THE STORY OF PHYSICS

Script by
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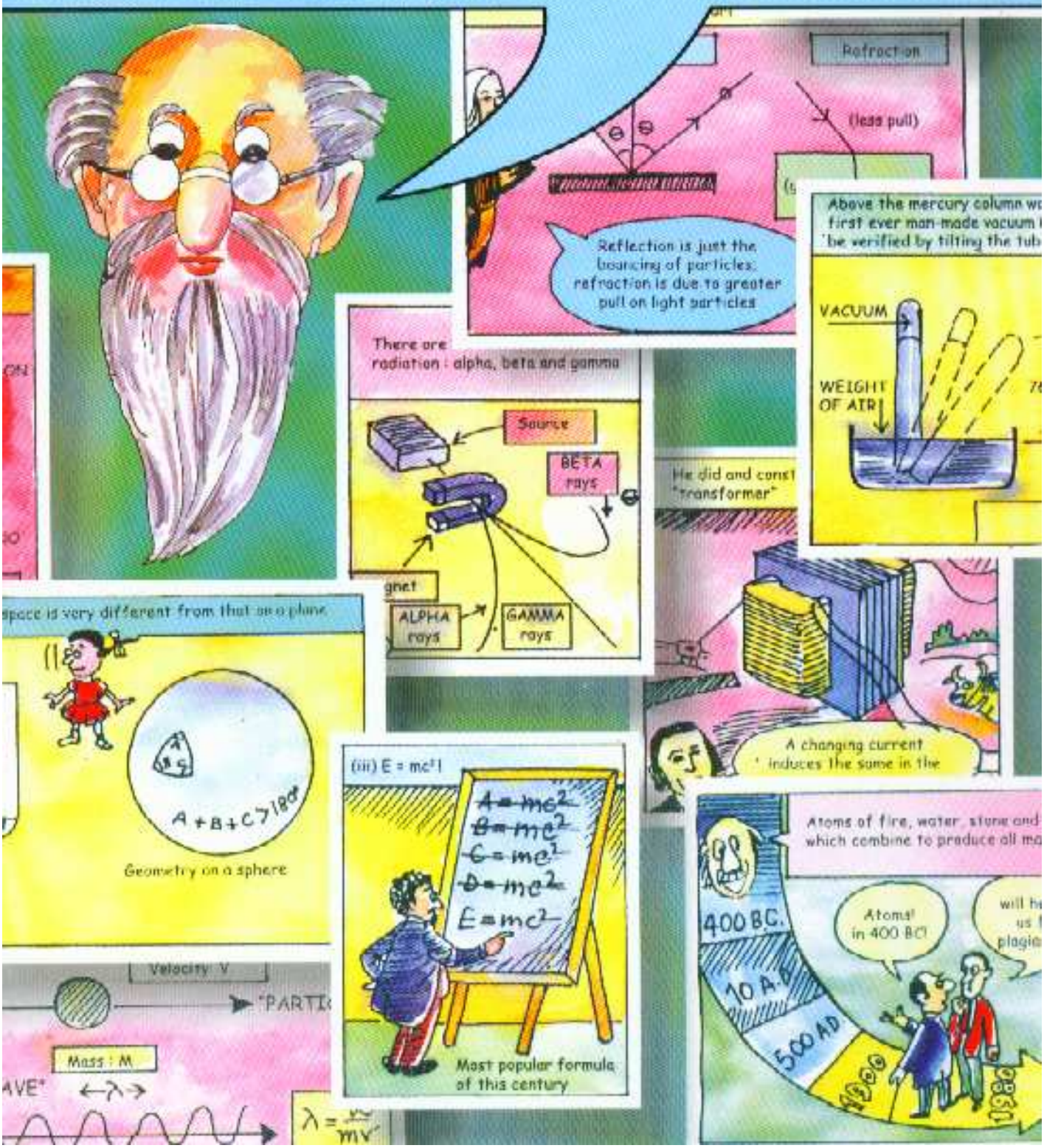
Illustrations by
KEITH FRANCIS

Redrawn by: **Avinash Deshpande**



The STORY of PHYSICS

OH BOY! WHAT WILL THEY DO NEXT?

SCRIPT by T.PADMANABHAN
ILLUSTRATIONS by KEITH FRANCIS
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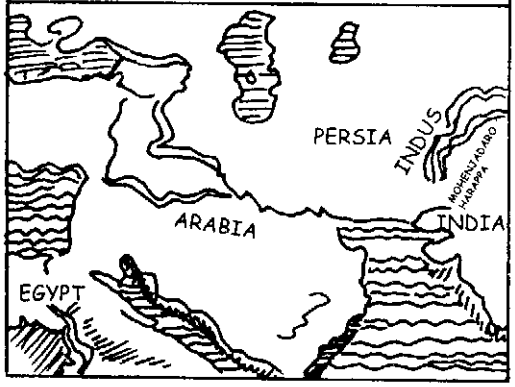
A long time ago, about 10,000 BC, there was home science....

..... and even appropriate technology

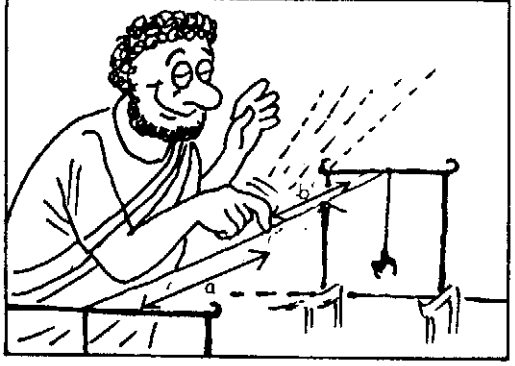
The earliest civilisations used many engineering concepts....



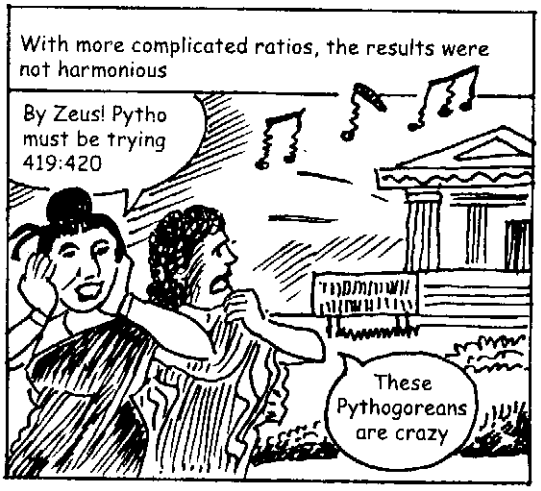
but physics - a scientific method that attempts to explain nature based on a set of laws - probably did not exist till the time of the Greeks.

Greece produced many thinkers and scholars: like Pythogoras (582 - 497 BC)

....who conducted experiments in harmony by plucking strings. When there was a simple ratio like 2:3 and 1:2 between the lengths a and b, the tune was pleasant

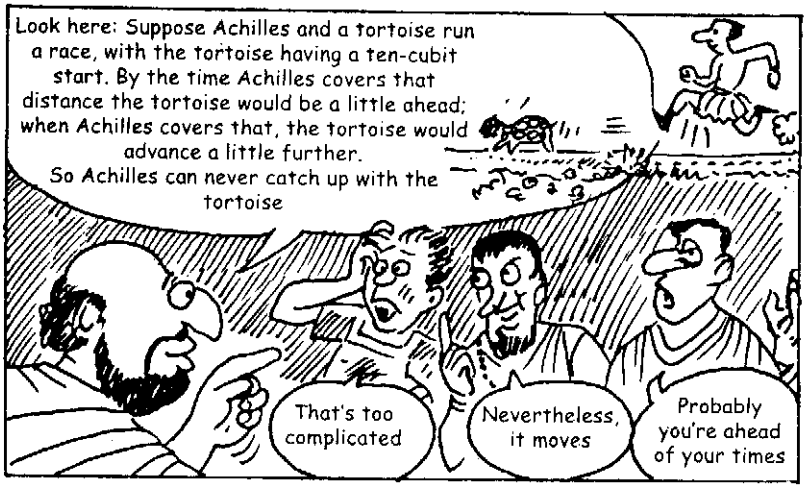


With more complicated ratios, the results were not harmonious

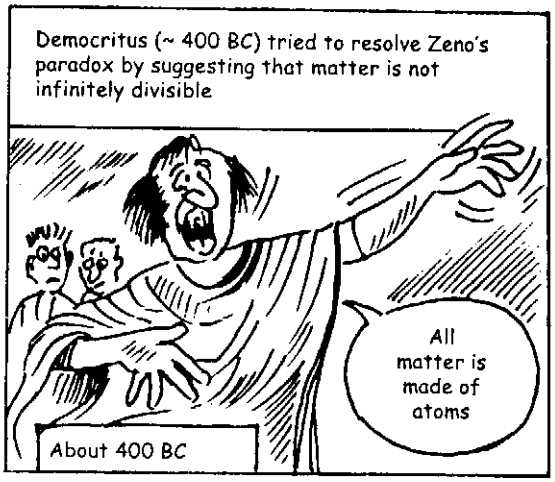


Zeno, a contemporary of Pythogoras, nearly proved that motion is impossible (Zeno's paradox)

Look here: Suppose Achilles and a tortoise run a race, with the tortoise having a ten-cubit start. By the time Achilles covers that distance the tortoise would be a little ahead; when Achilles covers that, the tortoise would advance a little further.
So Achilles can never catch up with the tortoise



Democritus (~ 400 BC) tried to resolve Zeno's paradox by suggesting that matter is not infinitely divisible



Atoms of fire, water, stone and air which combine to produce all matter

400 B.C.

10 A.D.

500 A.D.

1900

1980

Atoms! in 400 BC!

Will he sue us for plagiarism?

Between 336 and 323 BC, Alexander the Great was building the first empire ever

FROM MACEDONIA

PERSIA

INDIA

Around the same time his tutor Aristotle (384-322 BC) was attempting to build an empire of knowledge

He lectured at the Lyceum, in Athens on a wide variety of topics: Logic, Biology and Physics*

* He gave the subject its name

Unfortunately, many of his ideas of physics were incorrect

The Earth is the centre of the Universe

Earth is the centre, water, air, fire and ether above it. Since bodies tend to....

reach their natural state, a stone falls while a bubble rises

He also thought that heavier objects fall faster than lighter ones

Don't be silly. Aristotle can't be wrong*

Shall we drop these and see?

*This view held sway for a long time

After the death of Alexander, his generals divided the empire. Egypt came under Ptolemy

Mediterranean Sea

ALEXANDRIA

EGYPT

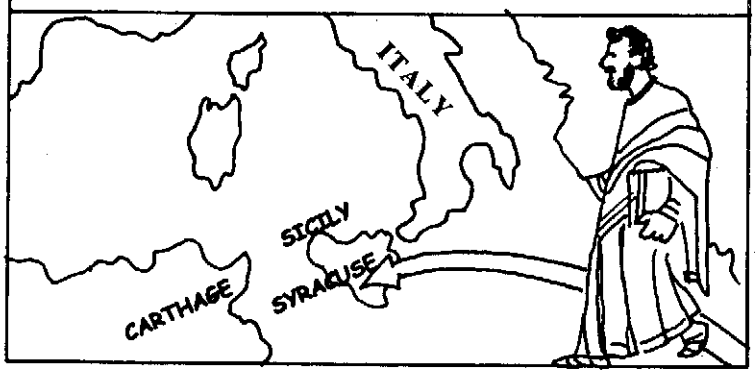
Alexandria, his capital, became the centre of intellectual activity. Alexandria inspired many scholars like Euclid (300 BC)

Among them was the greatest of ancient physicists...

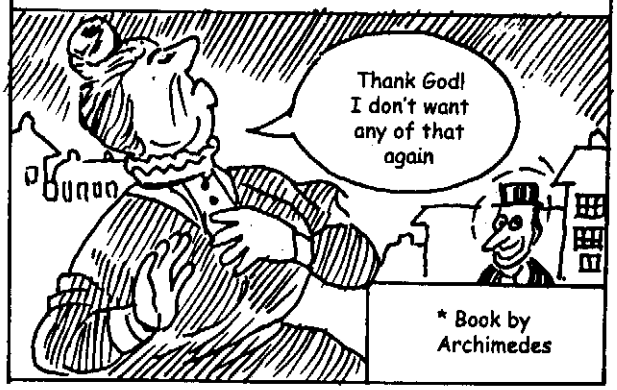
Hey! you mean the first streaker!

....Archimedes (287-212 BC)

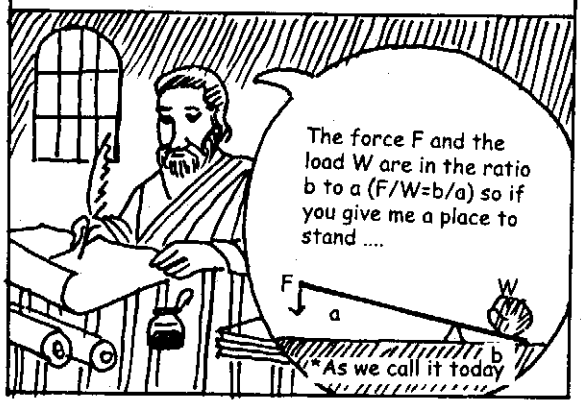
After his education in Alexandria, Archimedes returned to Syracuse, his native place, and enjoyed the royal patronage of Hieron

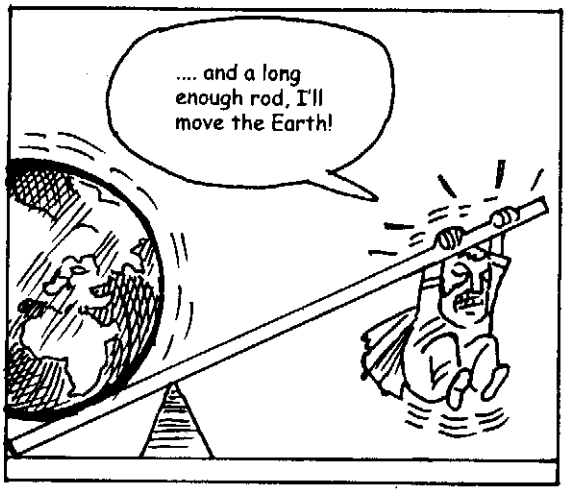


His law of "Floating Bodies"* and the story of "Eureka" are too famous to be retold



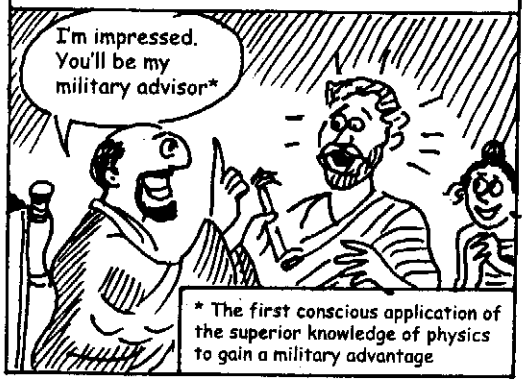
He was the first to develop the principle of statics in his book on the equilibrium of planes*





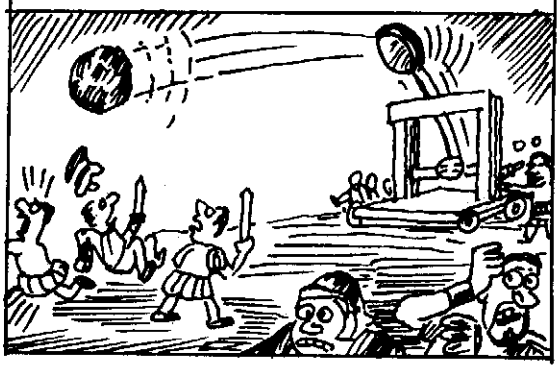
Ha! that's a lot of words! What about moving a ship?

The story goes that Archimedes actually pulled a sheep ashore with pulleys and levers

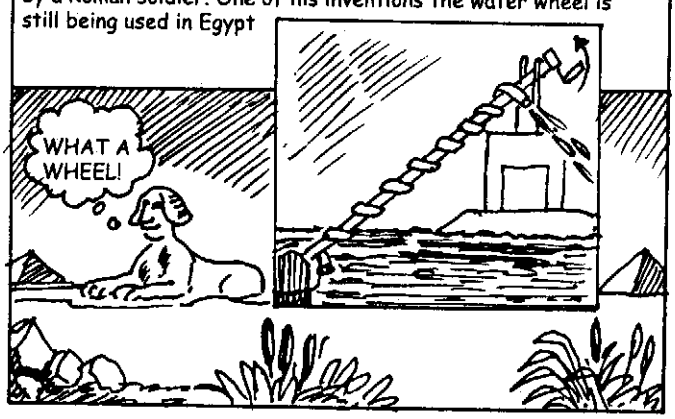


After Heiron, his grandson Heironymus became the king. During the 2nd Punic war (218 BC), seeing the success of the troops of Carthage, led by Hannibal, Heironymus broke his treaty with Rome and sided with Carthage. This led the Romans to lay seige on Syracuse

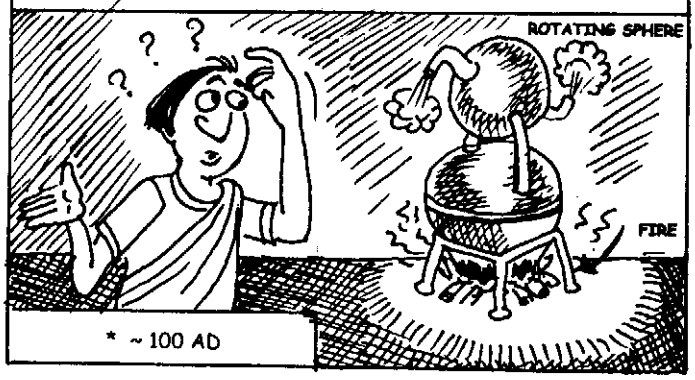
It is said that the war machines made by Archimedes kept the Roman General Marcellus at bay for more that two years



When the Romans finally took the city, Archimedes was killed by a Roman soldier. One of his inventions the water wheel is still being used in Egypt



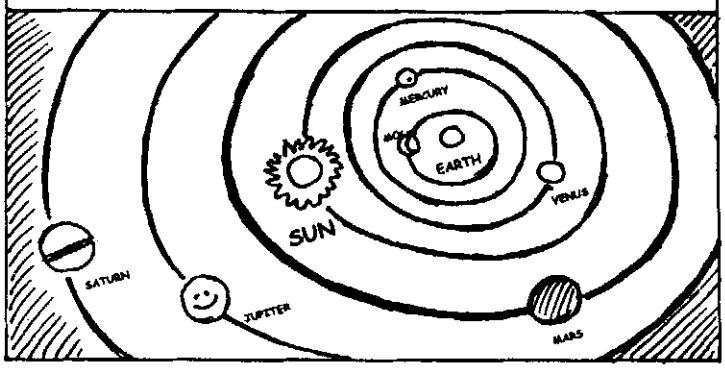
By 30 BC, Egypt was a Roman province having lost much of its glory. Among the few more geniuses it produced was Hero* who made the first steam engine*



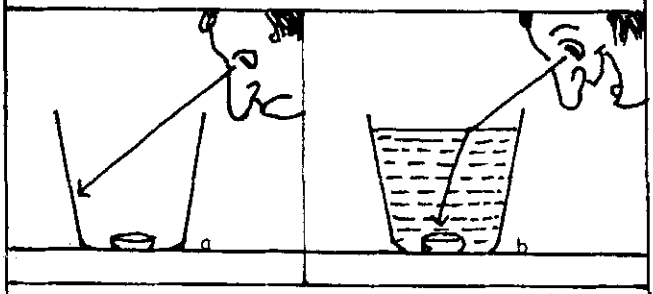
He also constructed the siphon and wrote books on mechanics and catoptrics. His views on vision reflected the thinking of those days

Light is emitted by the eye and is reflected by objects

Another great Alexandrian was Ptolemy (127-151 AD) who believed the Universe was concentric with the Earth at its centre. We now know he was wrong

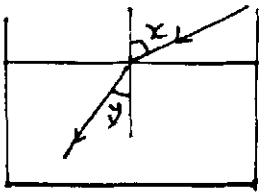


He also studied optics, especially the process of refraction



Refraction helps you to see the coin in (b) because light bends on crossing the boundary of water

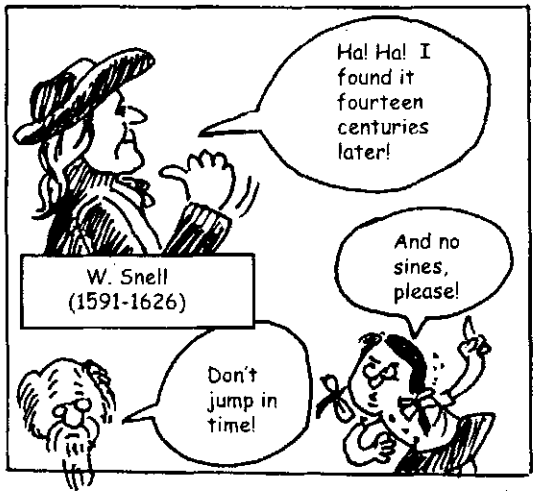
Ptolemy conducted an experiment and carefully noted the angles x and y....



