# 01. Pre-20th Century Physics

*Topics*:
1. Aristotelian Physics
2. Newton's Theory of Motion
3. Maxwell's Electrodynamics

## 1. Aristotelian Physics *4th century B.C. - 17th century*

*Aristotle's Theory of Motion*

I. *No motion without a mover in contact with moving body.*

II. Distinction between:

(a) *Natural motion*: mover is *internal* to moving body

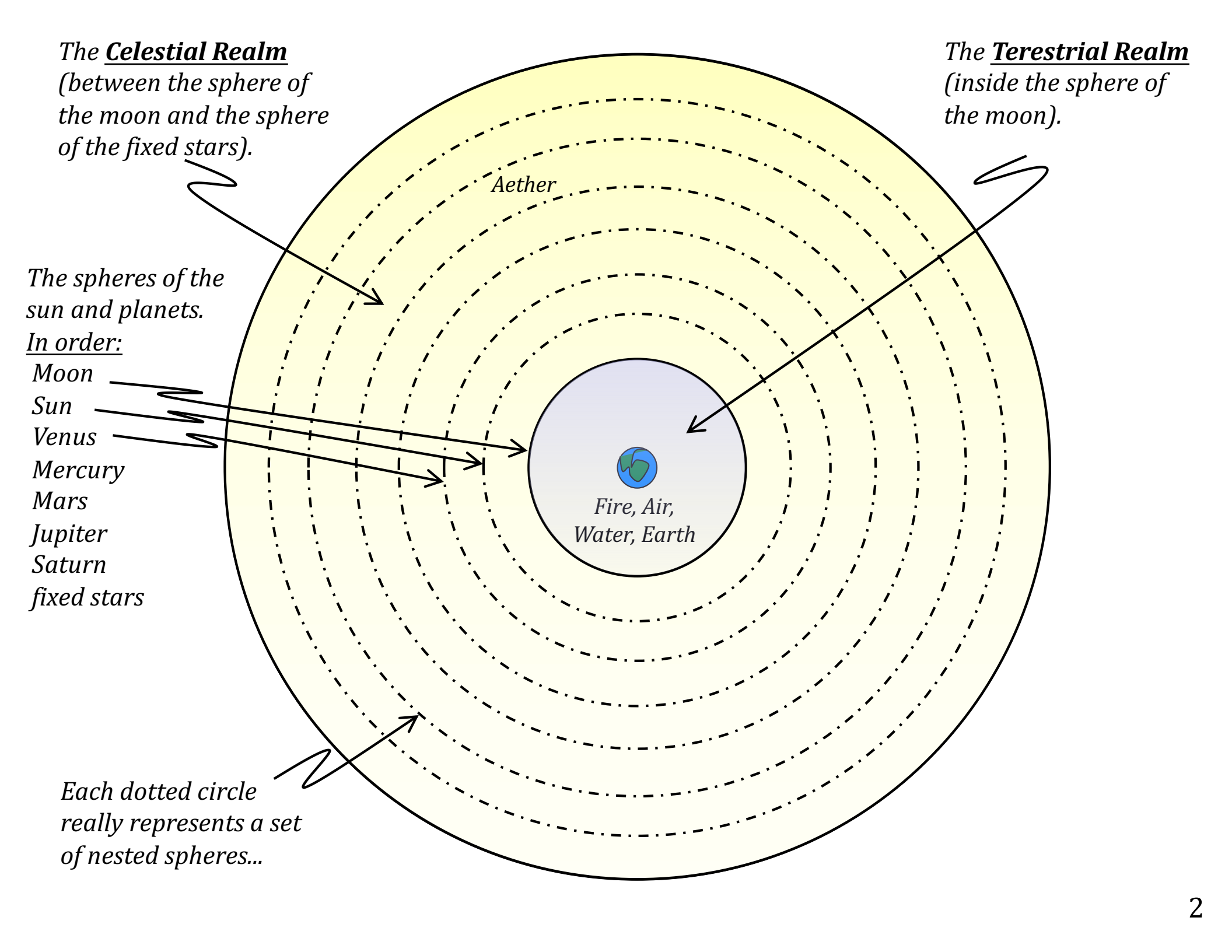
(b) *Forced motion*: mover is *external* to moving body

