How and Why to go Beyond the Discovery of the Higgs Boson

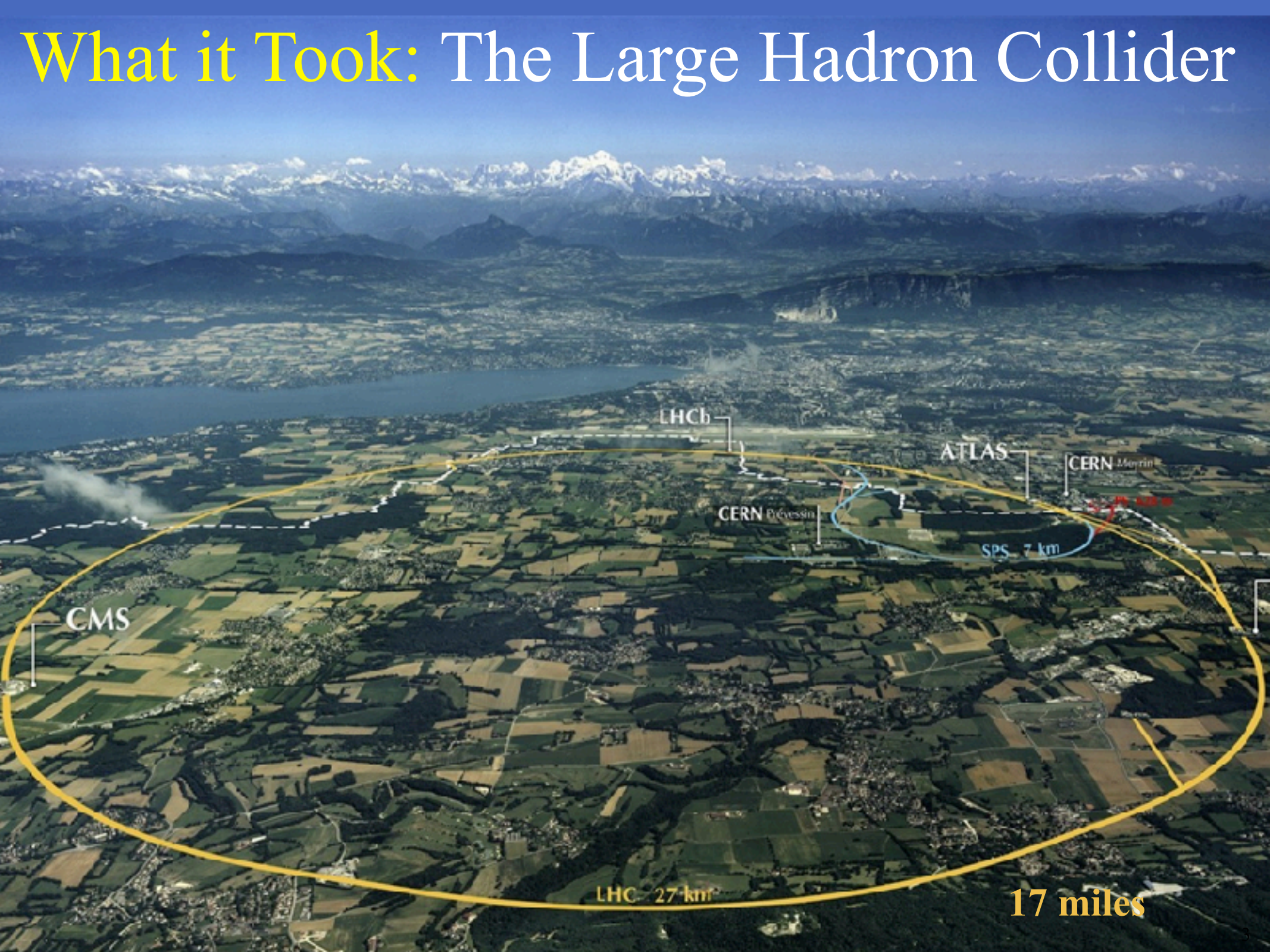
John Alison

University of Chicago

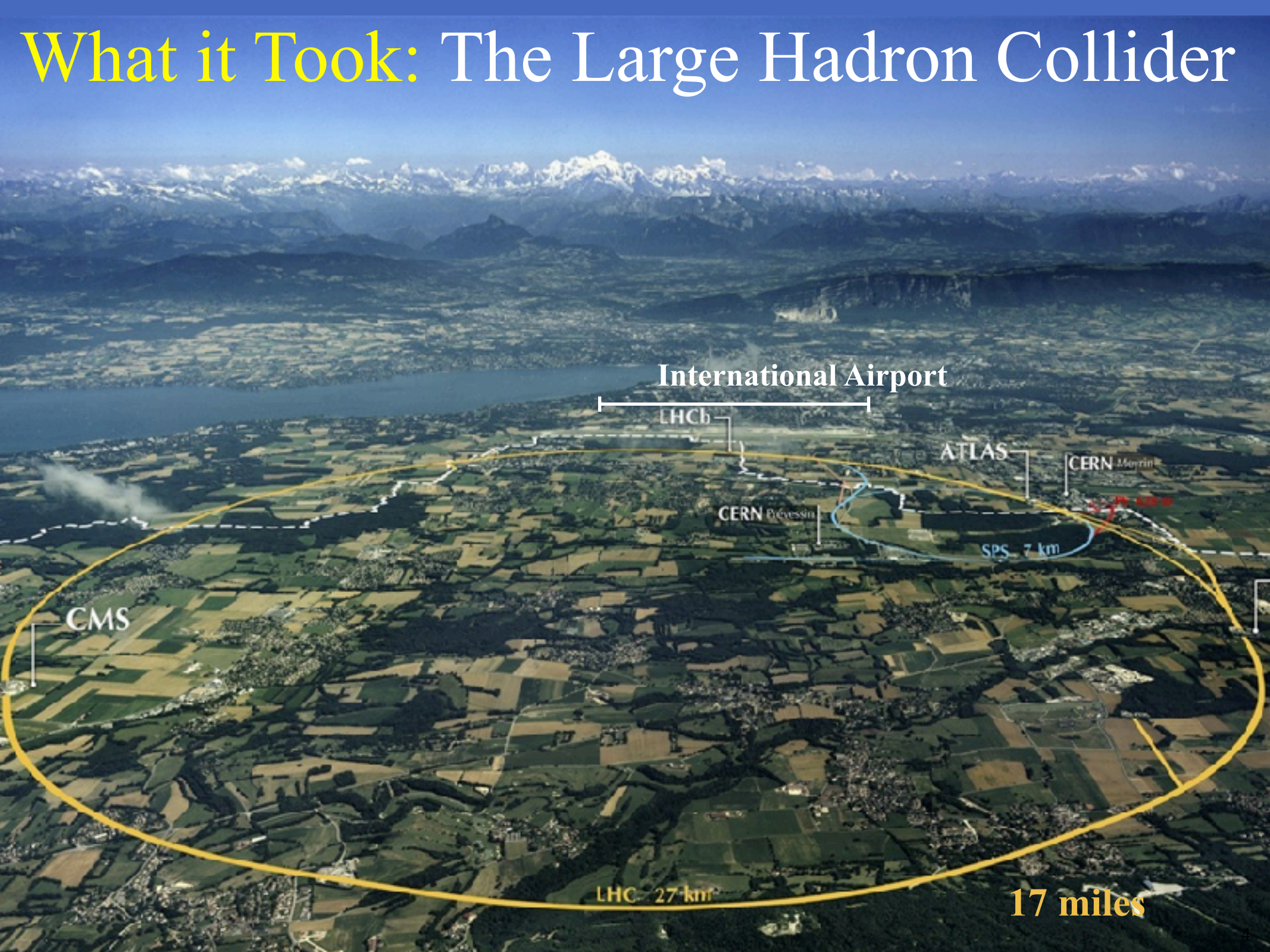
Discovery of the Higgs Boson

Nobel Prize

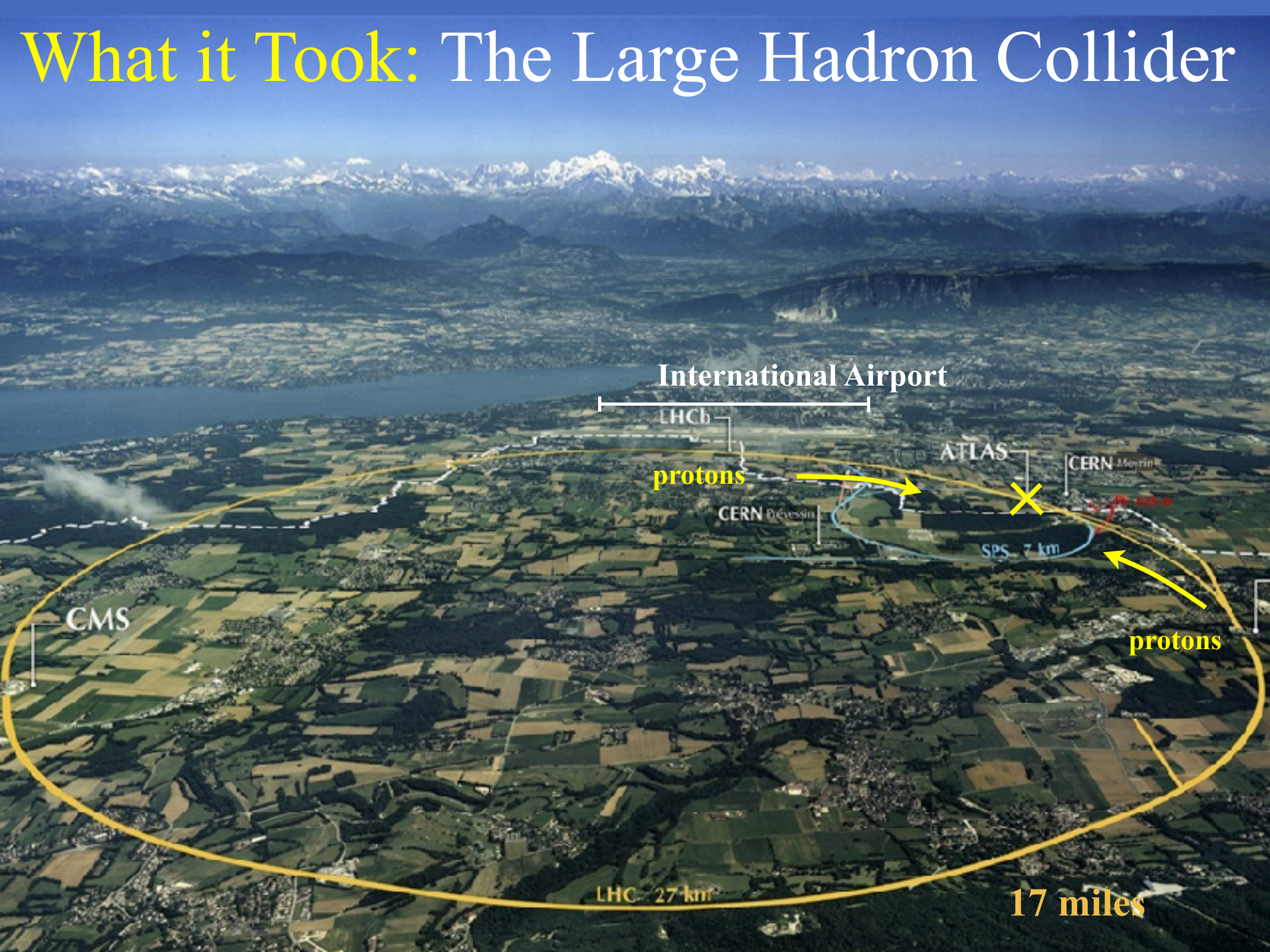
What it Took: The Large Hadron Collider



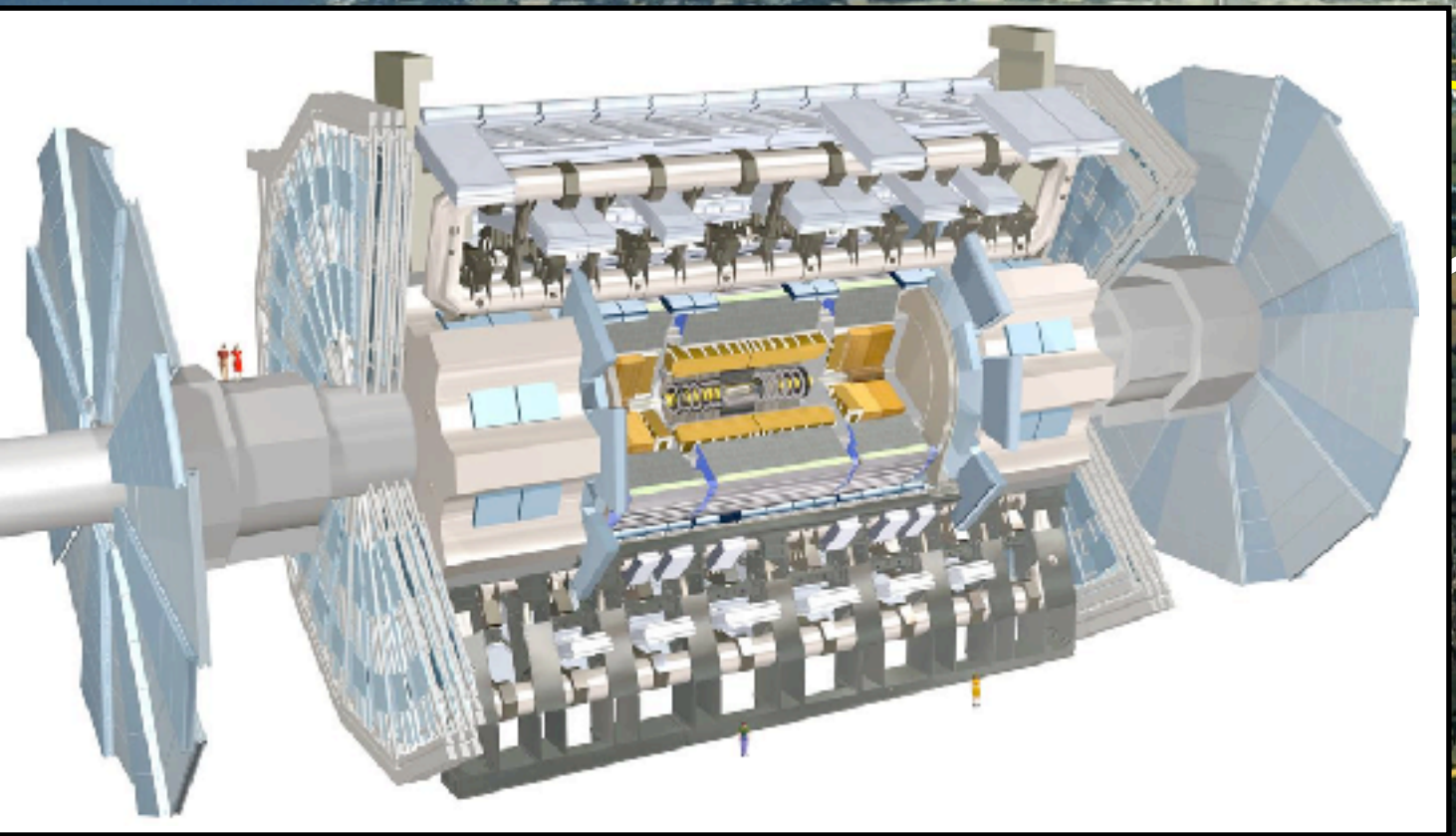
What it Took: The Large Hadron Collider



What it Took: The Large Hadron Collider



What it Took: The Large Hadron Collider



What it Took: In Numbers

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light
- **~1 billion** proton collisions / second (for 2 years)

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light
- **~1 billion** proton collisions / second (for 2 years)
- Total budget: **~10 billions dollars**

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light
- **~1 billion** proton collisions / second (for 2 years)
- Total budget: **~10 billions dollars**
- Detectors - size of apartment buildings - operating at **40 MHz**

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light
- **~1 billion** proton collisions / second (for 2 years)
- Total budget: **~10 billions dollars**
- Detectors - size of apartment buildings - operating at **40 MHz**
- Generate **80 TB/s** (~10 × size of library of congress)

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light
- **~1 billion** proton collisions / second (for 2 years)
- Total budget: **~10 billions dollars**
- Detectors - size of apartment buildings - operating at **40 MHz**
- Generate **80 TB/s** (~10 × size of library of congress)
- (Salary of physicist) << (Salary of banker or engineer)

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light
- **~1 billion** proton collisions / second (for 2 years)
- Total budget: **~10 billions dollars**
- Detectors - size of apartment buildings - operating at **40 MHz**
- Generate **80 TB/s** (~10 × size of library of congress)
- (Salary of physicist) << (Salary of banker or engineer)

What is the Higgs boson ?!?

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light
- **~1 billion** proton collisions / second (for 2 years)
- Total budget: **~10 billions dollars**
- Detectors - size of apartment buildings - operating at **40 MHz**
- Generate **80 TB/s** (~10 × size of library of congress)
- (Salary of physicist) << (Salary of banker or engineer)

What is the Higgs boson ?!?
Why did we need such extremes to find it ?

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light
- **~1 billion** proton collisions / second (for 2 years)
- Total budget: **~10 billions dollars**
- Detectors - size of apartment buildings - operating at **40 MHz**
- Generate **80 TB/s** (~10 × size of library of congress)
- (Salary of physicist) << (Salary of banker or engineer)

What is the Higgs boson ?!?
Why did we need such extremes to find it ?
Why look for the Higgs boson in the first place ?

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light
- **~1 billion** proton collisions / second (for 2 years)
- Total budget: **~10 billions dollars**
- Detectors - size of apartment buildings - operating at **40 MHz**
- Generate **80 TB/s** (~10 × size of library of congress)
- (Salary of physicist) << (Salary of banker or engineer)

What is the Higgs boson ?!?
Why did we need such extremes to find it ?
Why look for the Higgs boson in the first place ?
Are we done now that we have found it ?

Lecture Outline

April 1st: ***Newton's dream & 20th Century Revolution***

April 8th: **Mission Barely Possible: QM + SR**

April 15th: **Standard Model & Importance of the Higgs**

April 22nd: **The Cannon and the Camera**

April 29th: **Guest Lecture**

May 6th: **The Discovery of the Higgs Boson**

May 13th: **Going beyond the Higgs**

May 20th: **Experimental Challenges**

May 27th: **Memorial Day: No Lecture**

June 3rd: **What comes next ?**

Lecture Outline

April 1st: ***Newton's dream & 20th Century Revolution***

April 8th: **Mission Barely Possible: QM + SR**

April 15th: **Standard Model & Importance of the Higgs**

April 22nd: **The Cannon and the Camera**

April 29th: **Guest Lecture**

May 6th: **The Discovery of**

May 13th: **Going beyond th**

May 20th: **Experimental Ch**

May 27th: **Memorial Day: N**

June 3rd: **What comes next**

Sources:

- **Nima Arkani-Hamed**
- **Steven Weinberg**
- …

I will keep this list up to date as we go along.

Who am I ?

Who am I ?

Who am I ?

Who am I ?

Who am I ?

Penn
UNIVERSITY of PENNSYLVANIA

Who am I ?

Who am I ?

28

Today's Lecture

Newton's Dream: The direction of science

20th Century Revolutions:

- Relativity
- Quantum Mechanics

Scientific Explanation

Notion that diverse natural phenomena can be explained by simpler concepts dates back to the ancients.

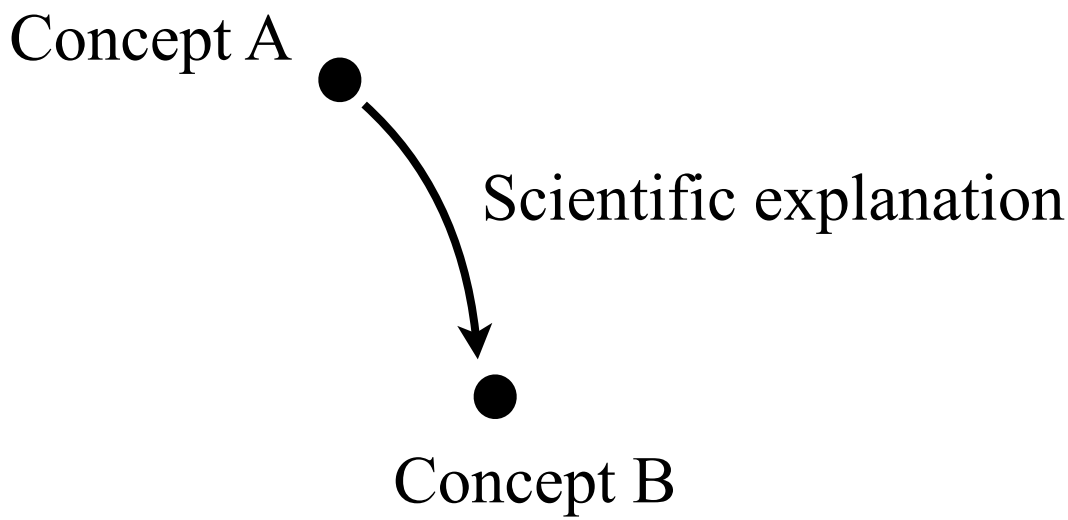
Scientific Explanation

Notion that diverse natural phenomena can be explained by simpler concepts dates back to the ancients.

Came to life with Newton (Galileo) :

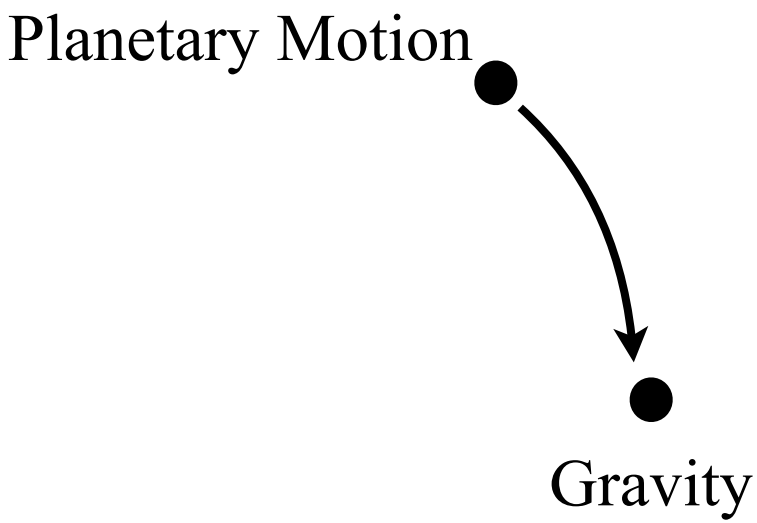
- Mathematics central to describing nature
- Developed new branch of math: calculus
- New laws of motion and gravity
- Biggest advance of all: ***"Newton's Dream"***

Scientific Explanation



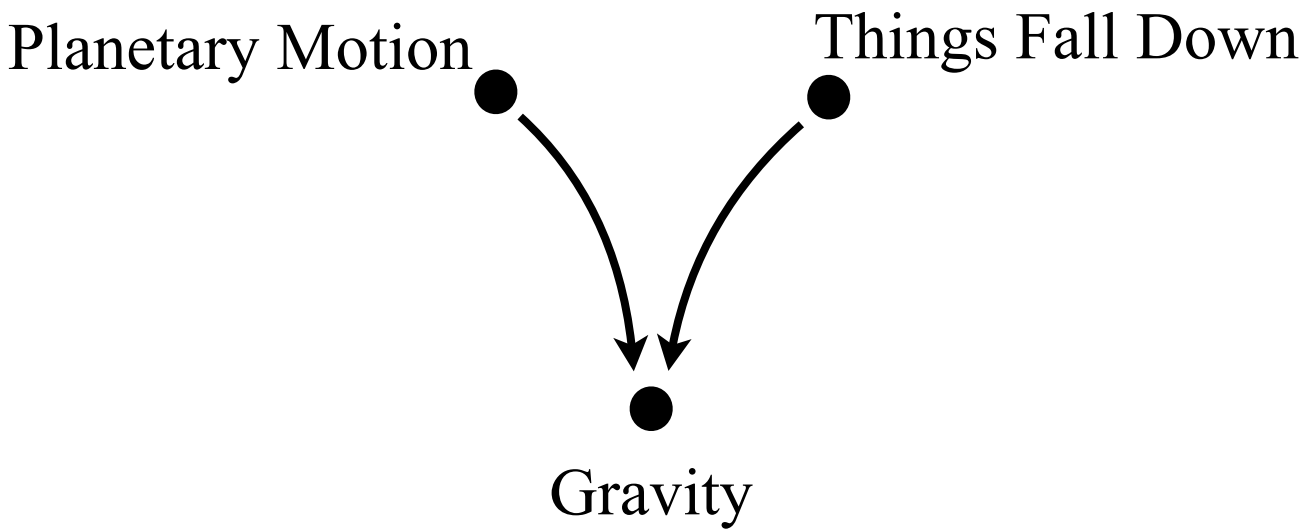
Scientific Explanation

Newton:



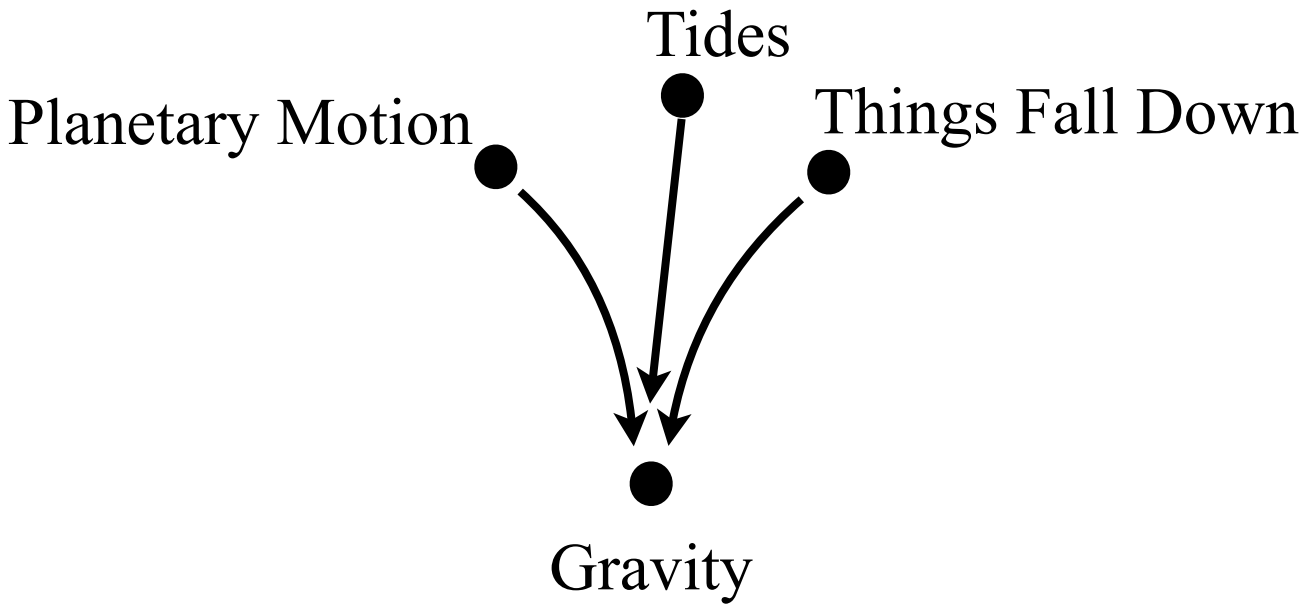
Scientific Explanation

Newton:



