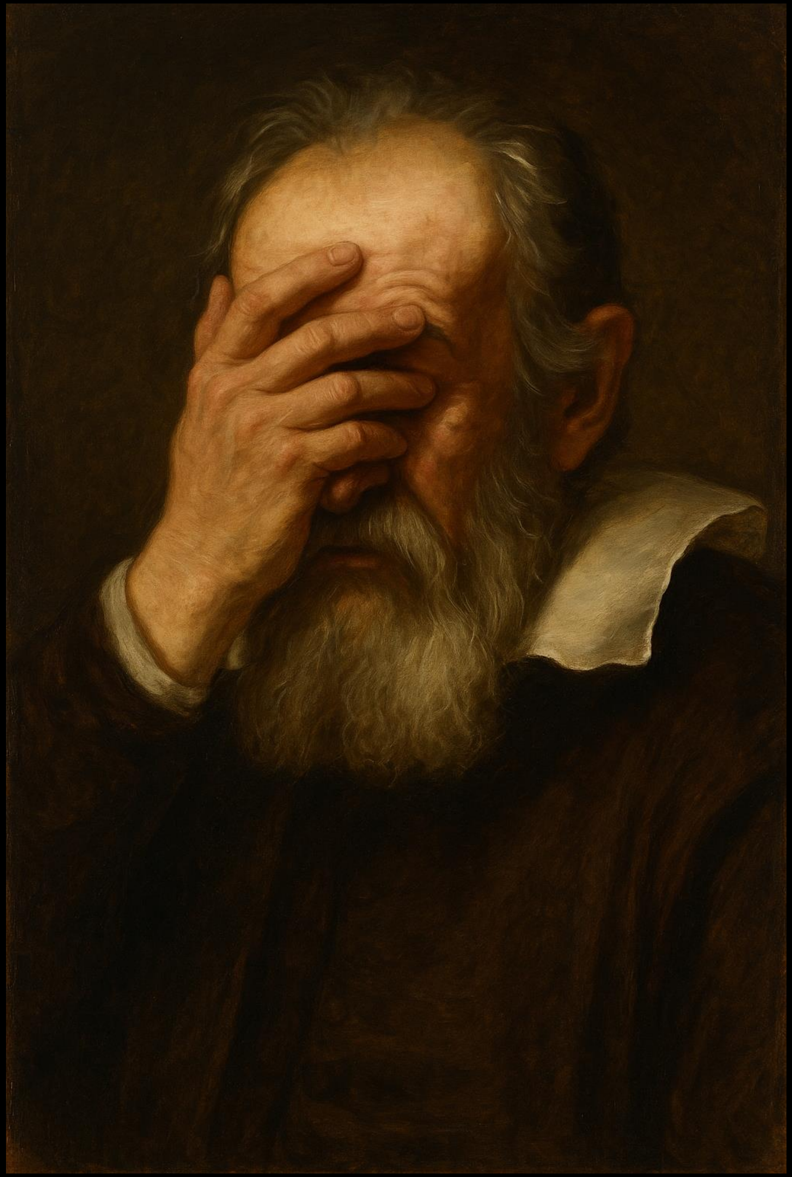
Recall Feynman's Golden Rule..



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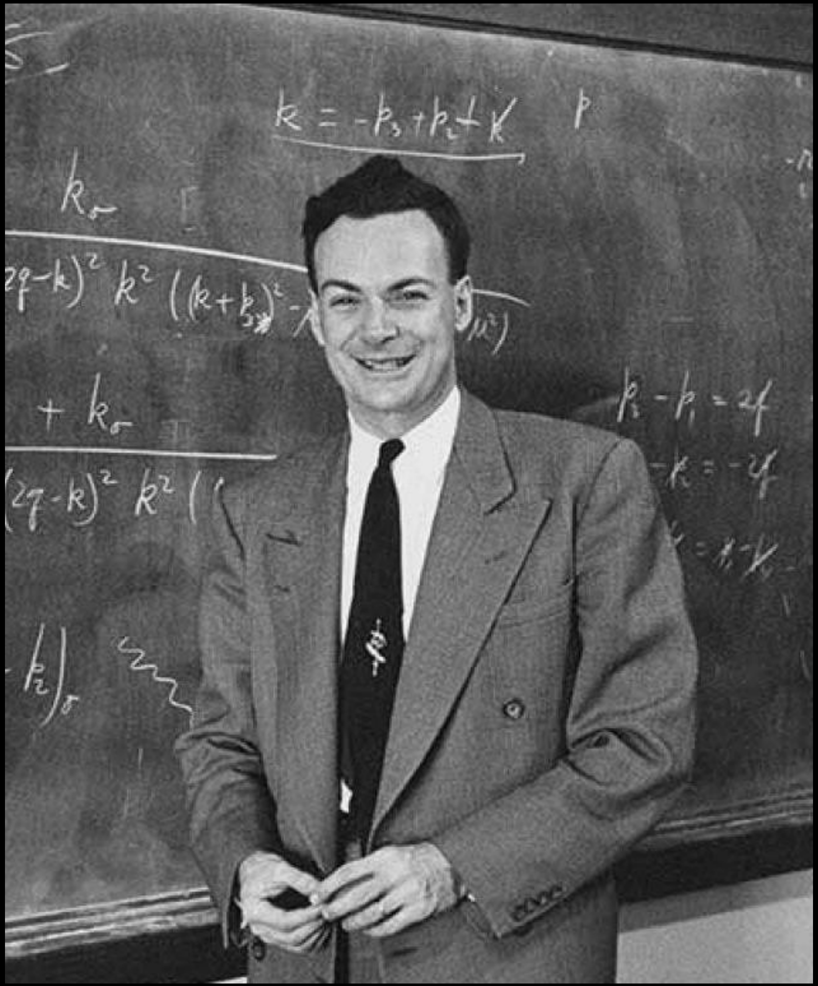
Theory vs Experiment

"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



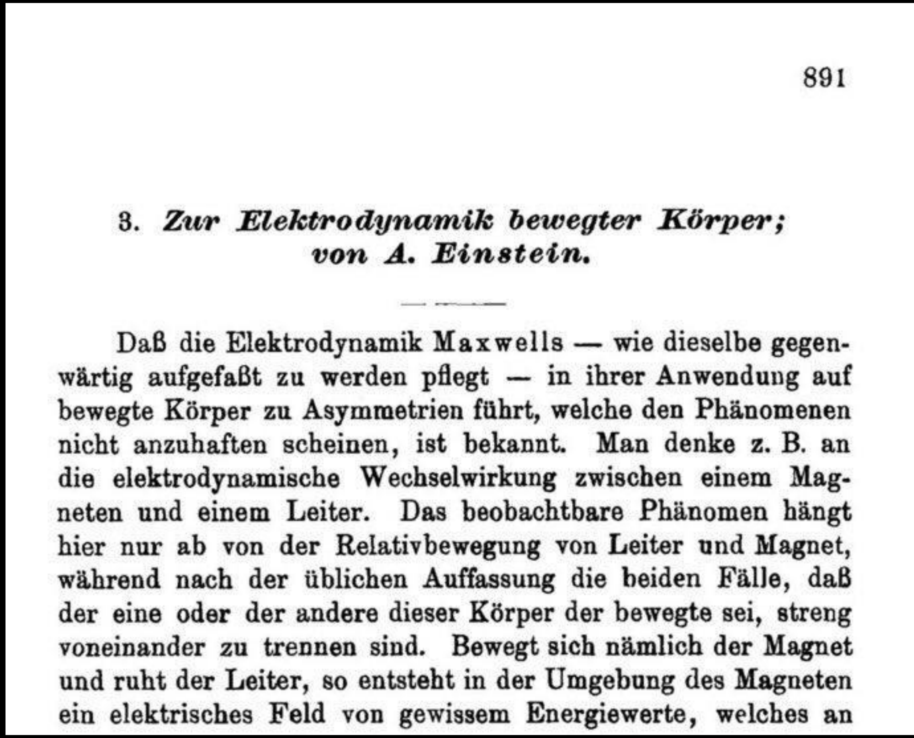
With insufficient theory to explain experimental observations, a **new theory is needed**.

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.



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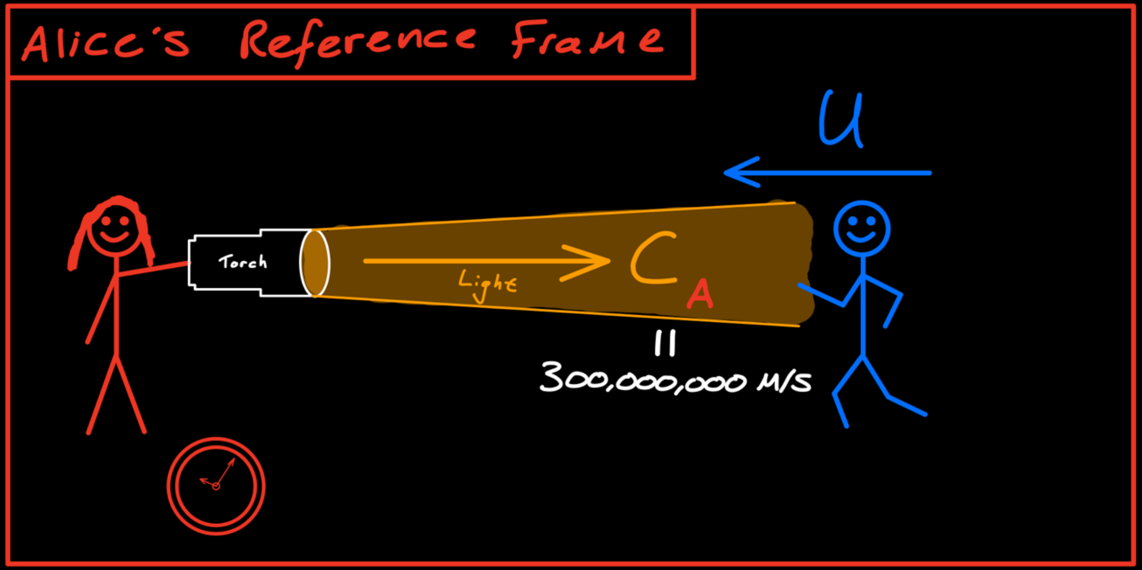
3. *Zur Elektrodynamik bewegter Körper;*
von A. Einstein.

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

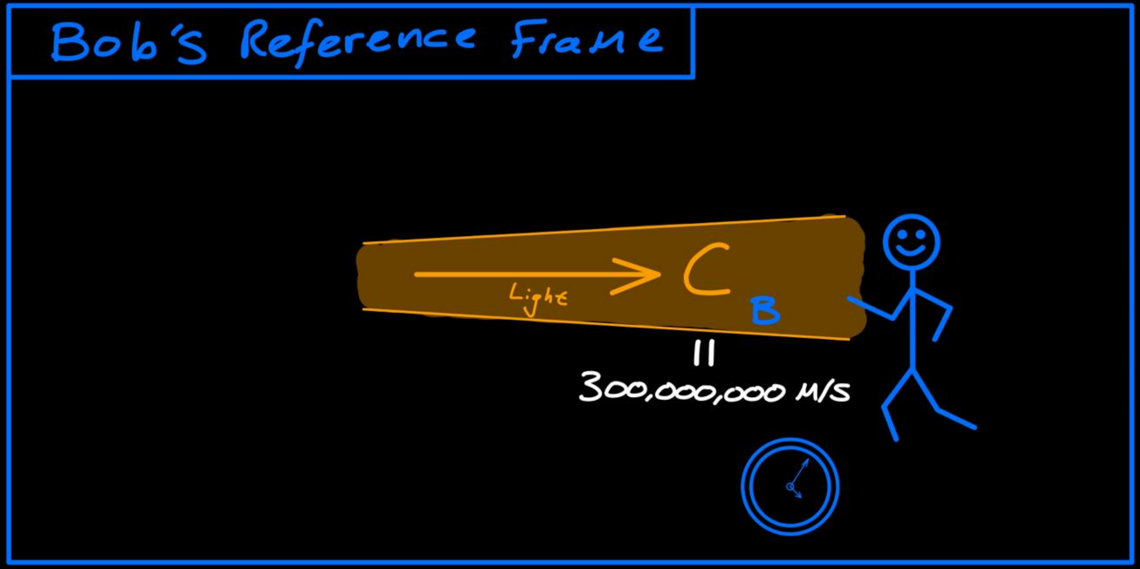
Albert Einstein, 1905.

Einsteinian Relativity



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.

Einsteinian Relativity

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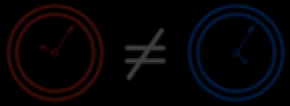

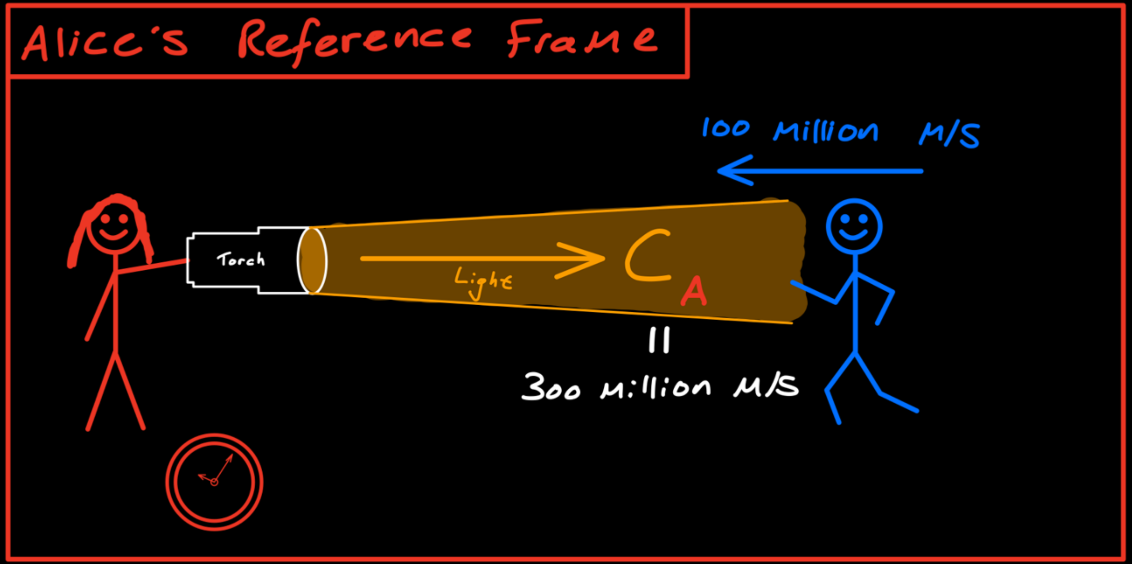

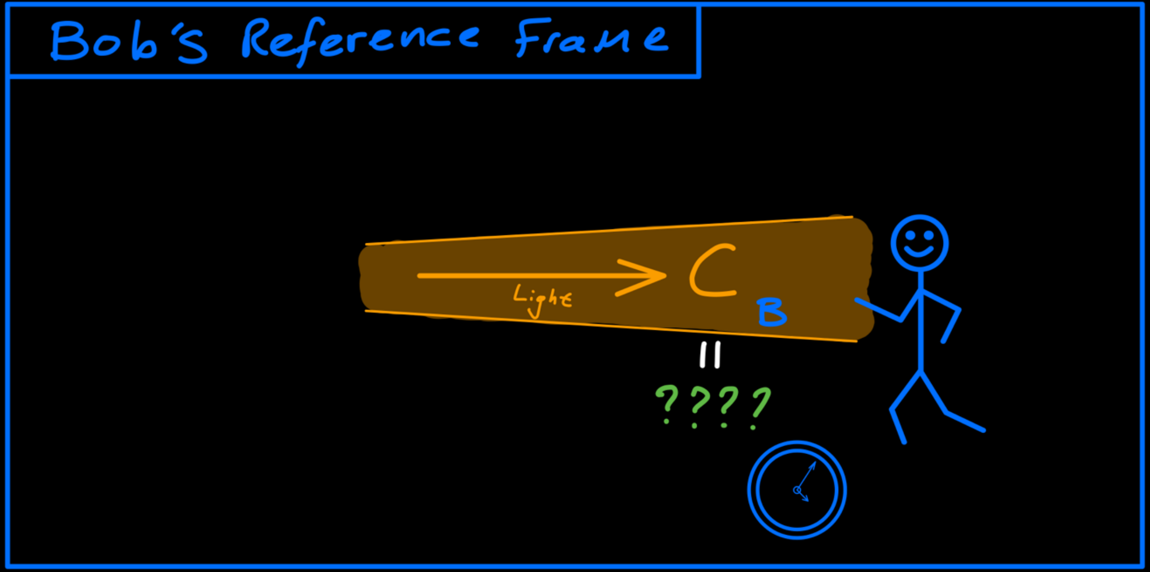

What do you think the speed of light seen by Bob should be?