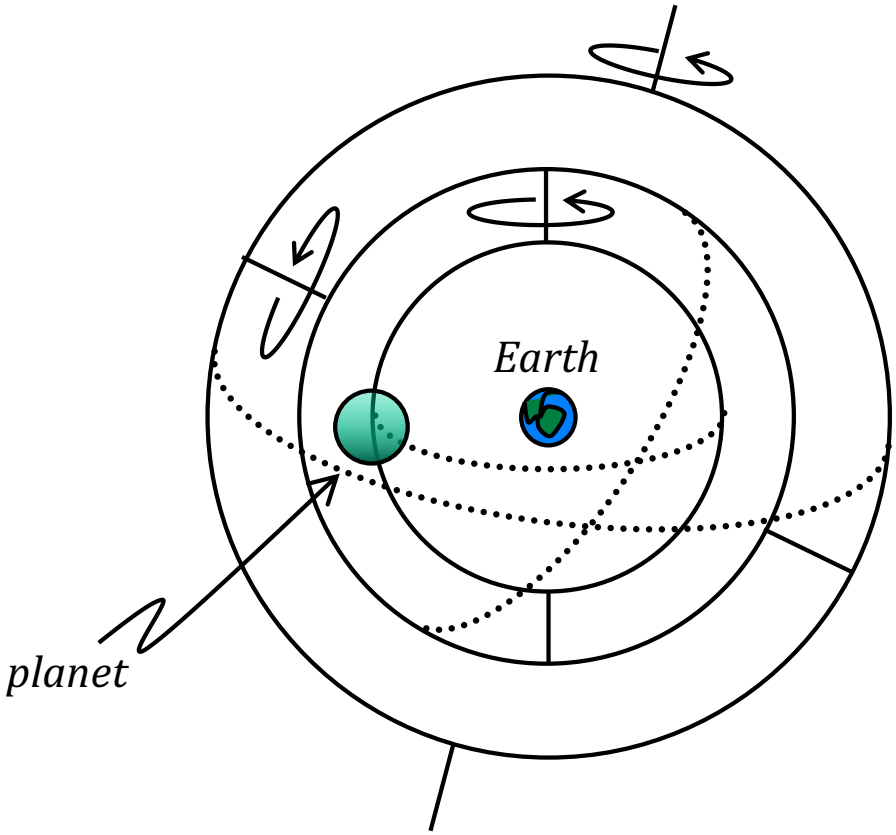
*3 Types of Natural Motion*

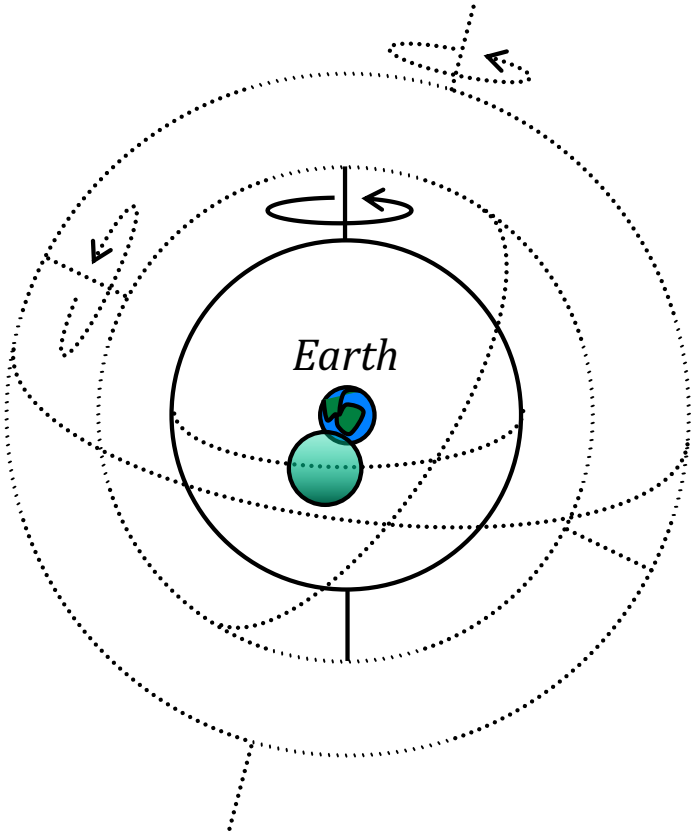
(i) In *straight line* towards center of the cosmos: earth, water

(ii) In *straight line* away from center of the cosmos: fire, air

(iii) In *circle* about center of the cosmos: aether


The **Celestial Realm** (between the sphere of the moon and the sphere of the fixed stars).
The **Terestrial Realm** (inside the sphere of the moon).
Aether
The spheres of the sun and planets.
In order:
Moon
Sun
Venus
Mercury
Mars
Jupiter
Saturn
fixed stars
Fire, Air, Water, Earth
Each dotted circle really represents a set of nested spheres...