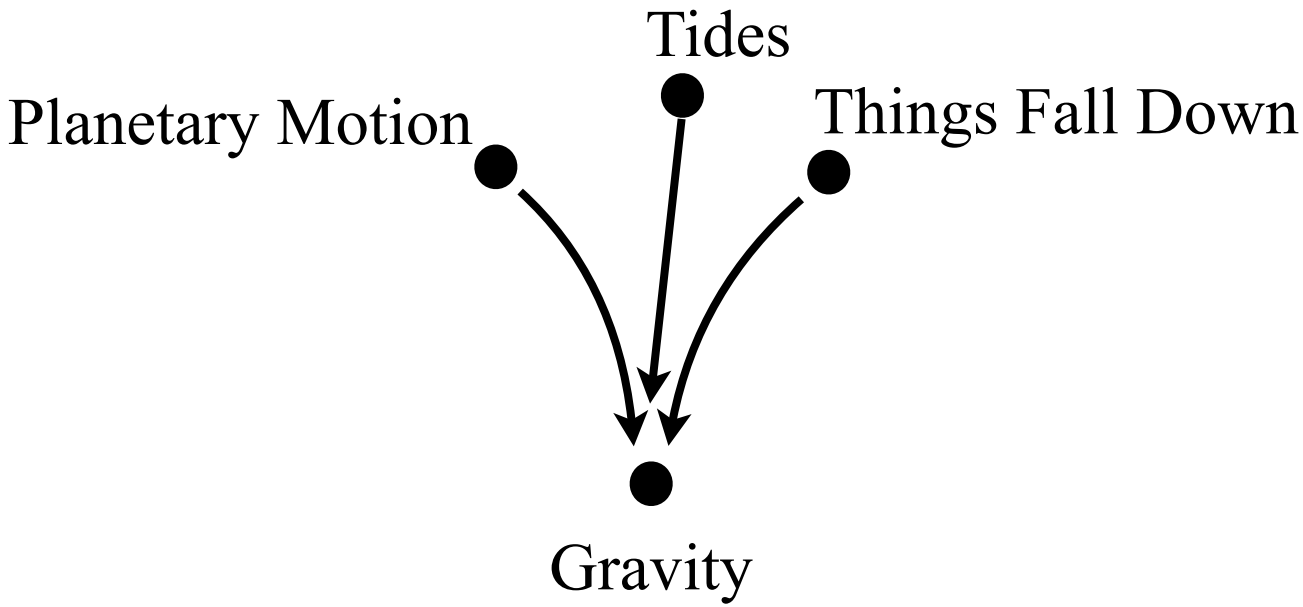
Scientific Explanation

Newton:



Scientific Explanation

Newton:

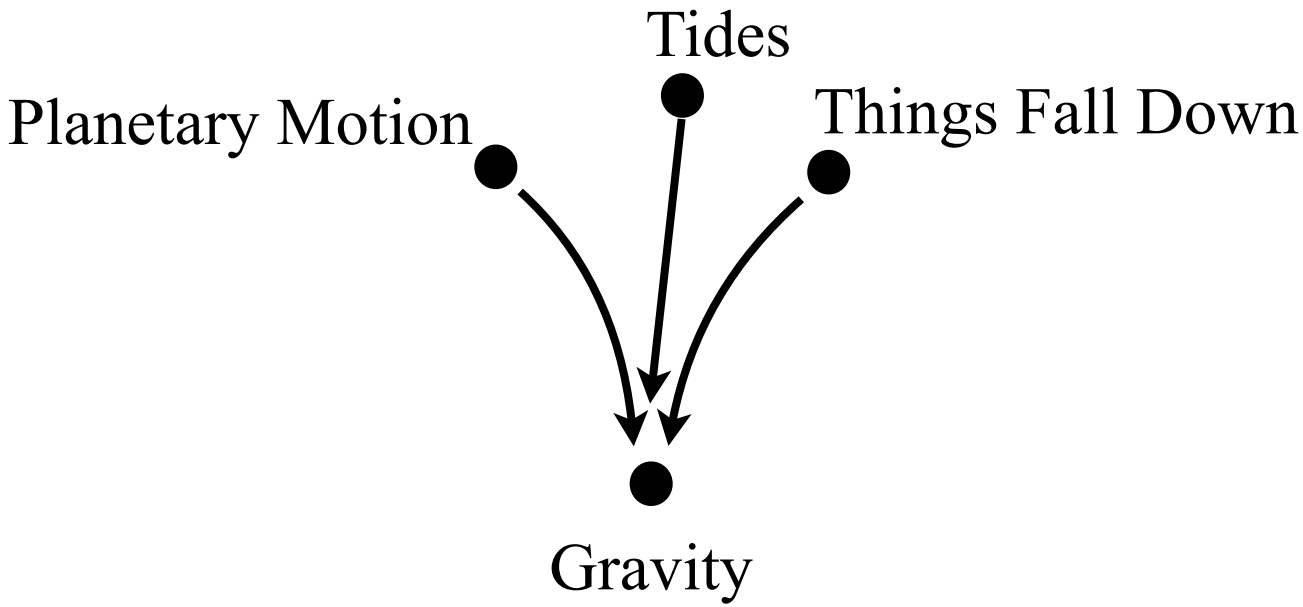


"I wish we could derive the rest of the phenomena of nature by the same kind of reasoning as for mechanical principles. For I am induced by many reasons to suspect that they may all depend on certain forces."

- Newton, Preface to Principia, 1686

Scientific Explanation

Newton:

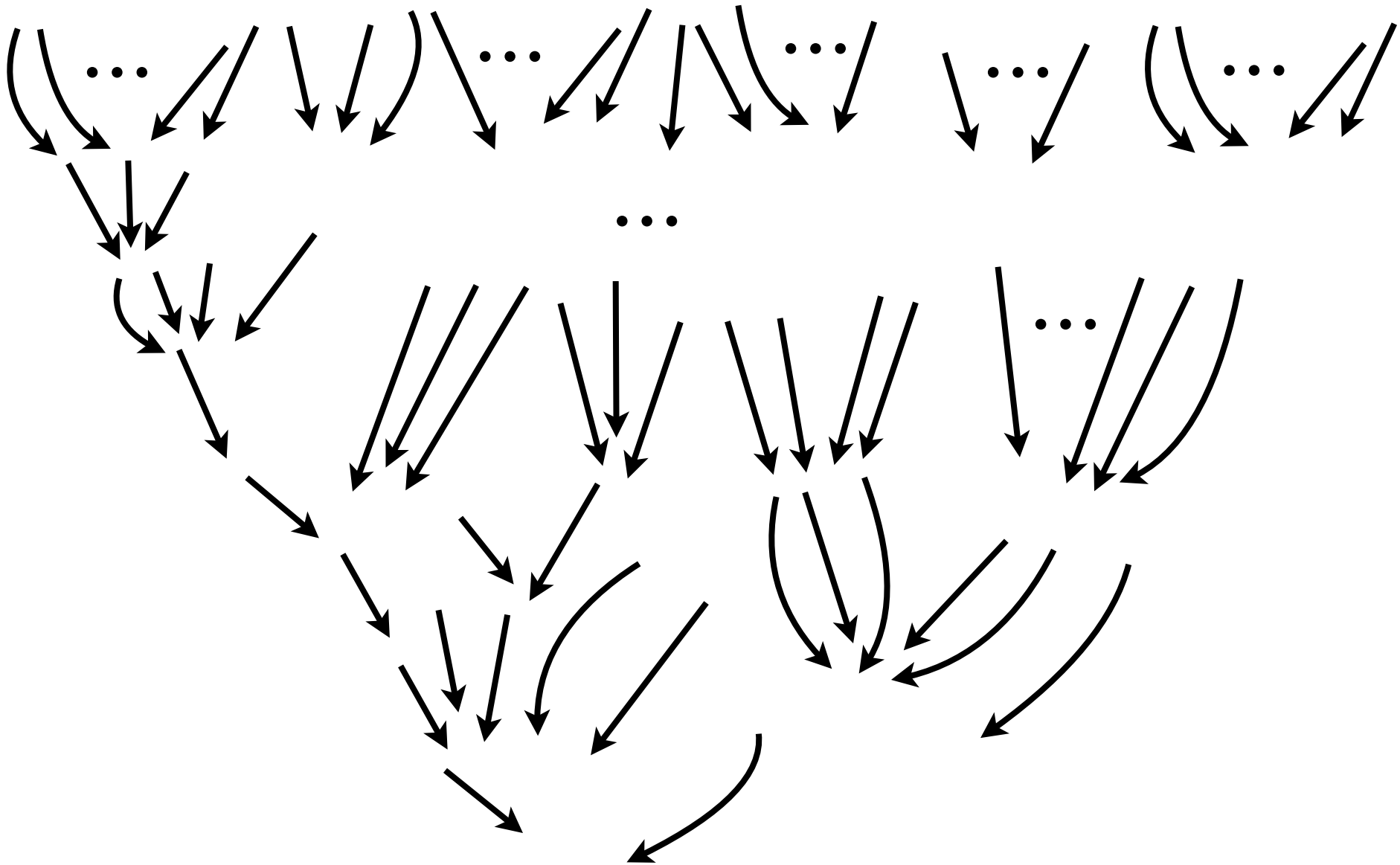


"I wish we could derive the rest of the phenomena of nature by the same kind of reasoning as for mechanical principles. For I am induced by many reasons to suspect that they may all depend on certain forces."

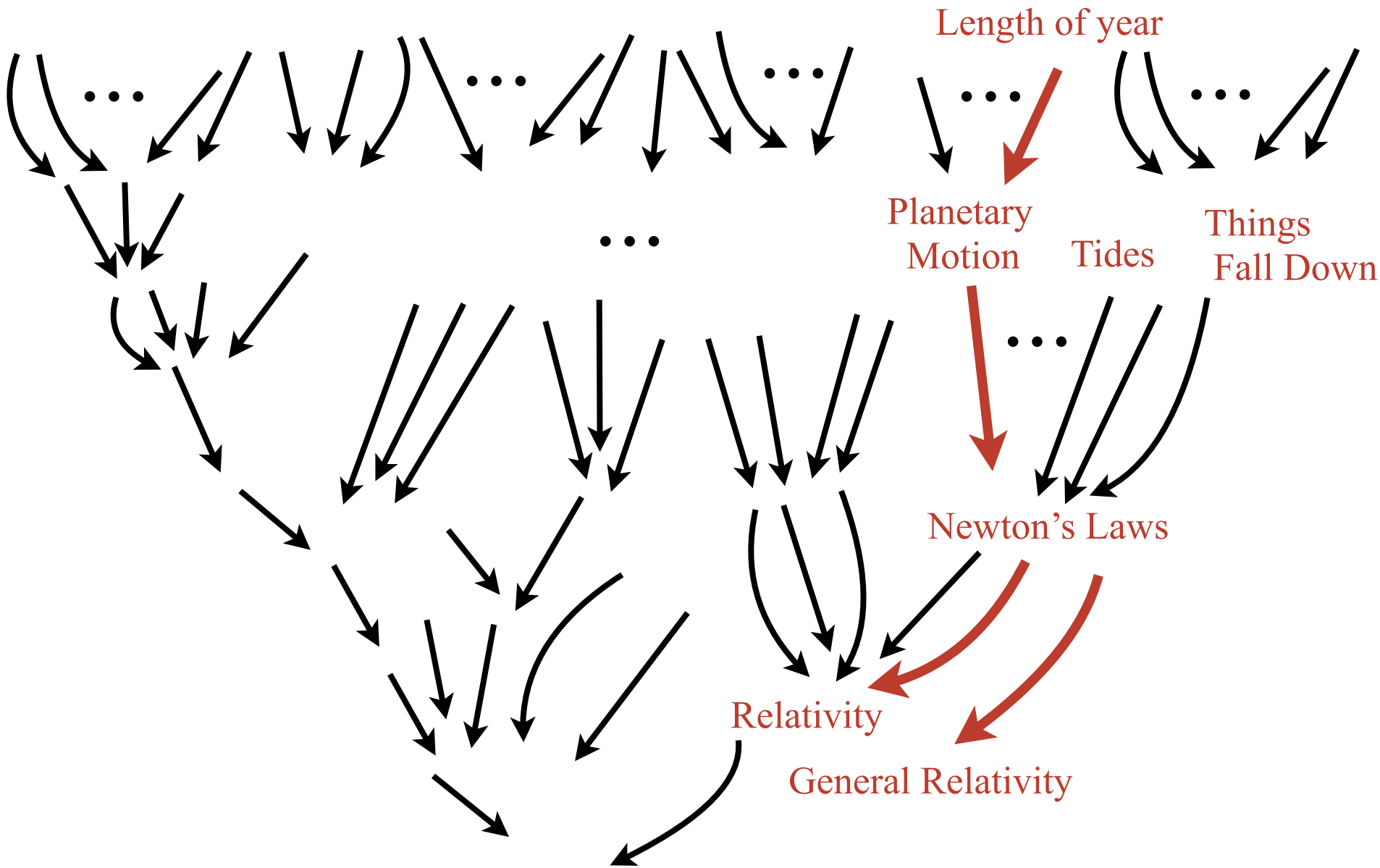
- Newton, Preface to Principia, 1686

Newton's Dream: Understand all of nature terms of simple principles

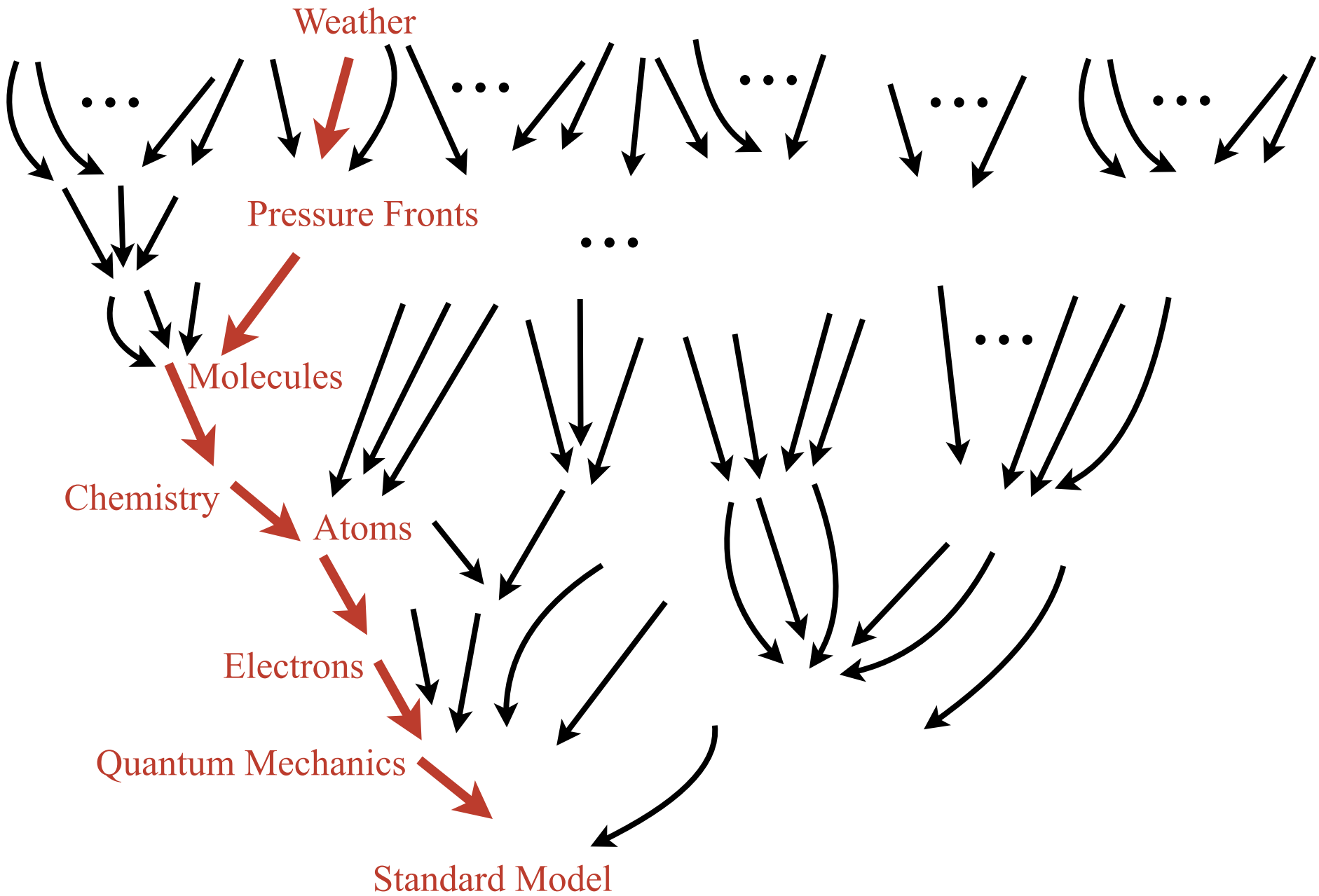
Realizing Newton's Dream



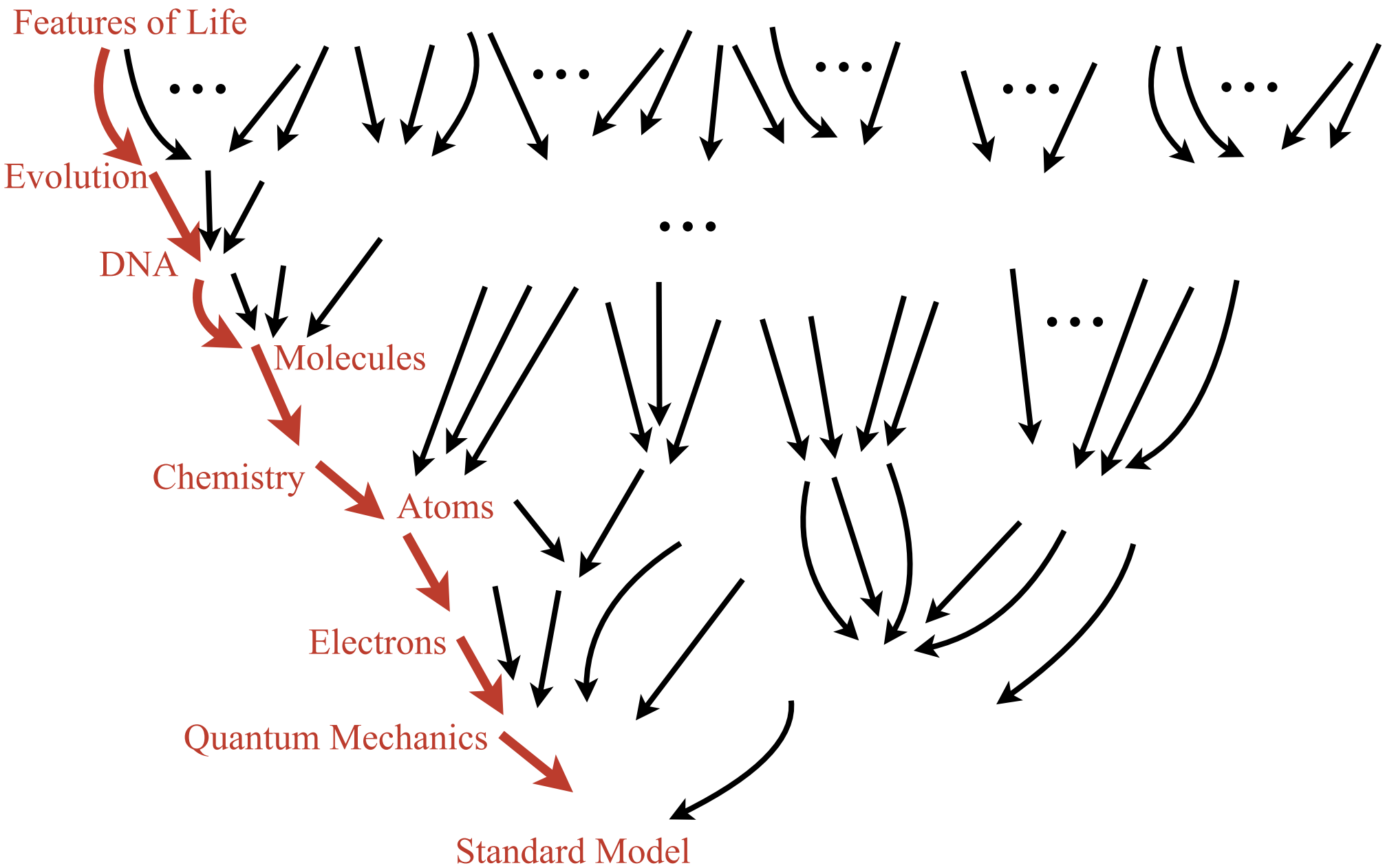
Realizing Newton's Dream



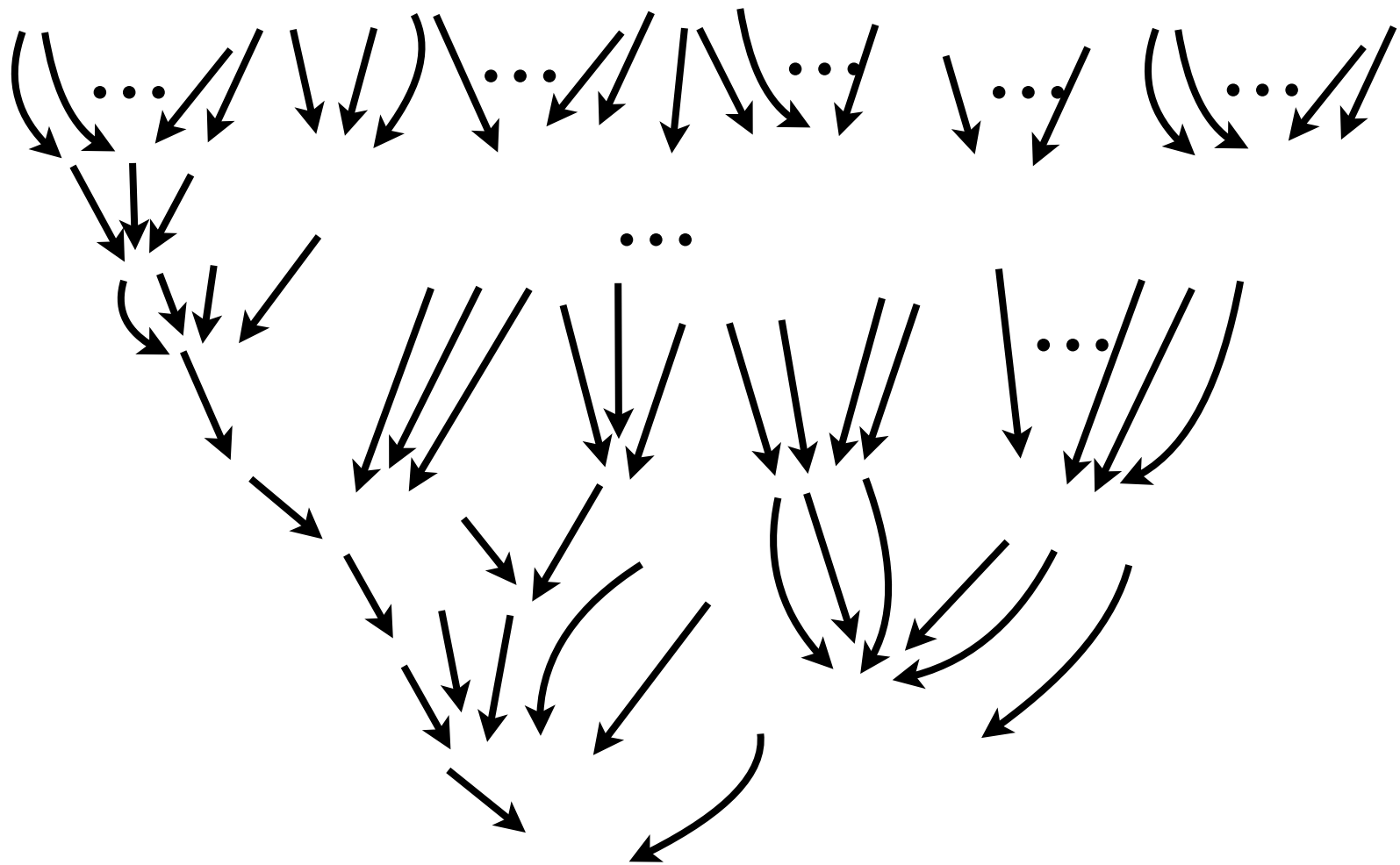
Realizing Newton's Dream



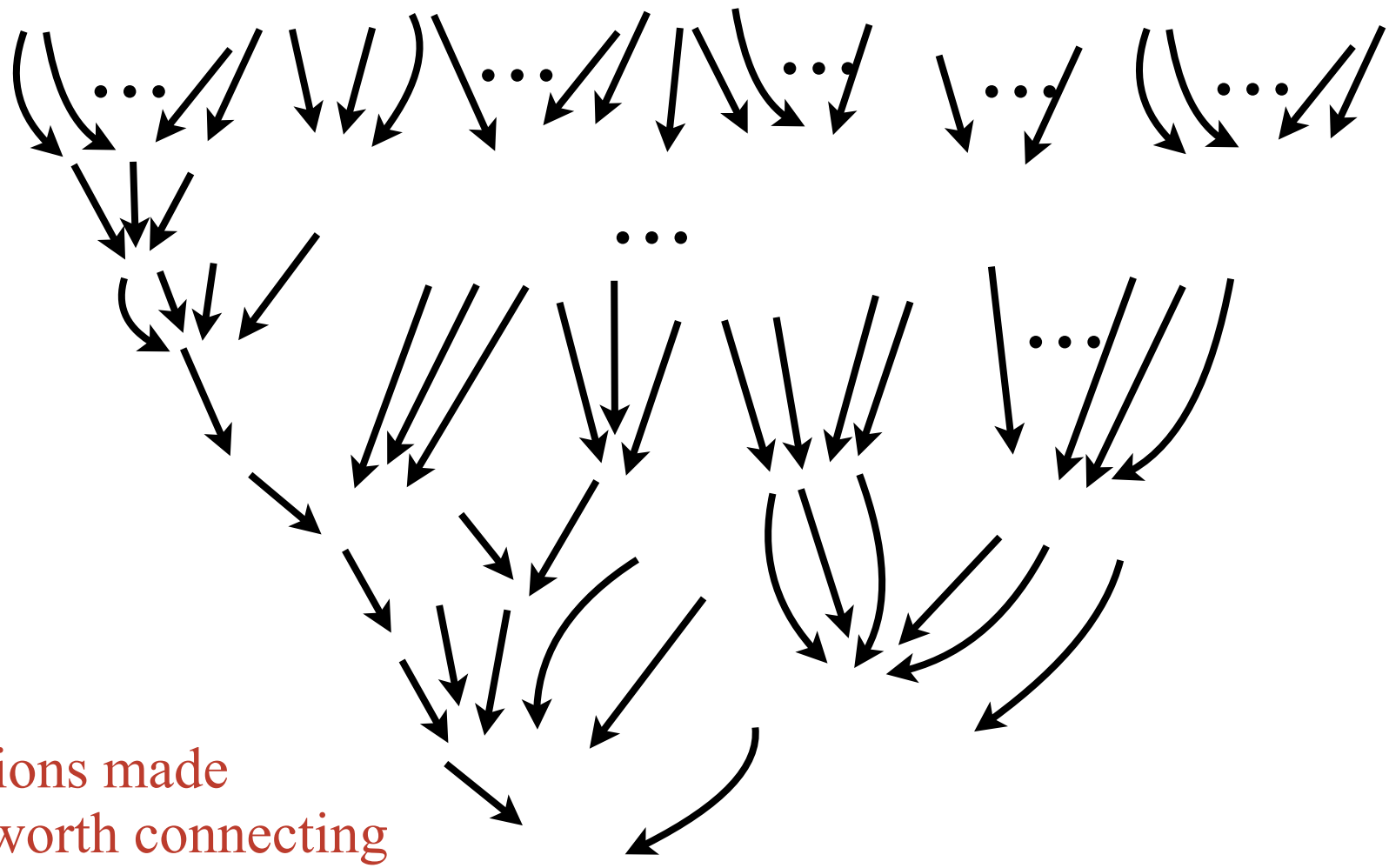
Realizing Newton's Dream



Sense of Direction in Science



Sense of Direction in Science

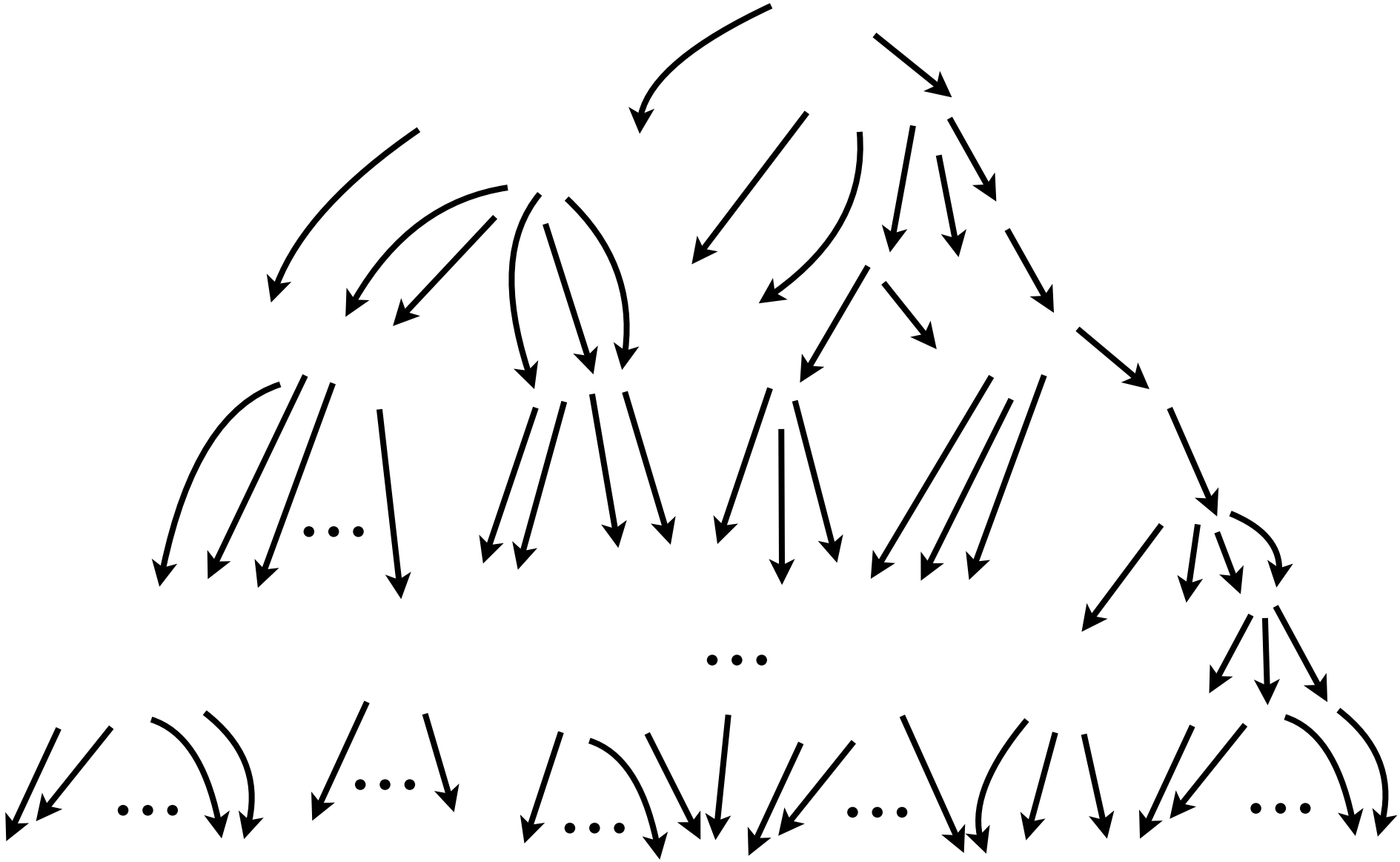


- Not all connections made
- Not all arrows worth connecting
- Direction/Convergence
- Fact about nature