Einsteinian Relativity

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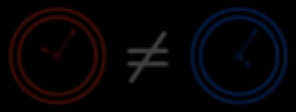
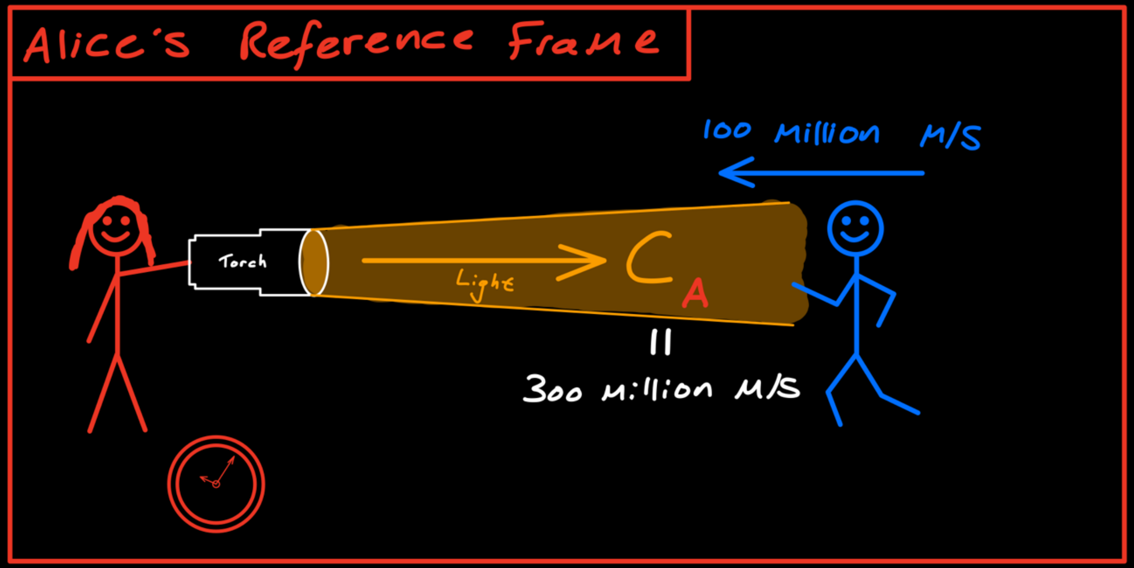
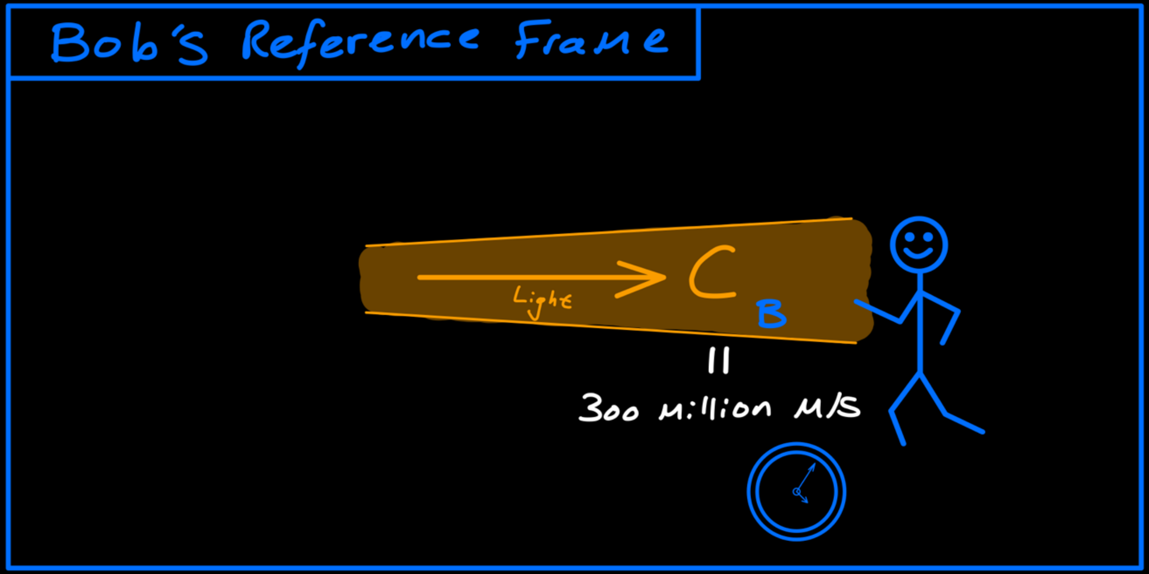
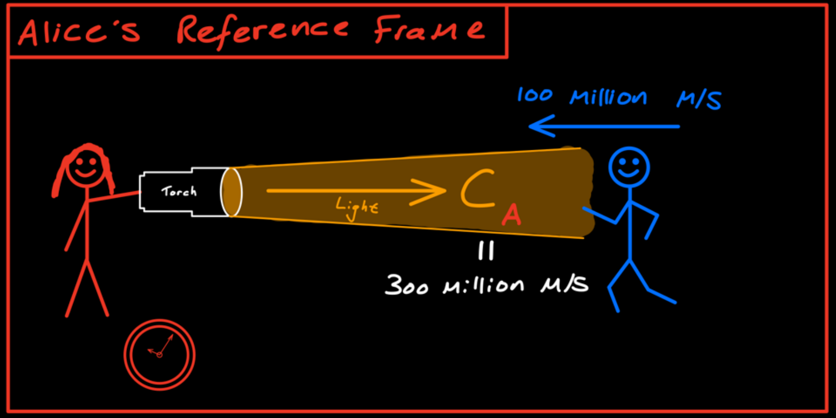


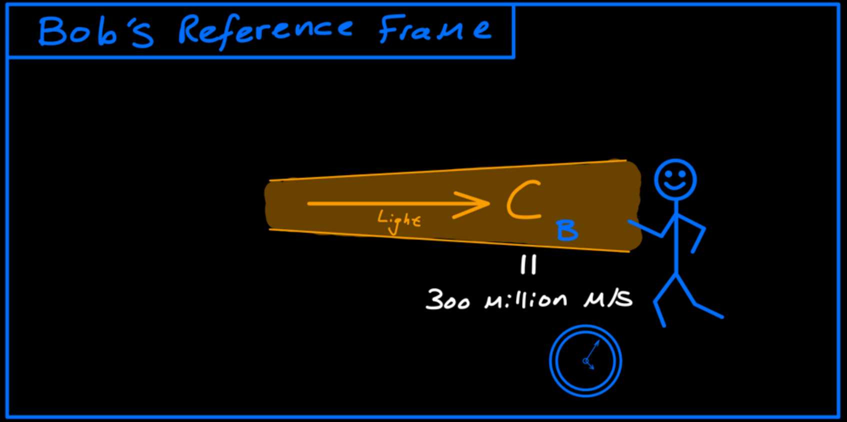




The Speed is unchanged! Light ALWAYS travels at the same speed, in any reference frame.

Einsteinian Relativity





The Laws

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

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$$C_B = C_A$$

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.

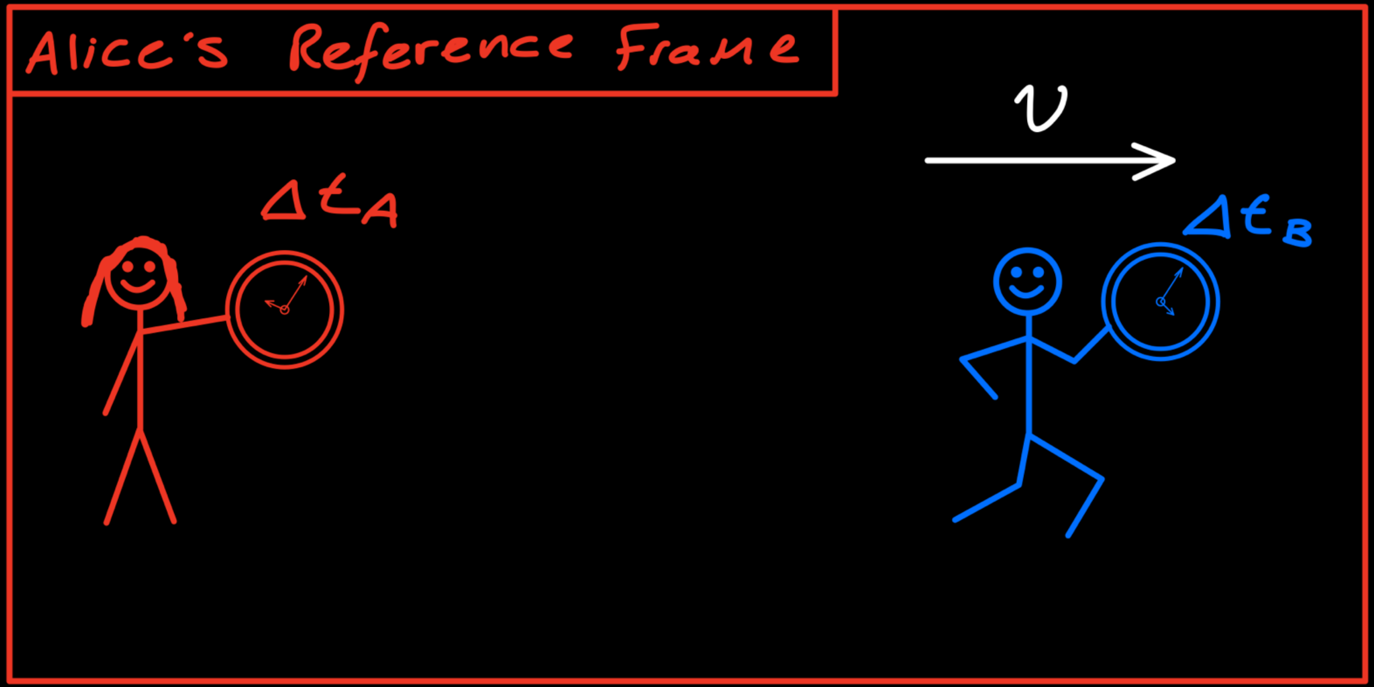
Plants growing on a highspeed rocket will germinate later than they would at rest on the Earth. Grey hairs will not appear as numerous, food will not spoil, clocks will not tick as far ahead.

Time Dilation

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.

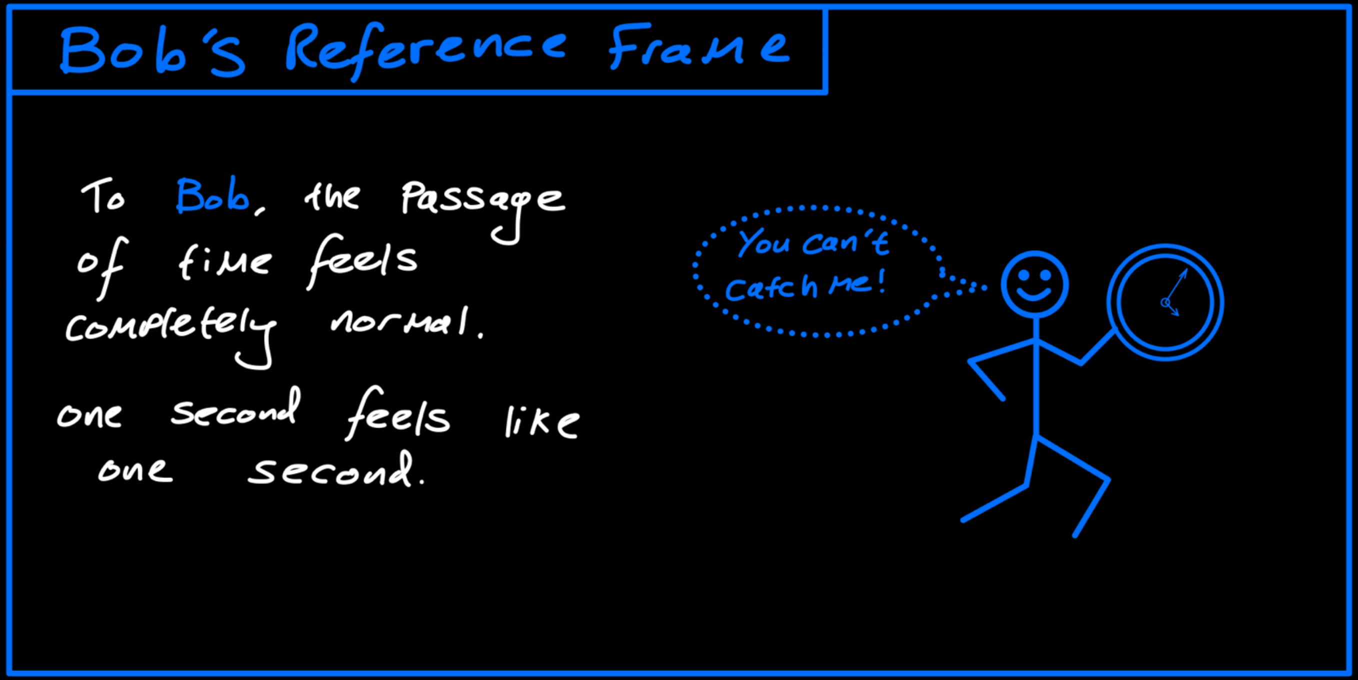
I derive this formula in full here.



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.



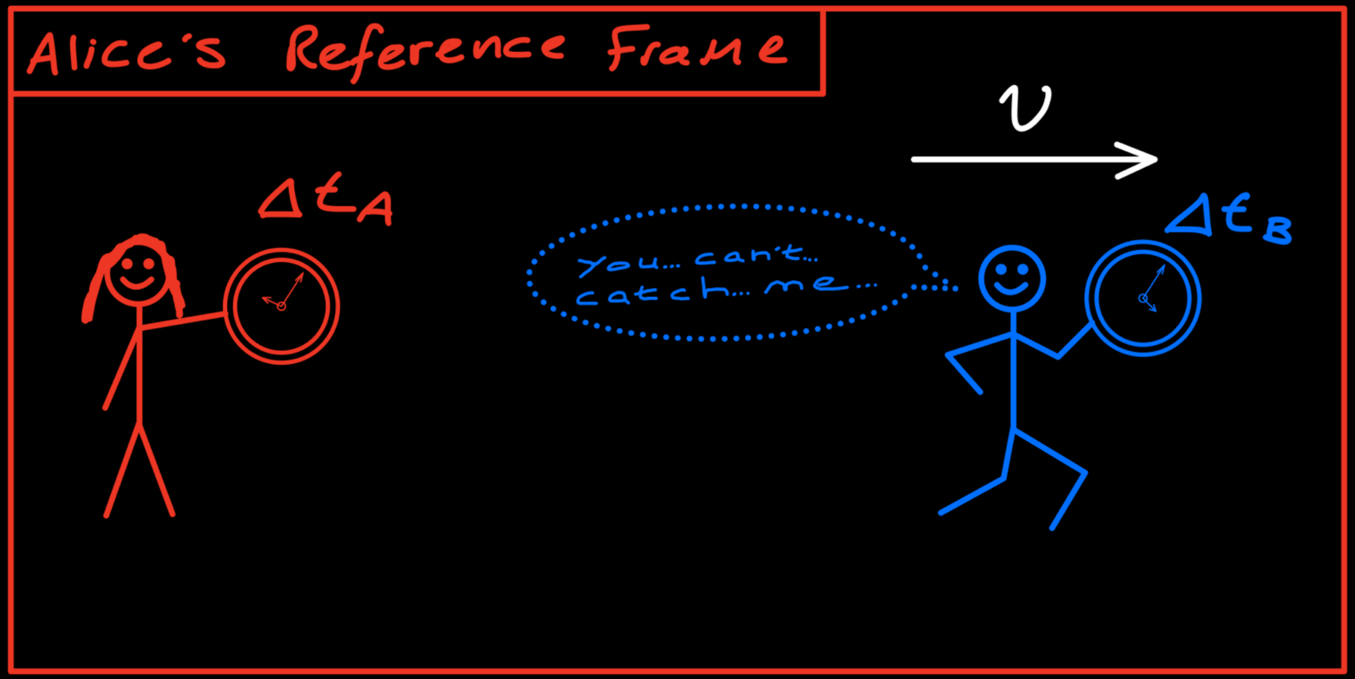
What would Bob's clock look like, as seen by Alice?

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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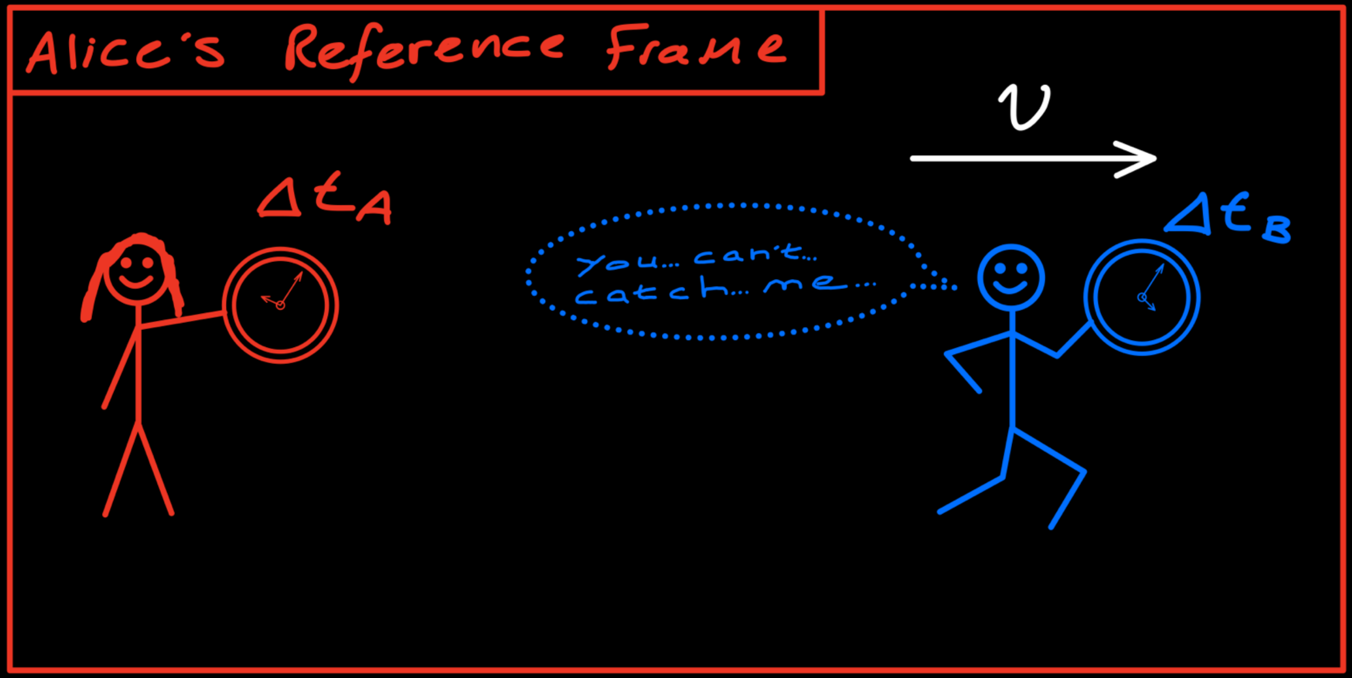


Hang on… Why do we not observe this phenomena in our every day lives?

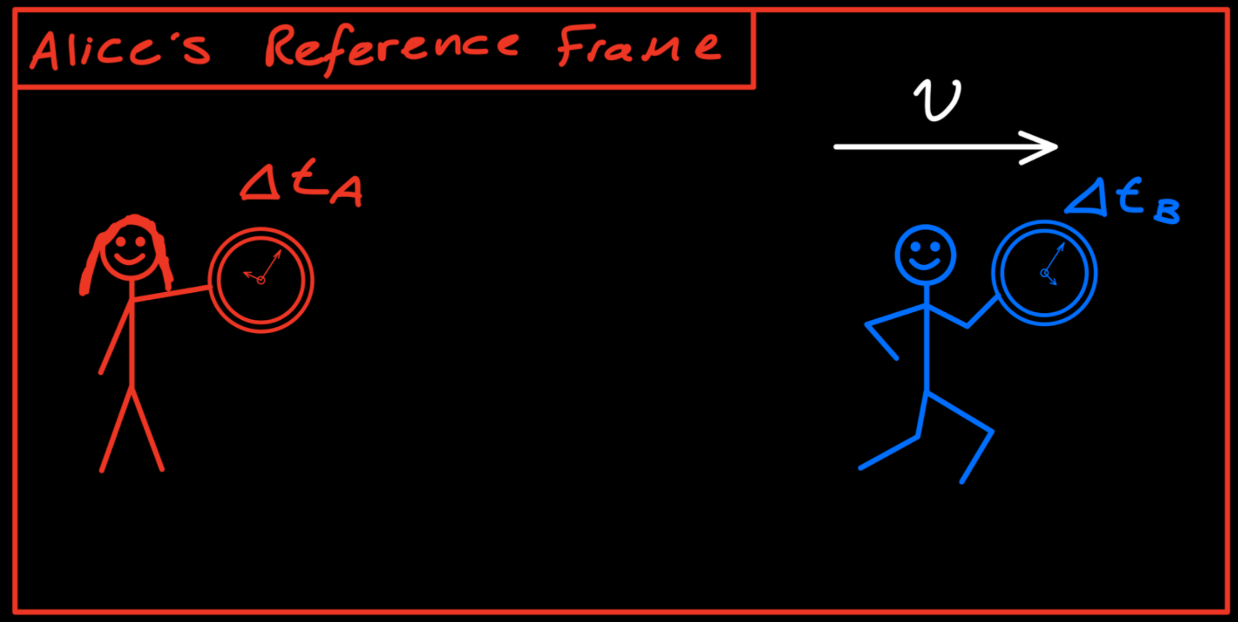
Not every jogger that runs past us moves in slow motion!