Earth
planet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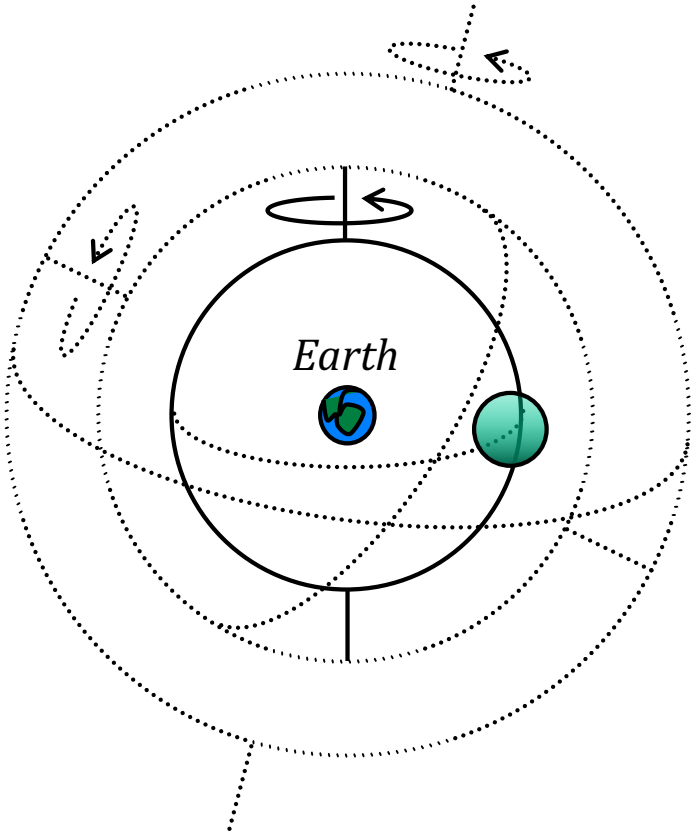
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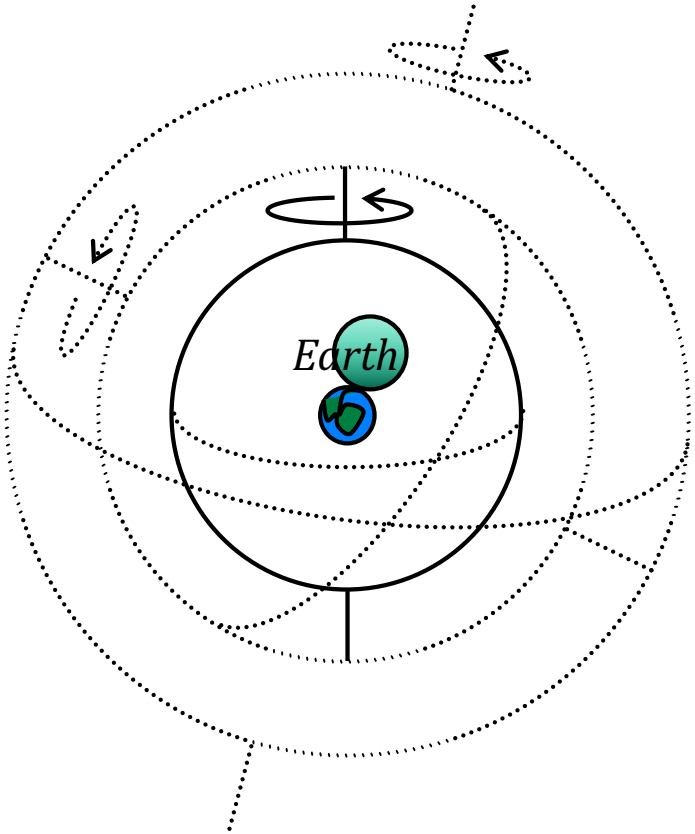
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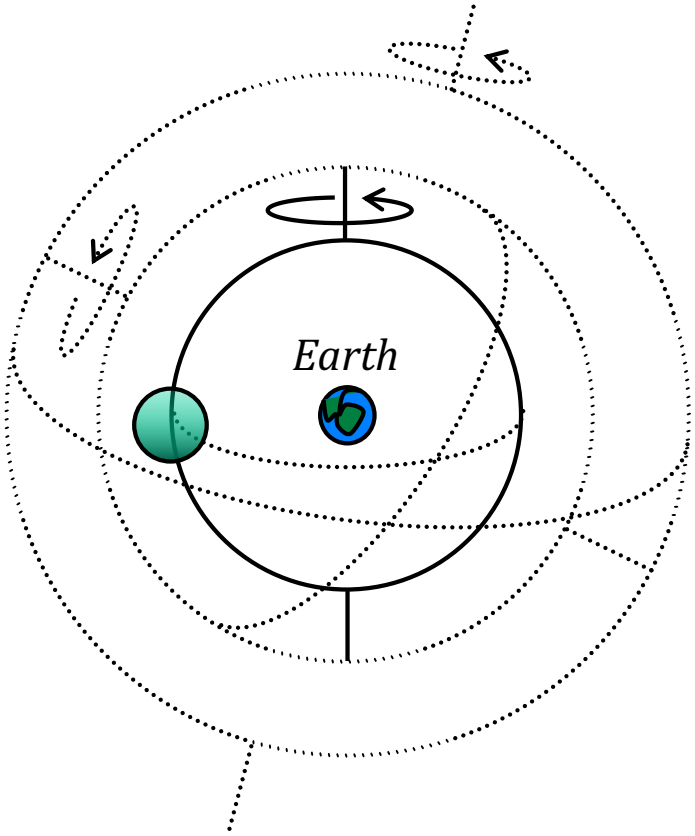