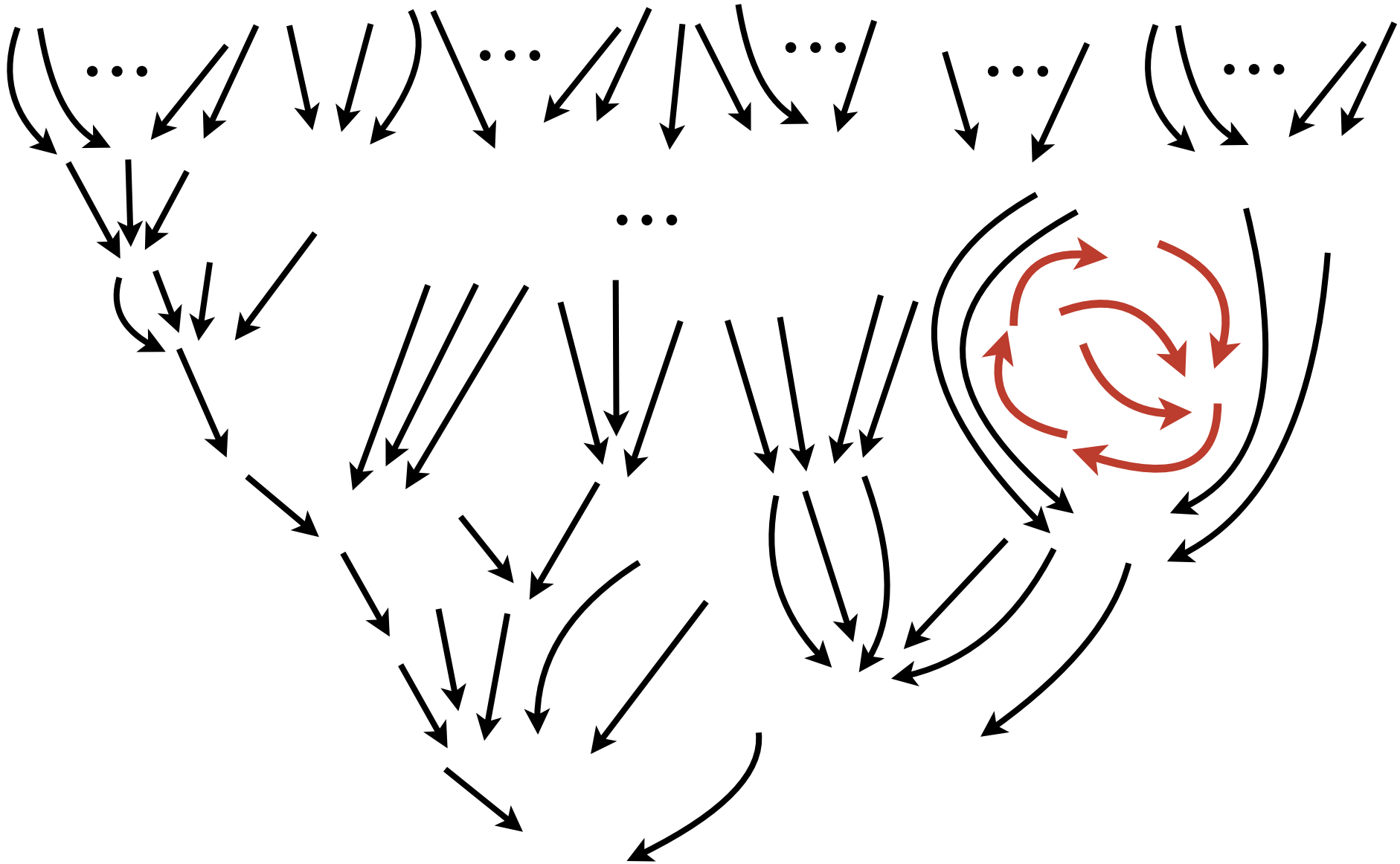
"Perhaps greatest scientific discovery of all" - Steven Weinberg

It could have been different.

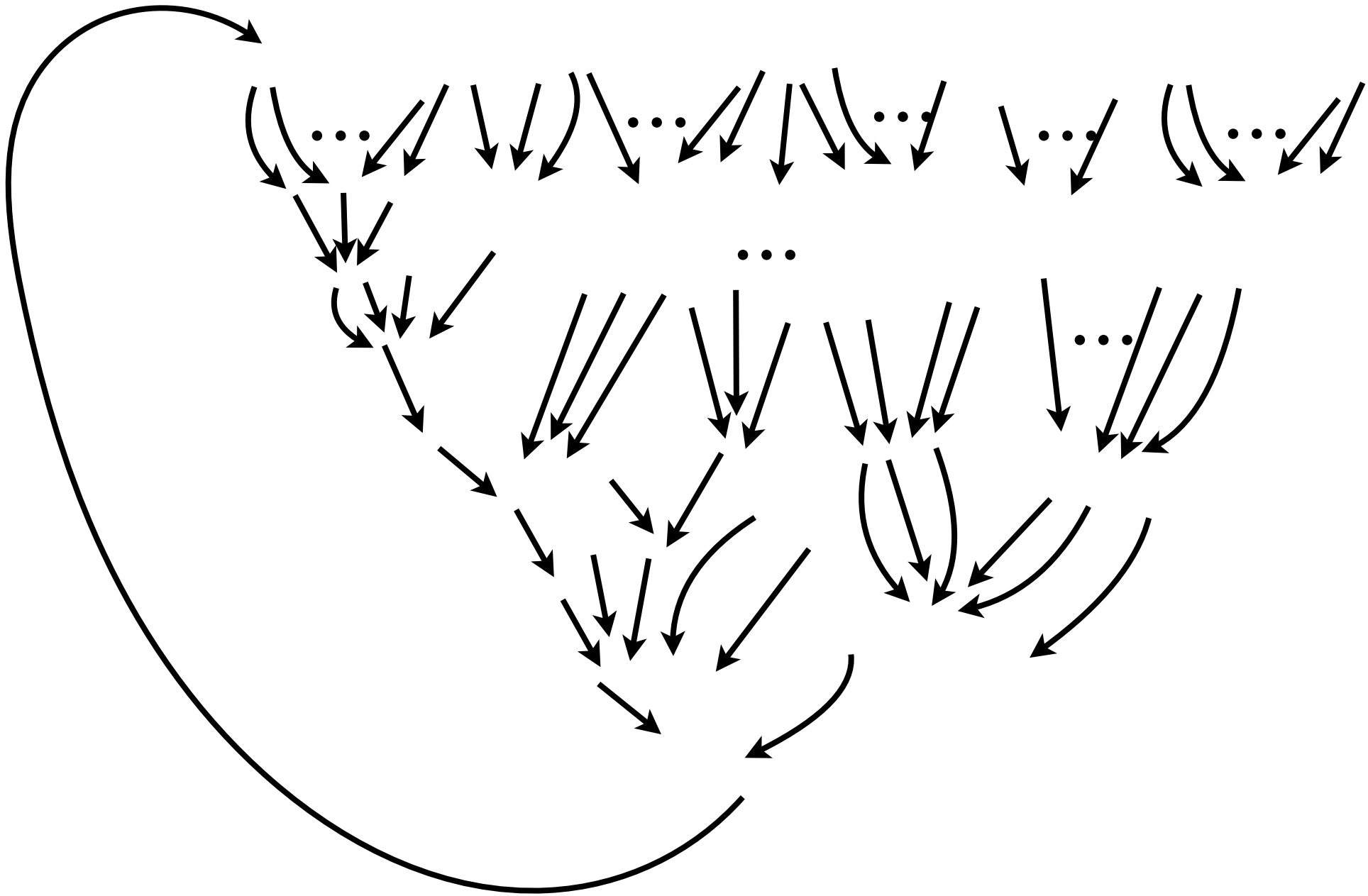
It could have been different.



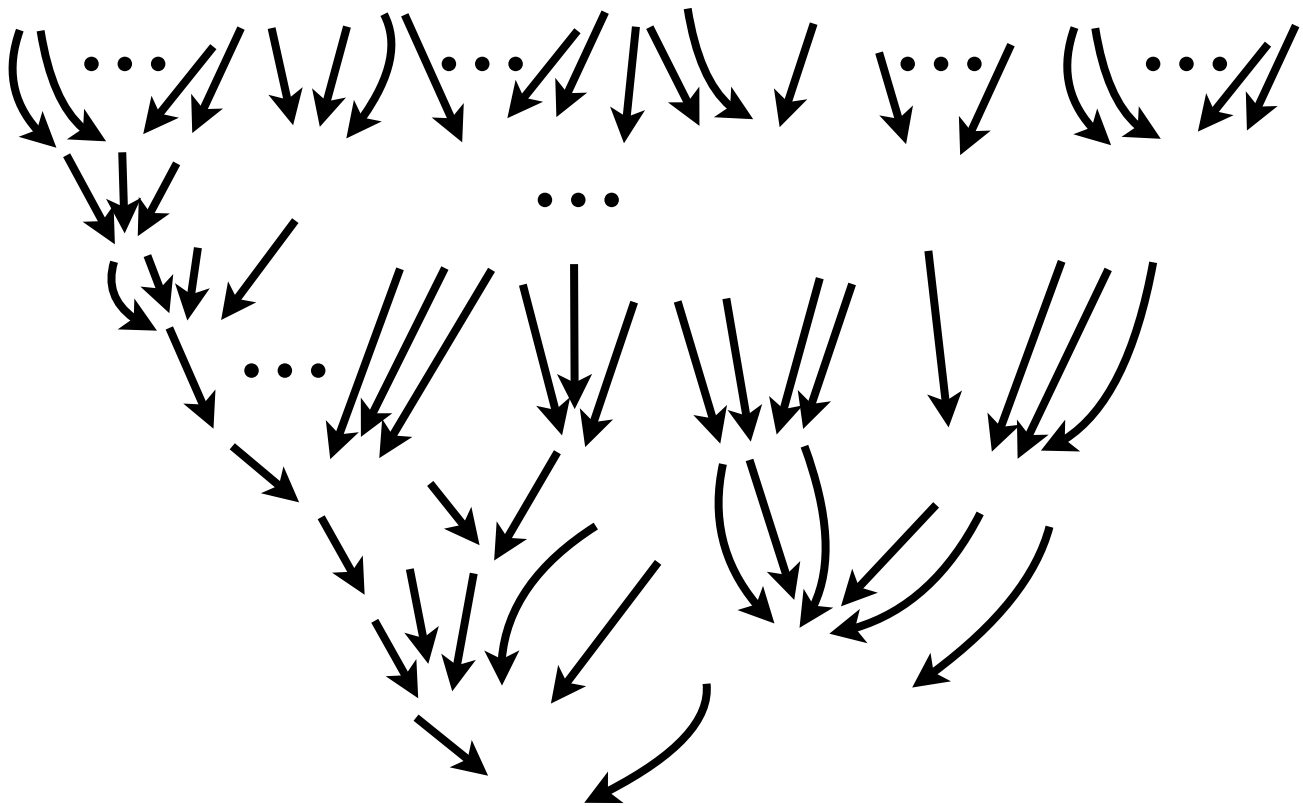
It could have been different.



Could have been different.

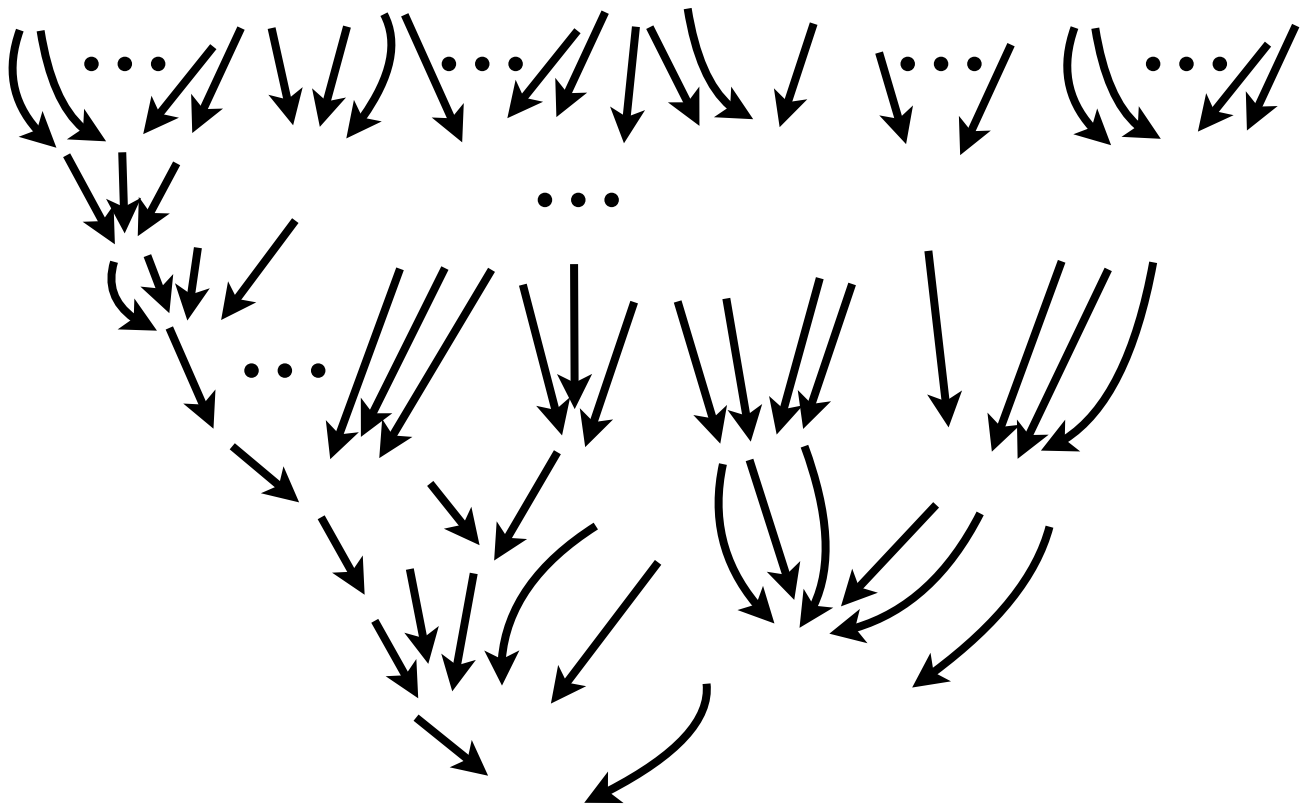


Newton's Dream Realized



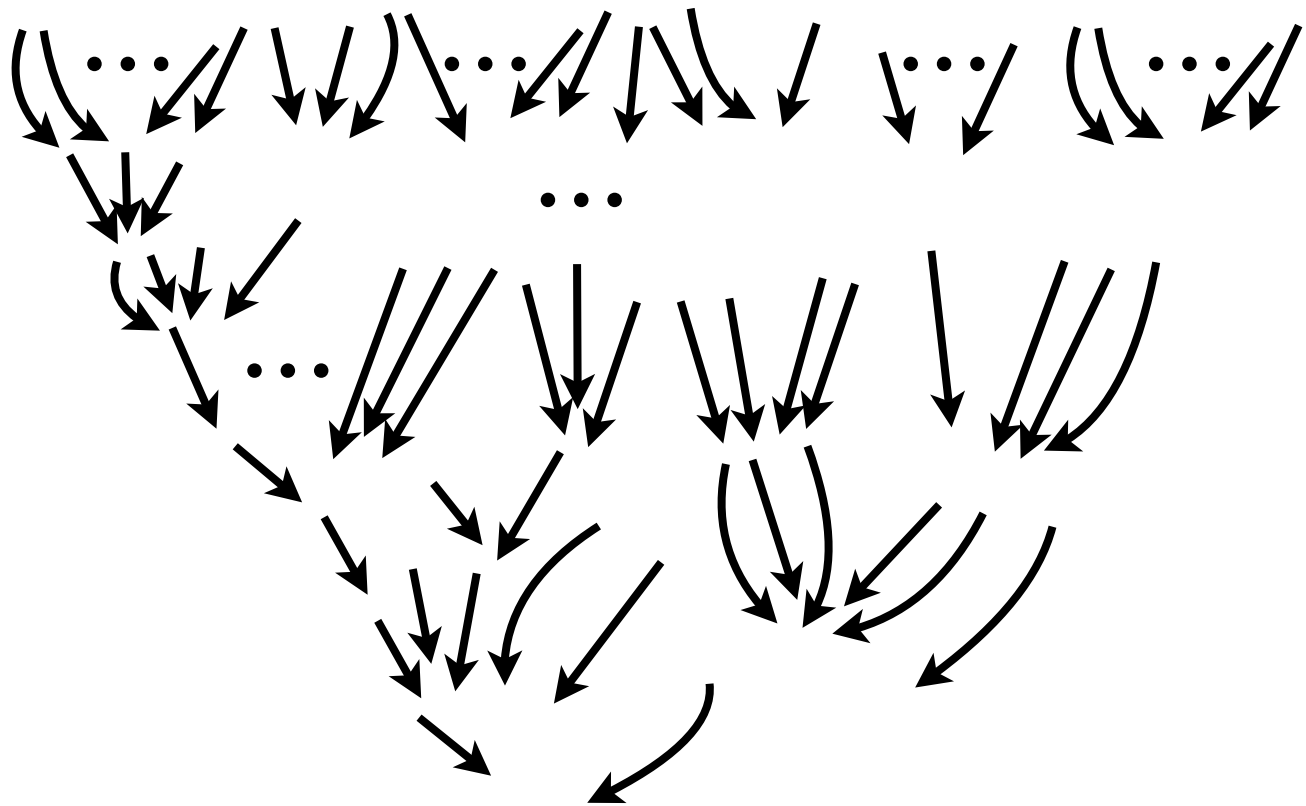
Can answer all basic questions of everyday world, w/simple principles

Newton's Dream Realized



Can answer all basic questions of everyday world, w/simple principles
Particle physics probing deepest level

Newton's Dream Realized



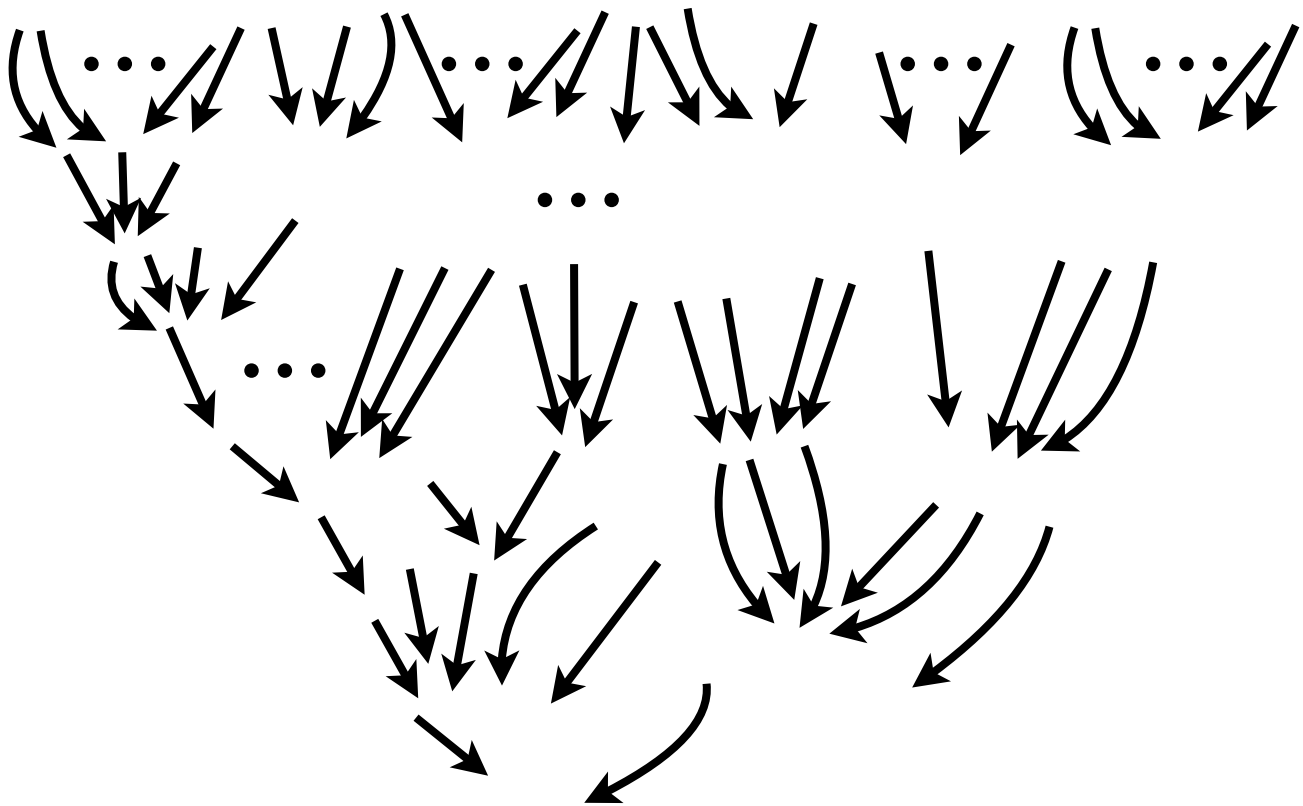
Can answer all basic questions of everyday world, w/simple principles

Particle physics probing deepest level

Hints that we are approaching the final explanation

- Principles get simpler (not the mathematics!)
- Fewer and fewer moving parts

Newton's Dream Realized



Can answer all basic questions of everyday world, w/simple principles

Particle physics probing deepest level

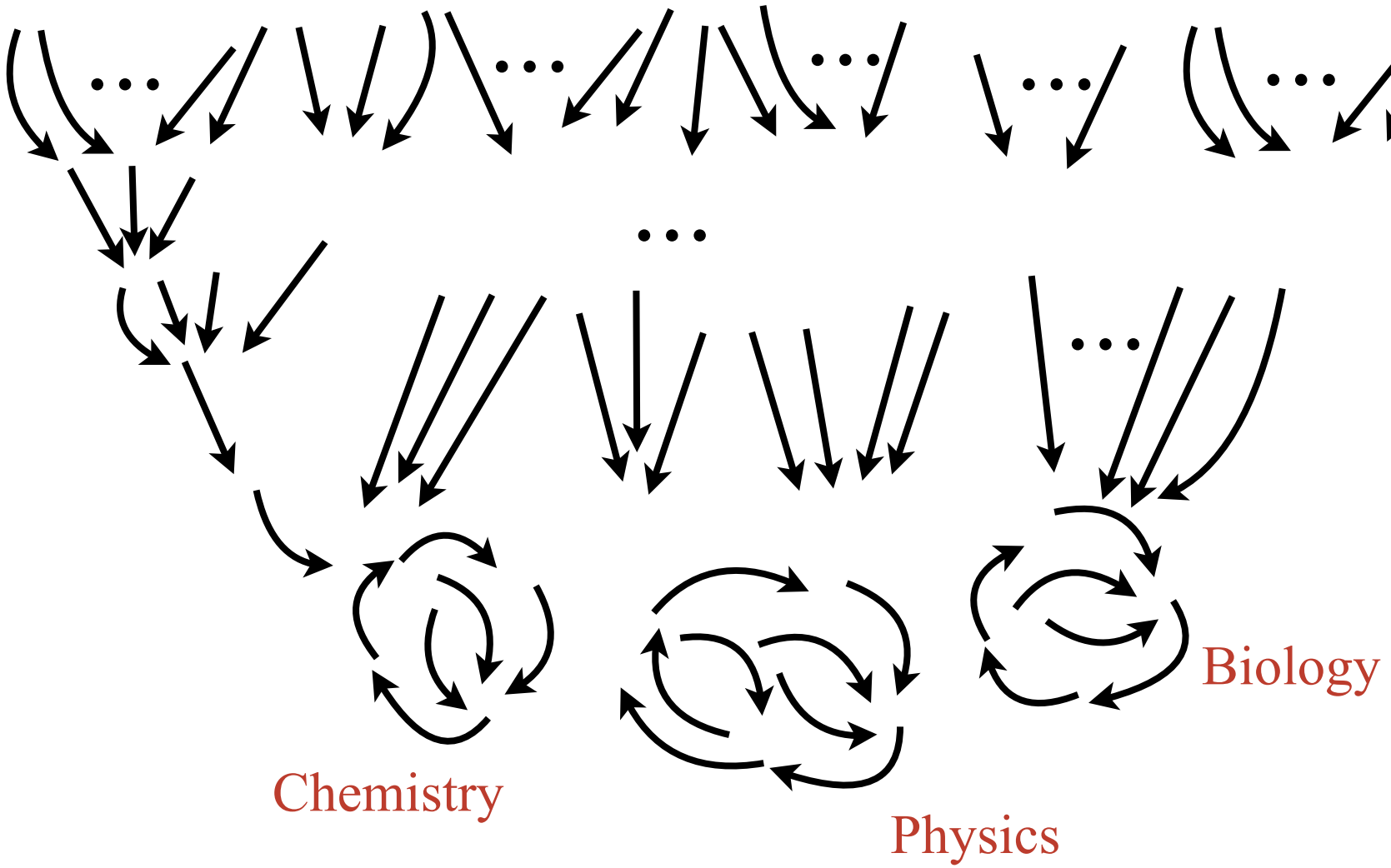
Hints that we are approaching the final explanation

- Principles get simpler (not the mathematics!)
- Fewer and fewer moving parts

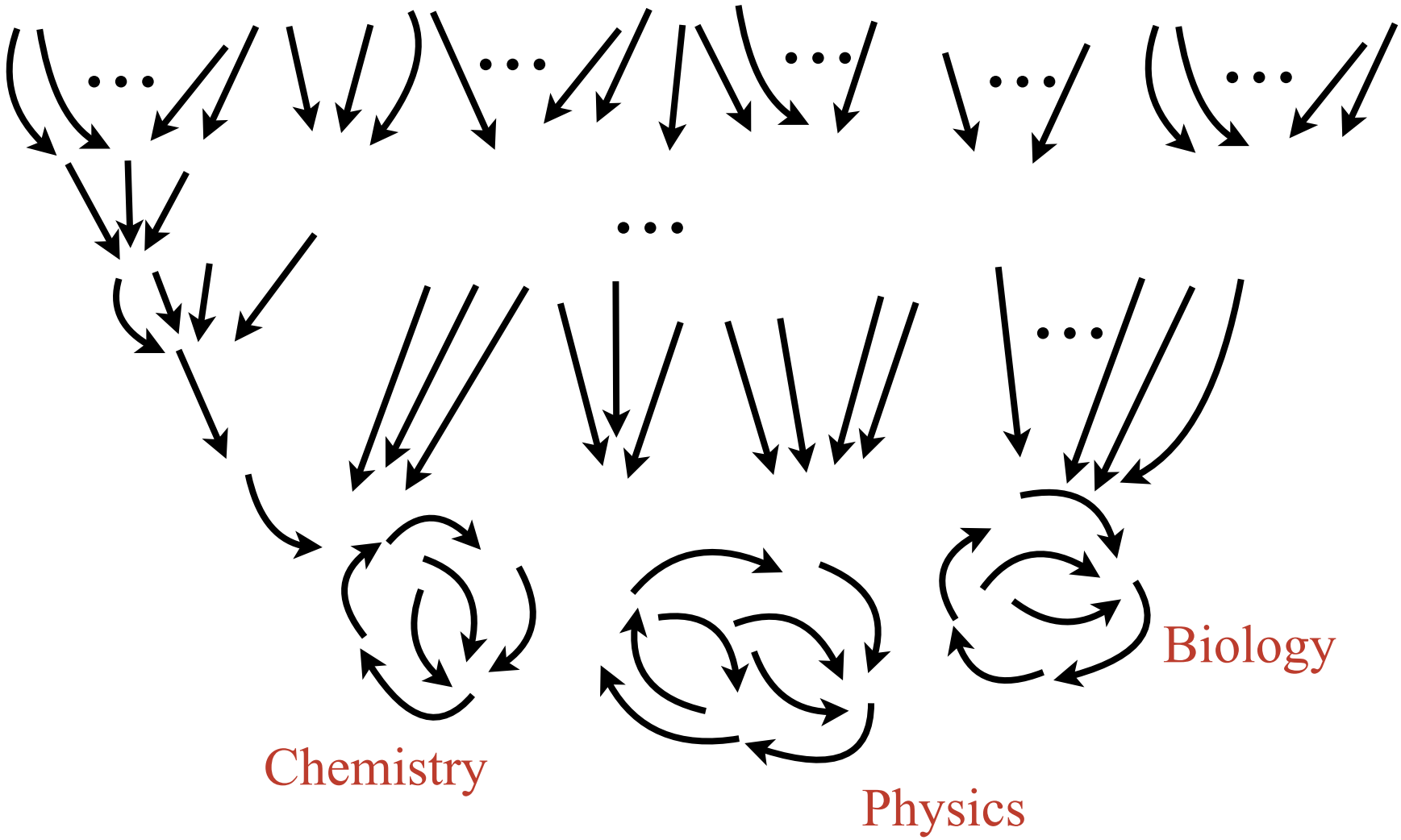
This, deep down, is the why!