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 on changes significantly when moving at speeds close to the speed of light.



Length of time recorded by Bob.

Length of time recorded by Alice.

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

speed of Bob, seen by Alice.

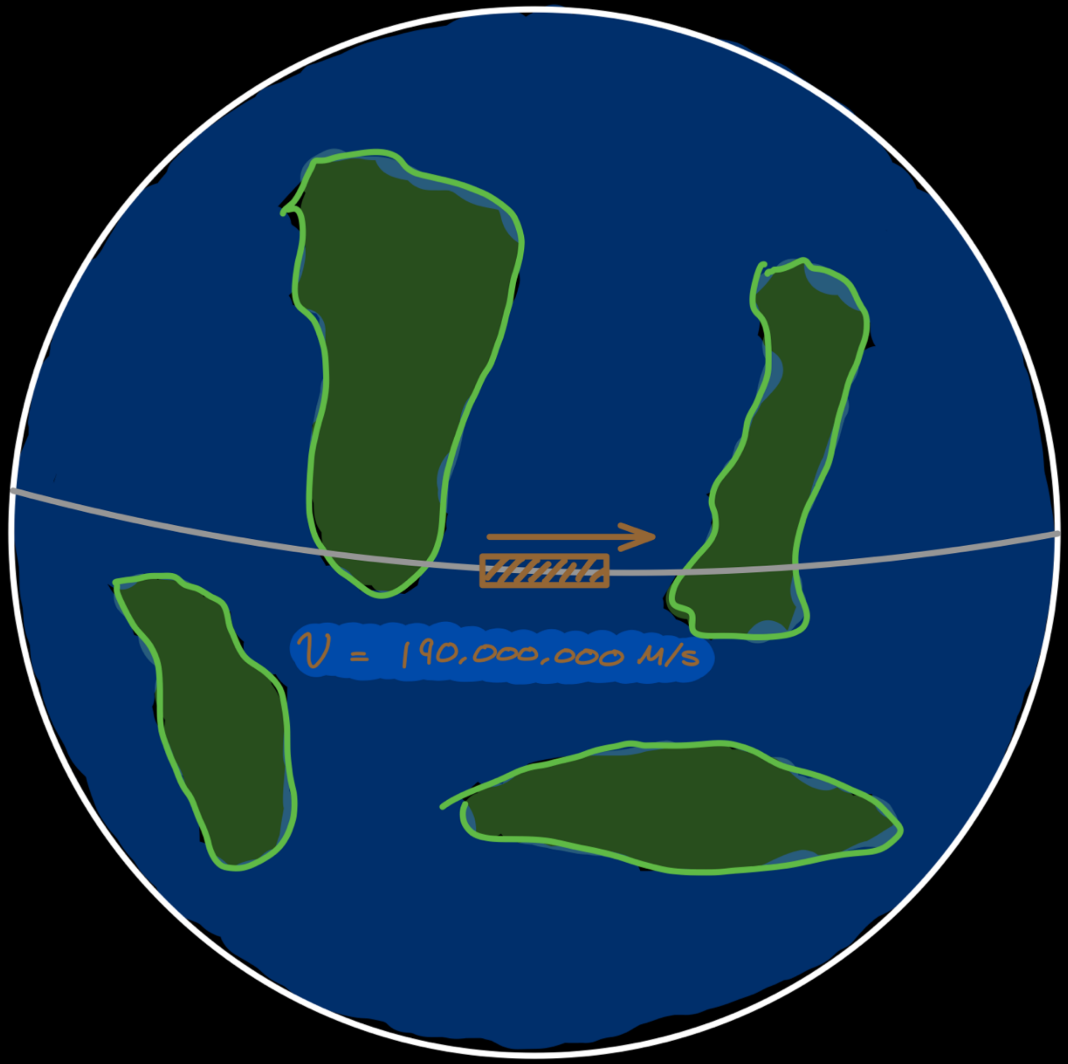
Speed of Light (300 million m/s).

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.

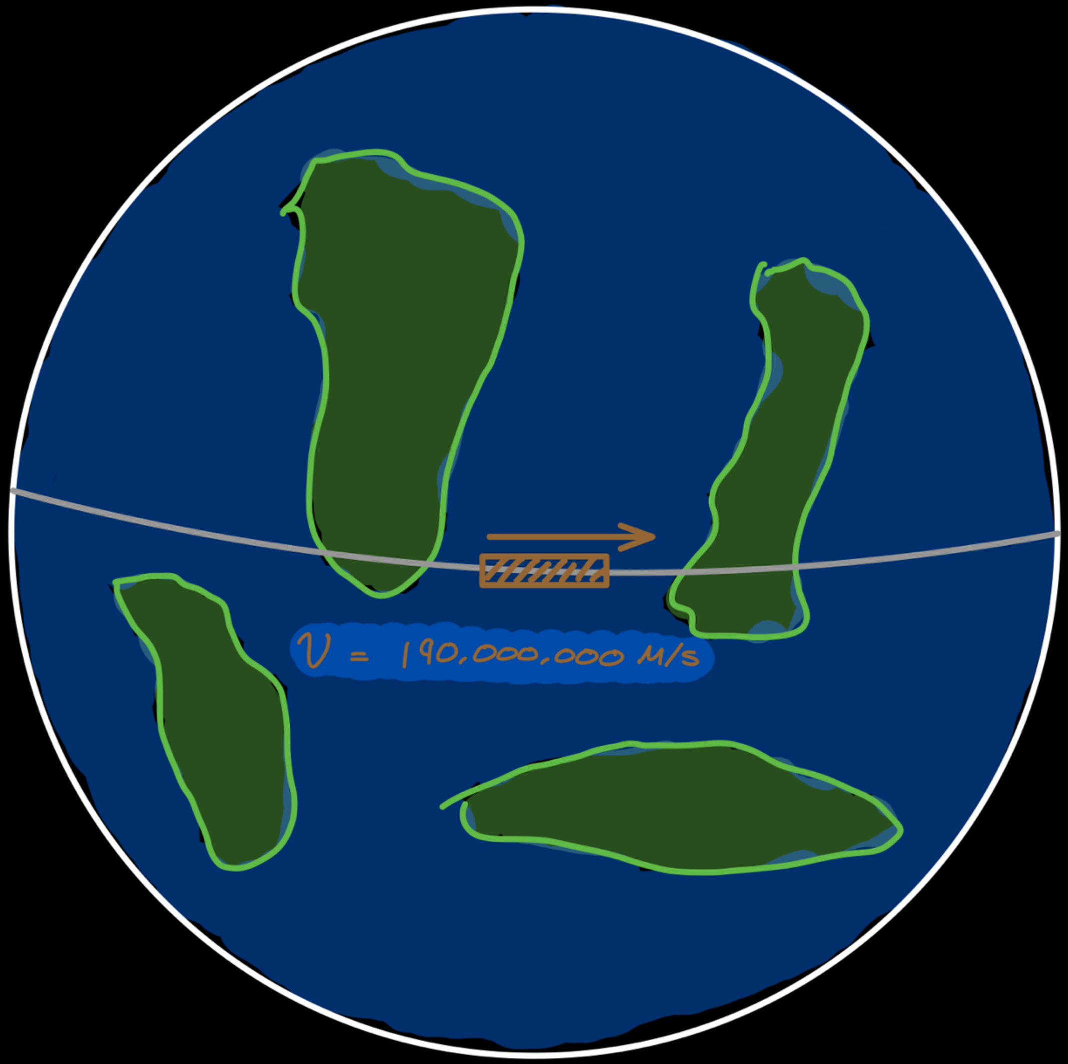
At this speed, the train moves at about **63%** of the speed of light.



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.

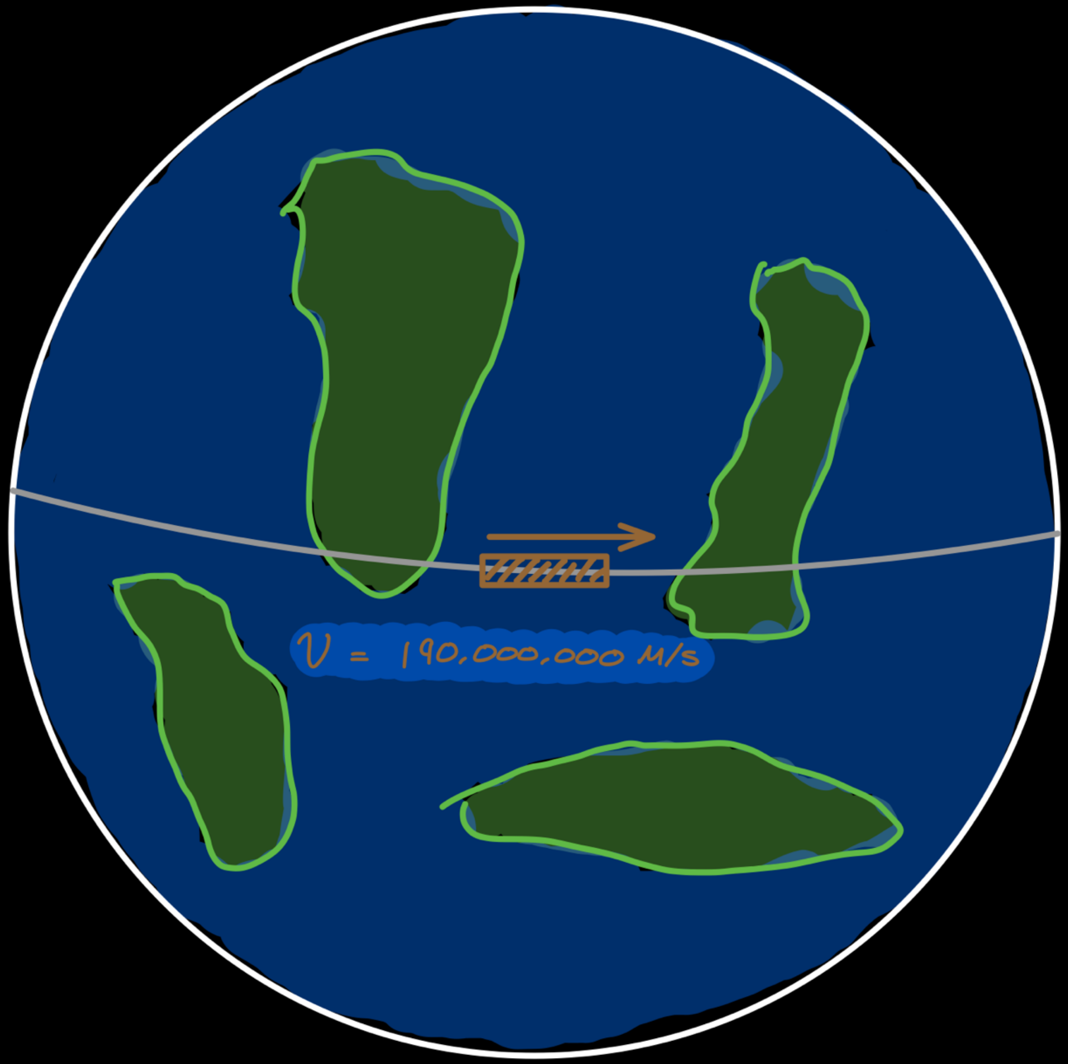


Forwards Time Travel

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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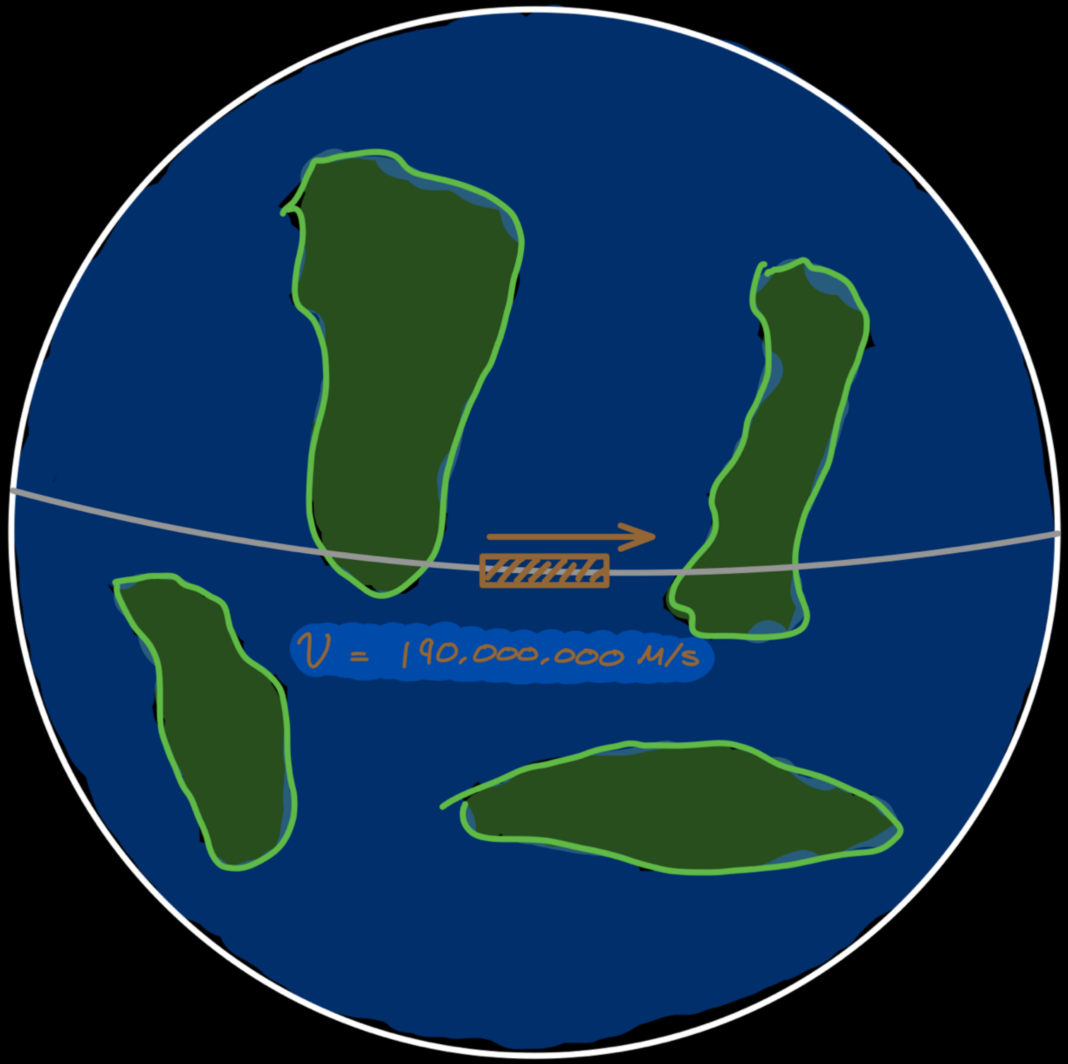
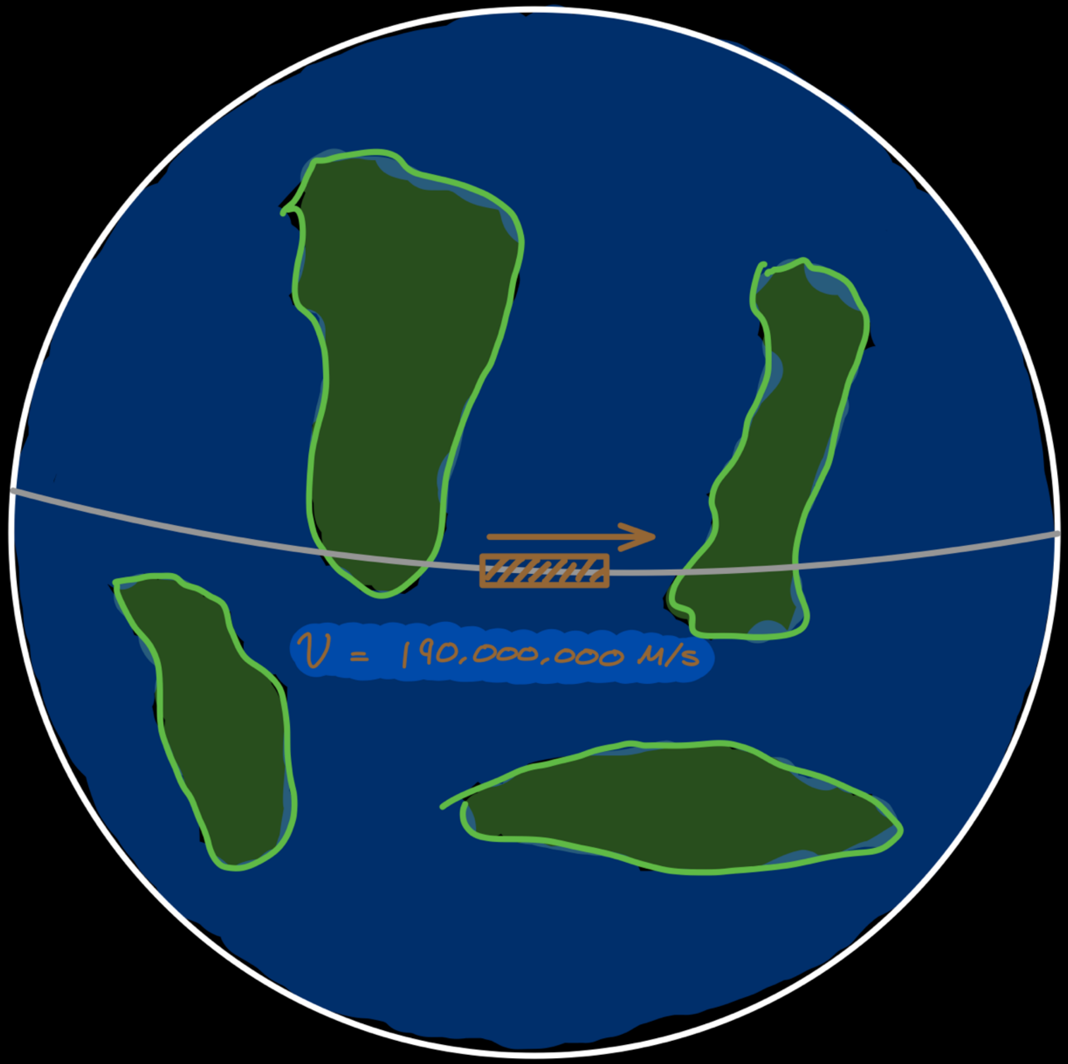


Forwards Time Travel

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.