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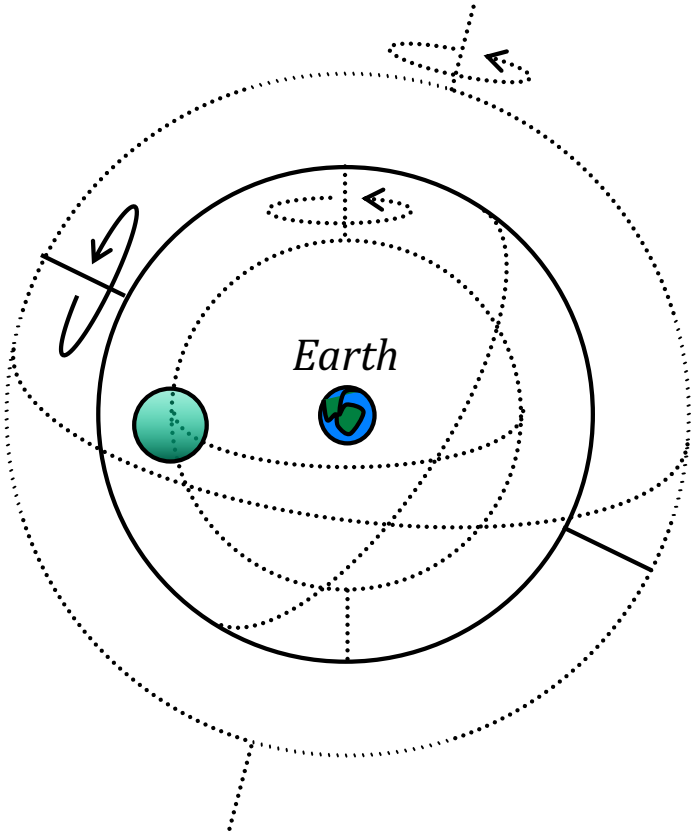
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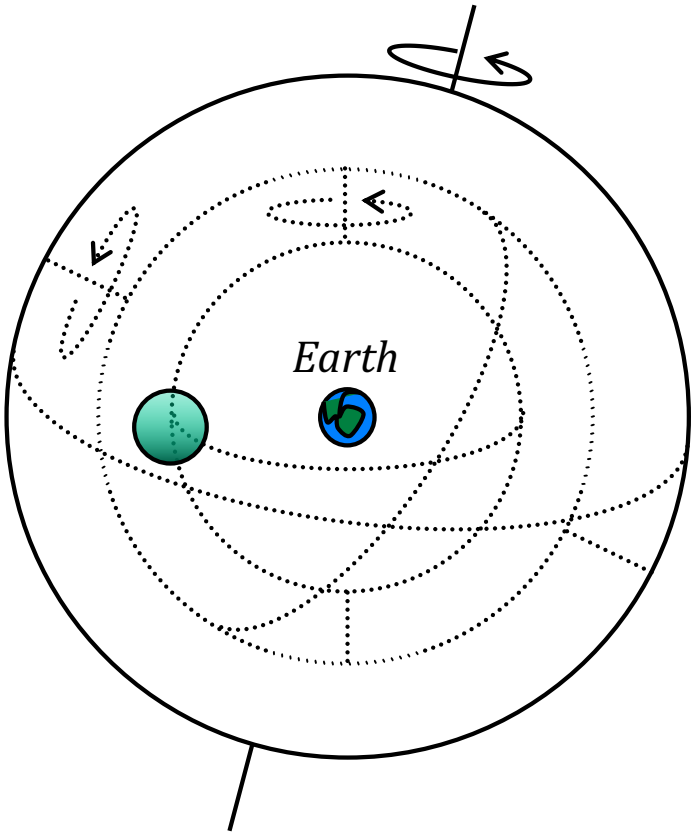
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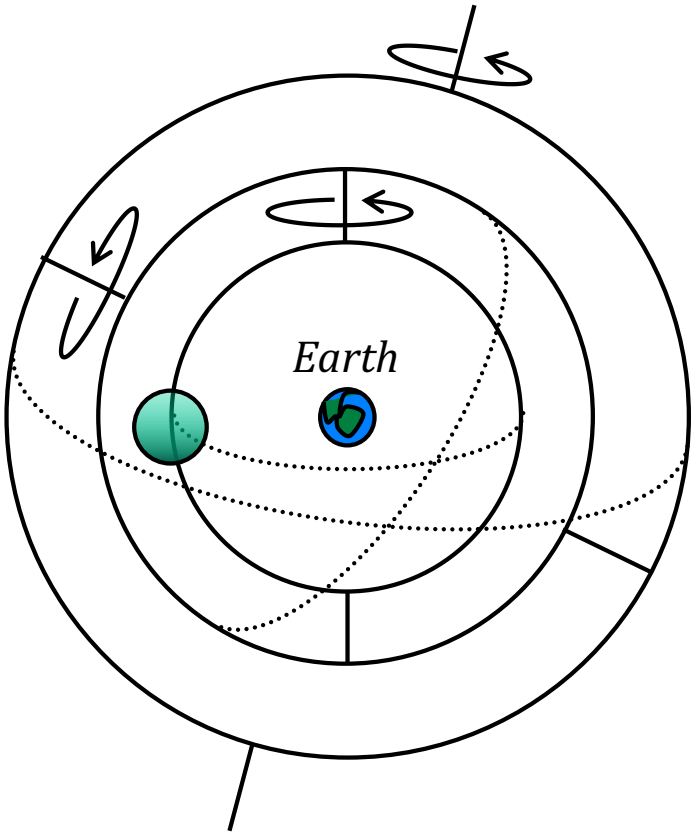