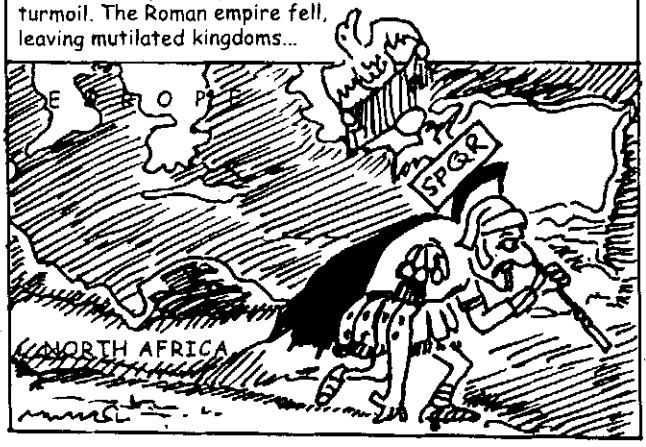
x	y
10°	8°
40°	25°
50°	35°
80°	50°

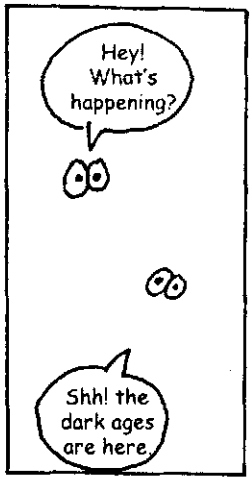
.... but failed to arrive at the formula connecting x and y

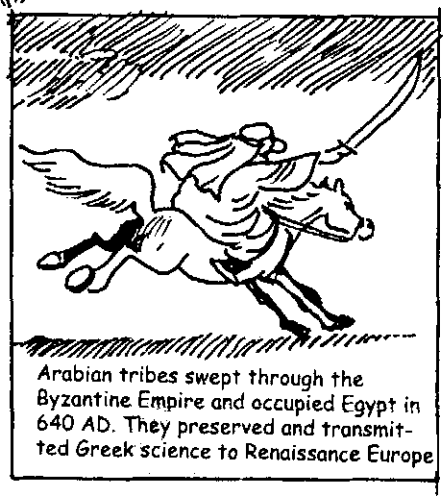
The law sine x and sine y is a constant. It's now called as Snell's Law



After Ptolemy, Europe was in turmoil. The Roman empire fell, leaving mutilated kingdoms...



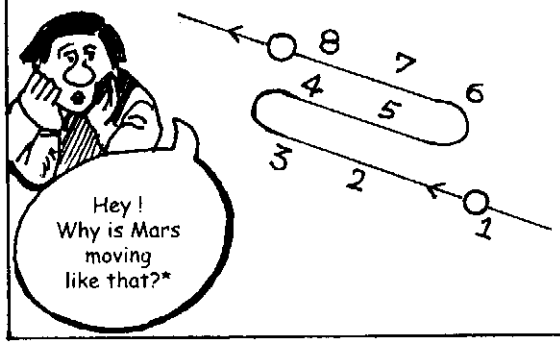


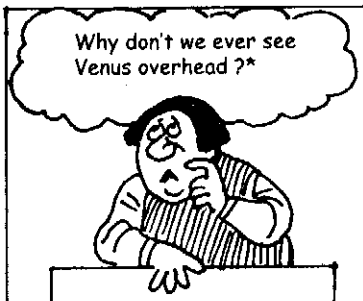


Arabian tribes swept through the Byzantine Empire and occupied Egypt in 640 AD. They preserved and transmitted Greek science to Renaissance Europe

The Renaissance was not really a rebirth for science. Europe was dominated by religious zealots

The religious faith of the post renaissance era did not encourage curiosity ....



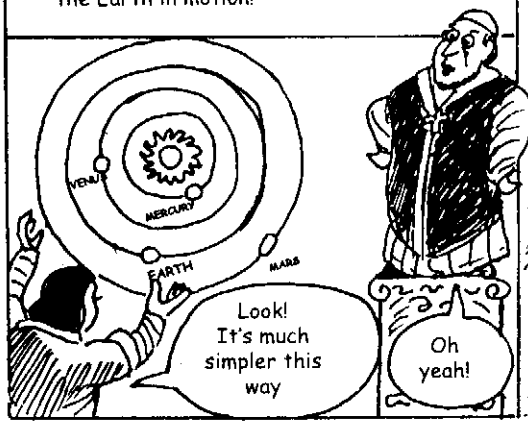


*These questions have no simple answers in Ptolemy's system of the universe

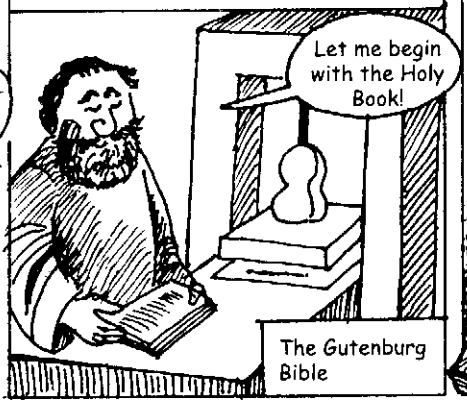
Then came a man....

.... Nicolaus Copernicus (1473 - 1543)

.... Who stopped the sun and set the Earth in motion!



Gutenburg had invented printing nearly 100 years before this ....



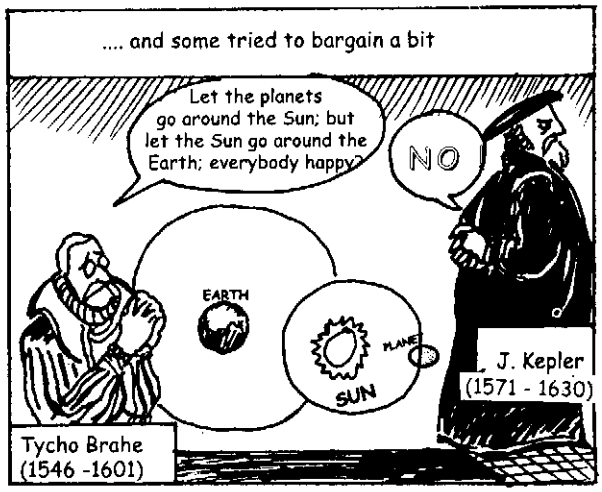
The Gutenburg Bible

The "unholy" tenets of Copernicus were printed in 1543....

All the same, some accepted the Copernican model at once...

Reinhold (1511-53) published the "Prussian table of planetary positions" in 1551.

.... and some tried to bargain a bit



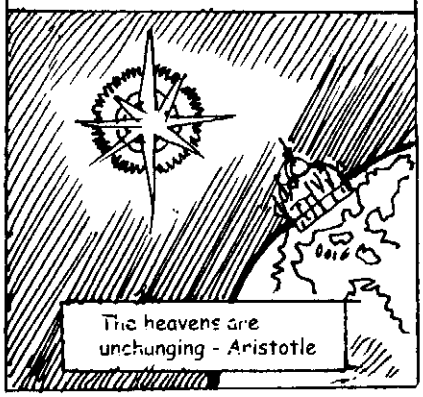
J. Kepler (1571 - 1630)

Tycho Brahe (1546 -1601)

Ironically' Tycho's observations made in his private observatory, Hveen, Denmark....

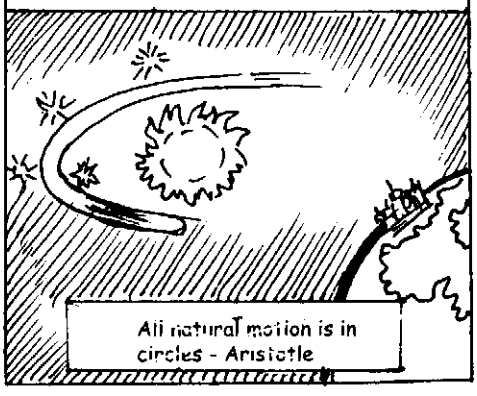
....had enough in them to support the Copernican model

Tycho observed the flaring up of a new star ("supernova") (1572 AD)



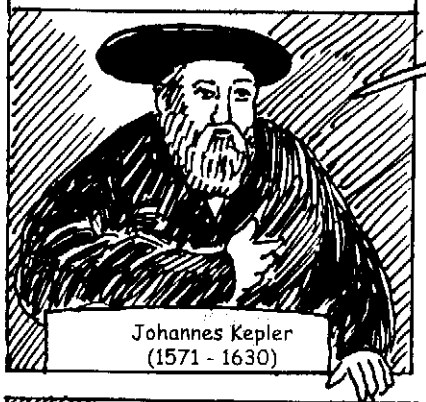
The heavens are unchanging - Aristotle

and a comet with an elongated orbit....



All natural motion is in circles - Aristotle

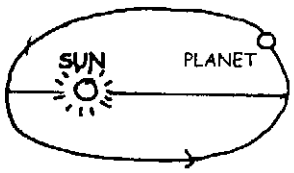
But the coup de grace to "Greek Physics" came from Tycho's student



Johannes Kepler (1571 - 1630)

Painstaking analysis of Tycho's data led Kepler to his three laws of planetary motion

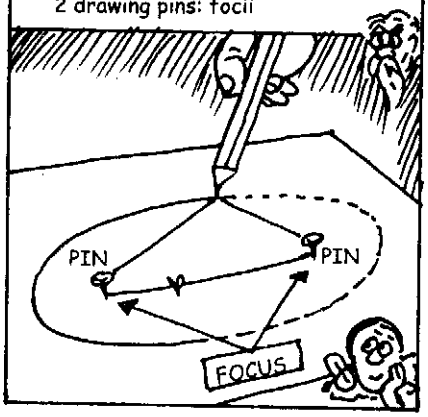
Planetary orbits are ellipses with the Sun at the focus



Hey, hold it! What's an ellipse? What's focus?

First law (1609 AD)

An ellipse, can easily be drawn with a pencil, string and 2 drawing pins: focii



It's one of the sections you get by slicing a cone at an angle. Besides an ellipse.

DID YOU SEE WHAT I SAWED?

ELLIPSE

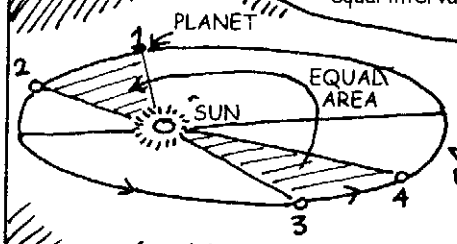
.... it is given by the equation....

No! No equation in a picture story!

Ok, Ok, Let's get back to Kepler

Second law (1609 AD)

The planet - Sun line sweeps out equal areas in equal intervals of time.



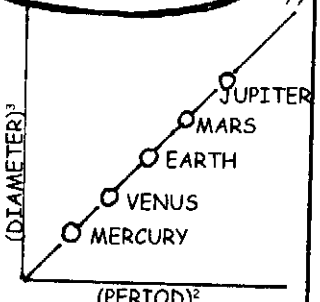
Thus it takes equal time to go from 1 to 2 as from 3 to 4. A planet moves faster when it is near the sun!

Kepler published these two laws in his "Astronomia Nova". The third law was given in his book "Harmony of the World" (1619) - A book full of mysticism!

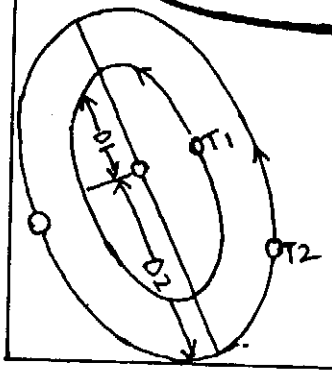
The squares of orbital periods are proportional to cubes of orbital semi diameter

Third law (1619 AD)

WHAT!



Kepler can never say it simply. Look if two planets have periods T_1, T_2 and distance D_1, D_2, then....



$$\frac{D_1^3}{D_2^3} = \frac{T_1^2}{T_2^2}$$

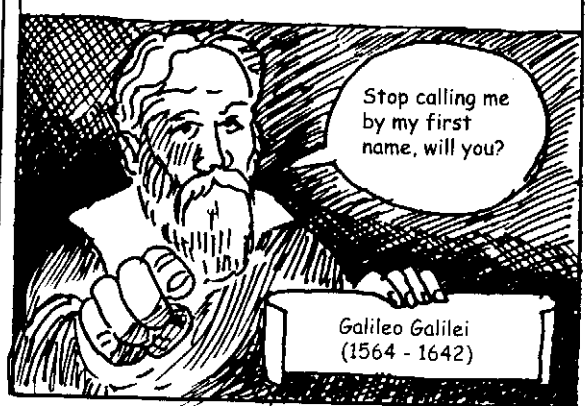
The planetary positions can now be predicted accurately

I'll dedicate this work to King Rudolf and Tycho Brahe

"Rudolphine Tables" 1627 AD

We have come a long way since the time of the Greeks. The heavens are in order. We know how they move. But why do they move?

The first step towards the laws of motion was taken by Galileo Galilei



Galilei, Kepler's contemporary, was never very religious. One day, while at church, a swinging chandelier caught his attention

At least it's more interesting than the sermon

That let him to make two important observations about the pendulum:

One: the period is independent of the arc of swing*

*Explanation from Newton (17th century)

"ARC OF SWING"

Two: the period is independent of the mass of the bob*

LEAD

COPPER

* "Real" explanation from Einstein (20th century)

He also knew that bodies of different weights when dropped from a height will hit the ground together

Hey! did you throw stones at me from the tower of Pisa yesterday?

No! I only wrote about it

Me? Never! He might have done it.

Stevinus (1548 - 1620)

Heavy objects fall faster - Aristotle

Simon Stevinus, another contemporary, has showed that the pull of the Earth is weaker on an inclined plane

A

C

B

Look! There are more balls on AB than along AC. So this "machine" will roll on and on! Since...

This is absurd: the pull of Earth must be weaker along AB than along the vertical AC

Galilei used the inclined plane to study the motion of objects

I wish I had a better clock

He should have used his pendulum. I did in 1656.

Huygens (1629 - 1695)

Galilei found that the distance covered by the rolling ball increased as the square of time interval....

D(DISTANCE)

T(TIME)

$D \propto T^2$

....while the speed increased linearly with time

(SPEED)

(TIME)

See! The pull of Earth changes the speed steadily, So....

....motion with unchanging speed needs no pull !

All motion is caused by force - Aristotle

He next considered the combined motion in two directions, asking....

If a stone is dropped from the mast of a ship, where will it hit the deck?

Hey wait. Let the captain get out of the way

Simplicious*

Well, if the boat is not moving it will fall straight down. Otherwise it will fall behind A, at B

(BOAT IN UNIFORM MOTION)

A

B

(STATIONARY BOAT)

* A character in Galilei's dialogues representing Aristotle's school

WRONG !

If the boat moves at uniform speed, the stone will again hit A

Galileo realised that motion in two directions can be combined

Uniform motion of boat retained by stone

X

XY: path of stone

Pull of Earth

Y

A when stone hits deck

Position of A when stone is released

What if the boat is moving with increasing speed ?

Then Simplicious, you're right. The stone will fall behind A, at B

You mean uniform motion is so special?

Quite!

This led to the "Galelian Principle of Relativity".

No mechanical experiment performed inside a closed cabin can distinguish uniform motion from a state of rest

I like the sound of it !

1500

1600

1700

1800

1905

Galilei, constructed the first astronomical telescope and observed the heavens

And I saw

The Moon full of hills and valleys....

Planets Venus and Mars, showing phases like our Moon...

Jupiter with three moons going around it

The Milky Way, masses of innumerable stars planted in clusters.

At last!

These observations lend undeniable support to the Copernican school !

That was more than the Church could tolerate. Galilei was put into solitary confinement and forced to recant

I abandon the false opinion.... that the Sun in the centre....

How I'd love another life, to get at the laws of motion!

Galelio Galilei, one of the greatest physicists, died, blind and tired in 1642

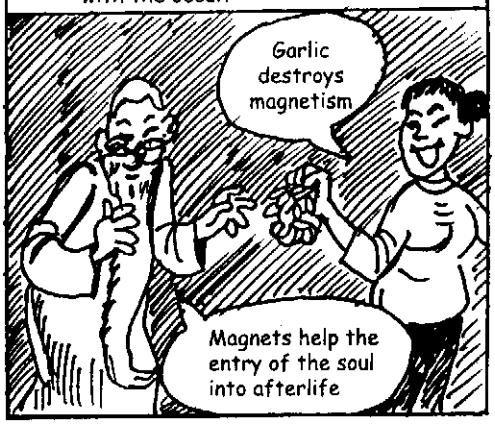
Hey ! Is all physics just mechanics?

Not all. Let's look at other things

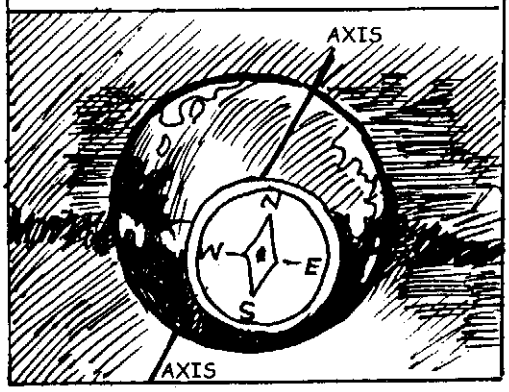
While the science of mechanics was racing ahead, magnetism and optics were crawling along....