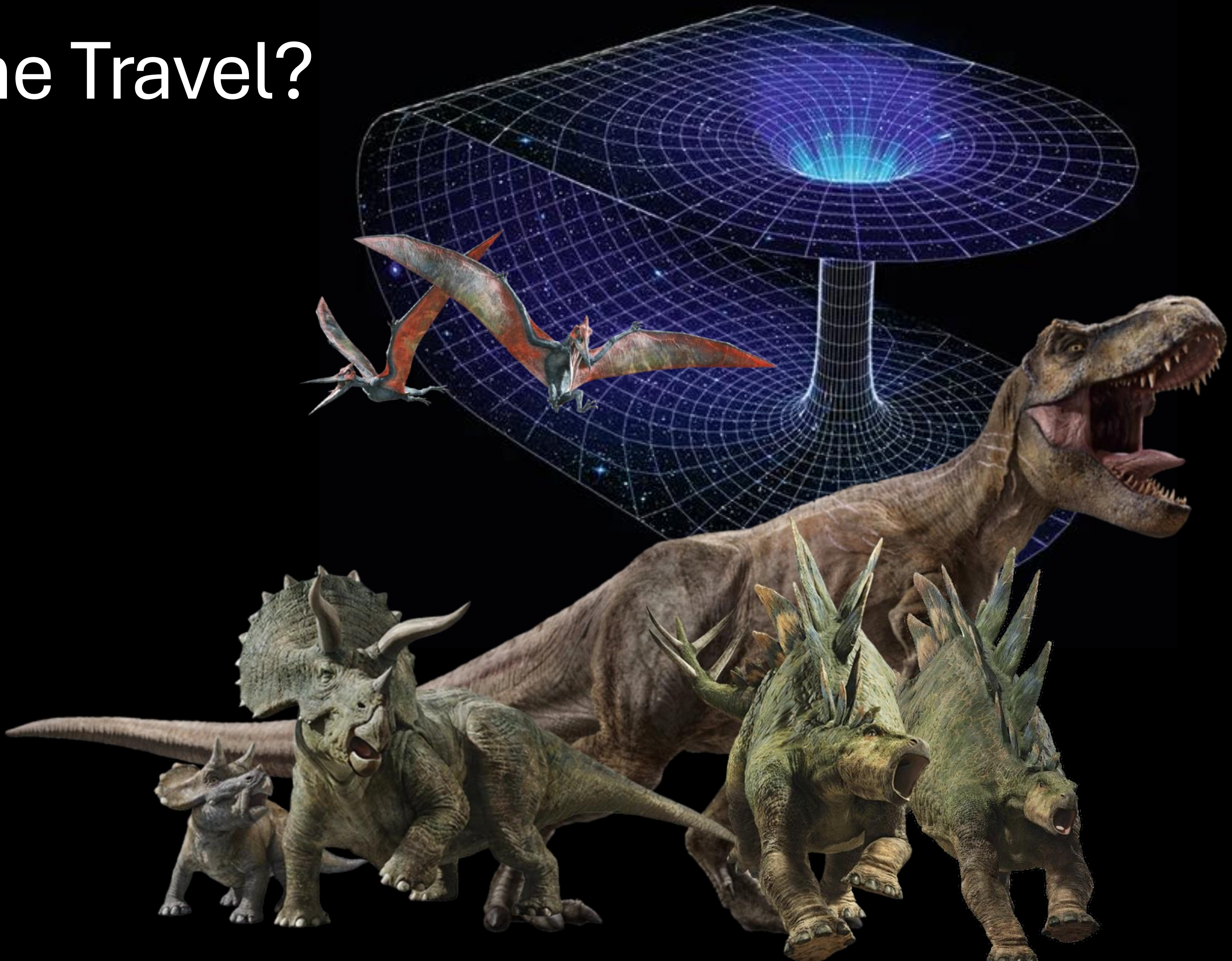


Backwards Time Travel?

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.

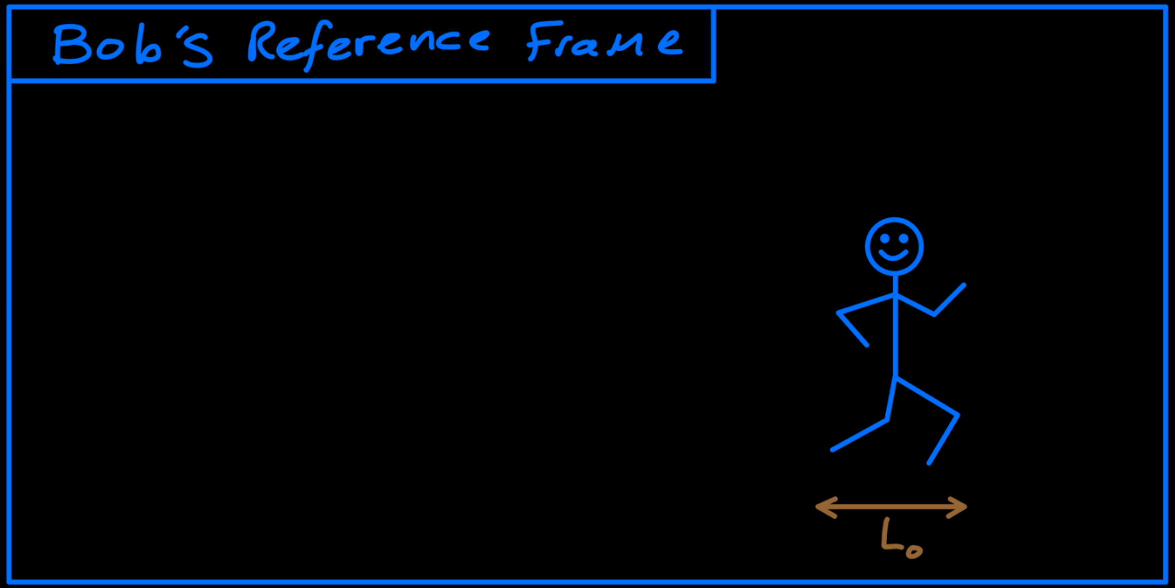


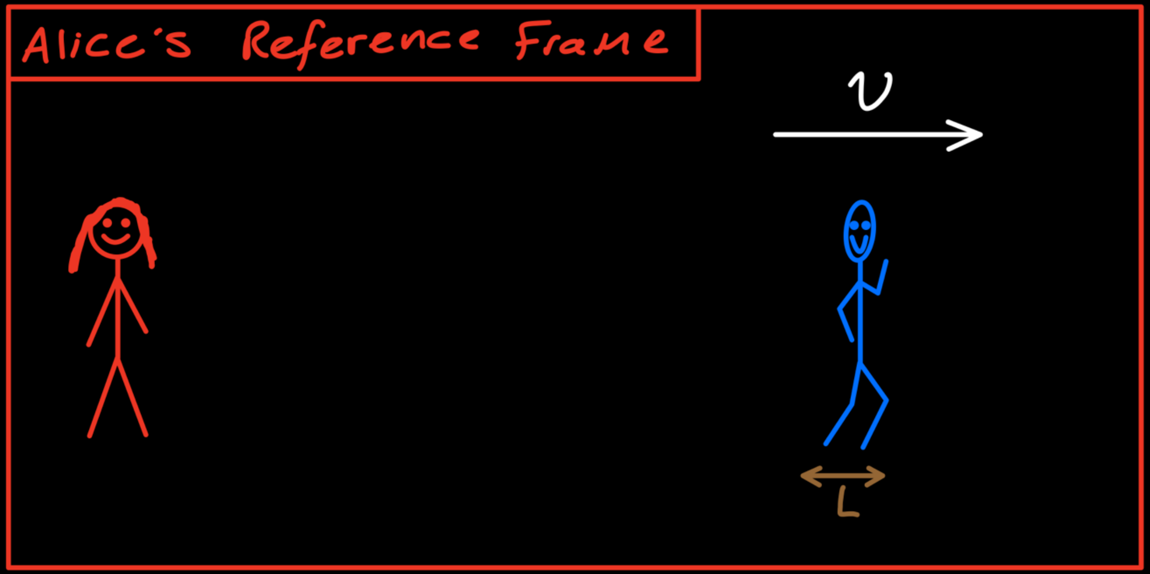
Length Contraction

In special relativity, *time is stretched*, and correspondingly *space is squashed*.

This is the phenomena of Length Contraction.

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}}$$



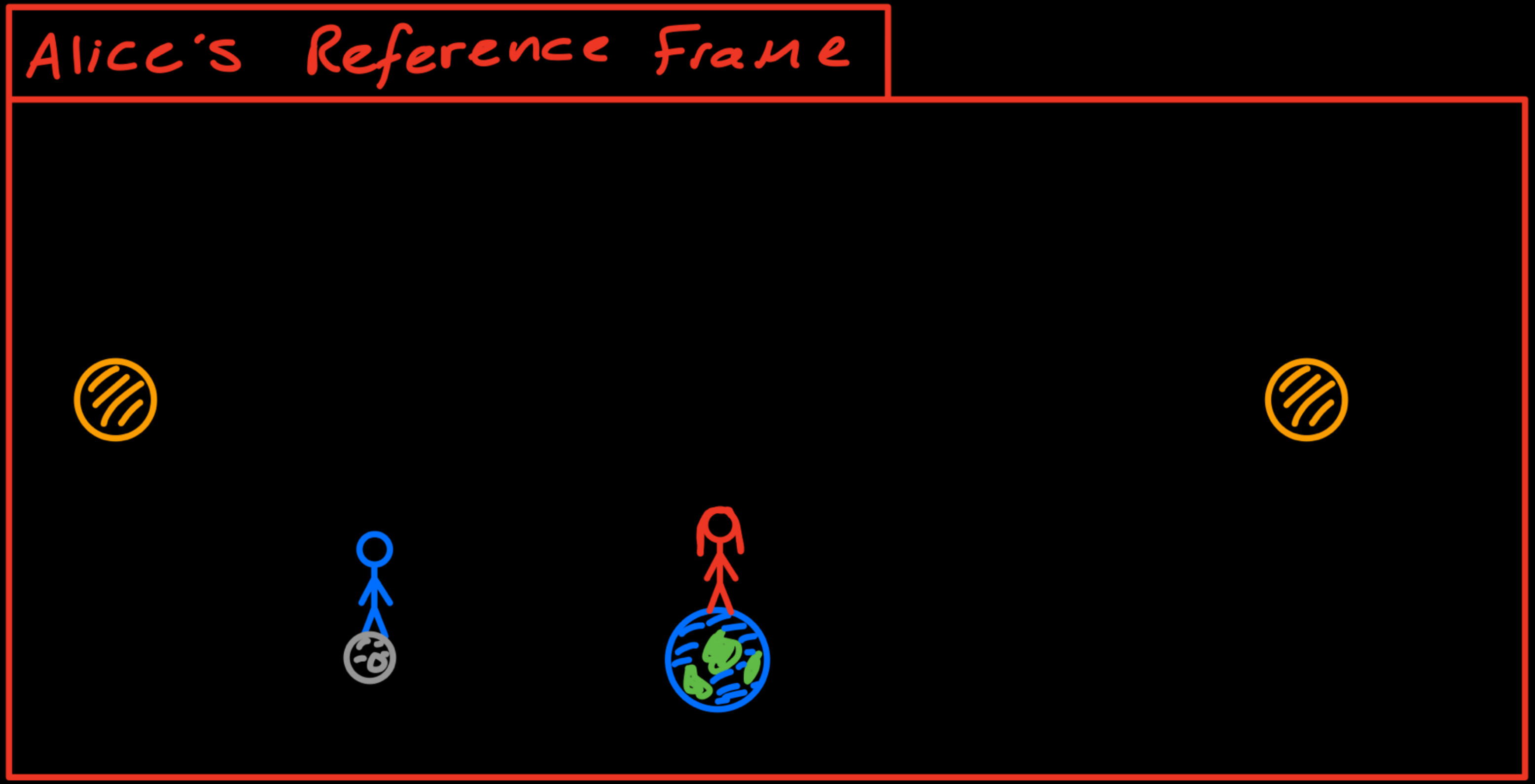


Simultaneity

One consequence of the relative nature of time, is the relativity nature of simultaneity.

Events that appear to occur at the same time for one observer, appear to occur at different times to another.

Suppose, Alice and Bob witness a pair of supernovae.



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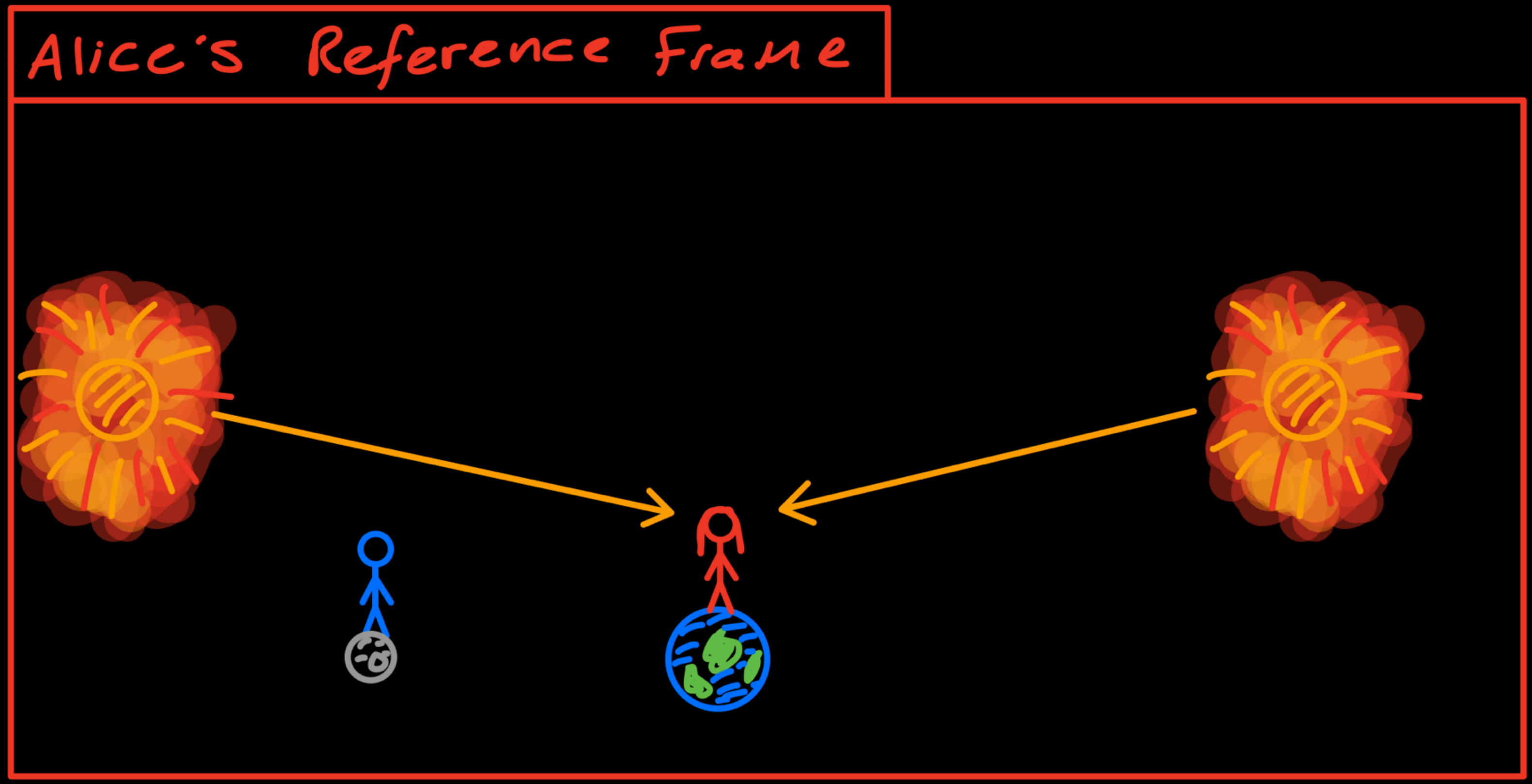
Suppose, Alice and Bob witness a pair of supernovae.

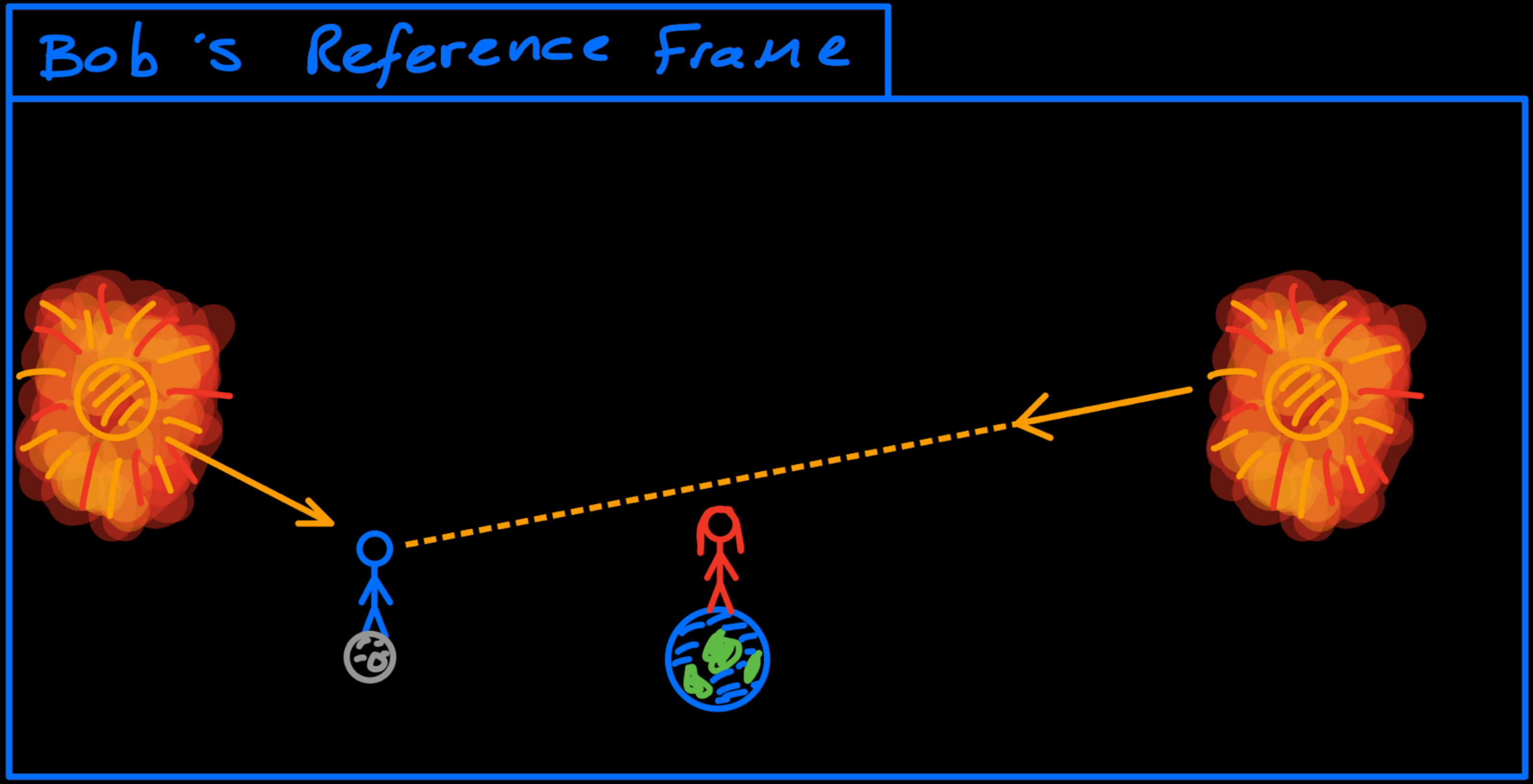
Alice is directly between these supernovae. From her point of view they occur simultaneously.