*How many spheres?*

| | Eudoxus | Callippus | Aristotle |
|---|---|---|---|
| Moon | 3 | 5 | 5 |
| Sun | 3 | 5 | 5 + 4 |
| Venus | 4 | 5 | 5 + 4 |
| Mercury | 4 | 5 | 5 + 4 |
| Mars | 4 | 5 | 5 + 4 |
| Jupiter | 4 | 4 | 4 + 3 |
| Saturn | 4 | 4 | 4 + 3 |
| fixed stars | 1 | 1 | 1 |
| | 27 | 34 | 56 |

- Explains retrograde motion.
- Aristotle requires additional spheres to counteract some of the motions of the planetary spheres.
  - *These additional spheres are placed between the outermost sphere of a given planet and the innermost sphere of the next planet and are one less than the number of spheres of the latter.*

# 2. Newton's Theory of Motion *Mathematical Principles of Natural Philosophy (1686)*

*3 Laws of Motion*

*Law I.* Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.

- Describes *natural motion* ("kinematics") for Newton: *uniform* motion (rest or constant velocity) in a *straight line*.
  - *Referred to as The Principle of Inertia.*
  - *inertia = tendancy in an object to obey Law I.*
  - *inertial motion = rest or constant velocity in a straight line.*

*Law II*. The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

*OR: The force needed to accelerate an object is proportional to the acceleration.* $F = ma = m\frac{d^2x}{dt^2}$

- Describes *forced motion* ("dynamics") for Newton.
  - *accelerated motion* = *non-uniform motion (non-constant velocity).*
  - *inertial mass* = $m$ = *measure of amount of inertia.*

*Law III*. To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts, and takes place in the direction of the straight line along which the force is impressed.

# *Newtonian Relativity Principle*

*The laws of motion are the same in all inertial reference frames*

*What this means:*

- *Inertial reference frames cannot be distinguished by Newton's laws of motion.*
- Any experiment involving moving objects performed in one inertial reference frame will produce the *same results* as in *any* other inertial reference frame:

  *Ex: Throw a ball straight up inside a constantly moving train car.*
  - *What happens?*

- How are inertial frames *related*, according to the Newtonian Relativity Principle?
  - *Need to determine the coordinate transformations that leave Newton's Laws of Motion the same (i.e., "invariant").*

*Galilean Transformations*

$$x \mapsto x' = \mathbf{R}x - v_0 t + x_0$$

$$t \mapsto t' = t + t_0$$

$\mathbf{R}$ = (components of) 3×3 rotation matrix
$v_0, x_0, t_0$ = constants

- These are the "symmetries" of Newton's 2nd Law $F = ma = md^2x/dt^2$.

*What this means mathematically*

If you substitute $x'$ for $x$ and $t'$ for $t$ in the 2nd Law, you don't affect its form.

*What this means physically*

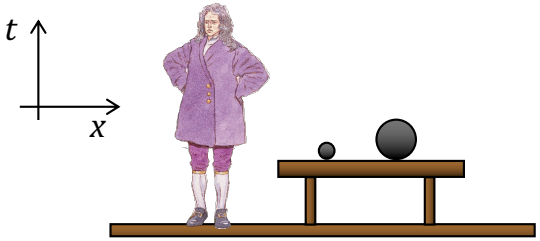
If your lab is initially in an inertial frame at rest, then any or all of the following will have no affect on experiments with moving objects governed by Newton's Laws:

(a) Rotating it (by $\mathbf{R}$).

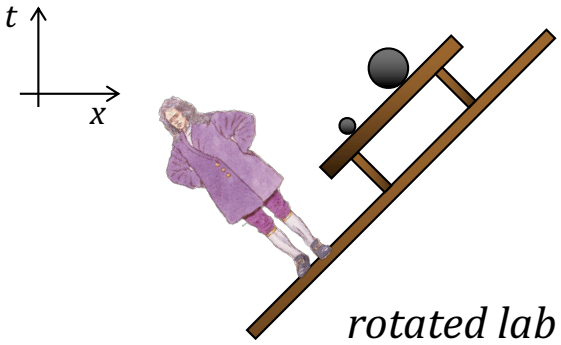
(b) Putting it into uniform motion (at speed $v_0$).

(c) Moving it a distance in space (by amount $x_0$).

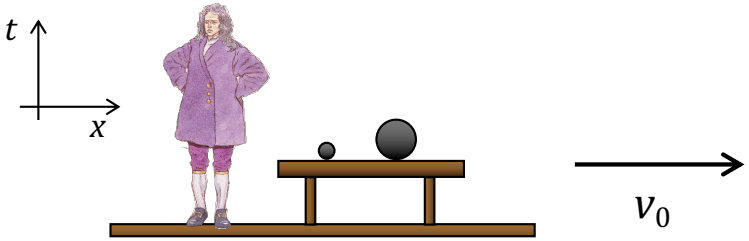
(d) Waiting a given amount of time ($t_0$).



