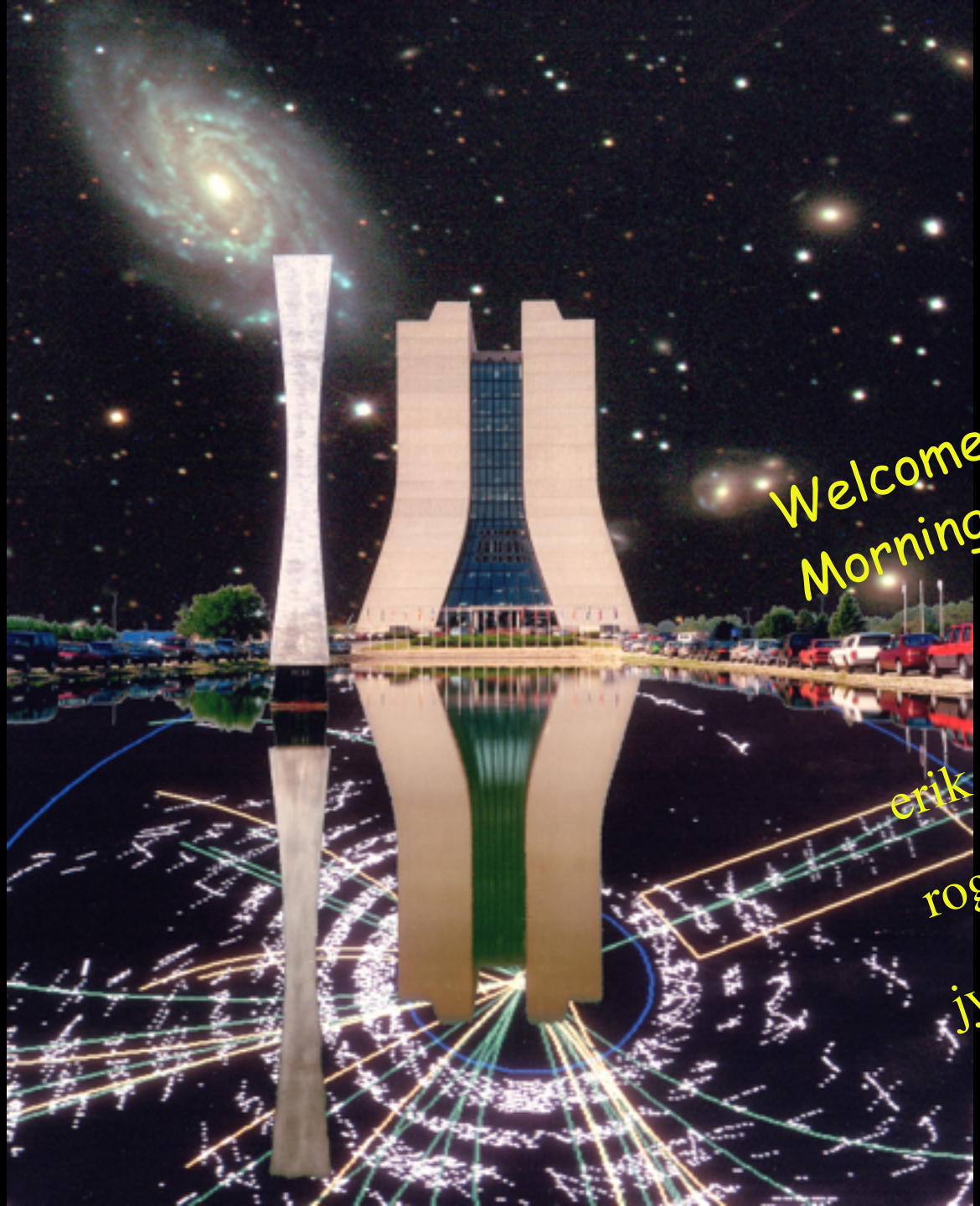


Welcome to Saturday Morning Physics

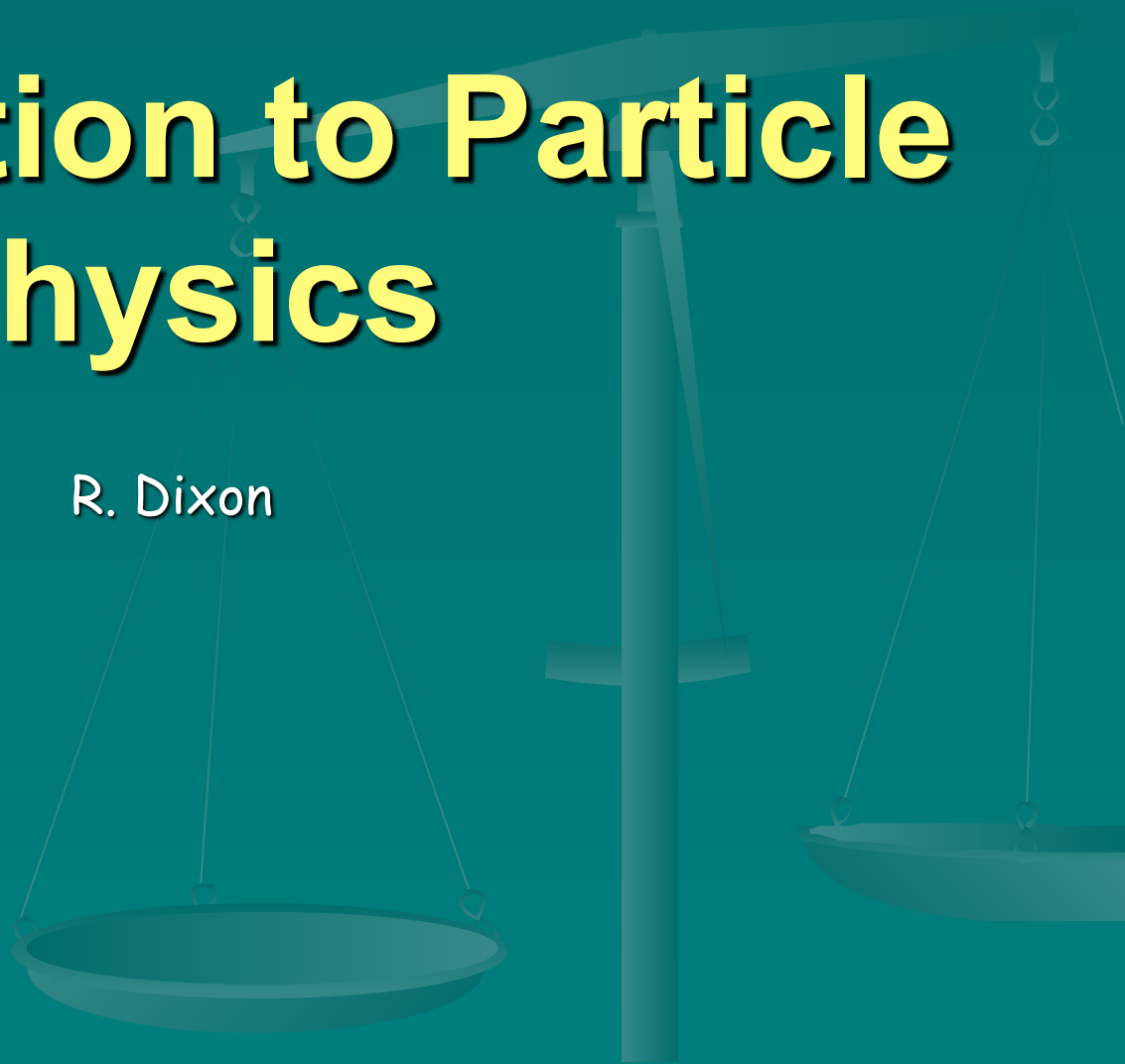
erik ramberg

roger dixon

jyotsna osta

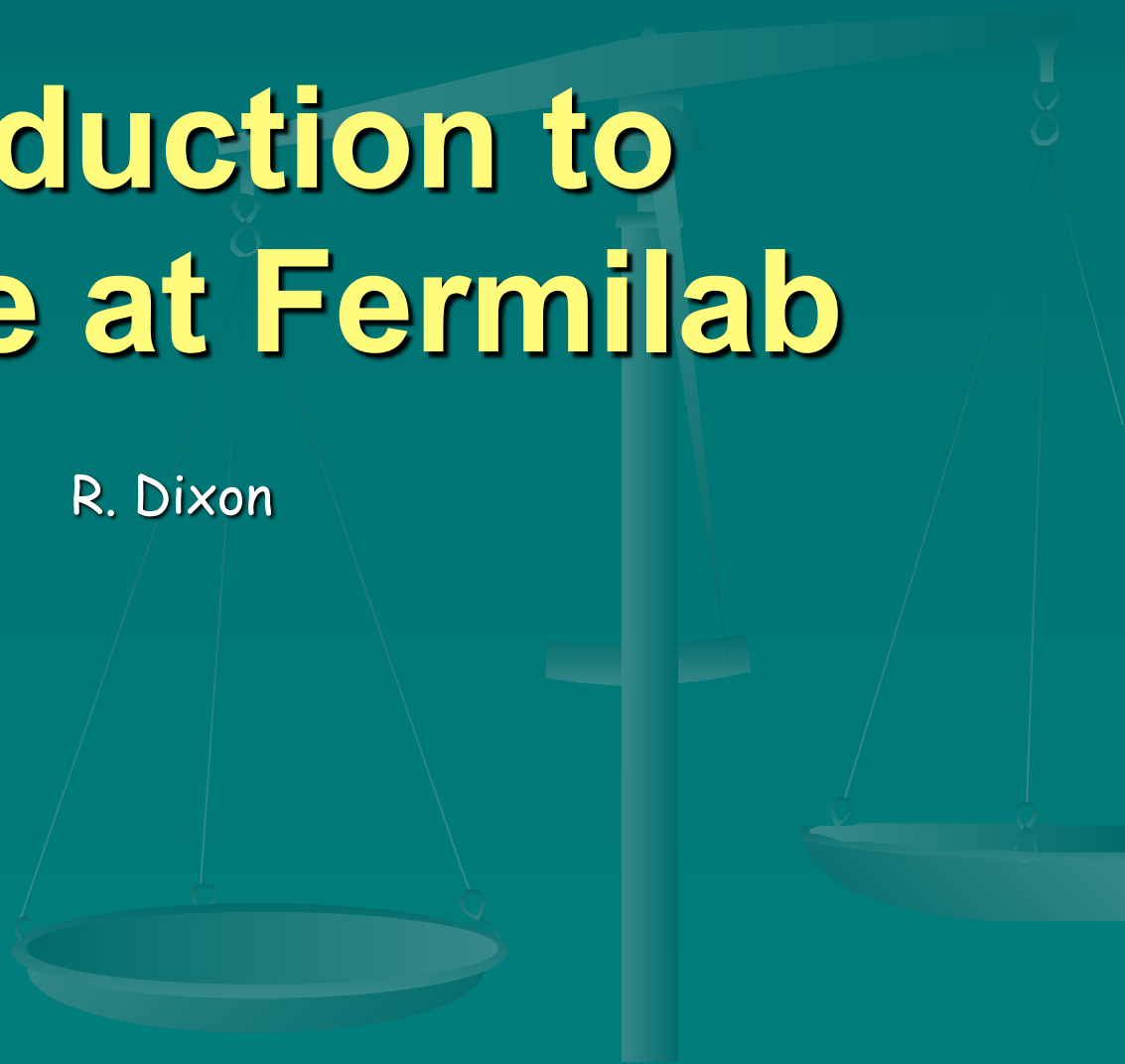
Introduction to Particle Physics

R. Dixon



Introduction to Science at Fermilab

R. Dixon



Overview

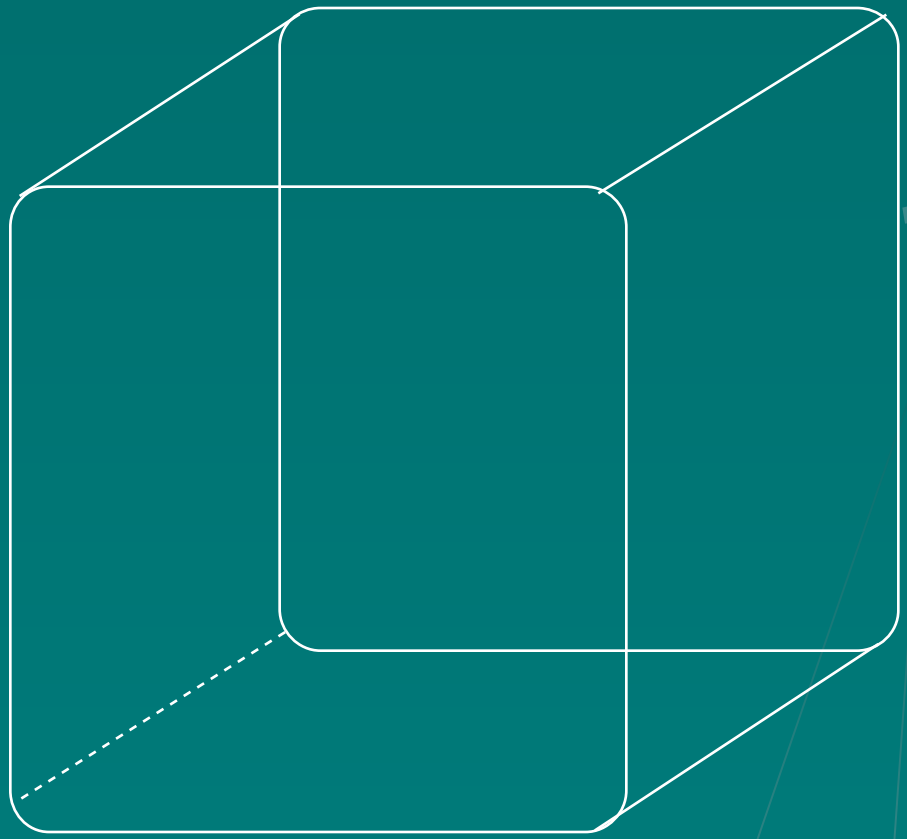
- Motivations for Science
  - Particle Physics
  - Astrophysics
- Fundamental Questions and Philosophy
  - Why is our science interesting and relevant?
- Historical Overview
  - How did we arrive here
  - Where are we going?
- Along the way a preview of the rest of the program including examples from
  - Special Relativity
  - Quantum Mechanics

Most Fundamental Questions

- Why does the Universe exist?
- What is the alternative
  - Nothing
    - What is nothing?
      - That which does not exist
      - Can we get from here (existence) to nothing?
      - Fact from basic physics
        - There is no place in the known universe where there is nothing, yet many of us think we know what nothing is
      - Maybe nothing is unstable
- What are the fundamental building blocks of the Universe?

A Simple Universe

A Simple Universe



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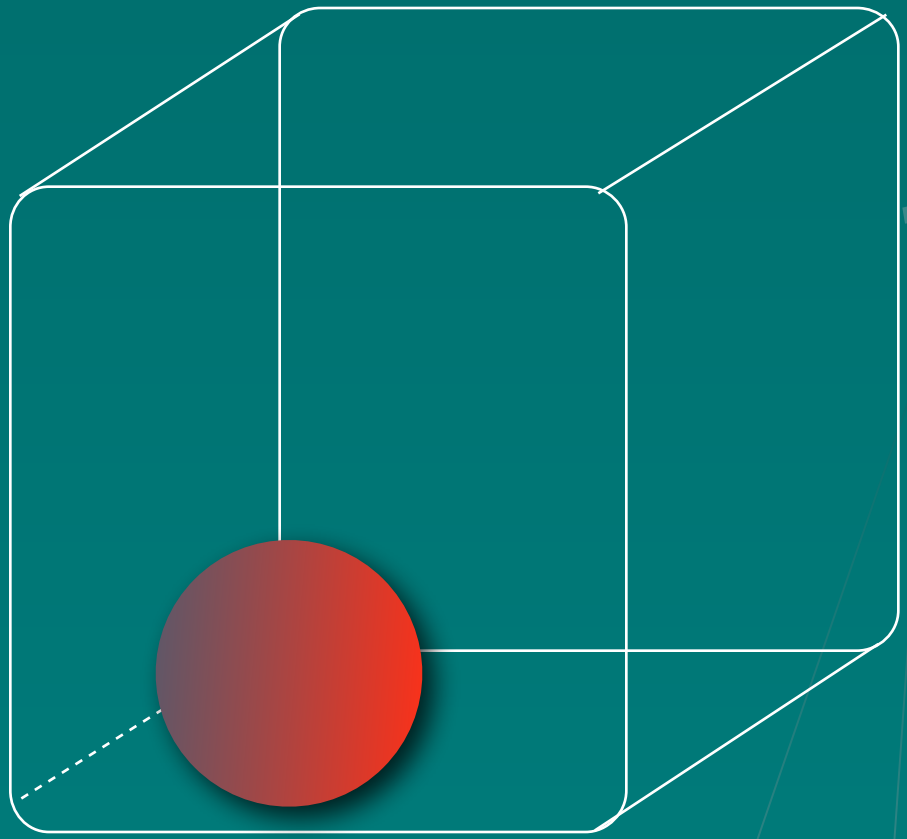

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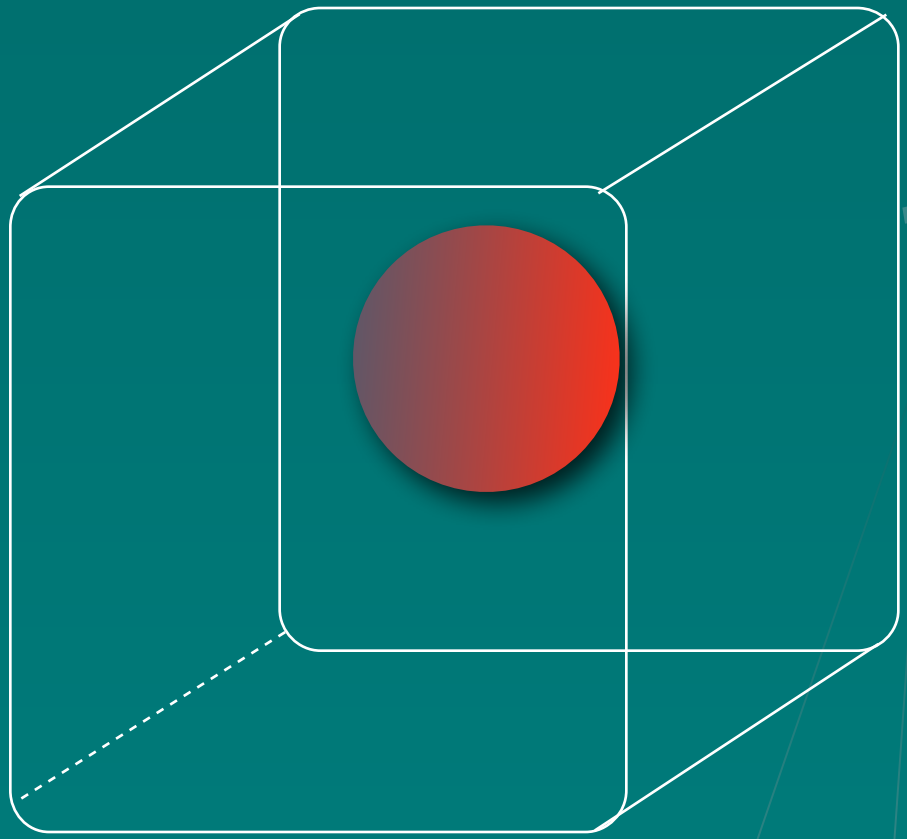

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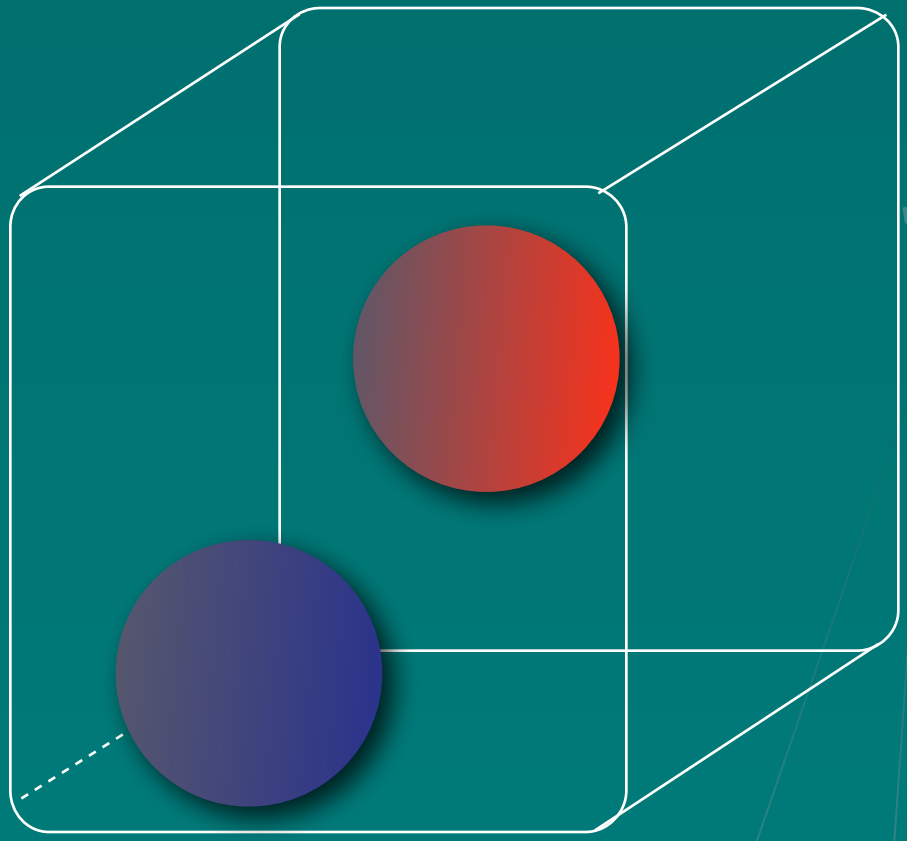

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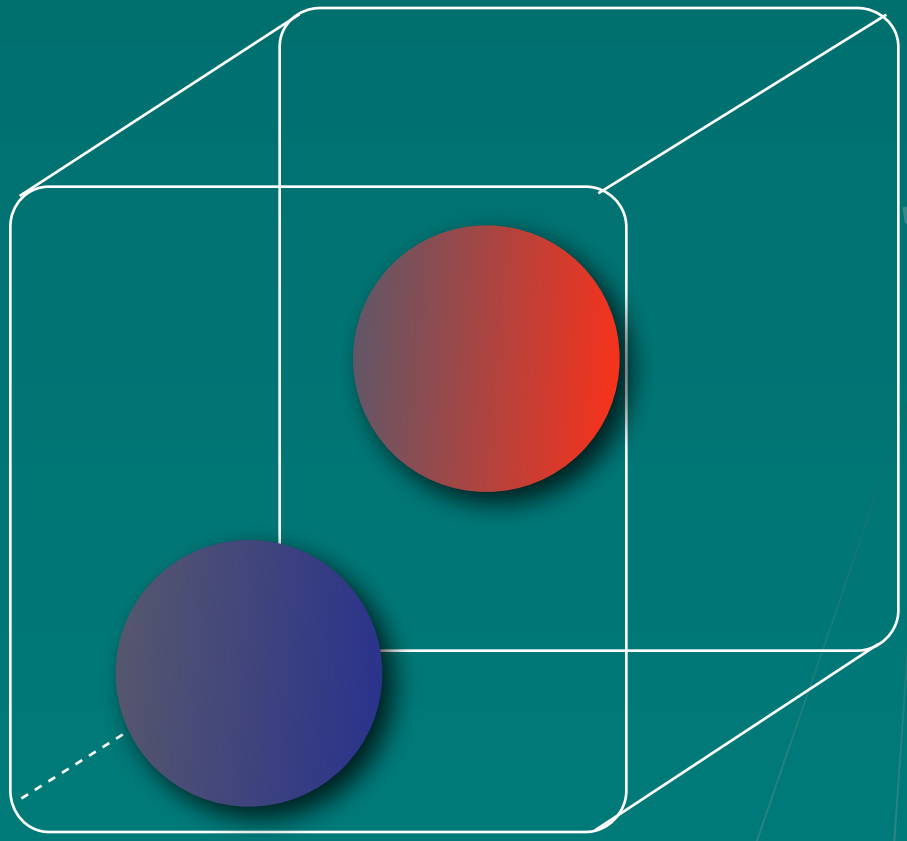

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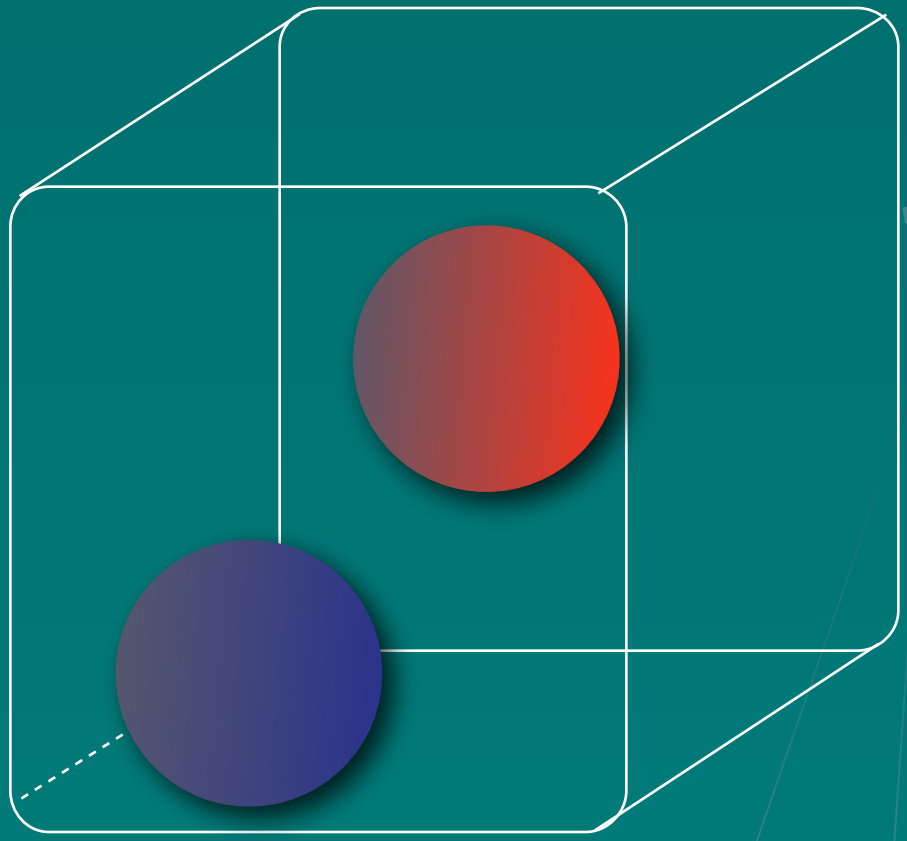

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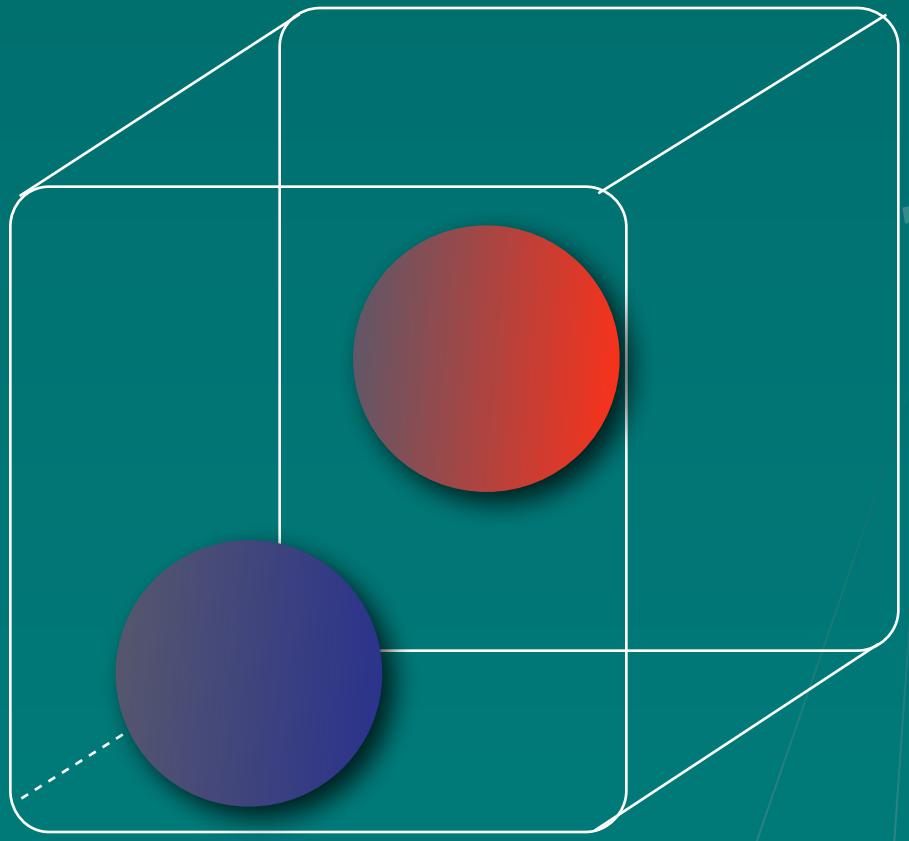

To Understand the Universe we must understand the Properties of:

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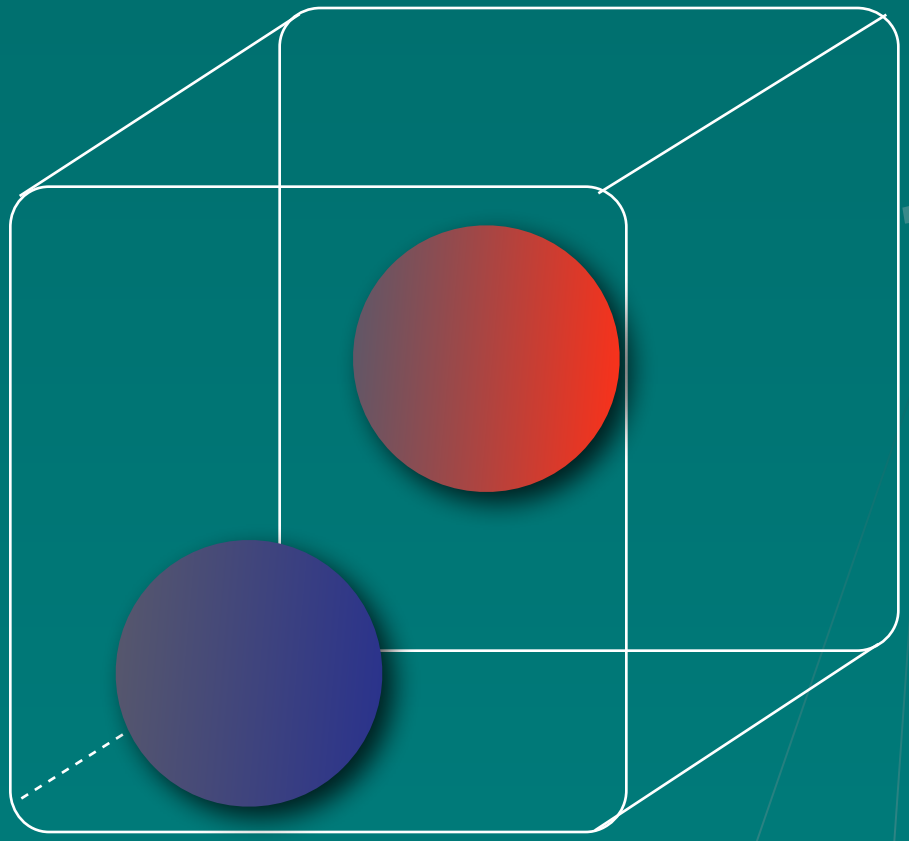

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Space– Shape, Dynamics

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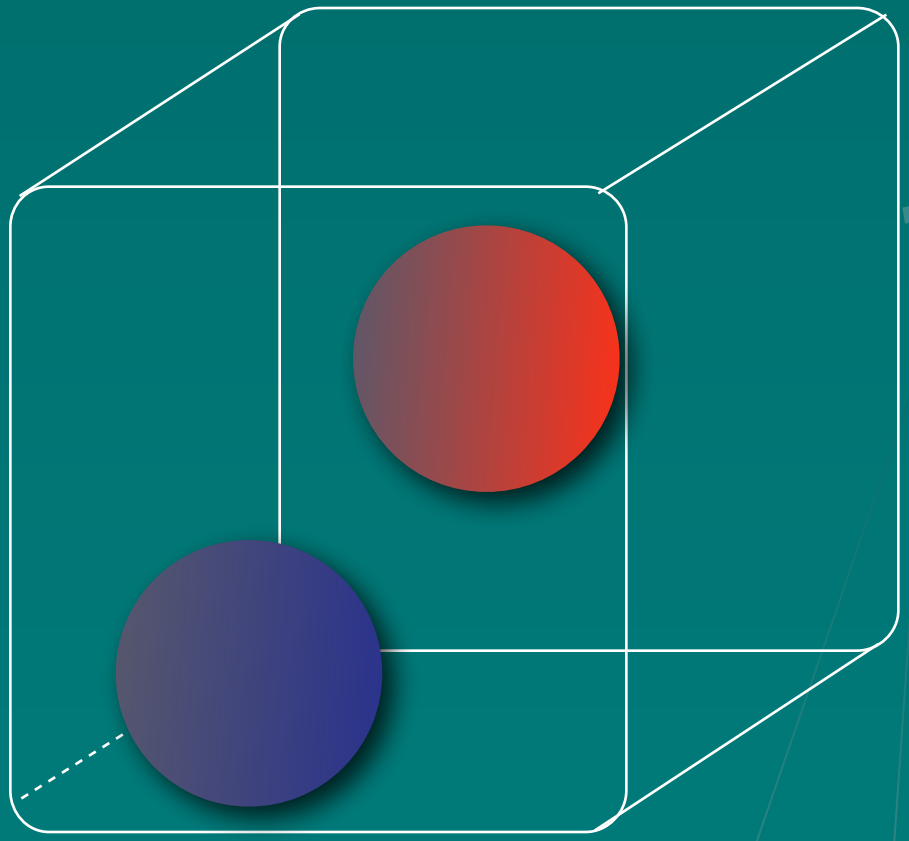

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Time– What is it?
Or is it at all?

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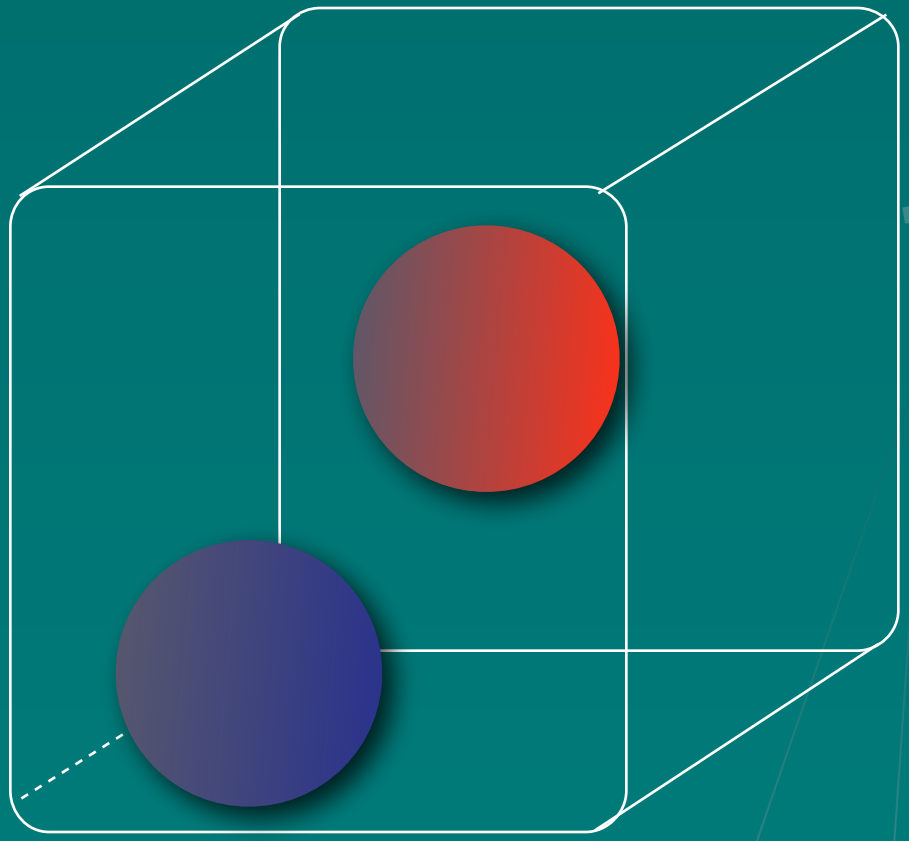

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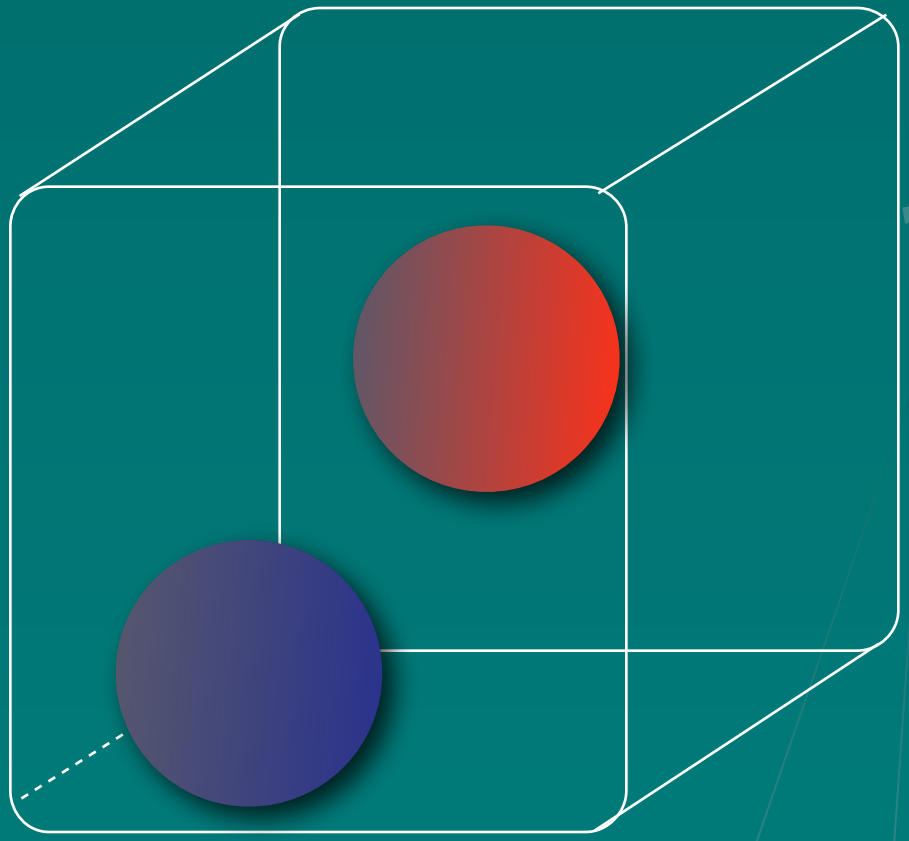

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Relationships between Space, time, and Particles!

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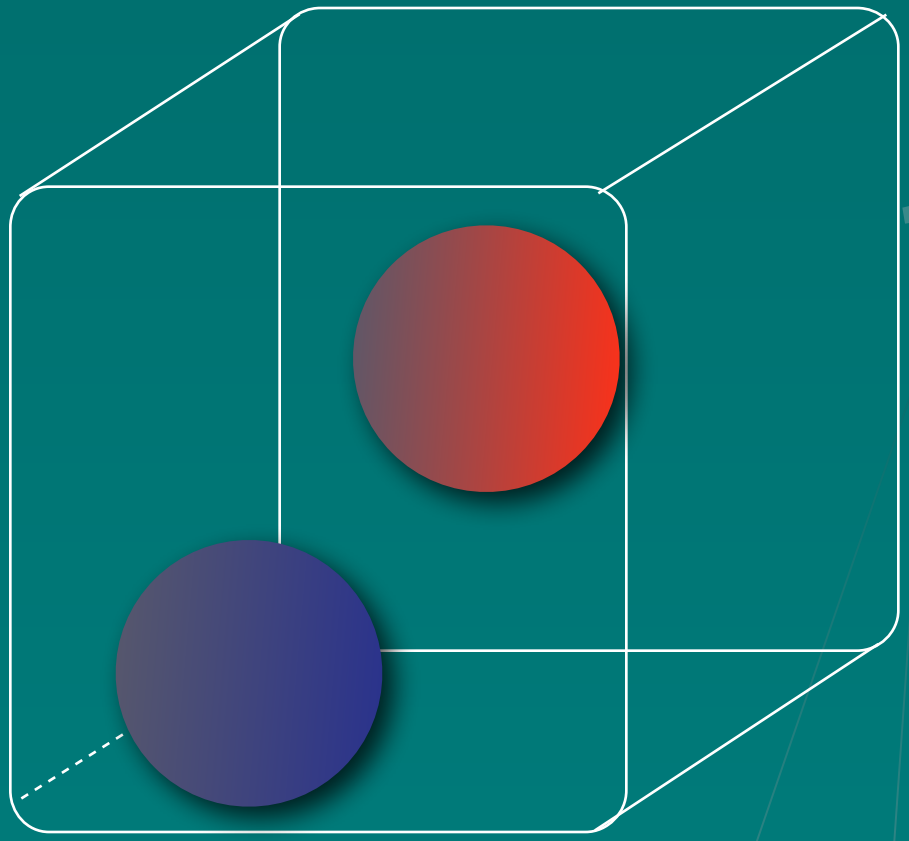

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Relationships between Space, time, and Particles!

Rules → Physics → Motion

What Makes up the World?

What Makes up the World?

- Matter (Stuff)
  - Details
    - Hot Dogs
    - Molecules
    - Atoms
    - Quarks
    - Leptons
    - . . .