Lode stones (natural magnets) were known to Chinese miners from ancient times (2500 BC)

Magnetism was always associated with the occult

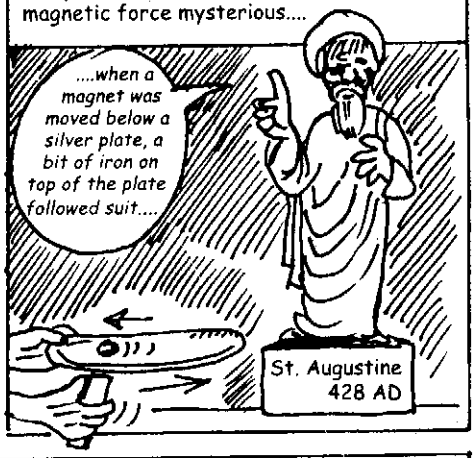


It is not known who discovered the "north seeking" property of magnets

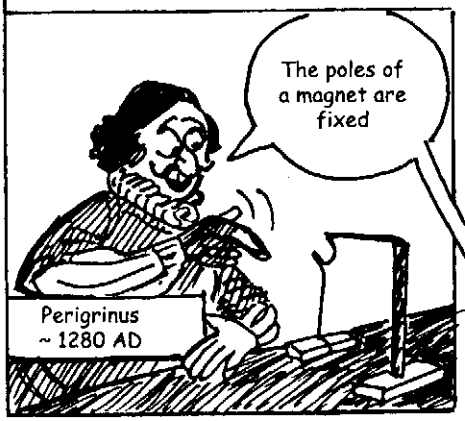


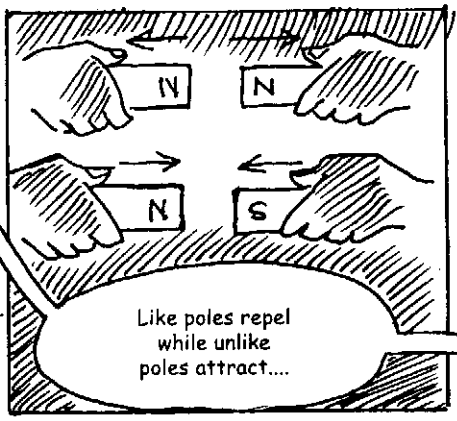
But even as early as 900 BC, magnetic needles were used as a navigational aid in stormy seas

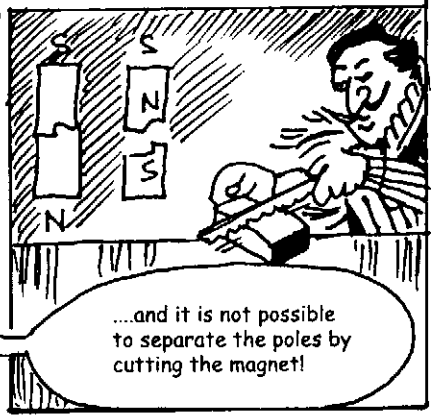
Many found the action of magnetic force mysterious....



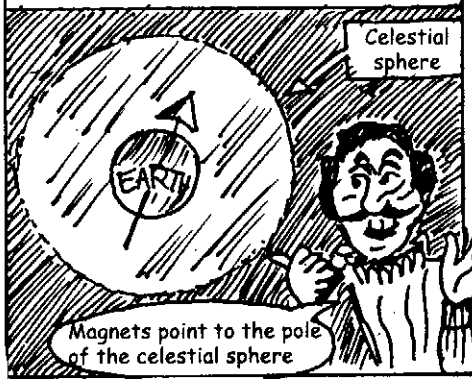
Perigrinus, the French engineer, probably conducted the first set of experiments with magnets. He noted many important features:





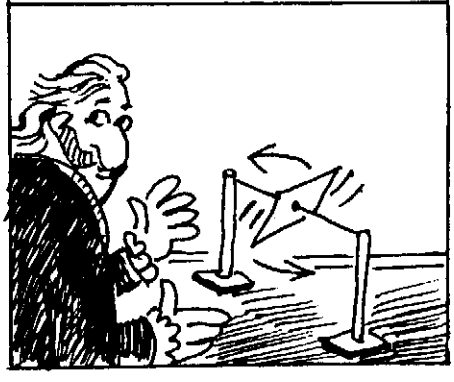


His explanation for "north seeking" behaviour was, however, wrong!

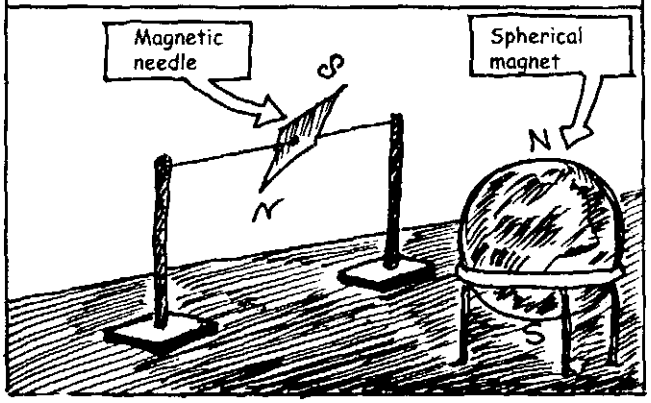


That is where the matter rested until the time of ..... William Gilbert (1544 - 1603)

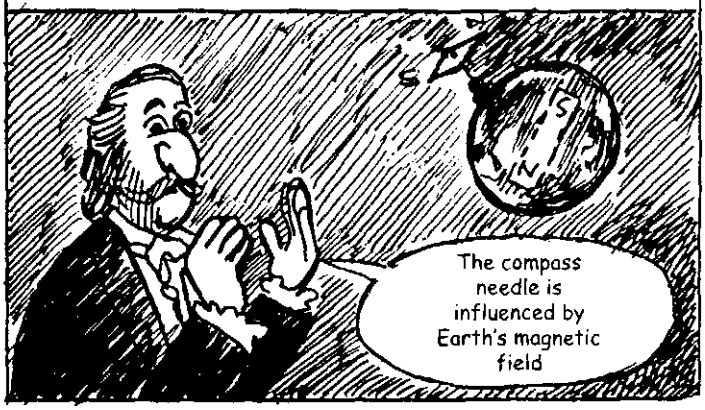
He noticed that a magnetic needle shows a "dip" towards Earth when vertical motion is allowed



Keeping a magnetic needle near a spherical magnet produced a similar "dip"



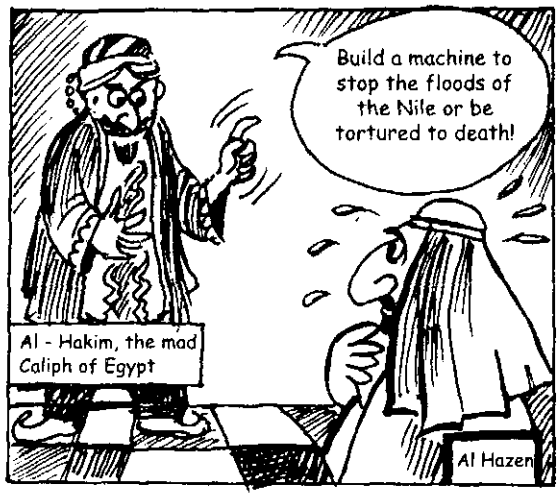
This made Gilbert suggest that Earth is a huge magnet!



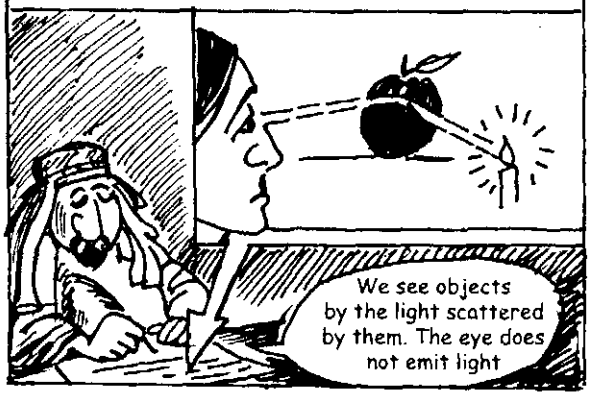
It was known, since the days of the Greeks, that rubbed amber could attract pieces of straw....

....Gilbert discoverd this effect in many other materials and called them "electrics"

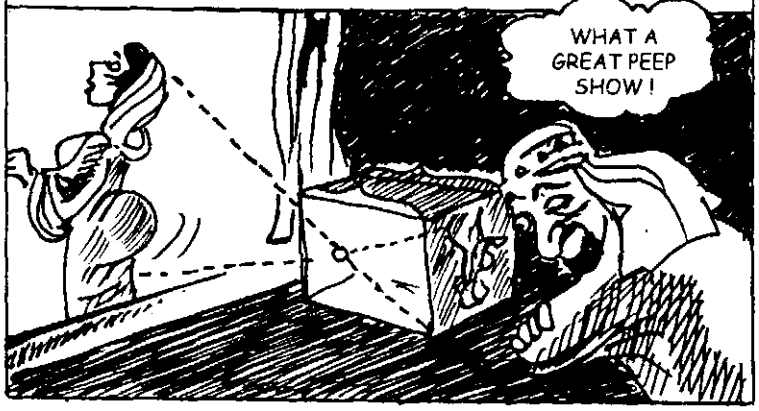
Another branch of physics wherein some development took place was Optics. Al Hazen (965 -1039AD) led an eventful life....



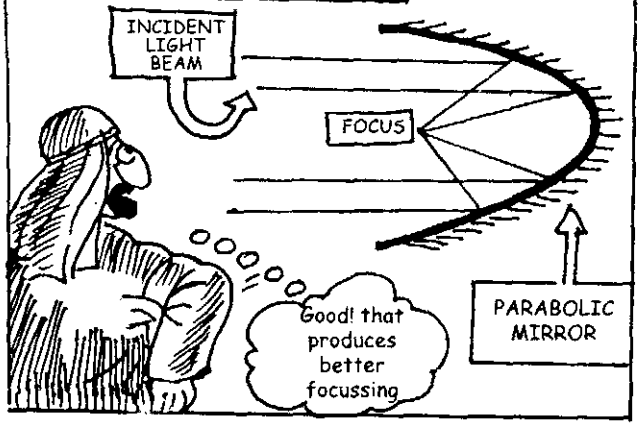
Al Hazen pretended insanity and conducted his experiments secretly!



He also constructed the pin-hole camera....



.... and parabolic mirrors!

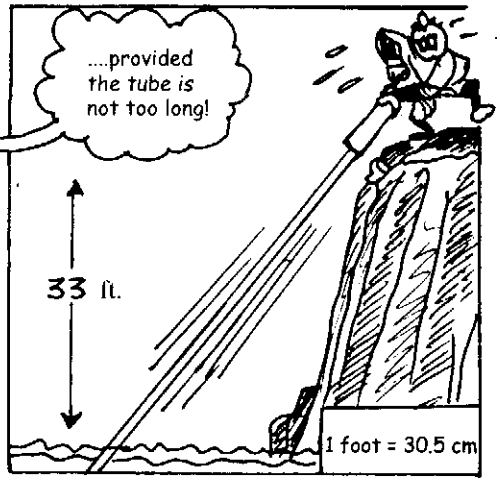


Al Hazen studied lenses and the phenomenon of refraction and reflection but failed to invent the telescope!

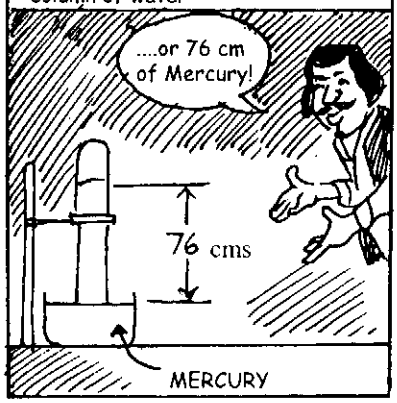
During his last days, Galilei had an able secretary....

E. Torricelli (1608 - 1647)

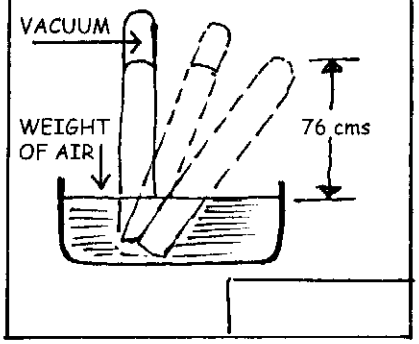
Torricelli was intrigued by the action of a piston



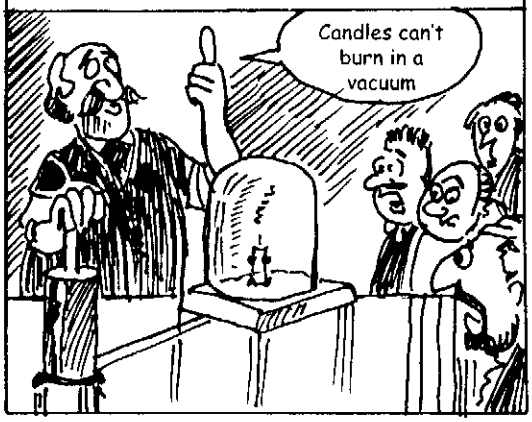
He concluded that it is the weight of air that supports the 33 foot column of water

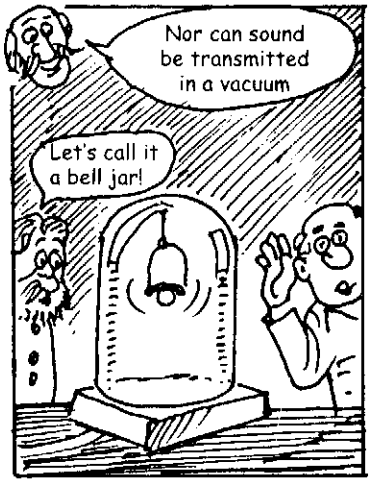


Above the mercury column was the first ever man-made vacuum (as can be verified by tilting the tube)

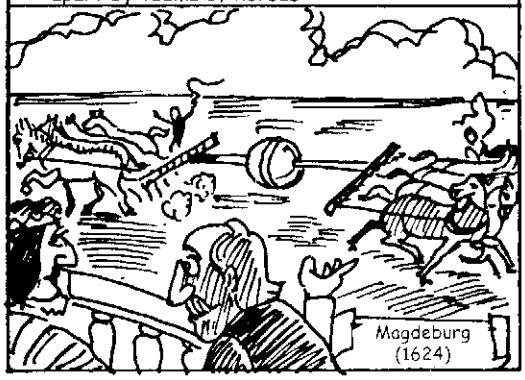


Otto von Guericke (1602 - 1686), a contemporary constructed the first air pump





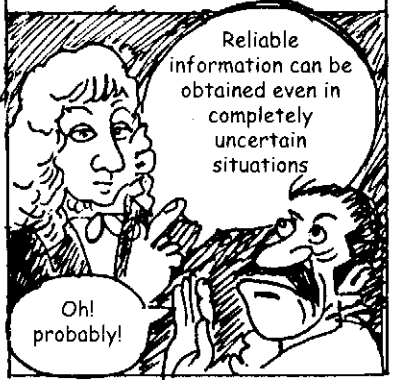
His famous experiment demonstrated the power of the vacuum in which 2 hemispheres held together by vacuum couldn't be pulled apart by teams of horses



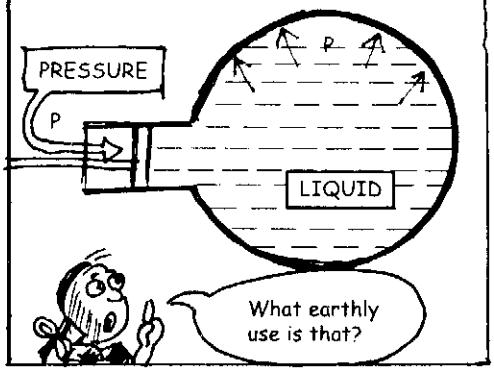
These ideas were taken further by Blaise Pascal (1623 - 1662), an infant prodigy

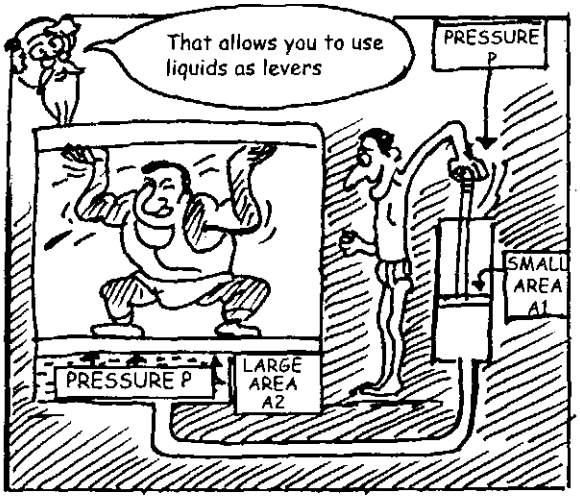
Pascal wrote a treatise on conic sections when he was 16, and made the first ever calculating machine at 19

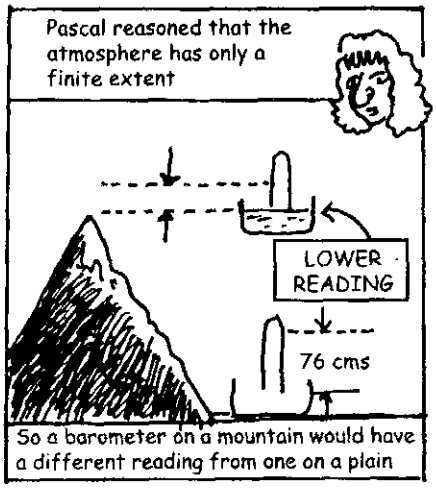
Pascal also founded the modern Theory of Probability which was extensively used in physics later



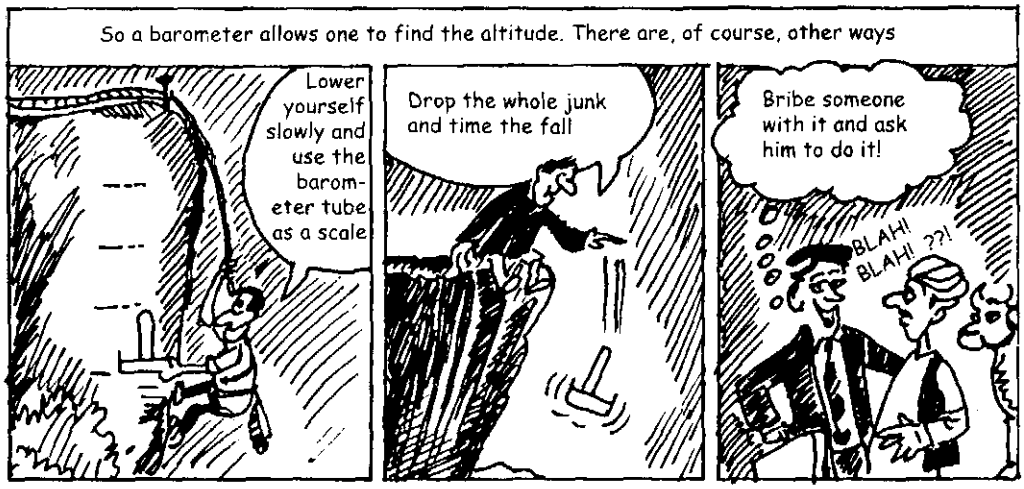
He realised that pressure applied on a liquid is transmitted undiminished




That allows you to use liquids as levers
PRESSURE P
SMALL AREA A1
PRESSURE P
LARGE AREA A2

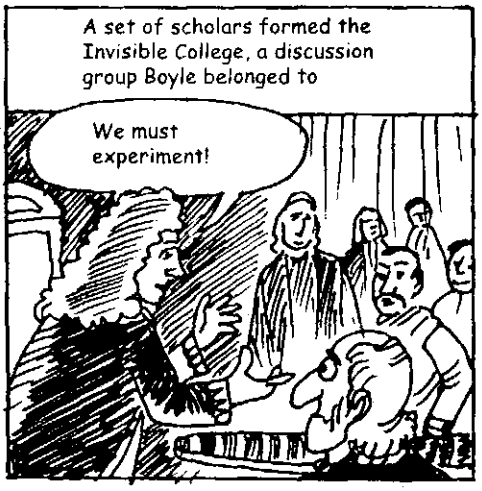

Pascal reasoned that the atmosphere has only a finite extent
LOWER READING
76 cms
So a barometer on a mountain would have a different reading from one on a plain

His brother-in-law verified this by climbing a mountain about a mile high
Hey! It's lower by 3 inches!