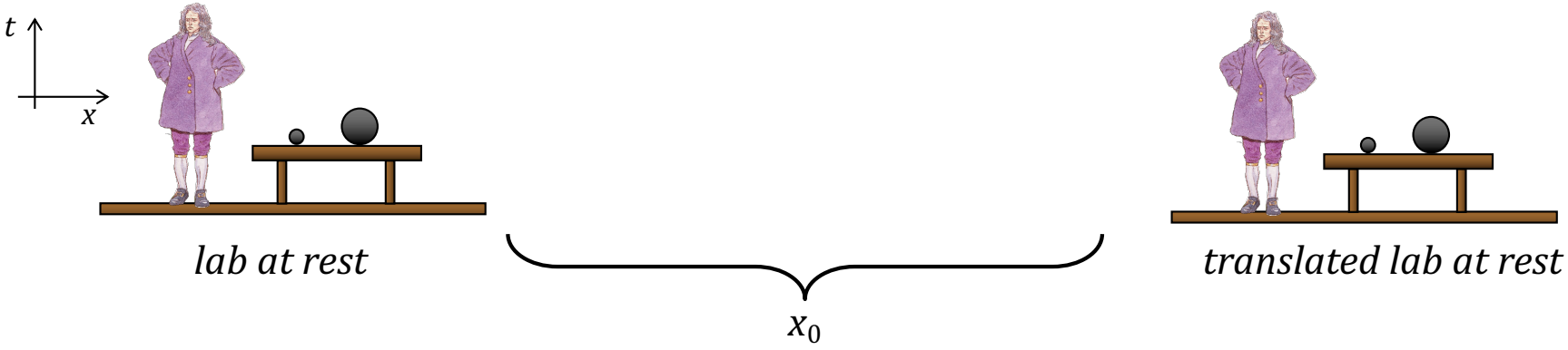

*lab at rest*

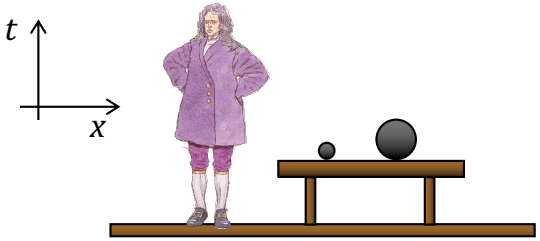



*rotated lab at rest*

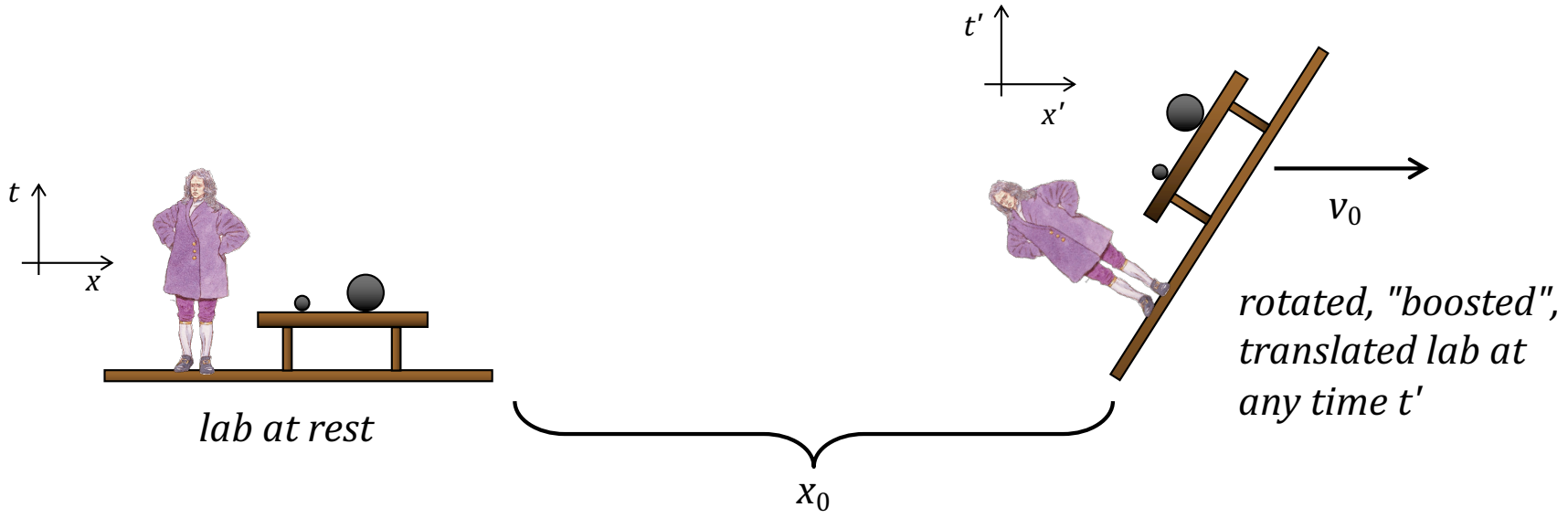



*lab in constant velocity*


t
x
lab at rest
$x_0$
translated lab at rest




*lab at rest tomorrow*
*at time* $t_0$




- Rest lab and rotated, spatially/temporally translated, moving lab are indistinguishable according to Newton's Laws of Motion!