Simultaneity

Bob is slightly closer to one supernova, that the other.

It takes the light from the supernova on the right a slightly longer time to reach him than the supernova on the left.

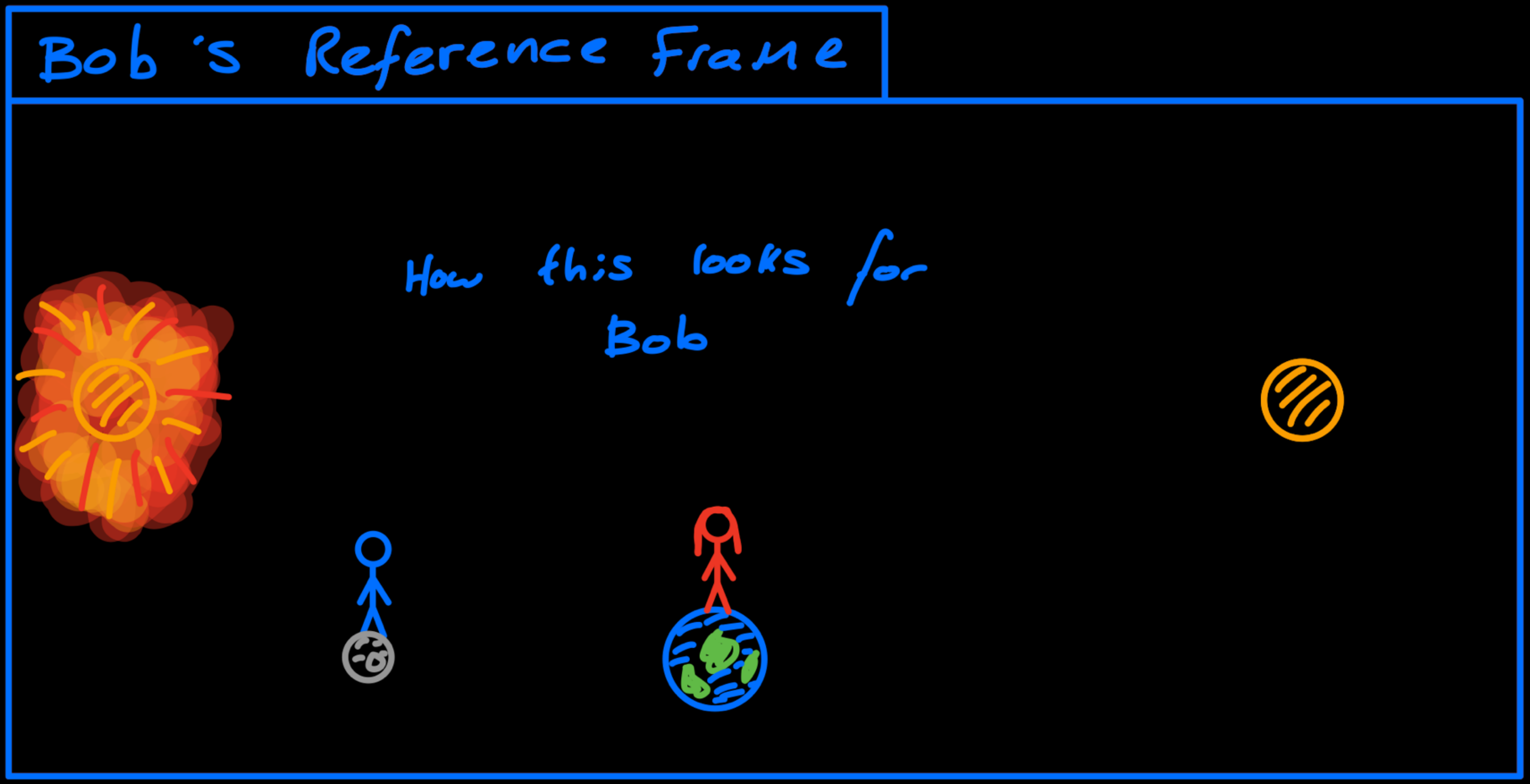


Simultaneity

Bob is slightly closer to one supernova, that the other.

It takes the light from the supernova on the right a slightly longer time to reach him than the supernova on the left.

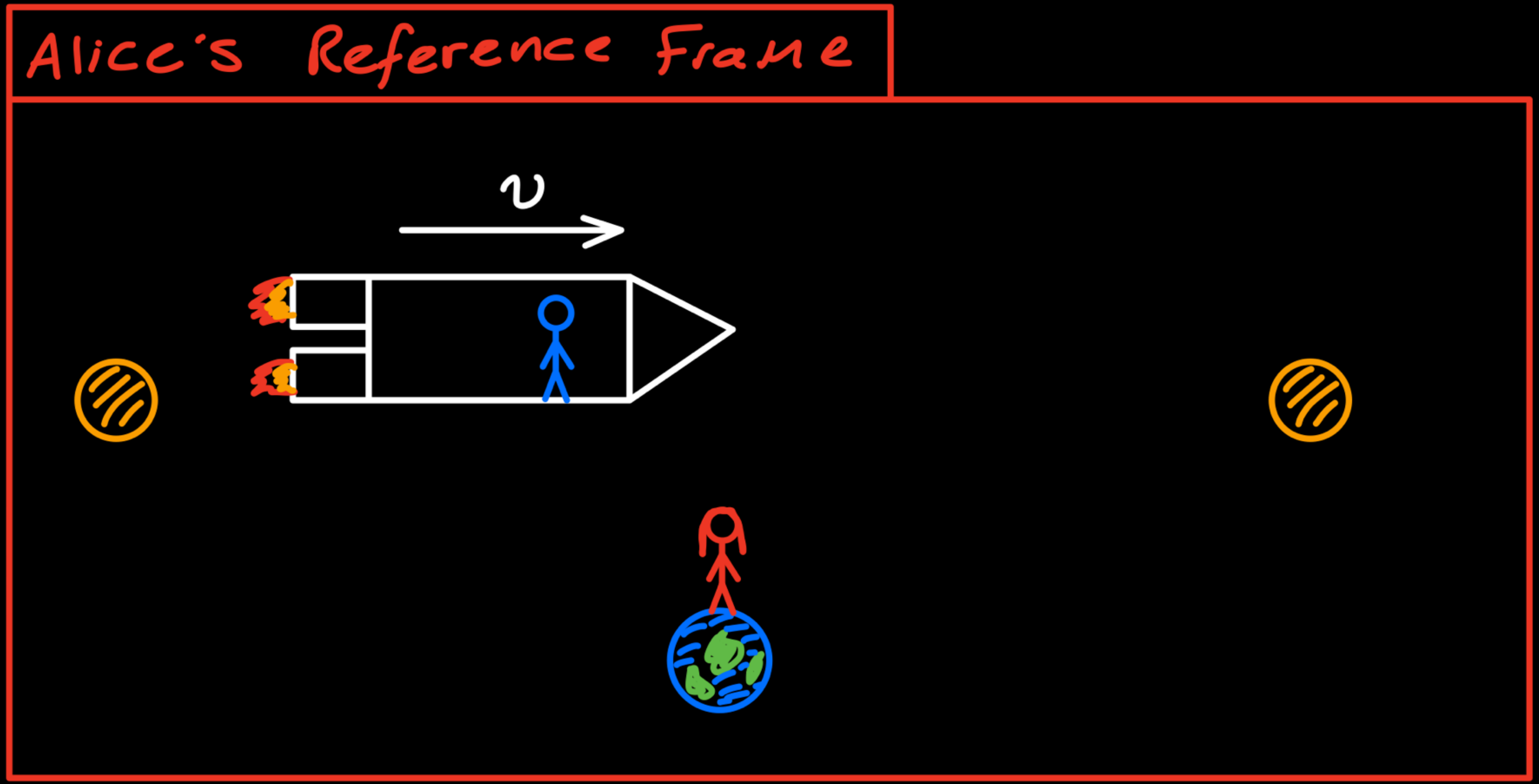
He does not perceive these supernova to be simultaneous.



Simultaneity

It isn't just position that alters simultaneity. Velocity does this too.

Suppose Bob passed the Earth on a rocket moving at high speed, when Alice perceives the supernova to occur simultaneously.



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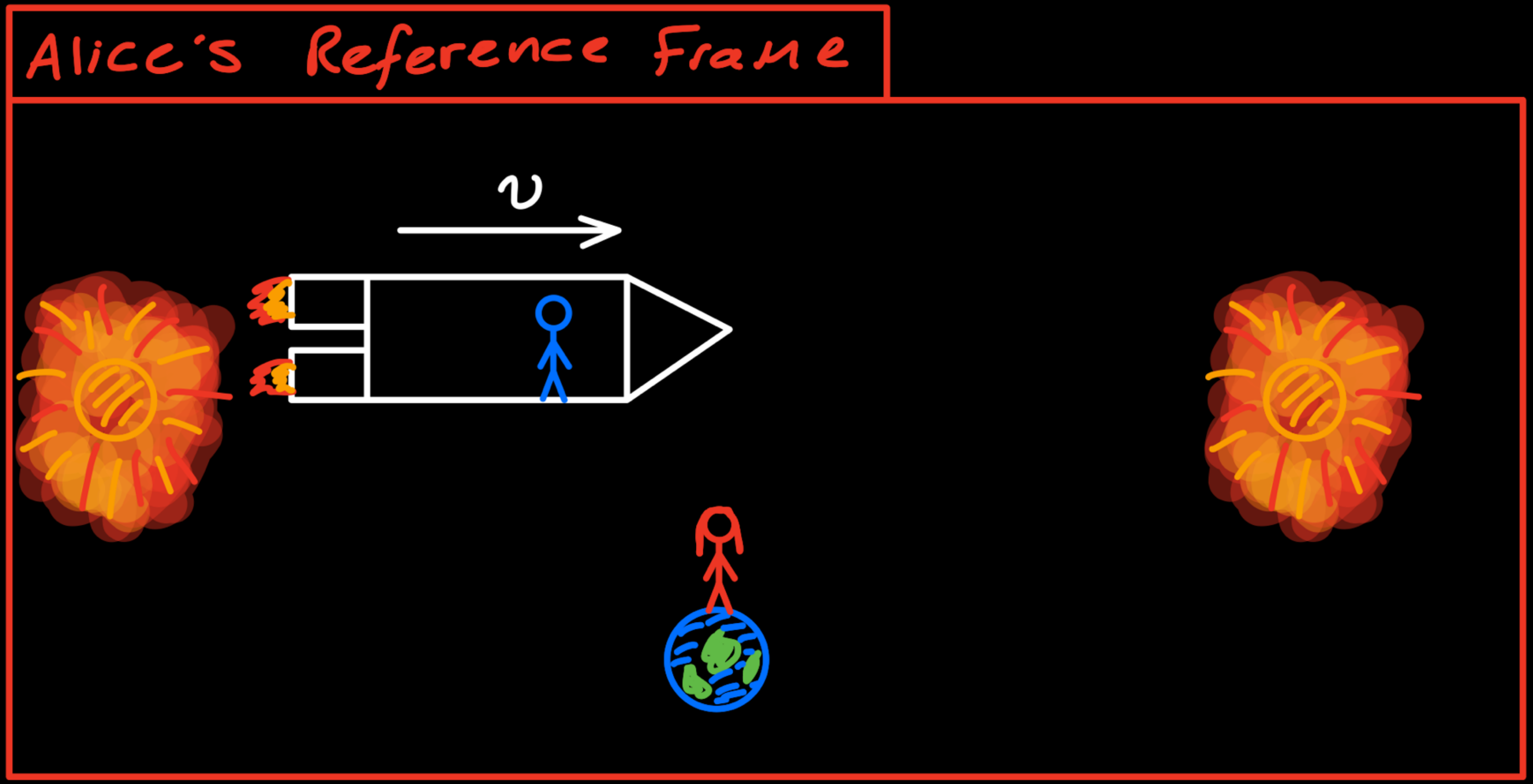

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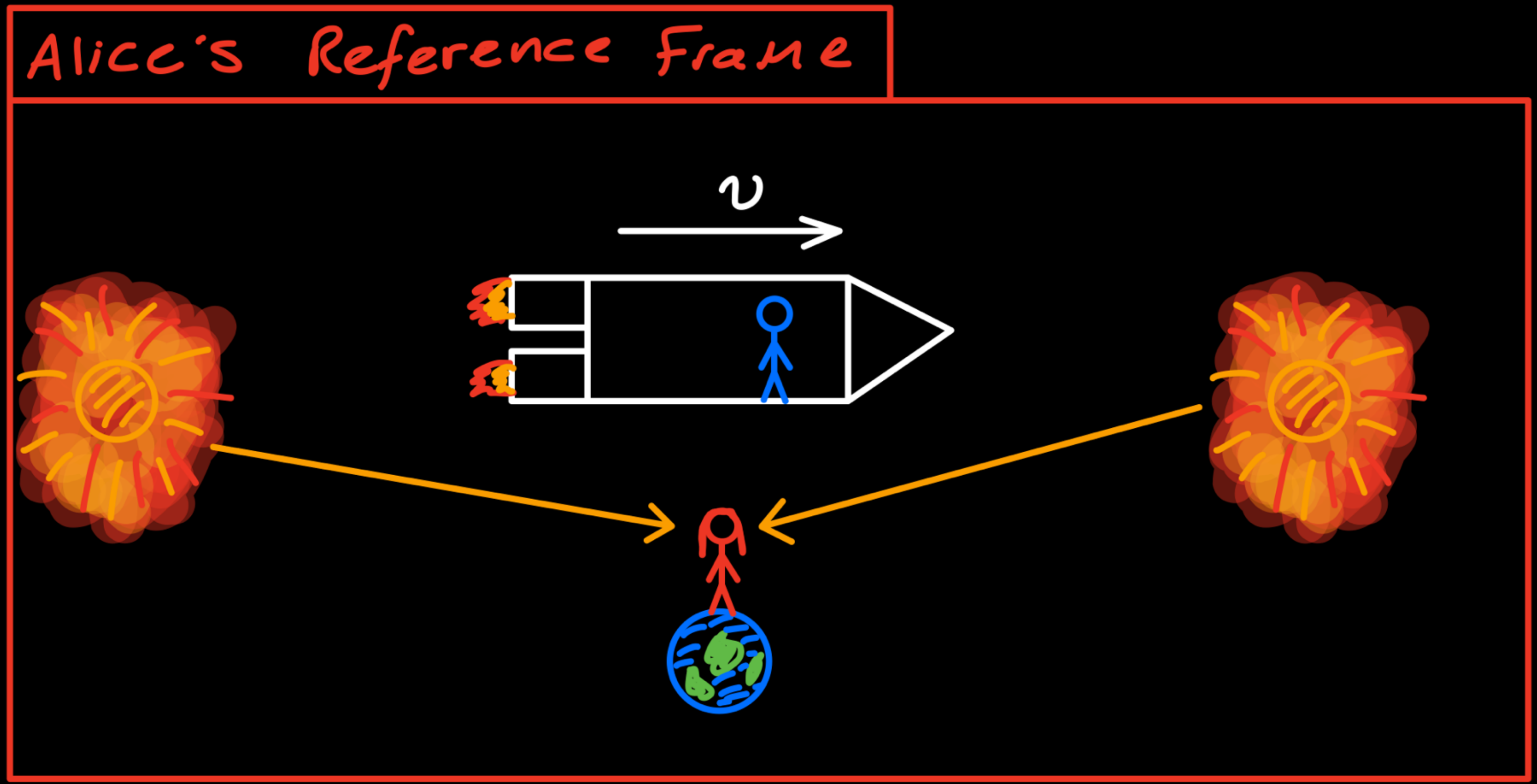
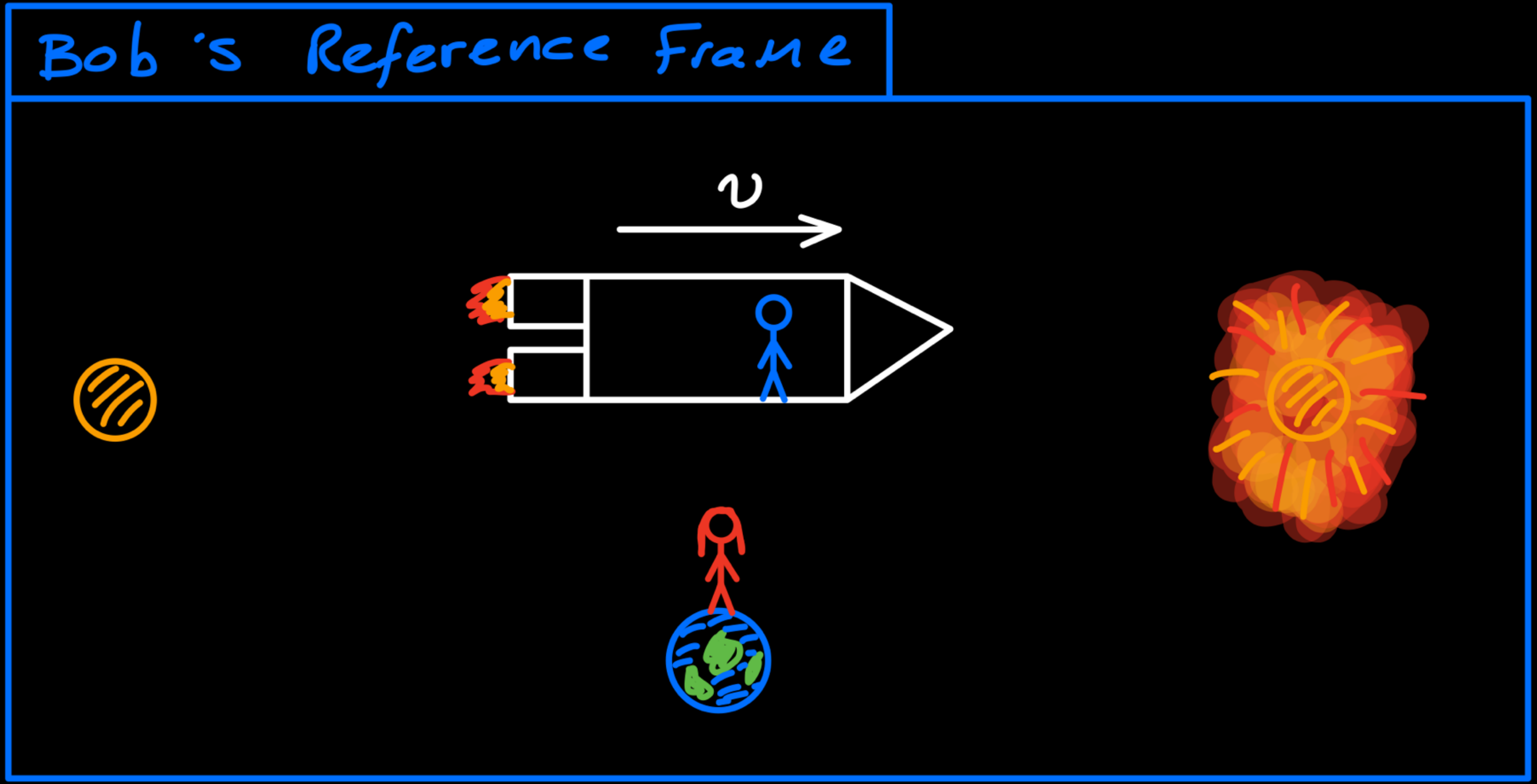


Simultaneity

Even though Bob passes directly by the Earth during the right stars supernova, the left star has not yet exploded.