20th Century Revolutions

Science at turn of 20th Century



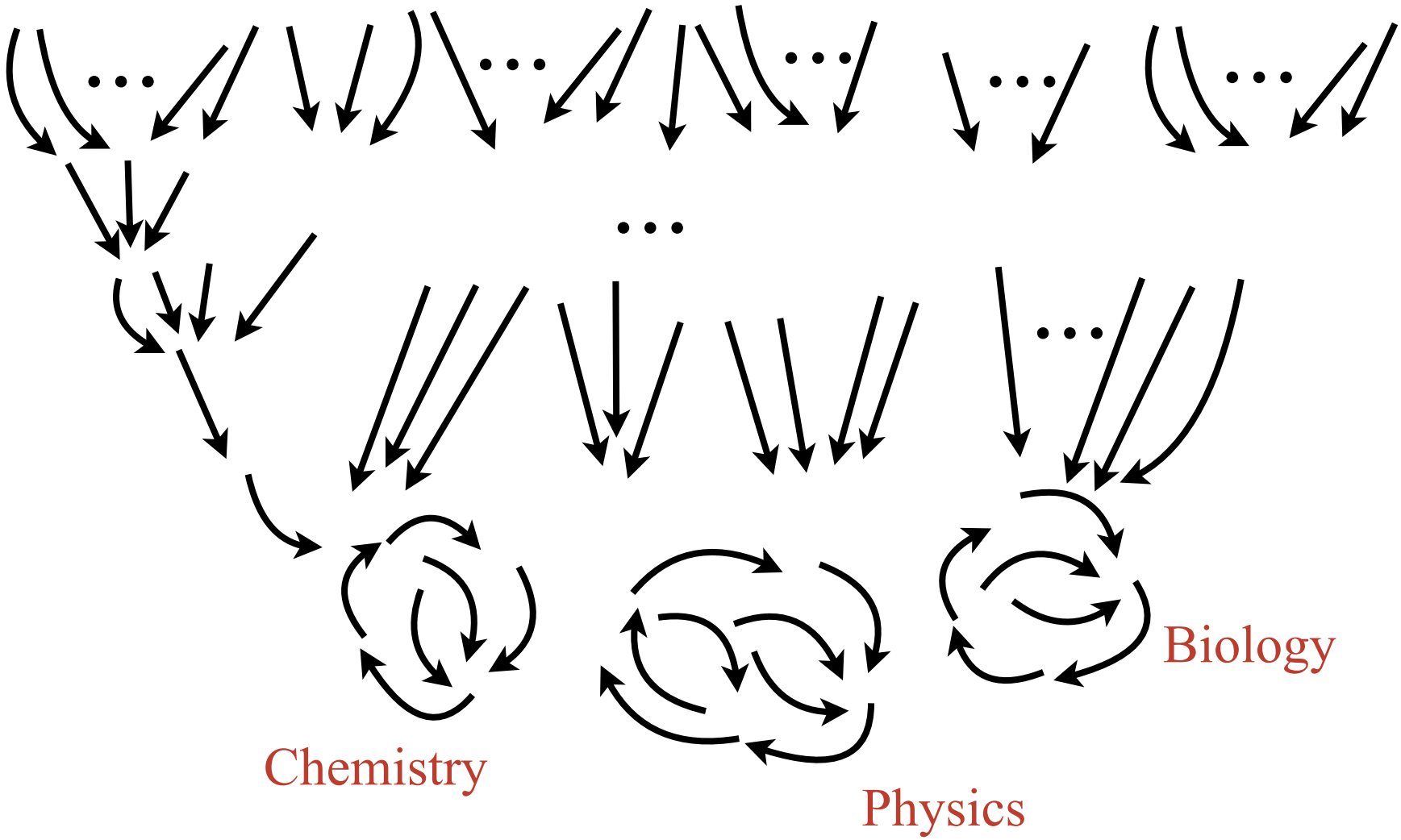
Science at turn of 20th Century



Nothing new to be discovered in physics - Albert Michelson

(Dedication of the University of Chicago's Ryerson Physical Laboratory)

Science at turn of 20th Century

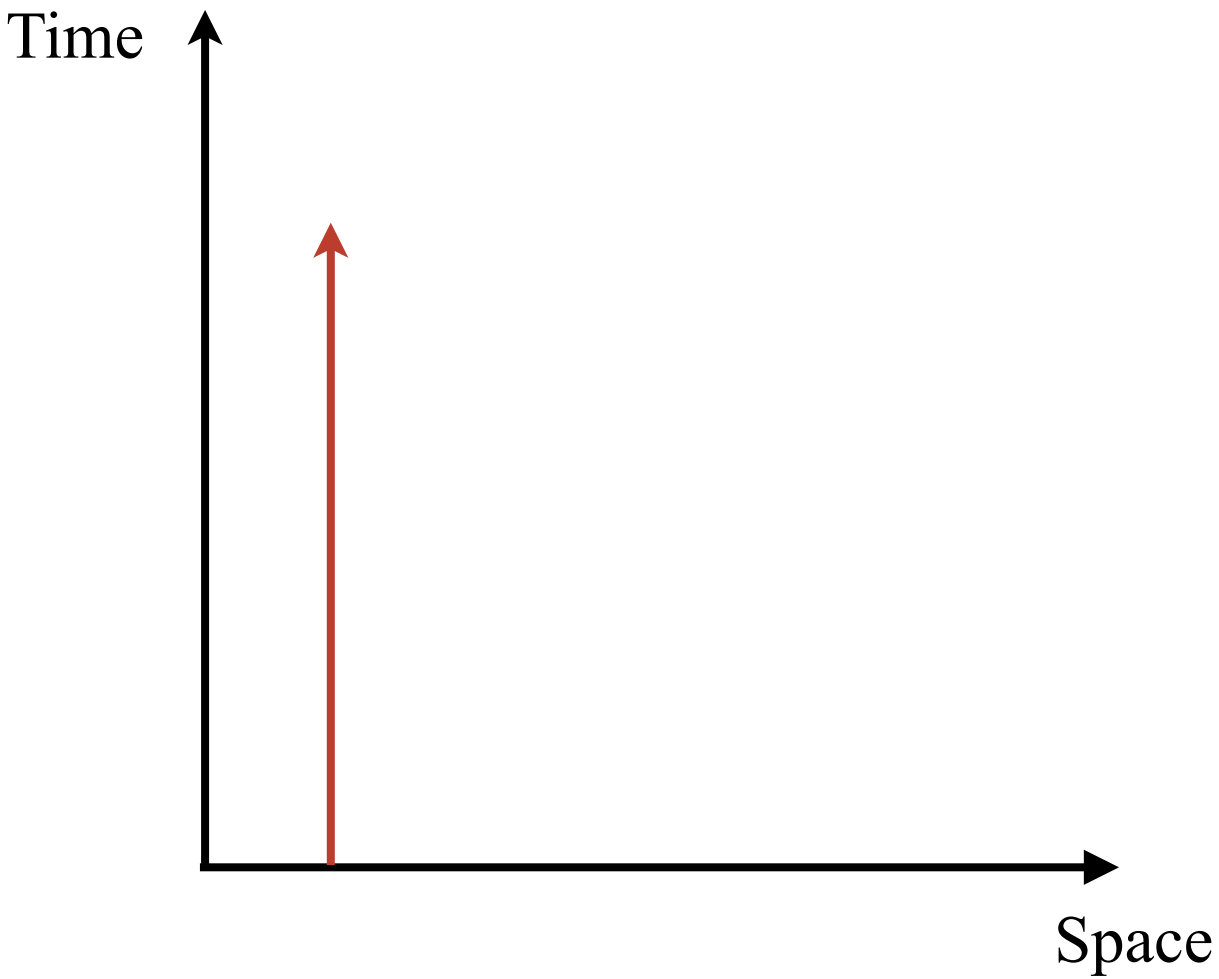


Nothing new to be discovered in physics - Albert Michelson

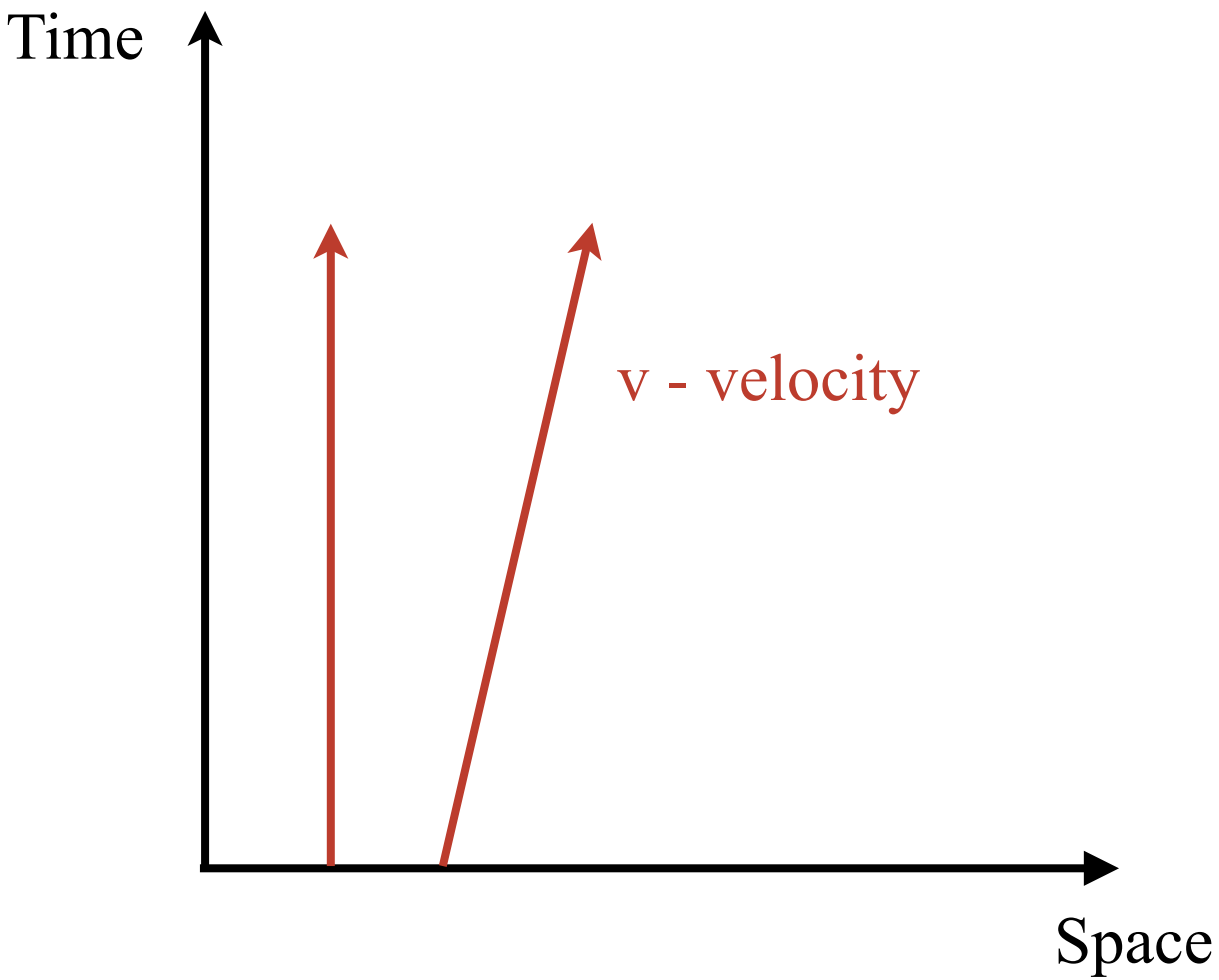
Radically changed by two revolutions: Relativity and Quantum Mechanics