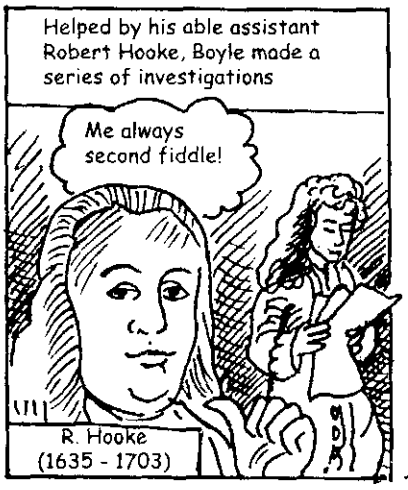

So a barometer allows one to find the altitude. There are, of course, other ways
Lower yourself slowly and use the barom-eter tube as a scale
Drop the whole junk and time the fall
Bribe someone with it and ask him to do it!
BLAH! BLAH! ??!

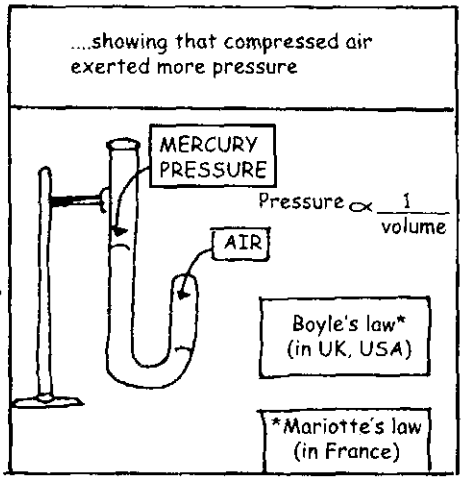
The next significant step in the study of pressure was taken by
Robert Boyle (1627 - 1691)

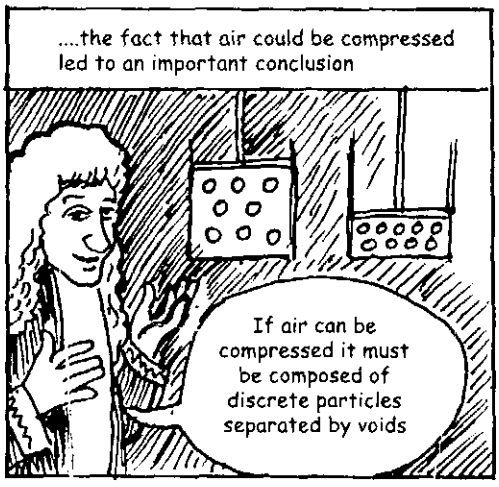
Just after the English civil war


A set of scholars formed the Invisible College, a discussion group Boyle belonged to
We must experiment!

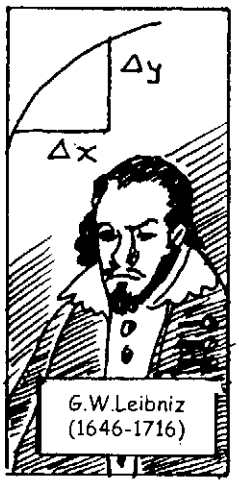
Once King Charles came to power, the Invisible College became the Royal Society
The Royal Society
"Nullis in Verba*
* "NOTHING BY MERE AUTHORITY"


Helped by his able assistant Robert Hooke, Boyle made a series of investigations
Me always second fiddle!
R. Hooke (1635 - 1703)

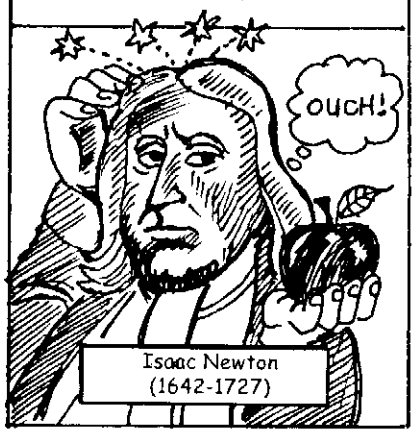

....showing that compressed air exerted more pressure
MERCURY PRESSURE
AIR
Pressure ∝ 1/volume
Boyle's law* (in UK, USA)
*Mariotte's law (in France)


....the fact that air could be compressed led to an important conclusion
If air can be compressed it must be composed of discrete particles separated by voids

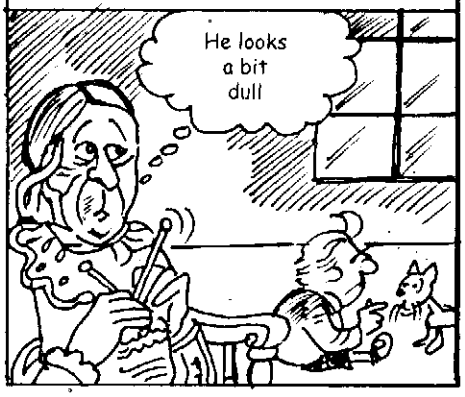
The latter half of the 17th century had an impressive starcast in European science...



....but the king among them was...

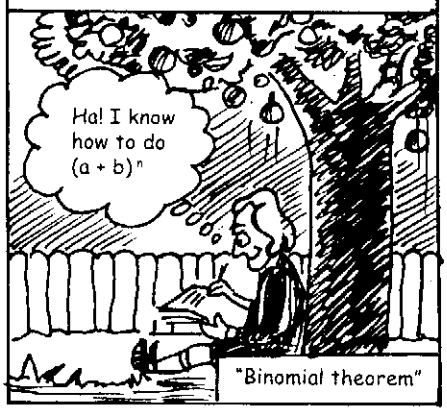


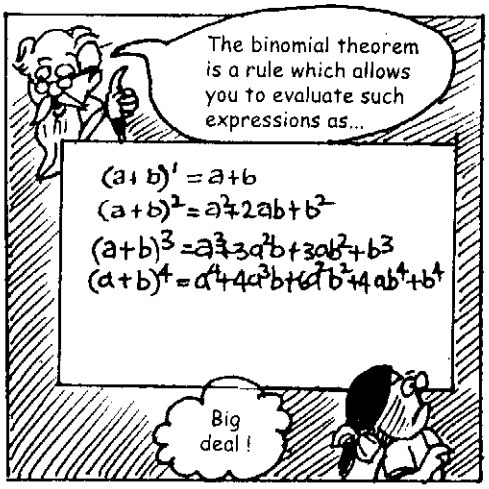
Newton, a christmas baby, was cared for by grandparents in his early years....

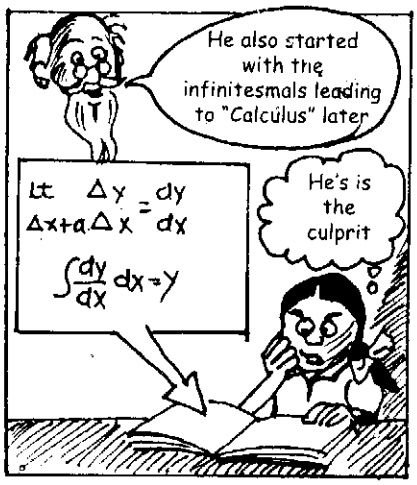


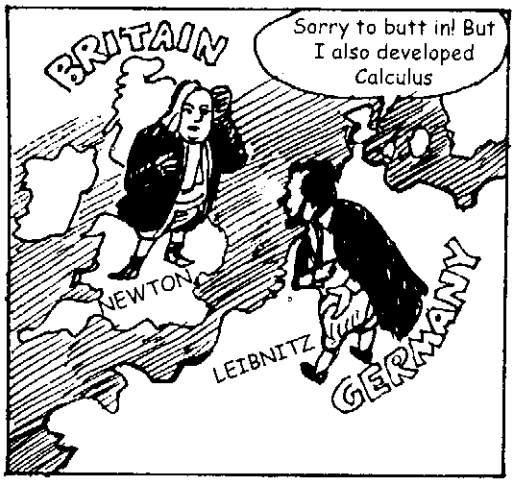
He graduated from Trinity College, Cambridge (1665), and survived the plague years (1666 - 67) on his mother's farm

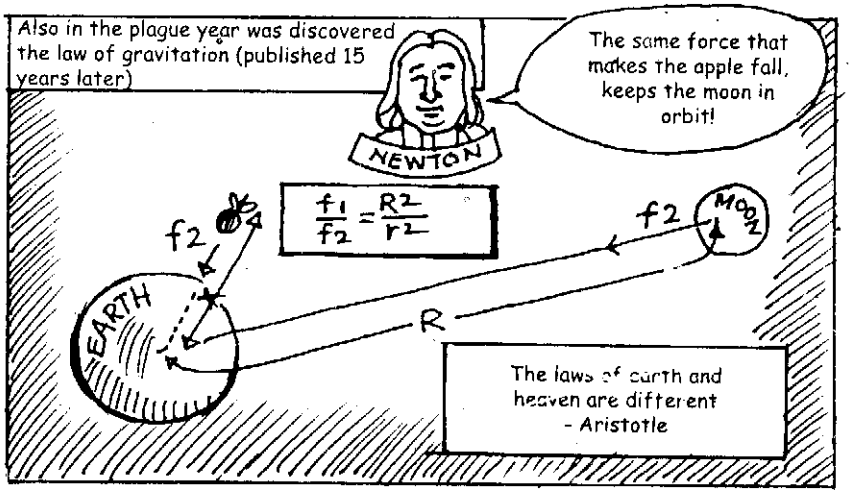
Once out of Academic Institutions, his genius flourished

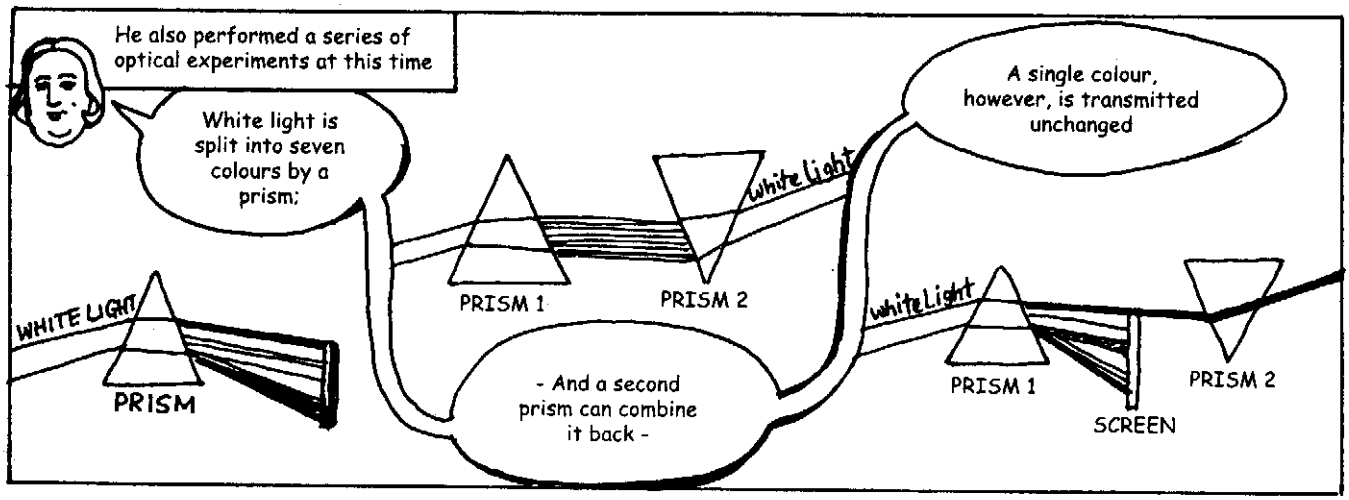




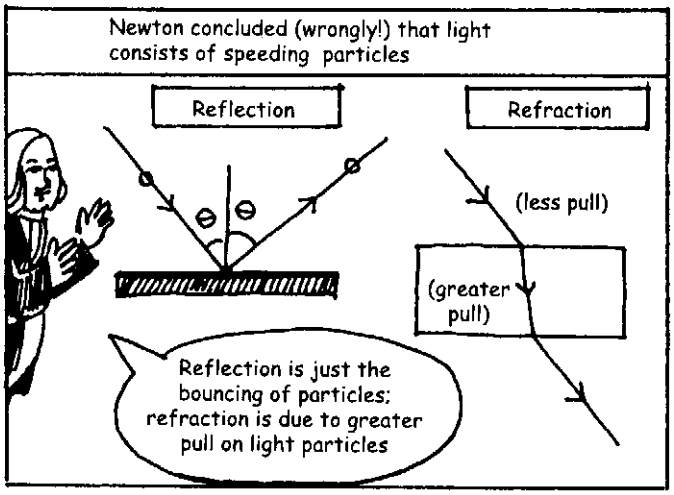


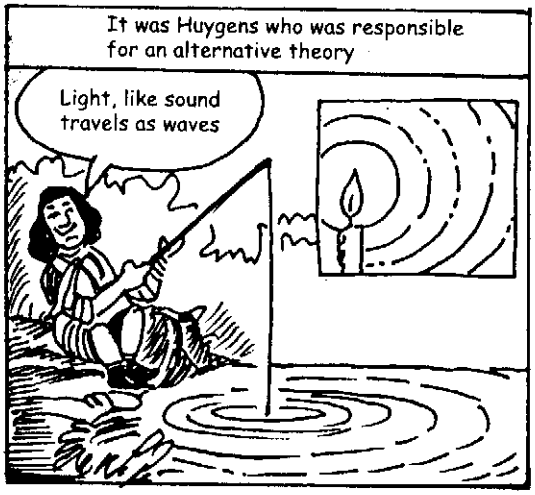


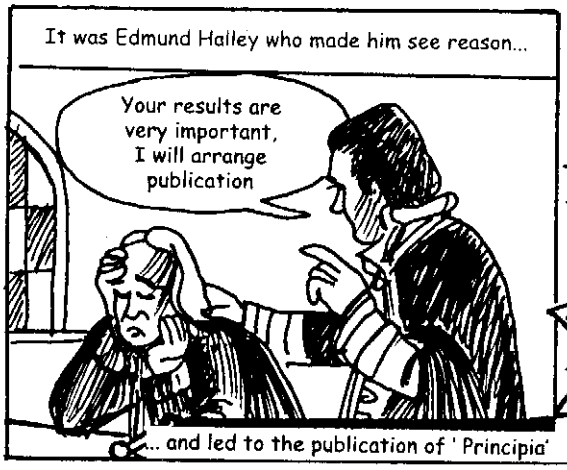


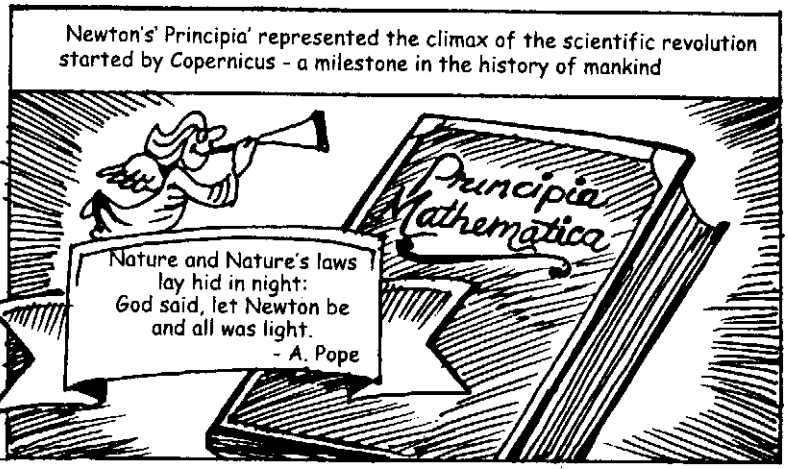


These experiments brought Newton fame and honour (Cambridge professorship in 1669, FRS in 1672) and also life long enmities, for example with Hooke



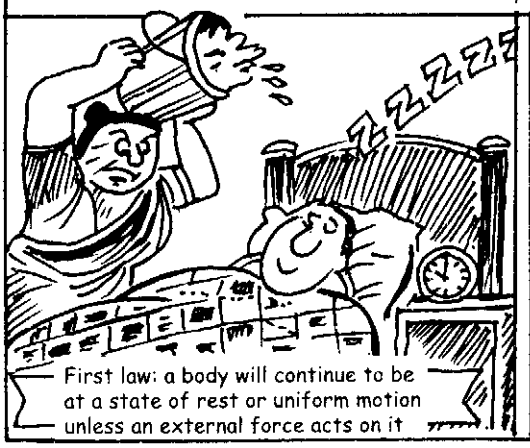






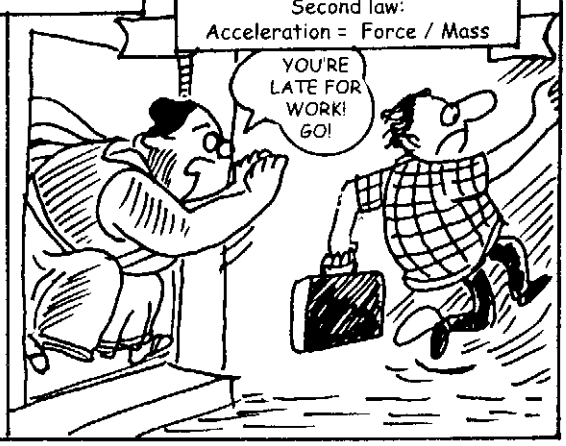
In his "Mathematical Principles of Natural Philosophy," Newton developed a comprehensive scheme for the mechanical universe

He codified the laws of motion, conceived by Galilei

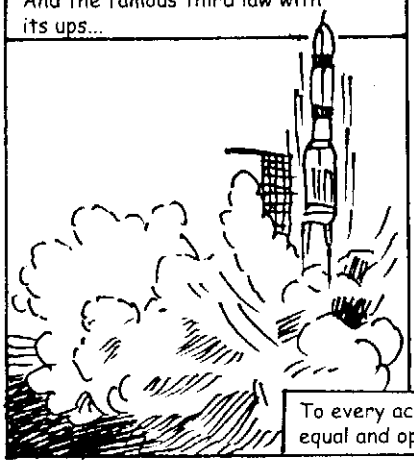


First law: a body will continue to be at a state of rest or uniform motion unless an external force acts on it

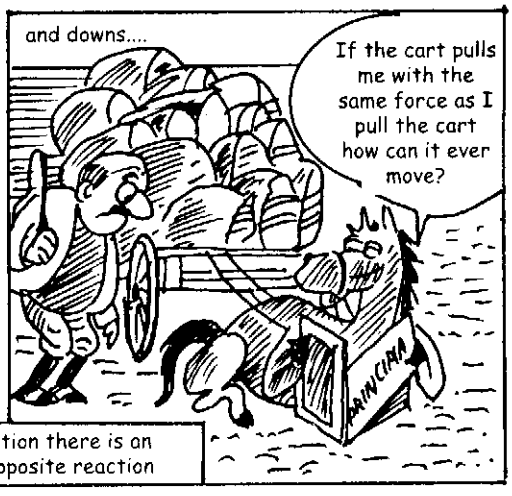
Second law: Acceleration = Force / Mass



And the famous third law with its ups...

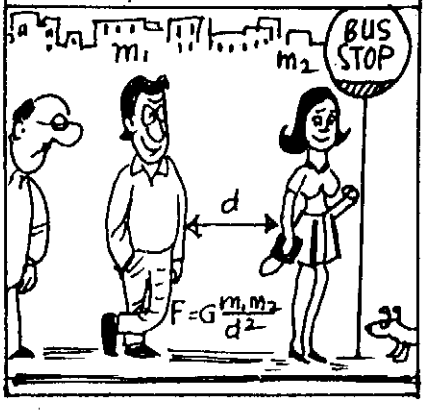


and downs....