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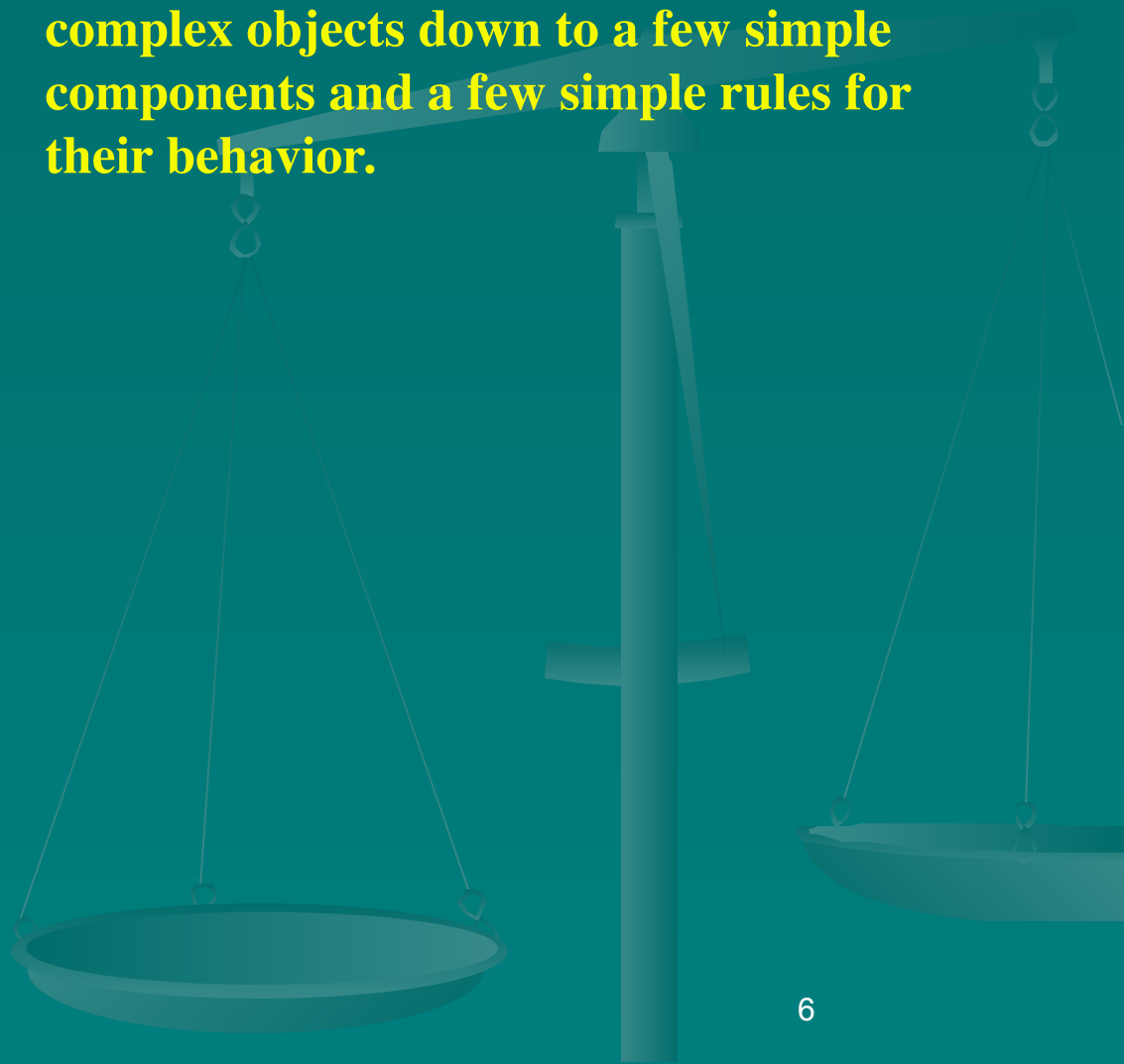
Science/philosophical Goal: Break complex objects down to a few simple components and a few simple rules for their behavior.



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  - 3 Dimensions
- Time
  - 1 dimension

Science/philosophical Goal: Break complex objects down to a few simple components and a few simple rules for their behavior.

How many basic ingredients do we need to make a hot dog? What role do space and time play?

What Motivates These Questions?

The Conscious Human Brain

- Curiosity
- Intellect
- Survival

Understanding how stuff is put together gives us the power to create.

- We can manipulate the structure of stuff and make it into something else; e.g., engineering, chemistry, and biology
- We can begin to ask the questions concerning how and why we are here

Tools for Understanding

- Human Brain
  - Philosophy
  - Logic
  - Mathematics
  - Science
  - Fantasy and Creativity
- Observations and Experiments
  - Patterns
  - Reproducibility
  - Reduction of many observations to a simple set of rules

Stuff-- An Early Attempt

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Earth

Air

Fire

Water

Stuff-- An Early Attempt

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Fire

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Stuff-- An Early Attempt

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Air

Fire

Water

Each ingredient is too complex

Stuff-- An Early Attempt

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Each ingredient is too complex

We need something like Legos

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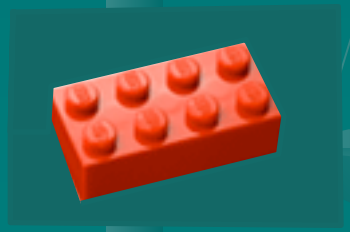
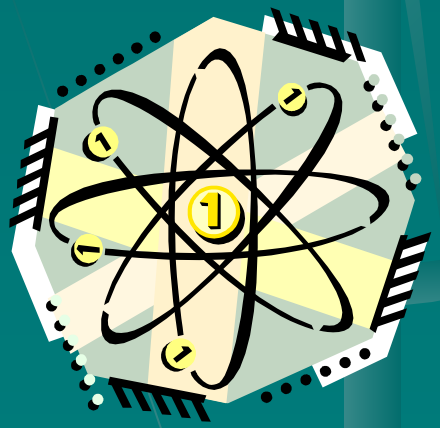


Origins of Atomic Theory

- Democritus
  - Atoms

  All Theory

  Is it correct?
- Aristotle
  - Observations



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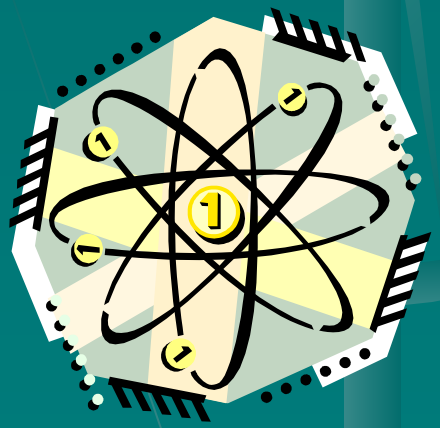
Philosophy
Logical Thinking



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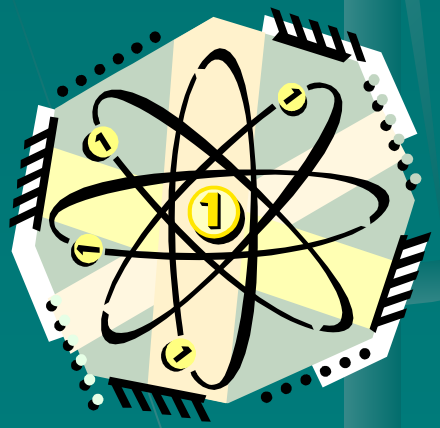
Philosophy

Logical Thinking

Constraining Thought

Science



How Do We Observe?

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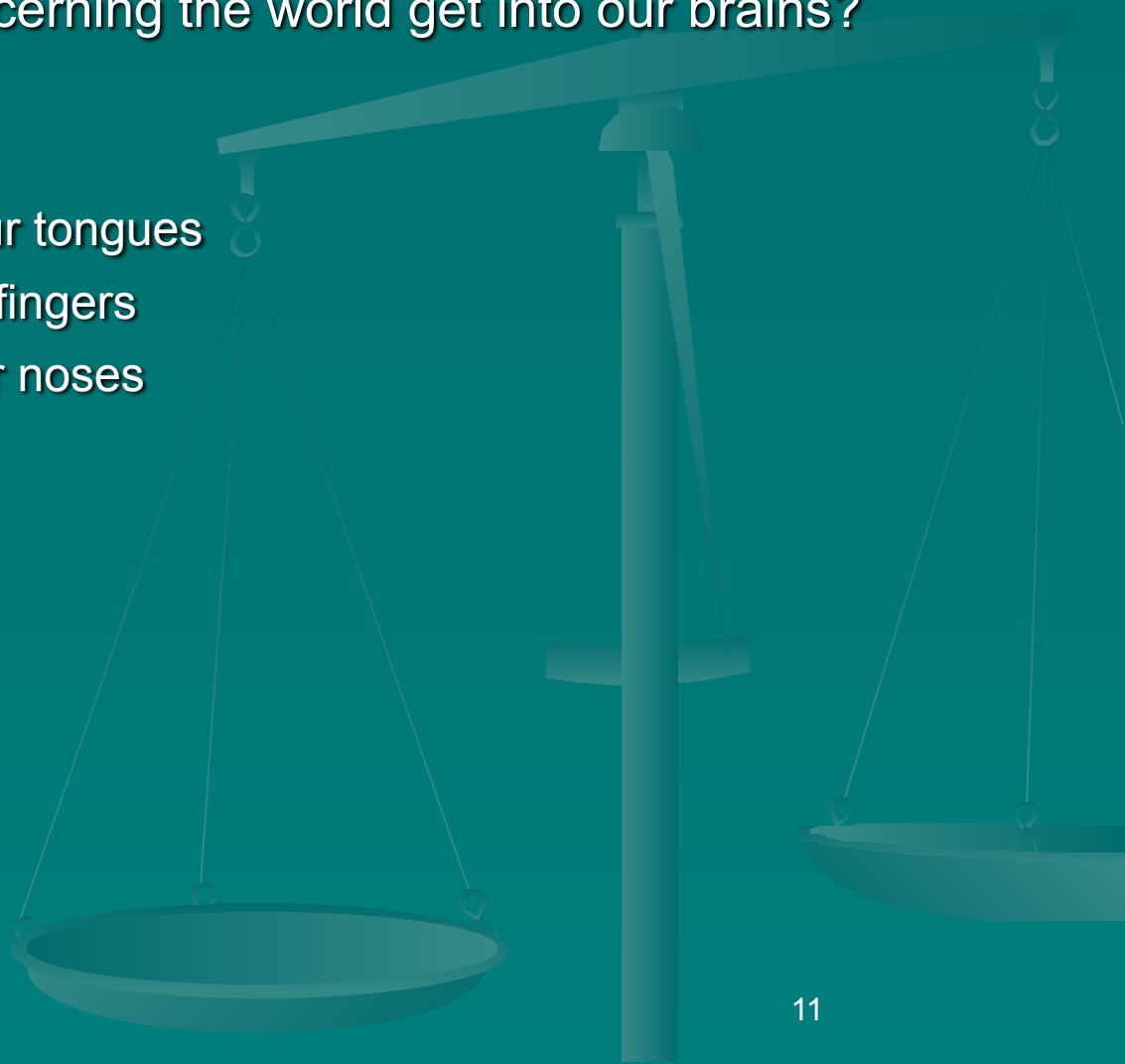
- How does information concerning the world get into our brains?
  - Light Waves
  - Sound Waves
  - Chemical reactions on our tongues
  - Chemical reaction in our fingers
  - Chemical reactions in our noses



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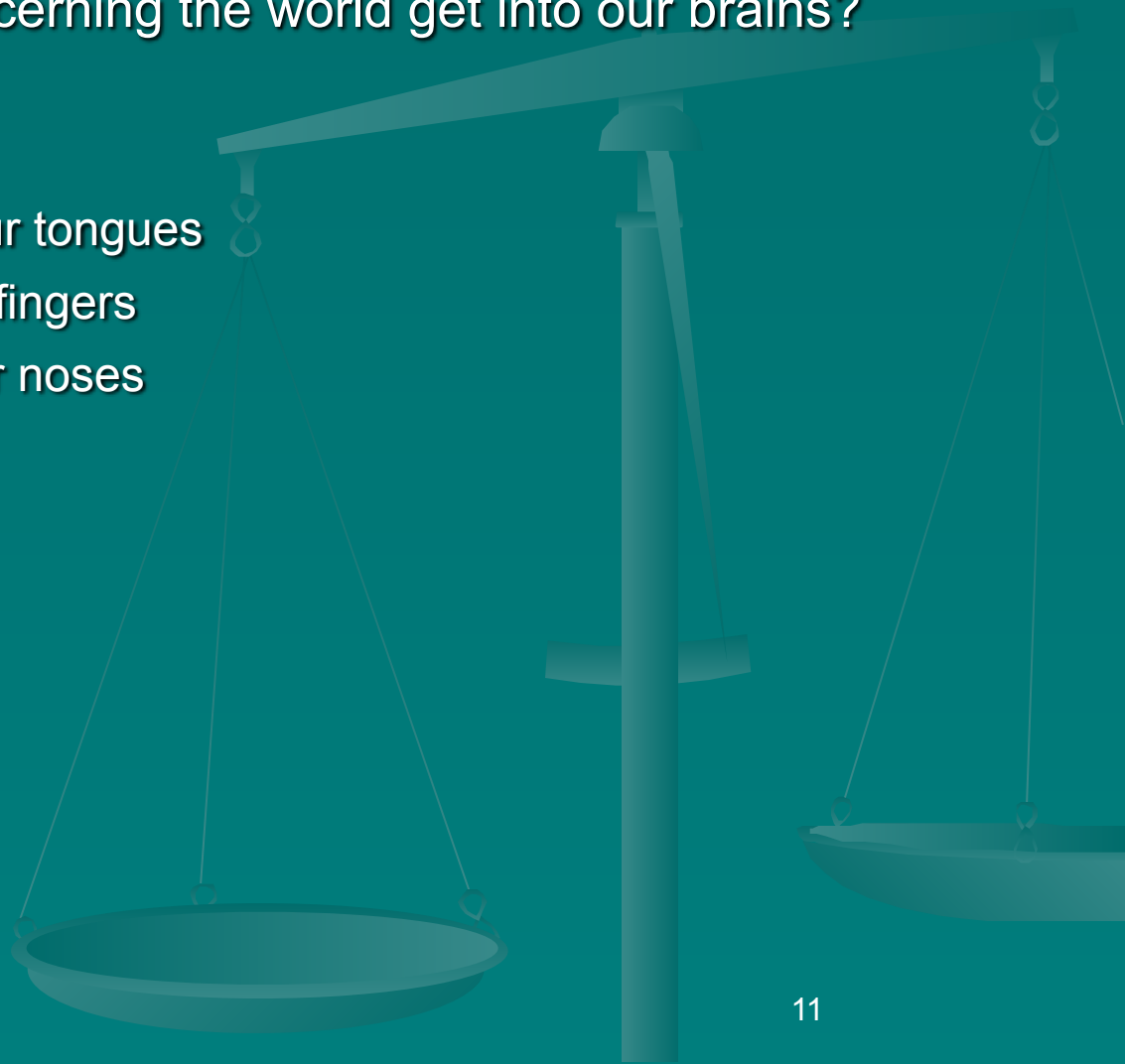

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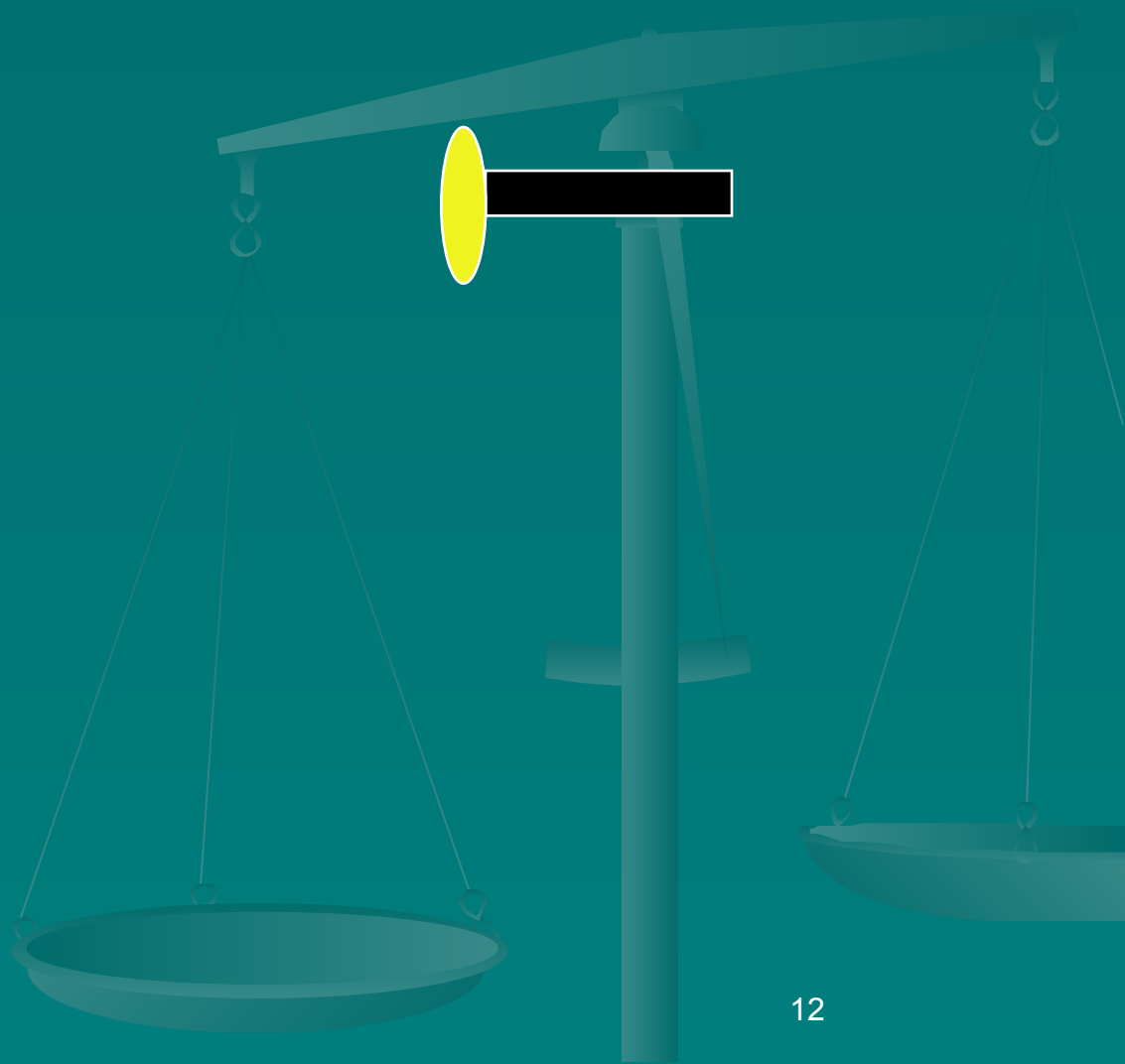

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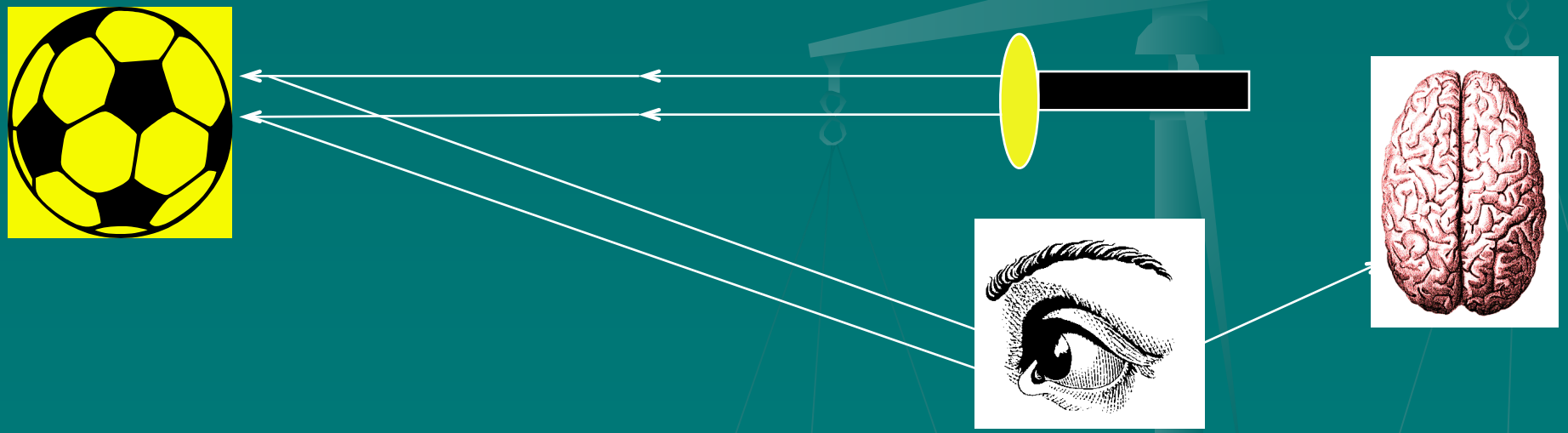

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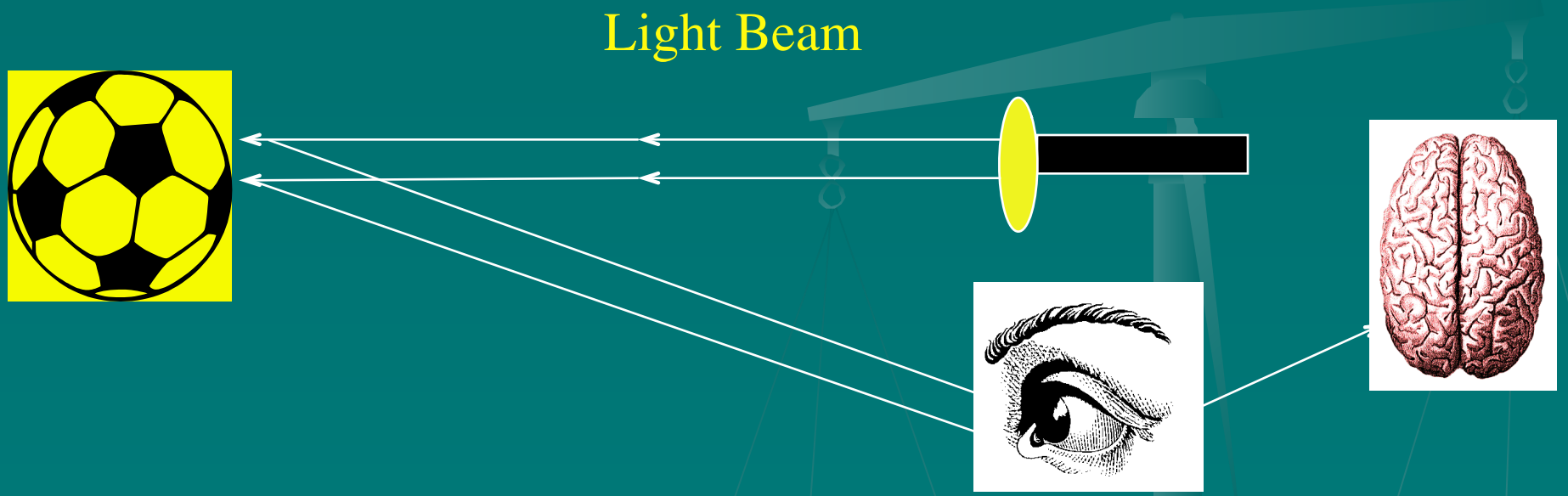

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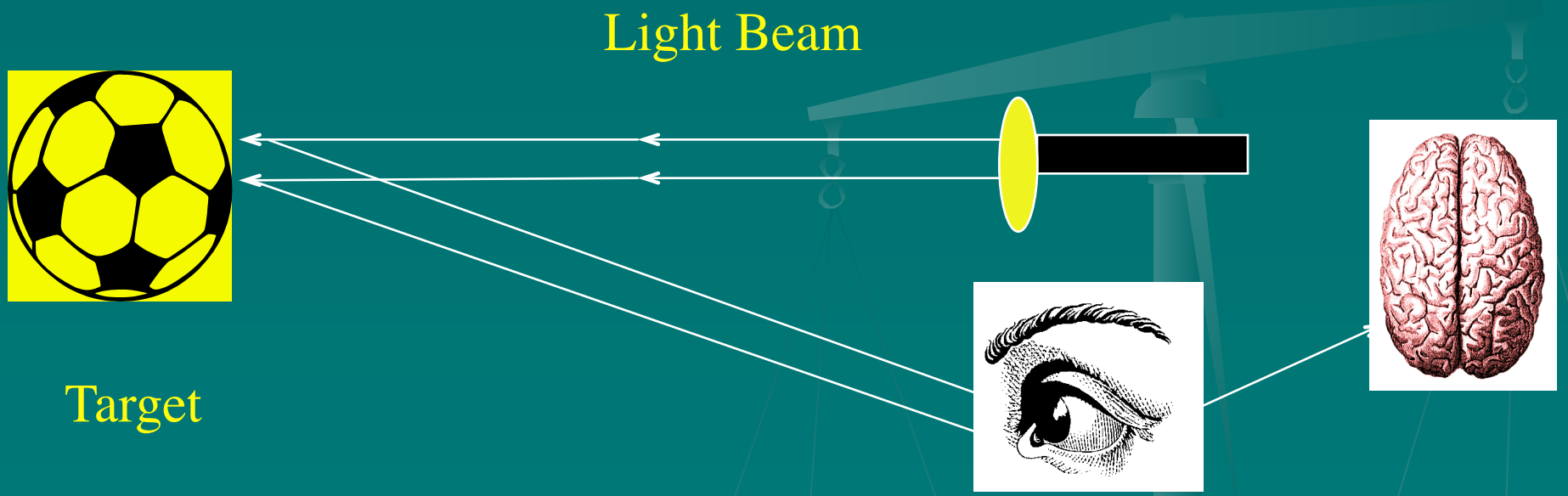

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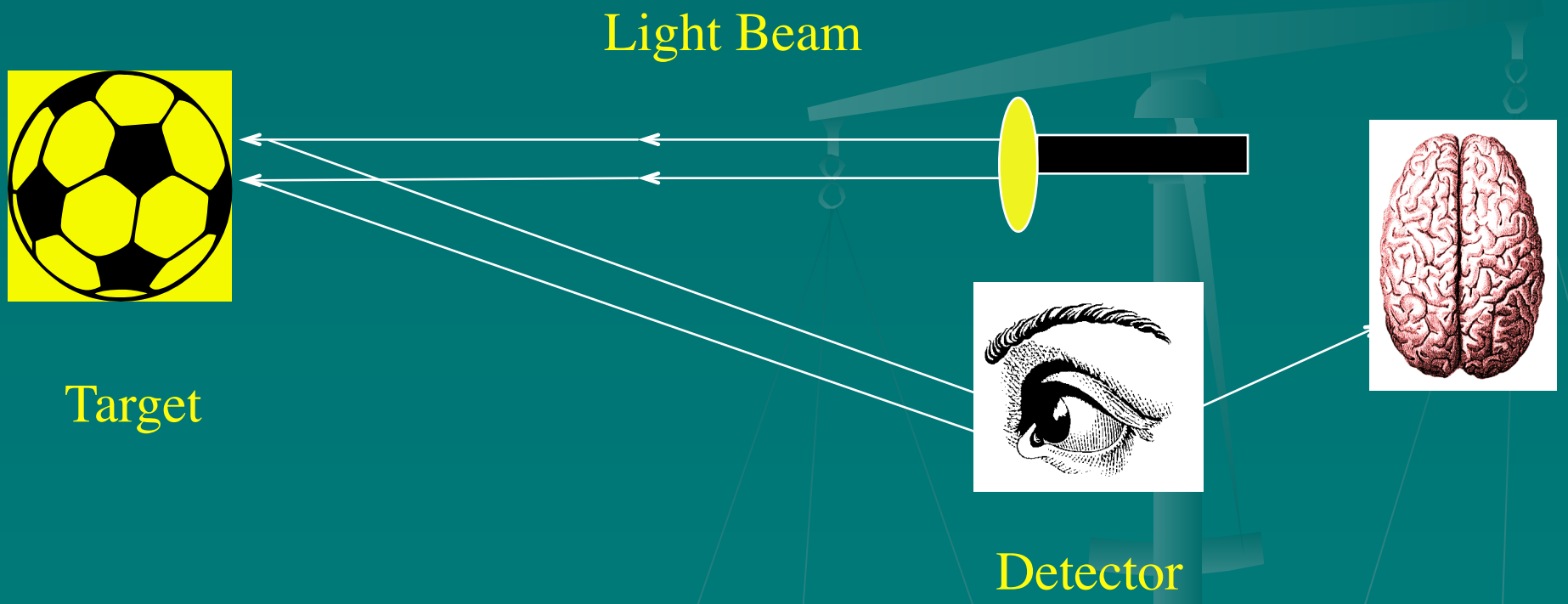

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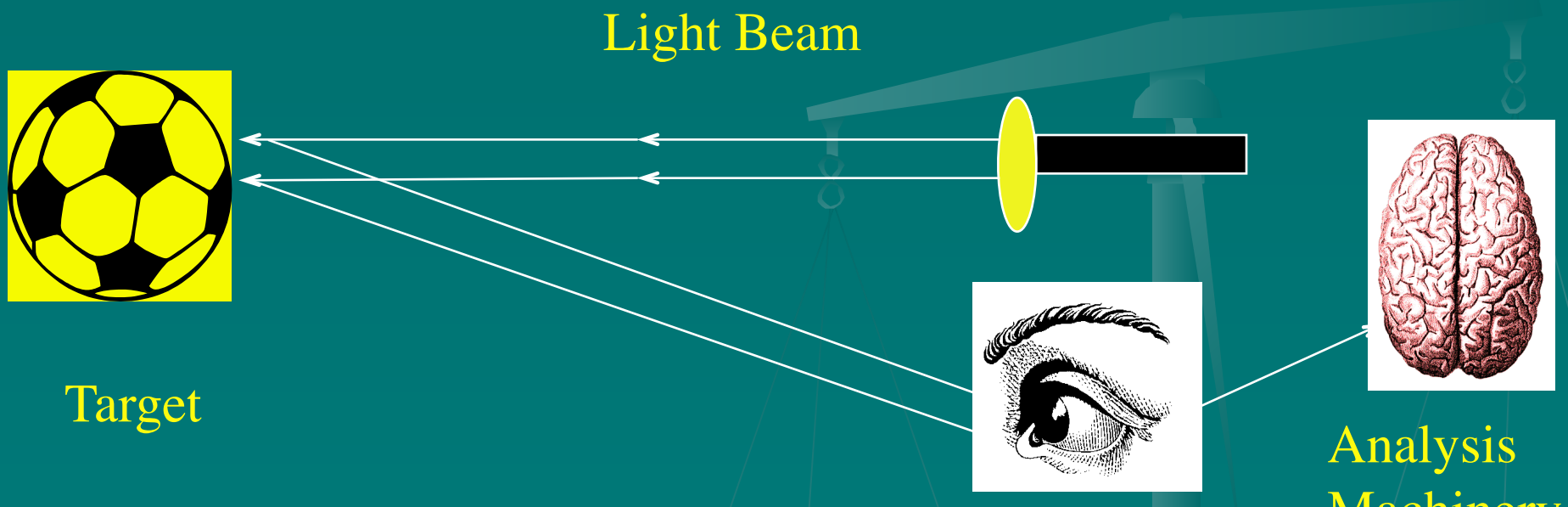


How Do We See?

Target

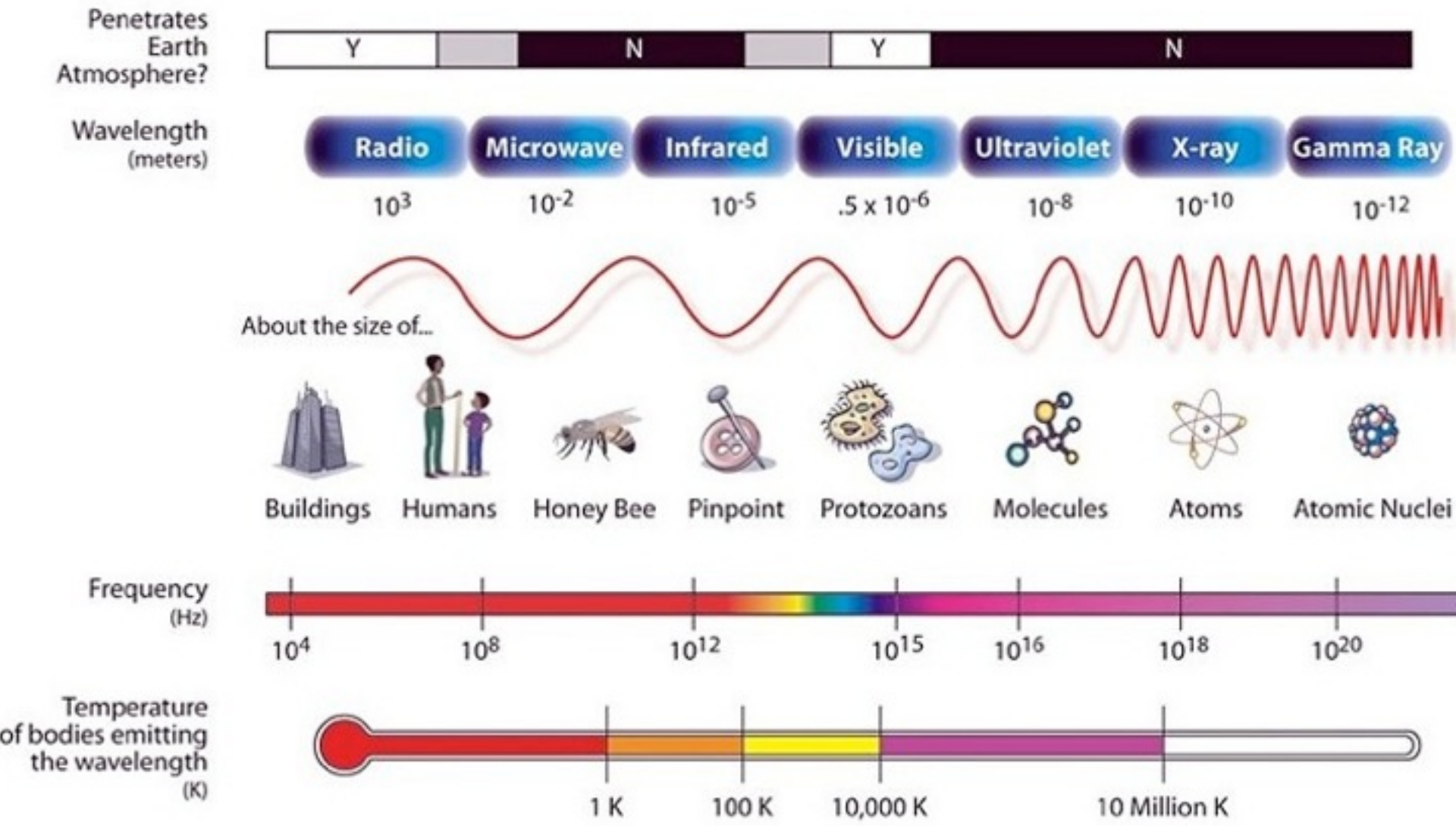
Light Beam

Detector

Analysis Machinery

Pattern Recognition!

THE ELECTROMAGNETIC SPECTRUM



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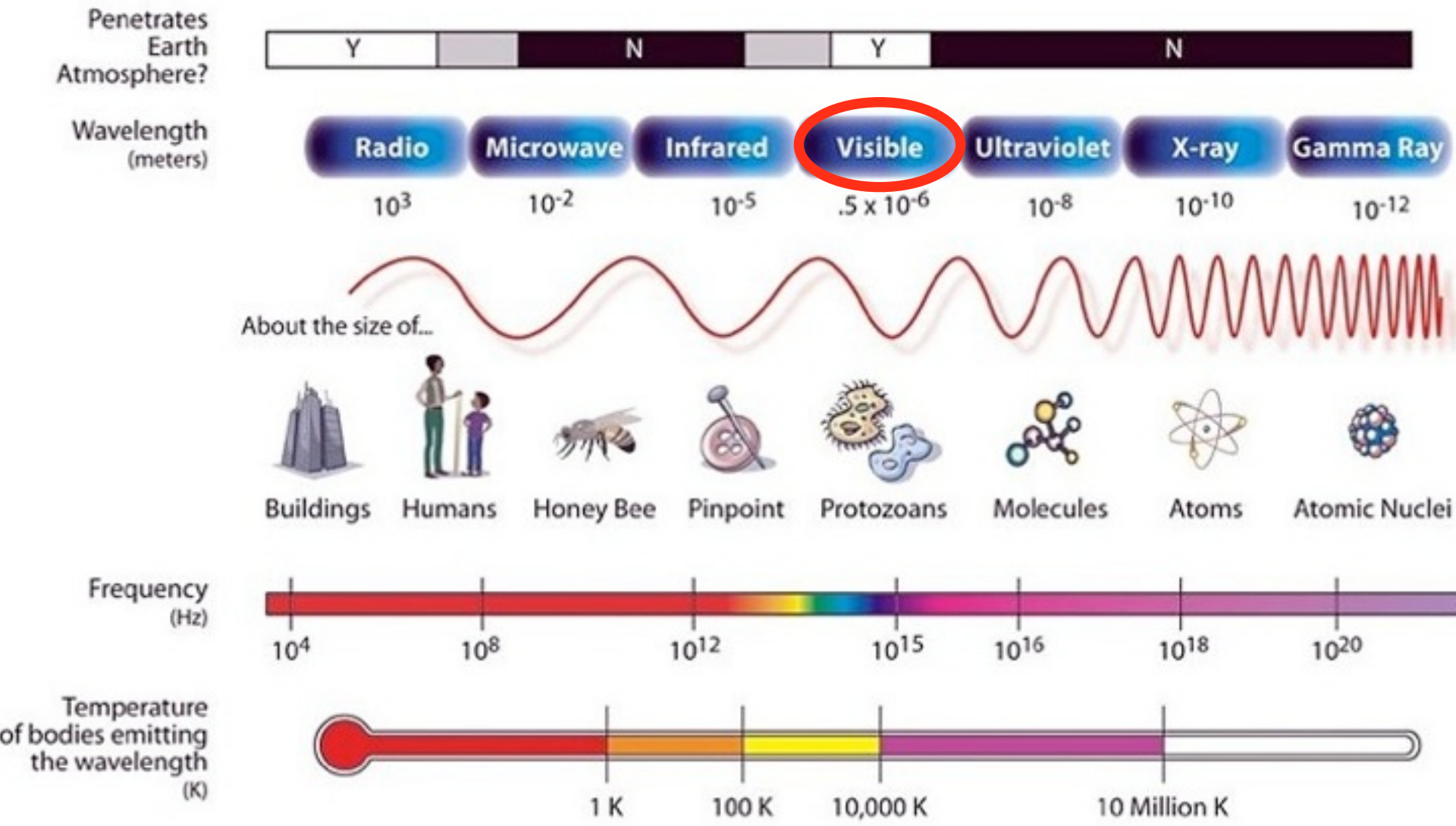

Beams and Detectors

- Suppose we want to see something much smaller than a protozoa, how could we do it?
- Suppose we could make a better beam-- How?
  - To see more detail we would want it to have a very short wavelength or high frequency
  - Does the beam have to be a light beam?
- Suppose we could made a better detector than the eye
  - We would want it to be able to see much shorter wavelengths of light so that we can “see” more detail
  - Would we want the detector to be sensitive to something other than light-- particles for example?

Beams and Detectors

- If we change the beam from light to particles and the detector from an eye to a photomultiplier tube, are we still “seeing”?
- Is it real?
  - The scattering process is the same
  - How are the beams and detectors different from our natural detectors?
    - They gather information based on the same principles
    - Information is analyzed using the same logic
- Is what we “see” using any combination of beams and detectors real?
  - We need a definition of reality

What is Real?

- What our senses tell us when our brain is chemical free
  - Our detectors and analysis system (goo) can be faulty for many reasons– it is a very complex system
- Can our artificial beams and detectors have defects that give us faulty information?
  - Yes
- Conclusion: All components of our beam, detector, and analysis system can be faulty
  - We must understand our beams, detectors and computers (including our flashlights, eyes and brains) to know what they are telling us

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So how do we determine when our beam, detector, and brain system is giving us good information and correct analysis?

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Science!

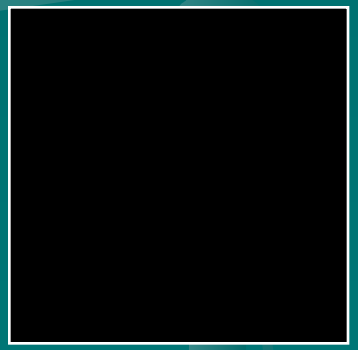
The Power of Science

The Scientific Method

Experiments are reproducible

This provides the only reliable definition for reality

Experimenter 1



Experimenter 2

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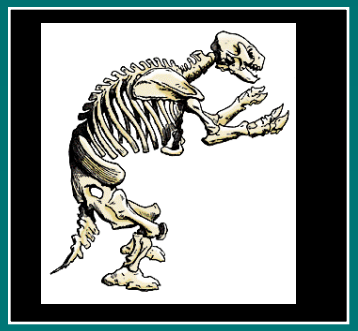

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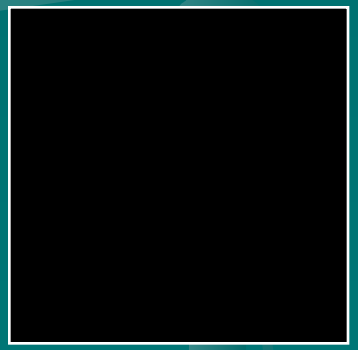

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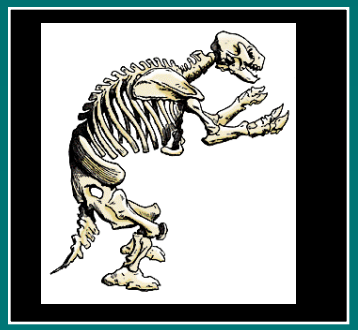

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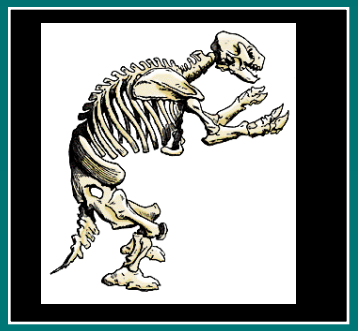

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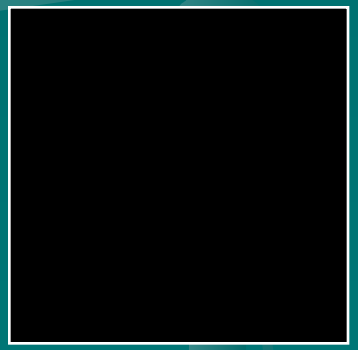

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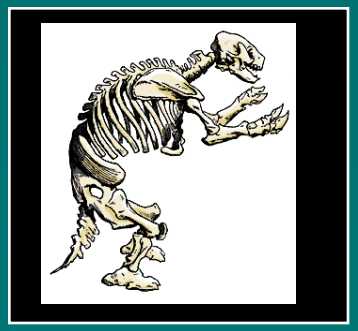

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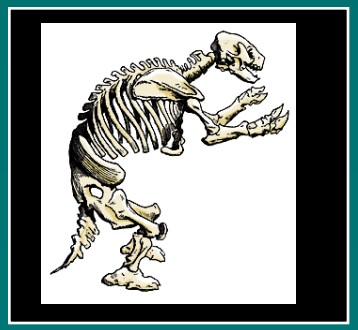

Experimenter 1

Experimenter 2

Qualitative Agreement?

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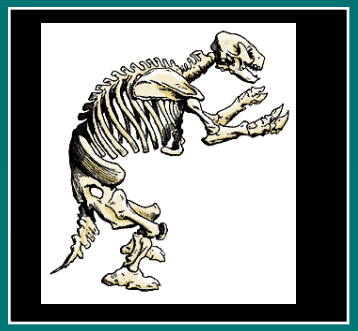

Experimenter 1

Experimenter 2

Qualitative Agreement? No!

The Power of Science

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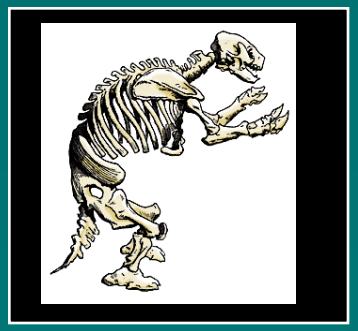

Experimenter 1

Experimenter 2

Qualitative Agreement? No!

Quantitative Agreement!