Physics Before the Revolution

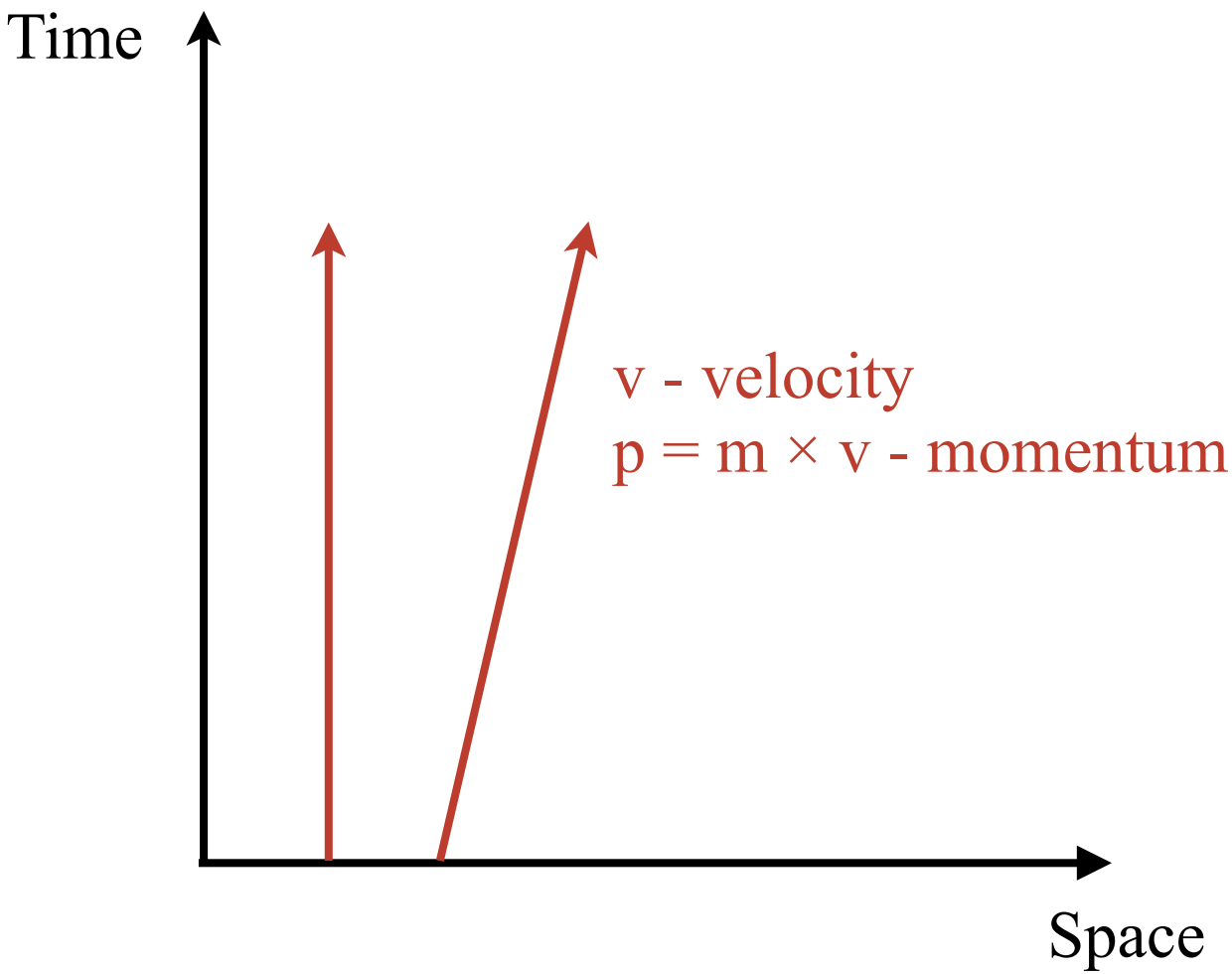
Physics Before the Revolution



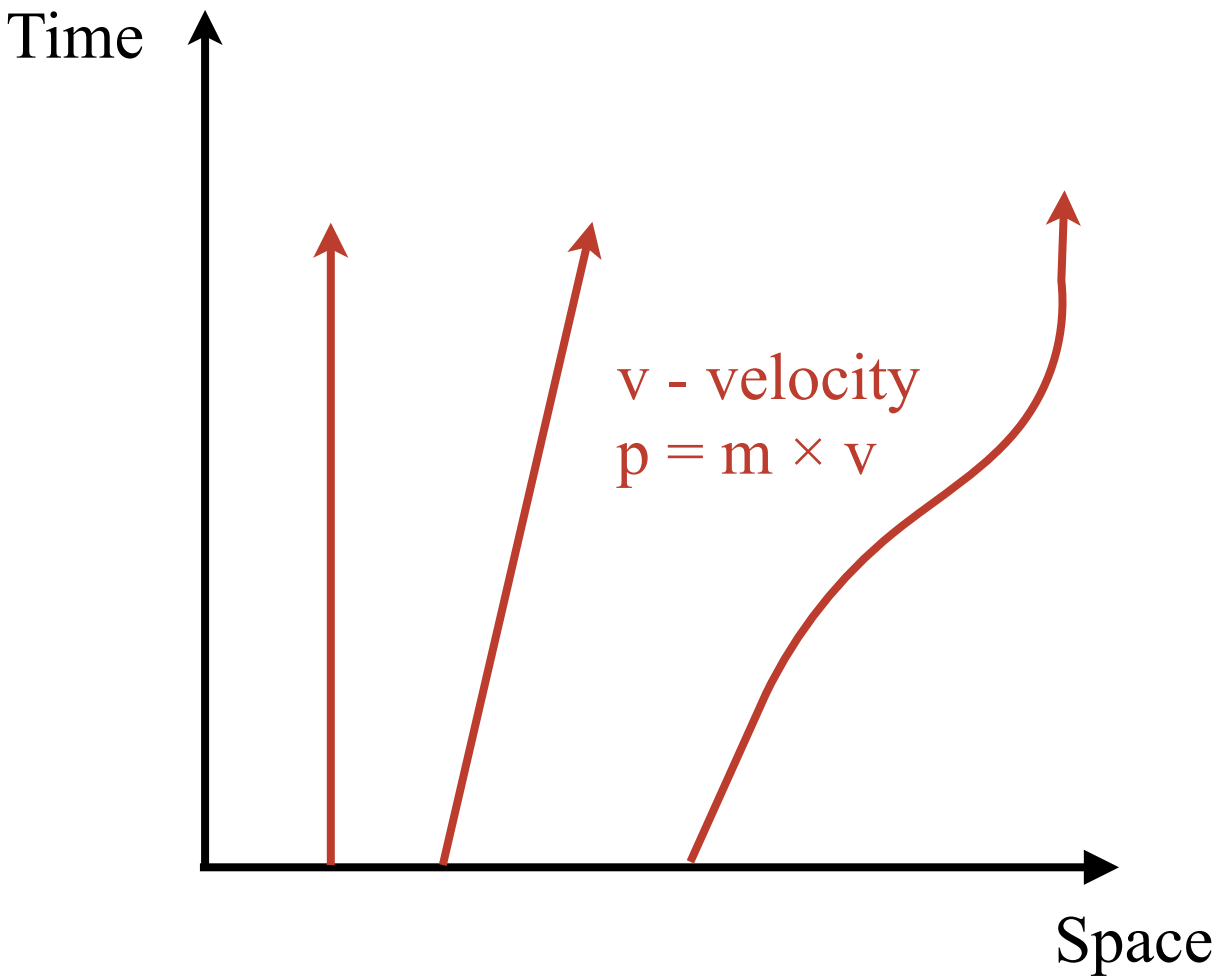
Physics Before the Revolution



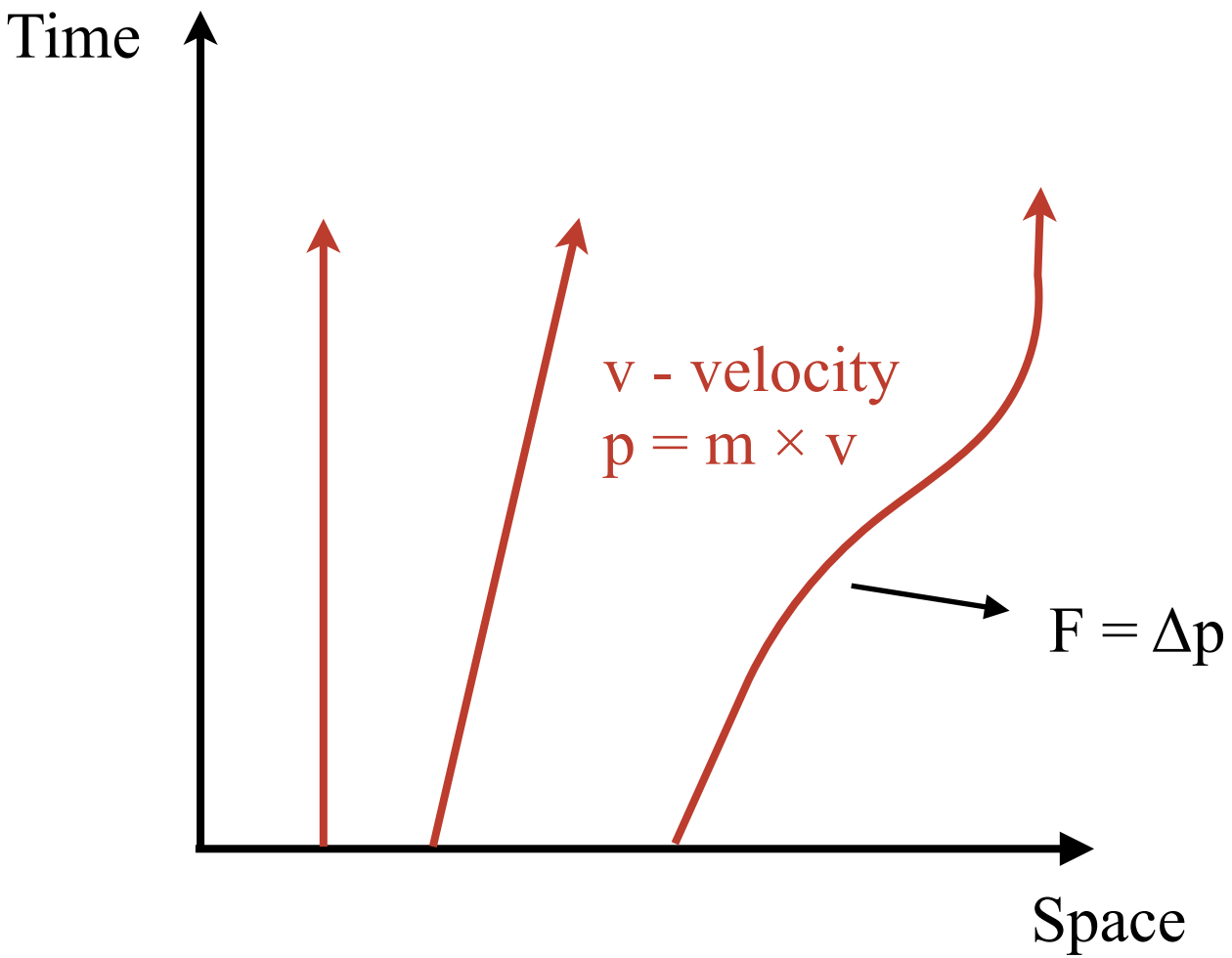
Physics Before the Revolution



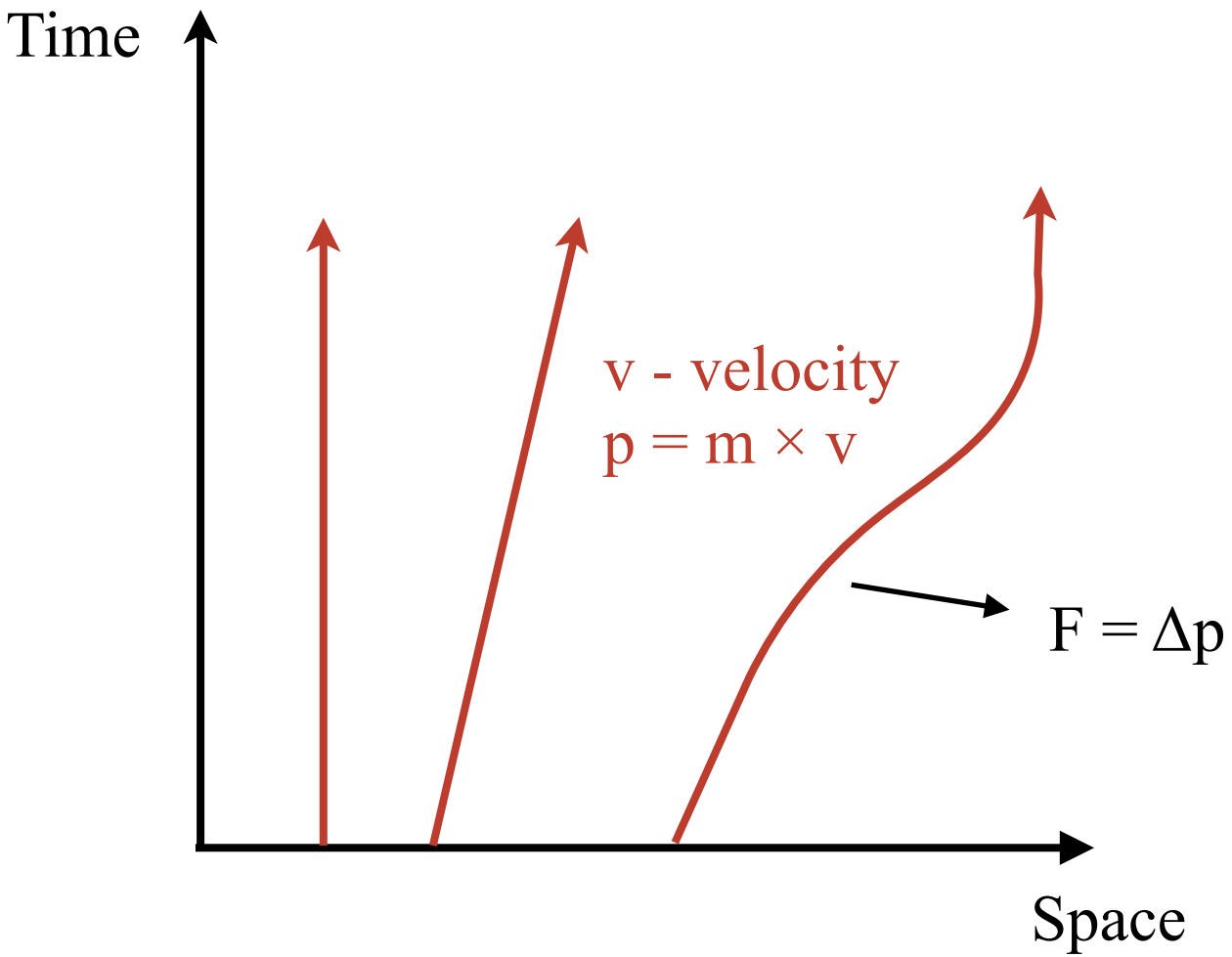
Physics Before the Revolution

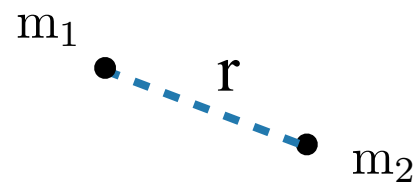


Physics Before the Revolution



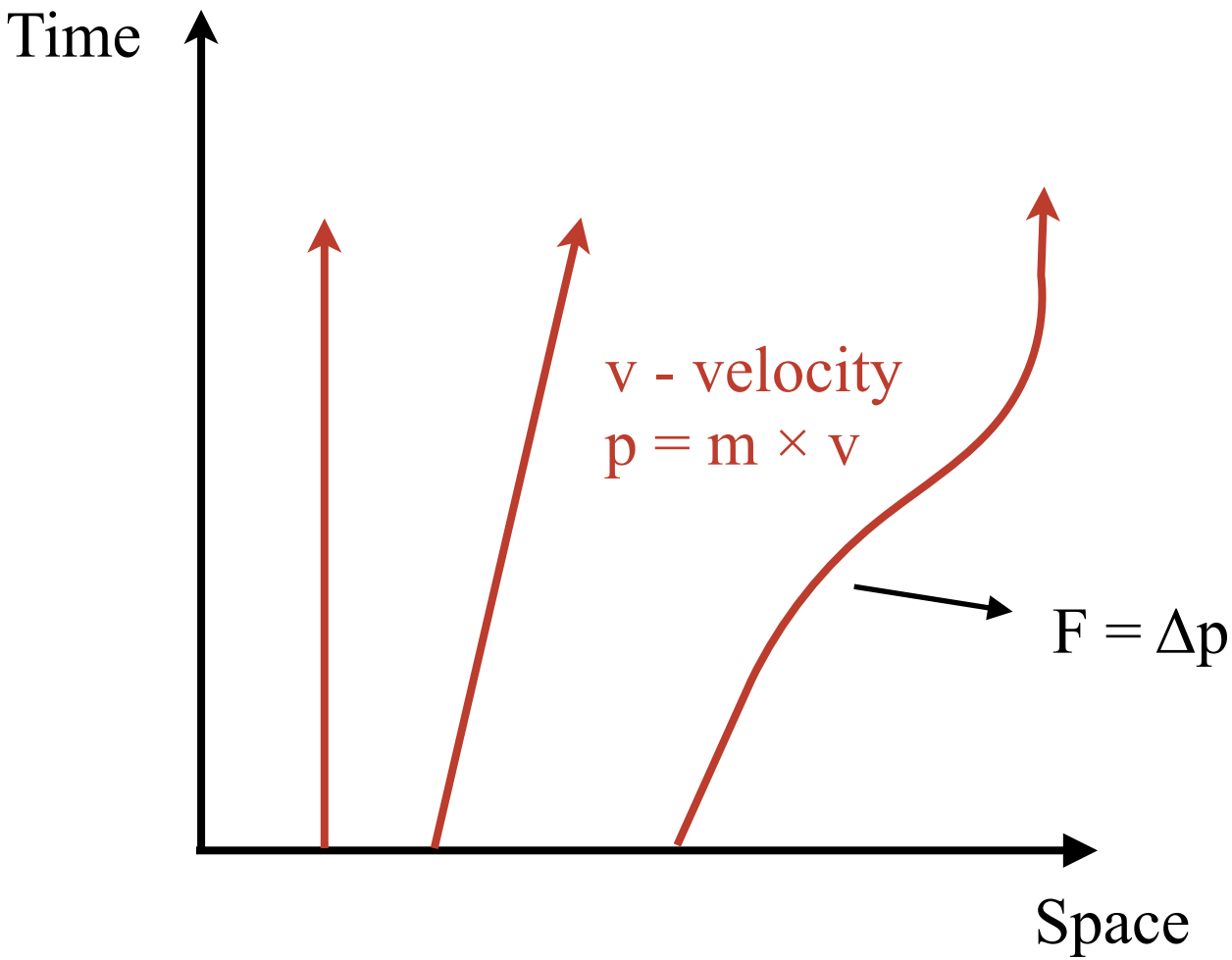
Physics Before the Revolution

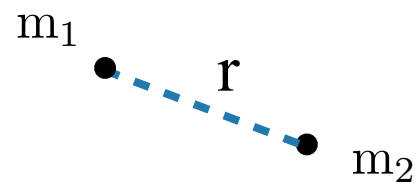




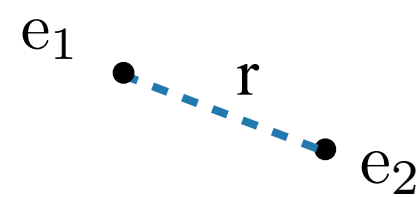
$$F = G_N \frac{m_1 m_2}{r^2}$$

Physics Before the Revolution



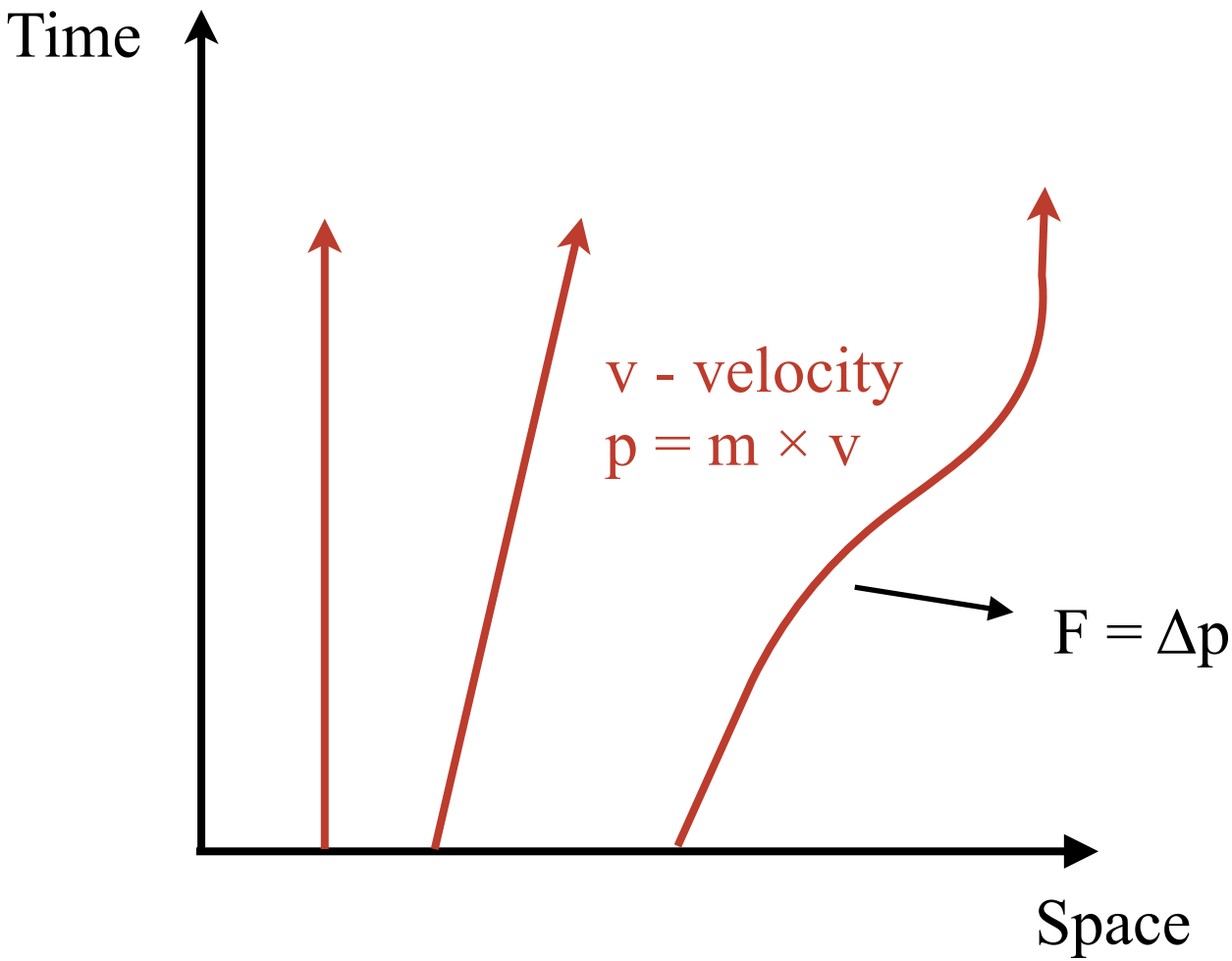


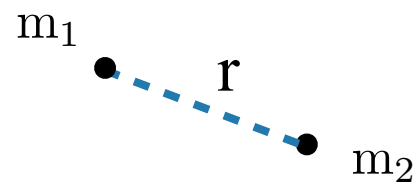
$$F = G_N \frac{m_1 m_2}{r^2}$$



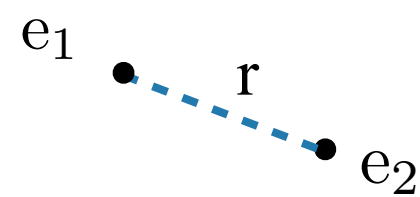
$$F = \frac{1}{4\pi} \frac{e_1 e_2}{r^2}$$

Physics Before the Revolution





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



$$F = \frac{1}{4\pi} \frac{e_1 e_2}{r^2}$$

- In principle can predict everything!
- Action at a distance

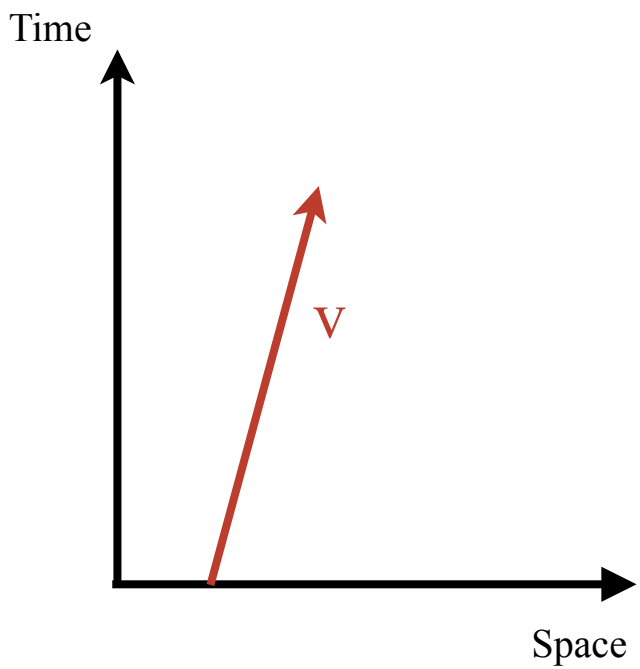
Principle of Relativity

Relativity before Einstein

Notion of relativity present in Newtons laws. Goes back to Galileo.

Relativity before Einstein

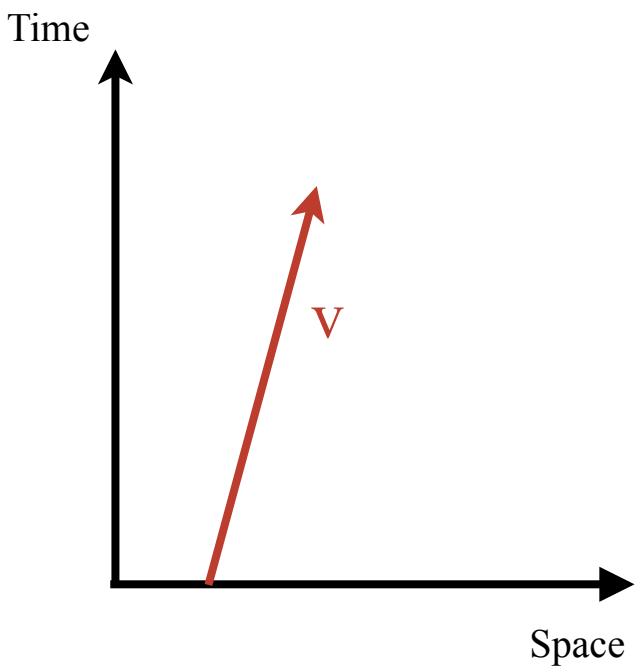
Notion of relativity present in Newtons laws. Goes back to Galileo.



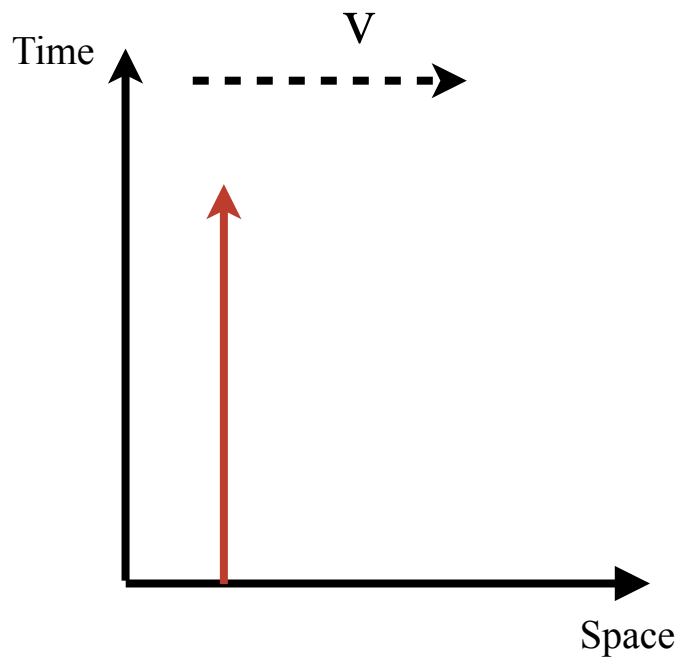
Some body standing still.
("observer at rest")

Relativity before Einstein

Notion of relativity present in Newtons laws. Goes back to Galileo.



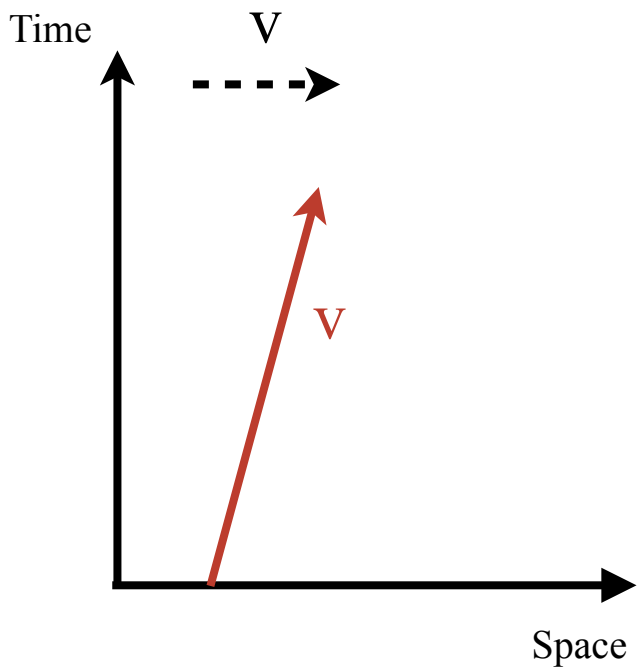
Some body standing still.
("observer at rest")



Observer moving at v
in the same direction

Relativity before Einstein

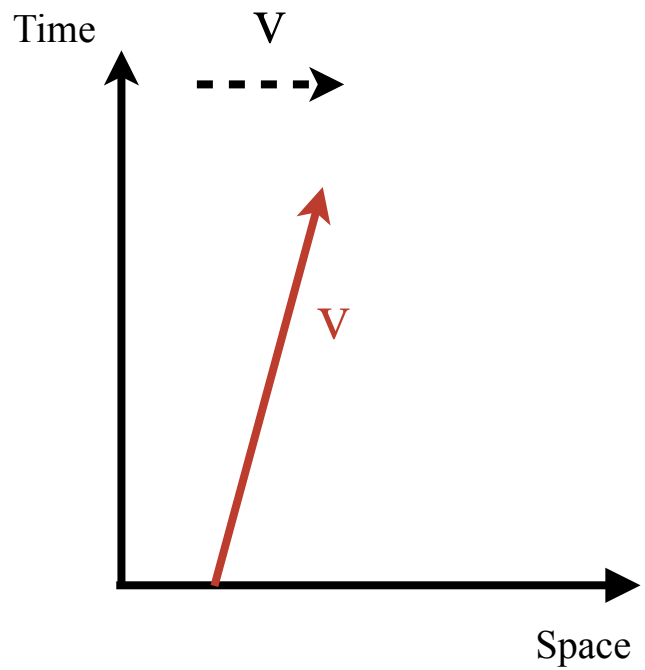
Another example

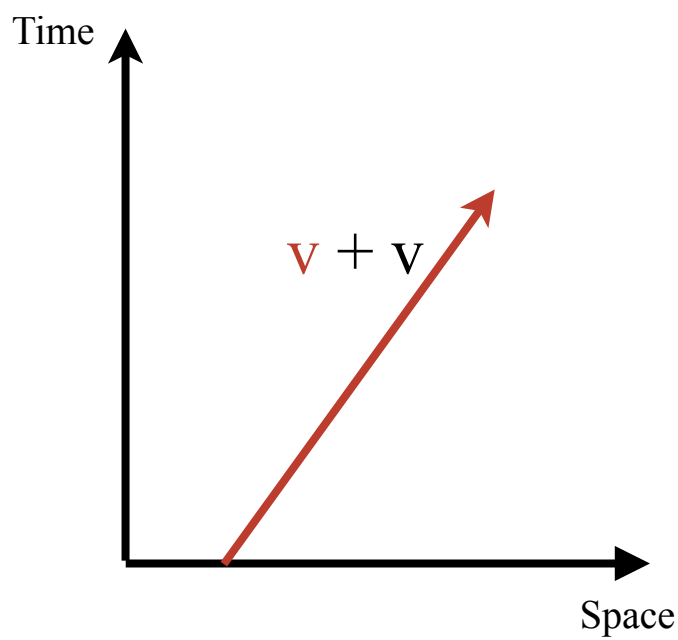


Observer in motion throws something

Relativity before Einstein

Another example



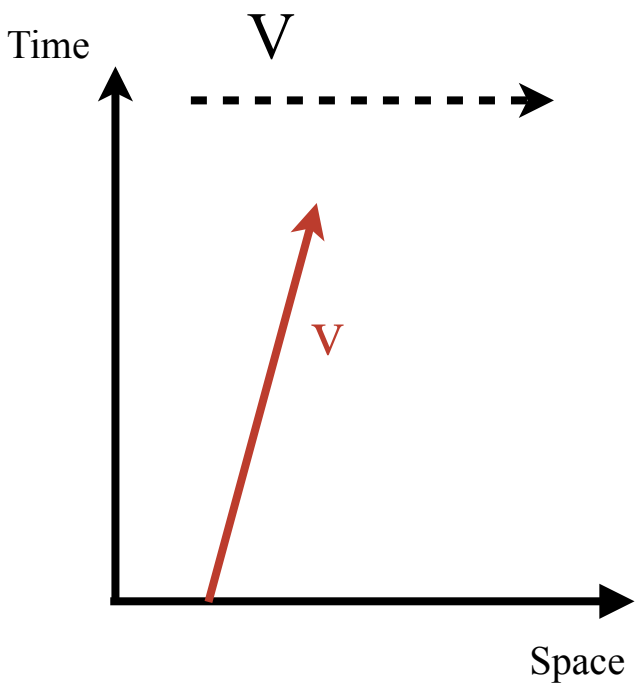


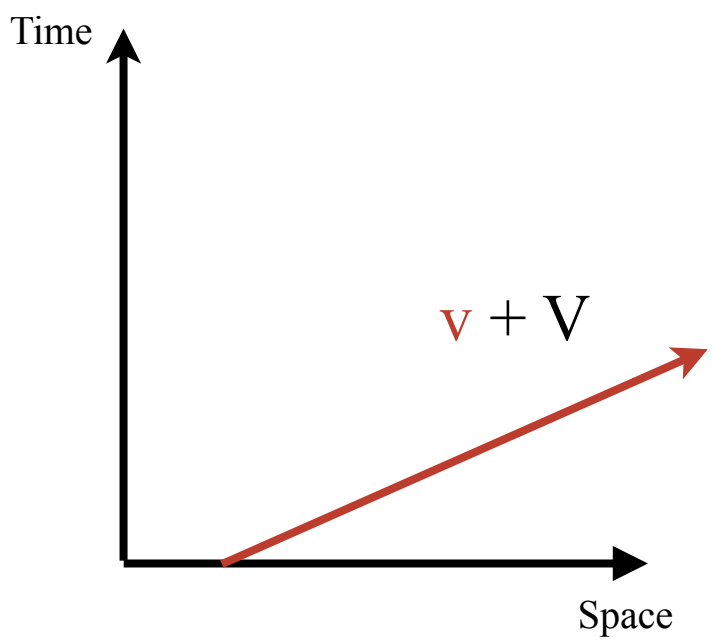
Observer in motion throws something

Observer at rest

Relativity before Einstein

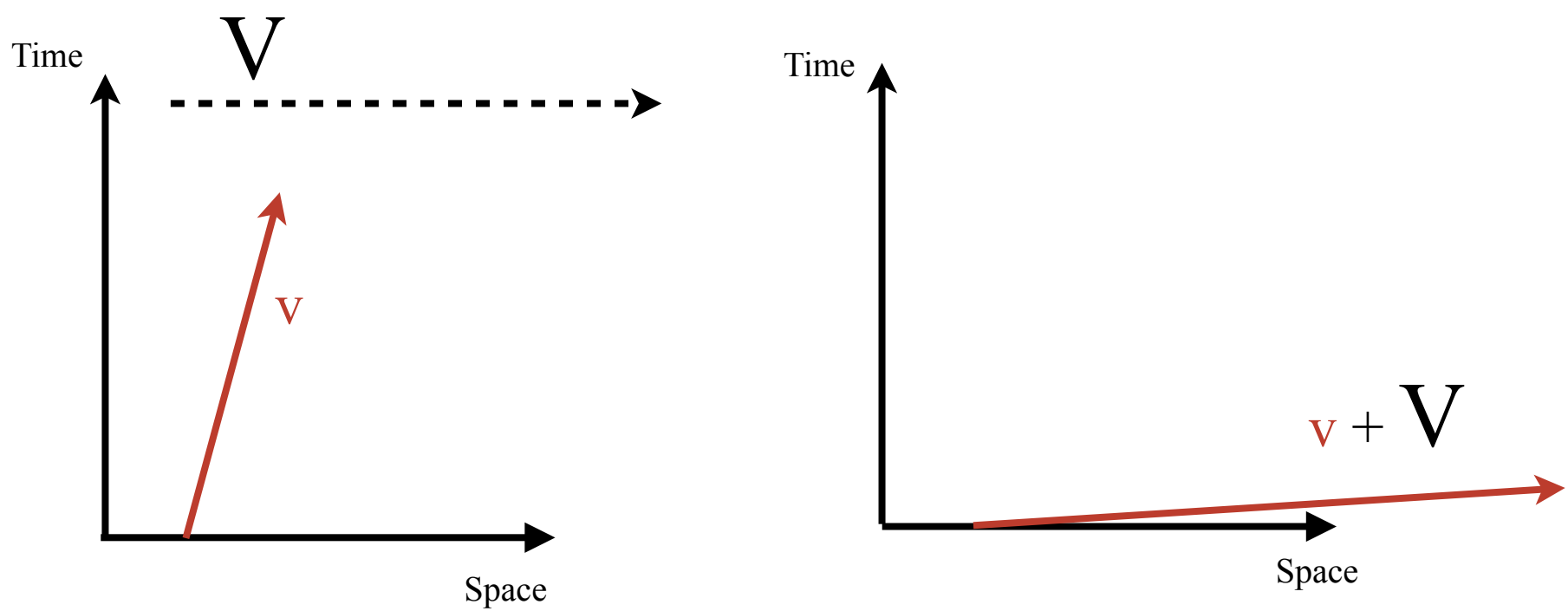
Another example





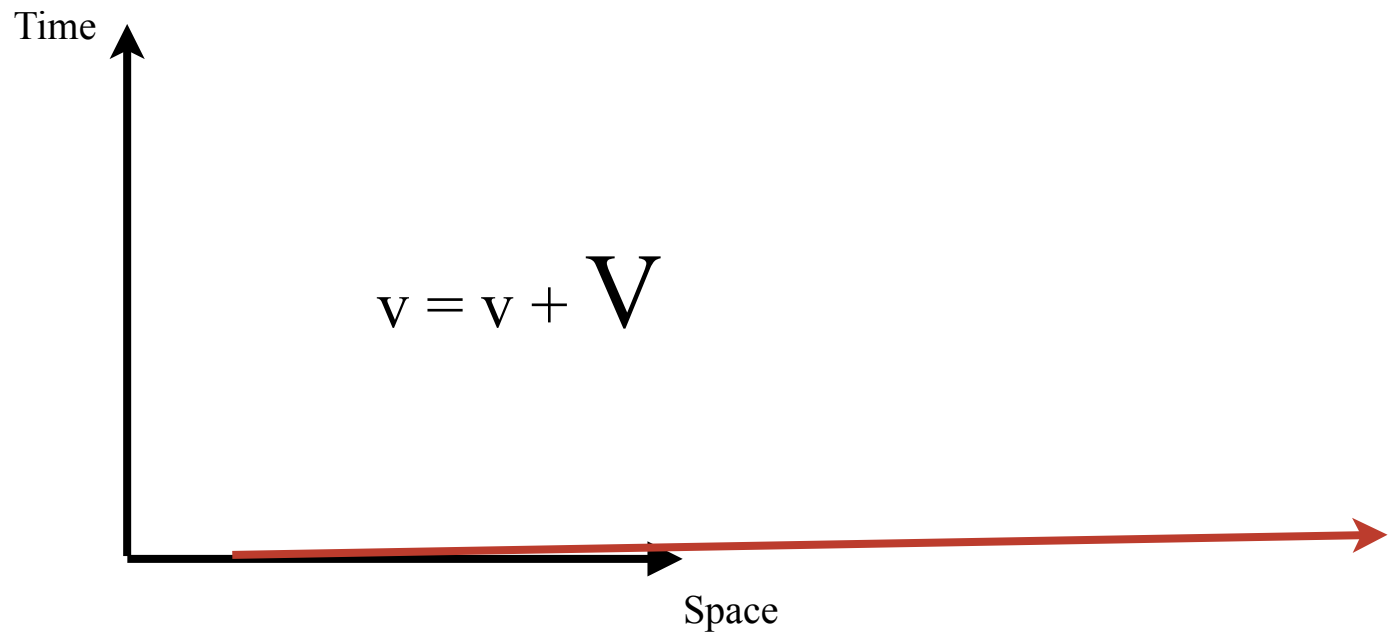
Relativity before Einstein

Another example



No limit to how fast we can make something

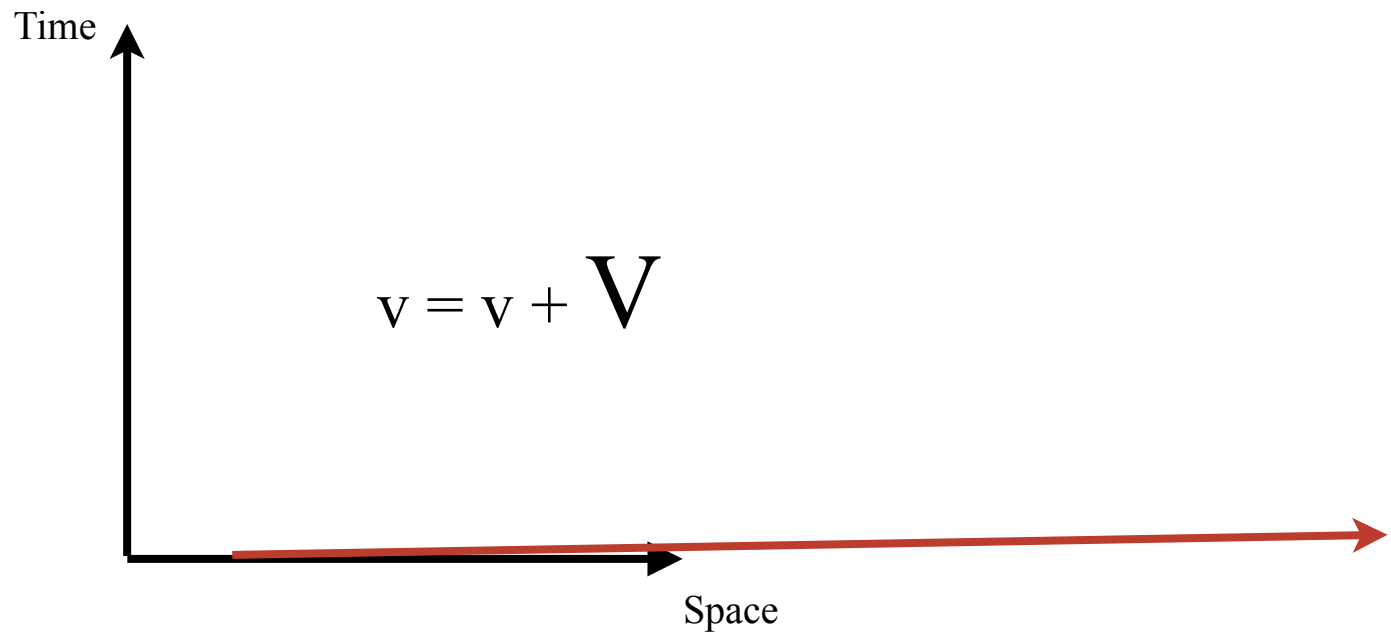
Relativity before Einstein



Can in principle send objects as fast as we want.