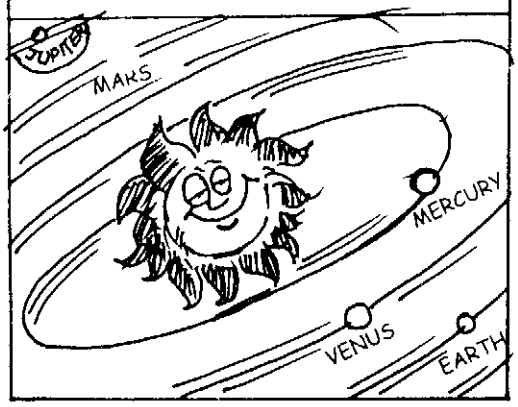


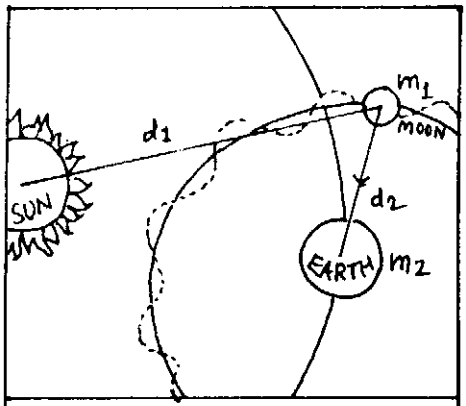
To every action there is an equal and opposite reaction

With tremendous intuition, Newton postulated gravitational attraction between any two bodies in the universe

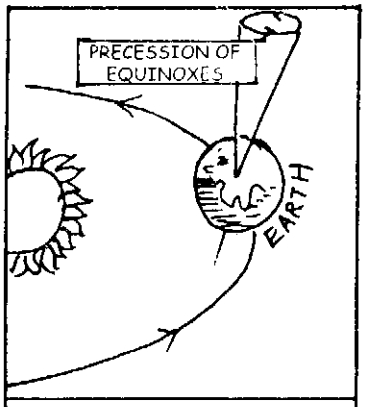


Newton could now derive Kepler's laws of planetary motion, setting the heavens in order.





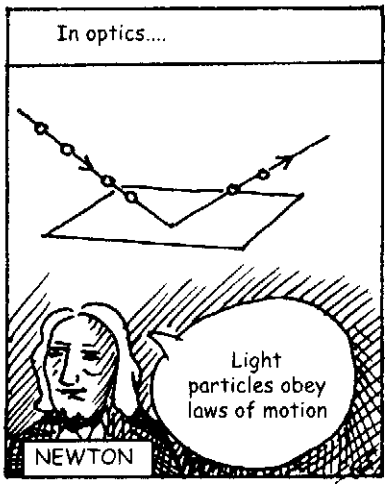
He could explain the irregular motion of the Moon....



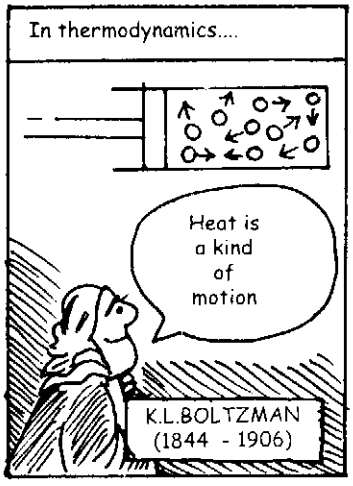
.... and the "wobbling" in the Earth's motion

As we shall see, Newton's mechanistic view of nature influenced physicists for a long time to come

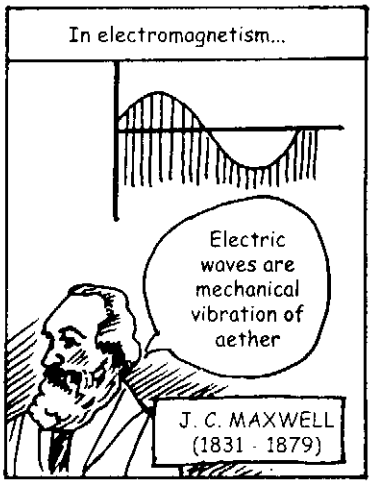
In optics....



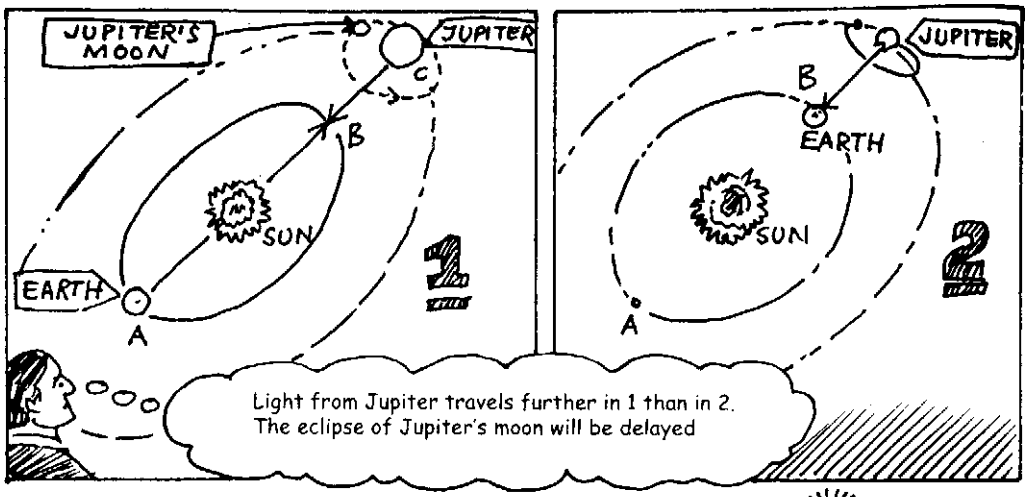
In thermodynamics....

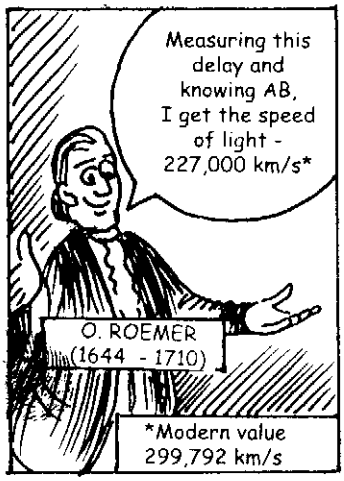


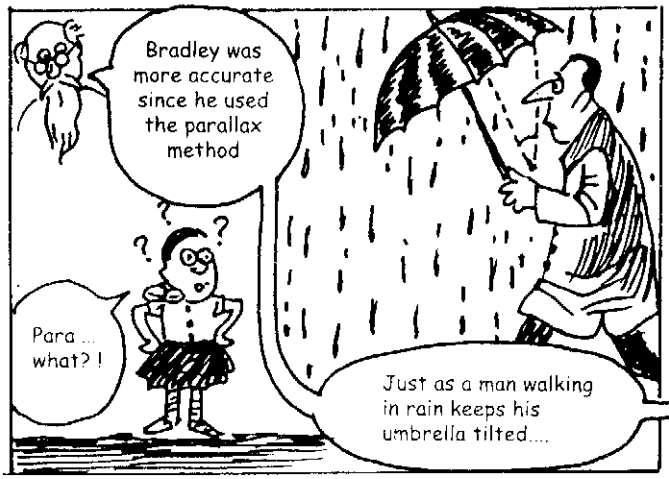
In electromagnetism...

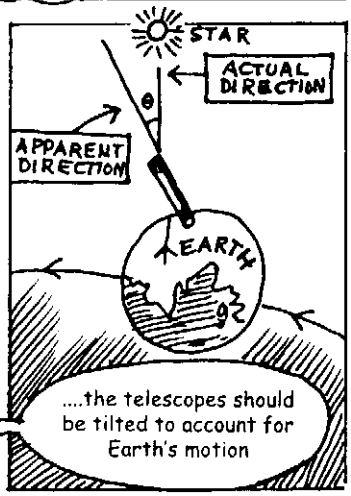


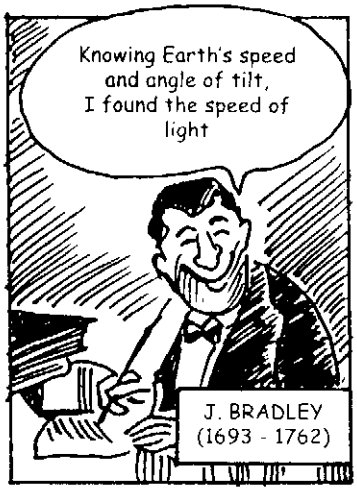
The post - Newtonian years witnessed a series of simple but important developments. Roemer measured the speed of light

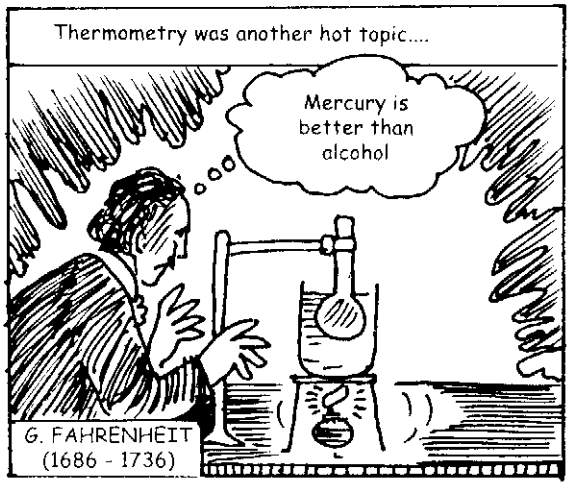


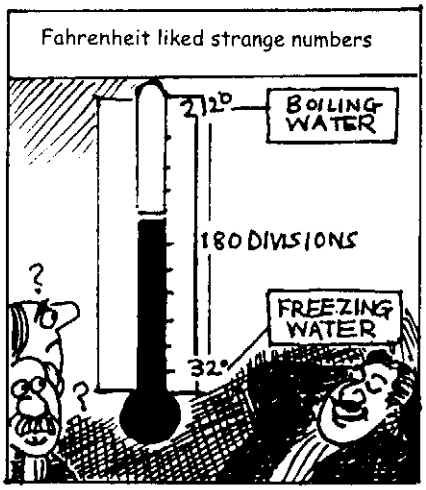


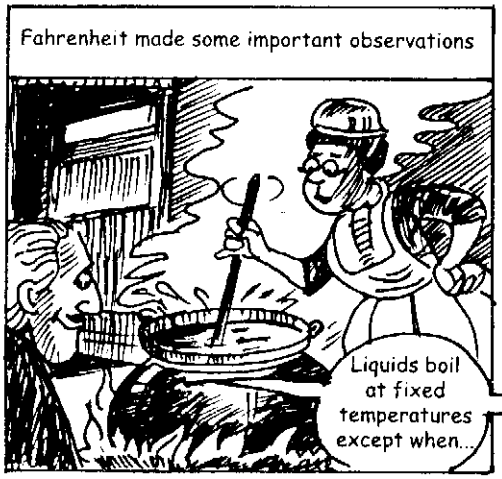


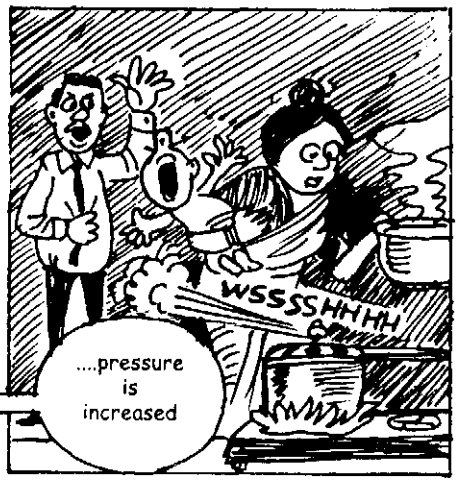




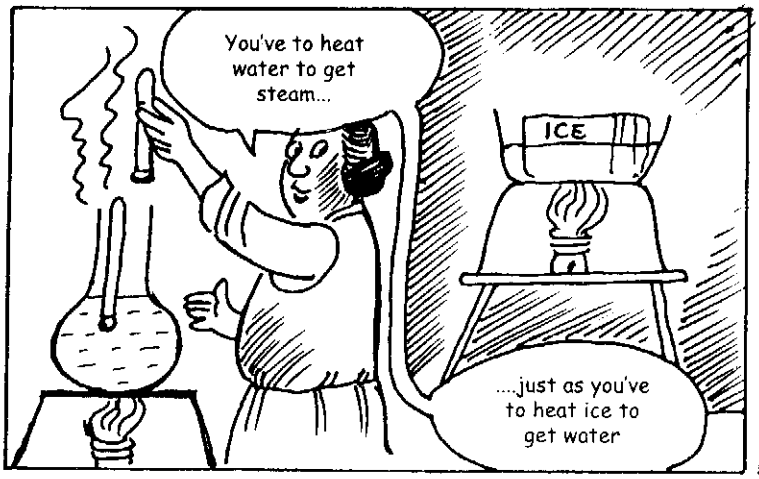


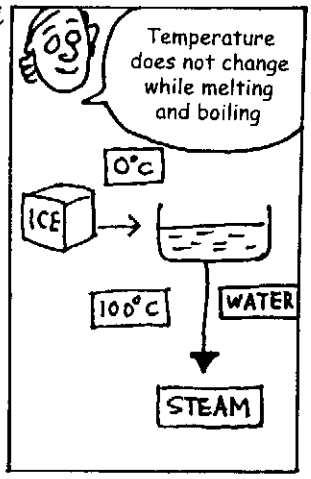


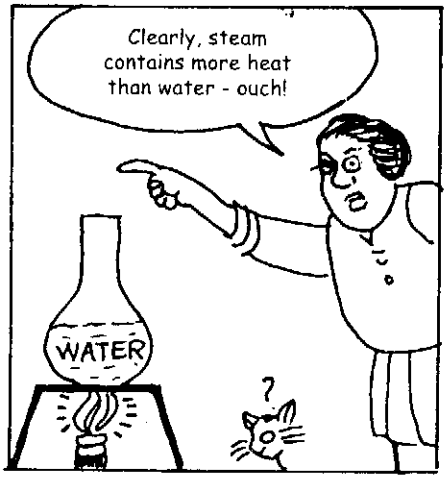


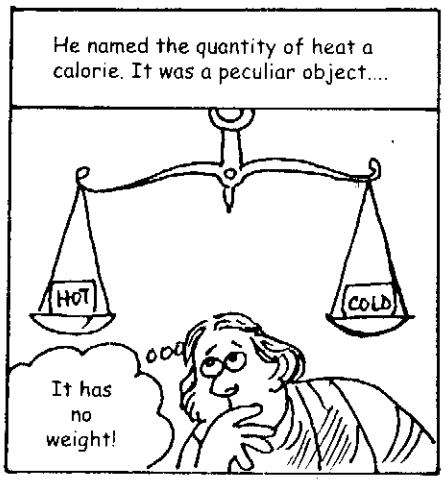


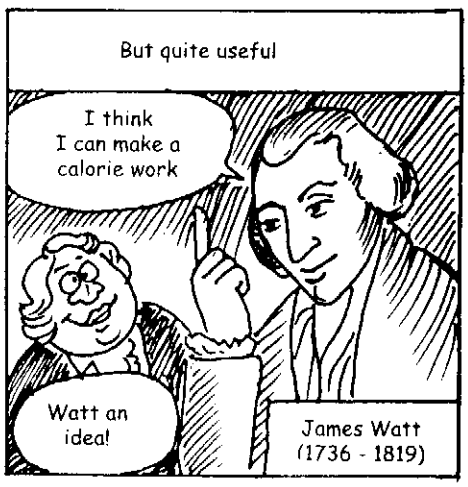
That there is more to heat than just temperature was first recognized by Joseph Black (1728 - 1799)

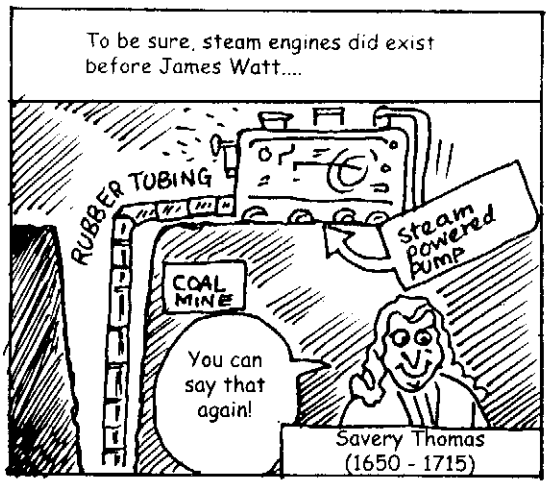


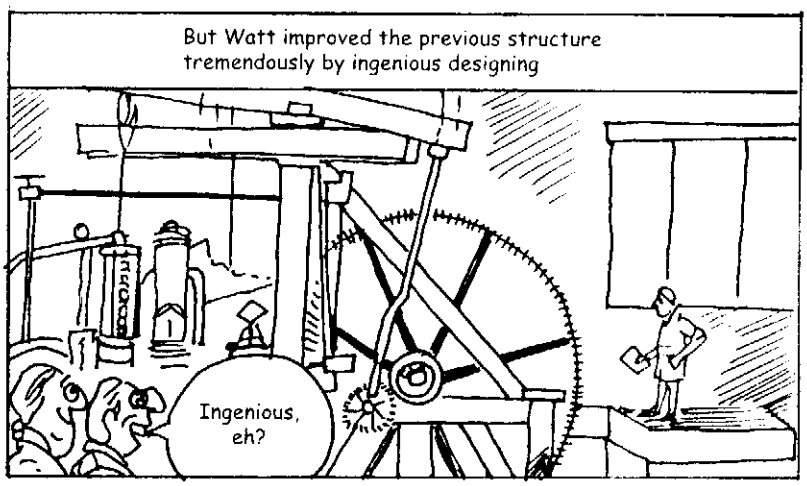




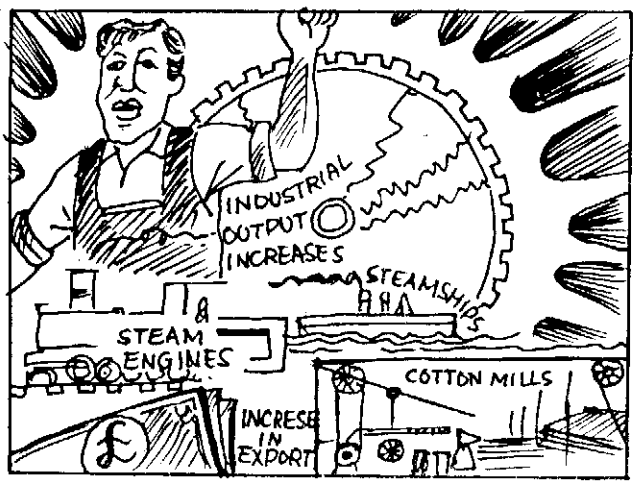


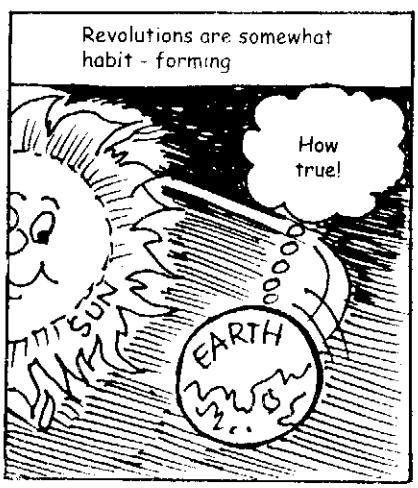






By the 1780's steam power was being used a lot, heralding the era of the Industrial Revolution....