The Power of Science

The Scientific Method

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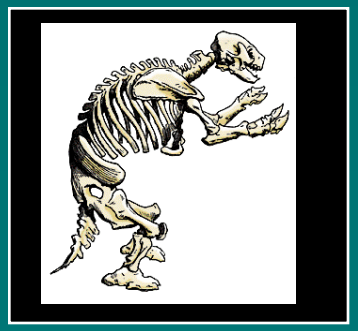

Experimenter 1

Experimenter 2

Qualitative Agreement? No!

Quantitative Agreement!

Numbers

Summary

- What we need to observe the world
- Beams (Flashlights, Accelerators)
- Detectors (eyes, ears,gamma ray detectors)
- Analysis of the information received form the detector
  - Logic and Reasoning
  - Pattern Recognition
    - Makes us think we know something
  - Numbers to quantify results in order to make detailed comparisons

In Search of Simplicity

In Search of Simplicity

- What do we want to look at with our improved "eyes" and beams?
  - Details of Matter
    - What do the Lego Blocks look like?
    - How do they work?
    - Structure
      - Atoms,Nuclei, Protons, Neutrons, Quarks, Leptons,Bosons . . .?
        - How are they put together, or how do they interact?
        - We want to see the Lego blocks and how they fit together
  - Can we also learn something about space and time?
  - What about light? Photons

The Lego blocks –Preview

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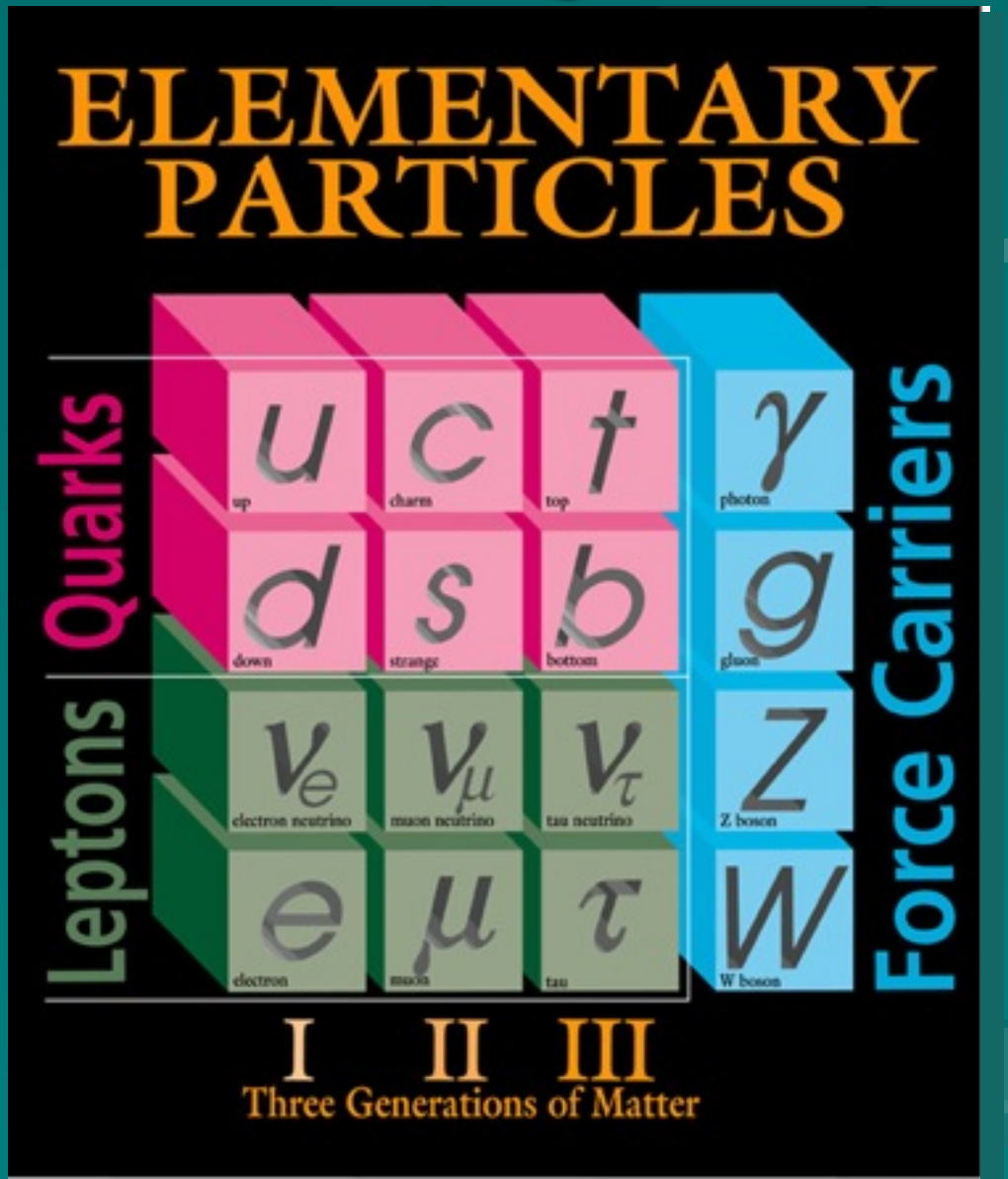
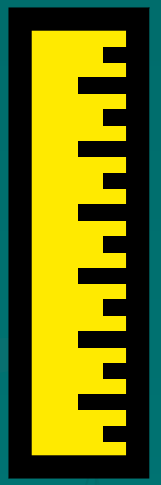


But this is not everything-- We will return to this

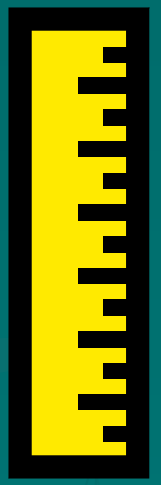
Space

Space



- A location for stuff to be
  - Can be measured; i.e., numbers can be assigned to points in space
    - Coordinates
    - Distance
    - Mathematics-- relationships between numbers that describe the organization of space and the stuff in it
    - Volume

Space



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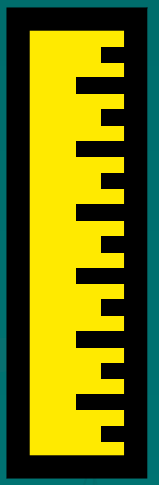
- What is space? Is it nothing? Does it "do" anything?

Space



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Space is expanding!!

Time

- What is time?
  - Something that separates events and gives them a particular order
  - Time is what keeps everything from happening at once
  - Without time nothing would happen–it would just be
    - Makes motion (change) possible
- How much time is there?
- Did it have a beginning?
- Will it have an end?
- Is it absolute?
- Is it real; i.e. can we agree on how to measure it?
- Is it really something different than space?
- Does time really exist or is it an organizational tool of the mind?

Time

Time

Without change or motion what is physics?

Time

Time

What is Life?

Time

What is Life?

Why is the clock running?

Time Measurement

- Time does not appear to hold still-- we must be clever to measure it
  - Observe regular patterns and events relative to some other event
    - The Sun and Moon
    - The seasons
- How do we make measurements quantitative?
  - Take note of regularities and define a unit of time based on a regularly occurring event
- Sundials, water clocks
- Mechanical clocks appeared in 13th century
- Atomic clocks

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What if the length of the second were changing? Could we tell?

Nature of Time

Nature of Time

- Remember time is:
  - Something that separates events and gives them a particular order
- Two Questions
  - Can every observer agree upon the amount of time that separates two events?
  - Can the order in time of the two events always be agreed upon?

Nature of Time

- Remember time is:
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- Two Questions
  - Can every observer agree upon the amount of time that separates two events?
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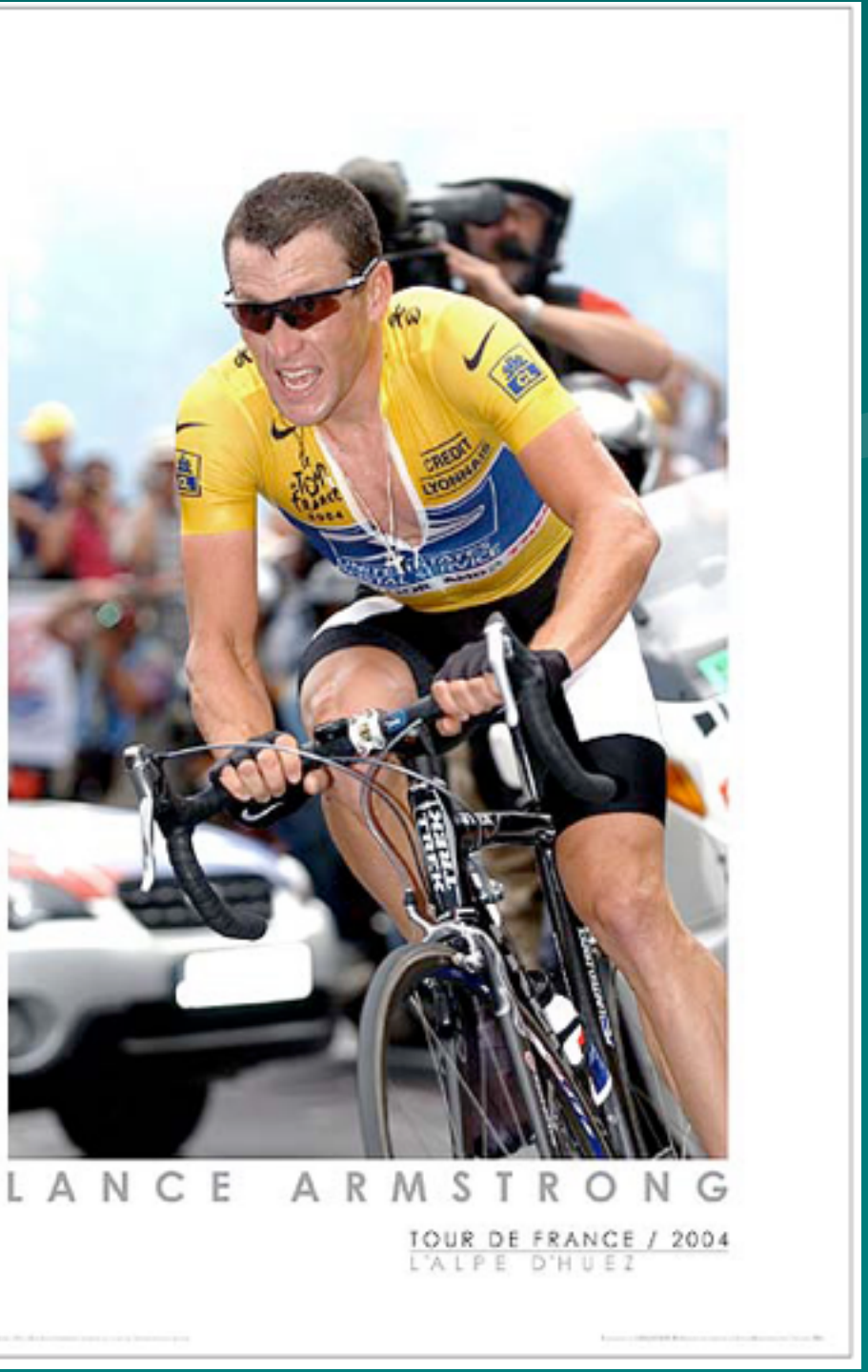
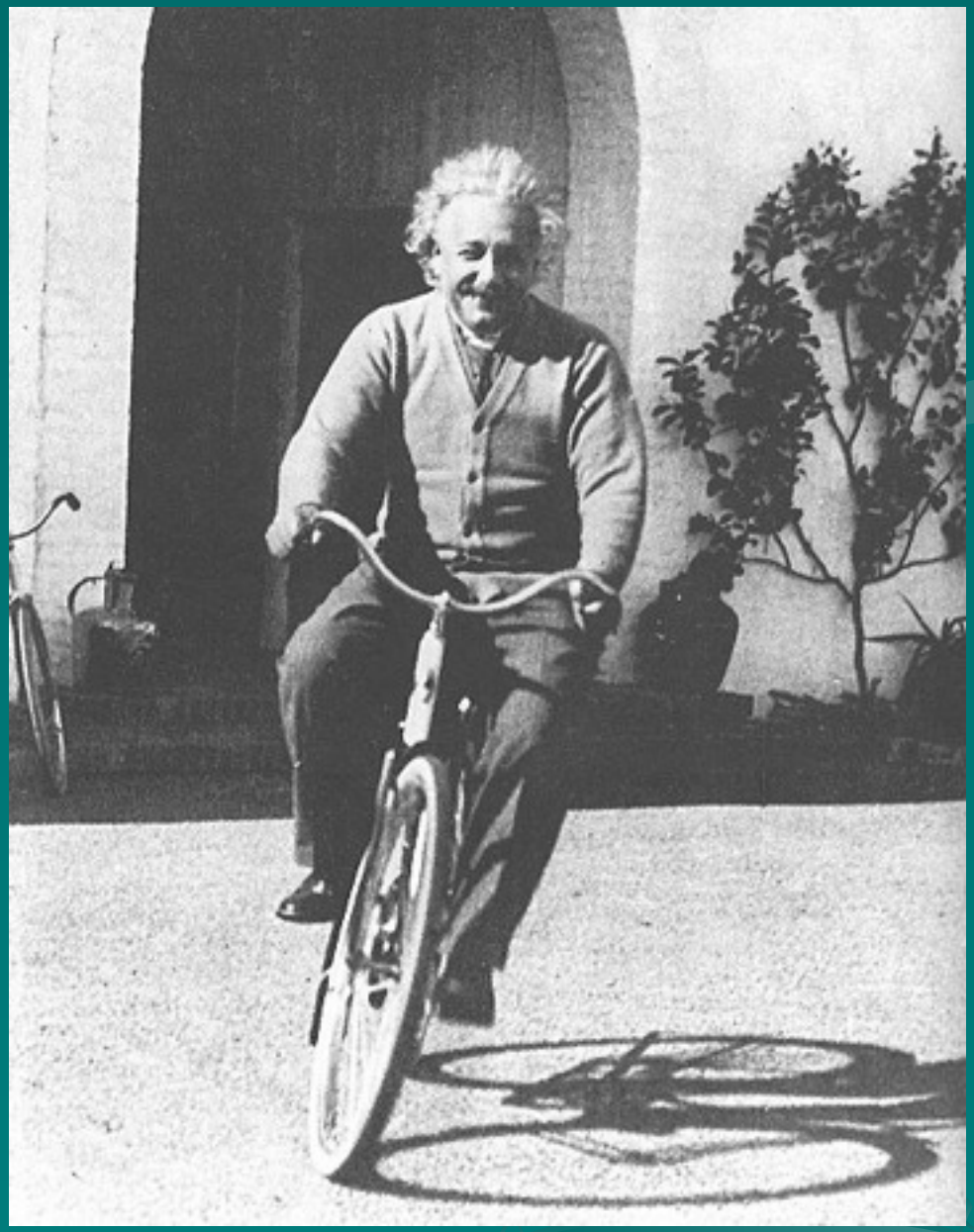
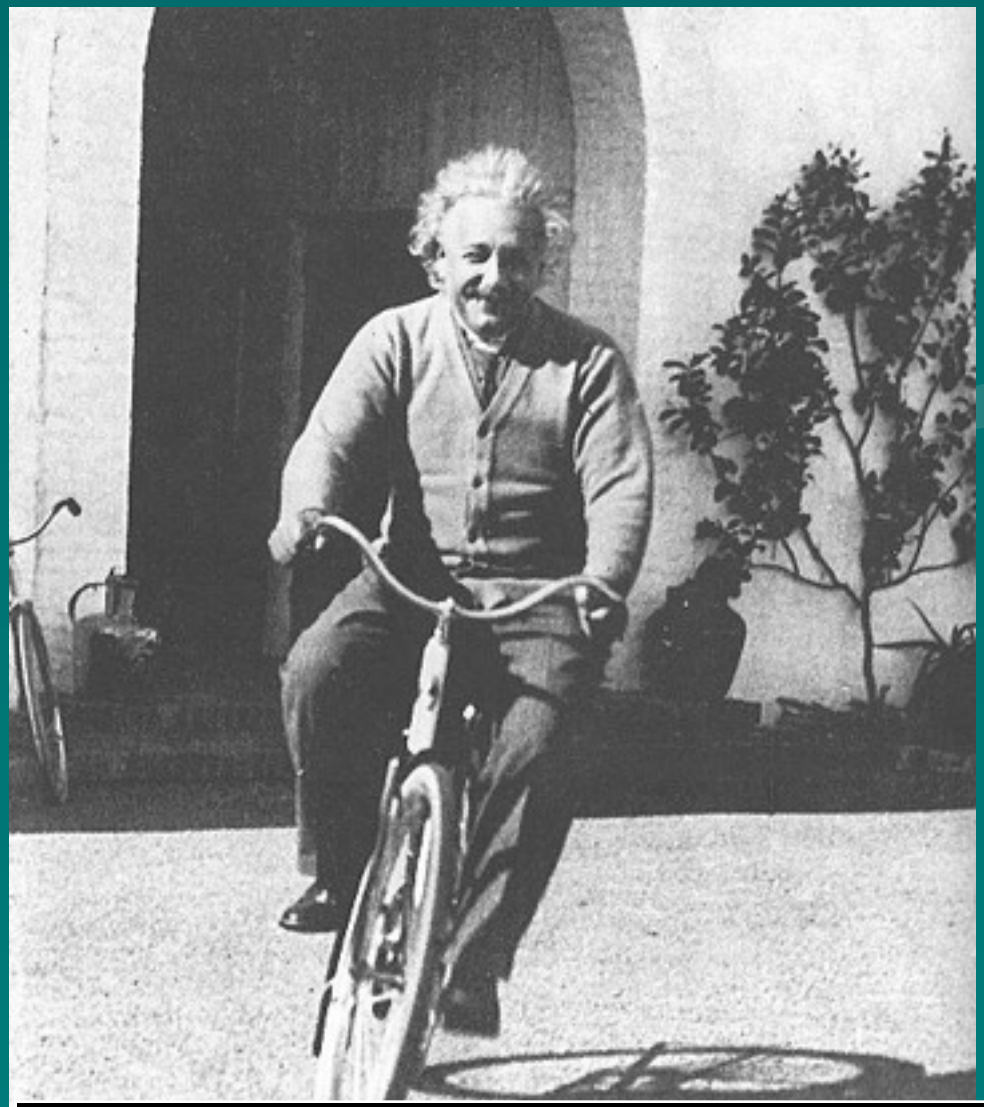
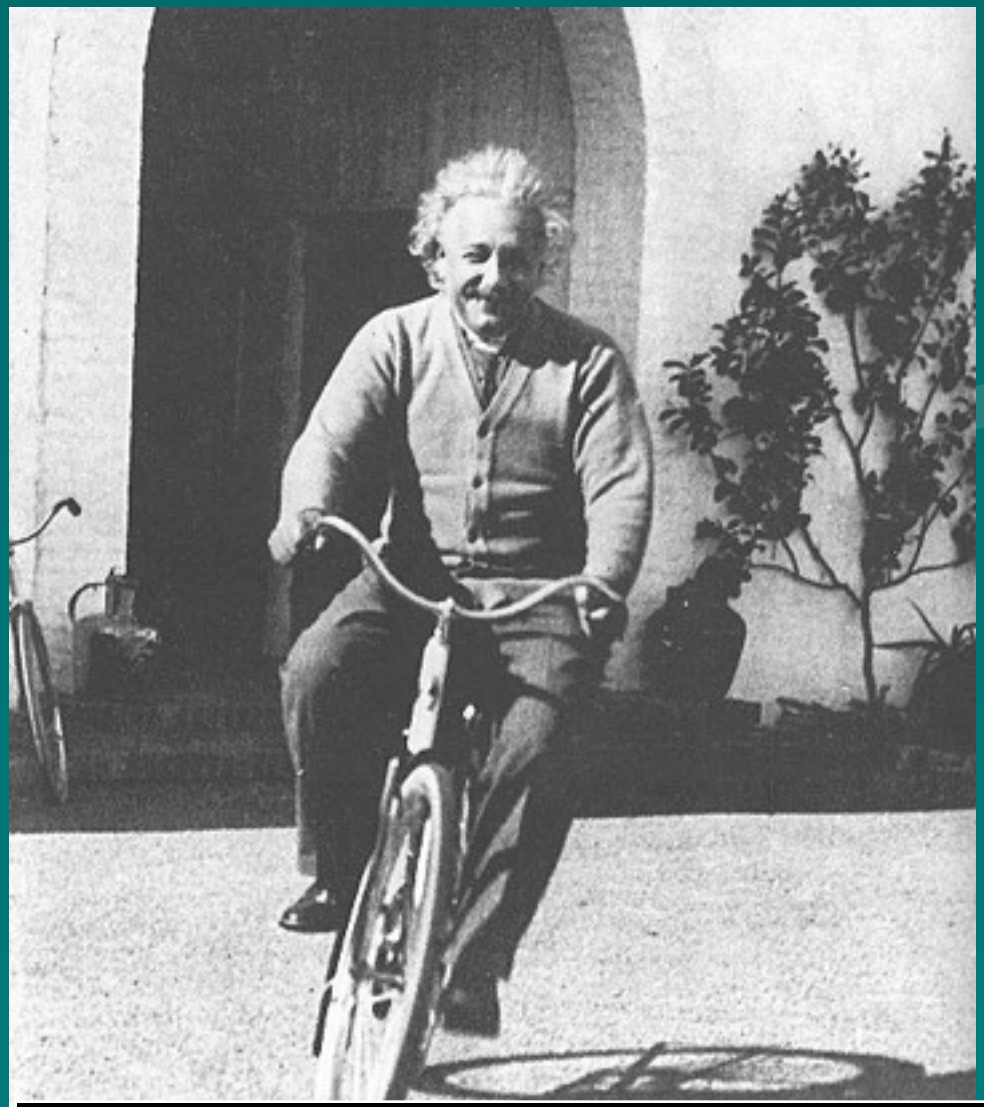
Surprisingly, the answer to both questions is no!


LANCE ARMSTRONG
TOUR DE FRANCE / 2004
L'ALPE D'HUEZ





Tested Clean for Performance Enhancing Drugs!



Tested Clean for Performance Enhancing Drugs!

Albert Einstein

Special Relativity

No Absolute Time

General Relativity connects stuff to space and time

General Principles

- Principle of Relativity:
  - "The motions of bodies included in a given space are the same among themselves, whether that space is at rest or moves uniformly forward in a straight line." Isaac Newton (corollary to the laws of motion initially stated by Galileo for mechanical systems)
  - Modern version
  - The laws of physics take the same form in all frames of reference moving with constant velocity with respect to one another (all physical systems)

Note that these principles came from experience (observations)i.e.; "common sense" and from playing catch on a moving train

Additional Principle

- The velocity of light, c, is constant independent of the motion of the source

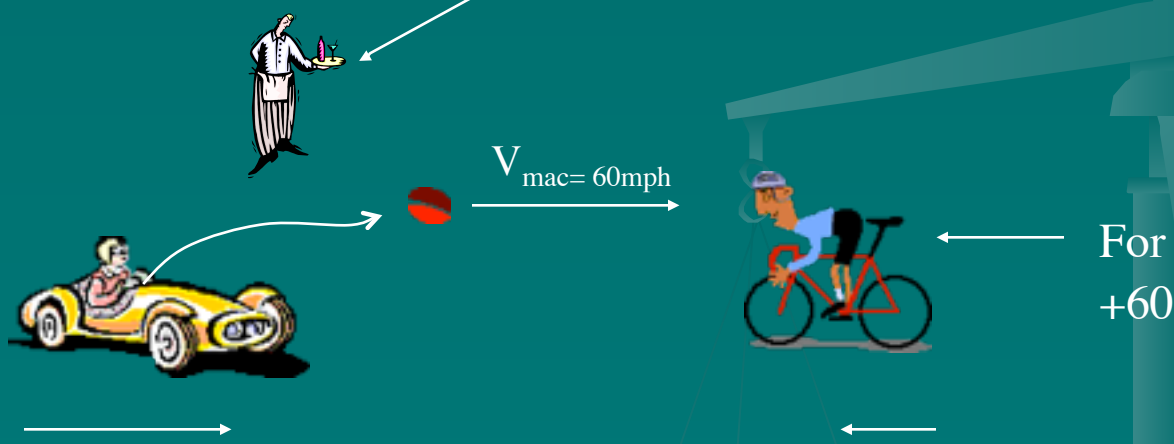
How do we come to this conclusion?

It does not appear to make common sense!

What does this mean for our observations and measurements?

Common Sense World

$V_{hamburger}$ = 60 mph (relative to car) = 120 mph to an observer standing by the road who watches the hamburger go by but is not quick enough to snatch it



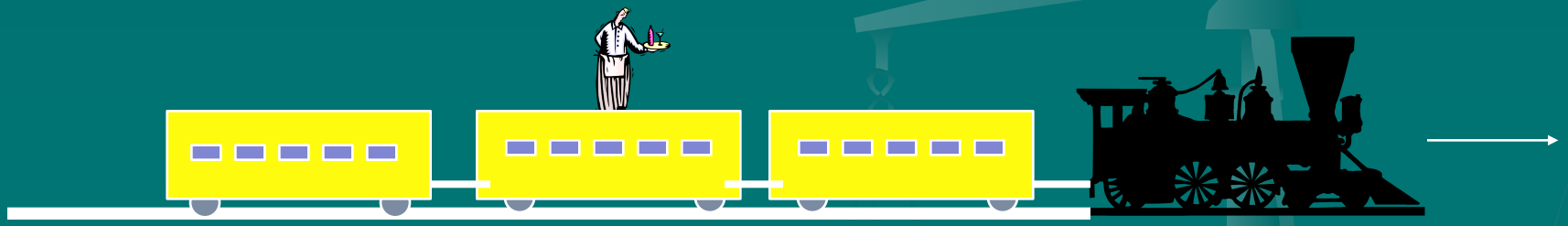
For the cyclist V = 60 +60 + 20 = 140 mph

Vcar = 60 mph

Vcyclist = 20 mph

$$V_{tot} = V_{car} + V_{mac} - (-V_{cyclist}) = 140 \text{ mph}$$

Trains and Embankments



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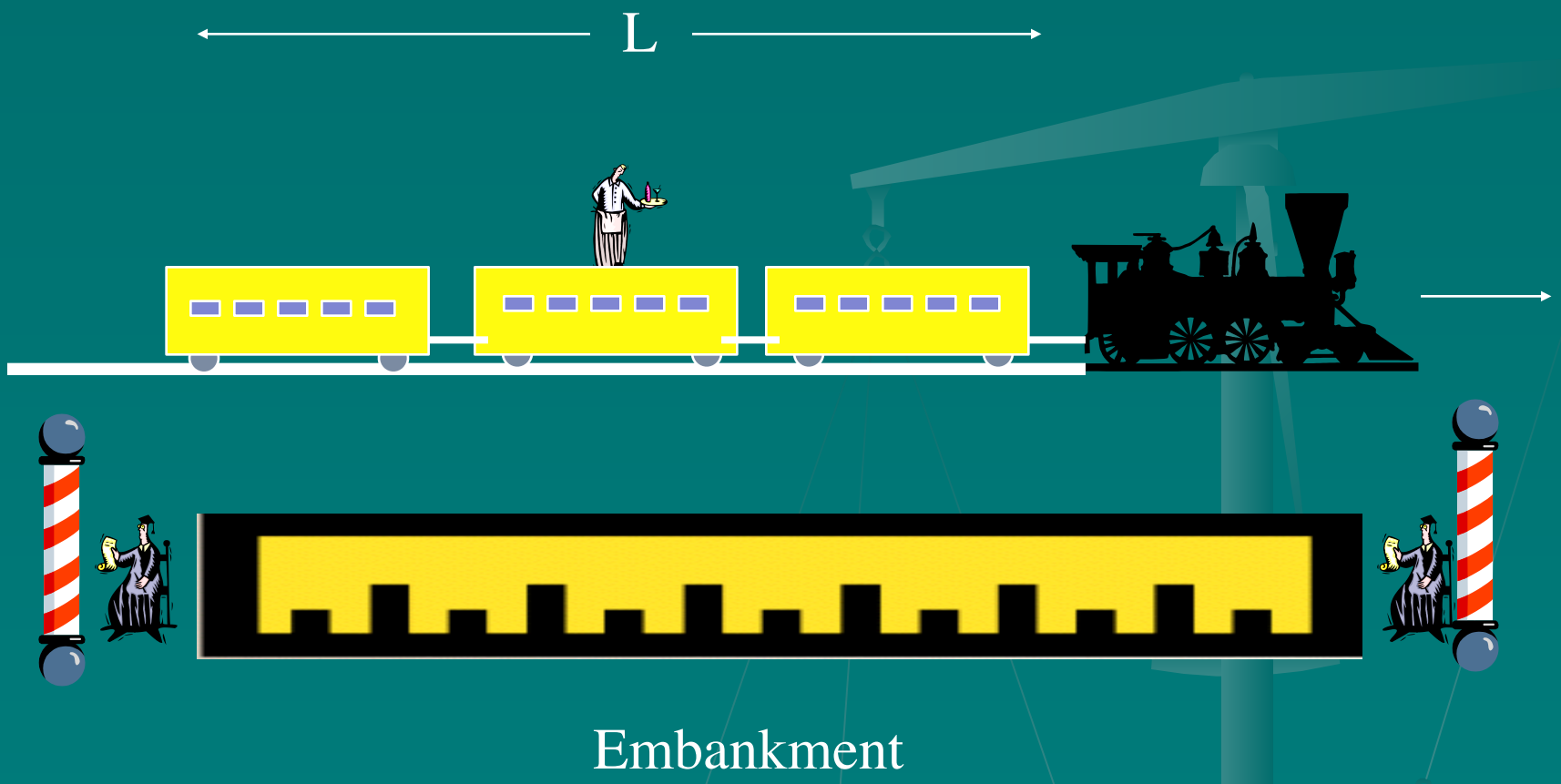

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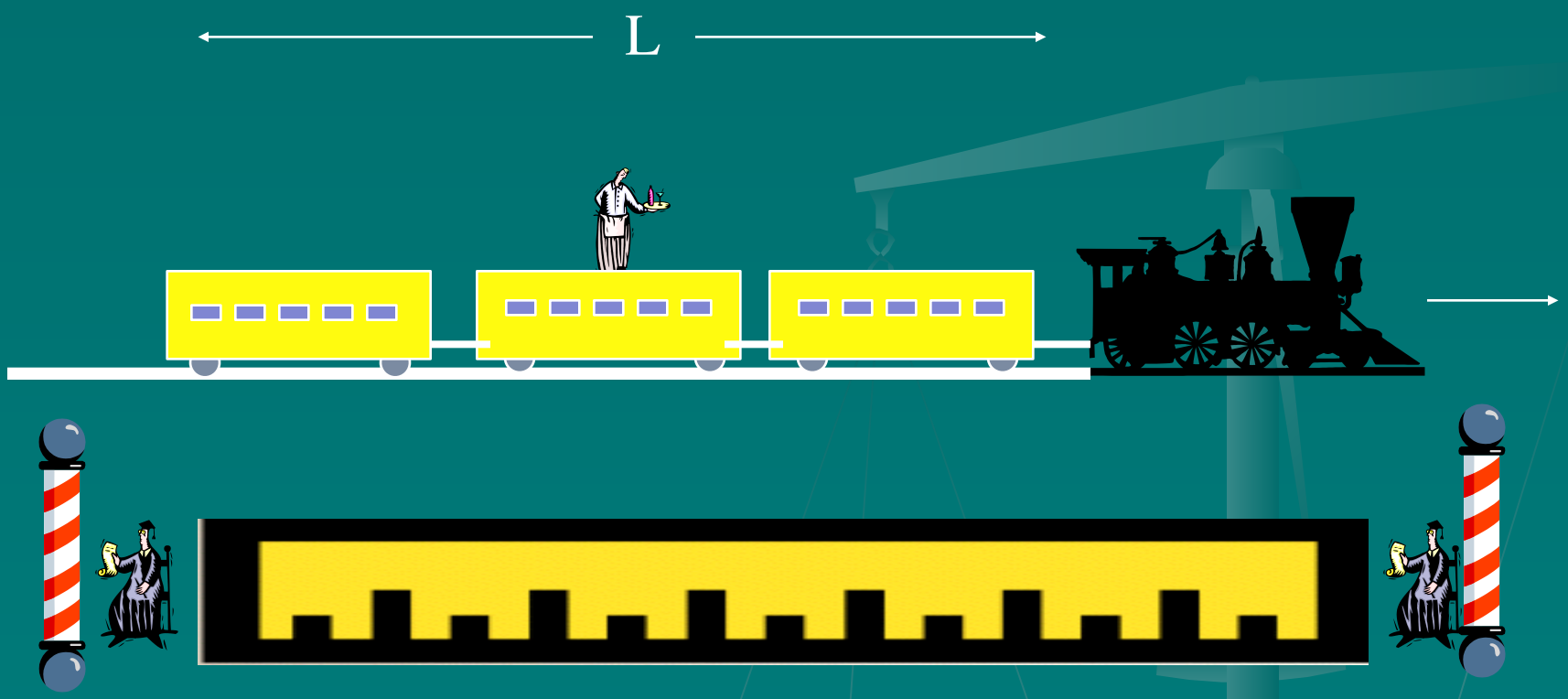

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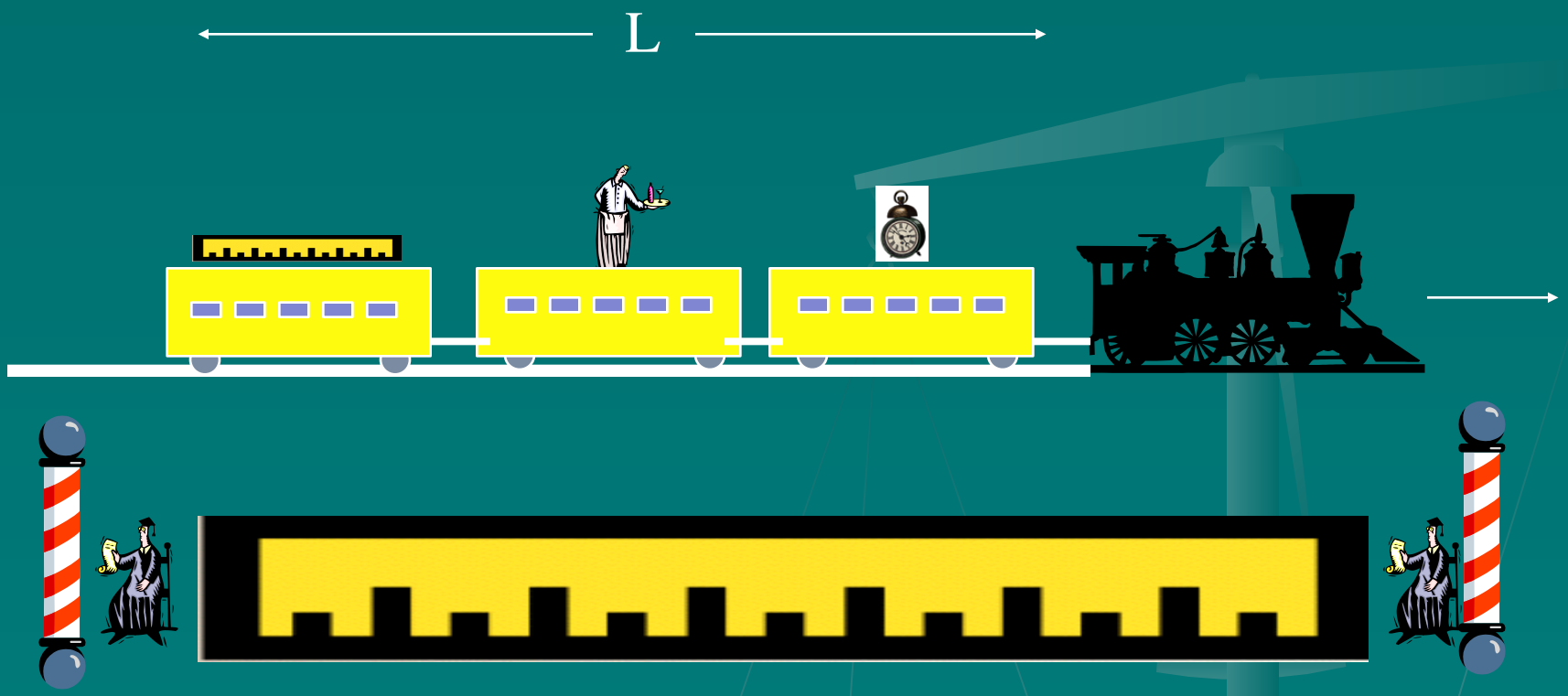
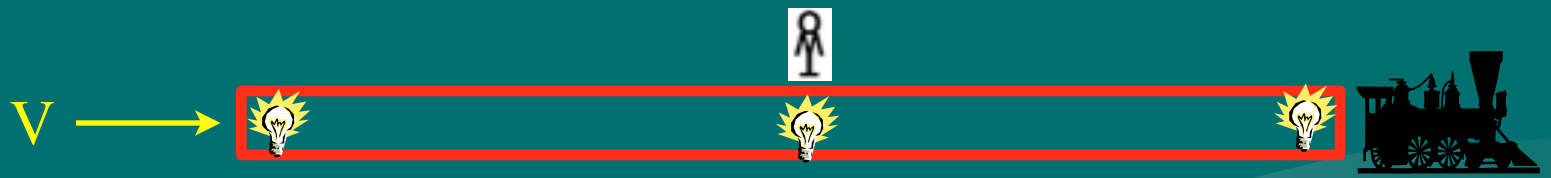
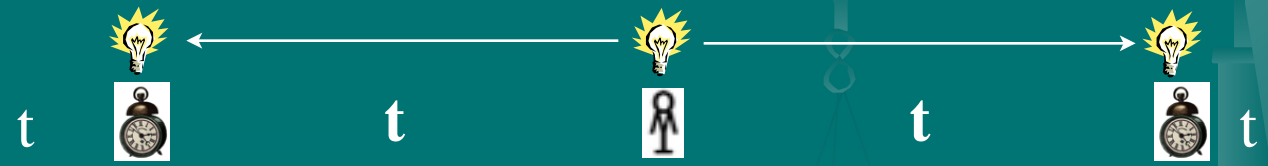


Measurement– Embankment





$t_2 = t_1 = t$

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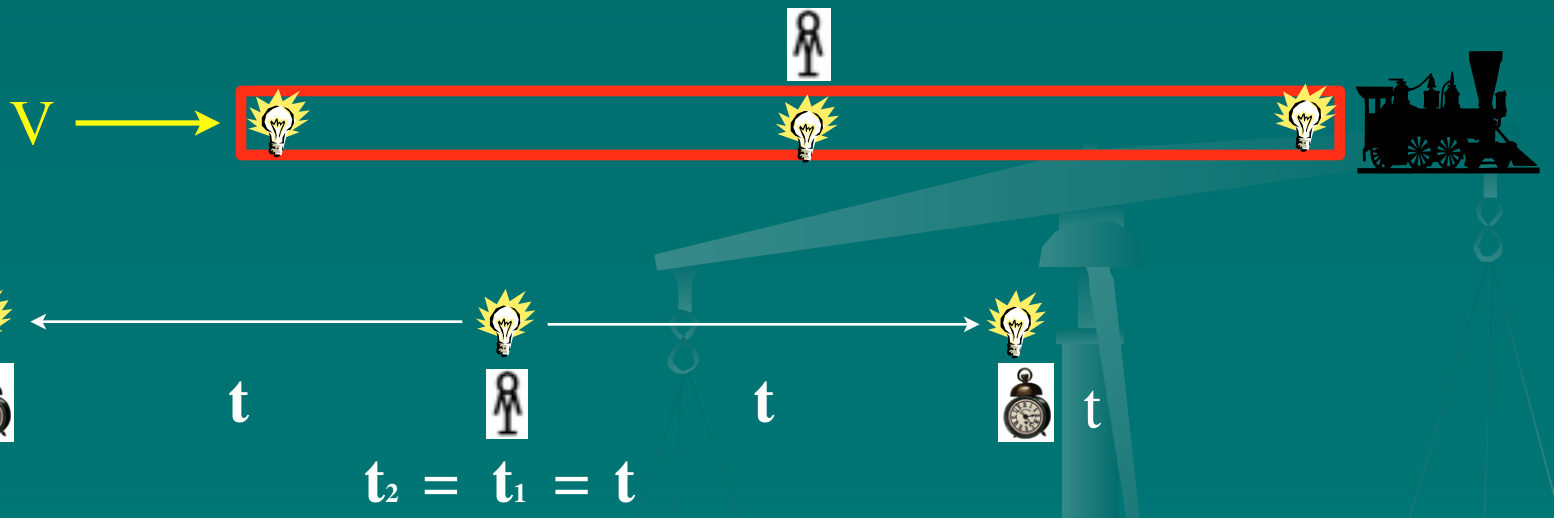

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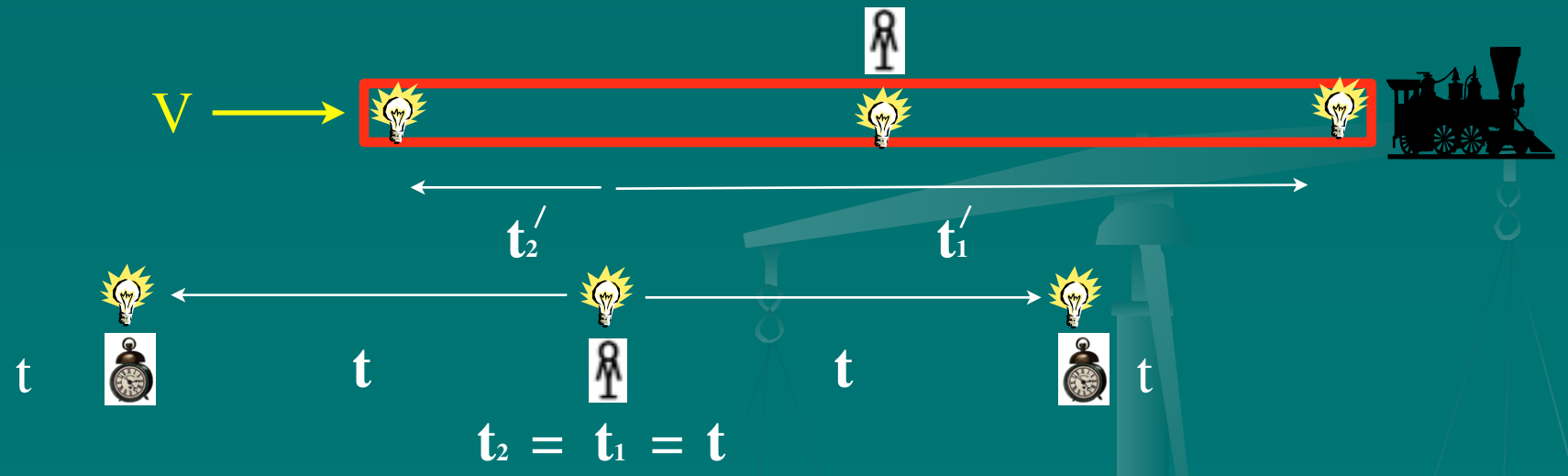

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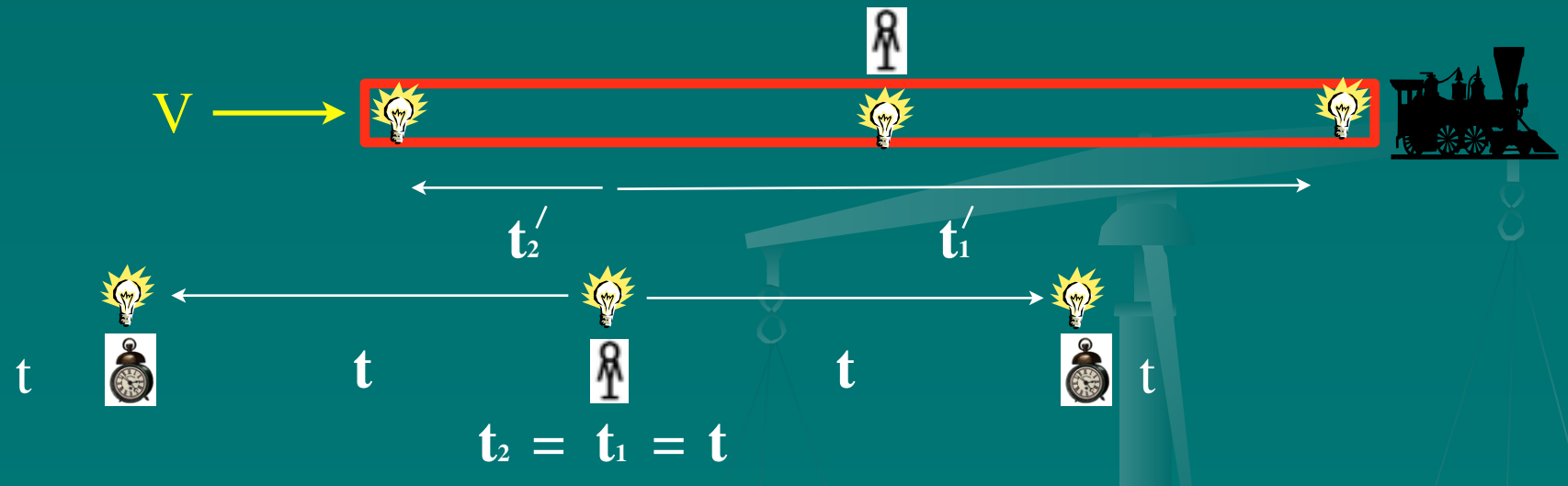

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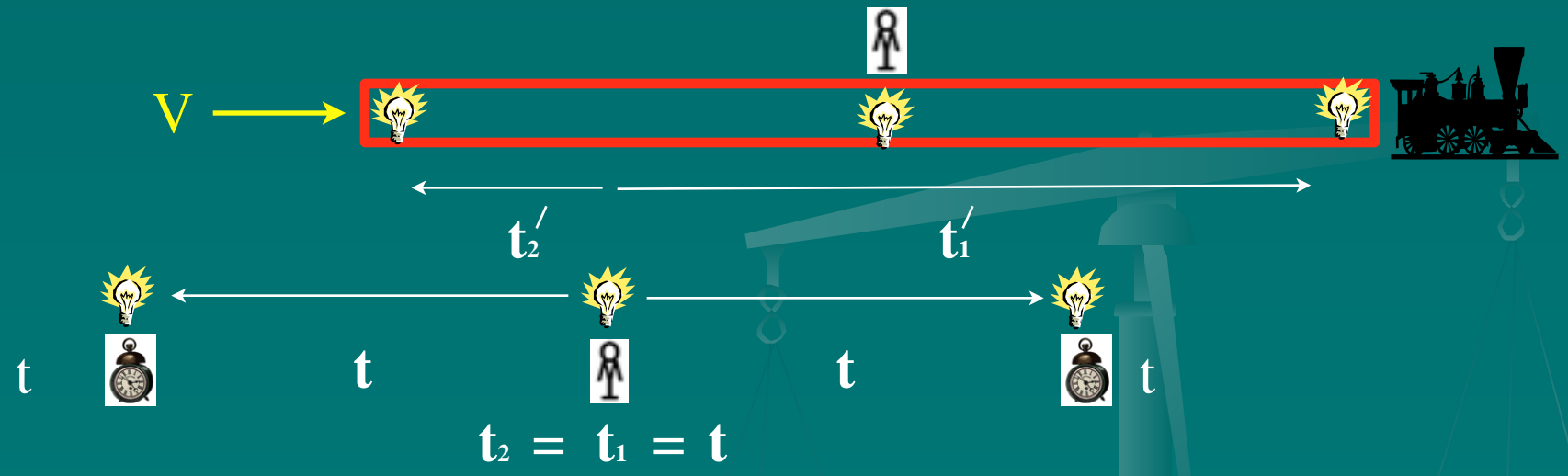

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Events that are simultaneous in an intertial frame are not simultaneous in a frame moving at uniform velocity in a different frame. Also has implications for measured lengths.