Regions arbitrarily far way can effect what is happening here and now.

Relativity before Einstein



Can in principle send objects as fast as we want.

Regions arbitrarily far way can effect what is happening here and now.

Einstein's Big Idea:

Limit the range over which things can have an affect

Einstein's Relativity

To limit the range over which things can have an affect:

-1) Must be a maximum speed.

-2) Max speed must be same regardless of how fast you are moving.

(otherwise we are back where we started v + V)

Einstein's Relativity

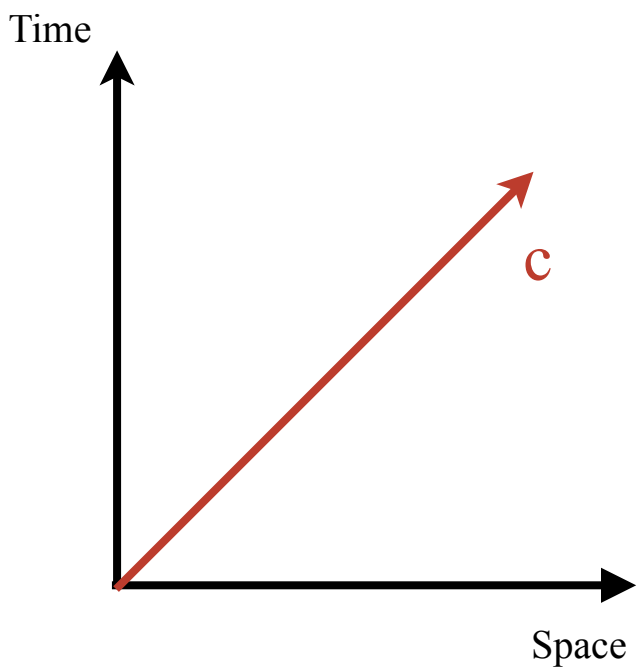
To limit the range over which things can have an affect:

-1) Must be a maximum speed.

-2) Max speed must be same regardless of how fast you are moving.

(otherwise we are back where we started v + V)

Maximum speed "c"



Einstein's Relativity

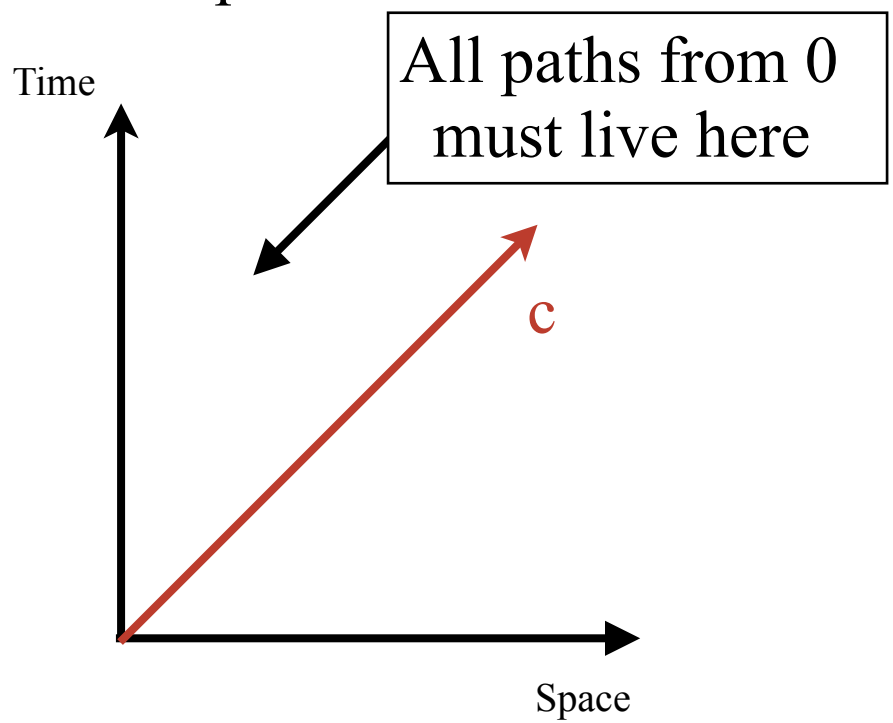
To limit the range over which things can have an affect:

-1) Must be a maximum speed.

-2) Max speed must be same regardless of how fast you are moving.

(otherwise we are back where we started v + V)

Maximum speed "c"



Einstein's Relativity

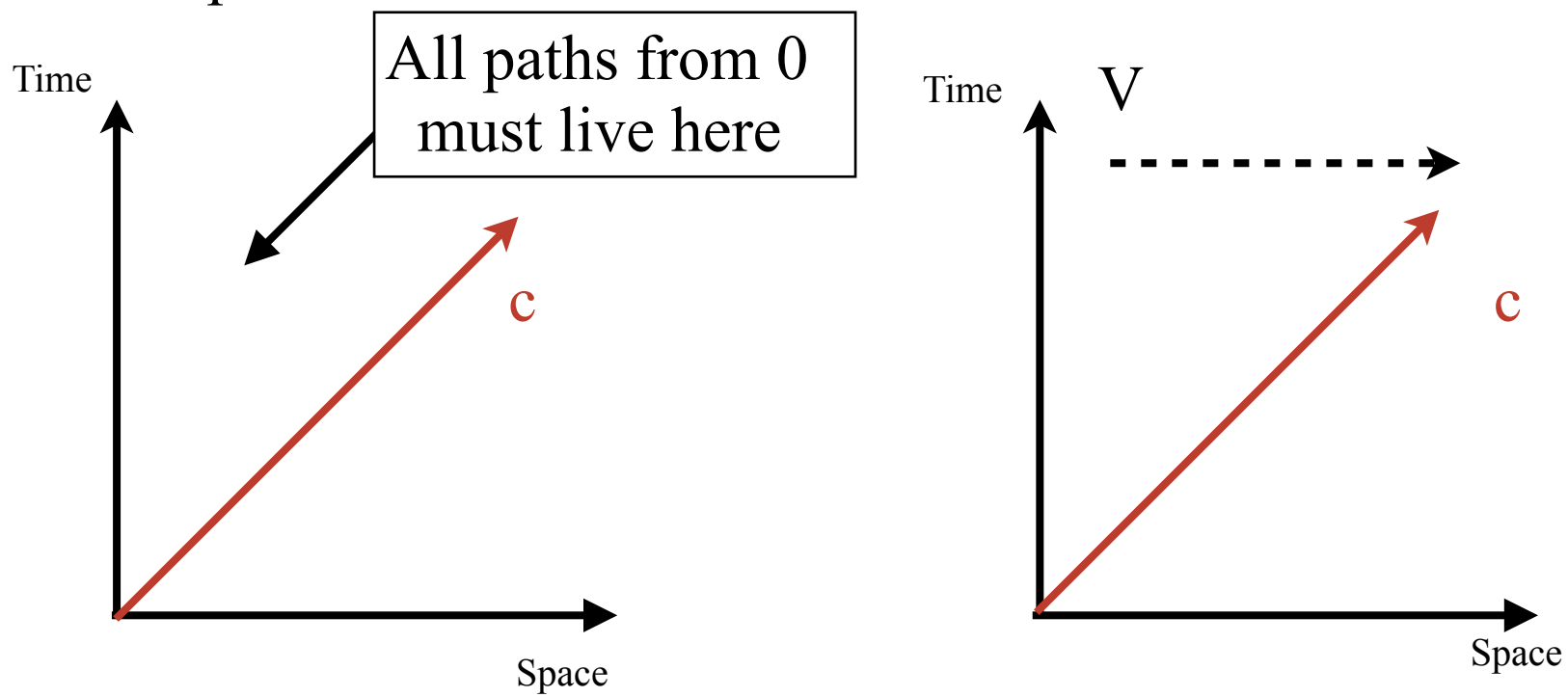
To limit the range over which things can have an affect:

-1) Must be a maximum speed.

-2) Max speed must be same regardless of how fast you are moving.

(otherwise we are back where we started v + V)

Maximum speed "c"



Einstein's Relativity

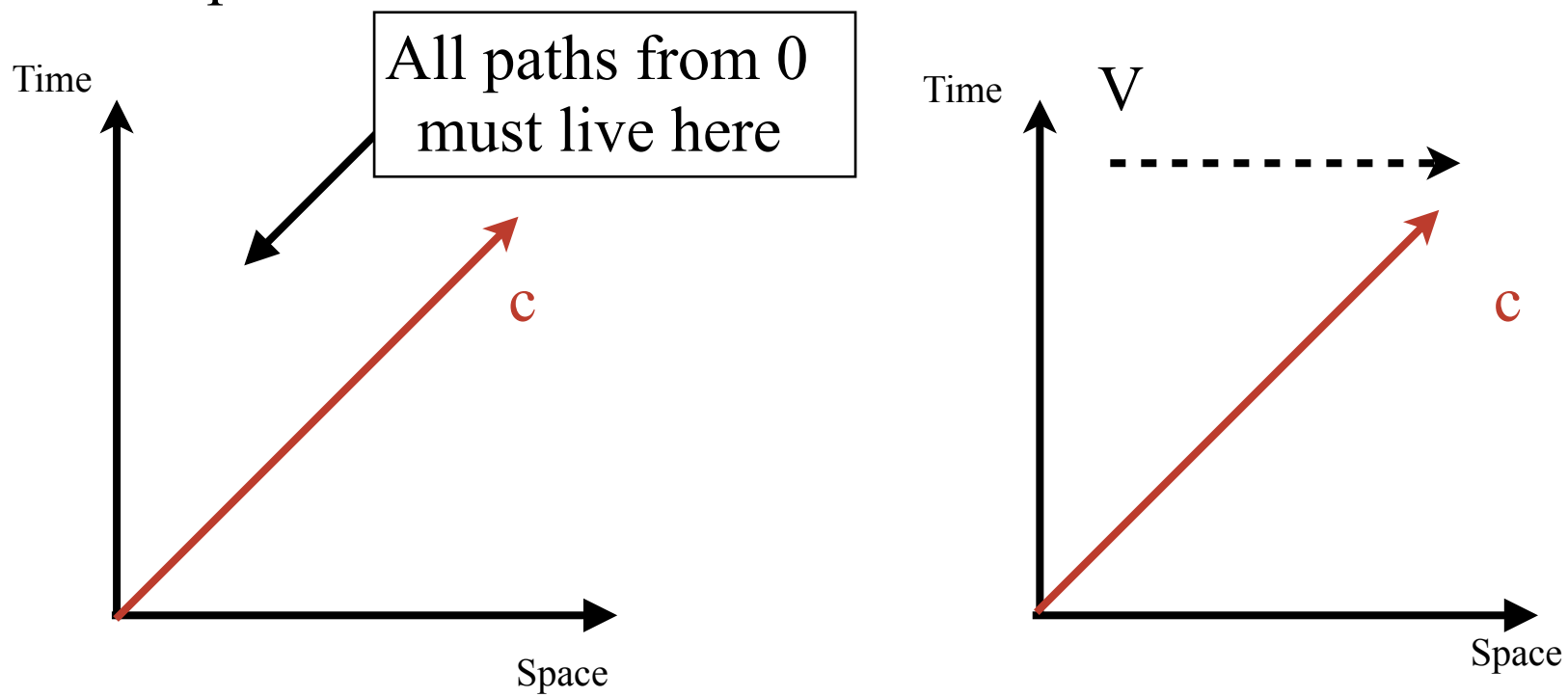
To limit the range over which things can have an affect:

-1) Must be a maximum speed.

-2) Max speed must be same regardless of how fast you are moving.

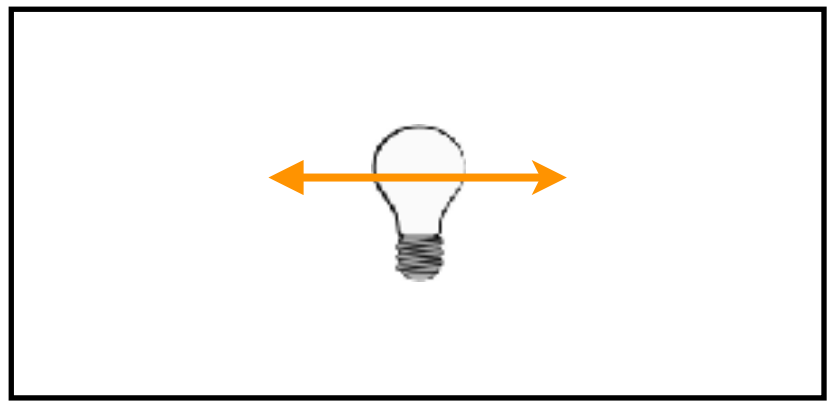
(otherwise we are back where we started v + V)

Maximum speed "c"

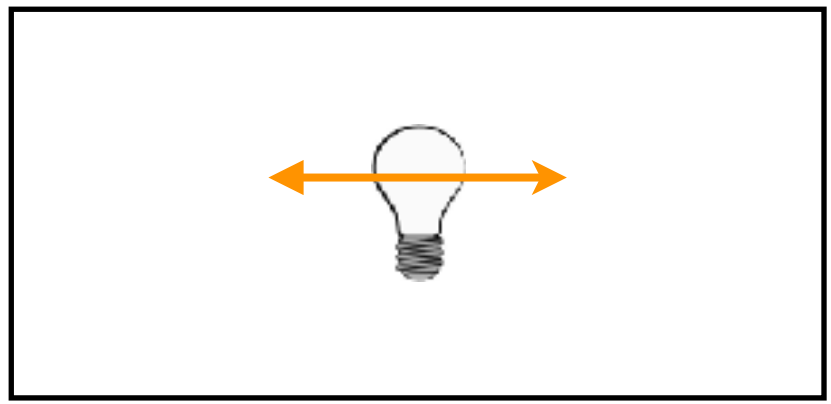


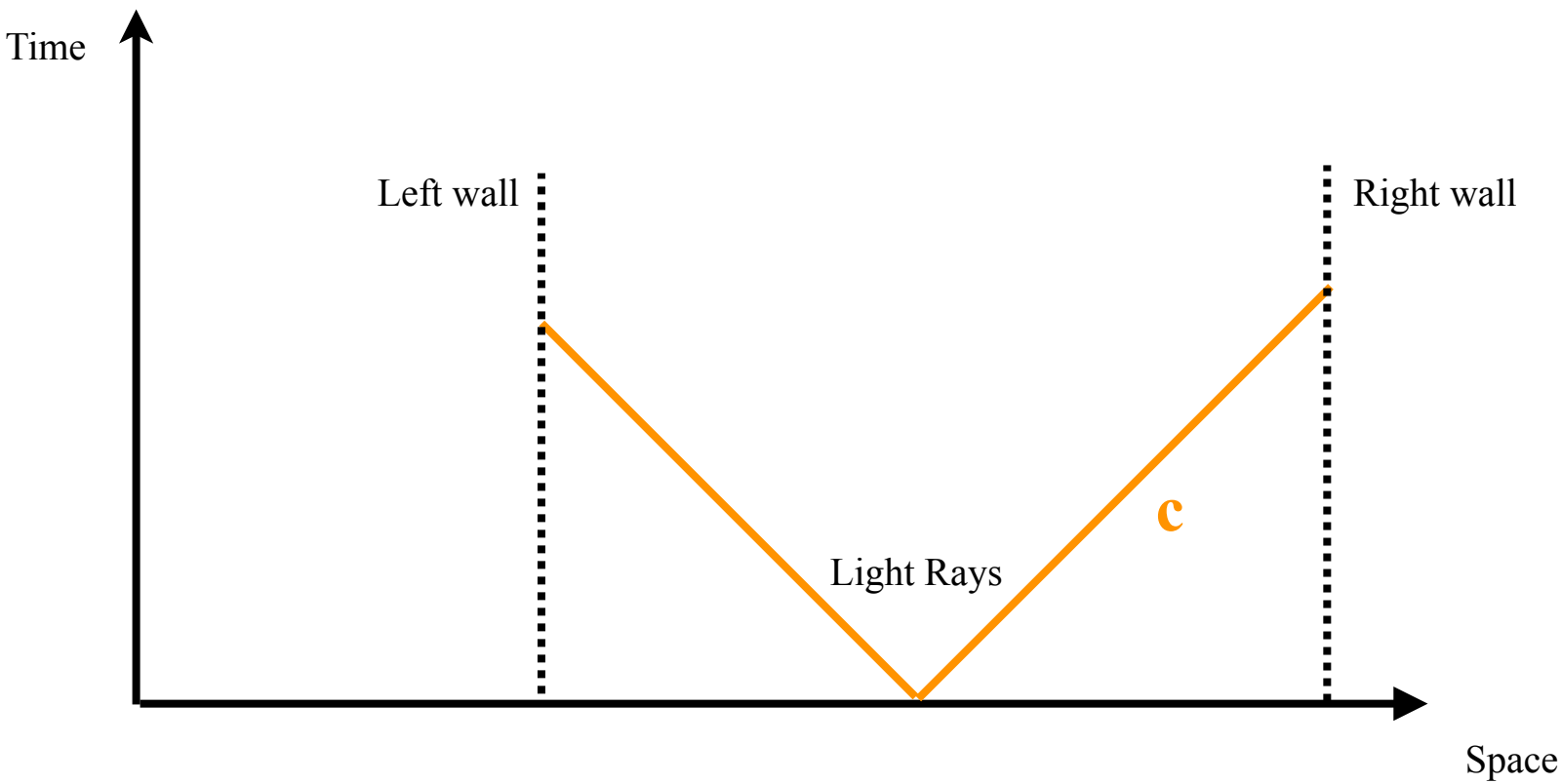
Simple requirement has profound implications.