*Consequences of Newtonian Relativity Principle:*

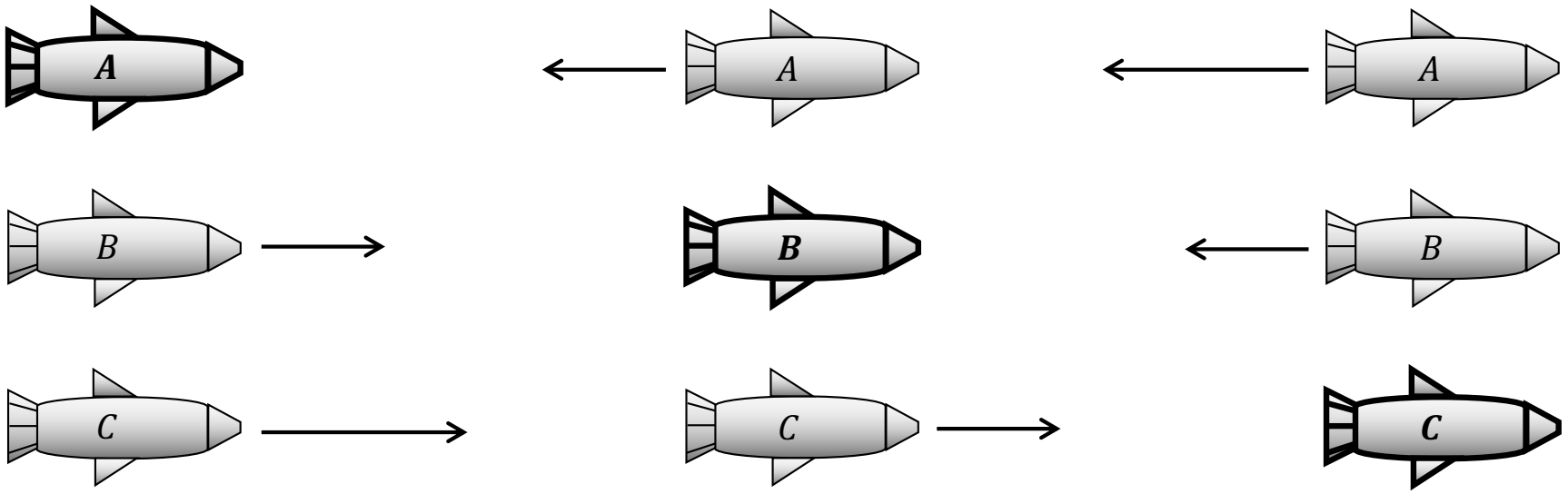
(1) Velocity is relative! (No preferred, absolute velocities in nature.)

(2) Position is relative! (No absolute positions in nature.)

(3) Orientation is relative! (No absolute directions in nature.)

(4) Acceleration is absolute! (Any given object has a unique value of acceleration.)

*Example*: *All velocities are relative to an inertial frame of reference.*



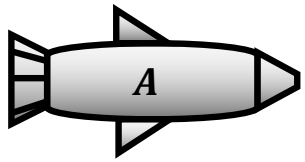

*Suppose:*
In $A$'s rest frame,
(a) $v_A = 0m/s.$
(b) $v_B = 50m/s.$
(c) $v_C = 100m/s.$

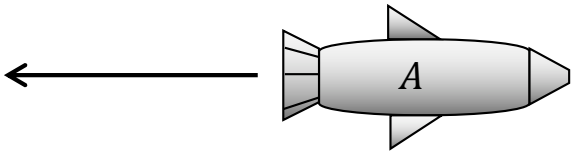
*Then:*
In $B$'s rest frame,
(a) $v_A = -50m/s.$
(b) $v_B = 0m/s.$
(c) $v_C = 50m/s.$

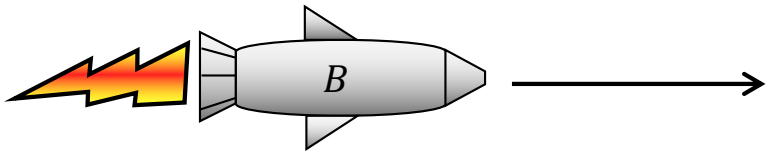
*And:*
In $C$'s rest frame,
(a) $v_A = -100m/s.$
(b) $v_B = -50m/s.$
(c) $v_C = 0m/s.$

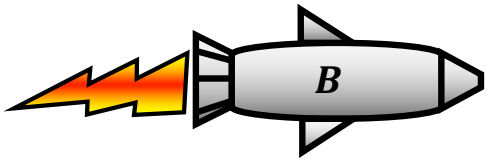
- Newton's Laws of motion cannot distinguish between the (inertial) rest frames of $A$, $B$ and $C$.

*But*: *Acceleration is not relative to inertial reference frames.*




*Suppose:*
*B fires it's engines and accelerates. In A's rest frame, B is accelerating to right.*

*Then:*
*In B's rest frame, A appears to be accelerating to left... But:*

- Newton's Laws of motion *can* distinguish between the rest frames of *A* and *B*.
- The rest frame that experiences *inertial forces* is the frame undergoing acceleration (in this case, *B*).