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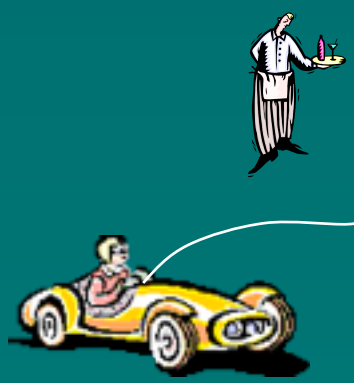

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+60 + 20 = 140 mph

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$$V_{tot} \neq V_{car} + V_{mac} - (-V_{cyclist}) = 140 \text{ mph}$$

$$V_{tot} = V_{mac} - (-V_{cyclist}) = 80 \text{ mph}$$

Twin Paradox

Twin Paradox

Marilyn

Twin Paradox

Marilyn

Carolyn

Twin Paradox

Marilyn & Carolyn

Twin Paradox

Marilyn & Carolyn

Twin Paradox

Twin Paradox

← 2 Million Light Years →

Andromeda Galaxy

Twin Paradox

2 Million Light Years

Andromeda Galaxy

Accelerate away from Earth withan acceleration of 1 g until you are halfway there and then turn around and decelerate with a deceleration of 1 g.

Twin Paradox

← 2 Million Light Years →

Andromeda Galaxy

Twin Paradox

2 Million Light Years

Andromeda Galaxy

- Carolyn is more than 80 years old when she gets back

Twin Paradox

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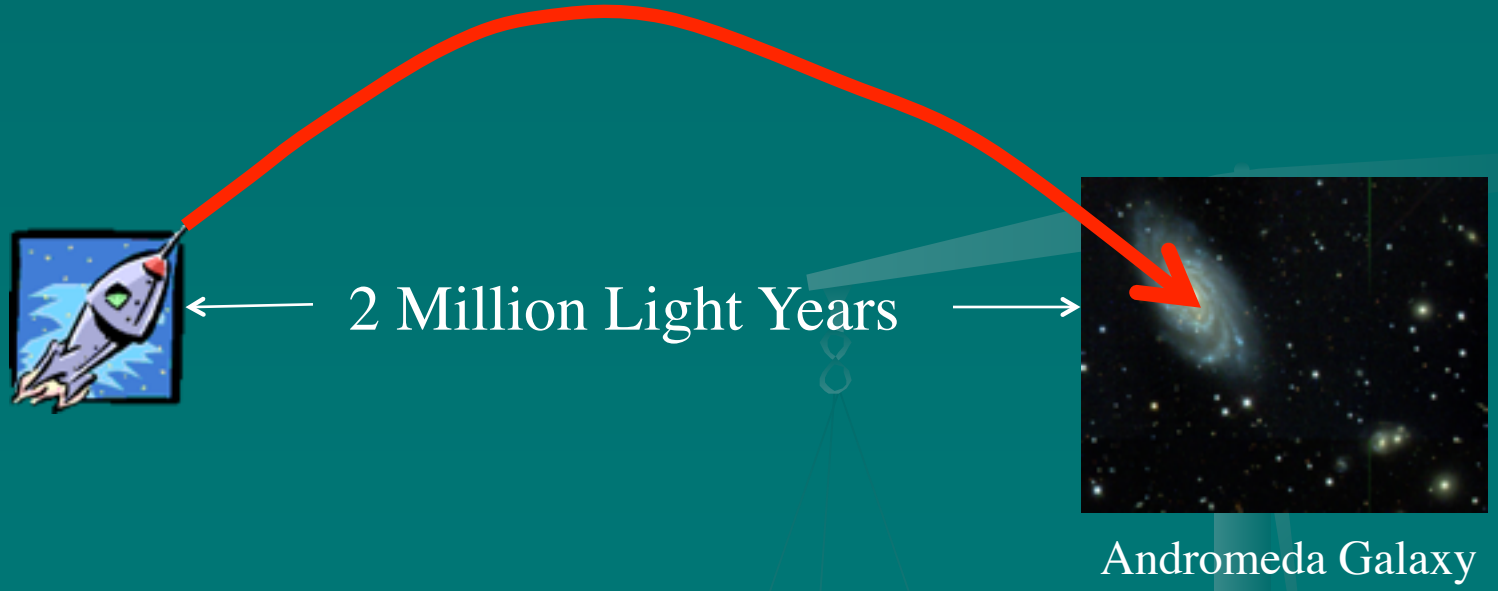


- Carolyn is more than 80 years old when she gets back

Marilyn has been dead for more than 4 million years!

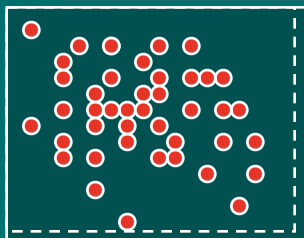
The Arrow of Time

- We can change the rate that clocks run
- Some questions
  - Can we stop time?
  - Can we reverse the direction of time?
  - Did time have a beginning?
    - Big Bang
  - Will it have an end?
  - How does time get a direction?
    - On the microscopic level time runs backwards as well as forward
    - Macroscopically it only runs in one direction

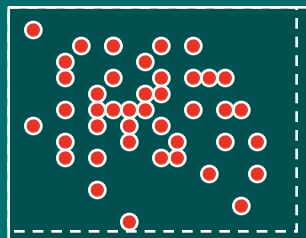
The Beginning of Time?

- How do we conclude that time had a beginning?
  - Observation, Reason, the Principle of causality
    - Does the Universe change or is it static?
    - Assume the principle of causality
      - Galaxies in the Universe are flying away from one another ==>Big Bang-- time has a beginning
    - Will time go on forever?
      - Will gravity pull the Universe back together and end time in a in a very hot point?
        - Measurements have been made to determine the answer to this question, and the answer is apparently no
      - Or could time end because things just quit happening?

Macroscopic Considerations



My Special Universe



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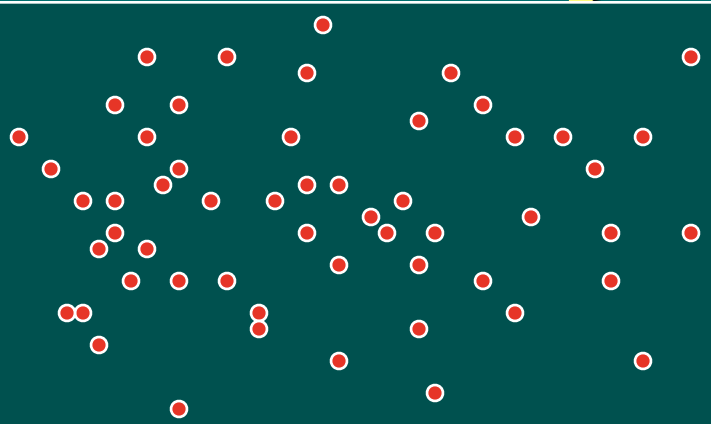

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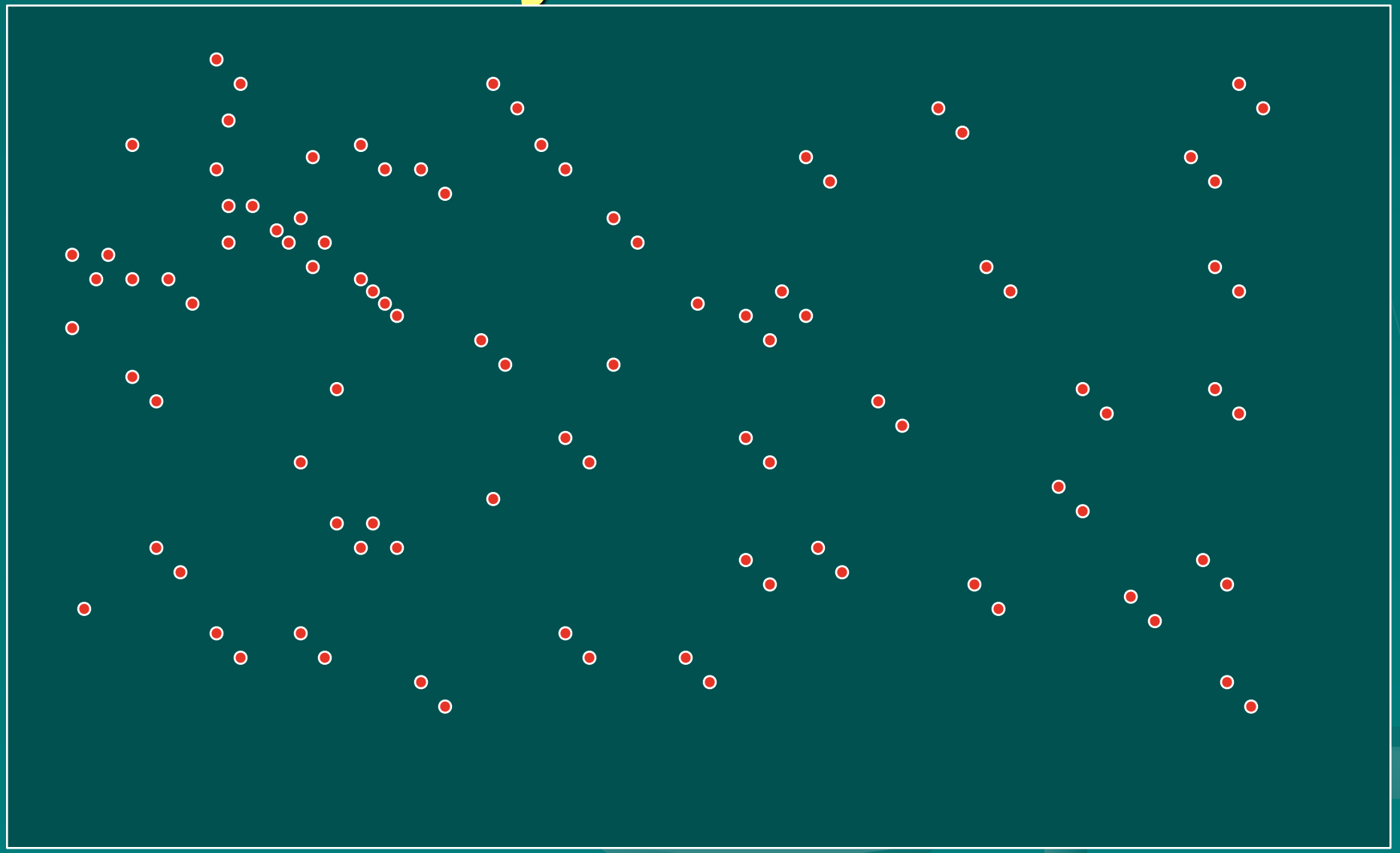

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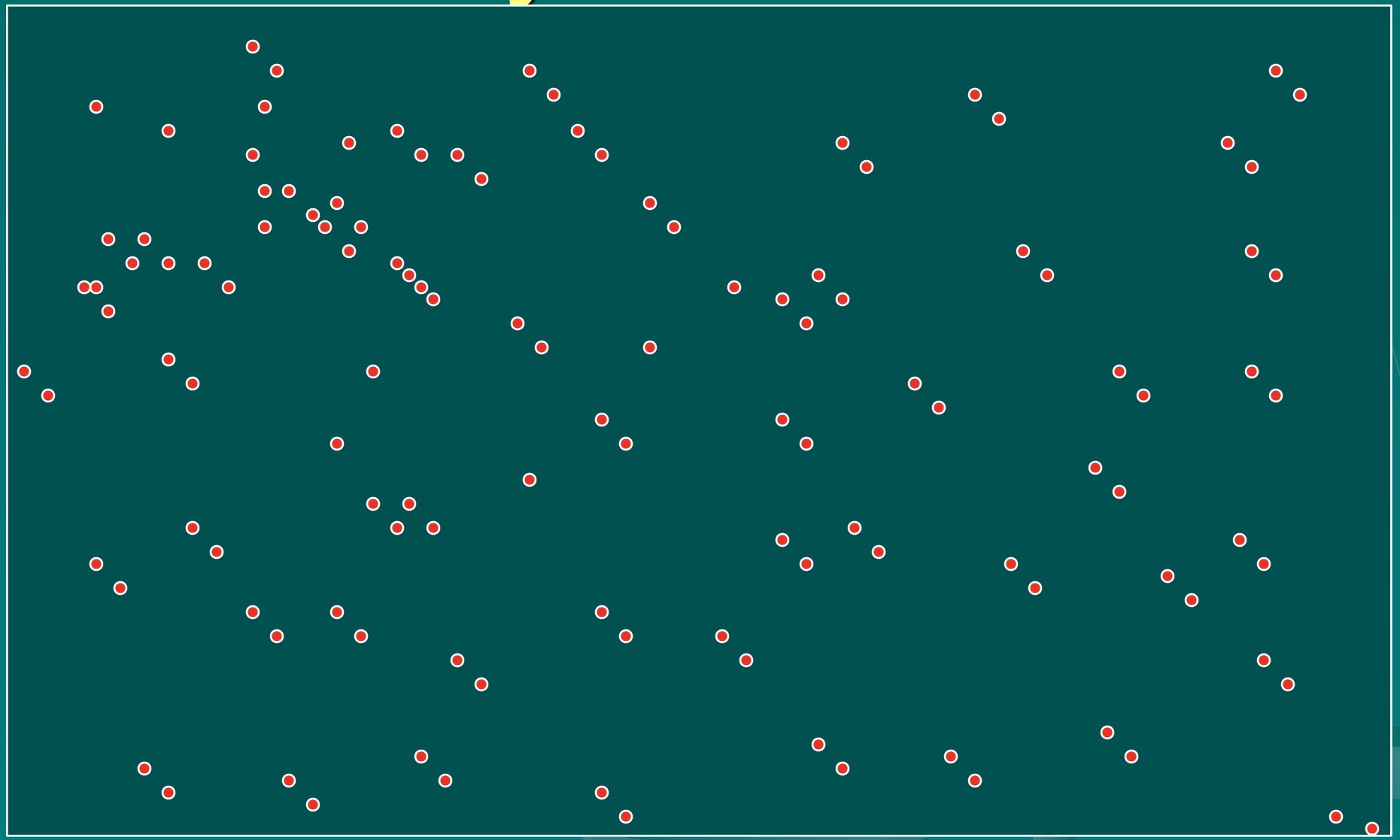

Time and Space Summary

- Time
  - Mysterious at best
- Space
  - Also distorted by Lorentz transformations
    - Moving train also became a shorter train as measured from the embankment
  - Dimensionality is not settled

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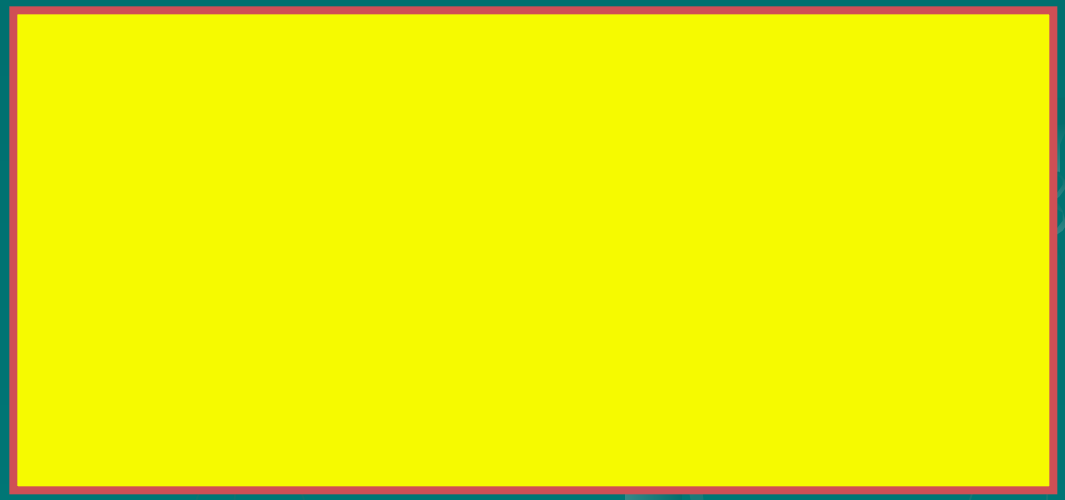
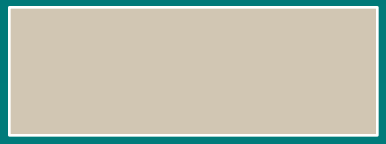
Whoa! New Wrinkle!

Numbers,Counting & Mathematics

Zork's Pasture



Moog's Pasture



Making up History

Zork's Pasture

Moog's Pasture

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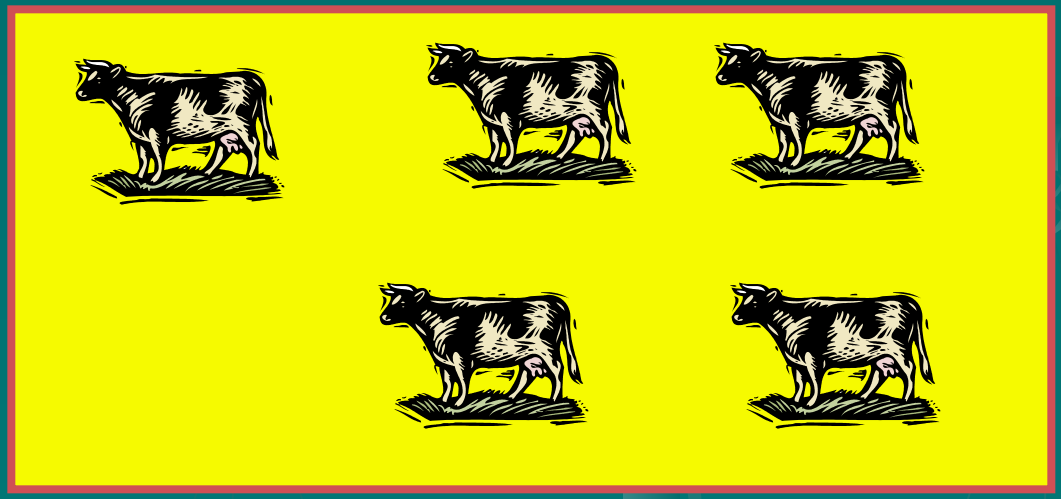

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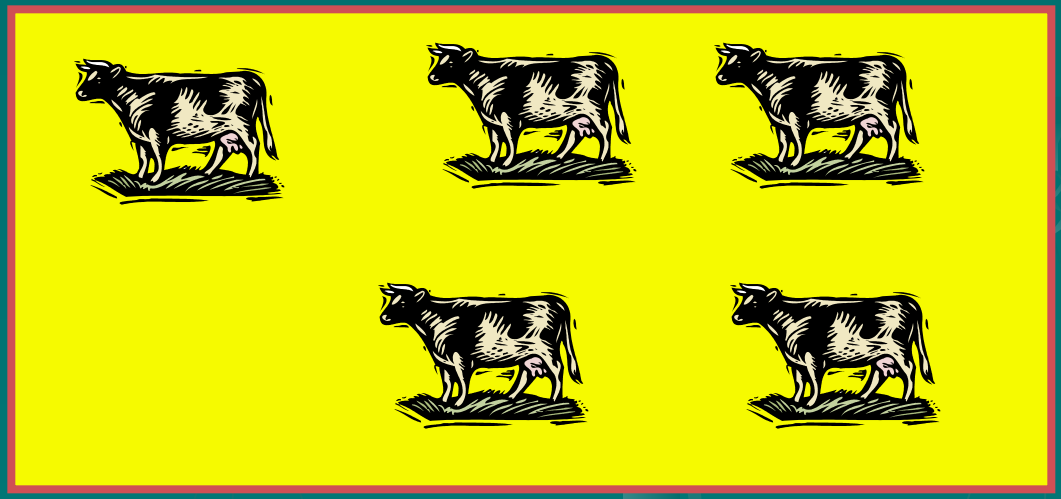

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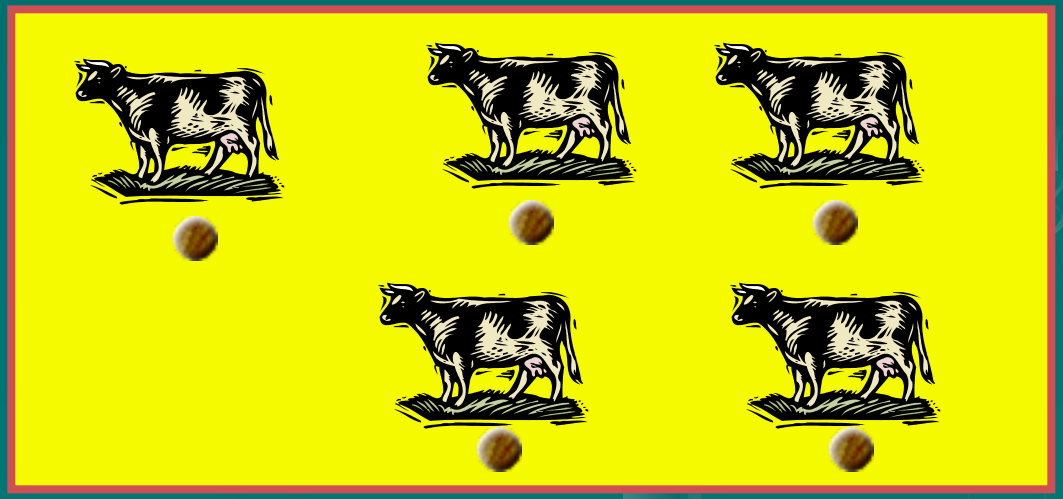

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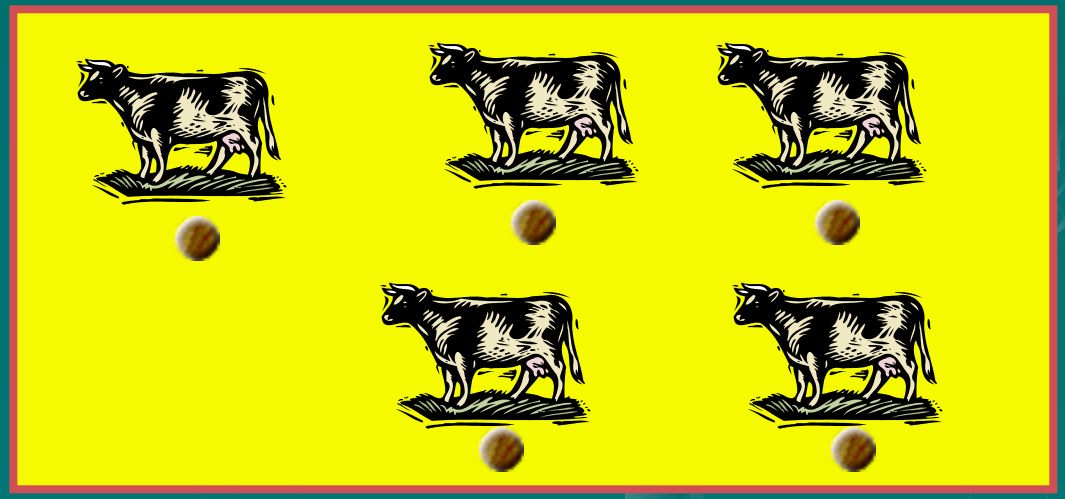

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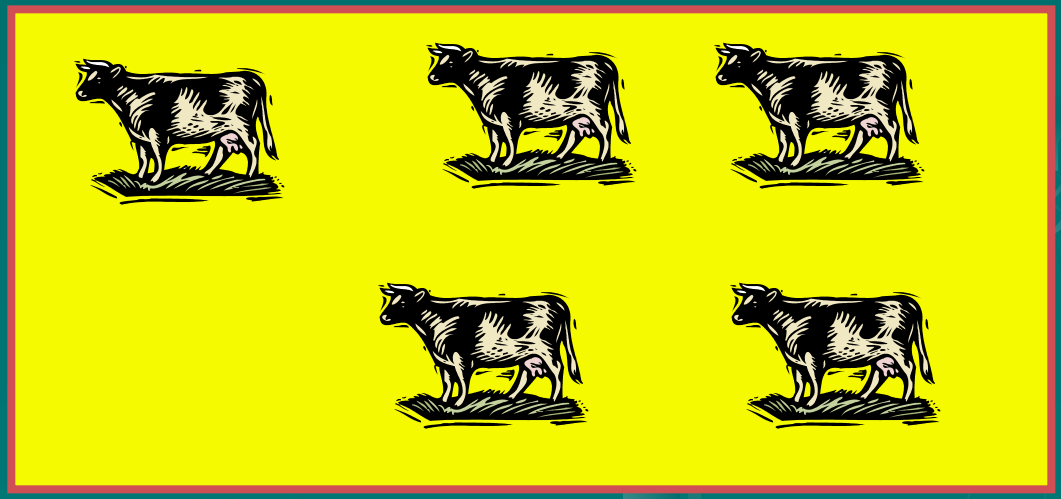

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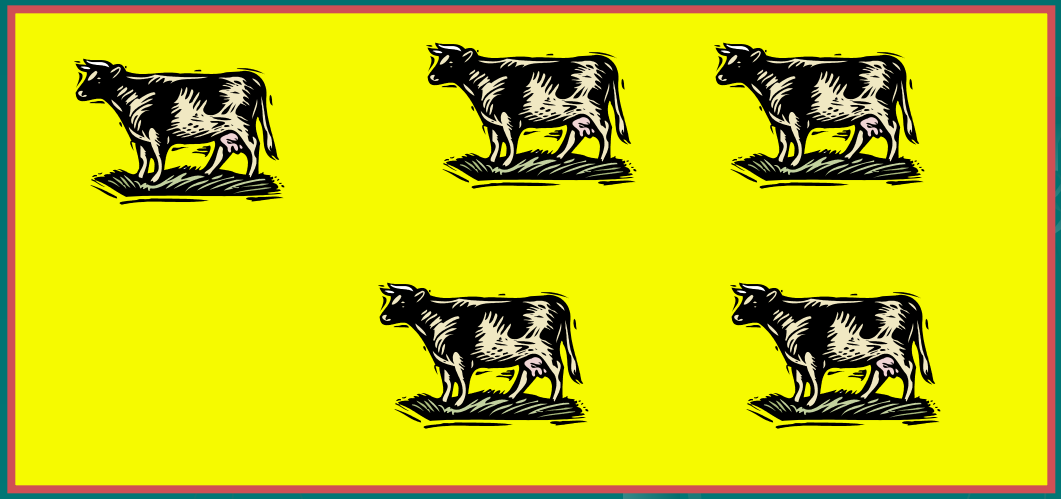

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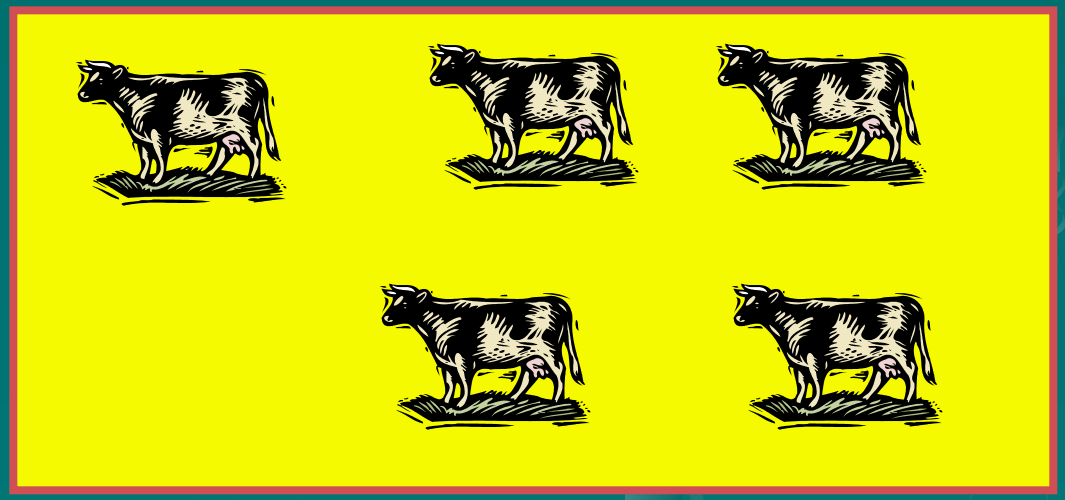

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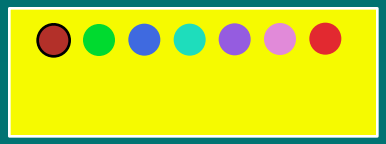

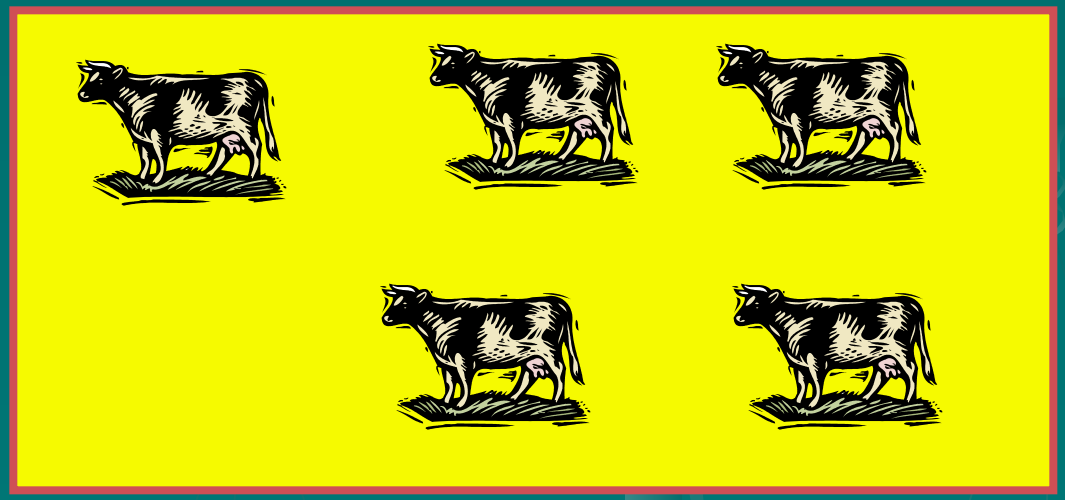

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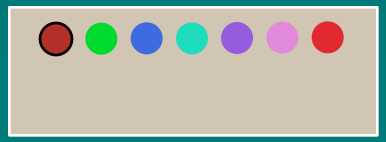

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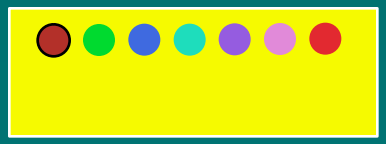
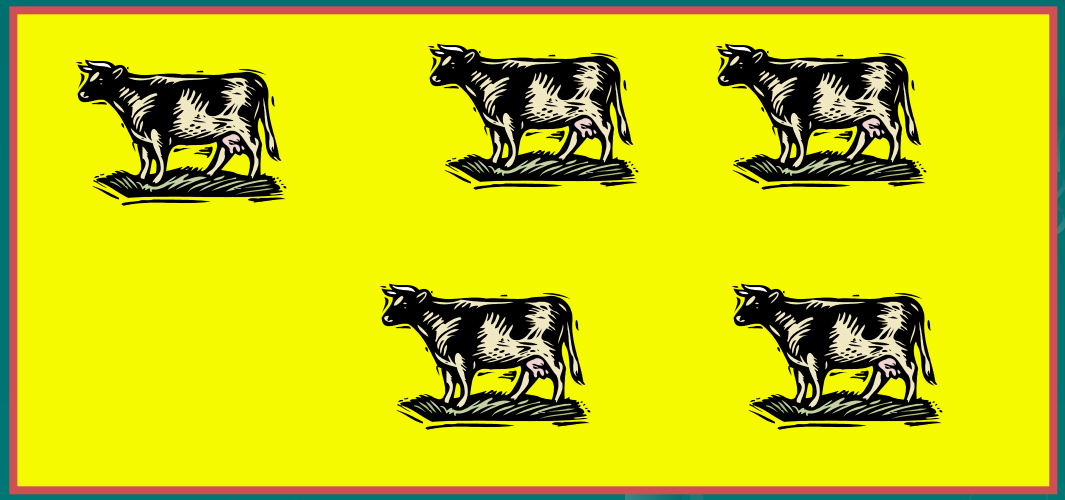
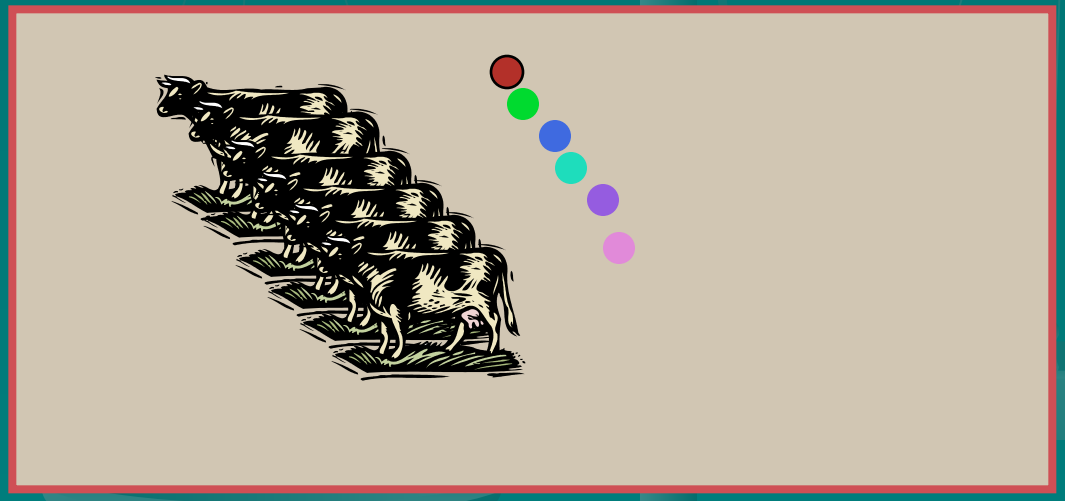
Zork's Pasture



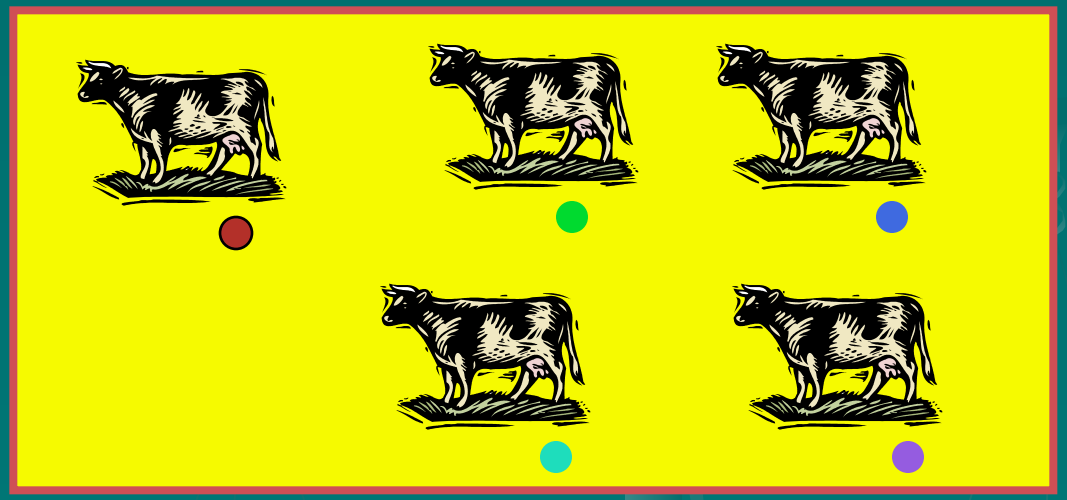


Moog's Pasture



Making up History

Zork's Pasture



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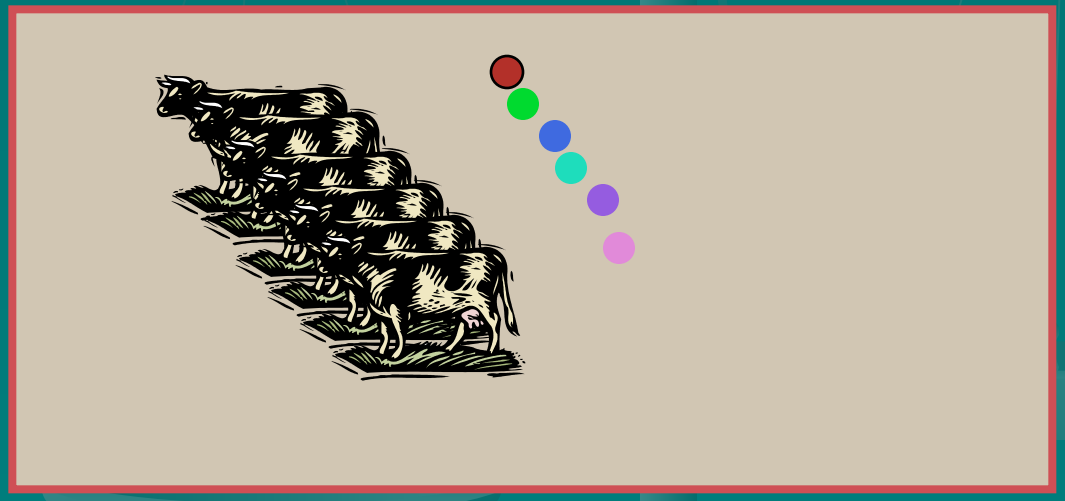

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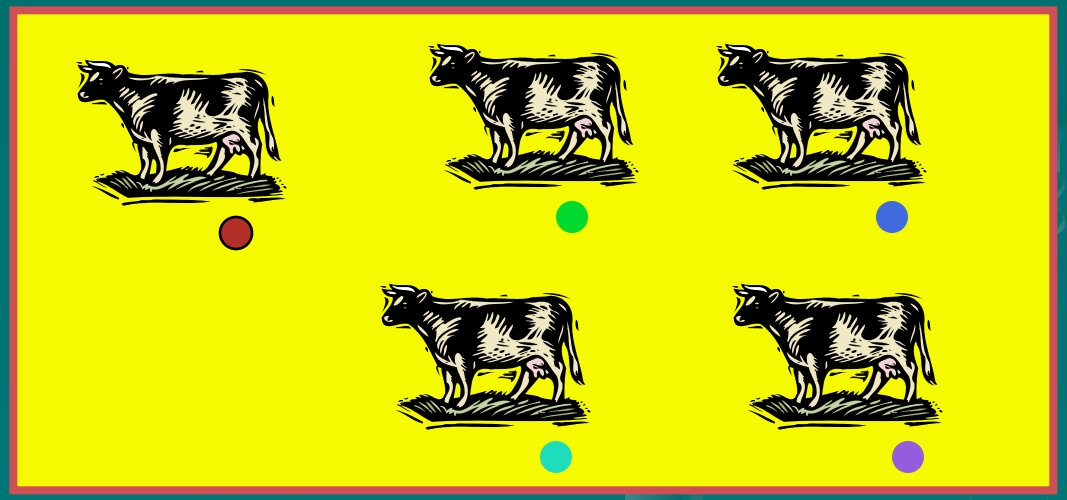
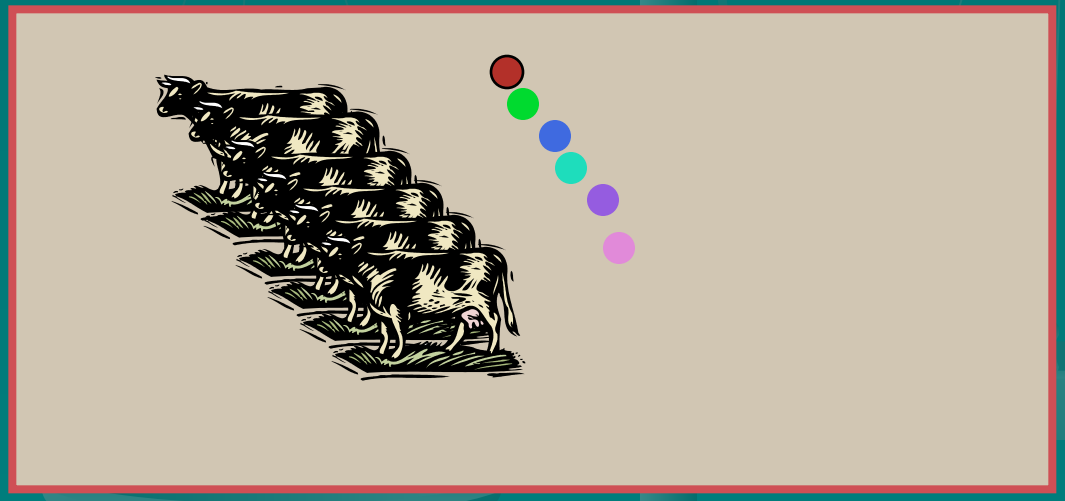


I II III . . .