There were others to follow: in America

I'm going to Britain

Count Rumford (1753 - 1814)

And in France...

HEH! HEH!

97....98...., 99.... ha! One more for a century

HUH?

Him next?

Amidst all this, Count Rumford worried about the real nature of heat

Watt's Steam Engine

Heat causes motion....

RUMFORD

....and the motion causes heat; are they related?

The popular view was against Rumford

Heat is a weightless fluid

Lavoisier (1743-1794)

And friction loosens up this fluid, causing heat

Lavoisier

Oh yeah! let me see

Rumford

Rumford measured the amount of heat produced on a brass boring job

UGH!

BRASS

More heat is released than required to melt brass!

BRASS

Since all this heat could not have been in brass....

....friction must be causing heat

Having disproved Lavoisier, Rumford proceeded to marry his widow. The marriage broke up soon with bitter words

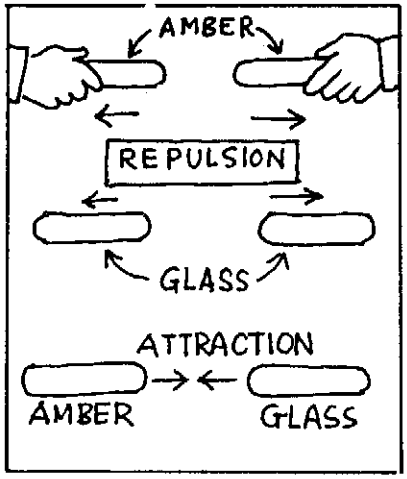
Lavoisier was lucky to be guillotined

you're a boring chap

In the meantime, electricity was coming of age

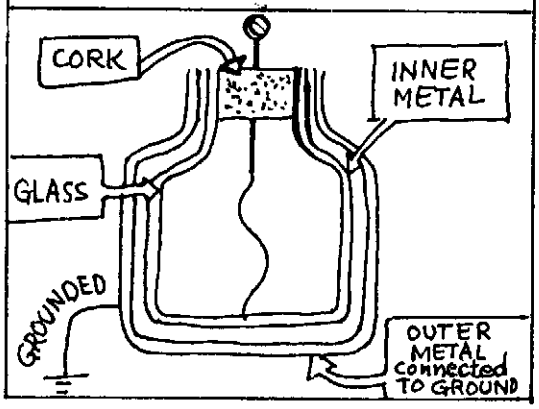
OUCH!

It was known by the 18th century that there are two kinds of electricity

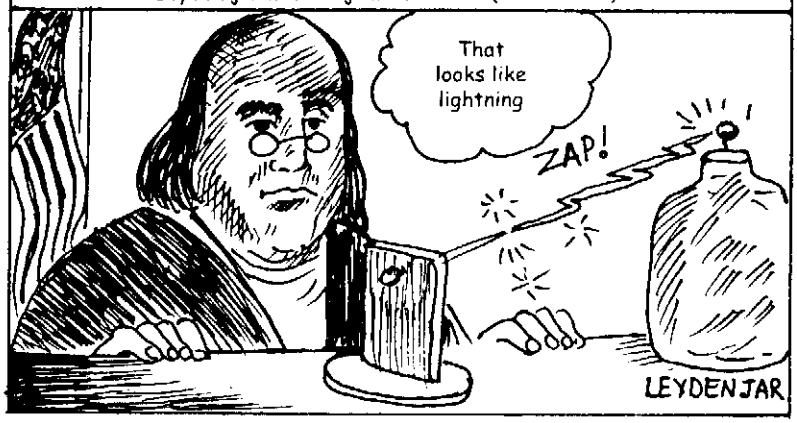


People knew how to store electricity

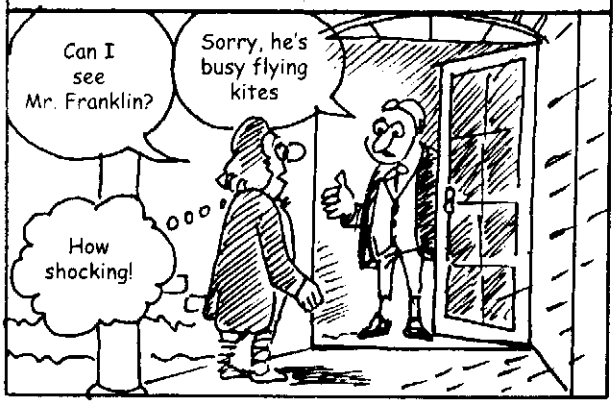
A Leyden jar consists of two metals separated by glass. The inner metal holds the charge

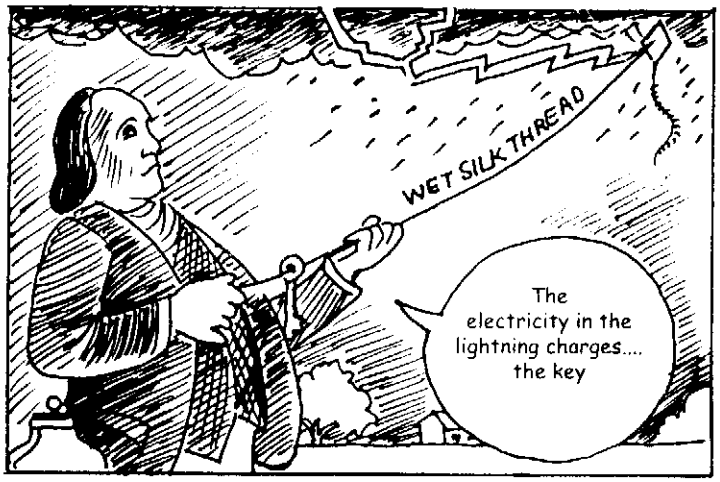


Among the many scientists experimenting with the Leyden jar was Benjamin Franklin (1706 -1790)

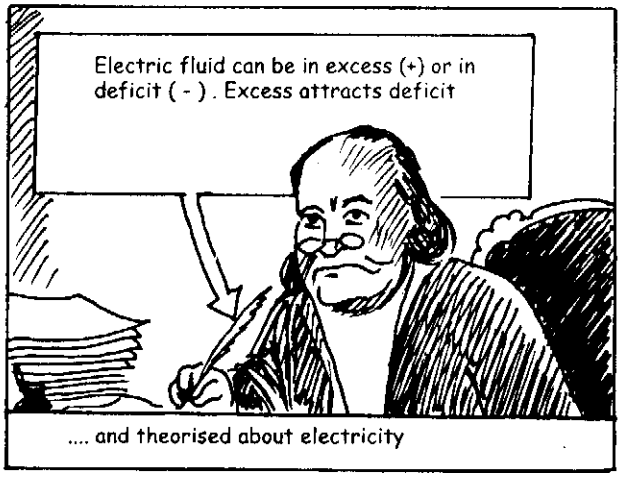


Franklin proceeded to check whether lightning was really an electrical phenomenon



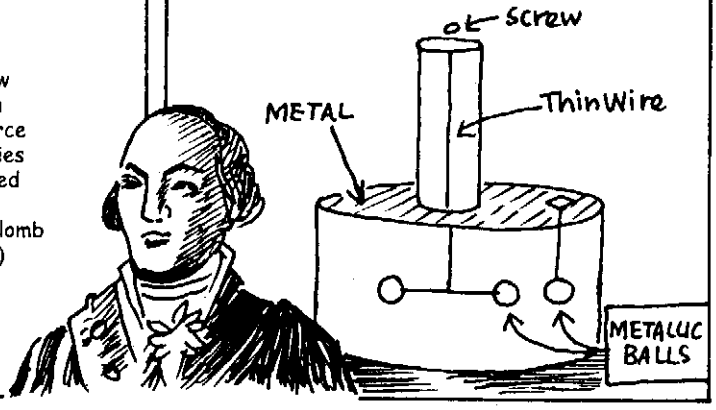


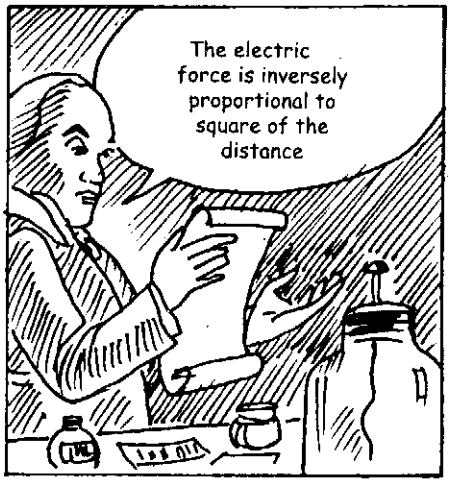
Franklin devised the first lightning arrester....



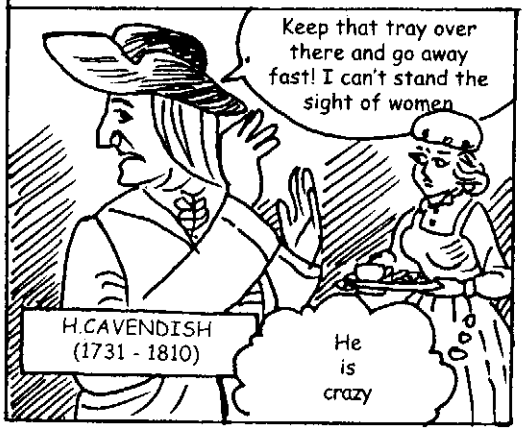
The exact law describing an electrical force between bodies was discovered by Charles Augustin Coulomb (1736 - 1806)

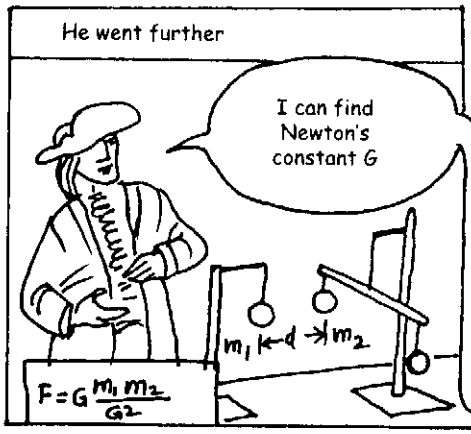
He devised a torsion balance to measure small forces

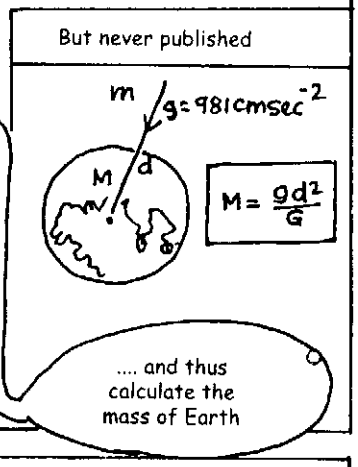


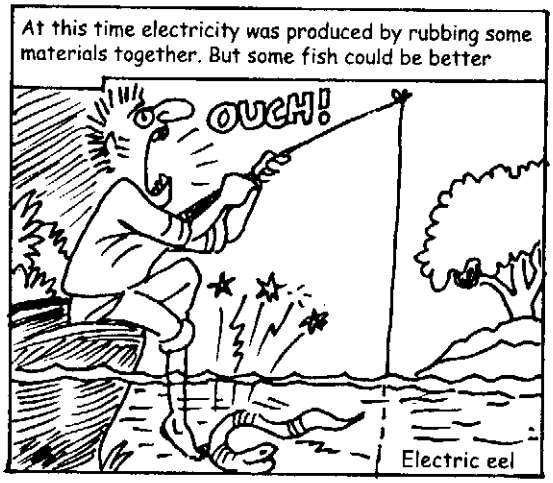


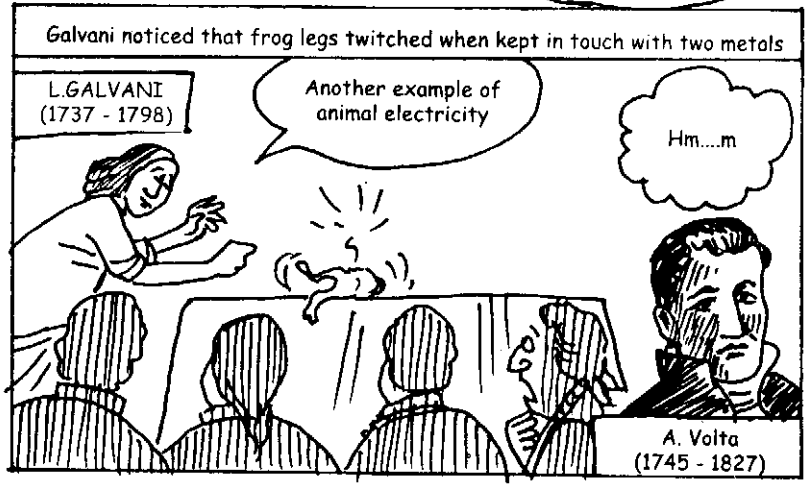
Meanwhile, a shy, recluse, also discovered this balance and the law

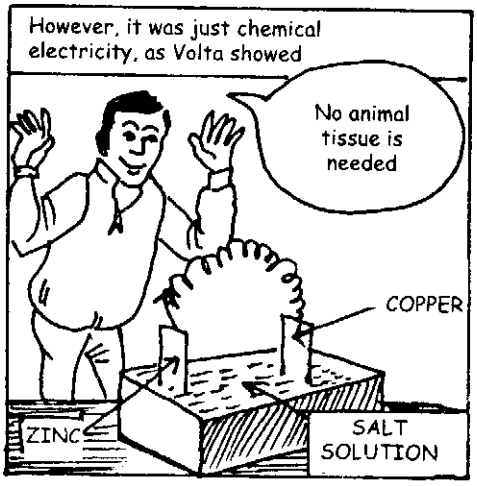


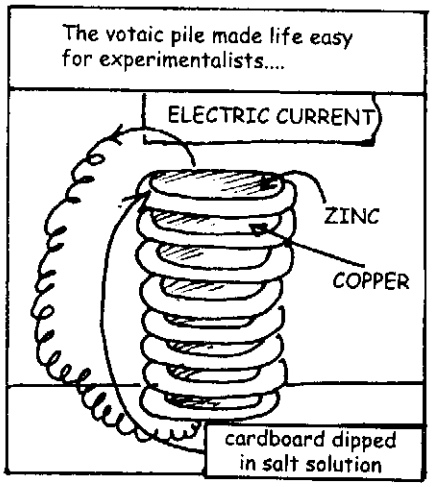


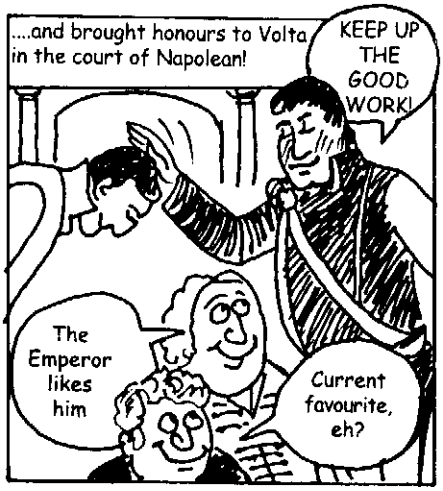












The voltaic pile made electrical experiments easy leading eventually to the unification...

.... of electricity and magnetism

Ha! an electric current does things to a magnetic needle

H.S.OERSTED (1777-1851)

STEADY CURRENT

VOL-TAIC PILE

The needle is deflected depending on the direction of the current

The experiment was followed by many, especiclly Ampere

Does one current affect another?

A. M. AMPERE (1775 - 1836)

VOL-TAIC PILE

It did !

When the currents are parallel, the wires attract, Mmm...

WIRE

Probably electric currents produce magnetism

Let me wind around a tube many turns of wire....

.... and pass a current through it

VOLTAIC PILE

Remarkably enough, the tube behaved like a bar magnet!

IRON FILINGS

*ELECTRO-MAGNET

It was a great moment in history

Electricity can cause magnetism

Ampere guessed right about magnetism

N S

Magnetic materials have tiny electric currents in them

I wonder if magnets can produce electricity

The answer was...

YES !

M. FARADAY
(1791 - 1867)

As one of ten children of a poor blacksmith, Faraday acquired an early advantage...

Look son! I can't afford your schooling

WOW !

....and put it to good use

Your book is bound but I'm reading it now. Come tomorrow

BOOK BINDERS

Having got a job with Humphrey Davy, he started electrical experiments

He could be my greatest discovery

H. DAVY
(1778 - 1829)

...and came up with startling results

A magnet moving in a coil produces a current

Clearly, magnetism caused electricity

MOVING MAGNET

S

N

DEVICE TO MEASURE CURRENT

COIL

Why not use an electromagnet?

TWO CHAIC PILE

He did and constructed the first "transformer"

A changing current induces the same in the second coil

Faraday's lecture demonstrations attracted vast crowds

Electricity can cause motion

He designed the forerunners of the electric motor and the dynamo - two milestones in technology

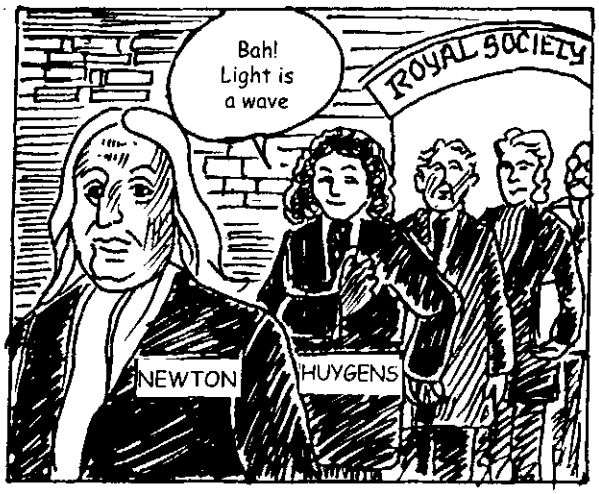
METER

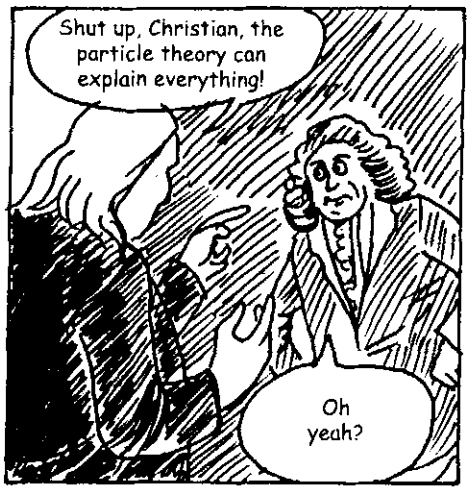
Probably more important, he completed the first unification of electricity and magnetism....

which soon led to the second unification

Let there be light

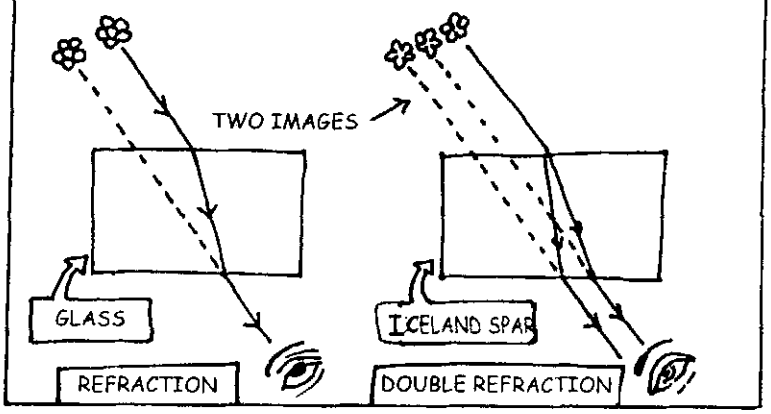
As we said before, Newton thought of light as particles, thereby casting sharp shadows





Everything? Not quite! There was this little trouble with a crystal called Iceland spar

Iceland spar split light into two beams...