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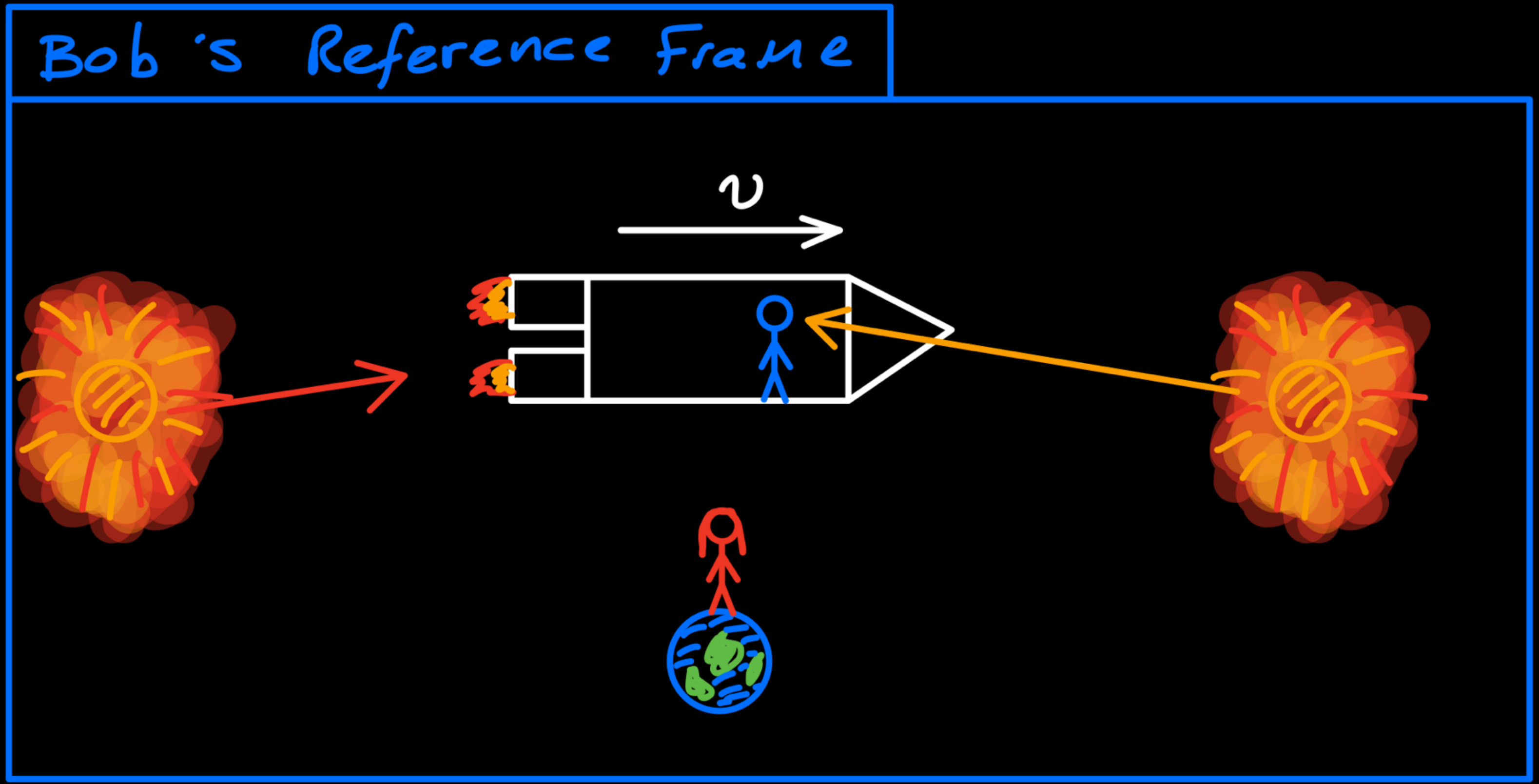
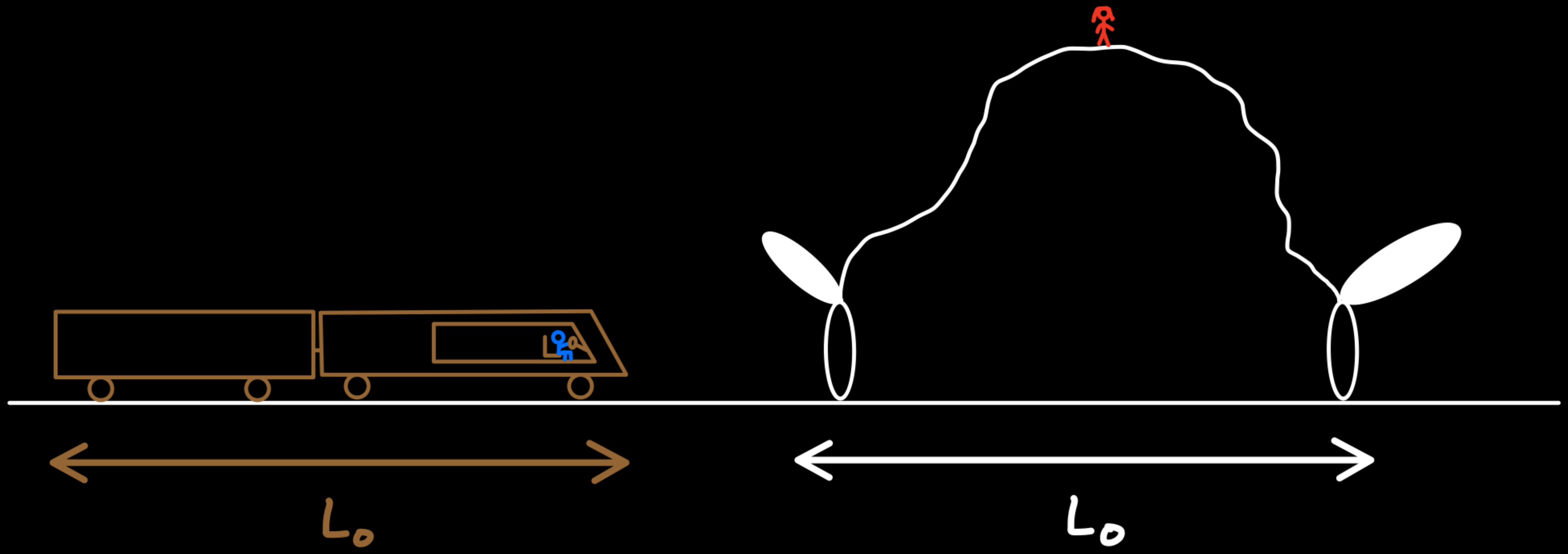


The Train Paradox



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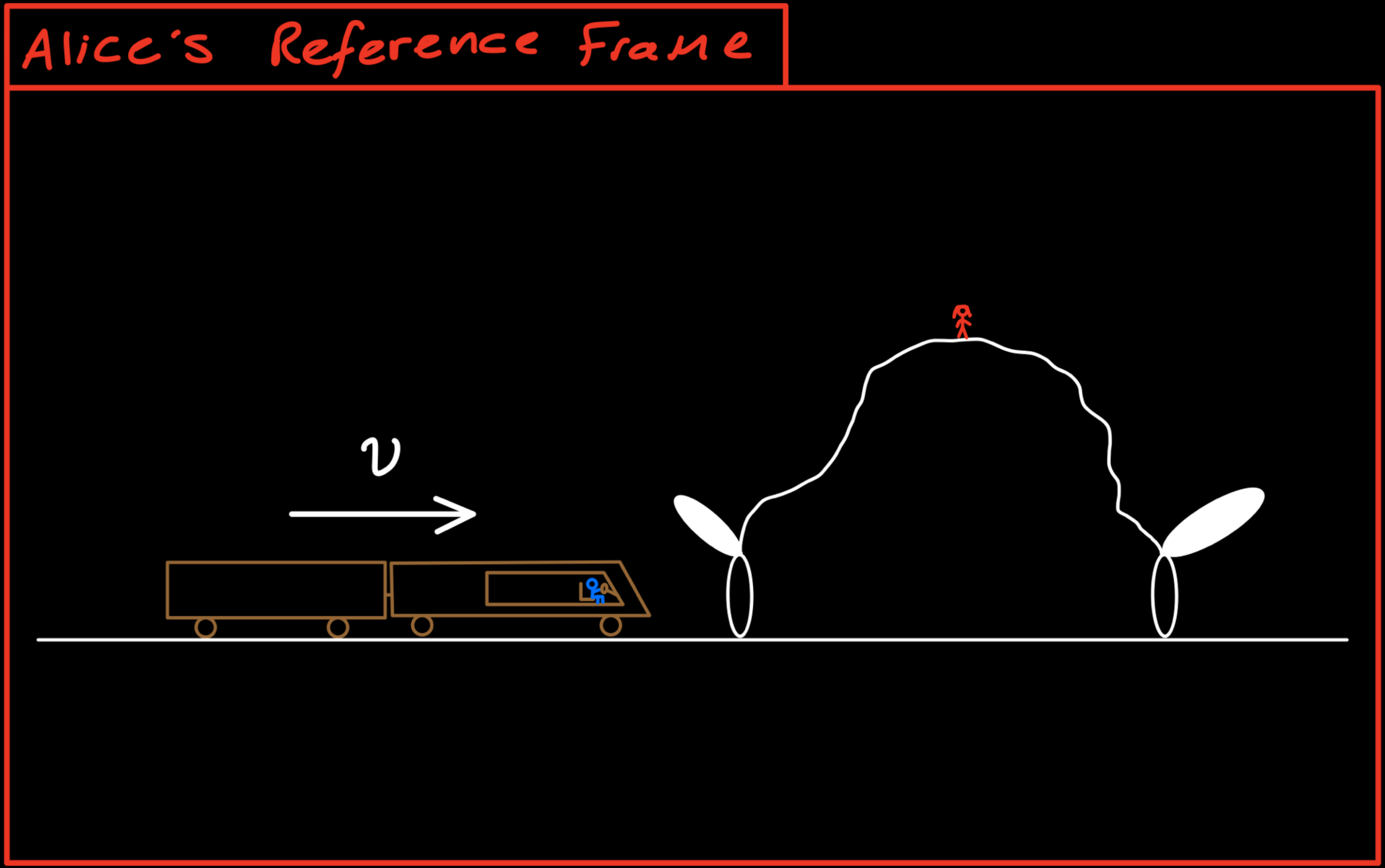

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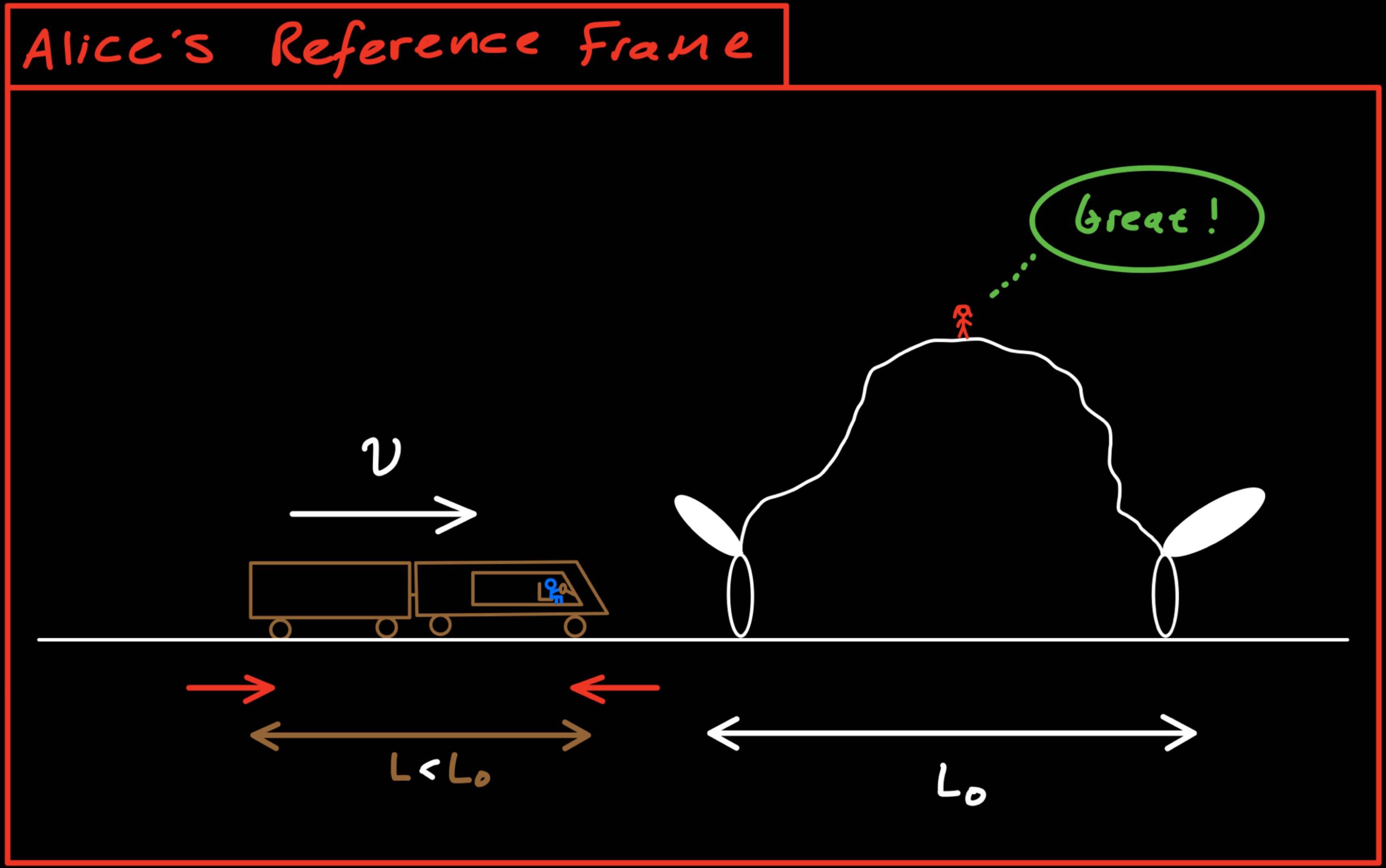

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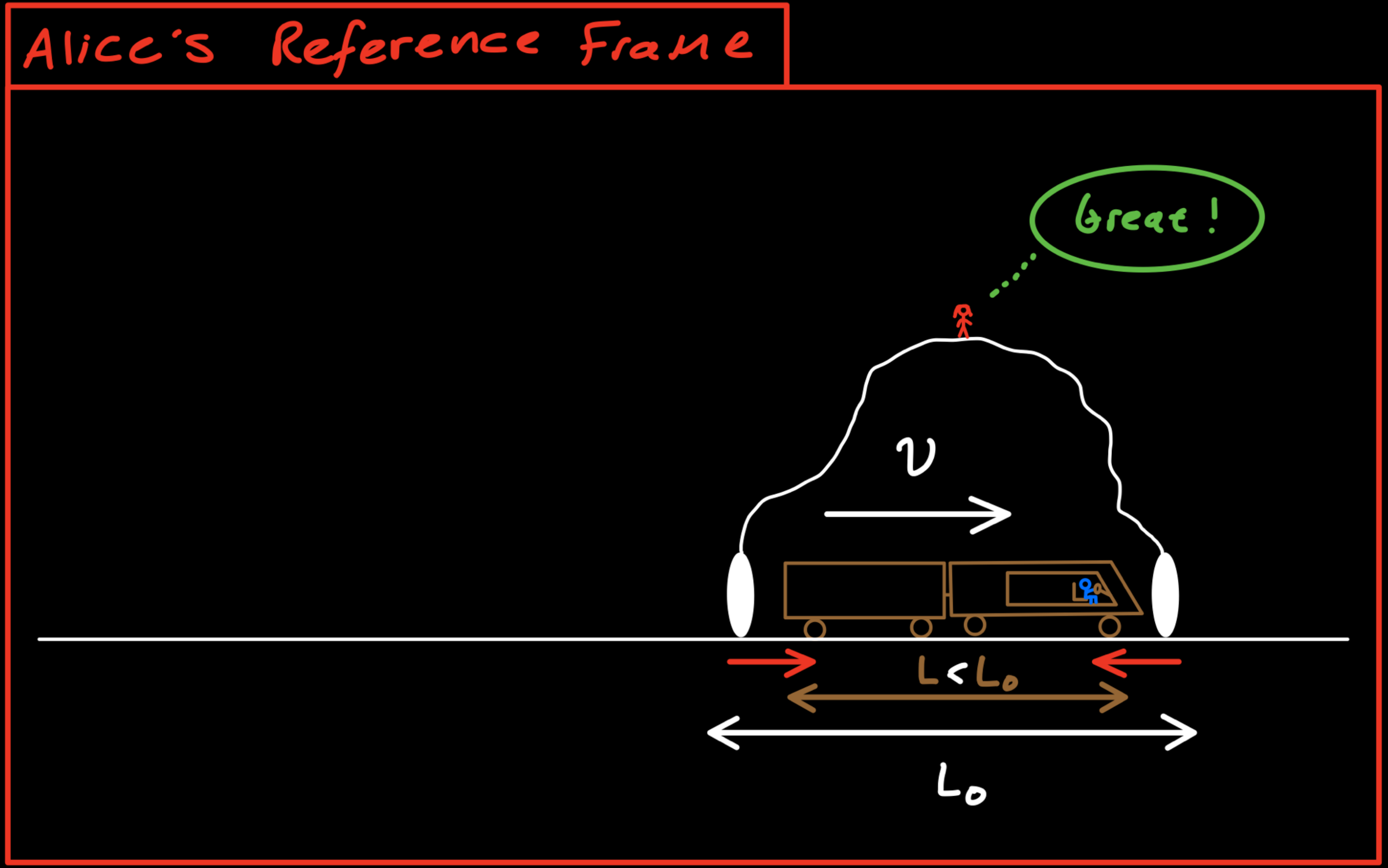