No Zero!

Moog's Pasture



Counting and Measuring-- Quantifying Space

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- Connecting numbers to geometry (Space)
  - Floods of the Nile
    - How much land do I have?
    - Where is it?
  - Learn something about geometry and areas

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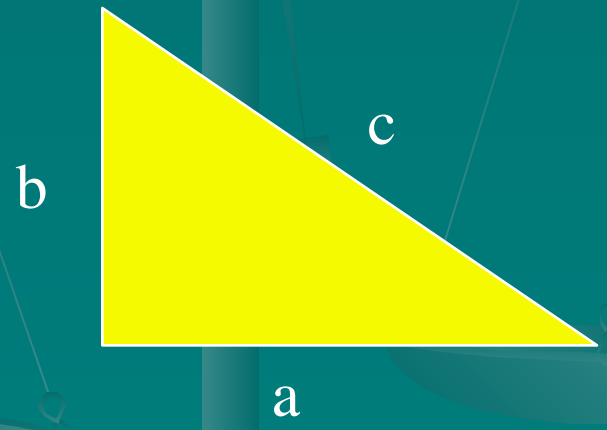

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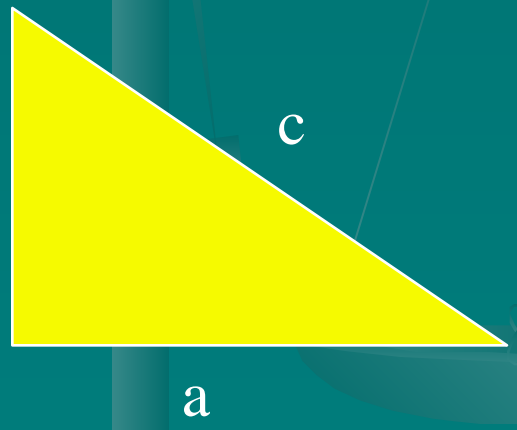
Pythagoras: $a^2+b^2 = c^2$



What are the Numbers

- Natural Numbers (0,1,2,3 . . .)
  - Zero used in calculations came from India
  - Most of the western world used spaces– but these were not the zeros needed for calculations
- Integers (. . . -1,0,1,2,3 . . .)
  - What does having -1 cows mean?
- Rational Numbers (a/b)
- Irrational numbers π, $\sqrt{2}$
- Imaginary Numbers $\sqrt{-1}$ or i (Moog tried to claim he had imaginary cows-- Zork was not impressed)

Gerolamo Cardano and Niccolo Tartaglia

Why do we need $\sqrt{-1}$?

Gerolamo Cardano and Niccolo Tartaglia

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Niccolo Tartaglia– used in
Solutions to cubic equations

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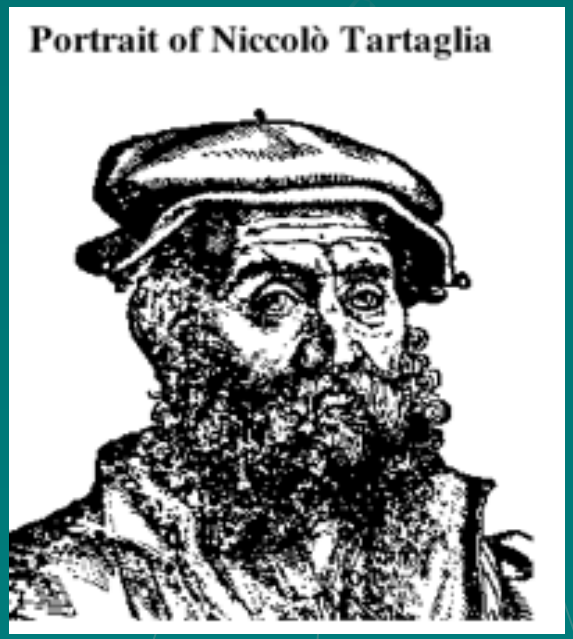

1499 - 1557

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1501 - 1576

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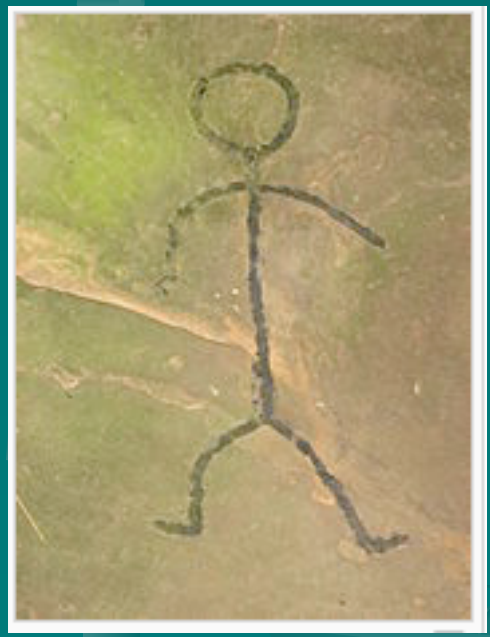
Scipione del Ferro



1465 - 1526

Evariste Galois

Radical Republican

Problem Child

1811 to 1832

Evariste Galois

Radical Republican

Problem Child

1811 to 1832

Foundations of Group Theory

Summary so Far

- Universe
  - Matter-- Looking for the Legos (Quarks and Leptons and ?)
  - Space -- Geometry– stage or actor
  - Time-- Mysterious, orders events, tied to space through relativity (Spacetime)
- Tools for Understanding
  - Observations & Experiments using
    - Rulers
    - Clocks
    - Numbers
    - Mathematics (Reason and Logic)
    - Beams and detectors

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Next: How our understanding of the physical world evolved

Intermission

Thales of Miletus

624 BC to 546 BC
Approximately

First Greek Philosopher
Attempted to explain existence without reference to mythology (birth of science)

Sought to understand the ultimate substance, change and existence

First true mathematician
Geometry– first credited mathematical discovery

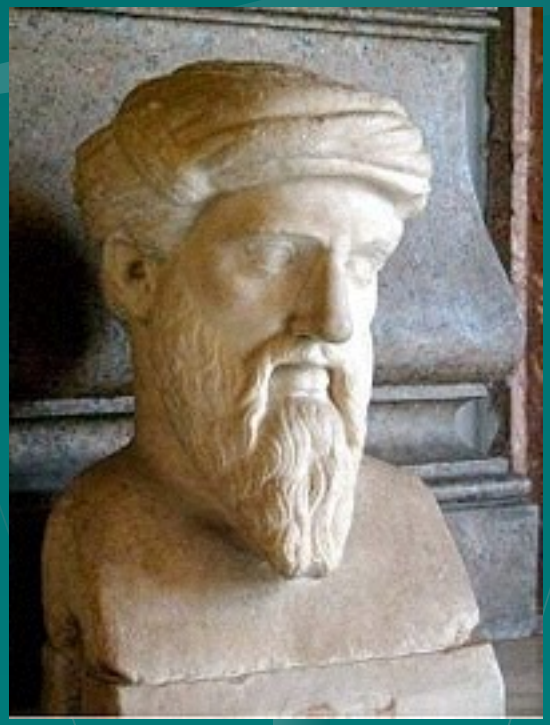
Pythagorus

Investigated the relationship between numbers, geometry and the physical world

He was also a religious leader

Known for the Pythagorean Theorem

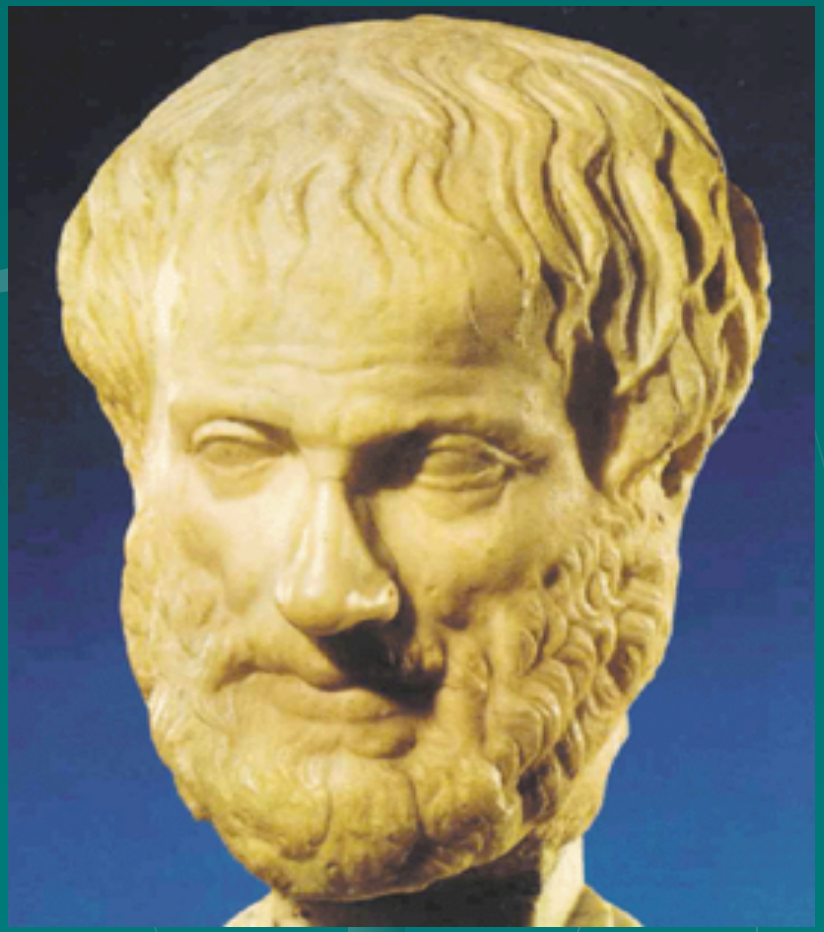
Leader of a mathematical cult– much is attributed to him, but there is no reliable information about him, and it is not clear what he really contributed



~ 580 BC to 500 BC

Aristotle

- Polymath
- Philosopher
- Educated at Plato's Academy
- Many contributions to civilization including
  - Catagorized Species
  - (observations)
- Created Physics
- Some have said he was the last person to know everything



384 BC - 322 BC

Dark Ages

- Scientific progress stalled
  - Dogma ruled the world
- Why? Scientific theories and ideas must be tested
  - Didn't happen
    - Even though Aristotle left a legacy of observations to test theories
  - Scientific theories reflect truth only to the limits where they work. The must be replaced when more precise observations are made indicating the theory does not tell the complete story.
- Dark ages philosophy required accepting the established theories without question

Early Dawn

1473 -1543

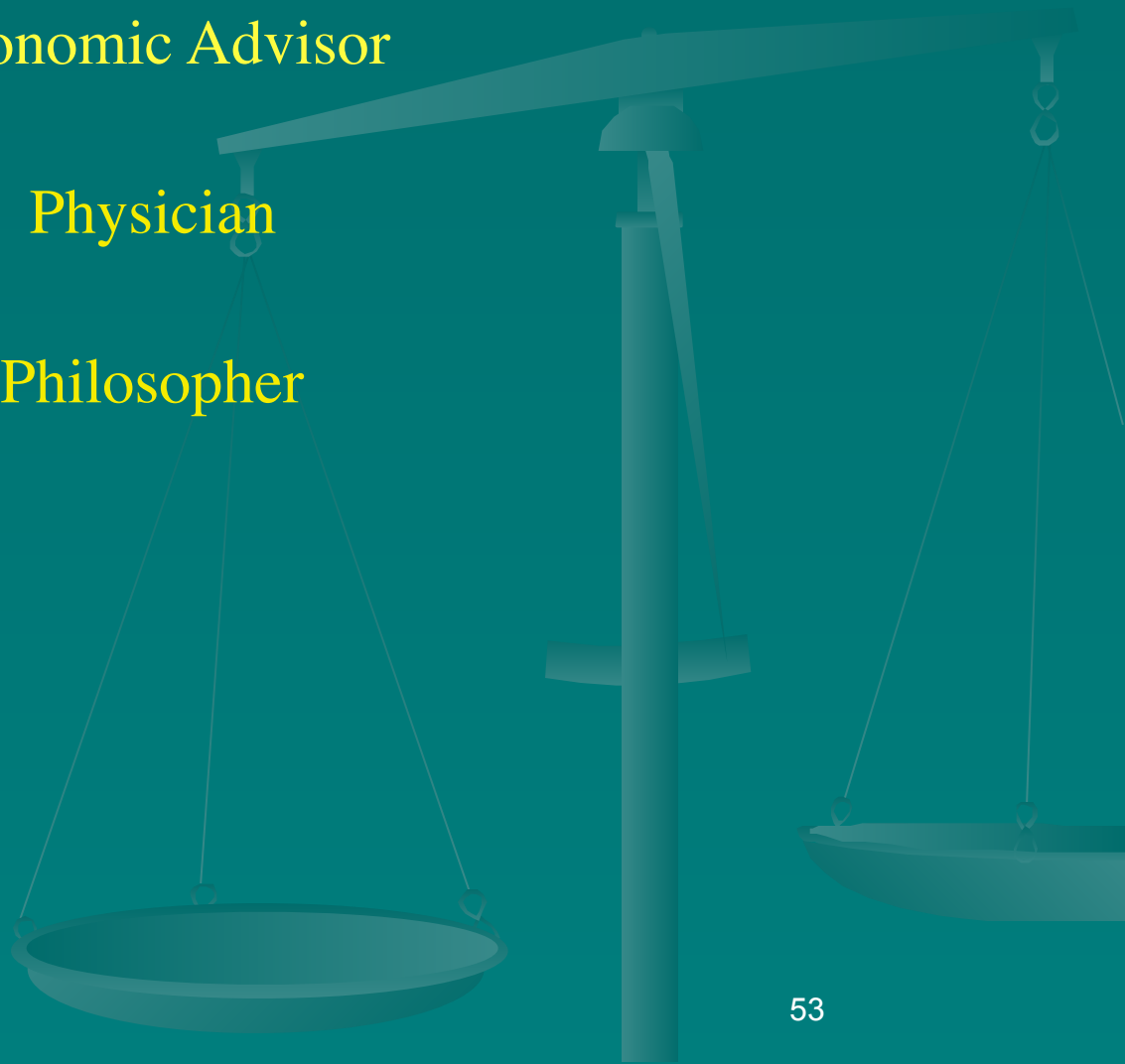
Nicolaus Copernicus

Early Dawn

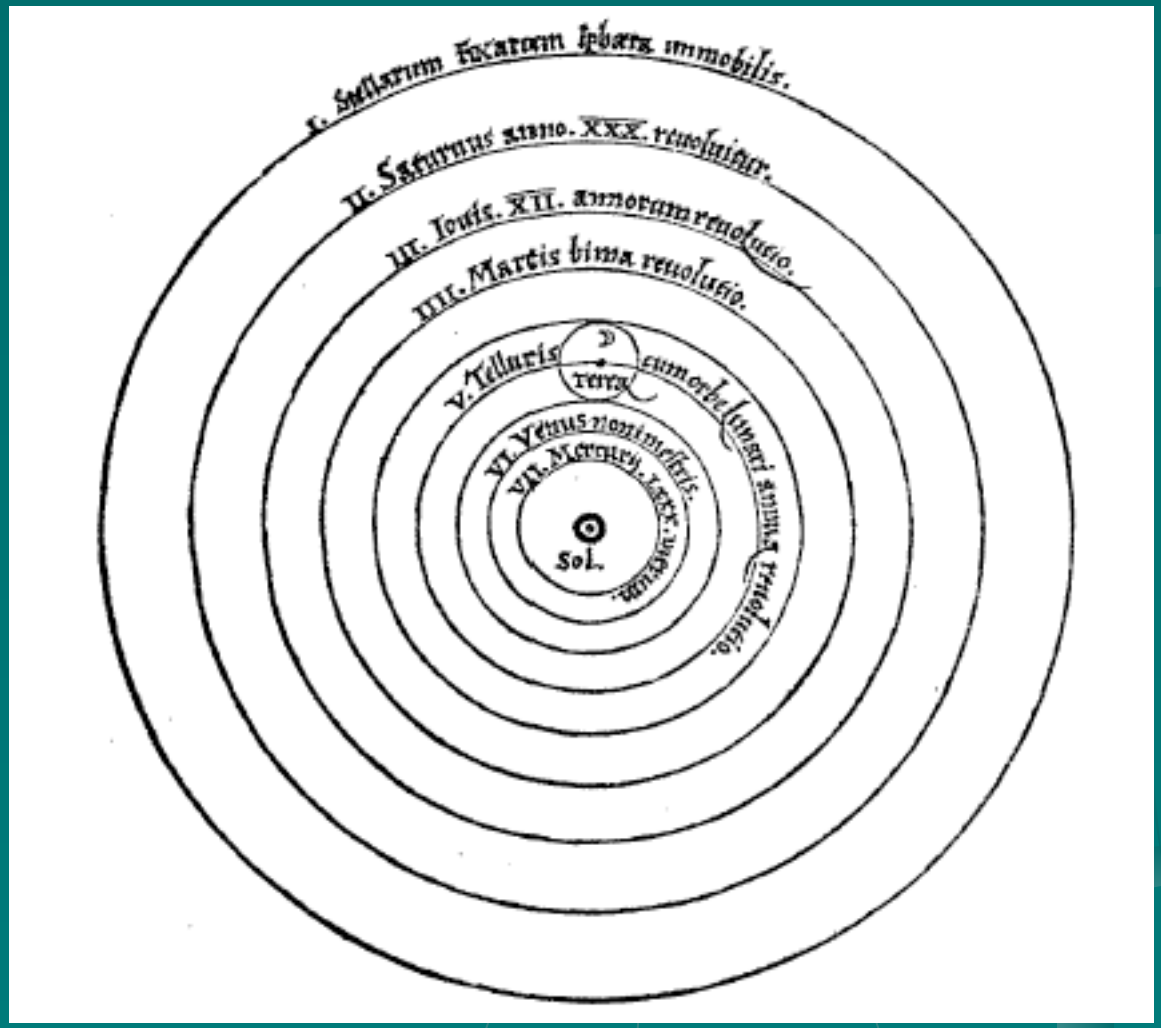
Economic Advisor

Physician

Philosopher



Early Dawn


I. Stellarum fixarum sphæra immobilis.
II. Saturnus annis. XXX. revolvitur.
III. Iouis. XII. annorum revolutio.
IIII. Martis bima revolutio.
V. Telluris
terra
cum orbe lunari annua
revolutio.
VI. Veneris mensis
VII. Mercurij. LXXX.
Sol.

Johannes Kepler

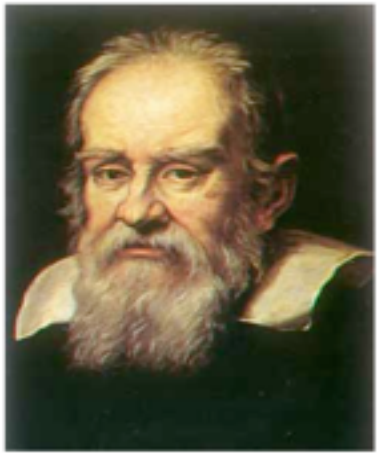
1571 to 1630

Laws of Planetary Motion
Astrologer
Religious Mystic
Mother almost burned as a witch
Data from Tycho Brahe–
How did Tycho die?

Planets have elliptical orbits!

Sunrise

Sunrise



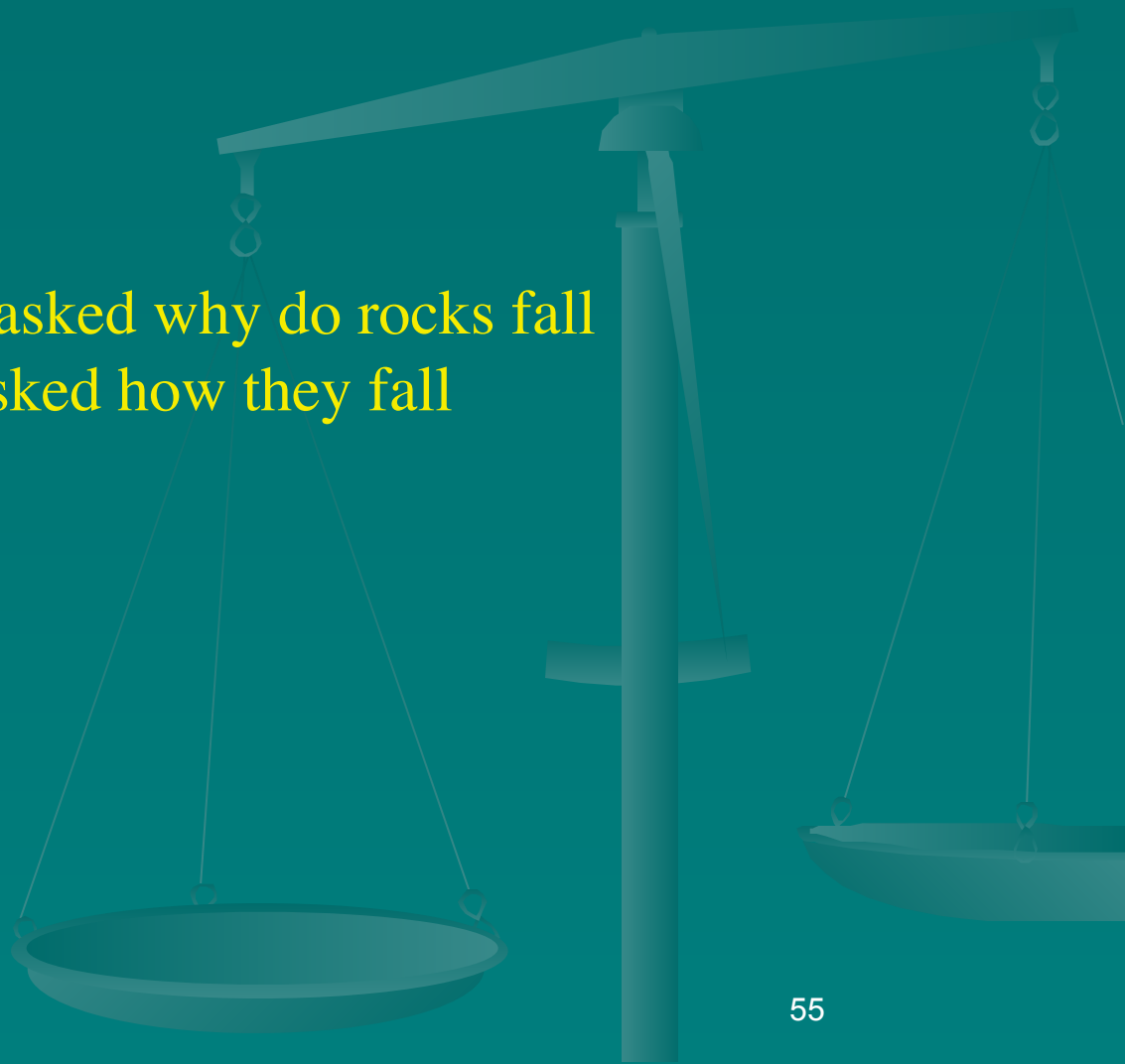
Galileo Galilei

lived from 1564 to 1642

Galileo Galilei formulated the basic law of falling bodies, which he verified by careful measurements. He constructed a telescope with which he studied lunar craters, and discovered four moons revolving around Jupiter.

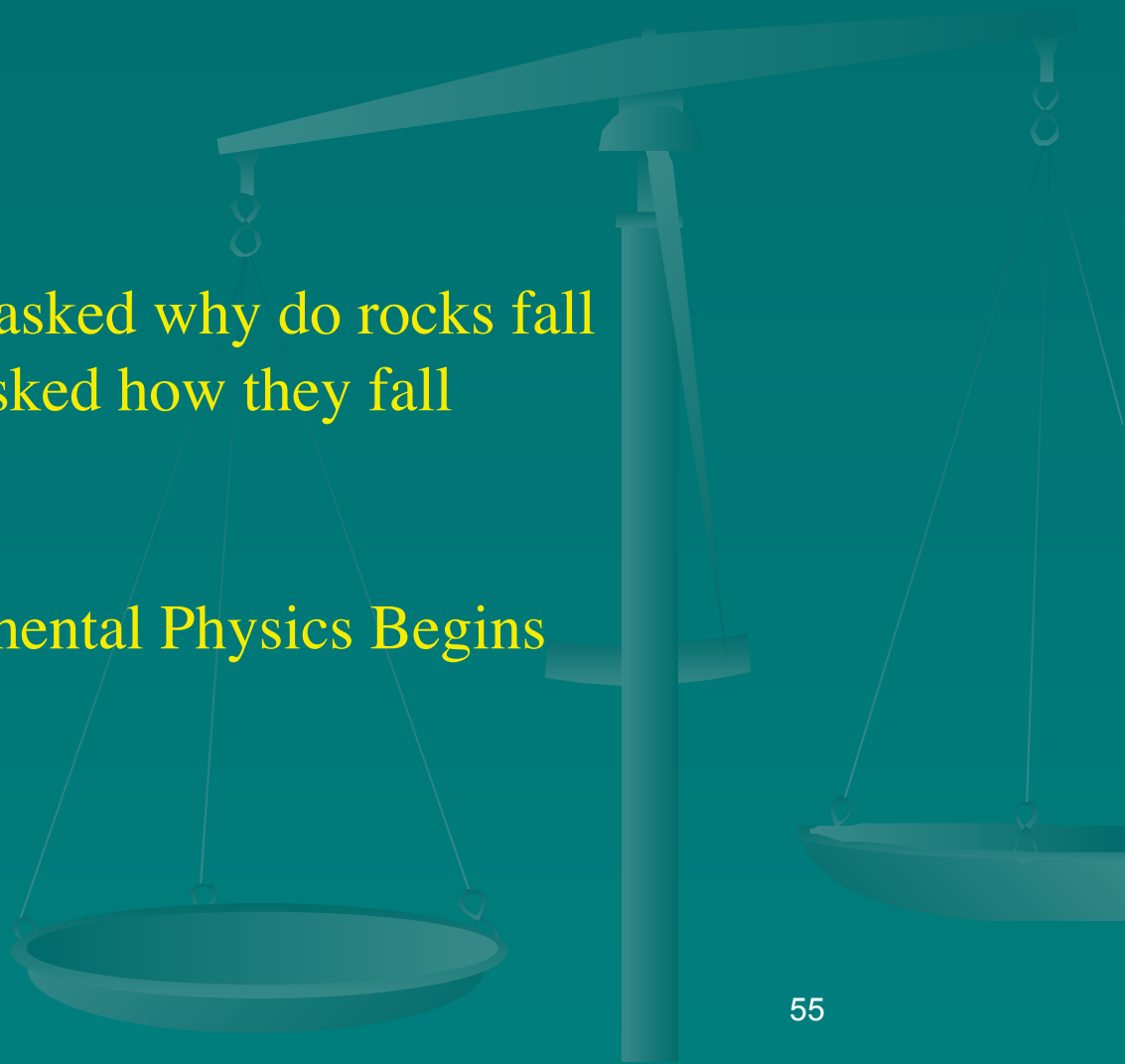
Sunrise

Sunrise



Aristotle asked why do rocks fall
Galileo asked how they fall

Sunrise



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Experimental Physics Begins

Midmorning

Midmorning

1642 to 1727

Midmorning

Midmorning

- Isaac Newton
  - Birth of the Royal Society and real published science
  - Laws of motion
  - Gravity
  - Space is something
  - Calculus with Leibnitz
  - Tracked down Counterfeiters

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The Clockwork Universe
by
Edward Dolnick

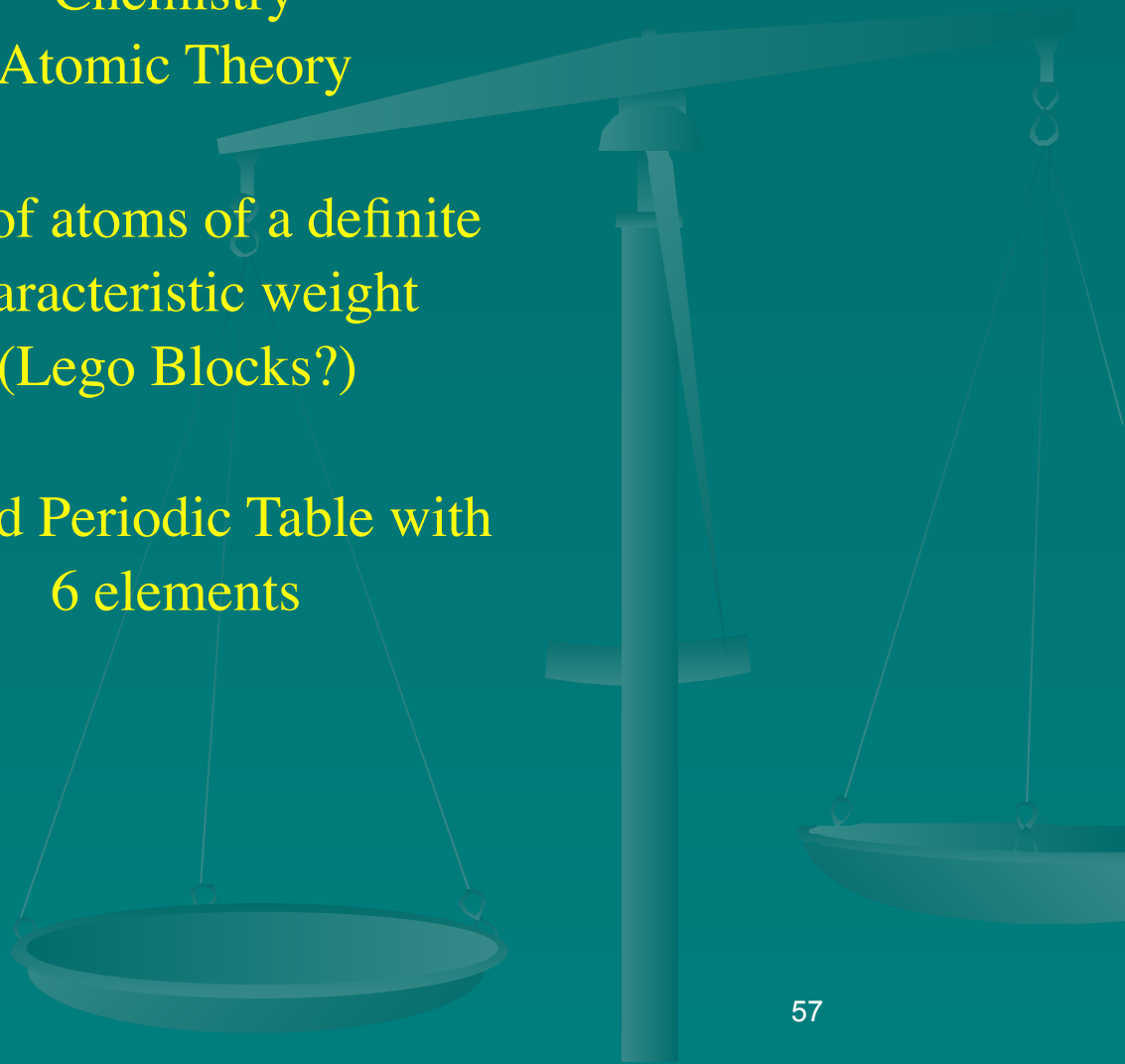
John Dalton

John Dalton

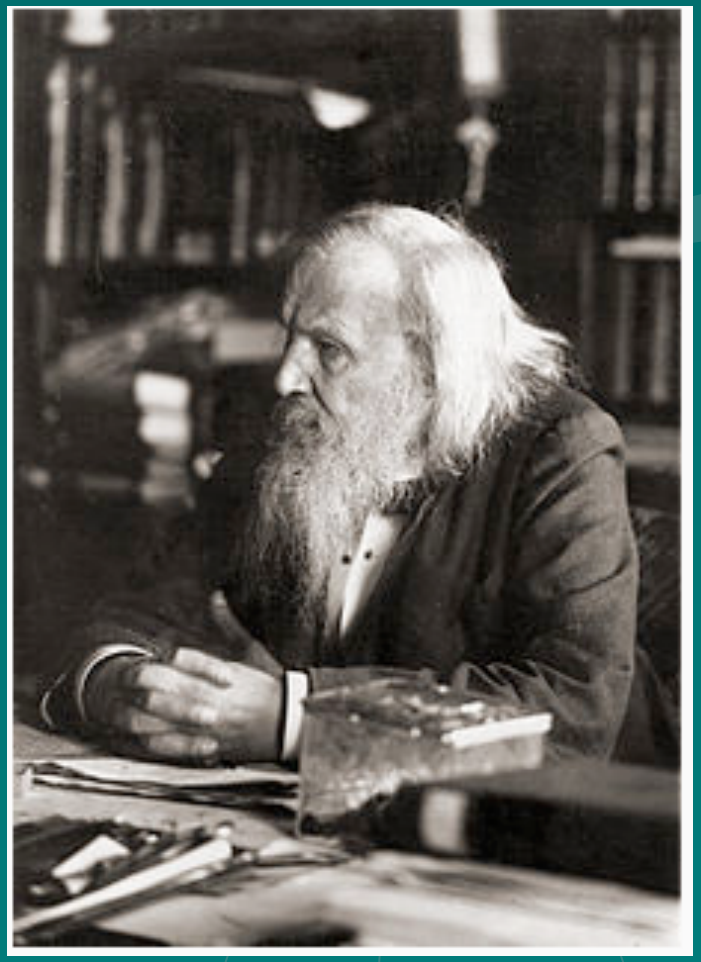
Chemistry
Atomic Theory

Idea of atoms of a definite characteristic weight
(Lego Blocks?)

Started Periodic Table with 6 elements



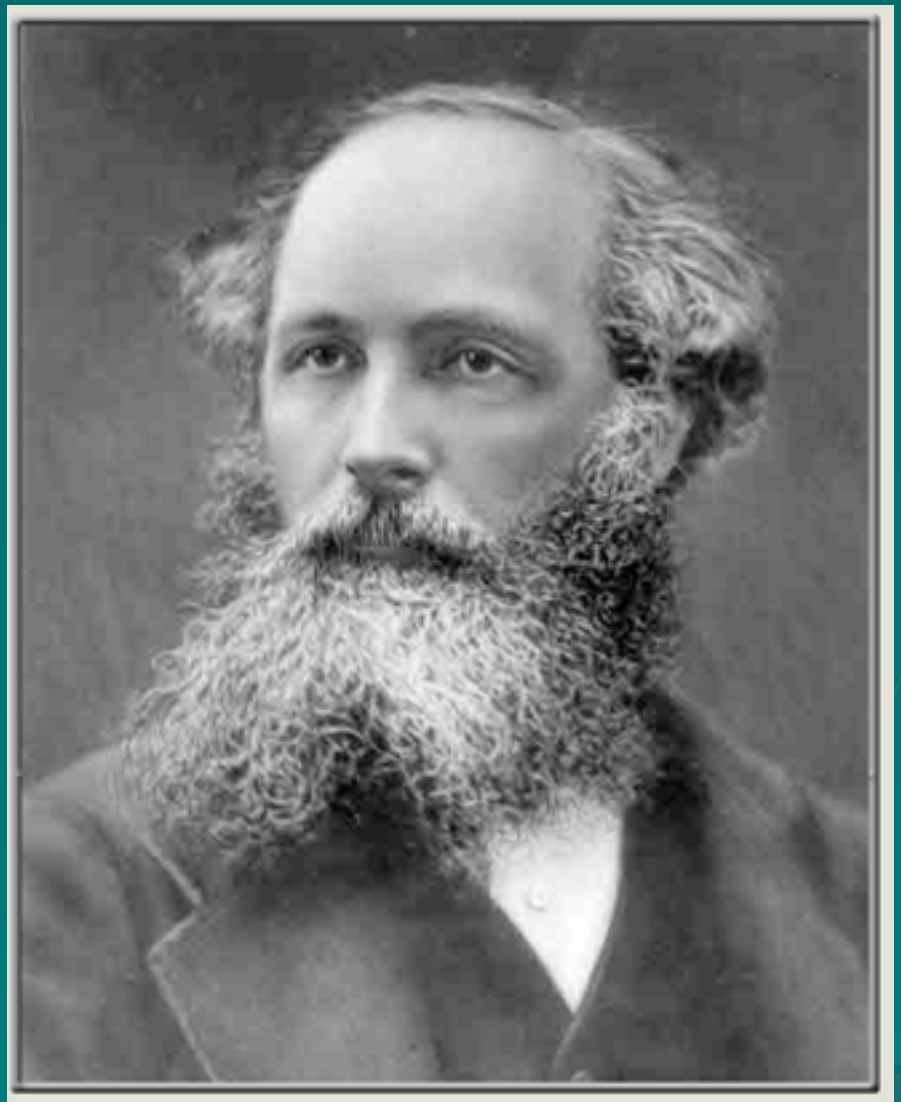
Dmitri Mendeleev



1834 to 1907

Periodic Table
of the Elements

James Clerk Maxwell



James Clerk Maxwell in his 40s.

Formulation in terms of *total* charge and current[note 2]

Name	Differential form	Integral form
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$	$\oiint_{\partial V} \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \frac{Q(V)}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\oiint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{A} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_S(\mathbf{B})}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0\mathbf{J} + \mu_0\varepsilon_0\frac{\partial \mathbf{E}}{\partial t}$	$\oint_{\partial S} \mathbf{B} \cdot \mathrm{d}\mathbf{l} = \mu_0 I_S + \mu_0\varepsilon_0\frac{\partial \Phi_S(\mathbf{E})}{\partial t}$

$$\nabla \cdot \mathbf{E} = 0$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0\varepsilon_0\frac{\partial \mathbf{E}}{\partial t}.$$

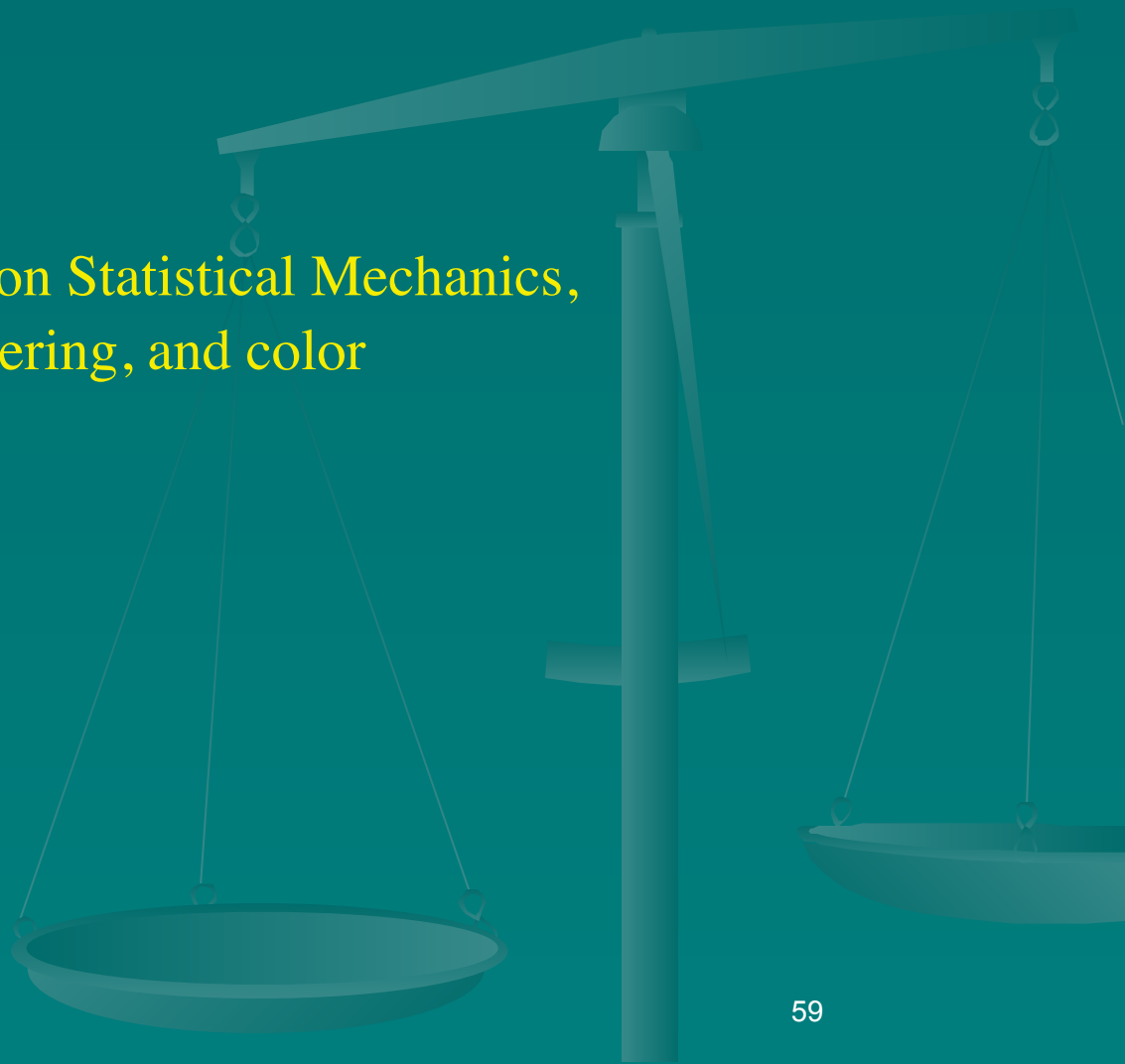
$$c = \frac{1}{\sqrt{\mu_0\varepsilon_0}}.$$

1831 to 1879

James Clerk Maxwell

James Clerk Maxwell

Also worked on Statistical Mechanics, bridge engineering, and color photography



Maxwell Family Portrait

Mr and Mrs James Clerk Maxwell 1869

Radioactivity

- Marie and Pierre Curie
  - Discovered and studied radioactive decay of elements (clues to internal structure of the atom)
  - Were awarded the Nobel Prize together
  - Pierre attempted to study seances scientifically

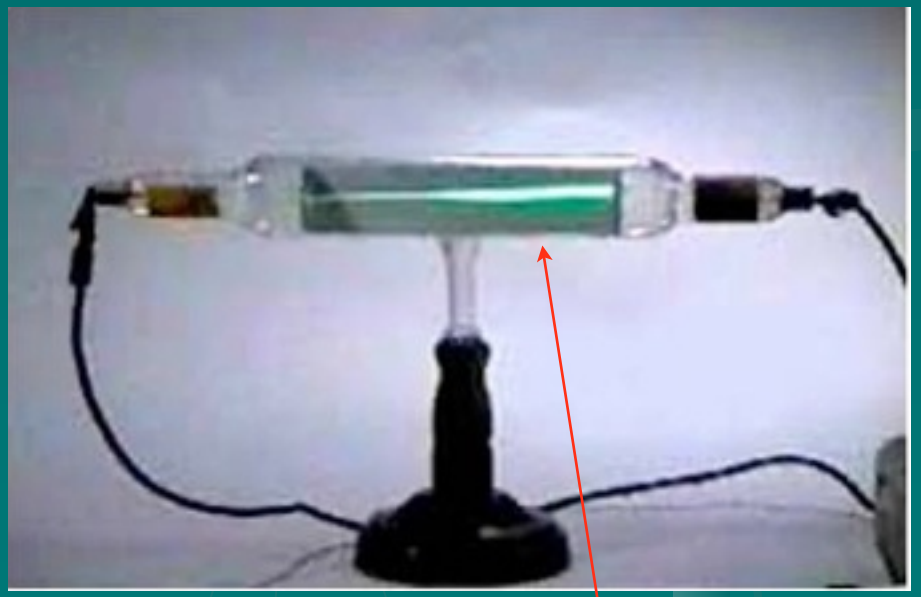
1867 -1934 1859 -1906

J. J.Thomson

1856 -1940

J. J.Thomson

Discovery of the Electron



Cathode Ray Tube, or Crookes Tube-- (an accelerator)

1879 - 1955

1879 - 1955

1879 - 1955

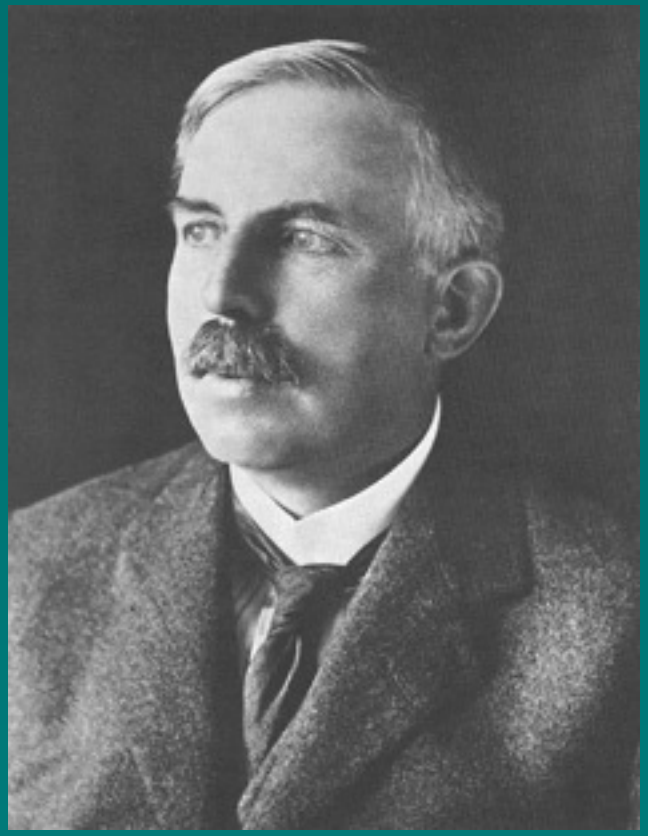
$E = mc^2$

Special Theory of Relativity

General Theory of Relativity

Quantum Mechanics?