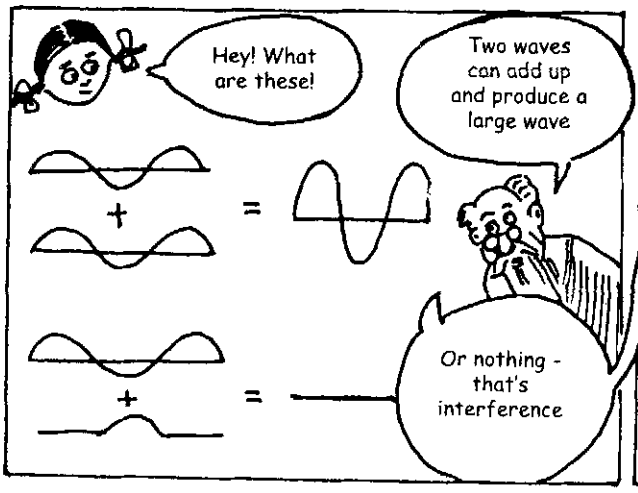


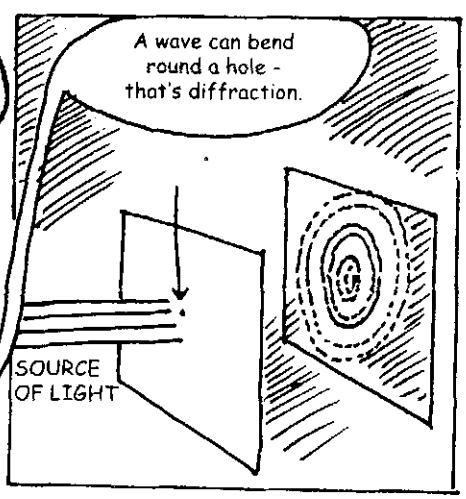
...which Newton couldn't explain....

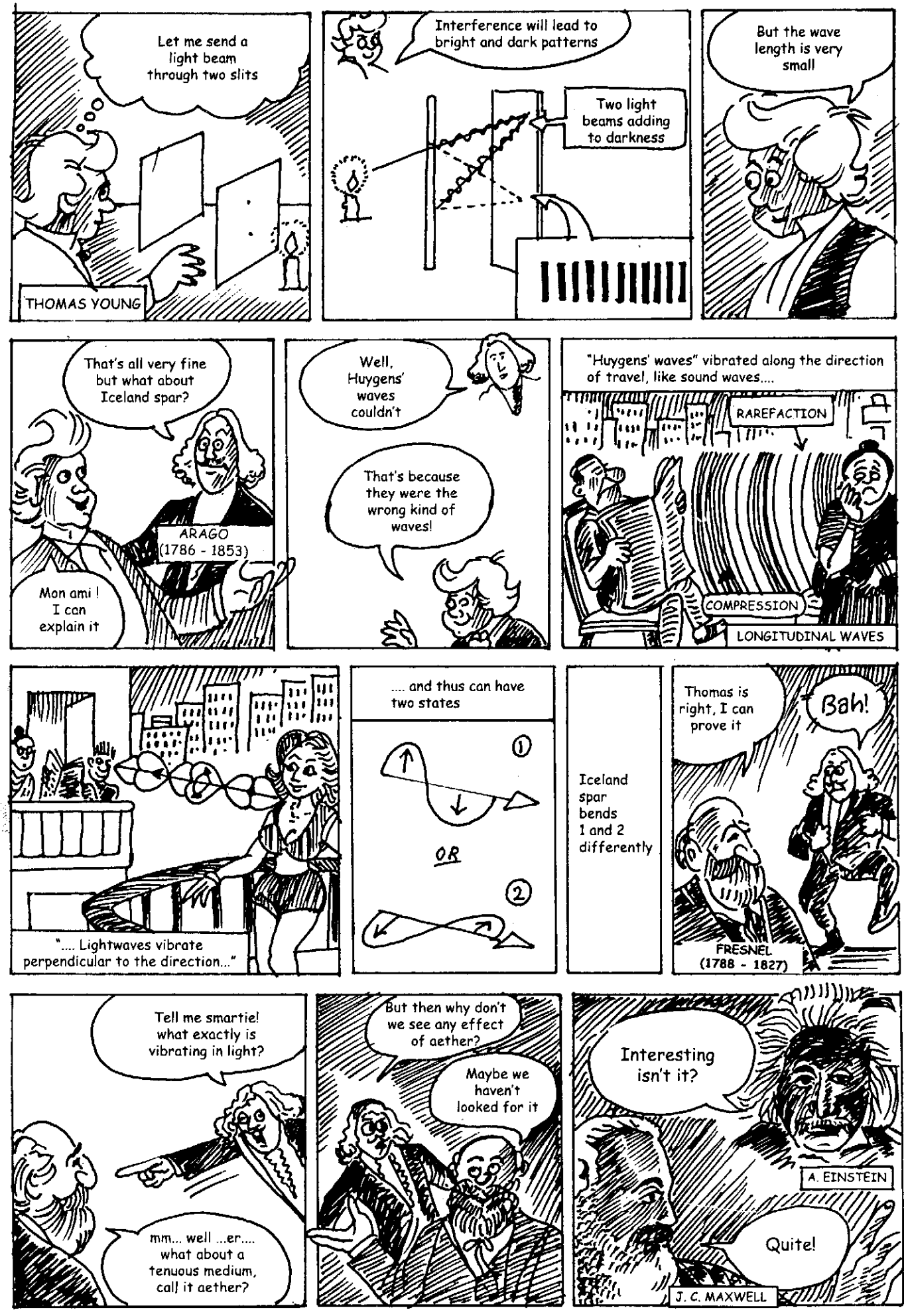
But then neither could Huygens!

These matters rested until the time of Thomas Young - another child prodigy

Young showed that light undergoes interference and diffraction






Let me send a light beam through two slits
THOMAS YOUNG
Interference will lead to bright and dark patterns
Two light beams adding to darkness
But the wave length is very small
That's all very fine but what about Iceland spar?
ARAGO (1786 - 1853)
Mon ami ! I can explain it
Well, Huygens' waves couldn't
That's because they were the wrong kind of waves!
"Huygens' waves" vibrated along the direction of travel, like sound waves....
RAREFACTION
COMPRESSION
LONGITUDINAL WAVES
"..... Lightwaves vibrate perpendicular to the direction..."
..... and thus can have two states
1
OR
2
Iceland spar bends 1 and 2 differently
Thomas is right, I can prove it
Bah!
FRESNEL (1788 - 1827)
Tell me smartie! what exactly is vibrating in light?
mm... well ...er.... what about a tenuous medium, call it aether?
But then why don't we see any effect of aether?
Maybe we haven't looked for it
Interesting isn't it?
A. EINSTEIN
Quite!
J. C. MAXWELL

The nature of light was illuminated by another intellectual giant James Clerk Maxwell (1831 - 1879)

Yet another infant prodigy....

Ha! Ha!

"Daffy" Maxwell! Ha Ha!

...whose first paper was read at Royal Society of Edinburg when he was 15

You know, this boy 'really has it

ROYAL SOCIETY

Later in his life he looked at electromagnetism....

Let me put together all that we know

$\varepsilon.\nabla.E=\rho$

There's this Coulomb's law

What's that funny ∇?

Forget it! That's the way people write it nowadays

And then there's Ampere's law?....

....current produces magnetism

OERSTED

$\varepsilon.\nabla.L=\rho$

$\nabla \times B \quad M.J.$

$\nabla \times E \quad -\frac{\partial \epsilon}{\partial t}$

Magnets can produce electricity

And that stuff due to Michael

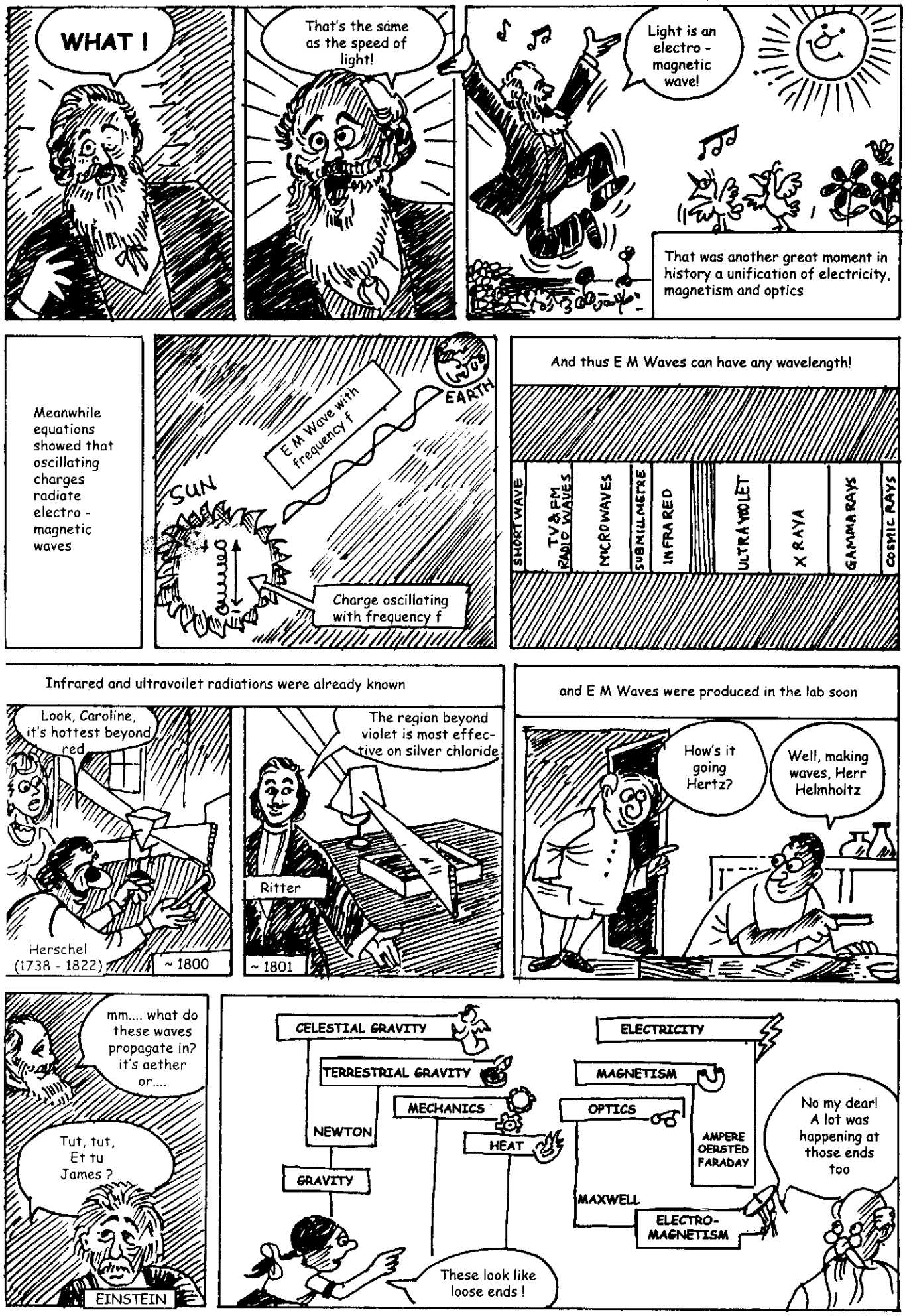
FARADAY

Oh! my! my! These are not okay!

Let me make it right

The correction led to remarkable consequences....

....There are wave solutions to these equations. Let me calculate the speed


WHAT !
That's the same as the speed of light!
Light is an electro - magnetic wave!
That was another great moment in history a unification of electricity, magnetism and optics
Meanwhile equations showed that oscillating charges radiate electro - magnetic waves
SUN
EARTH
E M Wave with frequency f
Charge oscillating with frequency f
And thus E M Waves can have any wavelength!
SHORTWAVE
TV & FM RADIO WAVES
MICROWAVES
SUBMILLIMETRE
INFRARED
ULTRAVIOLET
X RAYS
GAMMA RAYS
COSMIC RAYS
Infrared and ultravoilet radiations were already known
Look, Caroline, it's hottest beyond red
Herschel (1738 - 1822)
~ 1800
The region beyond violet is most effective on silver chloride
Ritter
~ 1801
and E M Waves were produced in the lab soon
How's it going Hertz?
Well, making waves, Herr Helmholtz
mm.... what do these waves propagate in? it's aether or....
Tut, tut, Et tu James ?
EINSTEIN
CELESTIAL GRAVITY
TERRESTRIAL GRAVITY
NEWTON
GRAVITY
MECHANICS
HEAT
These look like loose ends !
ELECTRICITY
MAGNETISM
OPTICS
AMPERE
OERSTED
FARADAY
MAXWELL
ELECTRO-MAGNETISM
No my dear! A lot was happening at those ends too

Joining heat and mechanics into "thermodynamics" was the work of many. To begin with there was Sadi Carnot

Terrible! Slow and expensive

Horses are better anyday

How efficient can a steam engine be?

S. Carnot (1796 - 1832)

He soon found the answer....

Hmmm.... even ideal engines aren't perfect

The efficiency of an ideal engine was less that one !

$E = 1 - (\frac{T_2}{T_1})$

T_1 = steam temperature

T_2 = cooling temperature

And most engines were far from ideal!

The engine you sold me ain't working!

Now, now, let me tell about Carnot cycles....

The connection between heat and motion was pursued by others

J. P. Joule (1818 - 1889)

W. T. Kelvin (1824 - 1907)

Joule made precise measurements of the heat produced by mechanical motion....

Churning heats up water

.... and had a scientific honeymoon

The water should be hotter there dear

?!!?

Finally he formulated the theory....

41, 800, 000 ergs of work produced one calorie of heat

.... which was rejected by journals....

CLONK!!!

OUCH!

....forcing Joule to start the practice of....

....doing science through* newspaper

what's all this junk?

Revolting stuff! isn't it?

*often only through

Joule began to be appreciated mostly through the influence of Kelvin

Come on now! He's talking sense

When a rolling ball comes to rest....

It has converted its kinetic energy to heat, thus raising the temperature

Kelvin now realised the importance of the "absolute scale of temperature" he had devised

100c
50°
0°c
-100°
- 200°
-273°c
373°k
273°k
73°k
0k
All motion ceases here

Heat as a form of energy led to the first law of thermodynamics, and to some....

WHEEL
PISTON
BOILER
FIRE
Total energy = Heat + Mechanical energy = Constant
HLF von Helmholtz (1821 - 1894)

.... disturbing questions !

Look Thomson! Why can't a ball start rolling all by itself lowering it's temperature?

Mmm.... that's a tough one

The answer was the 2nd law of thermodynamics;

$S = \int \frac{dQ}{T}$

"A closed system cannot reduce its level of disorder"

Classius (1822 - 1888)

* also called entropy

What disorder?!

Look! When this lid is removed

GAS
VACUUM
GAS
.... gas fills the box

But it will never go back to the initial state on its own!

GAS
GAS
VACUUM

What! never?

Oh, never!

Really, never?

Oh, hardly ever!

The 2nd law explains many observations....

A ball does not roll by itself lowering temperatures

Heat does not flow from cold bodies to hot ones

Milk and coffee, once mixed, do not unmix by themselves

But to explain the 2nd law on needs kinetic theory of gases

S. Boltzmann (1844 - 1906)

The complete connection between heat and mechanics was established by the works of Maxwell and ...

S. BOLTZMANN

The nature of motion we call heat ....

Gas consists of a large number of molecules obeying mechanical laws....

Thus gas properties can be derived from mechanics

PUFF HUFF PUFF

HUFF PUFF

Why don't all the molecules of the gas stay like this?

volume v/2

EMPTY

Total volume v

Simple! The chance for one molecule to be on the left half is (1/2)....

The chance for N molecules is (1/2 x 1/2 .... N times)

$P = (1/2)^N$

For a gas with 10^{23} particles this number is so low that it never occurs

$\frac{1}{10.0....00}$ (10^{22} zeros)

Boltzmann explained that pressure was due to molecular motion....

Pressure
= (number of collisiions / sec) x (momentum)
~ (nv) (mv)

Average velocity = v

....So that temperature became just a measure of random motion

I tell you! It's a hot game

To every degree of freedom of motion Boltzmann associated fixed energy

$E_\theta = 1/2\ KT$

VIBRATION

MOTION

ROTATION

Total Energy = $6\ E_\theta$

.... Which seemed to explain many observations but not all !

U=NkT

The calculated specific heat of gases is all wrong!

Similar difficulties occured when Boltzmann's ideas were used to explain emission of light by a hot black cavity

ENERGY

THEORY

OBSERVED CURVE

FREQUENCY

Rayleigh computed the number of different vibrational modes for light in the cavity

LORD RALEIGH (1842 - 1919)

Let me see, the wave-lengths can be 2L, 2L/2, 2L/3 .... 2L/10 .... 2L/1000..., There can be an infinite number of them....

....each carrying an energy (kT) there will be infinite energy in any cavity

$E \sim \int \nu^2 kT d\nu$

What rubbish is this!?

First indications of rigorous theory leading to manifest nonsense!

Specific heat of gases

Black body radiation

The behaviour of light was to create more headaches soon

Look, I can throw these with velocity v standing still....

A. MICHELSON (1852 - 1931)

E. MORLEY (1838 - 1923)

So if I do it running at speed u, then they travel with speeds (v + u) and (v - u)

(V+U)

(V-U)

Hey! watch out!

CRASH!

Ouch! Now.... you.... see.... Oops....

Hey! careful!

"Light was supposed to travel by vibrations in aether....

SUN

AETHER

EARTH

...in which case, Earth moving through aether will change the velocity of light in different directions"

C+V

C-V

EARTH

Earth's velocity v

A sensitive experiment to detect this effect....

.... produced a null result!

Is the speed of light independent of the motion of the source?

But ... how can that be?!

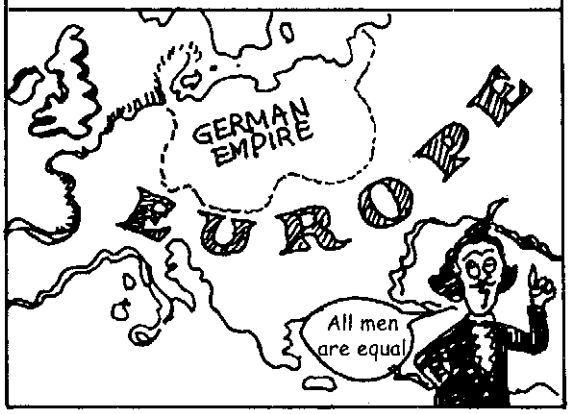
How is physics, Herr Professor?