## *Newton's Theory of Gravity*

Particular type of forced motion (when force is due to gravity).

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

$F$ = force of gravity on object of mass $m$ due to object of mass $M$
$r$ = distance between $m$ and $M$
$G$ = constant of nature (Newtonian gravitational constant)

- This is a *universal force* -- acts on all objects (*in exactly the same way*).
  - *It thus unites Aristotles' terrestrial and celestial realms (the "Newtonian Synthesis").*

*Einstein's Accomplishments*

- Modification of Newton's 3 Laws of Motion ⇒ *Special Relativity*
- Incorporation of gravity into Special Relativity ⇒ *General Relativity*

# 3. Maxwell's Electrodynamics *A Treatise on Electricity and Magnetism (1873)*

*Newtonian dynamics* = theory of motion for *uncharged* massive objects.

*Maxwell's electrodynamics* = theory of motion for *electrically charged* massive objects (*i.e.*, moving electrons).

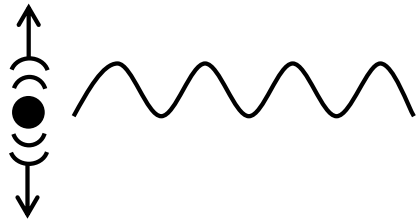
*Maxwell's Equations (Maxwell's Laws of Motion)*

$$\vec{\nabla}\cdot\vec{E} = 4\pi\rho \qquad \vec{\nabla}\times\vec{E} = \frac{1}{c}\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\cdot\vec{B} = 0 \qquad \vec{\nabla}\times\vec{B} = \frac{1}{c}\frac{\partial\vec{E}}{\partial t} + \frac{4\pi\vec{J}}{c}$$

$\vec{E}$ = electric field
$\vec{B}$ = magnetic field
$\rho$ = charge density
$\vec{J} = \rho\vec{v}$ = current density

- Describe motion of *electromagnetic waves* propagating with speed $c = 3\times10^8 m/s = 186{,}000\, mi/s$
- EM wave: Produced by an oscillating charged object.



- 1860s: *Aether* = supposed medium through which EM waves propagate.

*Mathematical Exercise*

- Maxwell's Equations are *not* invariant under Galilean transformations!
  - *What transformations leave Maxwell's Equations invariant?*
- *Answer* (provided by Lorentz, Poincaré, and others prior to 1905):

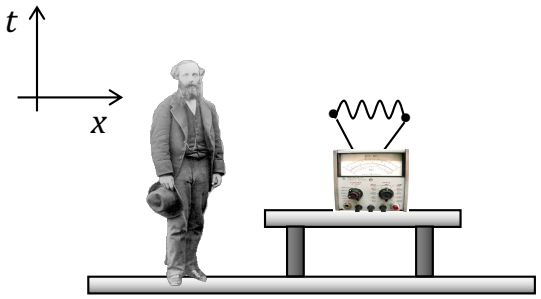
**Lorentz Transformations**

$$x \mapsto x' = \gamma_0(x - v_0 t)$$

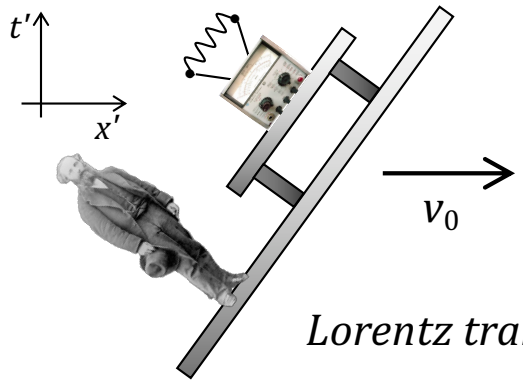
$$t \mapsto t' = \gamma_0\left(t - \frac{v_0 x}{c^2}\right)$$

$$\gamma_0 = \frac{1}{\sqrt{1 - \frac{v_0^2}{c^2}}}$$

*Key feature*: *c is a constant in all frames related by Lorentz transformations.*




*lab at rest*




*Lorentz transformed lab*

- Rest lab and Lorentz-transformed lab are indistinguishable according to Maxwell's Laws!
- *But*: Just how exactly are they related to each other physically? (Story to come!)

*Einstein's Insight*: Two theories with different symmetries!

- *This is a messy state of affairs!*
- *Something Must be done!*

*State of physics at beginning of 20th century:*

*Claim*: Newton + Maxwell = Theory of Everything!*

- The End of Physics!
- Only 2 "clouds"... "mere technicalities":

  (1) Determining speed of Earth through the aether. All experiments seem to indicate zero speed.

  (2) Describing black-body radiation -- peculiar type of heat radiation. All theoretical descriptions seem incoherent.

*Lecture delivered at the Royal Institution of Great Britian by William Thomson, Lord Kelvin (1824-1907)*

Cloud #1 leads to "Relativity Revolution": Special and general relativity.

Cloud #2 leads to "Quantum Revolution": Quantum mechanics.