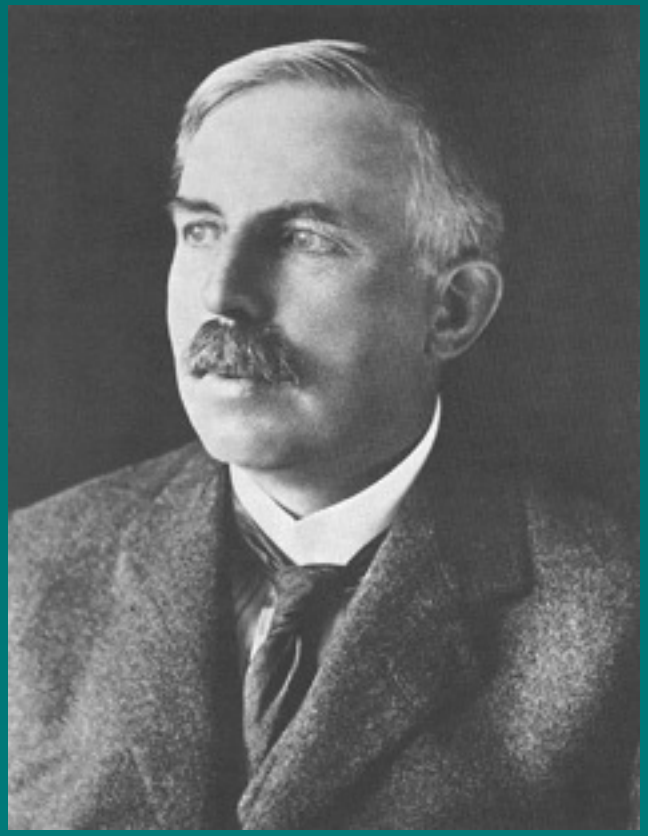
Rutherford and the Nucleus



1871 -1937

- Discovery of the Nucleus

Rutherford and the Nucleus



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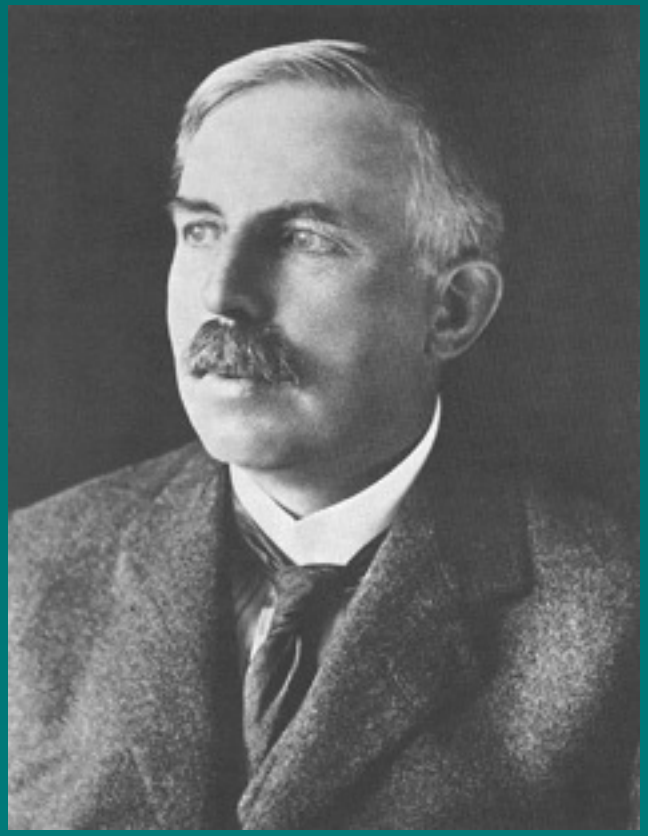

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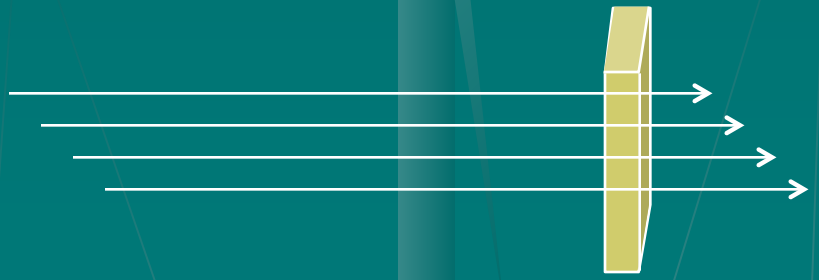

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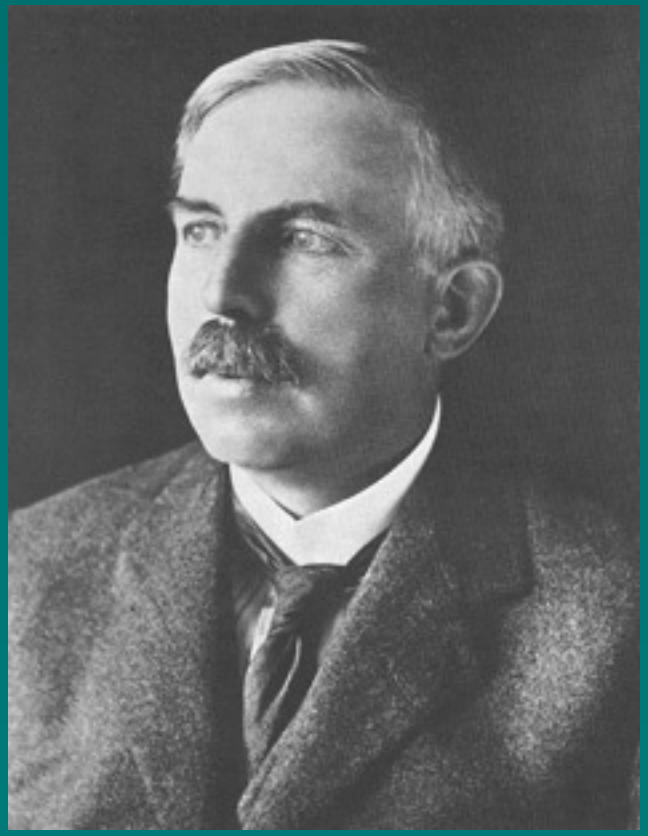

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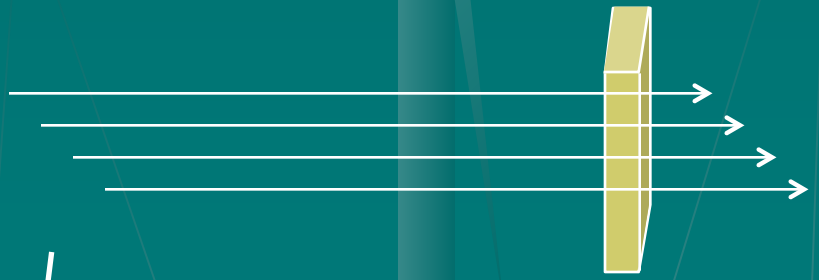

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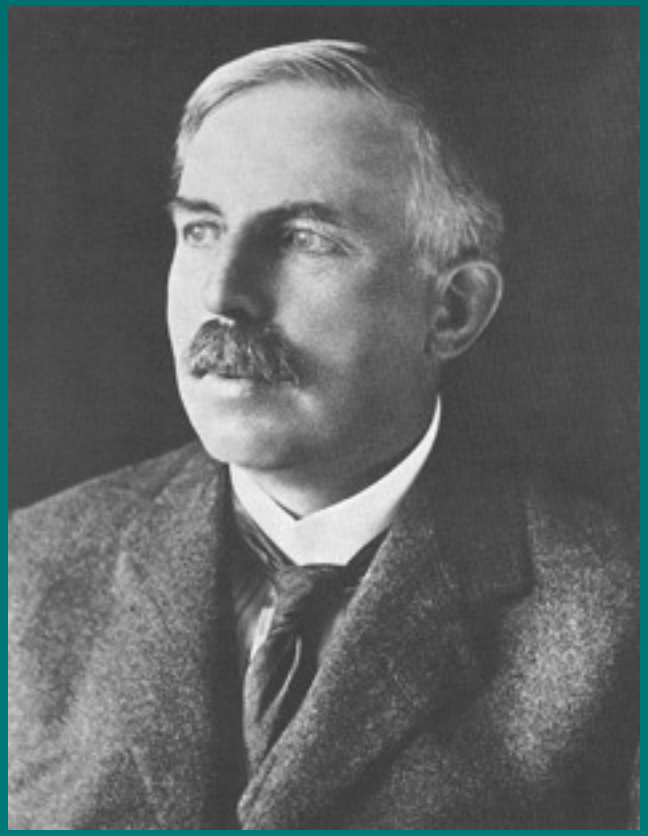

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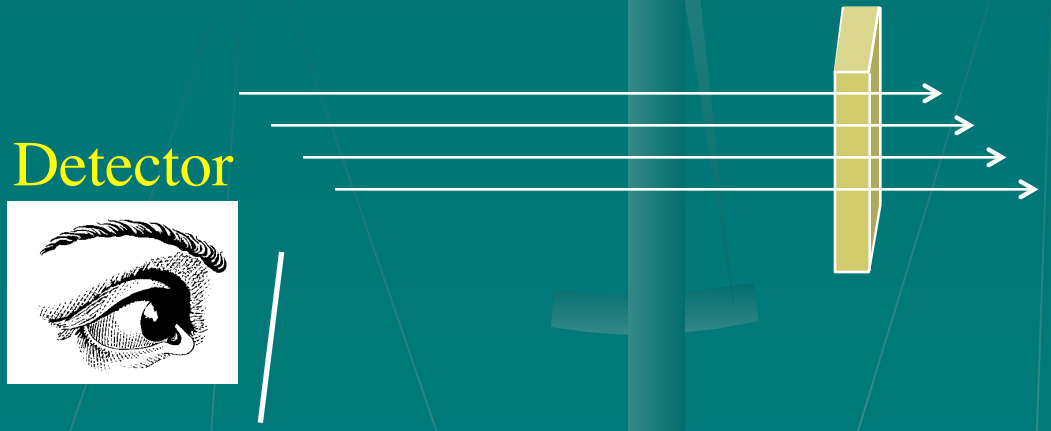
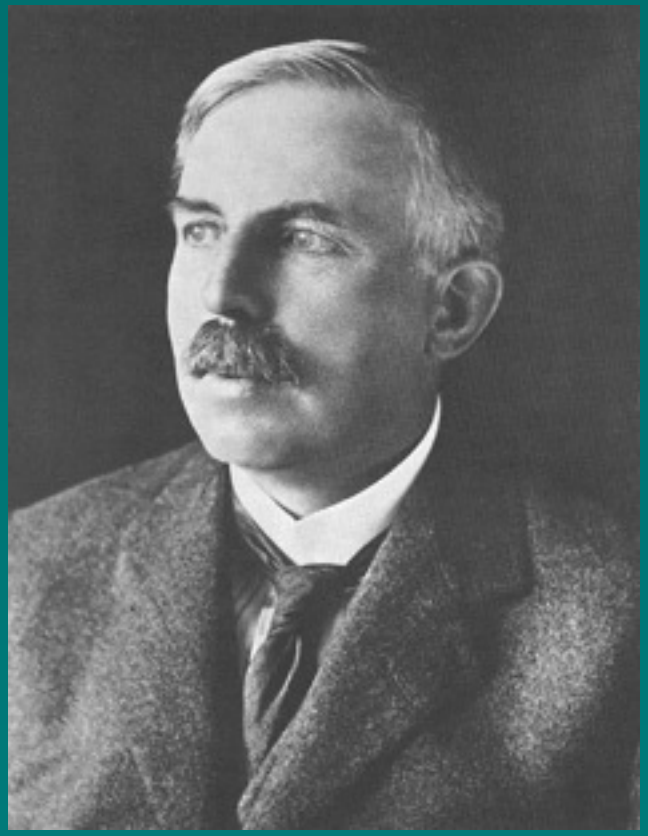


Rutherford and the Nucleus



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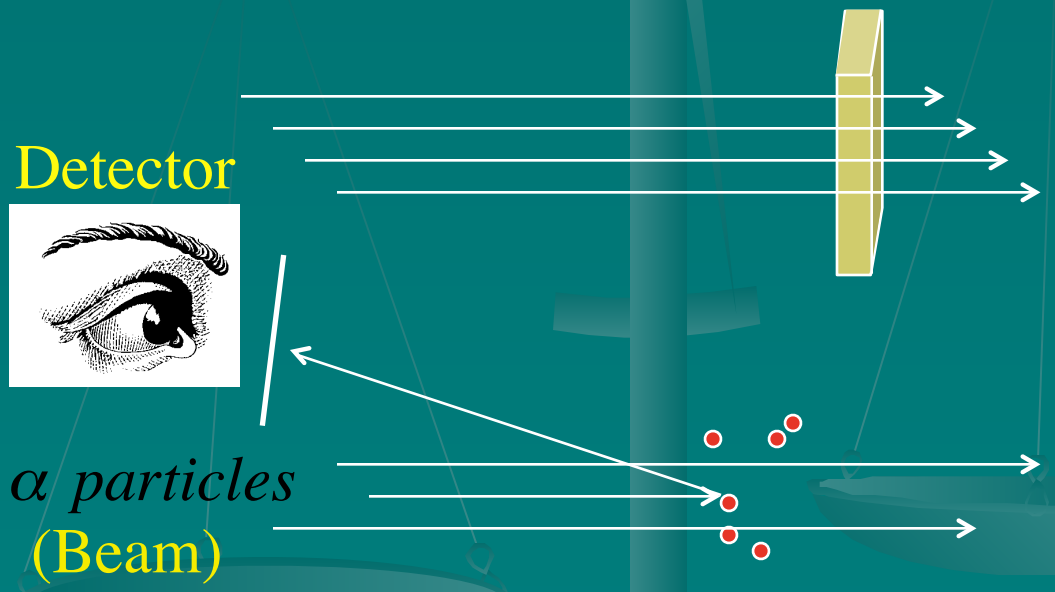

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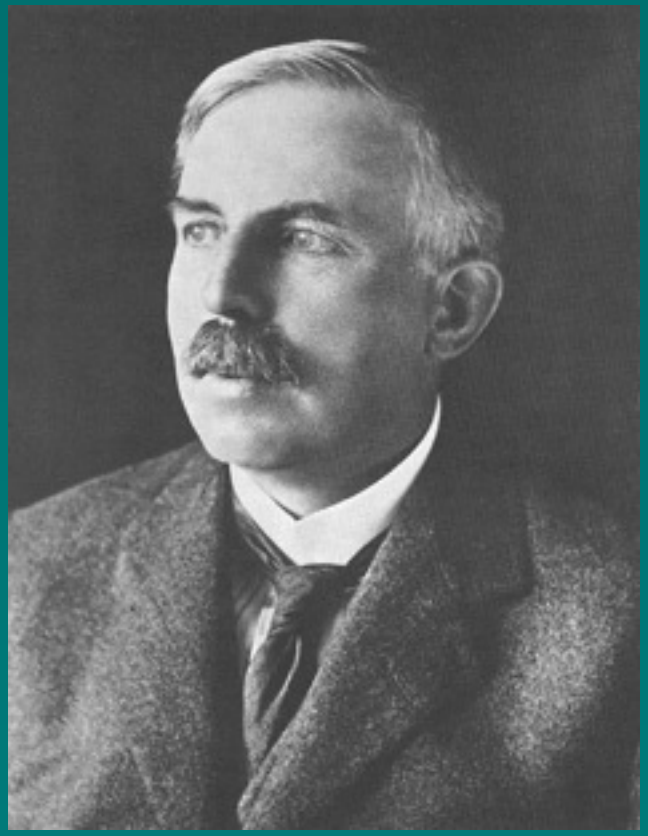

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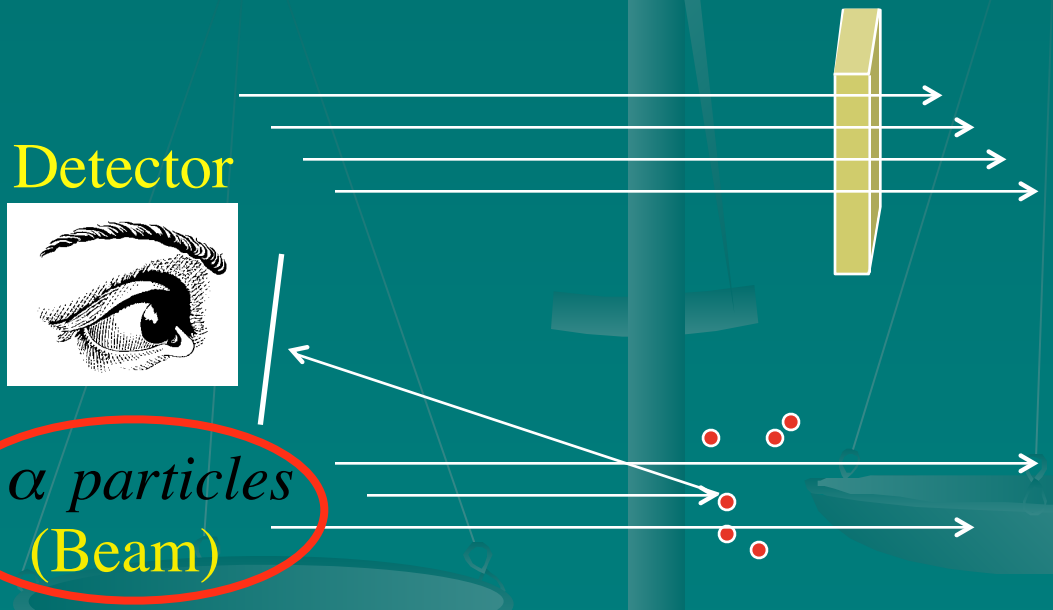

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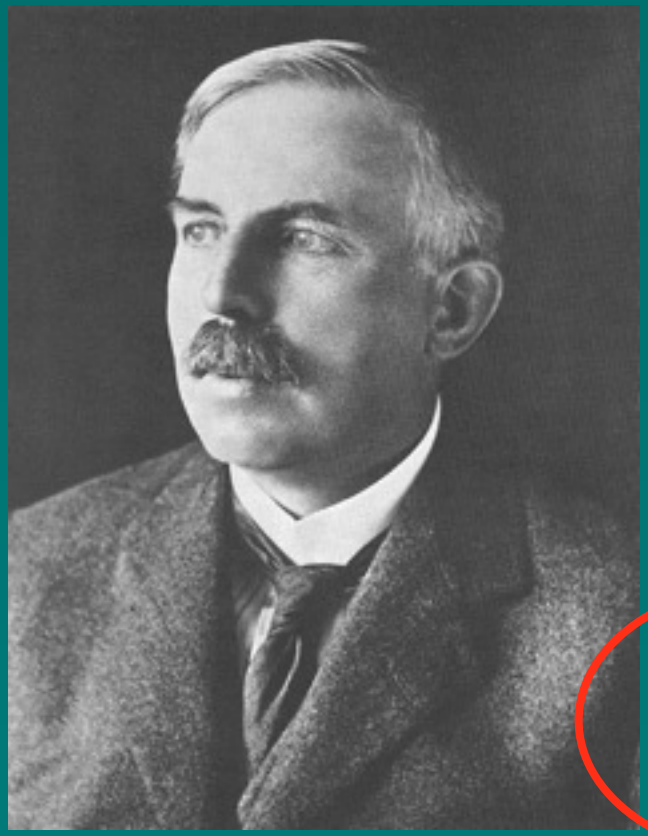

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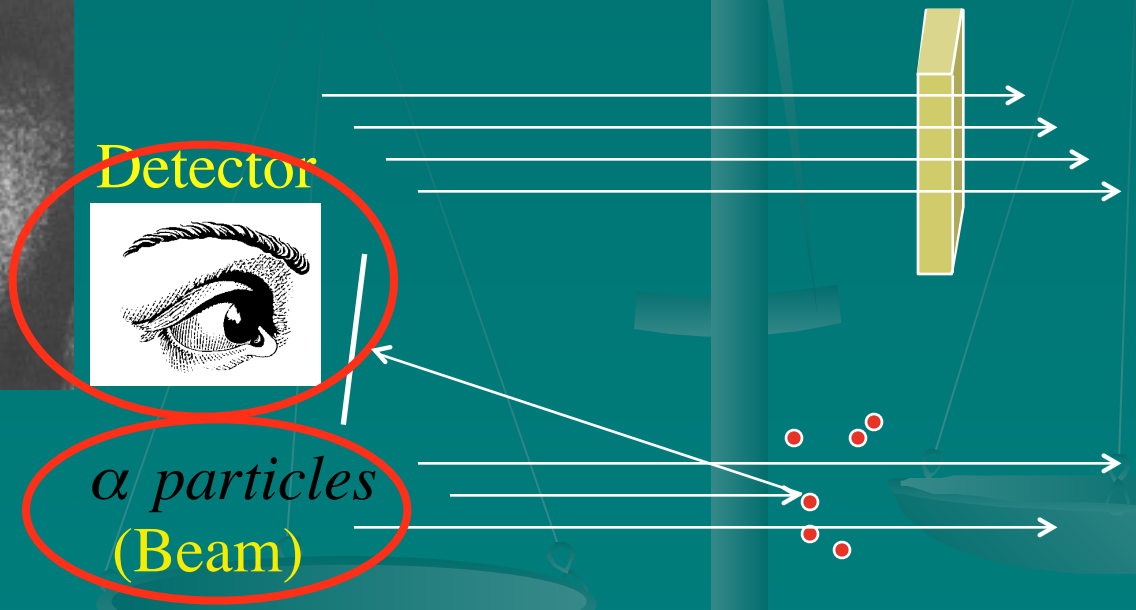
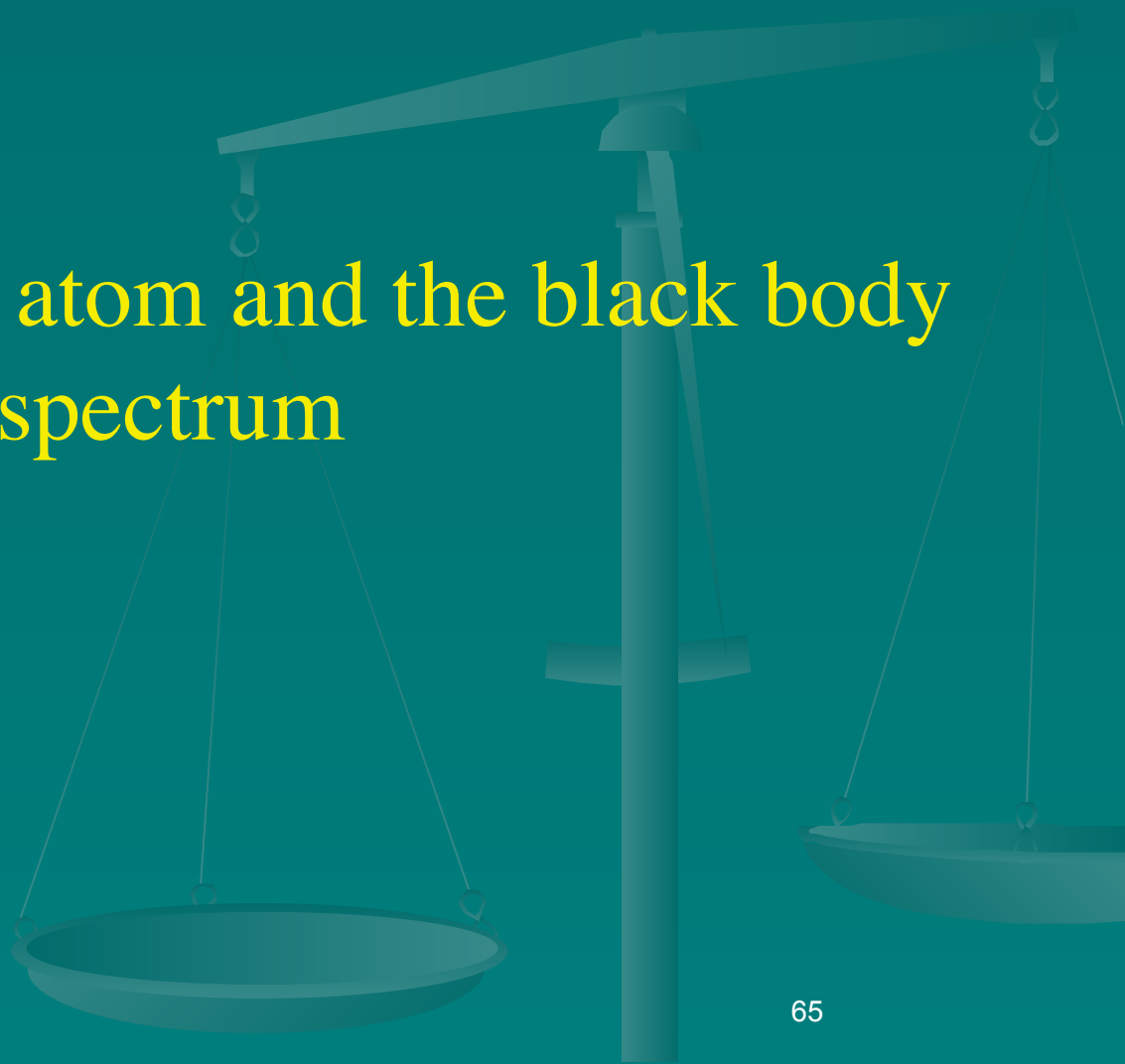


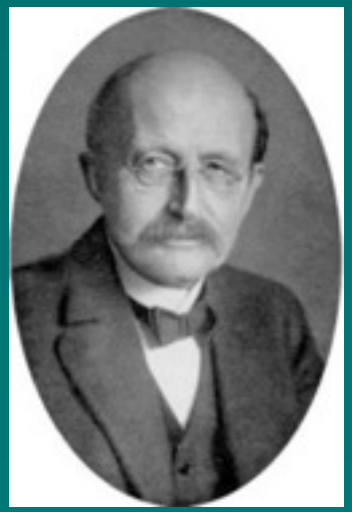
Quantum Mechanics

Problems of the atom and the black body spectrum



Quantum Mechanics

Quantum Mechanics

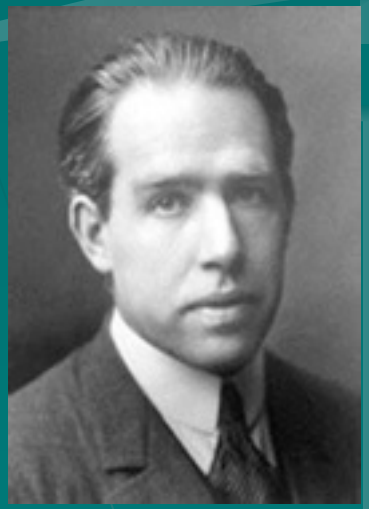


Max Planck

1858-1947

Louis de Broglie

1892 - 1987



Neils Bohr

1885-1962

Max Born

1882-1970

Quantum Mechanics

Quantum Mechanics

- Dual nature of matter AND light

Quantum Mechanics

- Dual nature of matter AND light
  - Waves

Quantum Mechanics

- Dual nature of matter AND light
  - Waves
  - Particles

Quantum Mechanics

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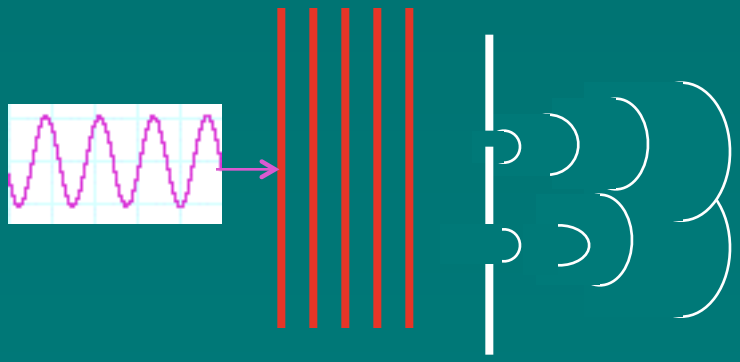
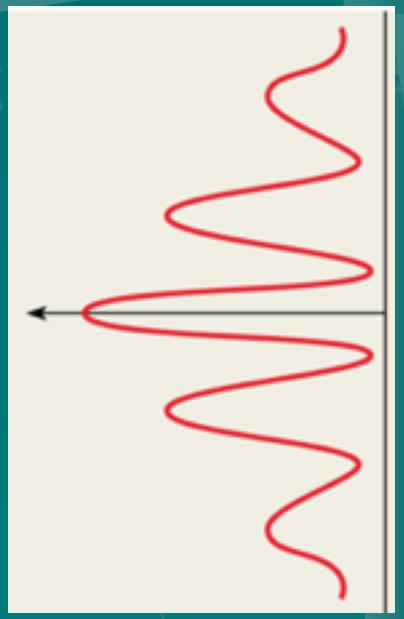
  - Waves
  - Particles





$$\lambda = \frac{h}{p}$$

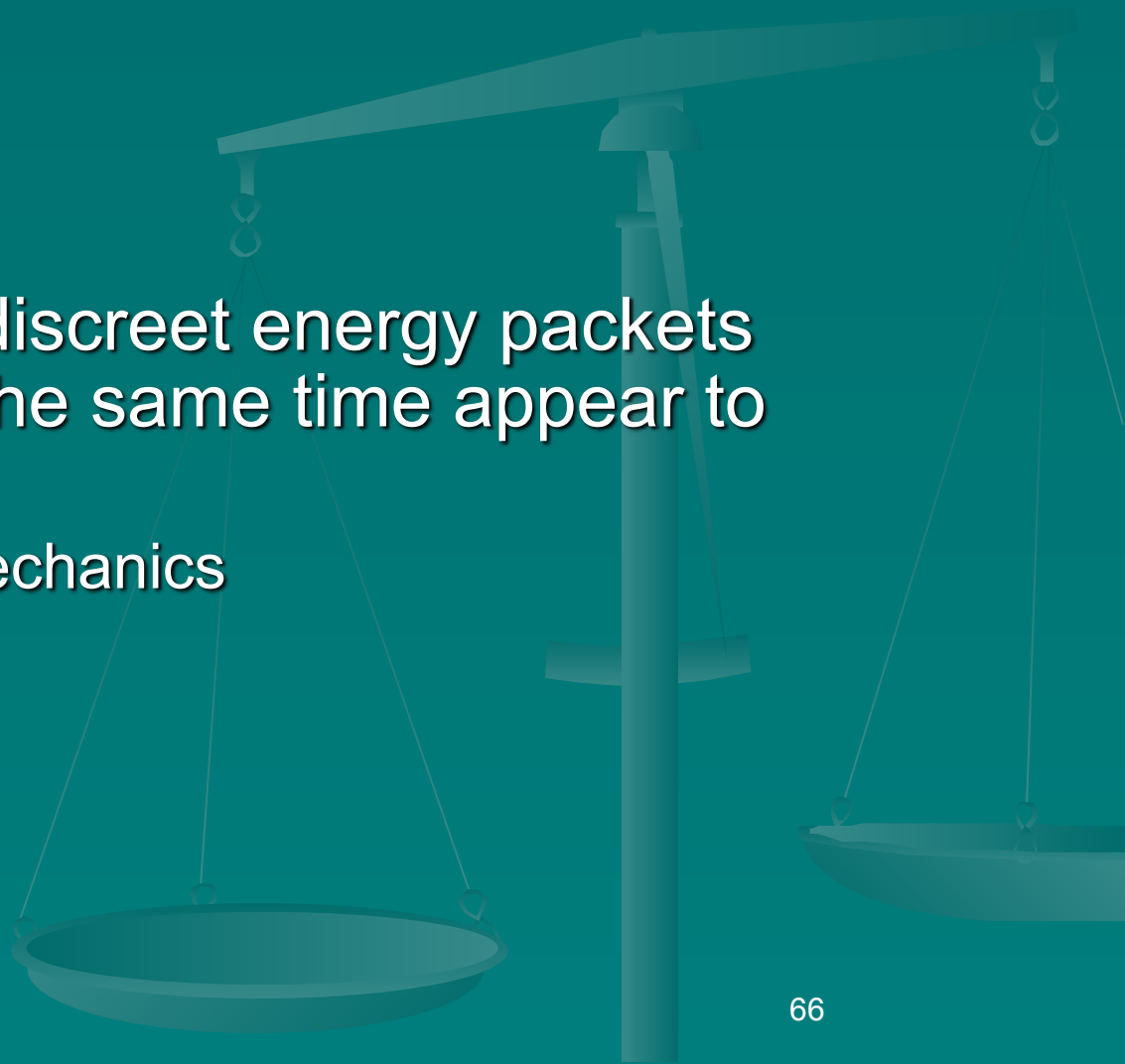
Quantum Mechanics

- Dual nature of matter AND light
  - Waves
  - Particles

Quantum Mechanics

- Dual nature of matter AND light
  - Waves
  - Particles

- But both come in discreet energy packets (particles) and at the same time appear to be waves
  - ==>> Quantum Mechanics



Quantum Mechanics

Quantum Mechanics

Black body Radiation

Max Planck

Quantum Mechanics

Black body
Radiation

Max Planck

Particle
Waves

Louis de Broglie

Quantum Mechanics

Black body
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Matrix
Mechanics

Max Born

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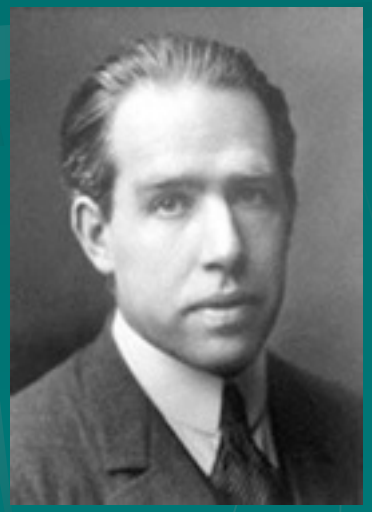


Solution to Atom

Neils Bohr

Quantum Mechanics (Con't.)