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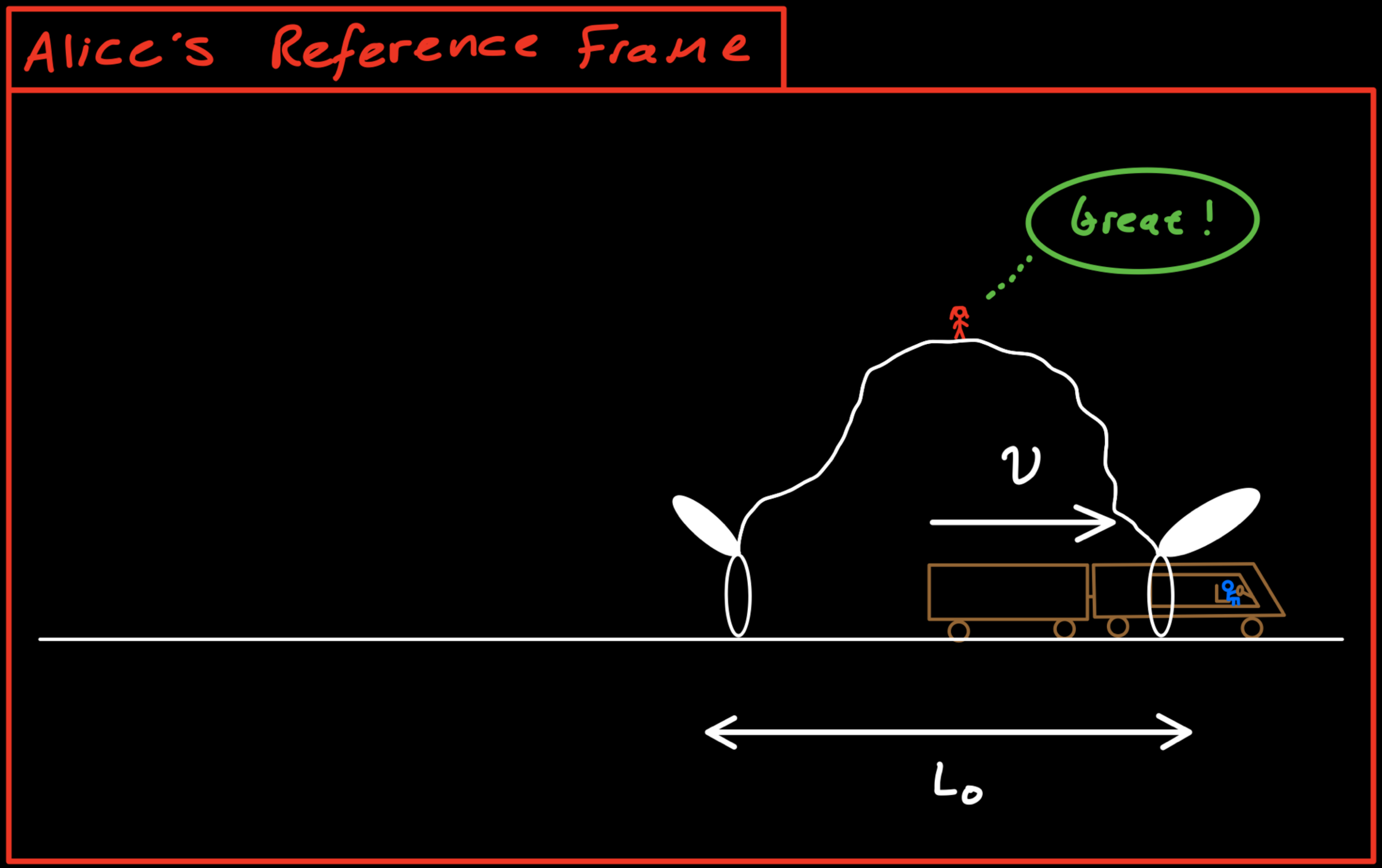

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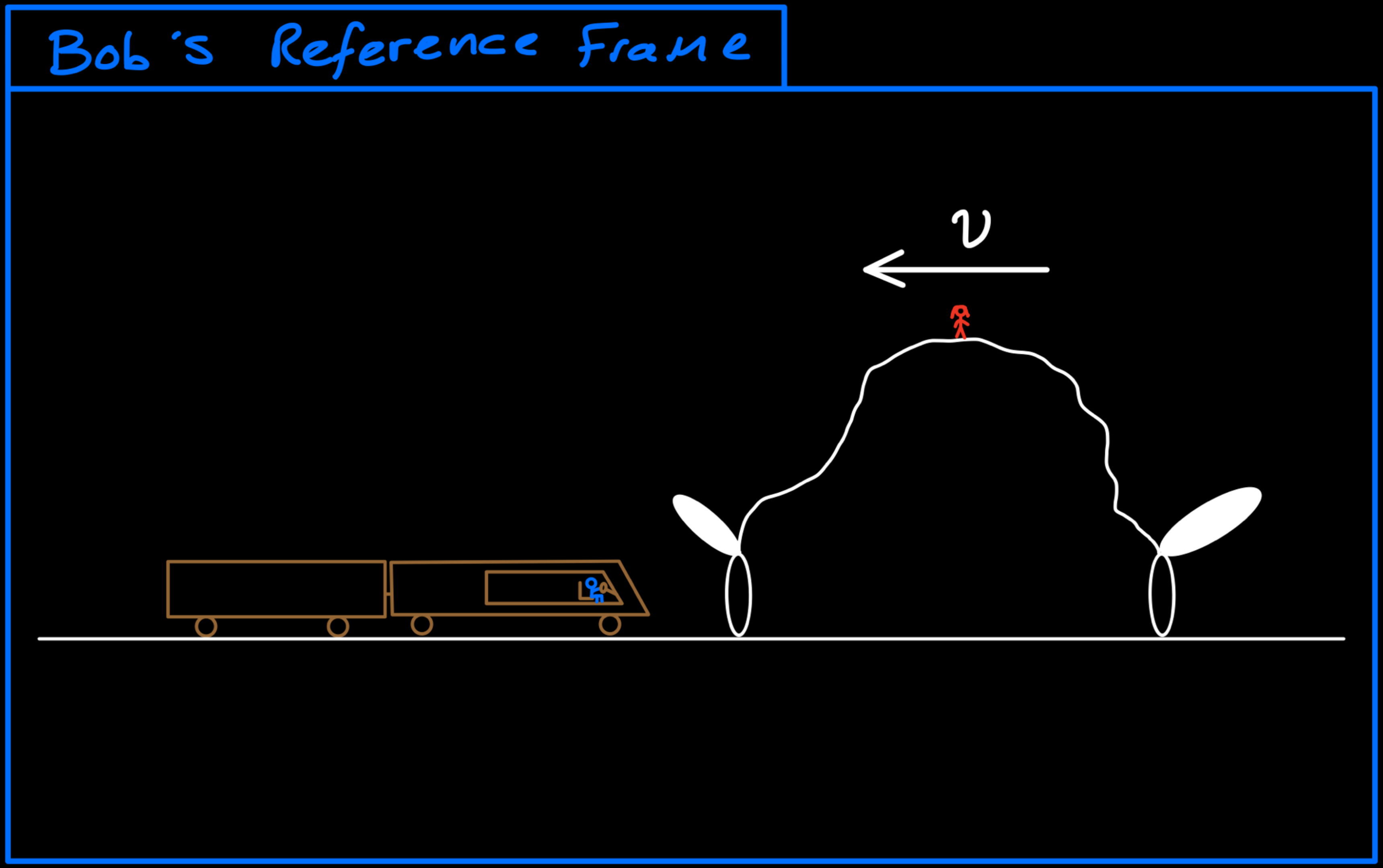

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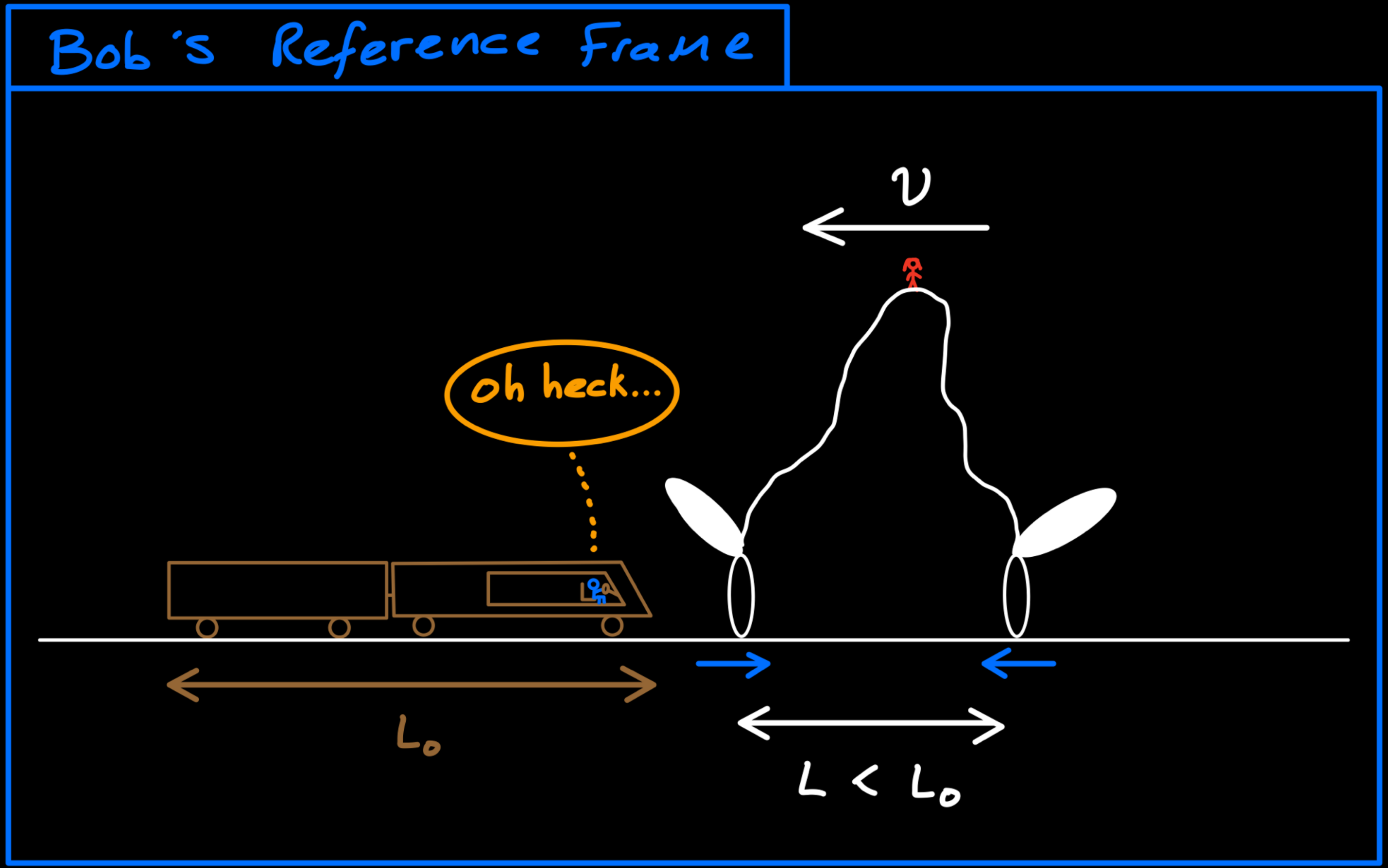

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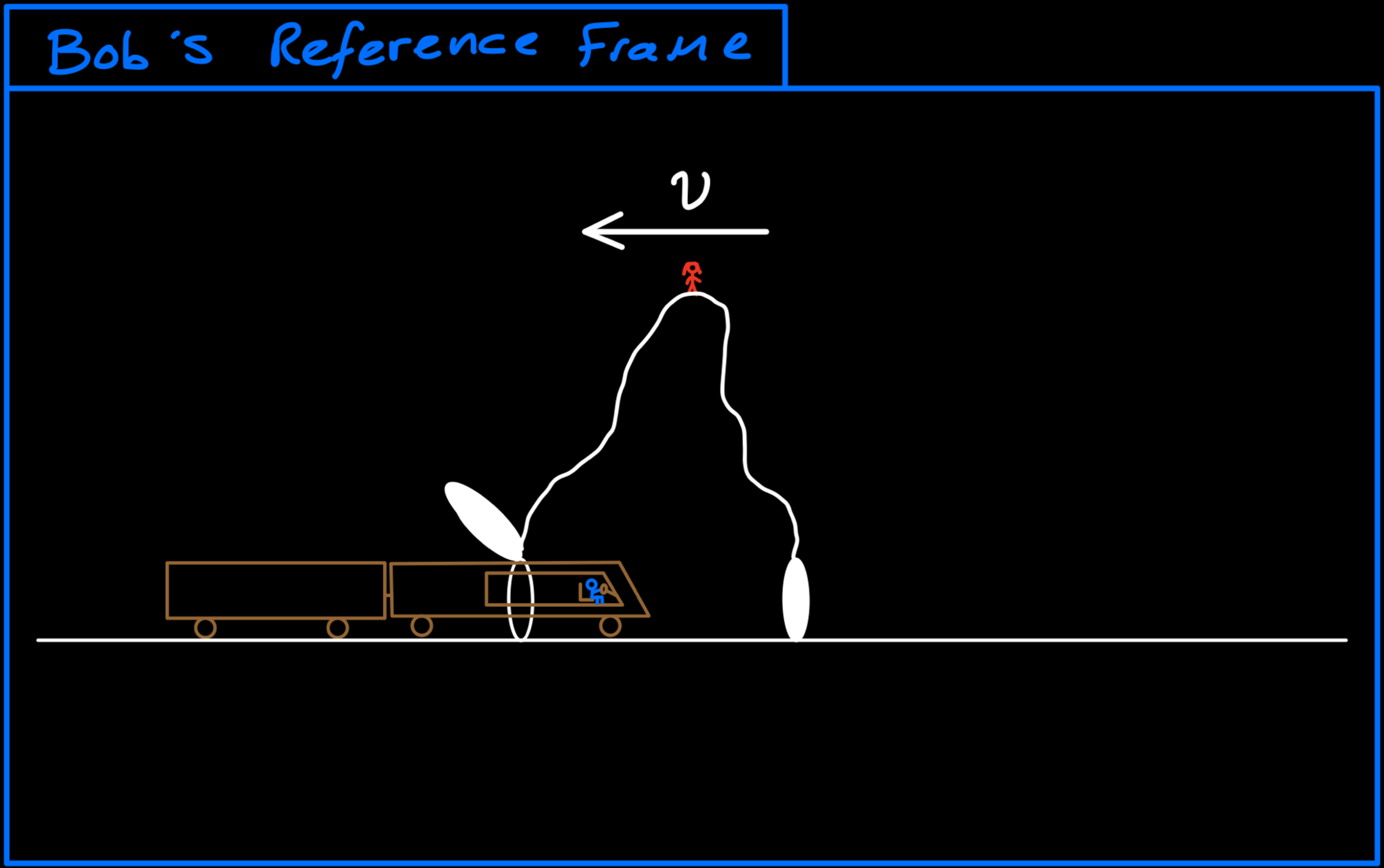

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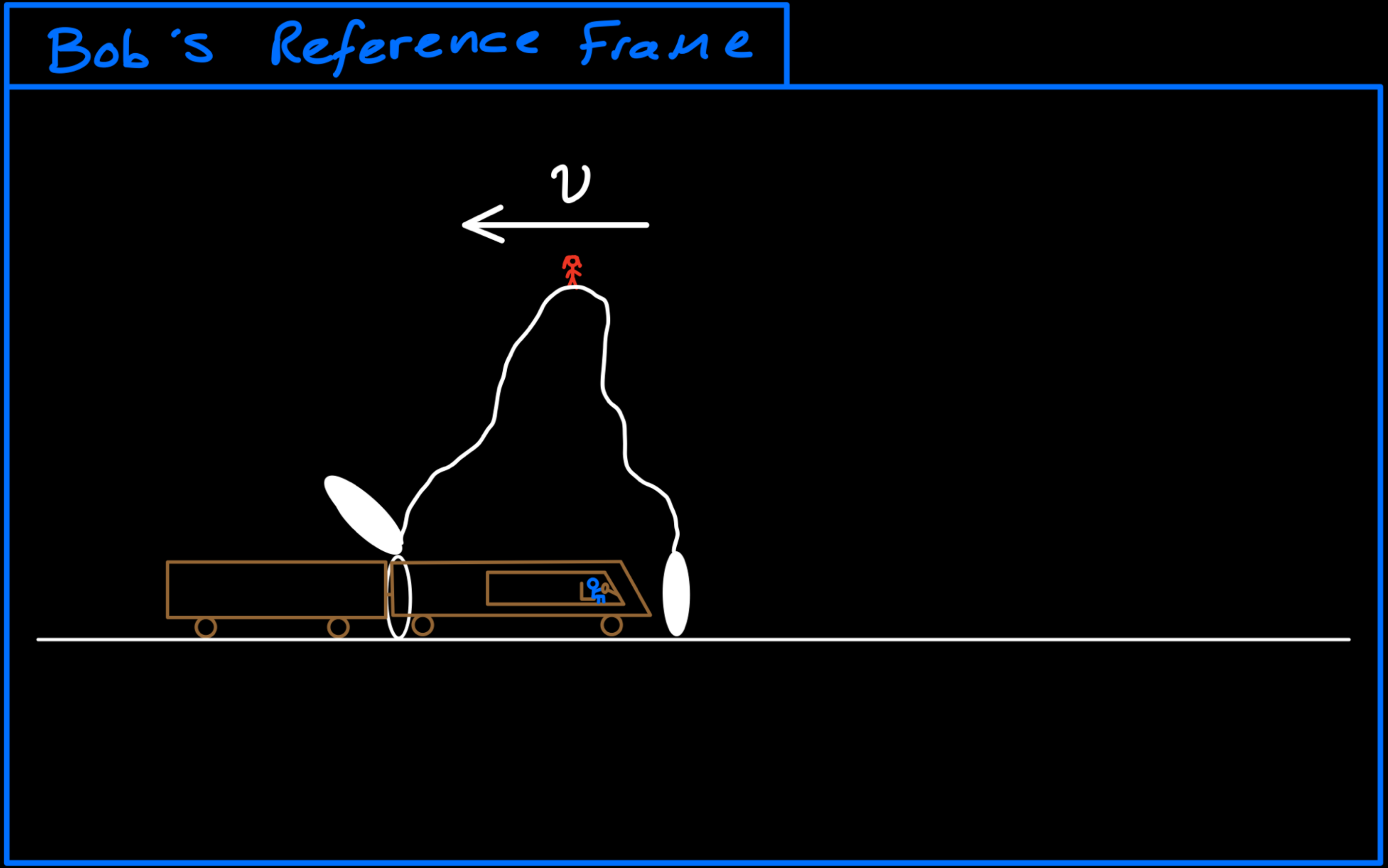