Effect on Time

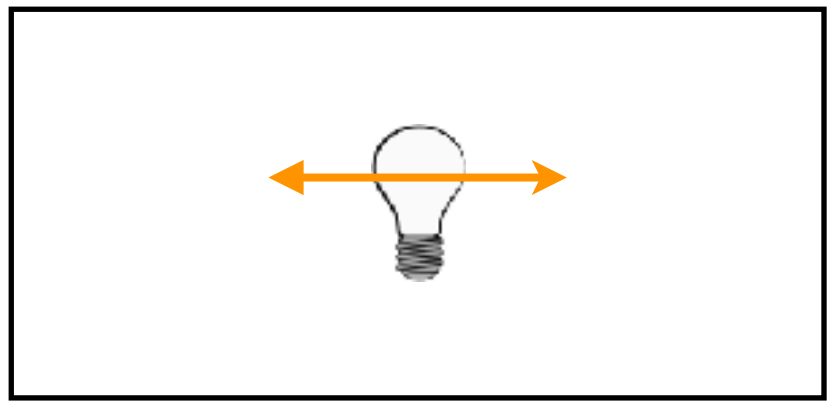


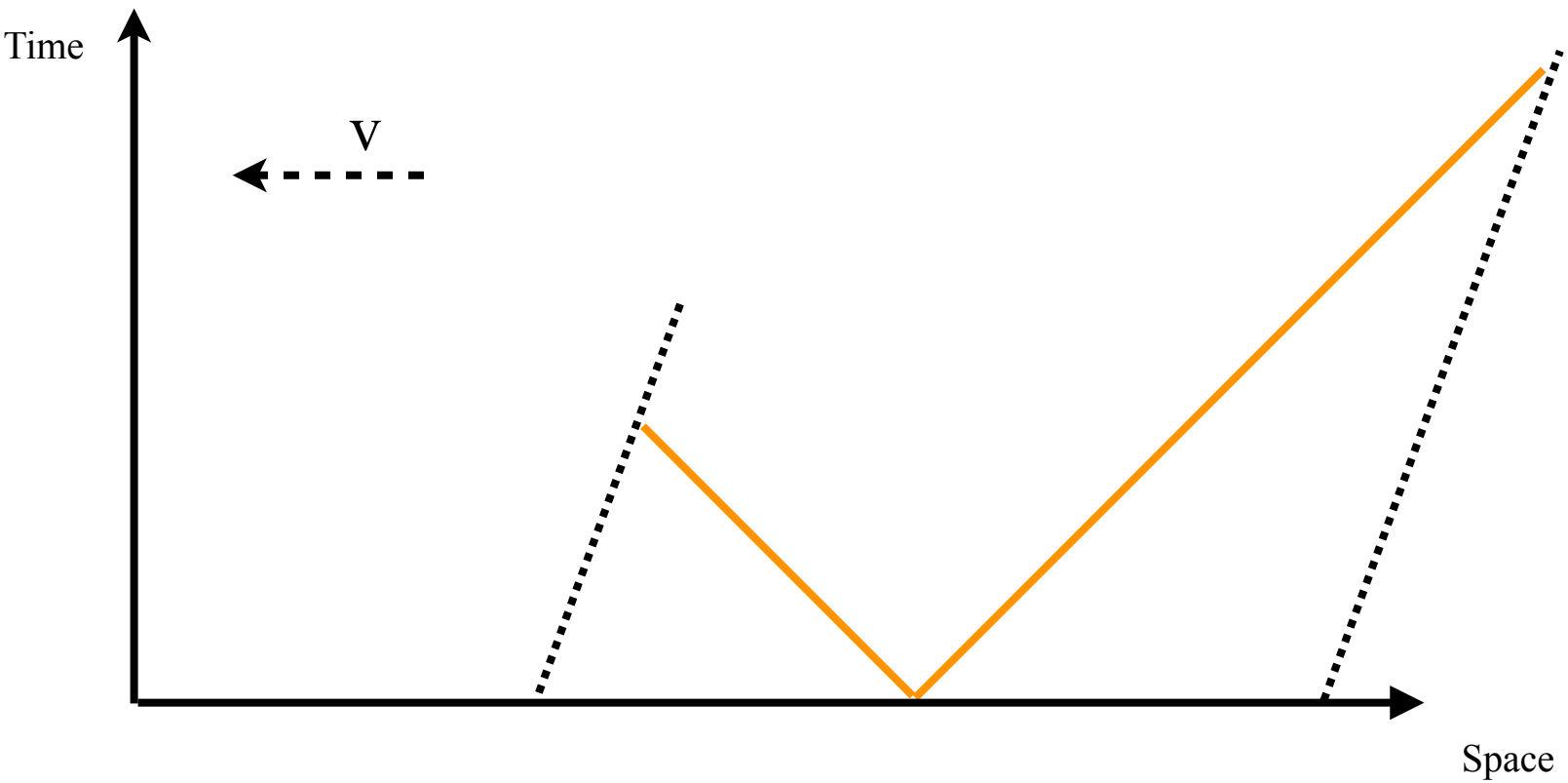
Effect on Time



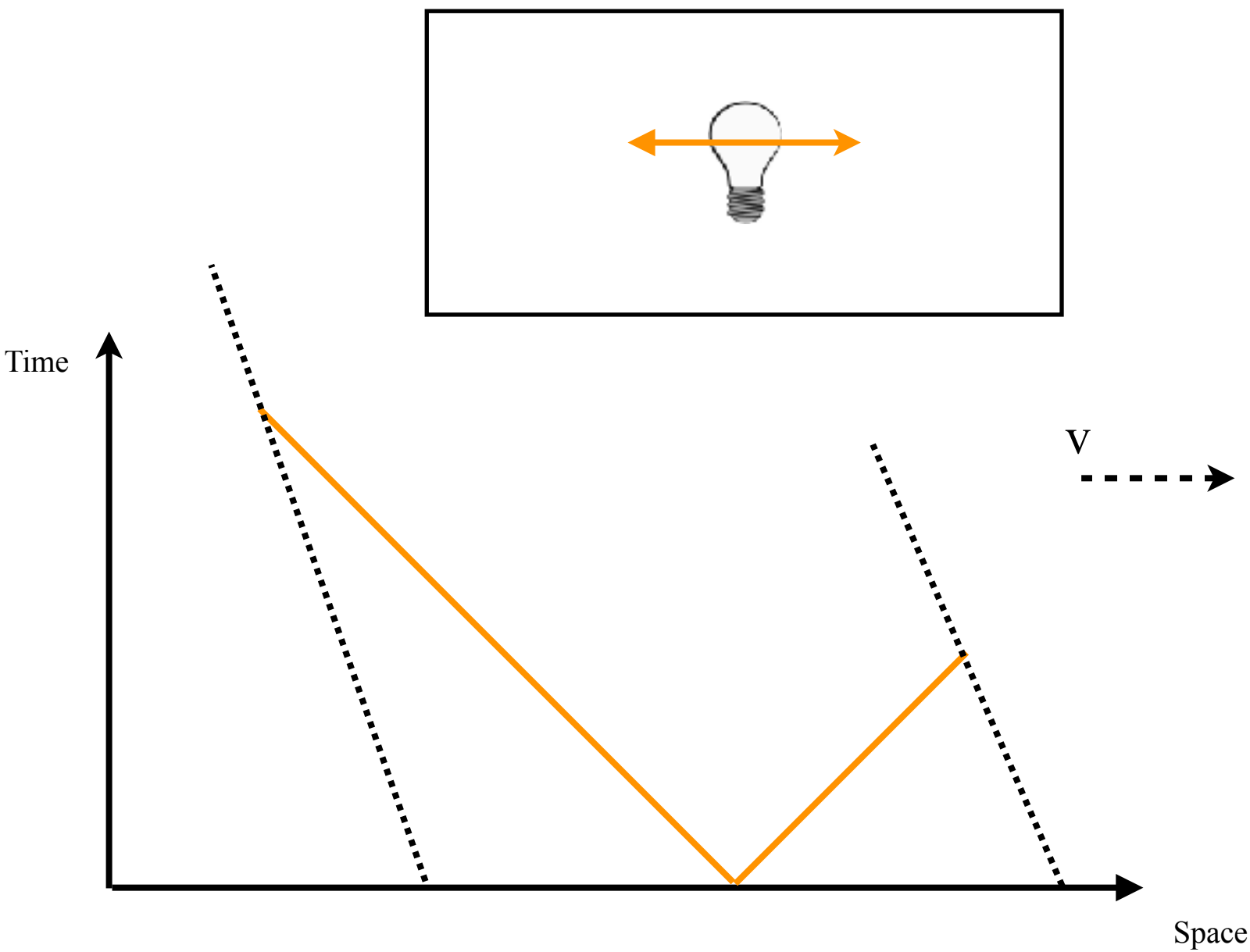


Effect on Time



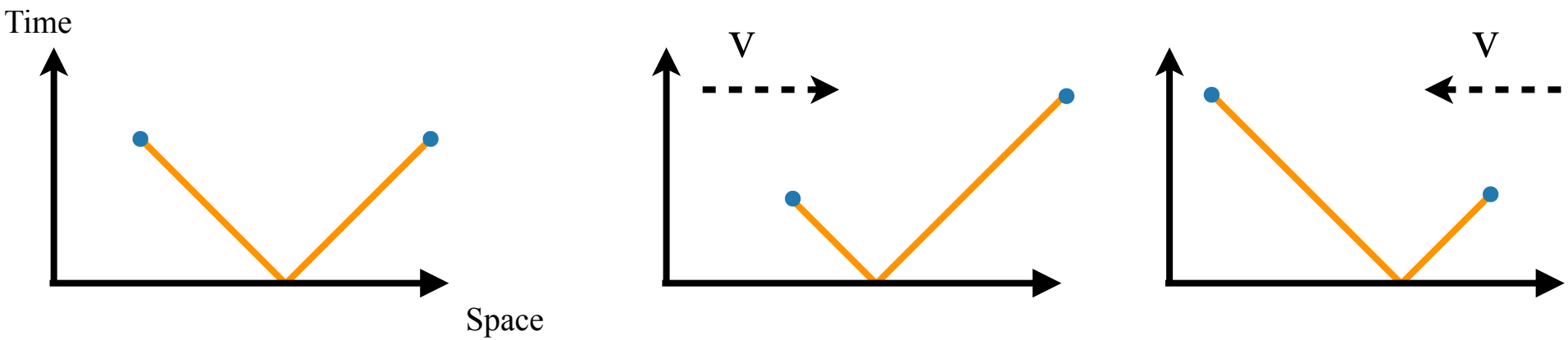


Effect on Time



Effect on Time

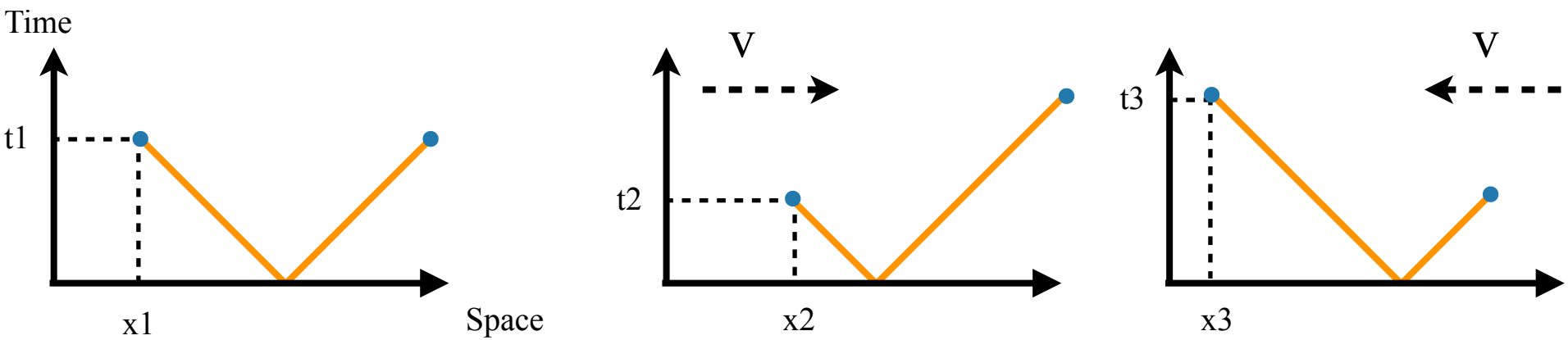
Time is not absolute !



Which order of what came first depends on how you are moving.

Effect on Time

Time is not absolute !



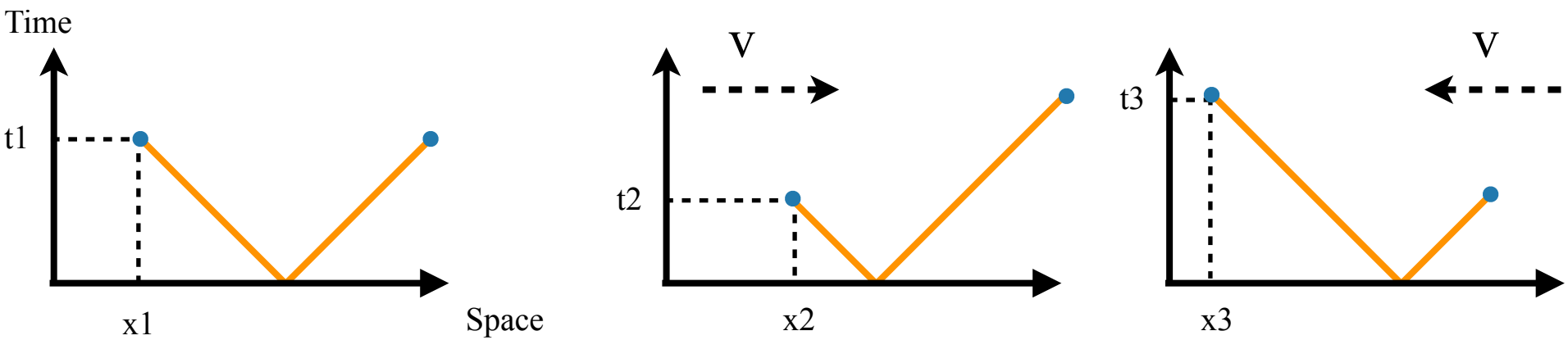
Which order of what came first depends on how you are moving.

Observers do agree on the speed: $x = c \times t$

$$x_1 = ct_1 \qquad x_2 = ct_2 \qquad x_3 = ct_3$$

Effect on Time

Time is not absolute !



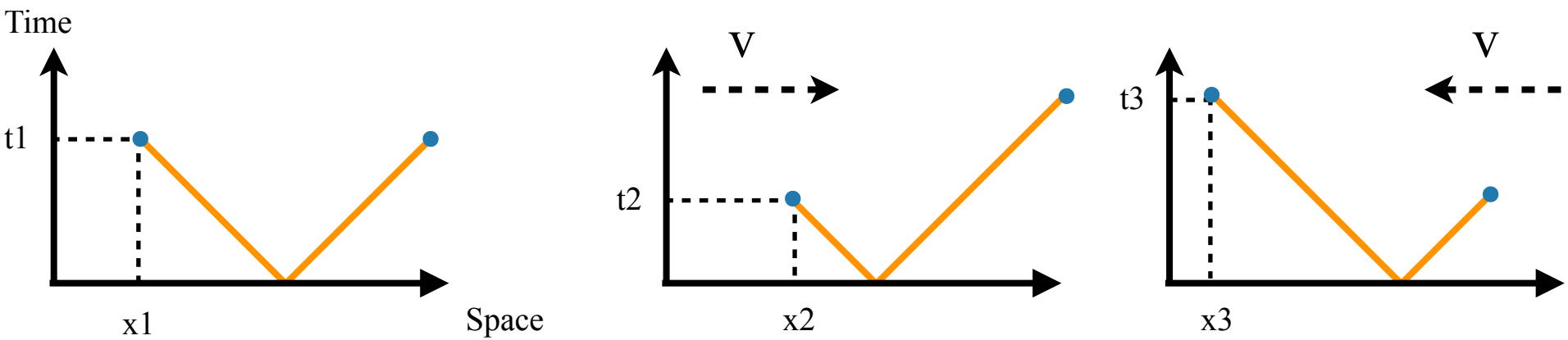
Which order of what came first depends on how you are moving.

Observers do agree on the speed: $x = c \times t$

$$x_1^2 - (ct_1)^2 = 0 \qquad x_2^2 - (ct_2)^2 = 0 \qquad x_3^2 - (ct_3)^2 = 0$$

Effect on Time

Time is not absolute !



Which order of what came first depends on how you are moving.

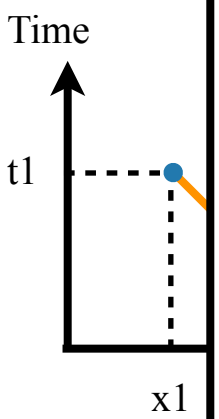
Observers do agree on the speed: $x = c \times t$

$$x_1^2 - (ct_1)^2 = 0 \qquad x_2^2 - (ct_2)^2 = 0 \qquad x_3^2 - (ct_3)^2 = 0$$

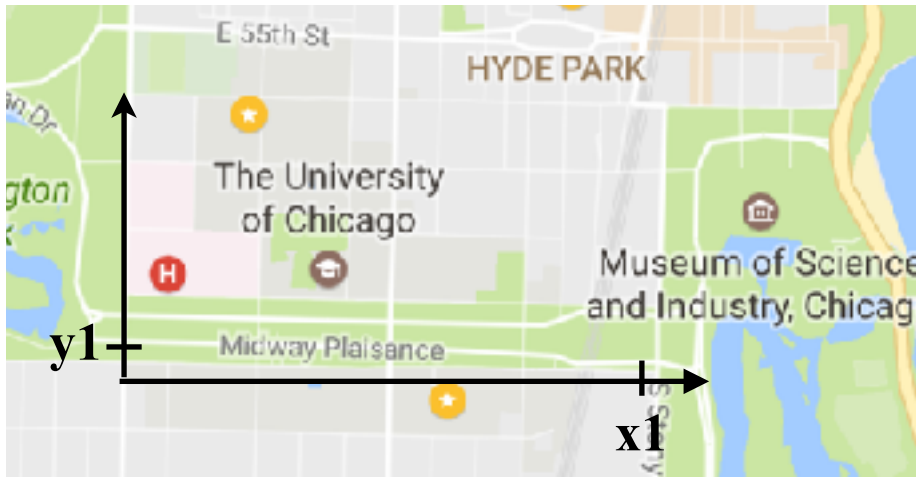
$x^2 - (ct)^2 = 0$ is "invariant", independent of how you are moving.

Effect on Time

Time is not absolute !



Direct analog: Length - Independent of angle that your looking



g.

Obser

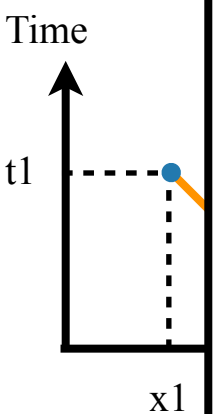
x_1^2 –

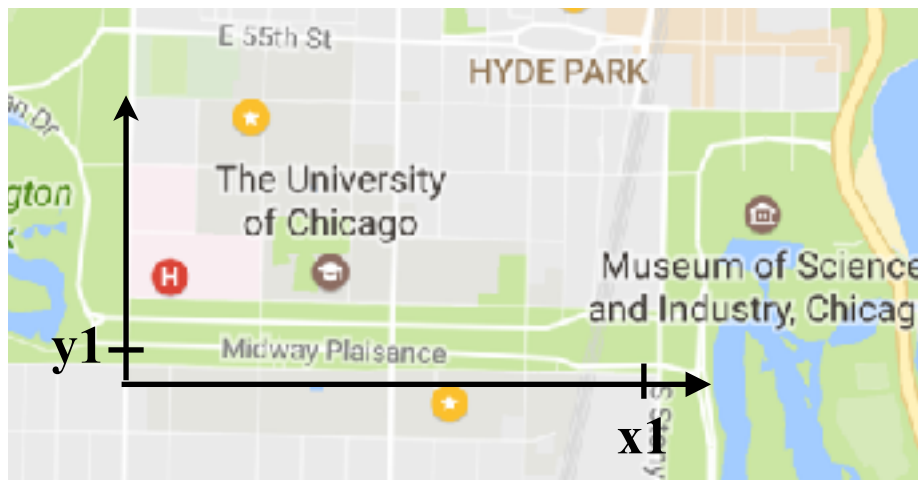
x^2 –

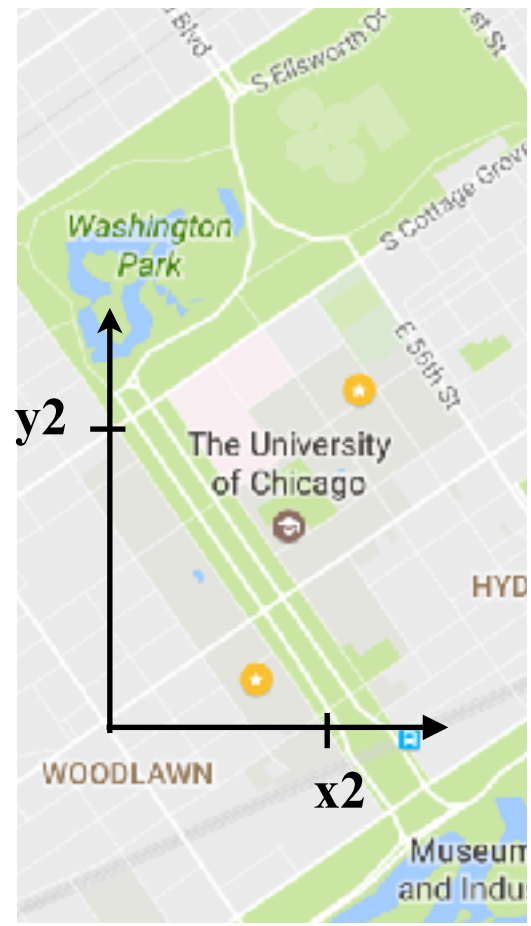
Effect on Time

Time is not absolute !

Direct analog: Length - Independent of angle that your looking







g.

Obser

x_1^2 –

x^2 –

Effect on Time

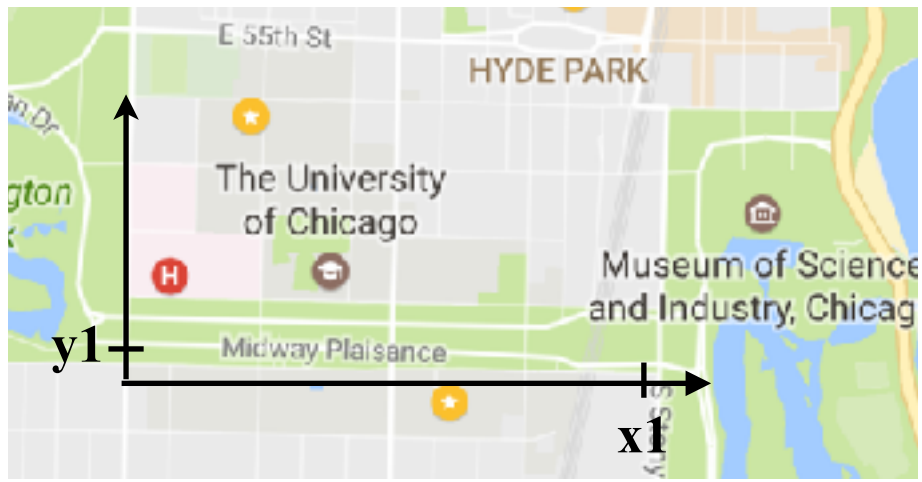
Time is not absolute !

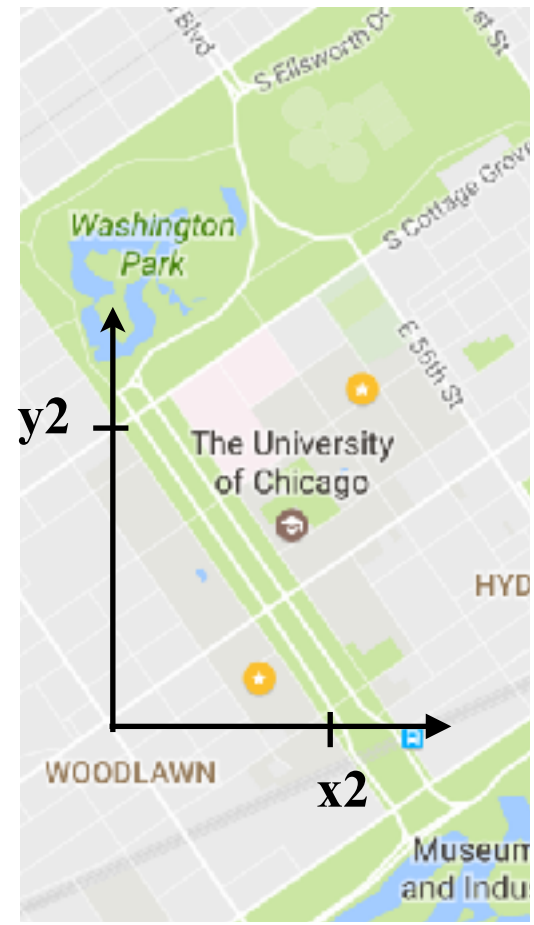
Time

t1

x1

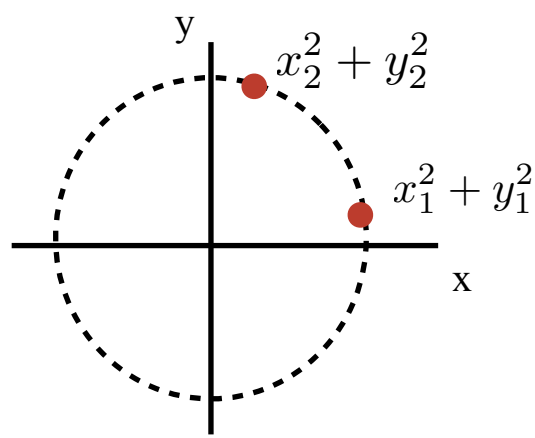
Direct analog: Length - Independent of angle that your looking





g.