Erwin Schrodinger

1887 - 1961

Wave Equation for Particles

Werner Heisenberg

1901 - 1976

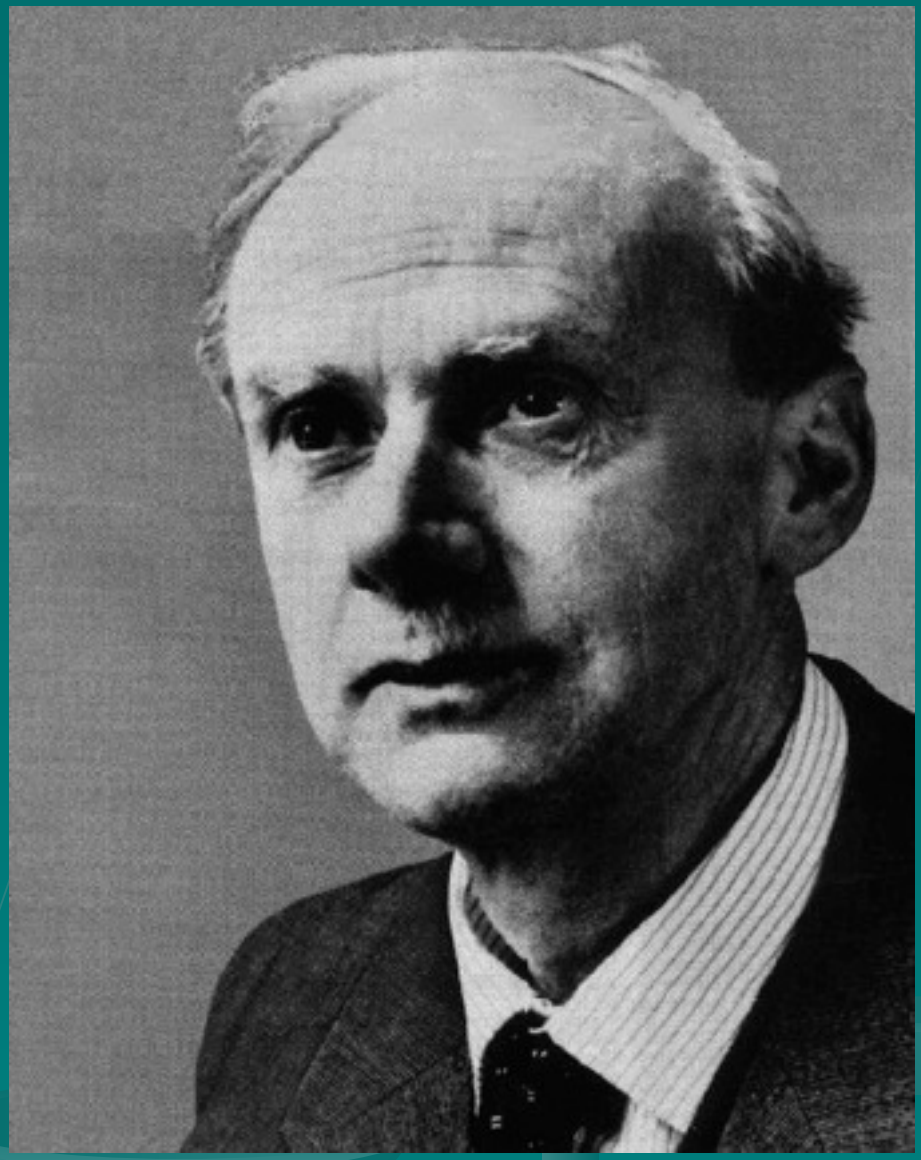
Matrix Mechanics

Wolfgang Pauli

1900 - 1958

Pauli Exclusion Principle

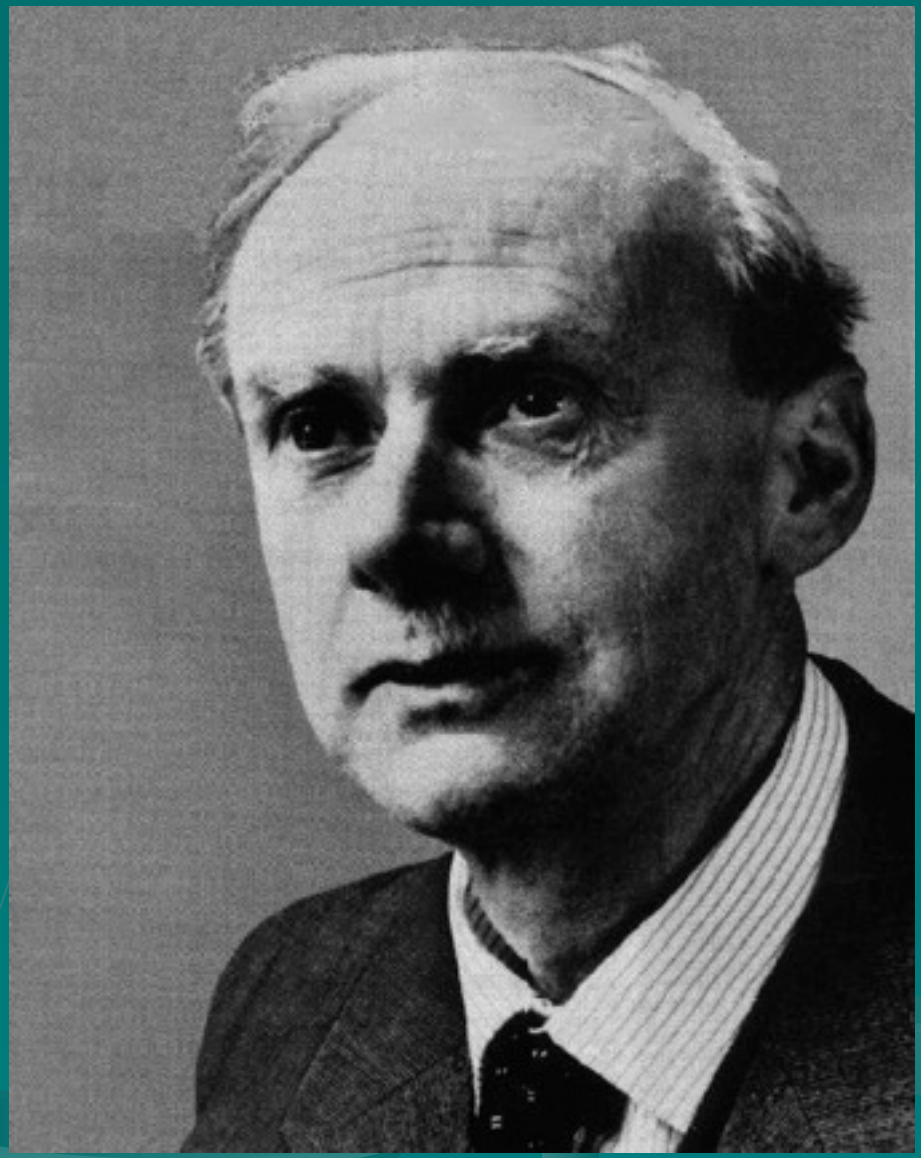
Antimatter



1902 - 1984

Antimatter

- Paul Dirac
  - Quantum Mechanics and relativity
  - ==>> Negative energy solutions to his equation predicted antimatter



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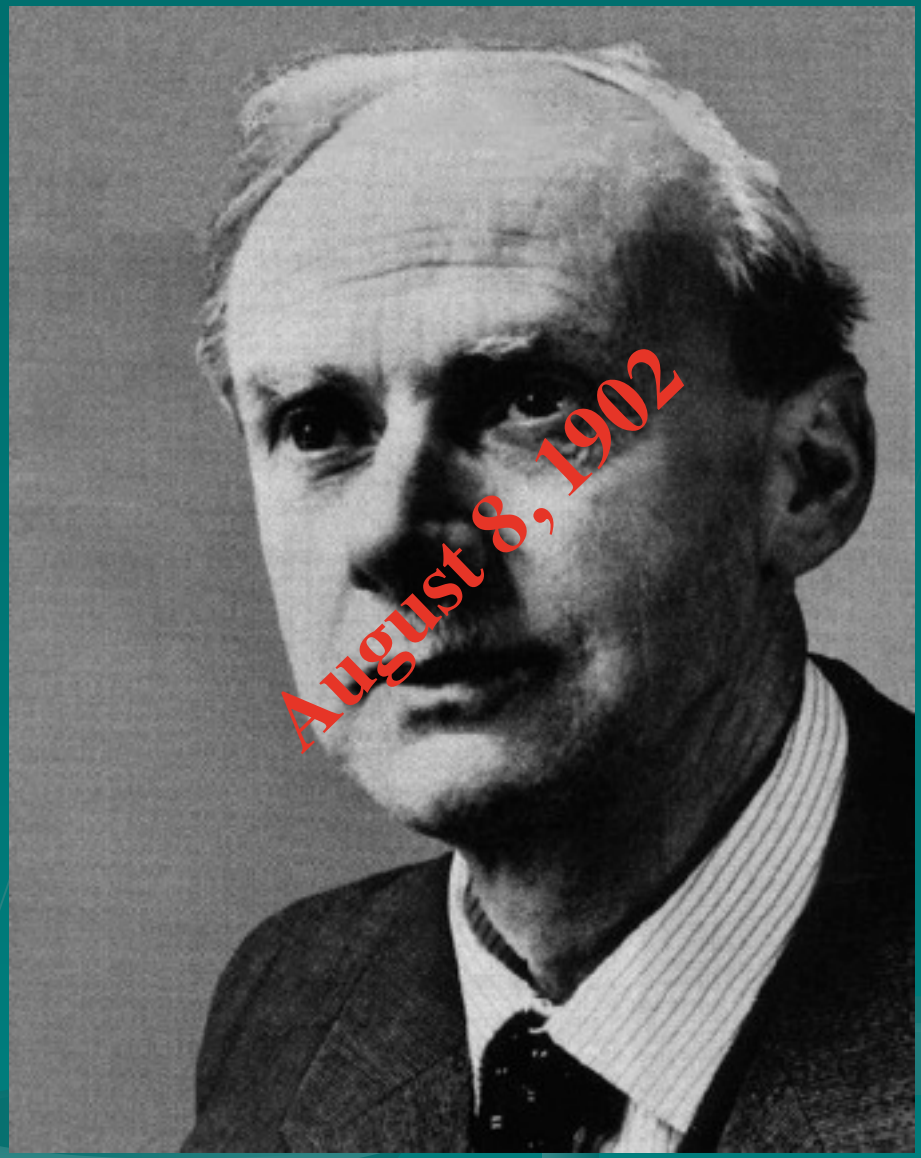
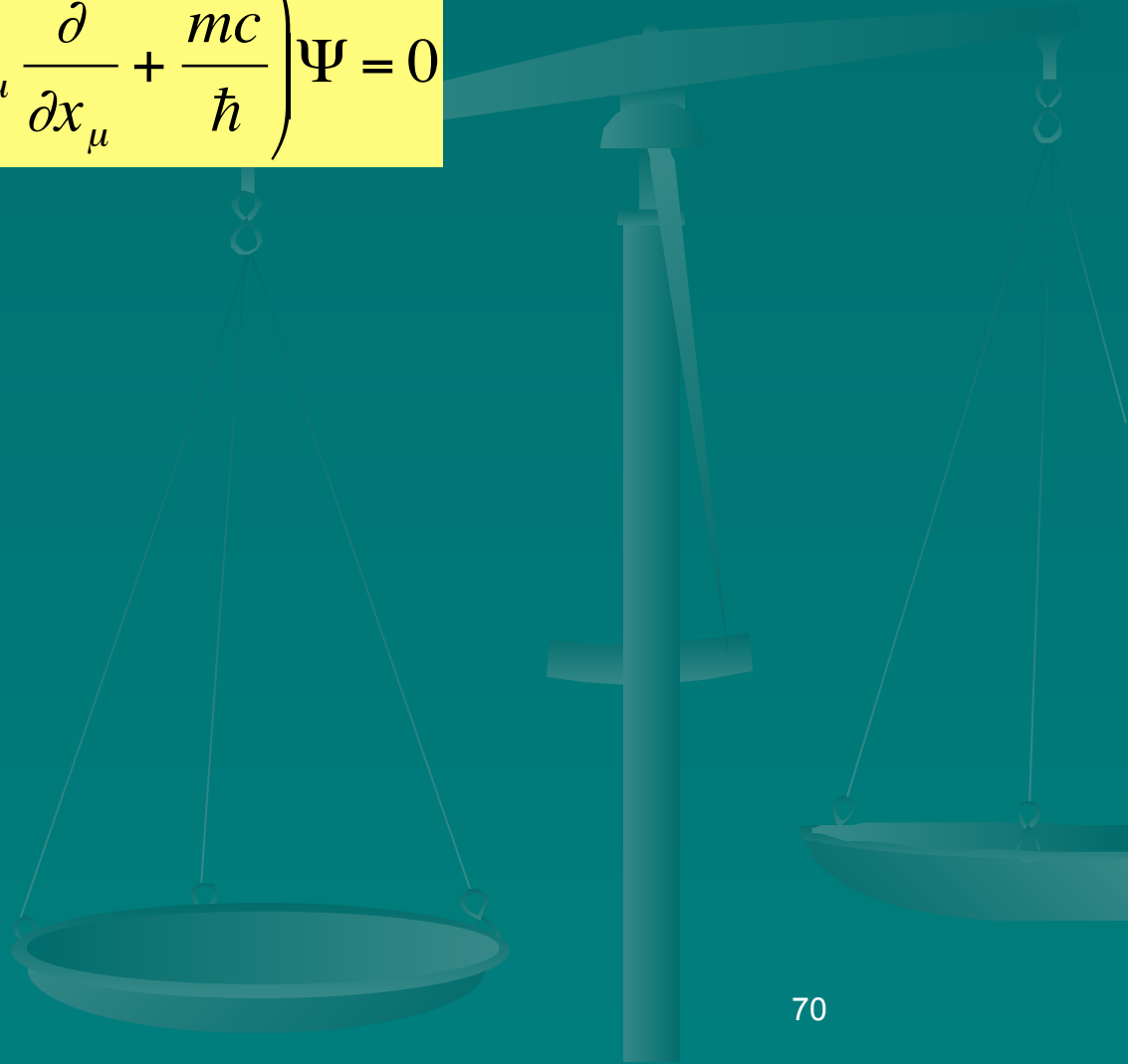


Dirac Equation

Dirac Equation

$$\left(\gamma_\mu \frac{\partial}{\partial x_\mu} + \frac{mc}{\hbar}\right)\Psi = 0$$



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- Attempting to make special relativity and quantum mechanics compatible

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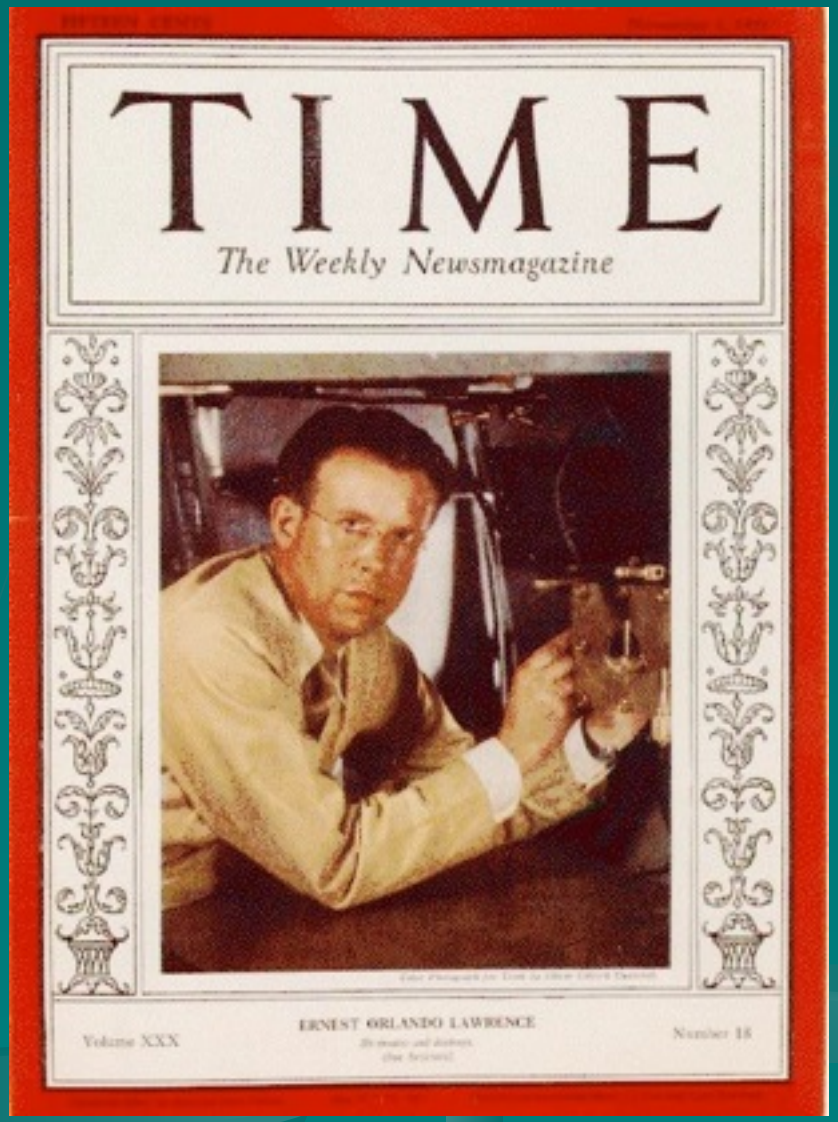
- Attempting to make special relativity and quantum mechanics compatible
- In science one tries to tell people, in such a way as to be understood by everyone, something that no one ever knew before. But in poetry, it's the exact opposite. Quoted in H Eves *Mathematical Circles Adieu* (Boston 1977).

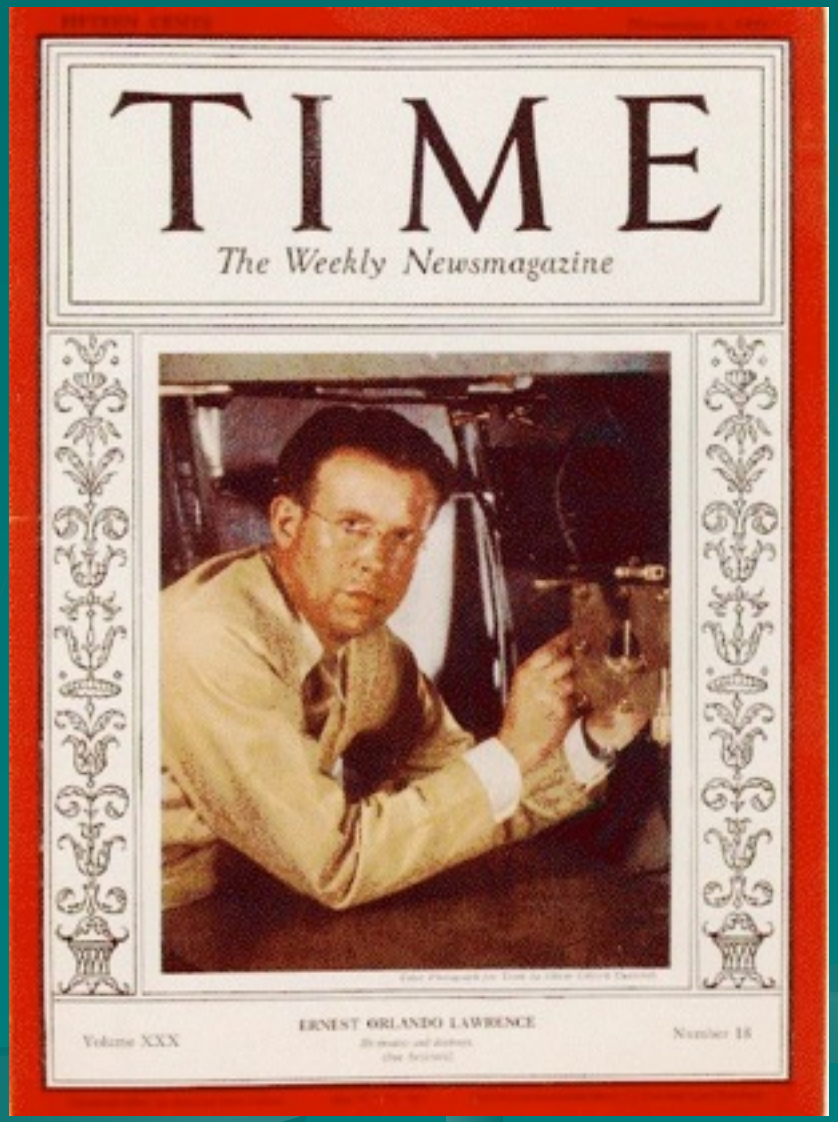
Accelerators



1901 - 1958

Accelerators

- Cockroft
  - Electrostatic generators
- Ernest Lawrence
  - Cyclotron
  - ==> Synchrotron
  - ==> Storage Rings
- Why?



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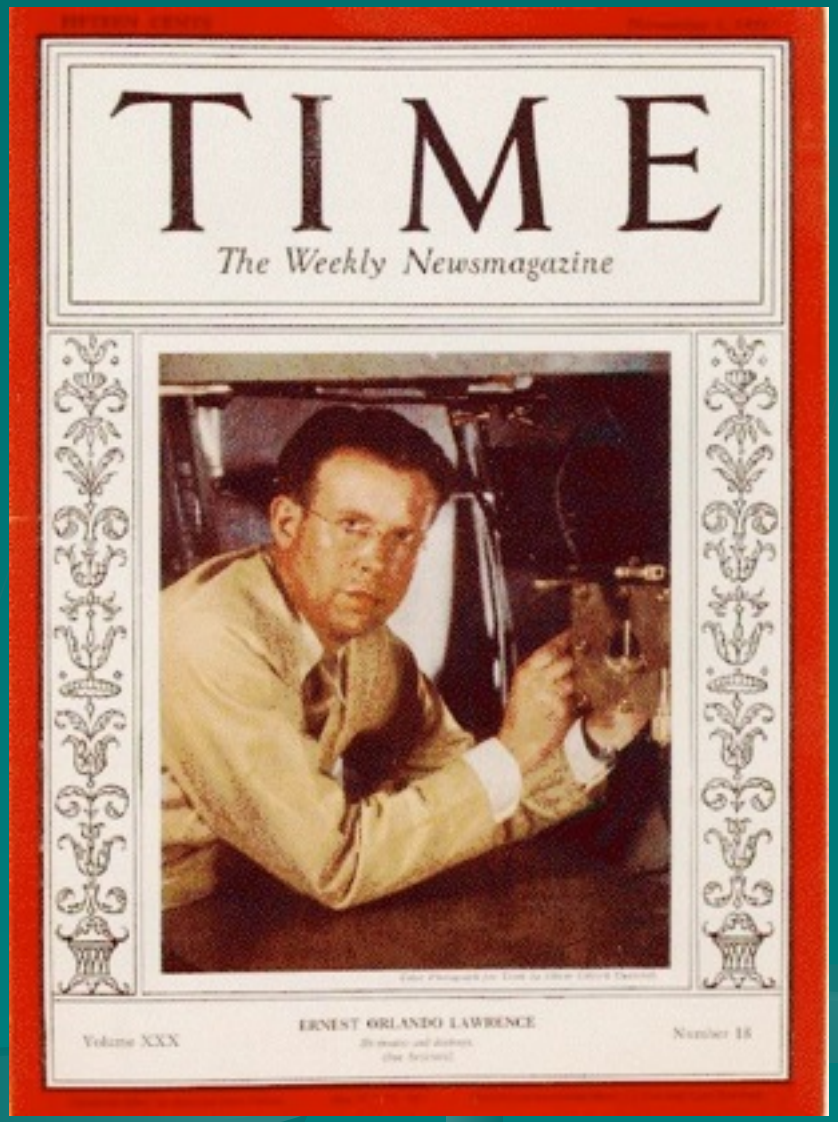

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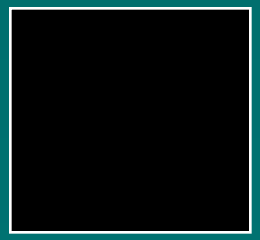

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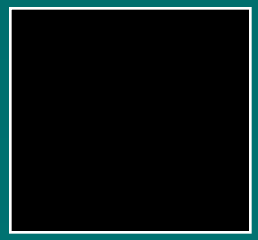

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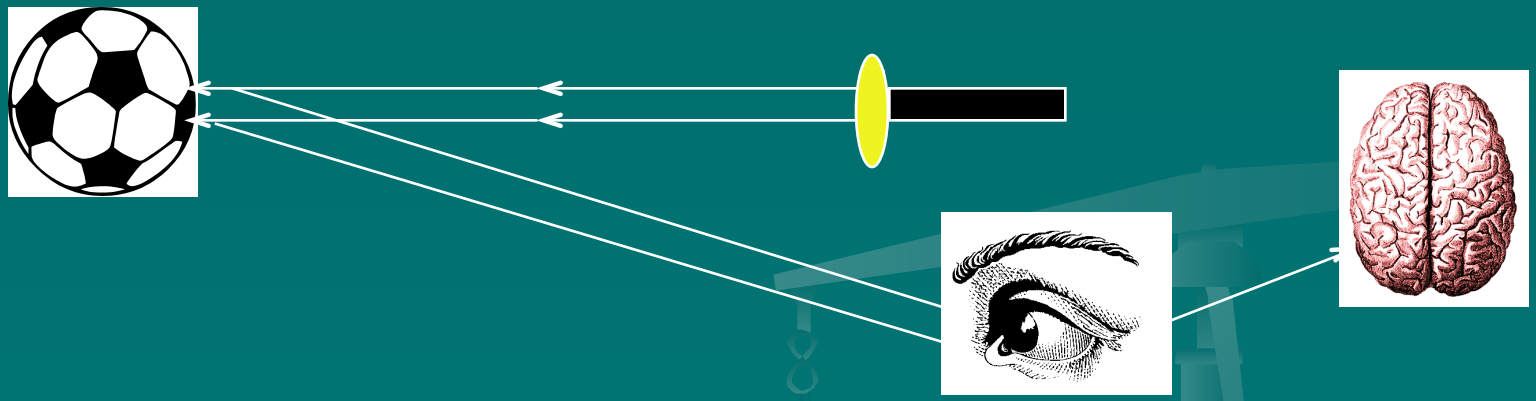

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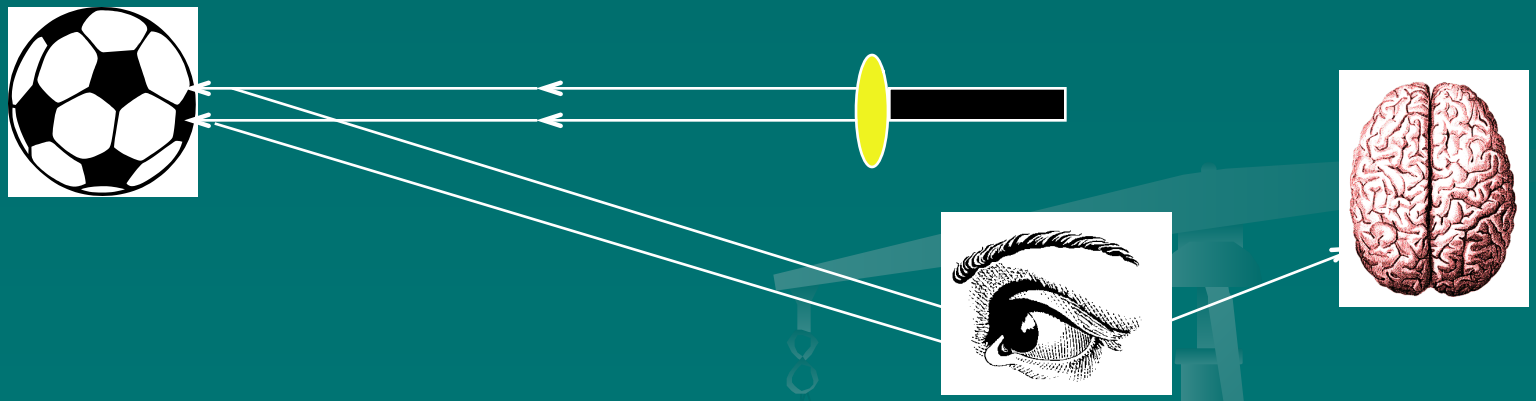
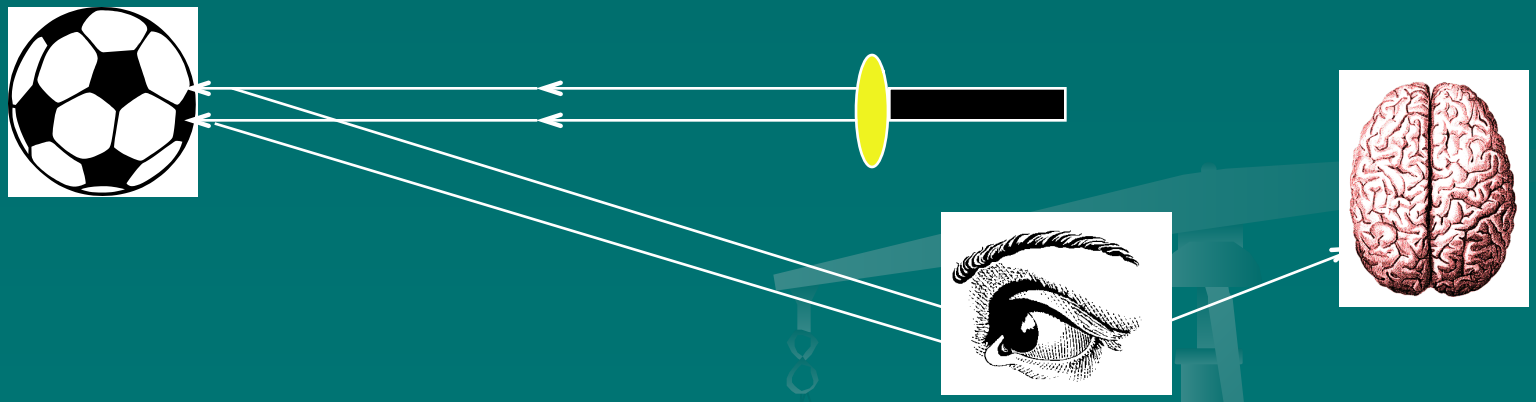


Target

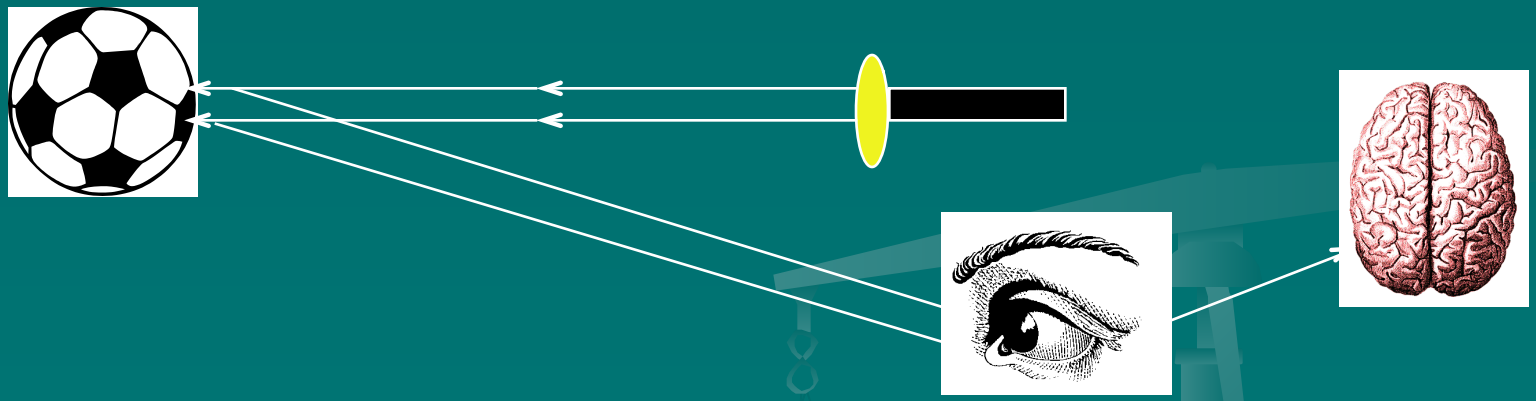
What Does an Accelerator Do?

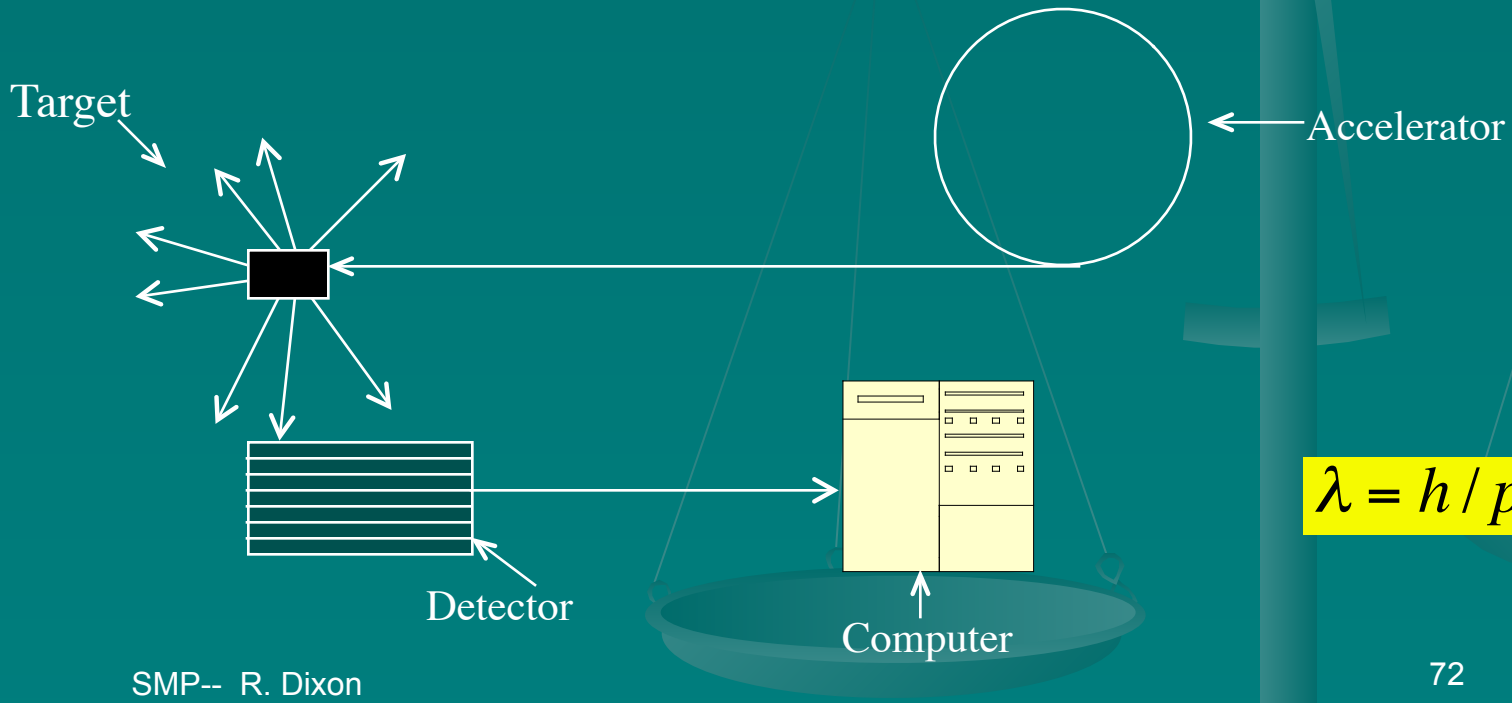


Target

Accelerator

What Does an Accelerator Do?





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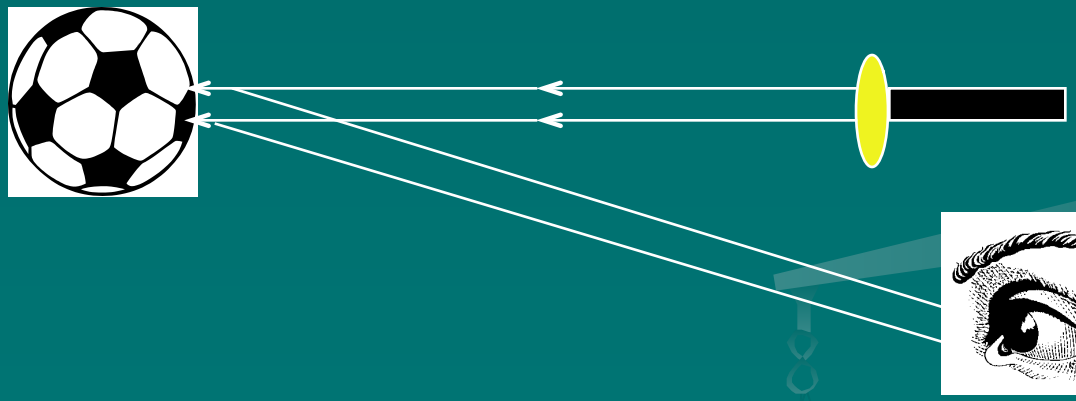

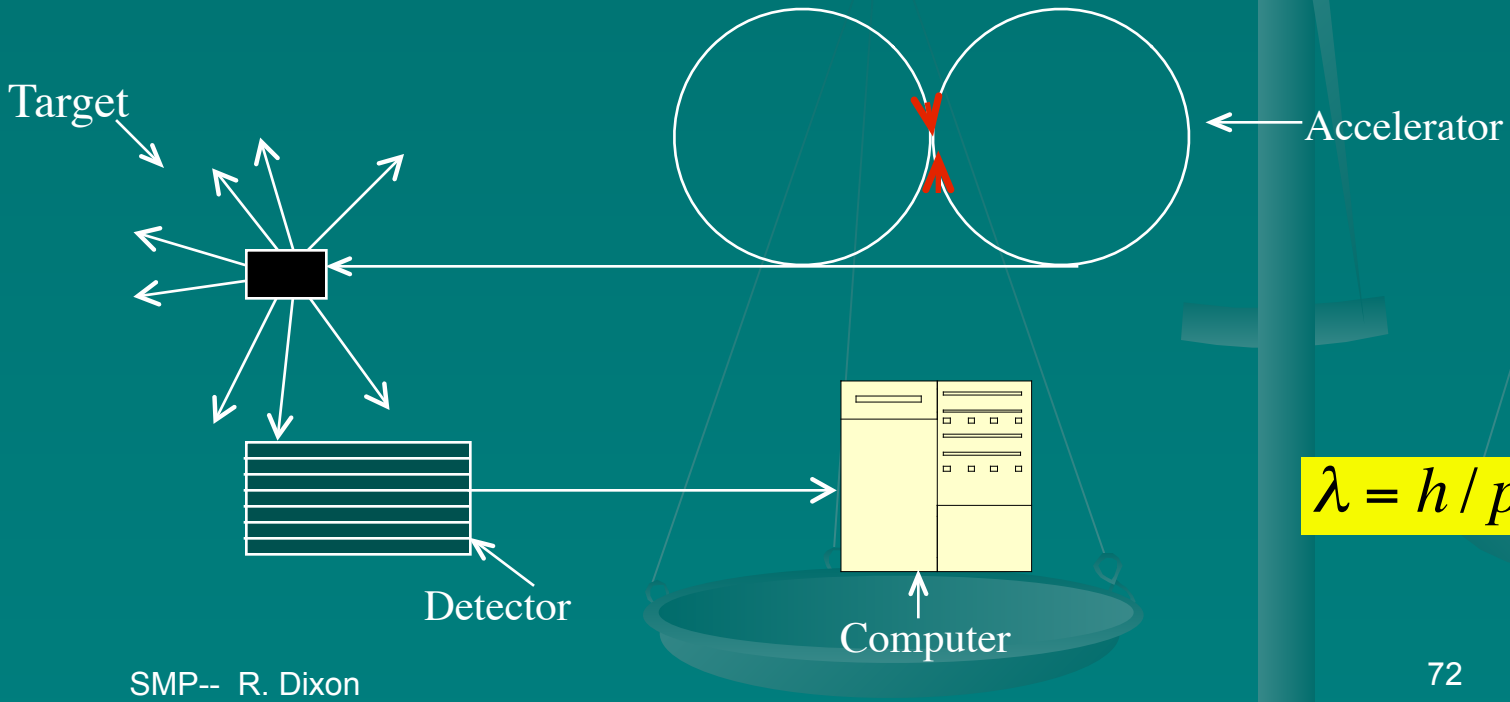

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Structure

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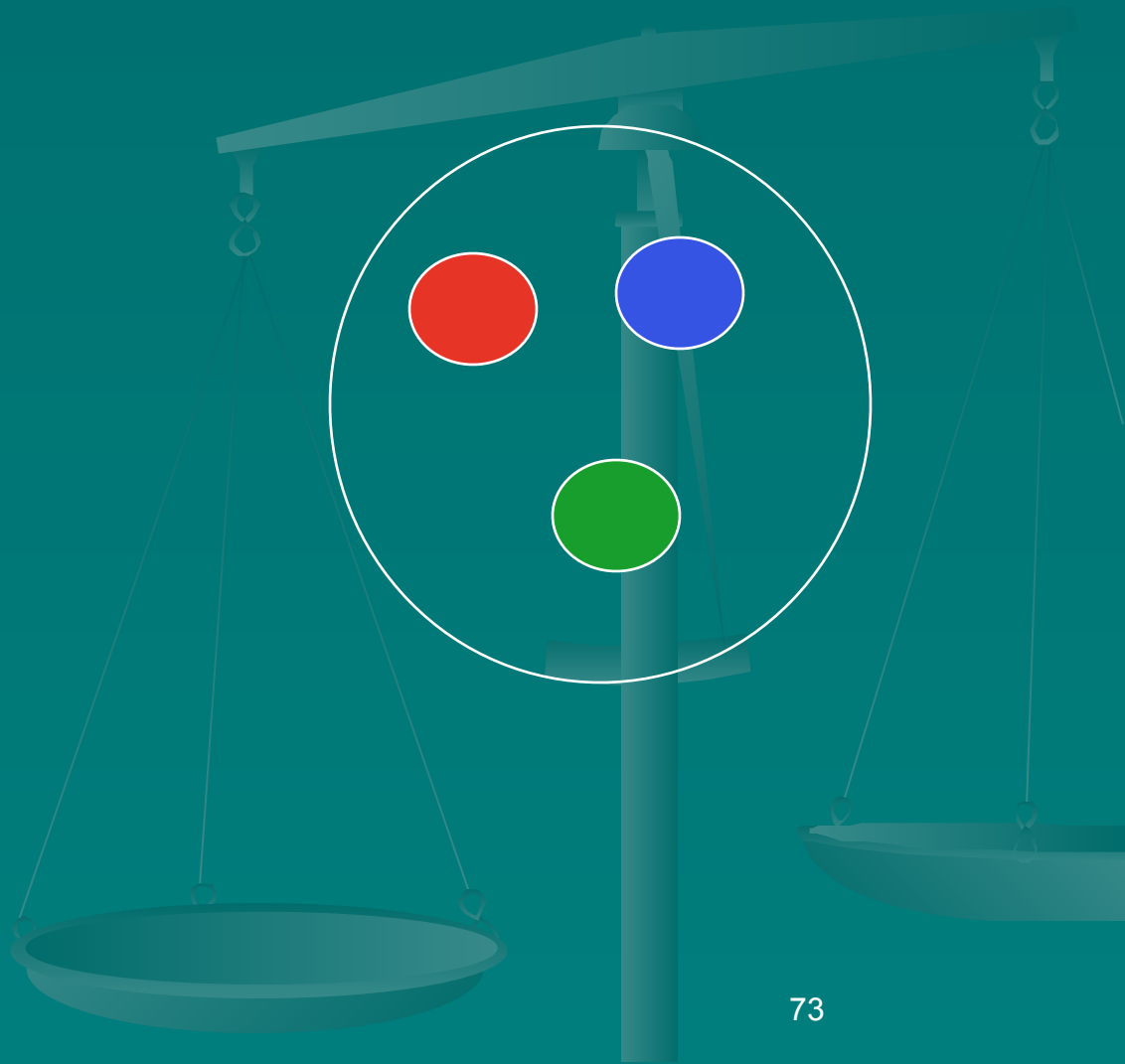

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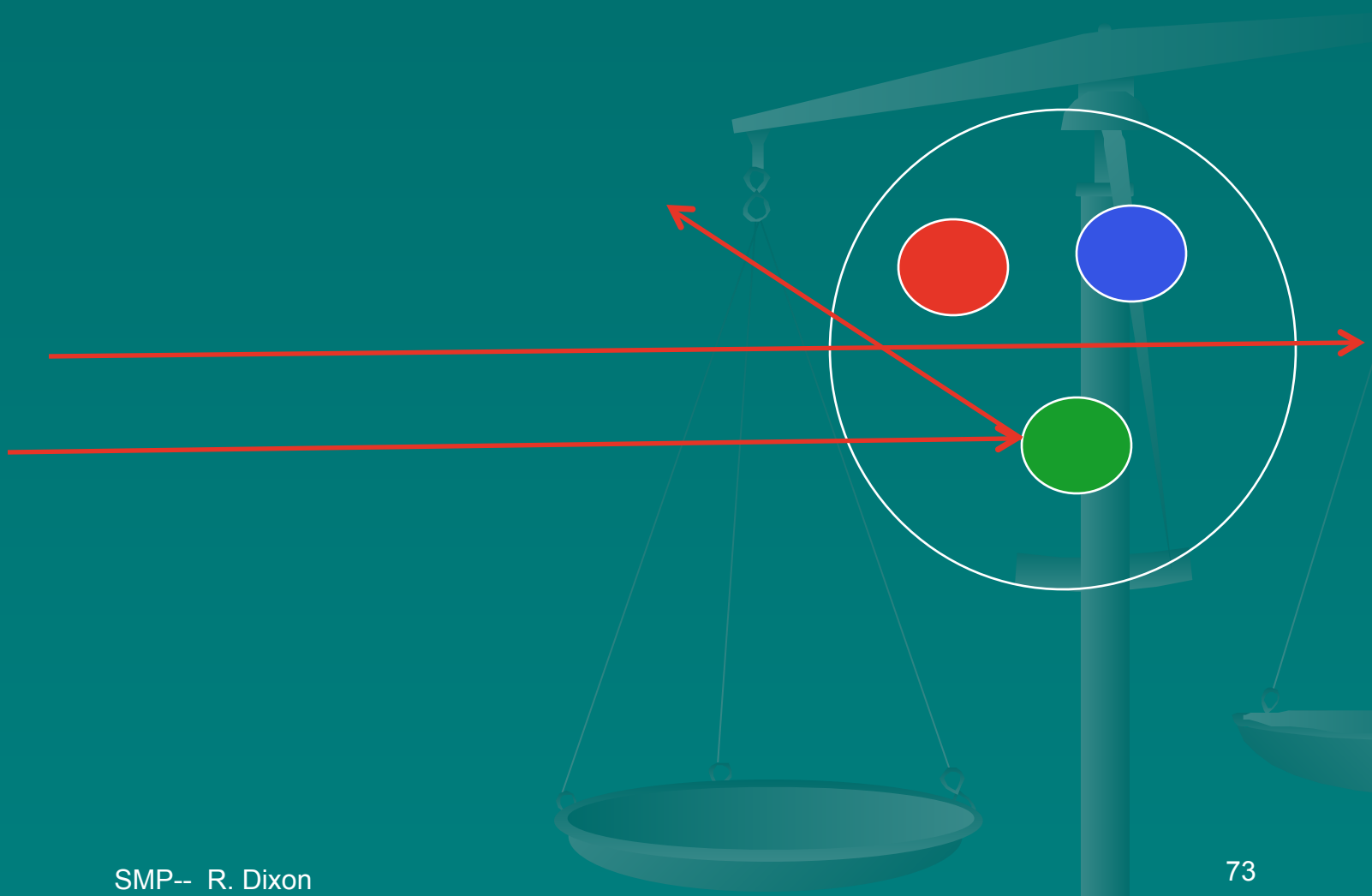