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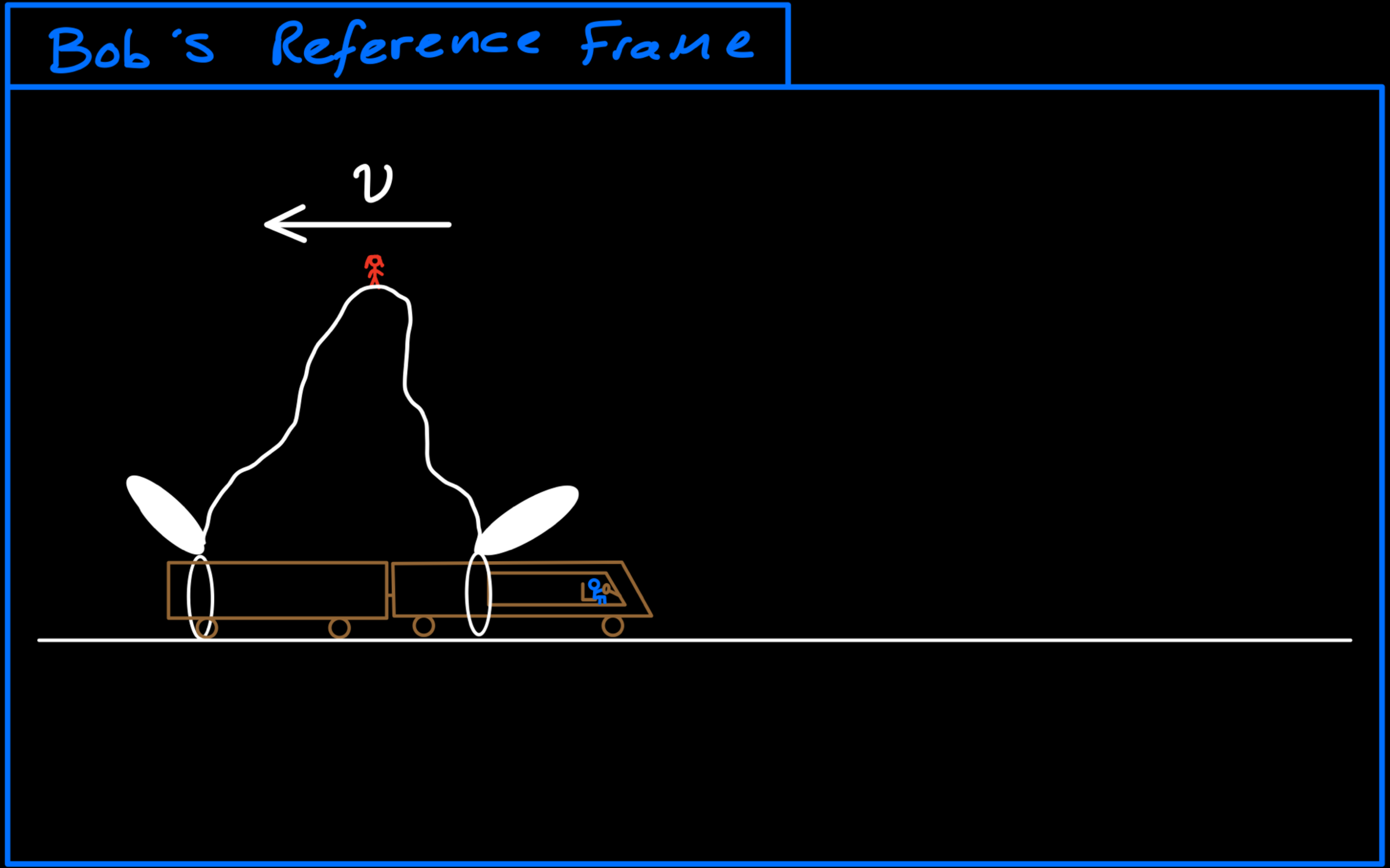

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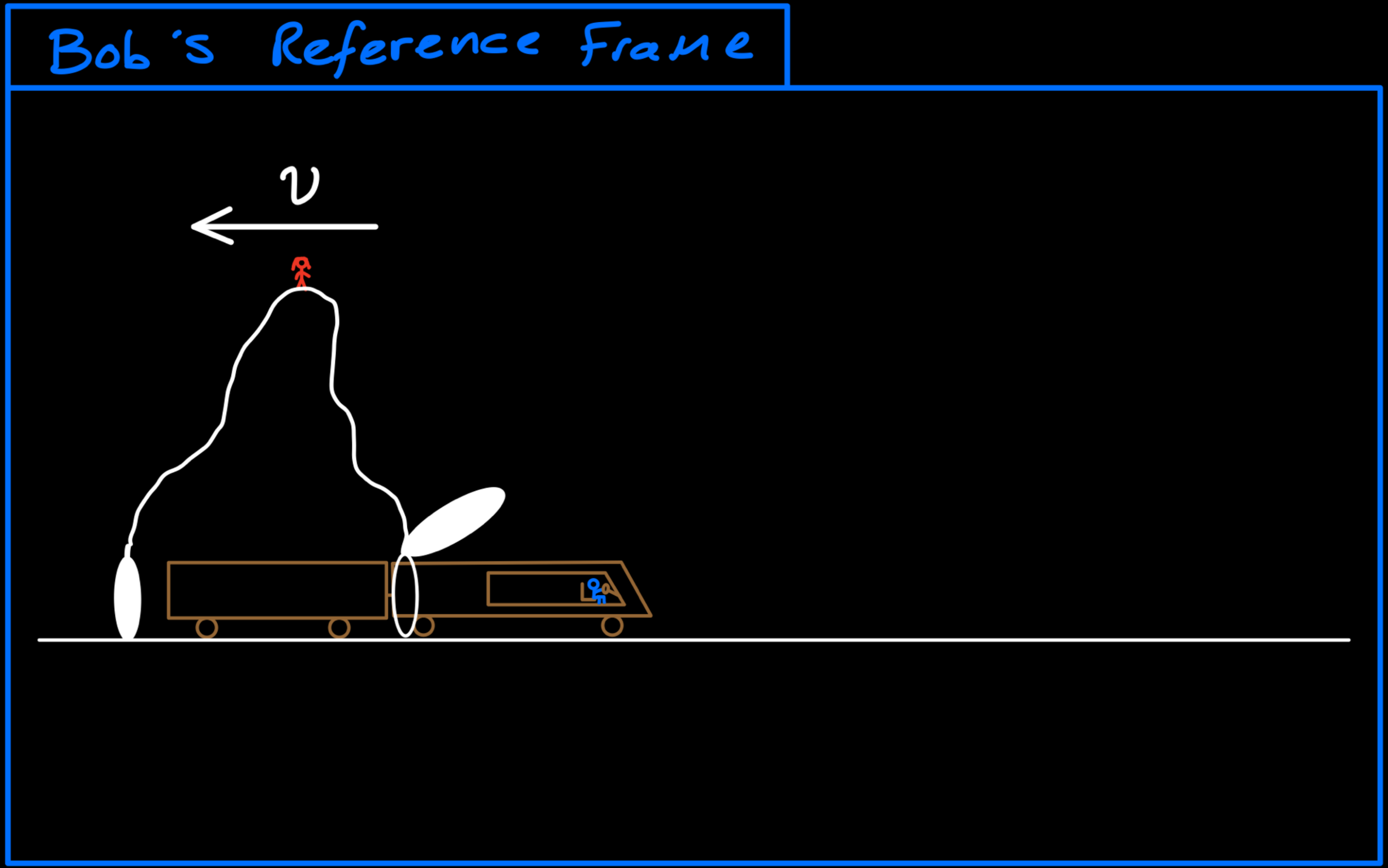

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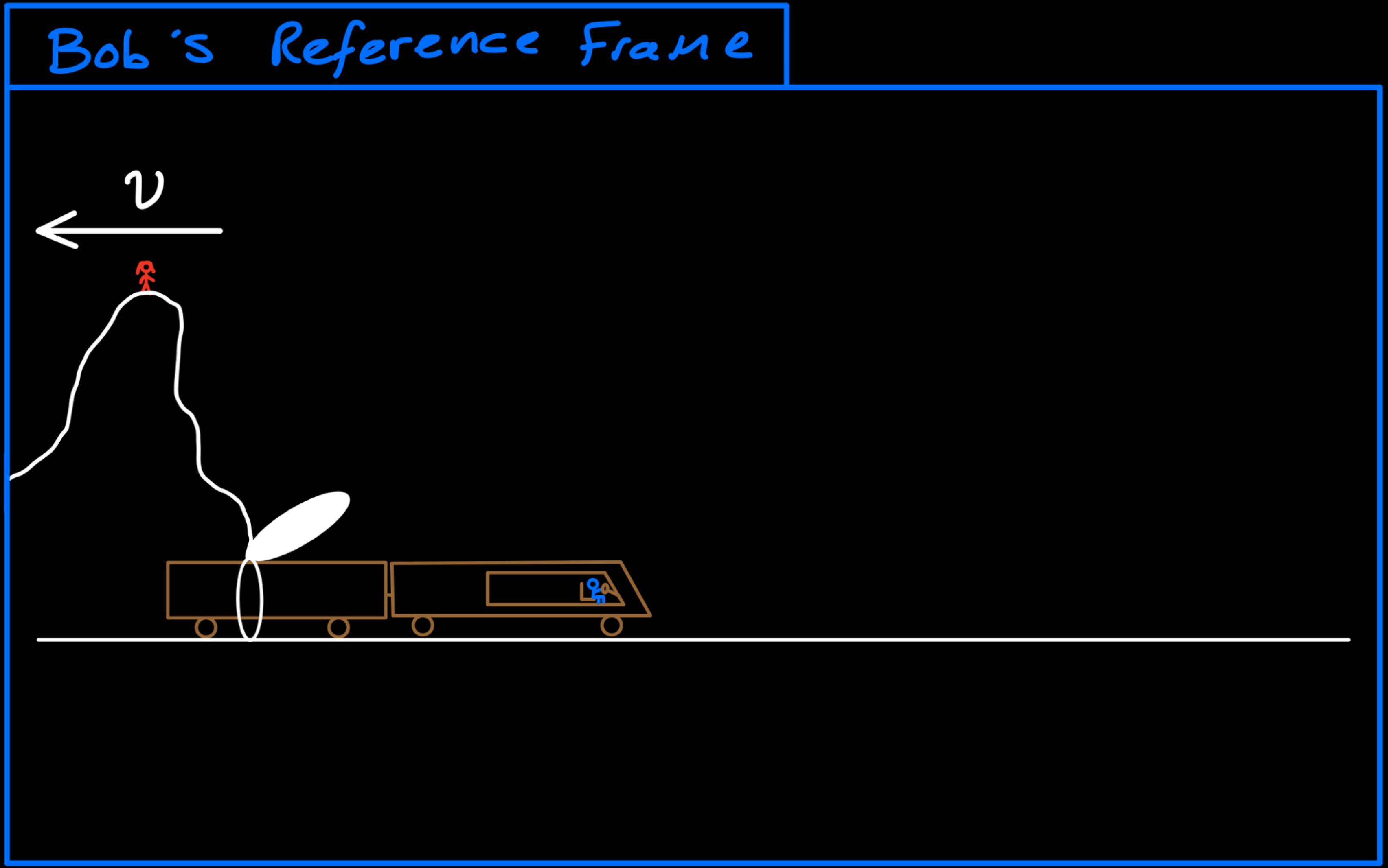


Questions!

Coming Up...

The Science of Space: A Physicists Guide to the Galaxy

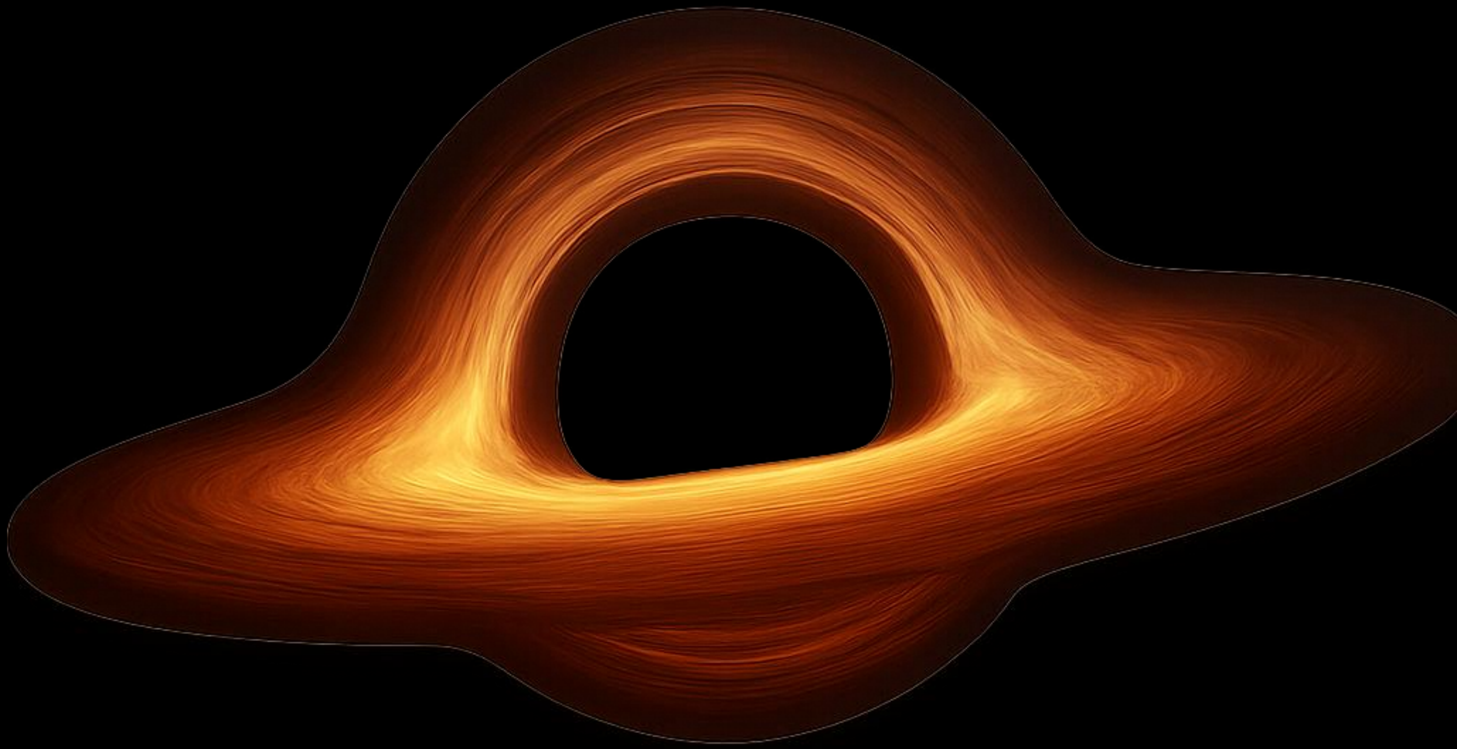
Every Sunday 11:30am in May @ The Beecroft Gallery Lecture Theatre

~~*‘Our Place in the Cosmos’ (04/05)*~~

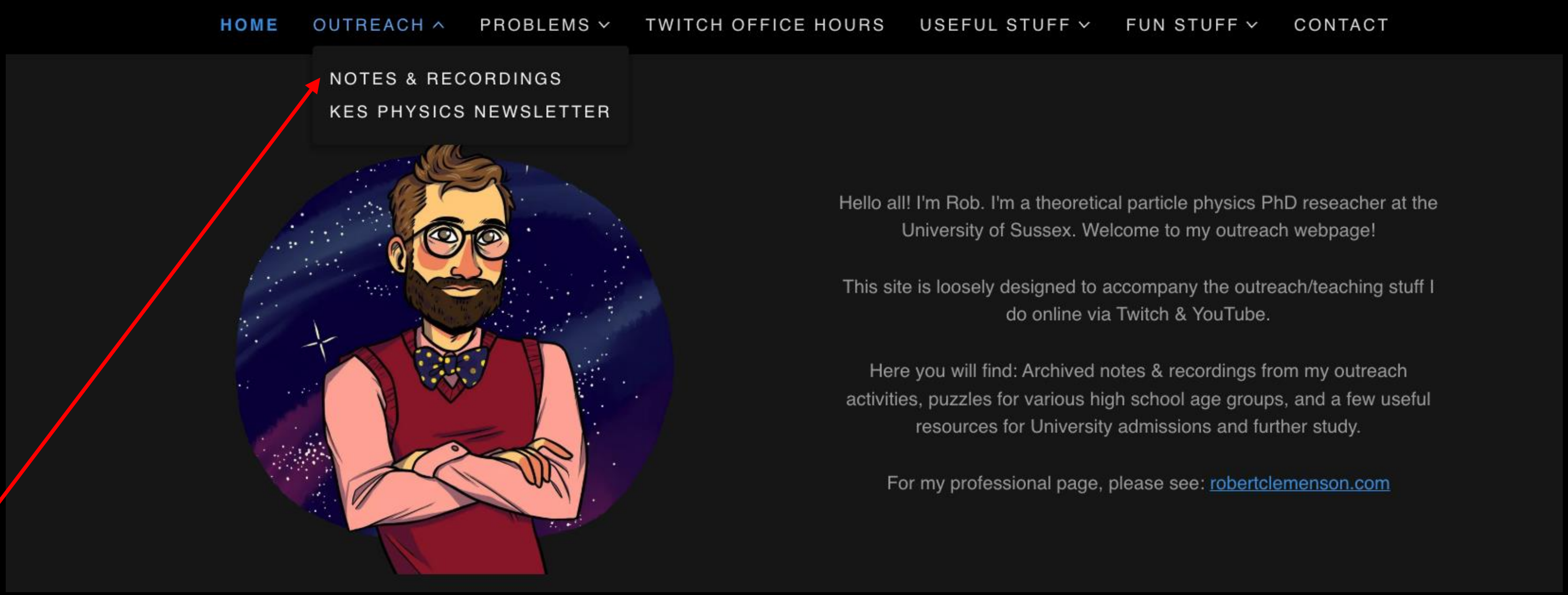
~~*‘Schrodinger’s Cat in the Particle Zoo’ (11/05)*~~

~~*‘Time Travel 101’ (18/05)*~~

‘Black Holes and Beyond’ (25/05)



Lecture Slides



These lecture slides are available on my outreach website:

CosmicConundra.com