Obser

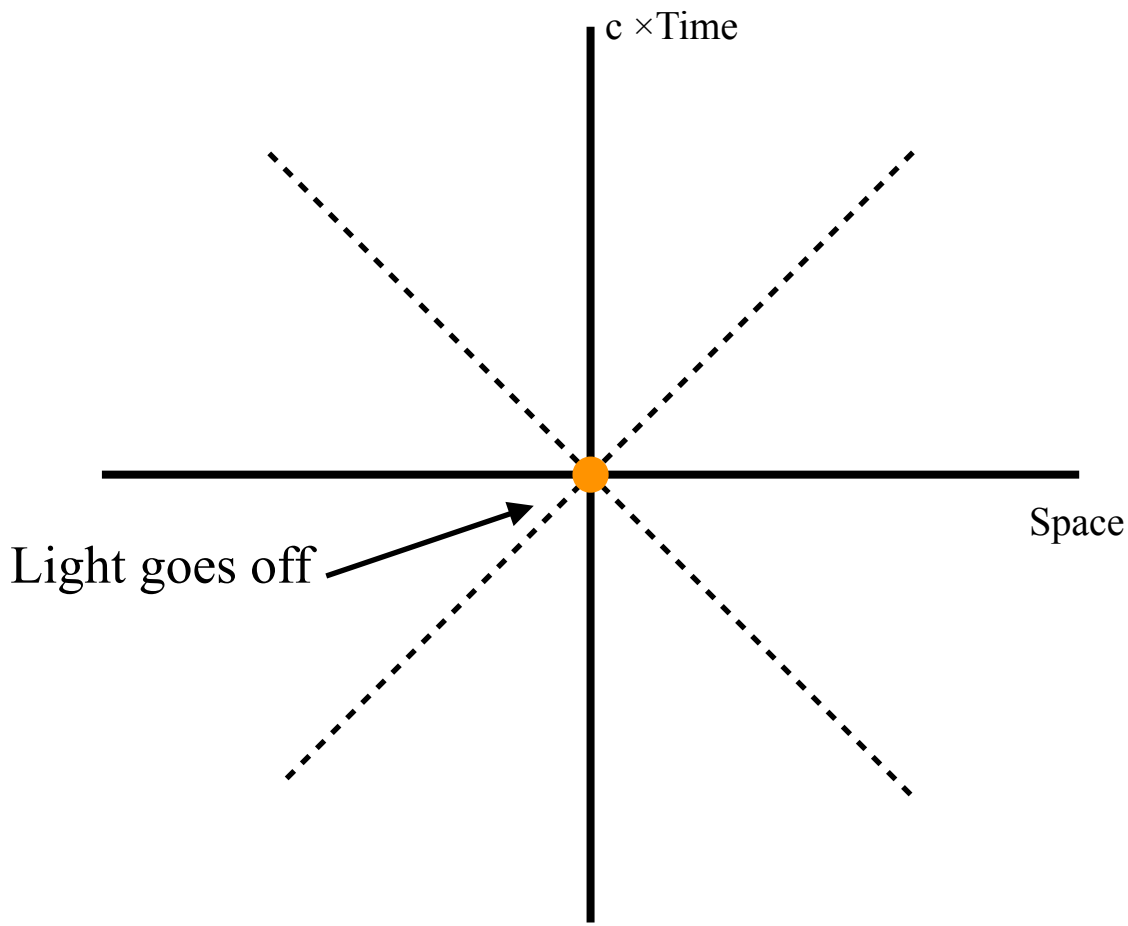


x_1^2

x^2

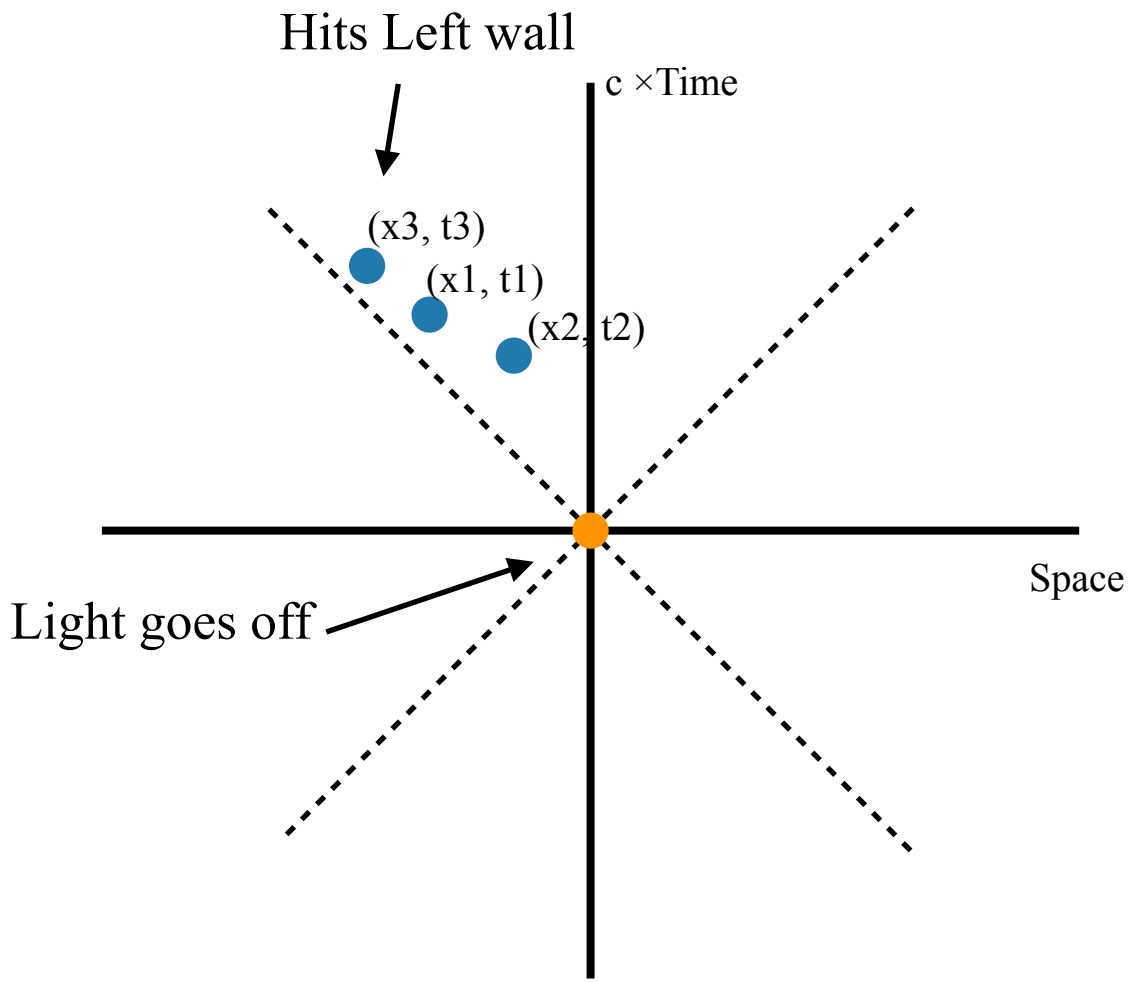
Space-Time

Mixing of space and time



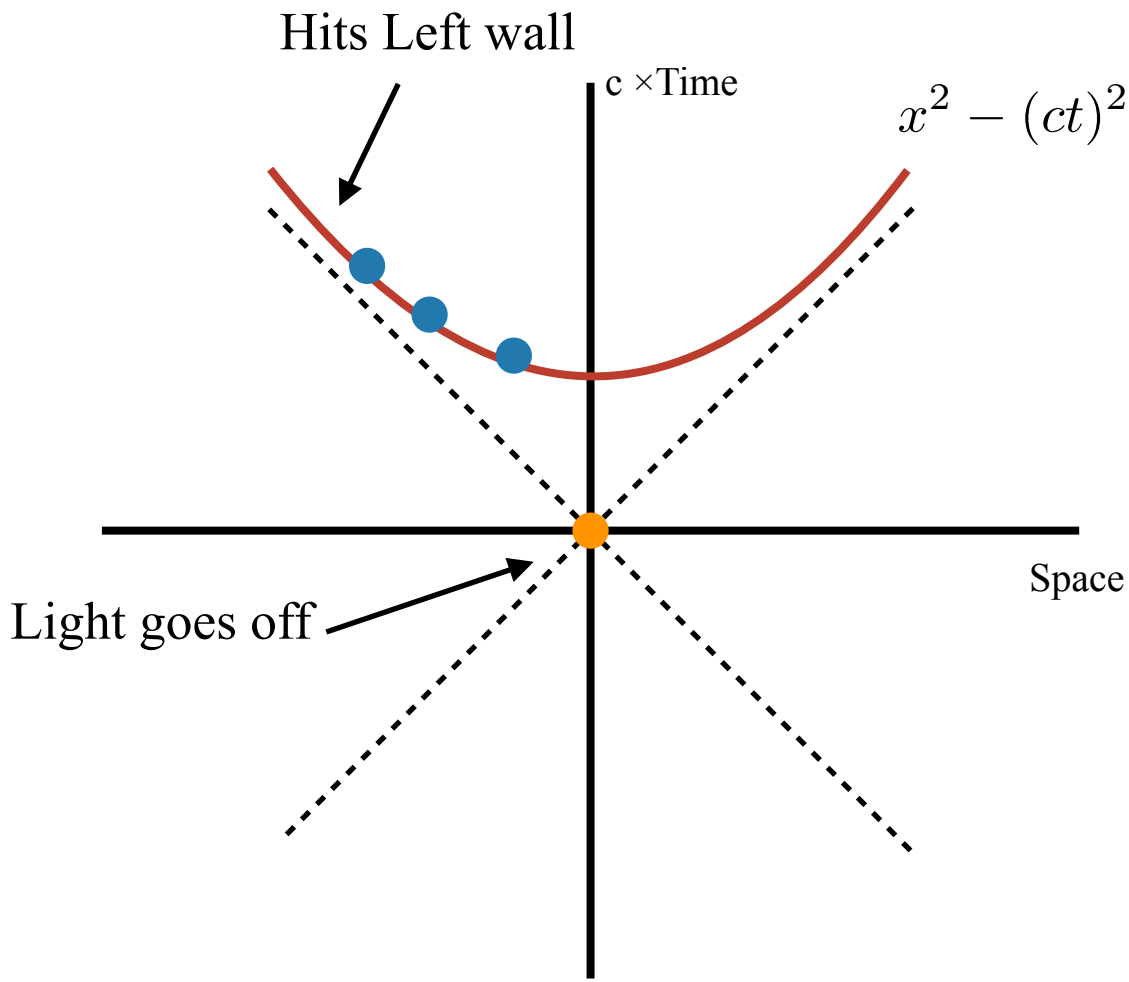
Space-Time

Mixing of space and time



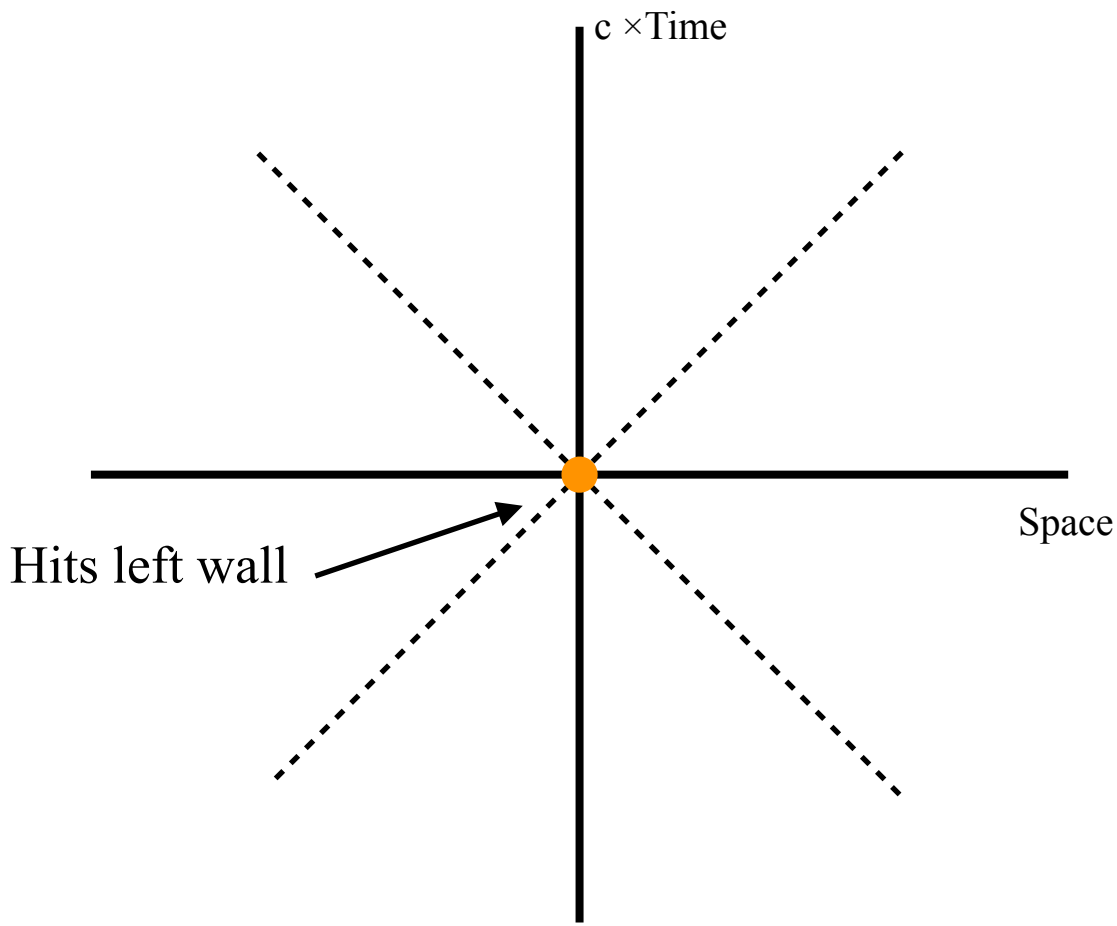
Space-Time

Mixing of space and time



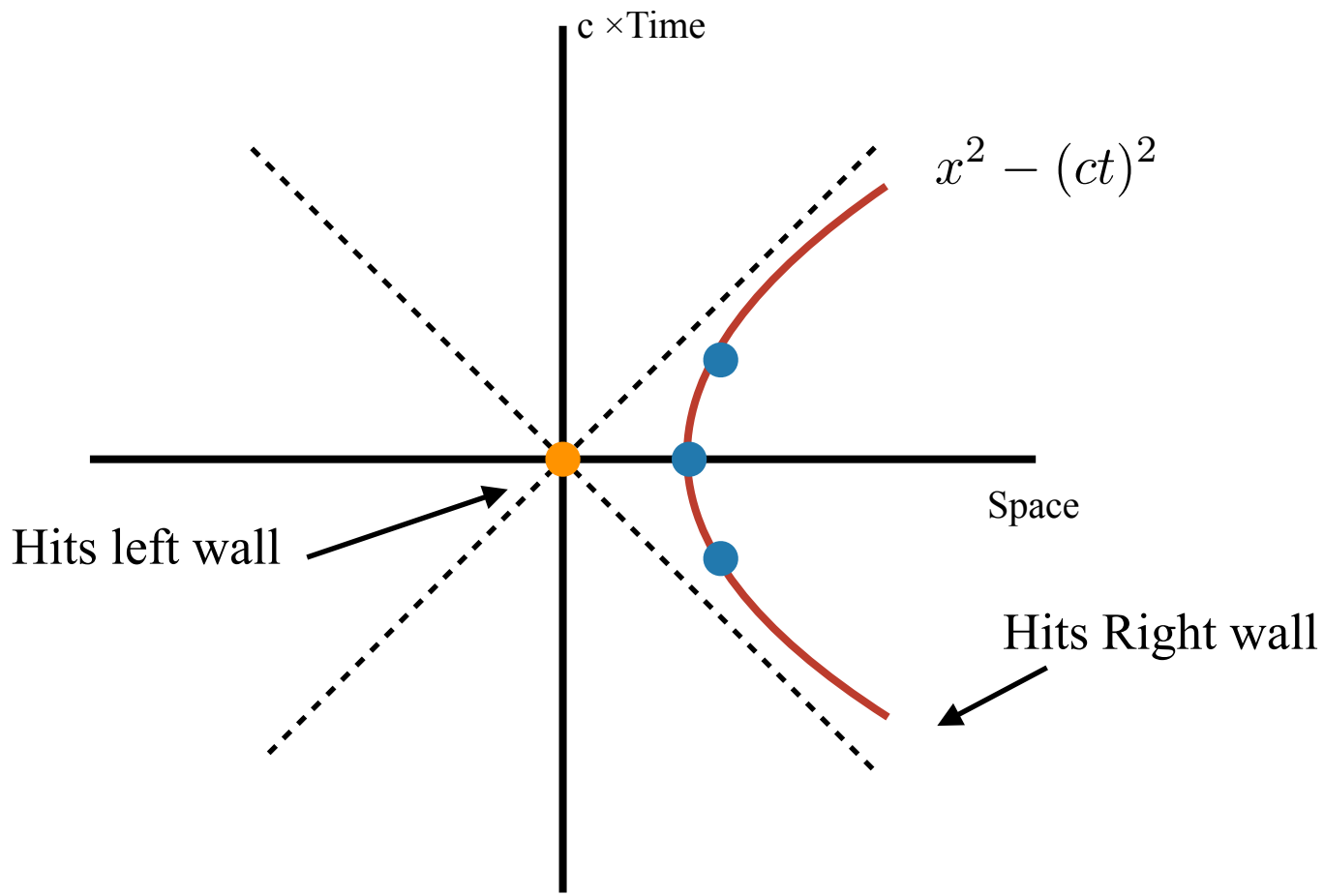
Space-Time

Mixing of space and time



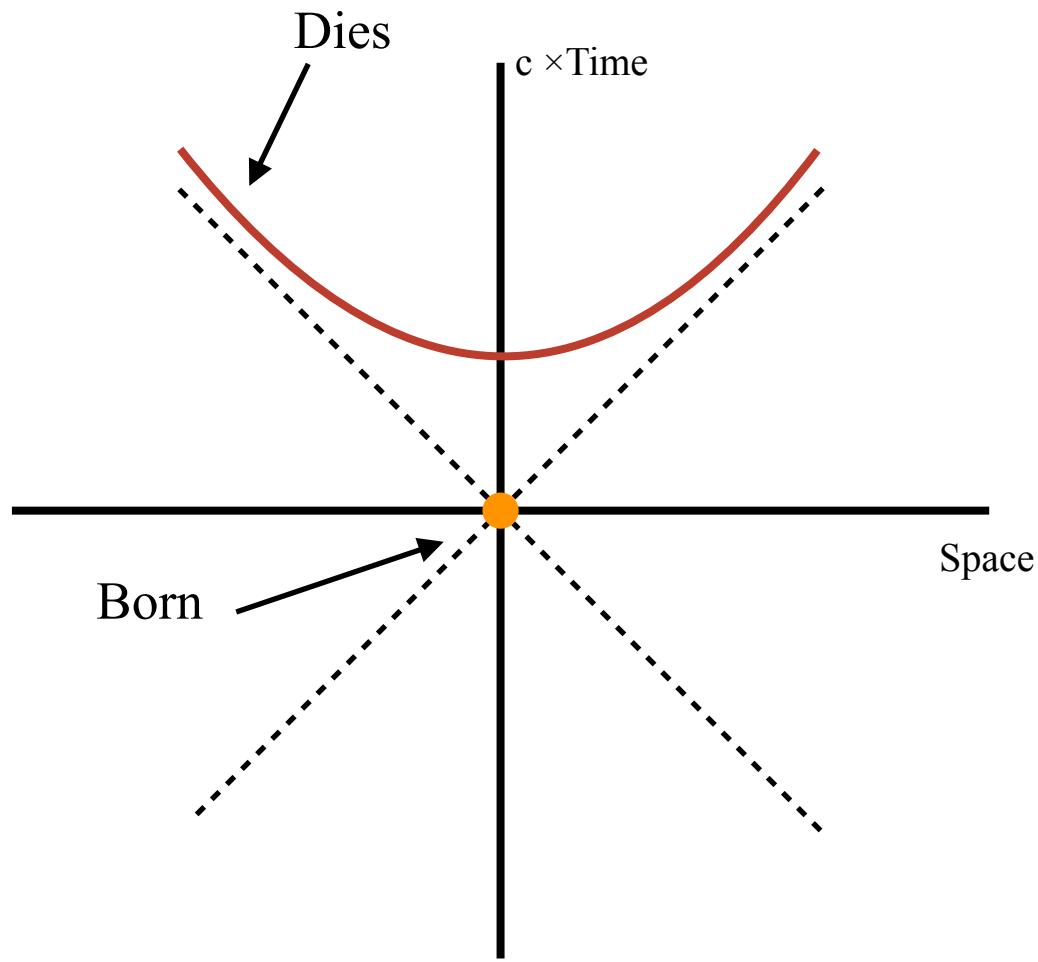
Space-Time

Mixing of space and time



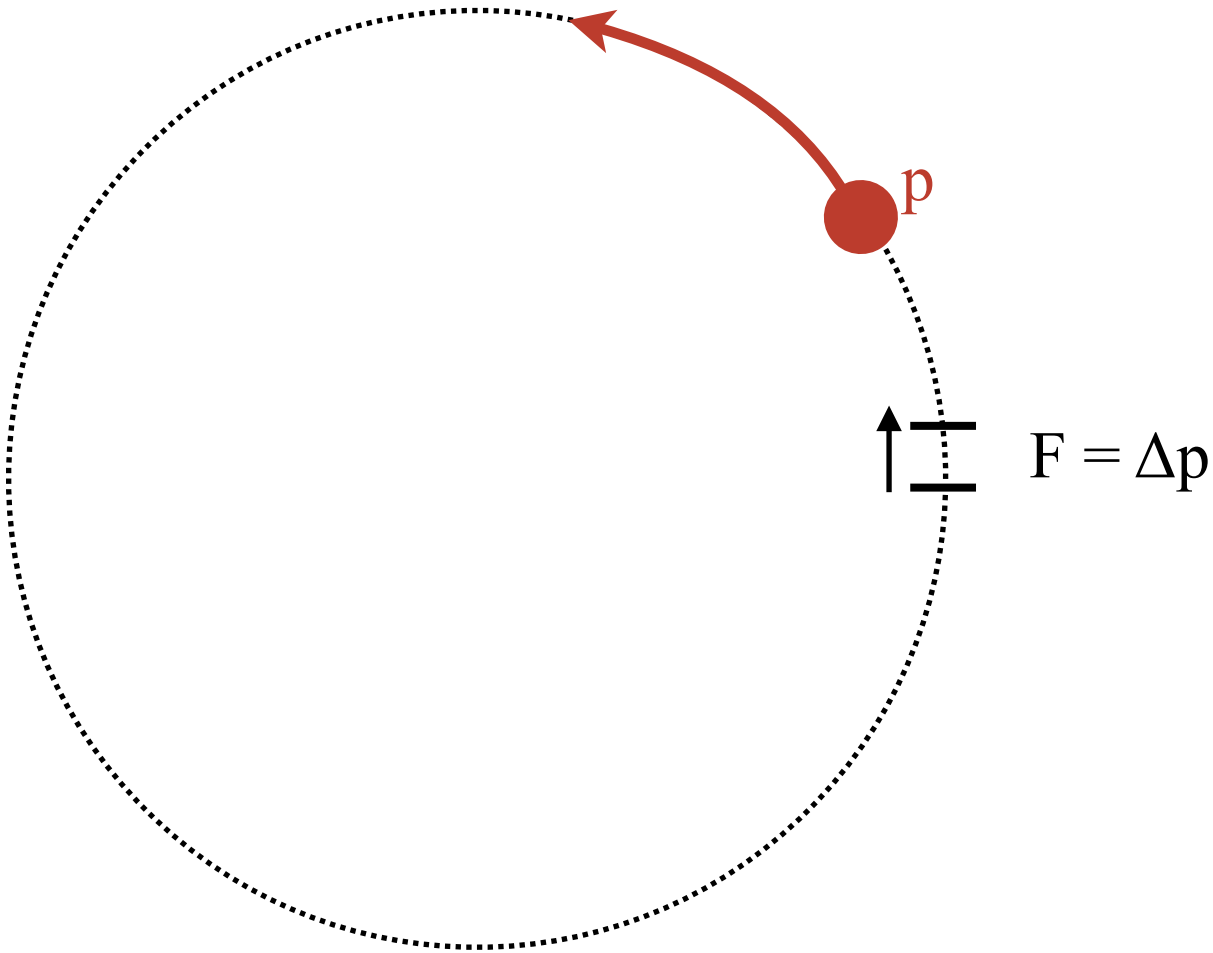
Space-Time

Mixing of space and time

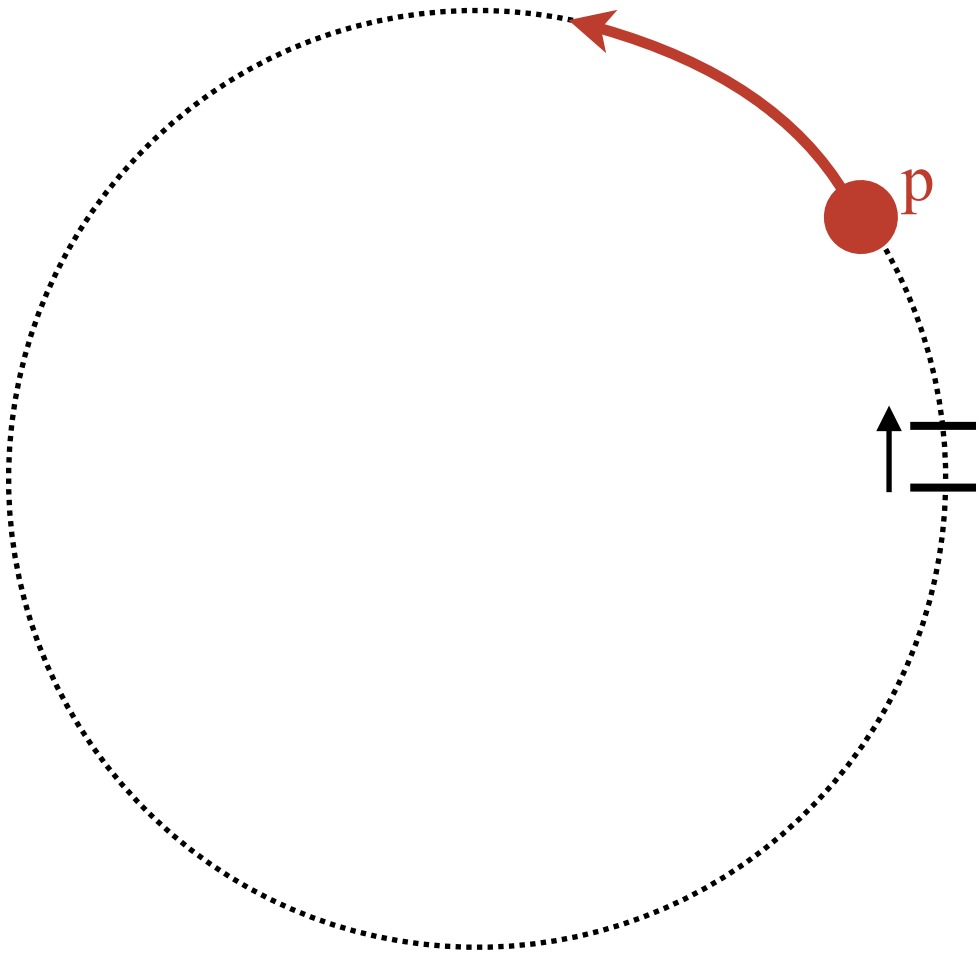


- Time dilation
- Crazy but true ! μ are hitting us now

Effect on Mass



Effect on Mass

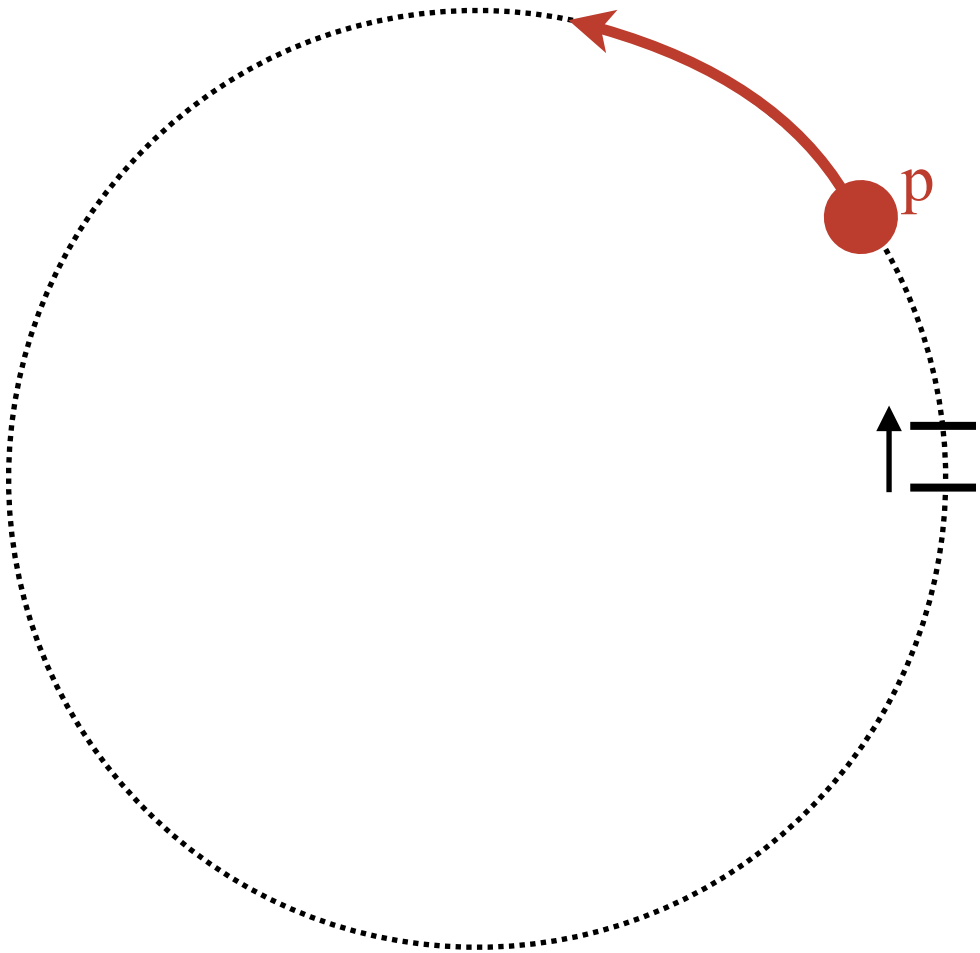


$F = \Delta p$

$\Delta p = F \times (\text{Number Cycles})$

$= \Delta (mv)$

Effect on Mass

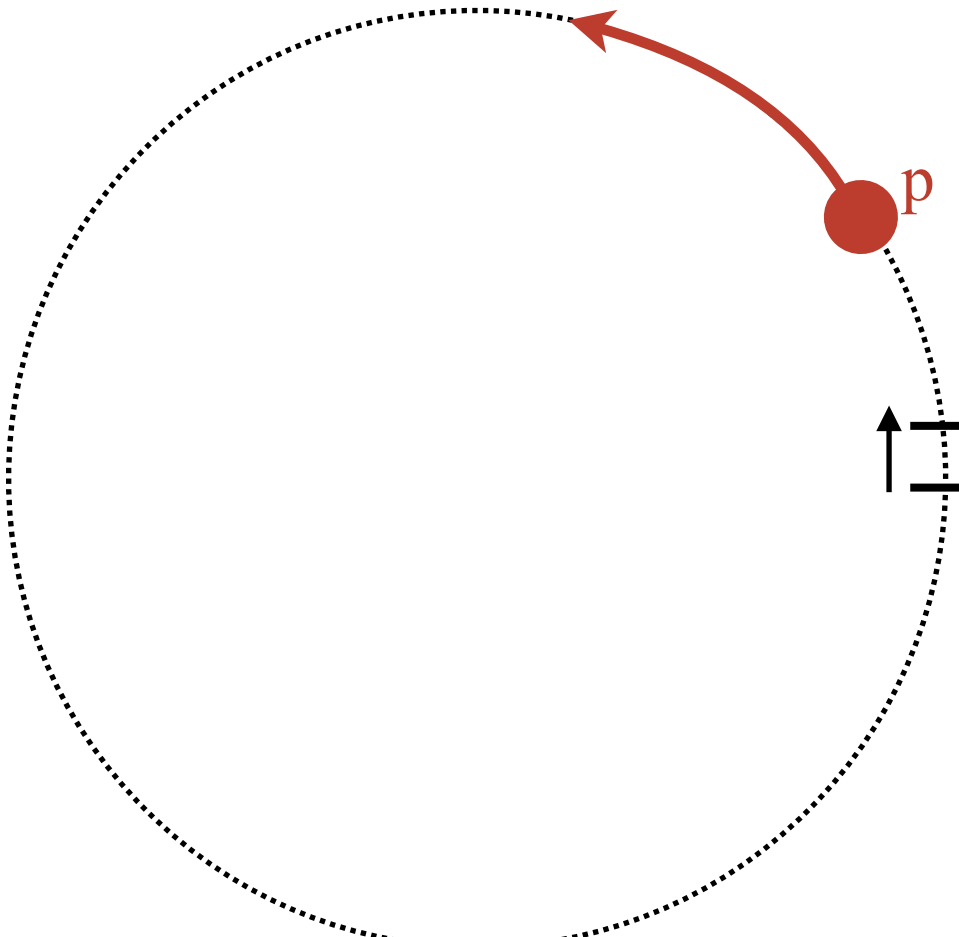


$F = \Delta p$

Can be arbitrarily large.
(as long as we can keep p in the circle)

$\Delta p = F \times (\text{Number Cycles})$
$= \Delta (mv)$

Effect on Mass



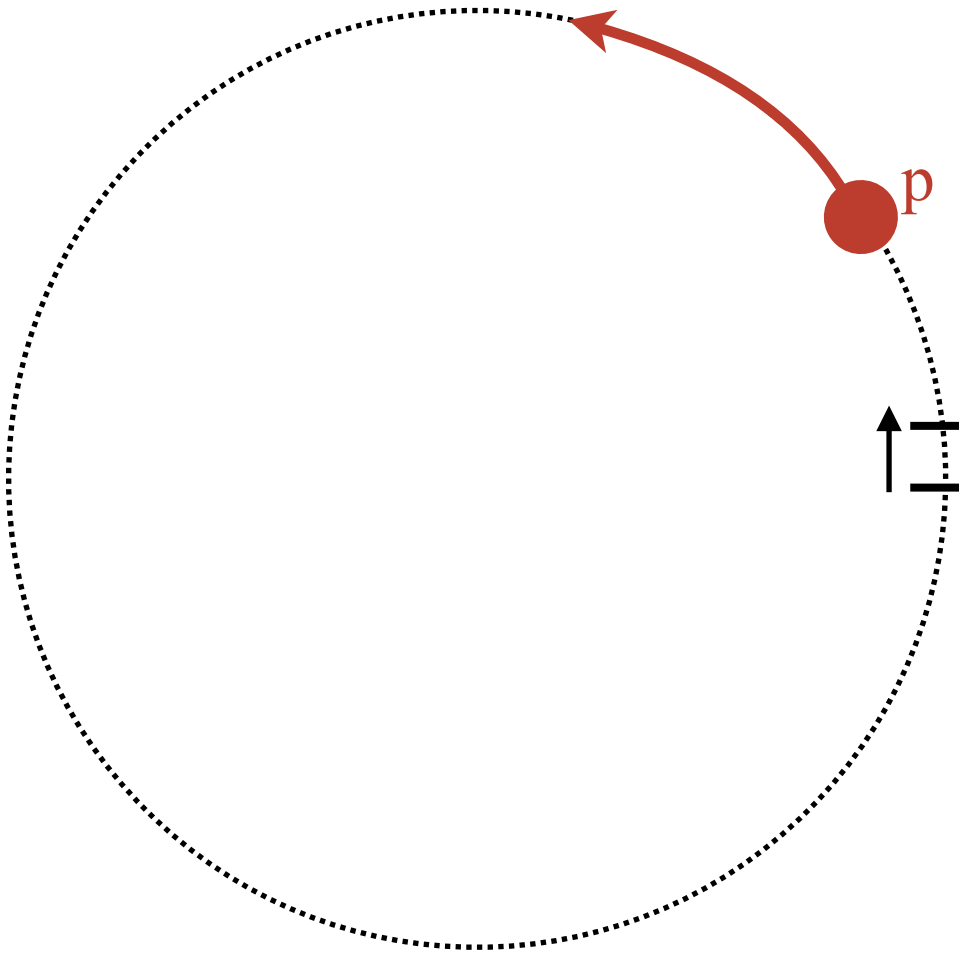
$F = \Delta p$

Can be arbitrarily large.
(as long as we can keep p in the circle)

$\Delta p = F \times (\text{Number Cycles})$
$= \Delta (mv)$

When $v \sim c$, Δp must come from Δm

Effect on Mass



$F = \Delta p$

Can be arbitrarily large.
(as long as we can keep p in the circle)

$\Delta p = F \times (\text{Number Cycles})$
$= \Delta (mv)$

When $v \sim c$, Δp must come from Δm

Mass increases with speed!

Next Time: Quantum Mechanics