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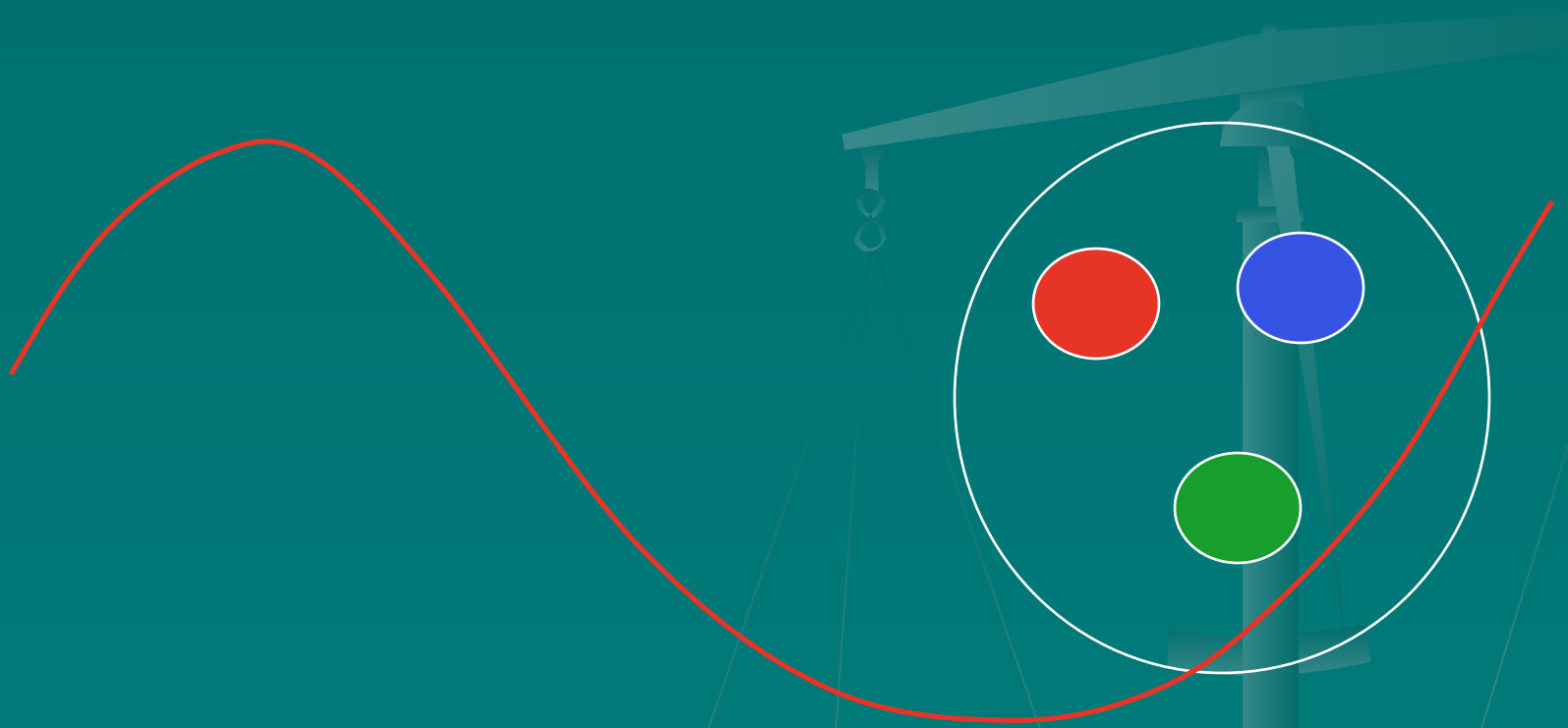

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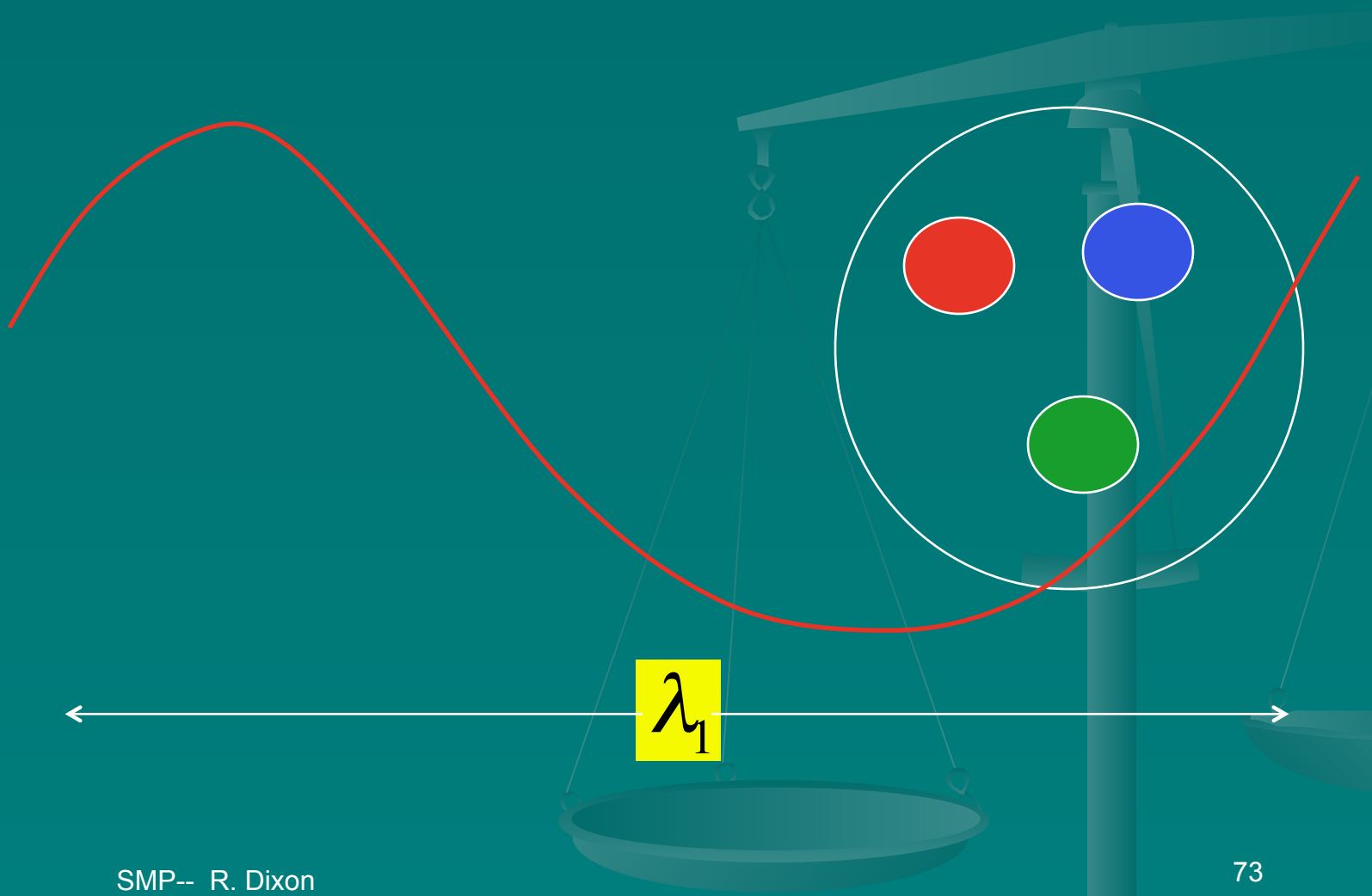

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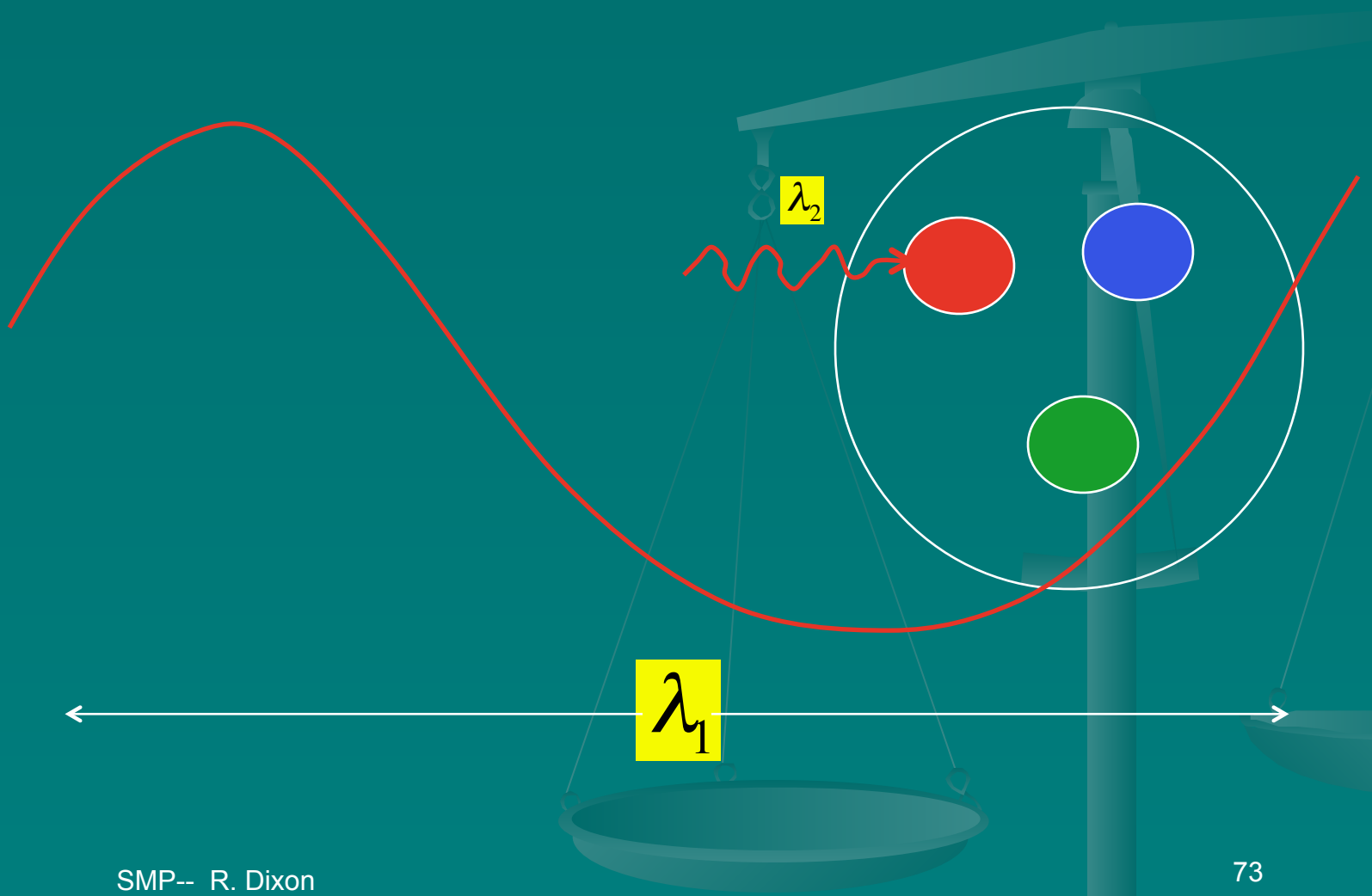

Structure

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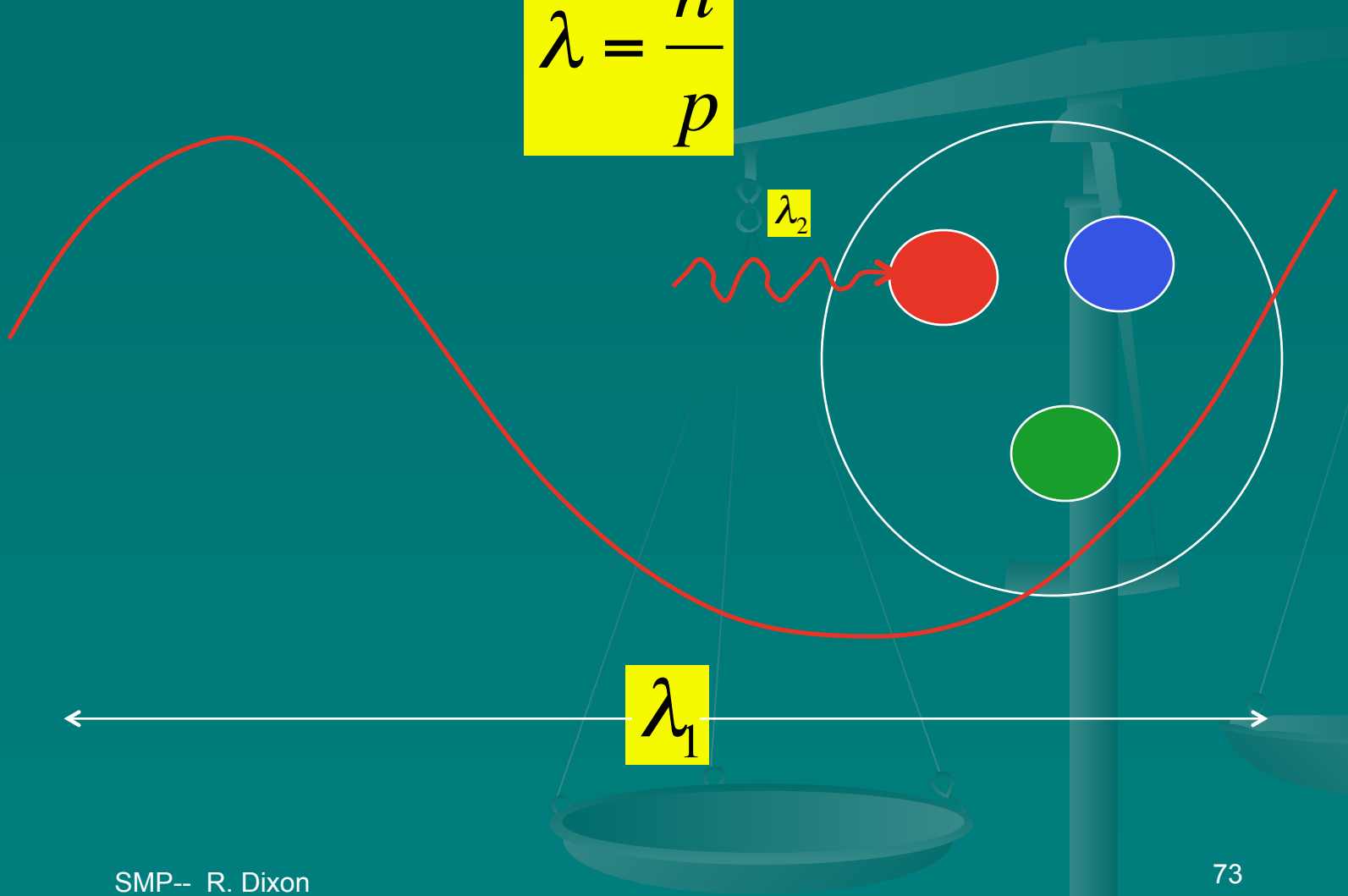

Forces

- One particle interacts with another
  - A force is exerted that changes the direction and momentum of the two interacting particles
- Macroscopic forces are built up from these fundamental forces
  - I cannot push my hand through the table because the electromagnetic force prevents the molecules from passing by one another

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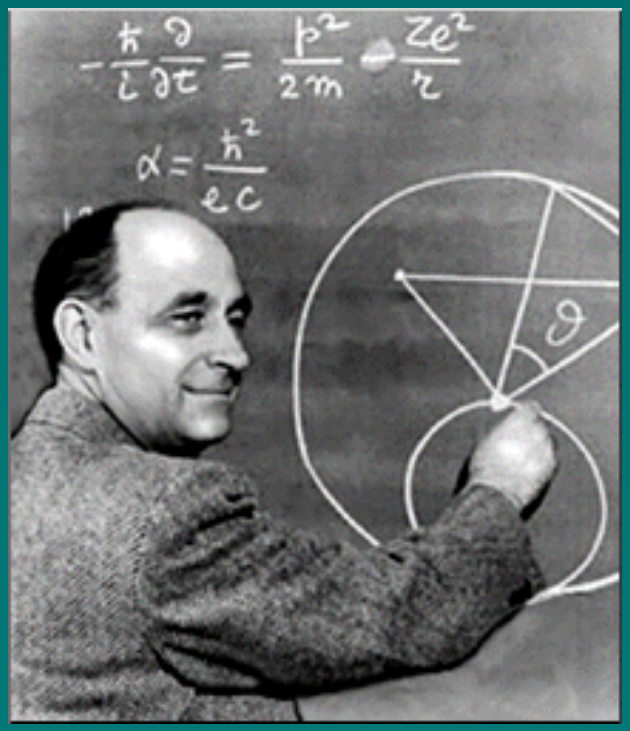
Events/time

Interactions



Enrico Fermi
1901 - 1954

Beta Decay/Weak Interactions

Richard Feynman
1918 - 1988

Quantum Electrodynamics

Forces of Nature

- Gravity
  - Keeps us off the ceiling
- Weak Force
  - Results in radioactive decays
  - Necessary for the the Sun to shine
- Electromagnetic Force
  - Keeps atoms together
  - Runs your hair dryer
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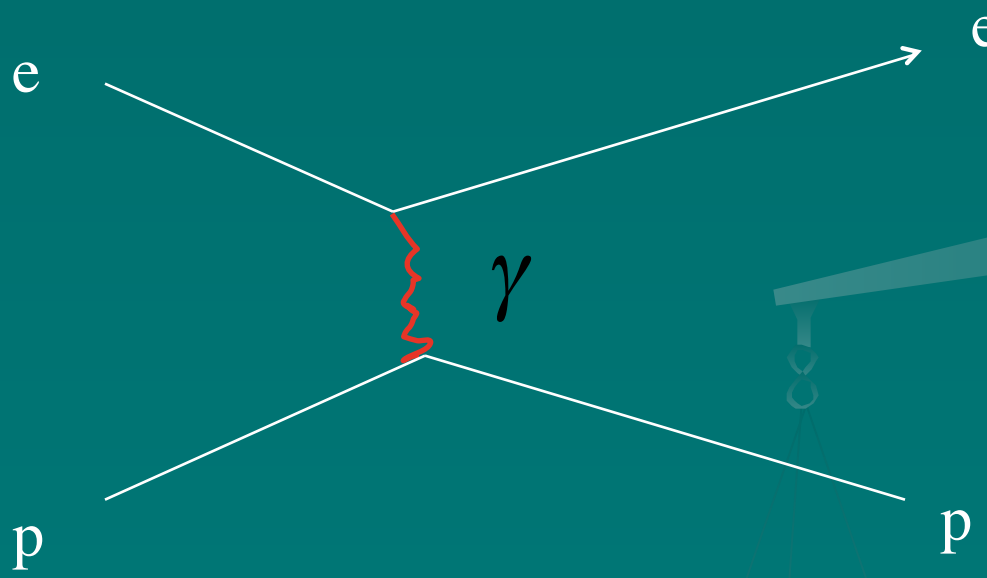
Why are these forces different?
How do they work?
Why do we think there are places where they are all the same force?
Comparing clocks?

Feynman Diagrams

Feynman Diagrams

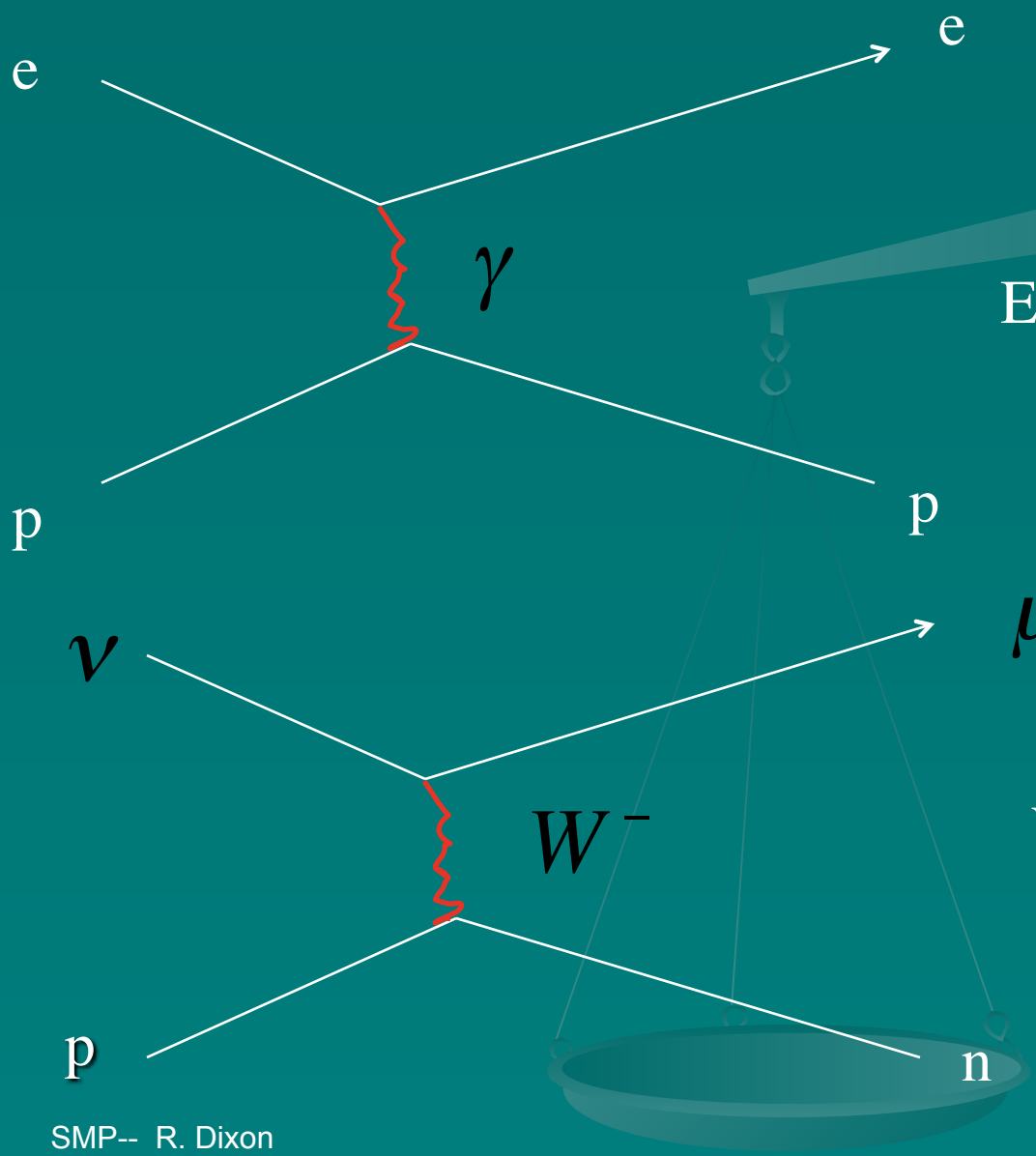
Electromagnetic

Feynman Diagrams



Electromagnetic

Feynman Diagrams



Electromagnetic

Weak

Summary

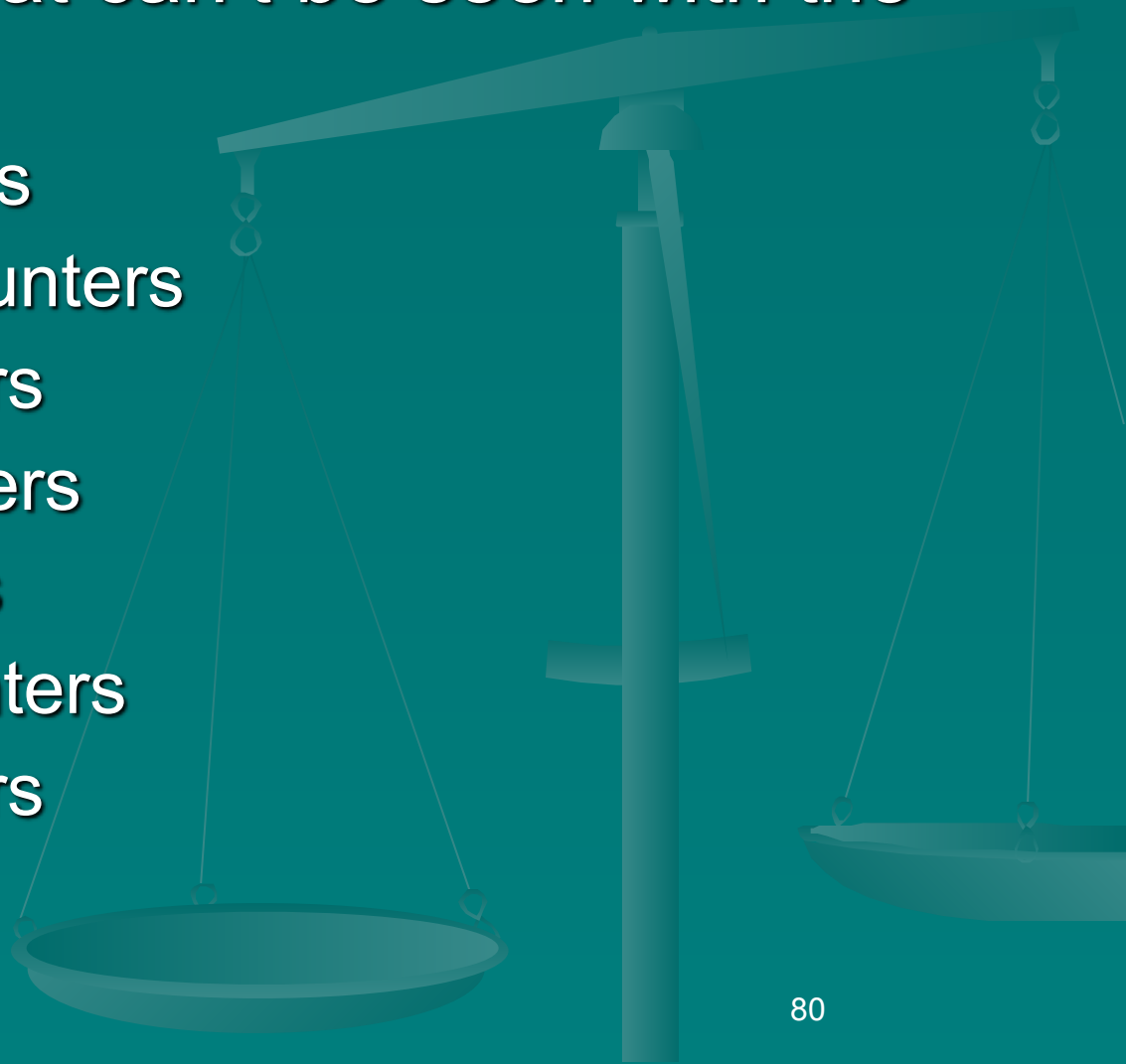
- We have now covered the philosophy and tools we use in our science. Now we are ready to do a quick review of what we have learned so far

Accelerators

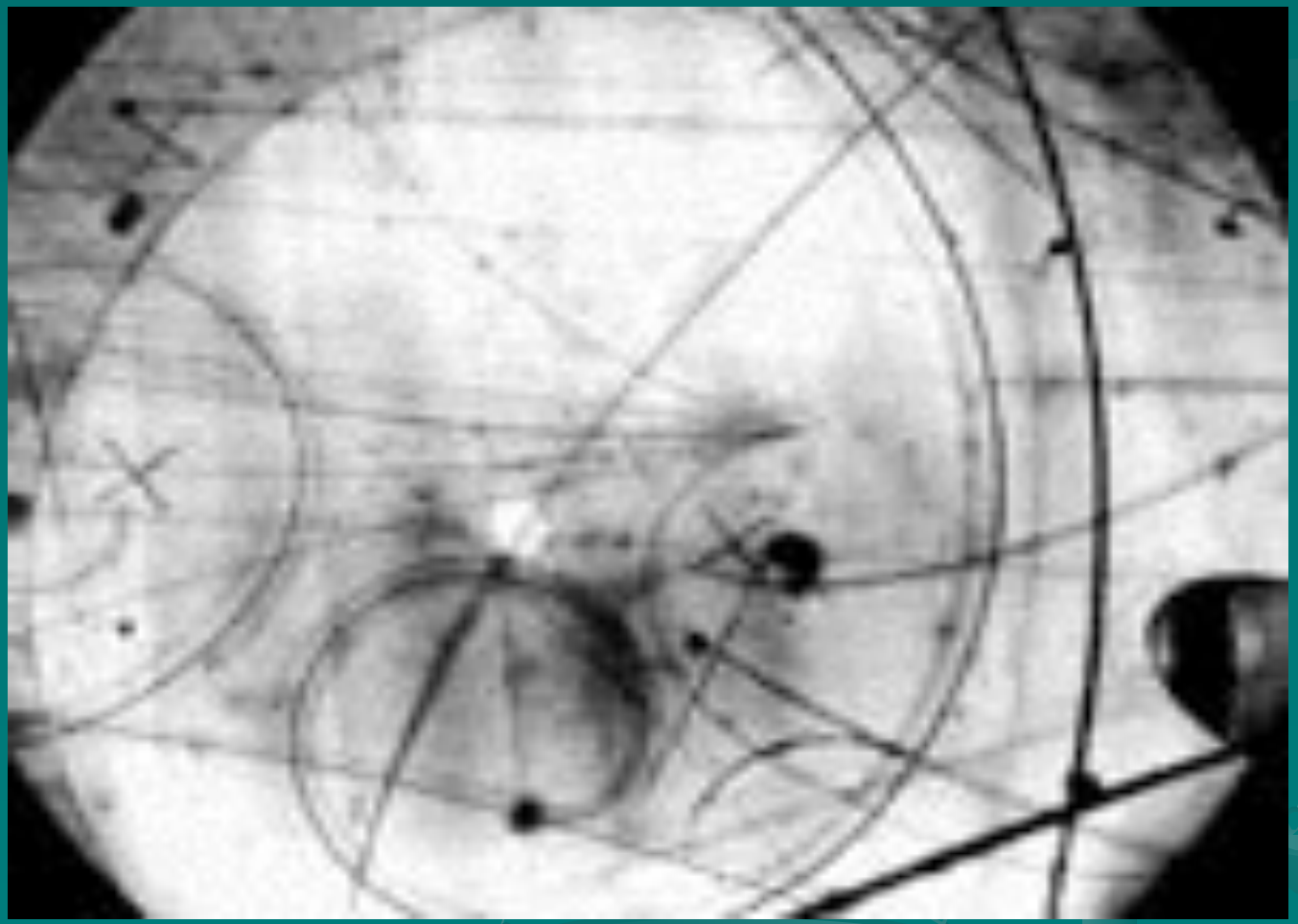
- Linear Accelerators
- Synchrotrons
- Storage Rings
- Extracted Beams
- Colliding Beams

Detectors

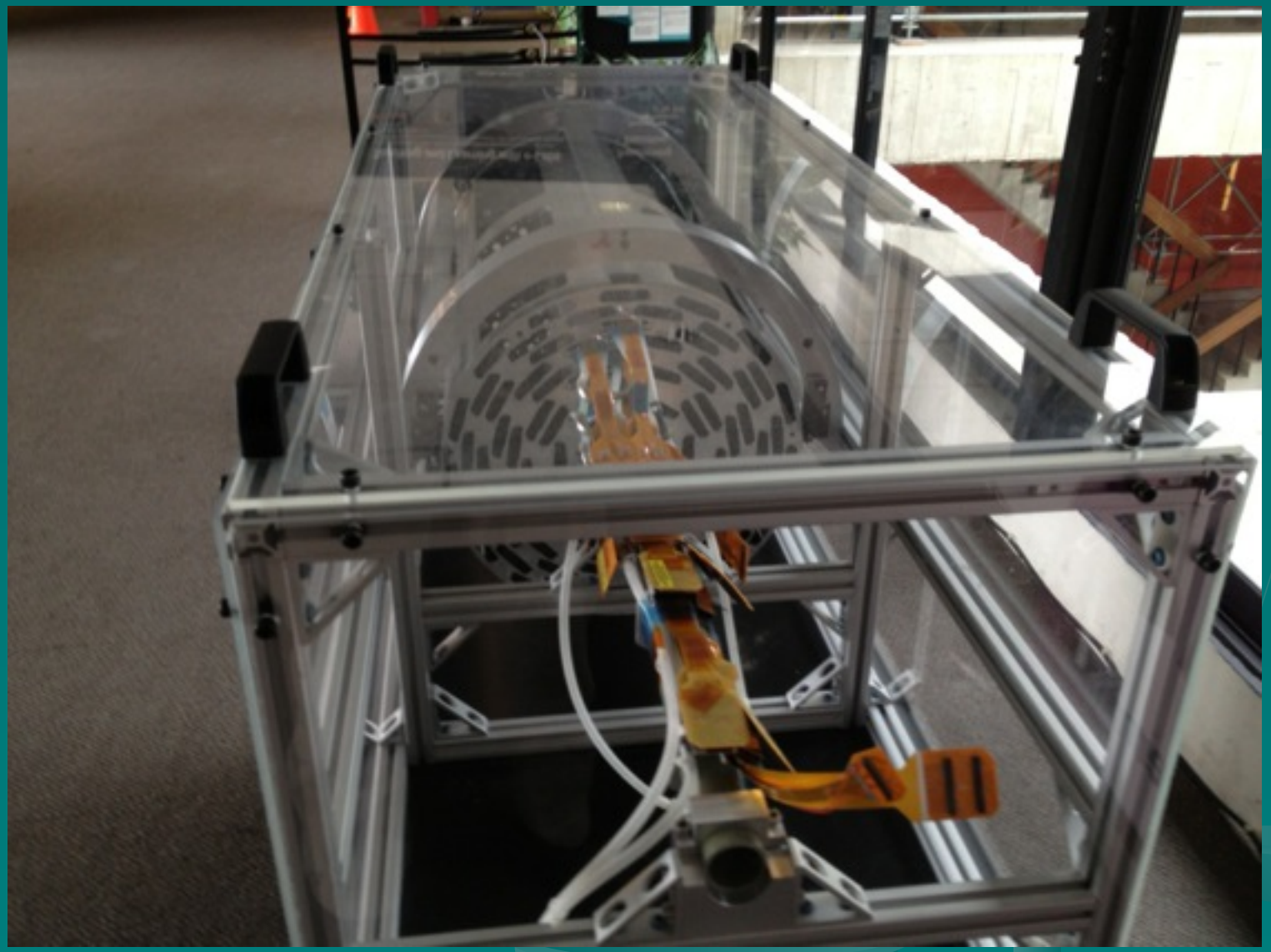
- To see things that can't be seen with the eye
  - Geiger Counters
  - Scintillation Counters
  - Cloud Chambers
  - Bubble Chambers
  - Wire Chambers
  - Cerenkov Counters
  - Silicon Detectors
  - Calorimeters



Bubble Chamber Photograph



Silicon Vertex Detector



Early Particle Discoveries (Looking for the Legos Blocks)

- Electron
  - Thompson 1897
- Proton
  - Rutherford??
- Neutron
  - Chadwick 1932
- Positron
  - Anderson 1932

Muon
Anderson & Neddermeyer 1936

Pi Meson or pion
Powell 1947
Predicted by Hideki Yukawa in 1935

Neutrino
1956 Reines & Cowan
Predicted 1930 by Pauli

Strange particles and more . . .

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Strange particles and more . . .

Birth of Fermilab

Modern Particle Discoveries

- Quarks -- Gellman/Zweig-- 1964
  - Deep inelastic scattering at SLAC
    - Bjorken -- 1970
  - Up quarks, down quarks, strange quarks
- Charm quark-- 1974 (BNL,SLAC)
- Bottom quark-- 1977 (Fermilab)
- Tau Lepton-- 1977 (SLAC)
- W and Z Bosons 1983 (CERN)
- Top Quark-- 1995 (Fermilab)
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- Higgs-- 2012 CERN (Seen also at Fermilab)

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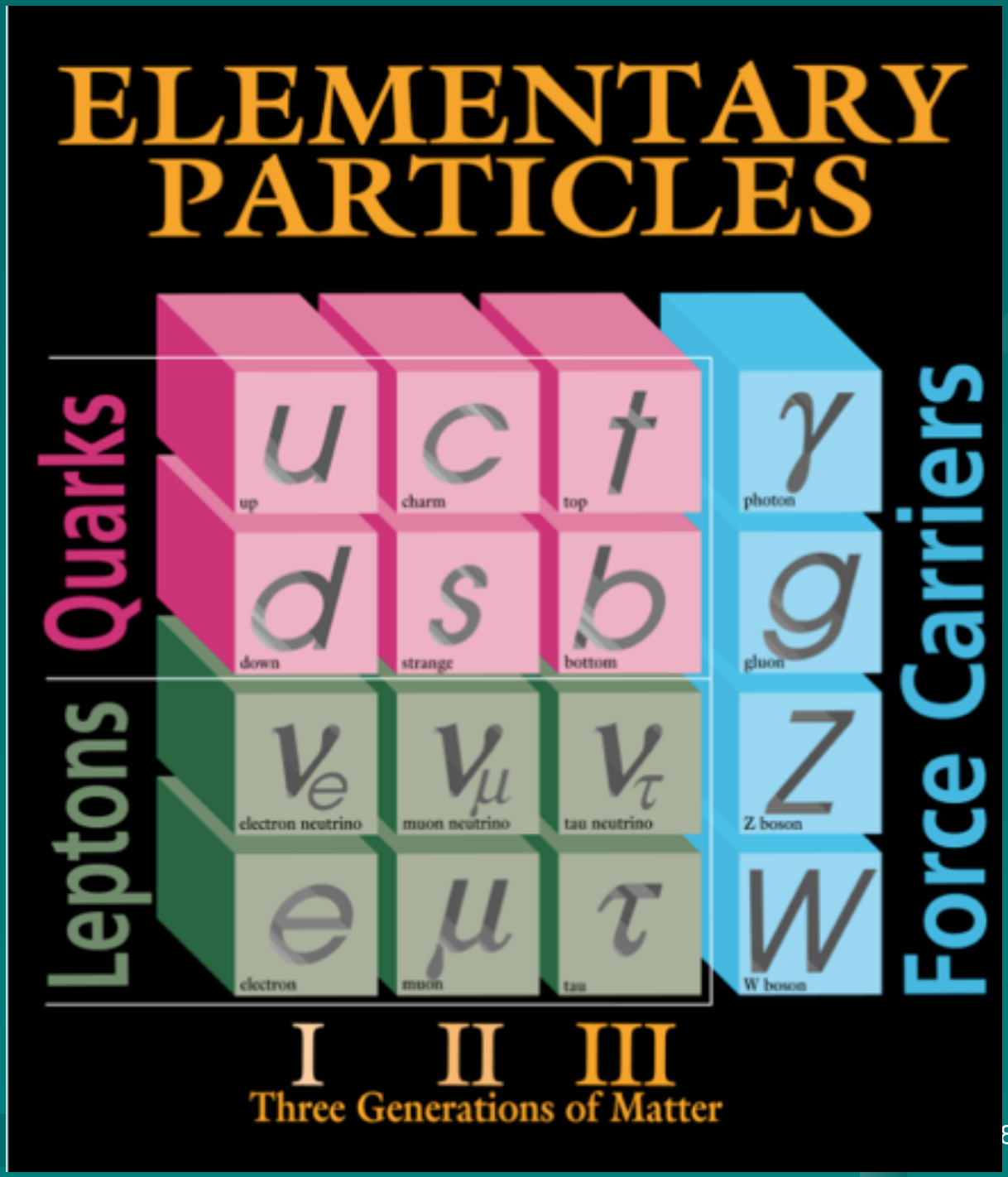
Standard Model of Particle Physics


ELEMENTARY PARTICLES
Quarks
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u
up
c
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t
top
γ
photon
d
down
s
strange
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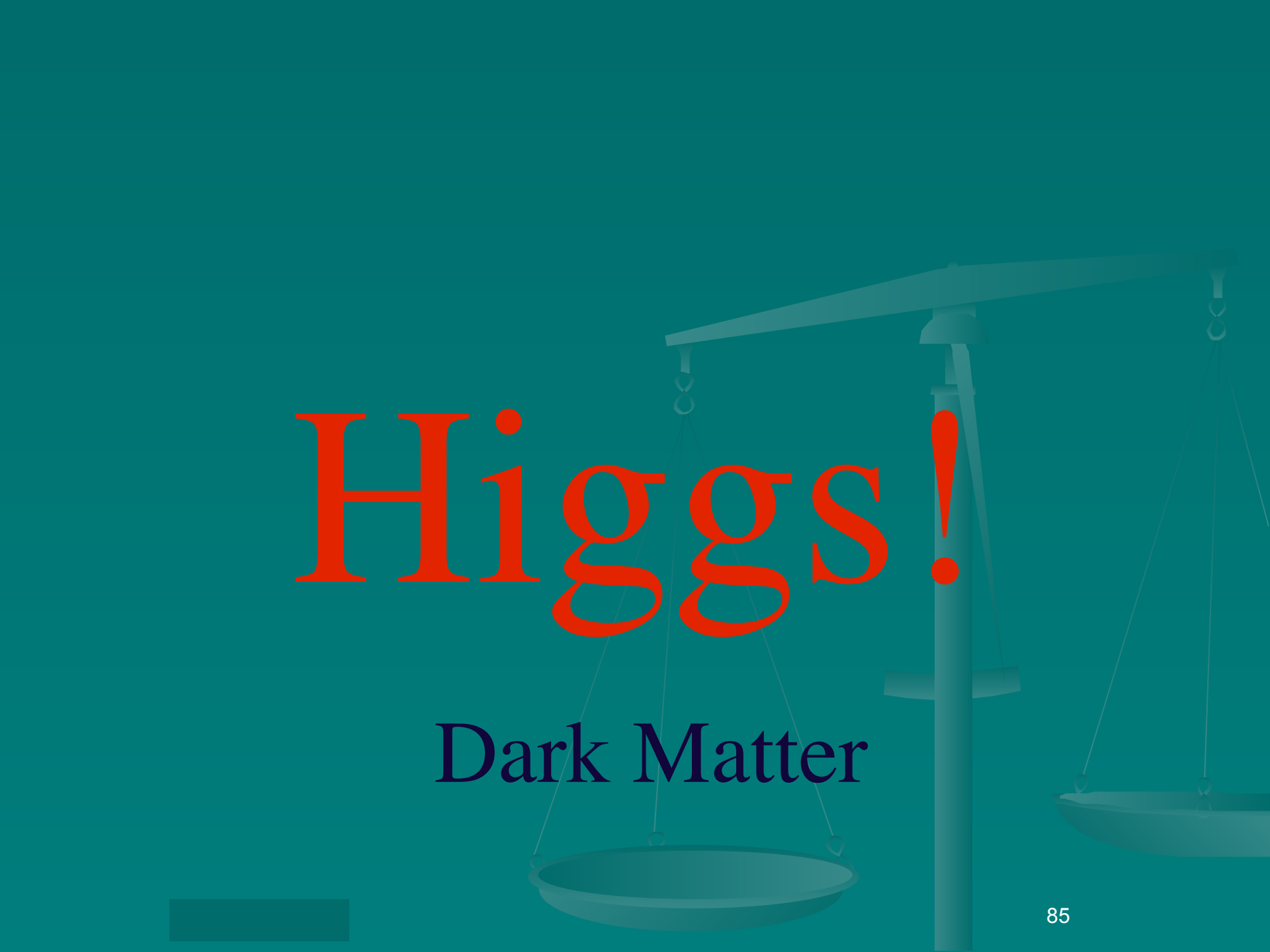
bottom
g
gluon
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson
I II III
Three Generations of Matter

Higgs!


Higgs!
Dark Matter

What's Left?

- Galaxies all moving away from us
  - The farther they are, the faster they are moving-- Hubble's Law
  - Big Bang
    - Cosmic microwave background too smooth
    - Inflation?
- How did the structure of the Universe come about?
- We don't understand the simple motions of the galaxies about one another
  - Too much mass
- The universe is accelerating apart
  - Dark energy

Beyond The Standard Model

- Theory
  - Supersymmetry
  - String Theory (TOF)
    - Similar to situation with Democritus-- no technology to do the experiments
  - Spacetime
- Experiment
  - Neutrinos have mass and they oscillate
  - Dark Matter and Dark Energy-- what are they?
  - Higgs Standard Model or not

Summary

- Introduction to science and particle physics
  - Emphasis on fundamental questions
    - What is time?
    - What is space?
    - What is a particle?
    - How does a force work?
      - How are these objects connected?
    - How do we see (detect) them?
    - How do we quantify and describe what we observe?
      - Numbers and Mathematics
    - How do we think about these things?
      - Compare patterns, look for symmetries, make conjectures
      - Test the conjectures
      - Produce good explanations
- Many questinos raised, few answered-- that's my job