Oh, good! Good except for these specific heat and aether experiments

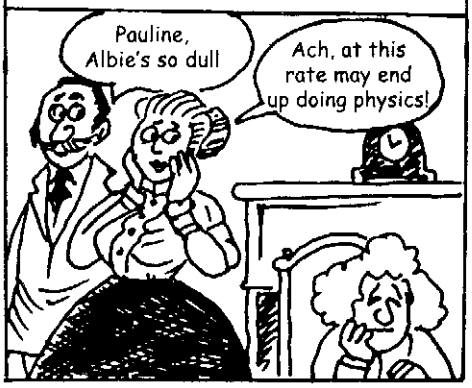
That's how physics was at the end of the 19th century

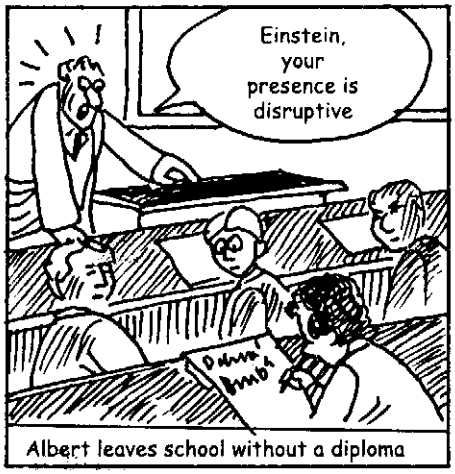
The problems of classical physics led to a drastic revision of basic concepts, via relativity and the quantum theory. Relativistic revolution was the work of...

... a boy born in 1879, Albert Einstein



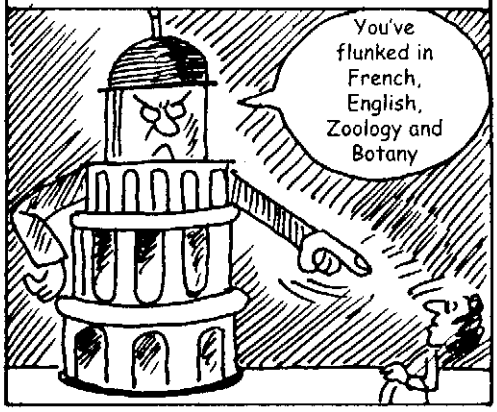
Albert's early life would give hope to every dumb nitwit.....



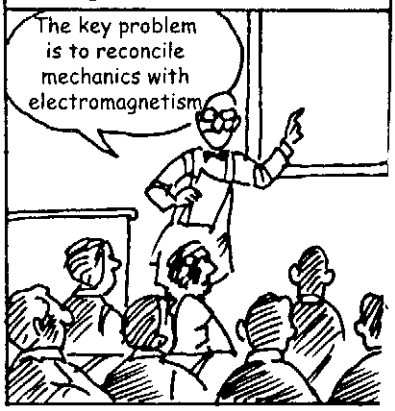


Albert leaves school without a diploma

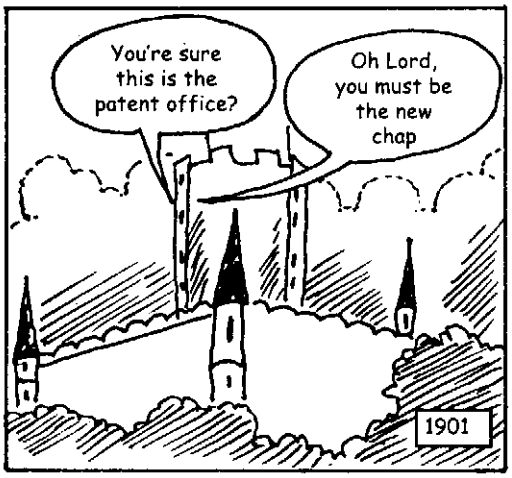
.... and fails miserably at the entrance test in Eth, Zurich



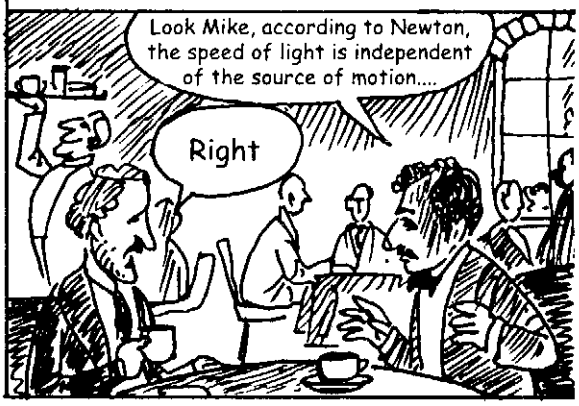
Joins C Antonal School at Aarau and graduates in 1896

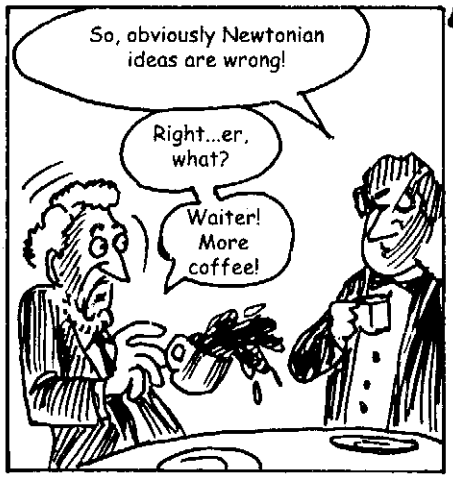


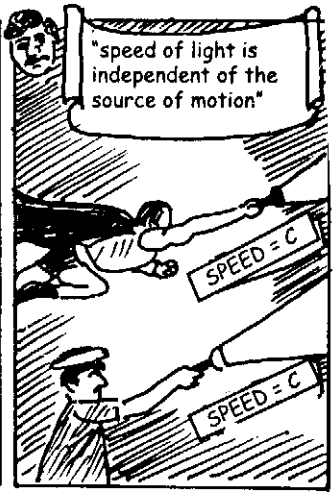
After five years in Zurich, he gets a job at Bern, only because of the influence of a friend Marcel Grossmann



Albert used to discuss physics with his friend Mike Besso







Albert also believed that the laws of physics should not distinguish between state of rest and state of uniform motion

EINSTEIN: "we shall raise this conjecture ("relativity") to the status of a postulate...."

GALILEO: Watch out for the Church!

Given these, what happens?

Oh, I can prove a lot of stuff now

To begin with, the flow of time is relative

I don't like him

Yean.... a Jew boy

"Use a light beam to measure time

LIGHT RECEIVED

LIGHT REFLECTED

LIGHT EMITTED

L

Light travels different distances according to different observers"

Distance = 2L

L

MAN IN TRUCK

Light has travelled more than 2L

Different distances, same C.... Mmm, different rates for watches!

Calculation shows....

$$t = \frac{t'}{\sqrt{1-v^2/c^2}}$$

t = time elapsed for man on road
t' = time elapsed for man in truck
v = speed of truck

Absolute time flows equably without relation to anything
- Newton

Will you stop these maddening derivations and get on with the facts!

Okay, okay, keep your hat on

Albert had a few more "simple conclusions:
(i) simultaneity is relative

All start at the same time

Simulta-neously, eh?

(ii) velocity addition is different and ....

EINSTEIN: $u = \frac{V_1 + V_2}{\left(1 + \frac{V_1 V_2}{c^2}\right)}$

NEWTON: $u = V_1 + V_1$

$V_1 = c$

$V_2 = c$

How fast is that light? let me see

$u = \frac{c+c}{1+\frac{c}{c}} = c$

(iii) $E = mc^2$!

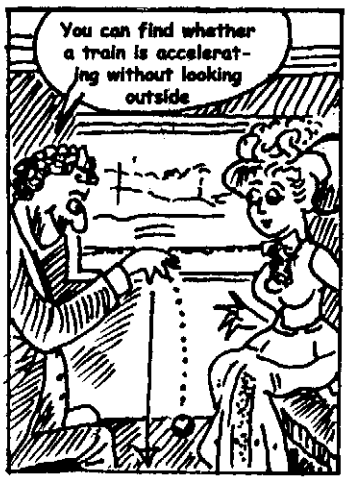
~~$A = mc^2$~~
~~$B = mc^2$~~
~~$C = mc^2$~~
~~$D = mc^2$~~
$E = mc^2$

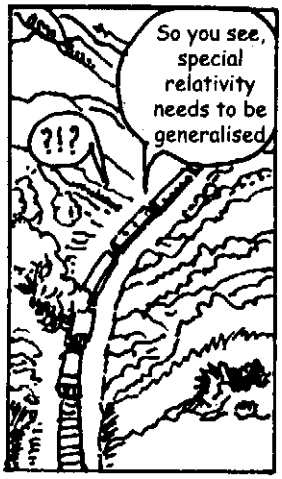
Most popular formula of this century

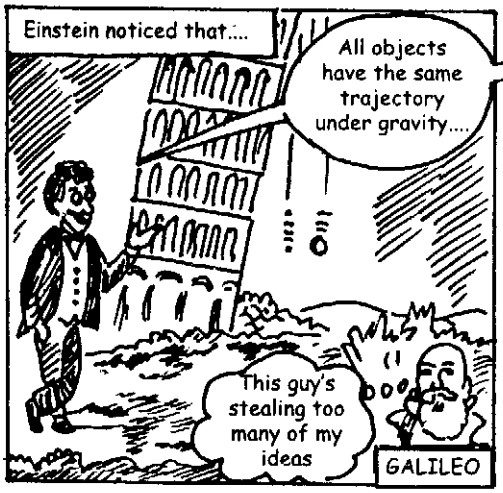
Albert, however, was not satisfied

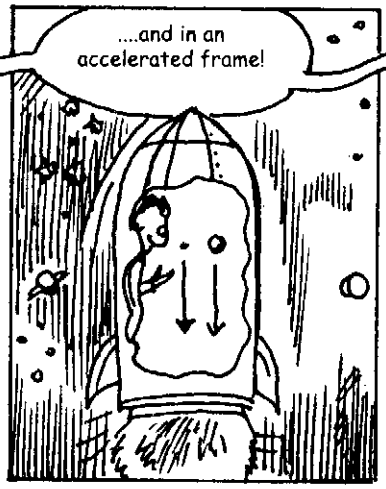
It's still incomplete. Why only uniform motion?

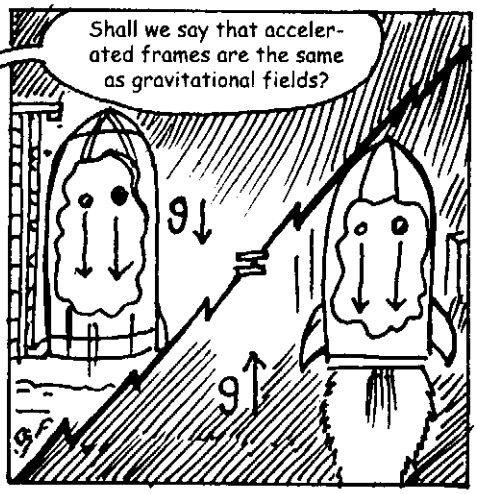
Dissatisfied with the role of motion Einstein generalised further, constructing the most beautiful theory devised so far

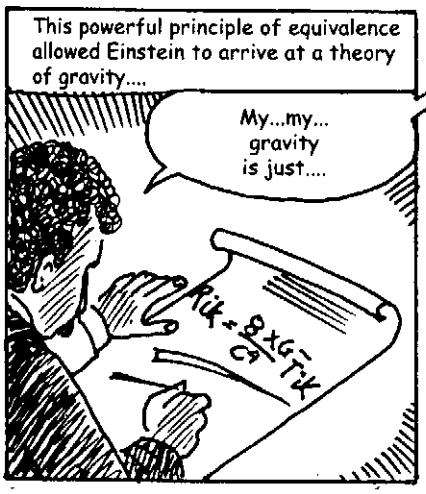


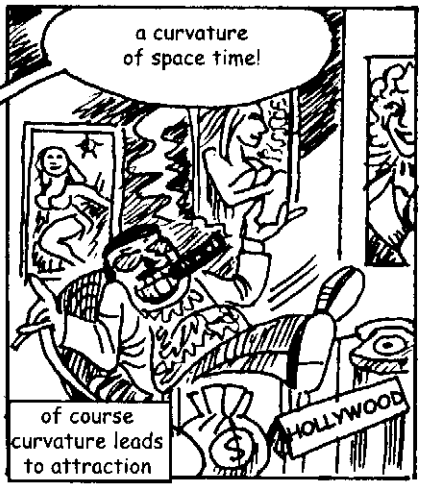


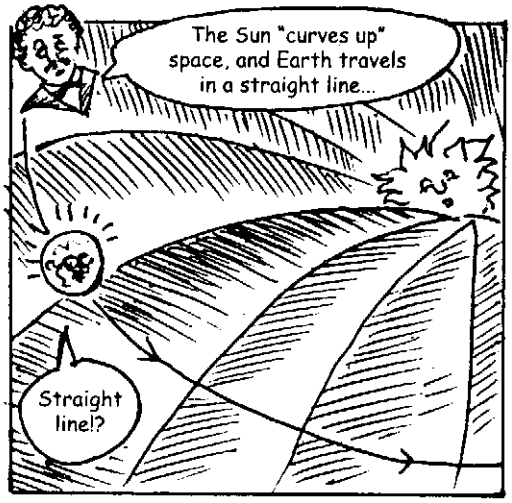


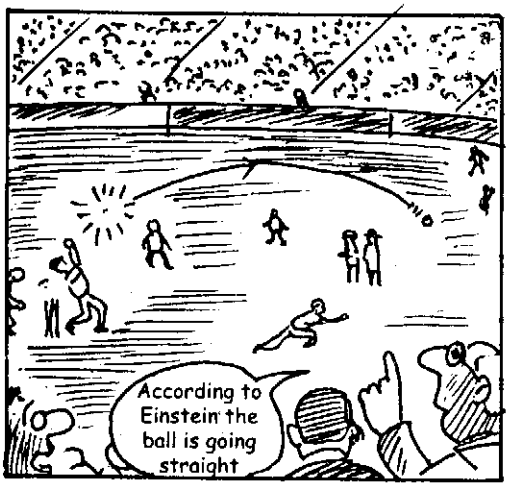


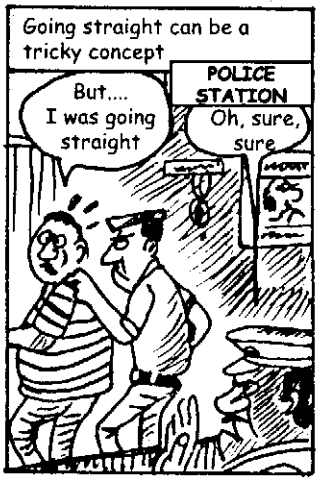


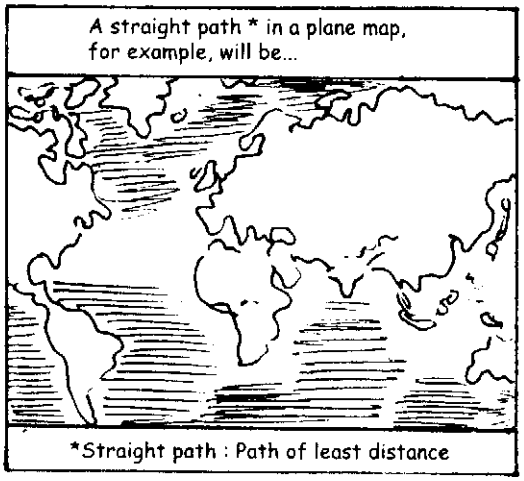




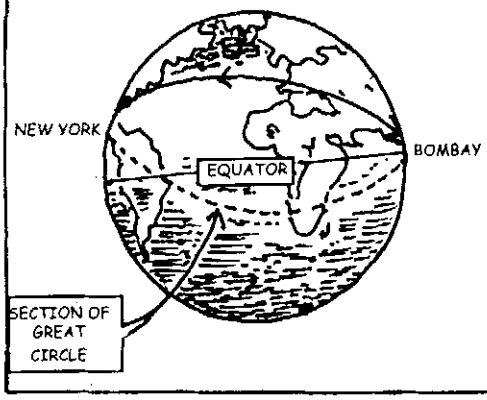




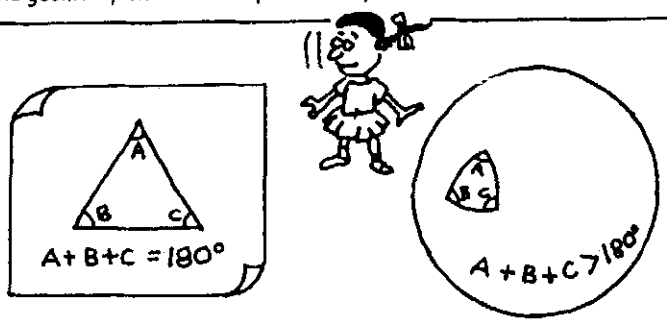




....longer than a straight path on the globe!



The geometry on a curved space is very different from that on a plane

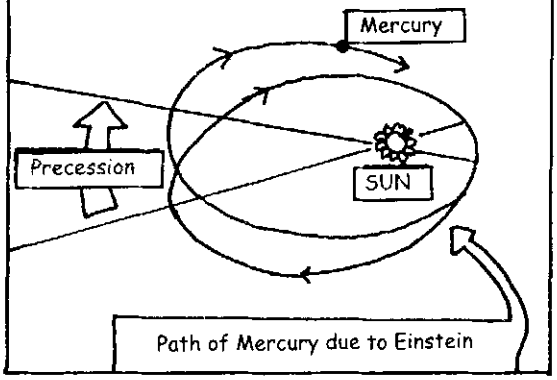


Geometry on a plane

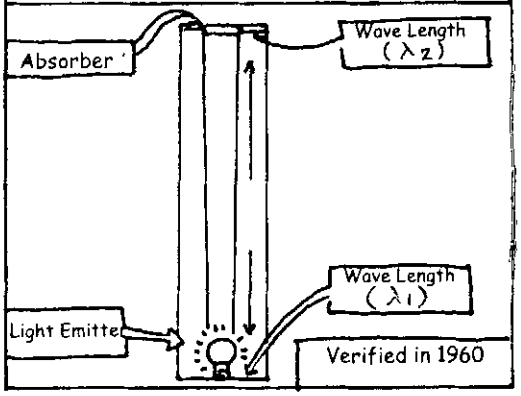
Geometry on a sphere

Using the correct geometry for curved space time Einstein worked out the consequences of his theory of gravity

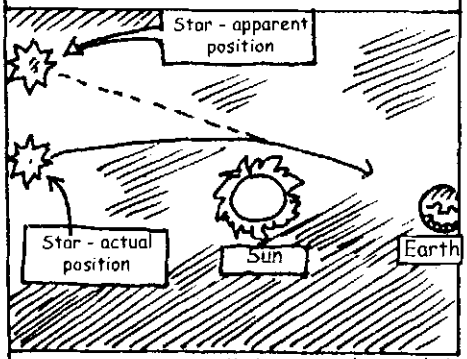
1. He could explain an (unaccounted) precession of Mercury

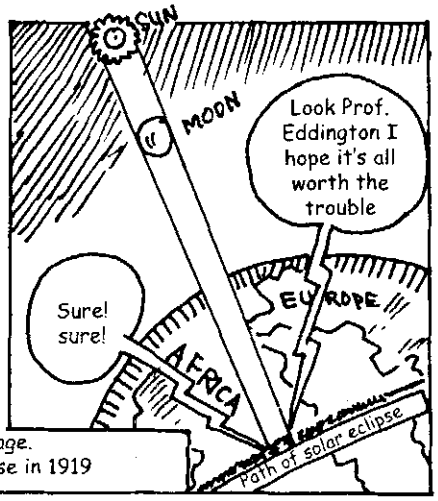


2. Light undergoes a shift of wavelength (towards red) in a gravitational field



3. Light bends while travelling near the Sun....





.... producing a small change in the star's image.
This was tested during the total solar eclipse in 1919

The photographs of the star dramatically confirmed the theory

Never since Newton has a single man achieved so much or become so famous

Fortunately, Einstein remained a human being till his death

While the relativistic revolution was in progress, an army of physicists was trying to understand the structure of matter. To begin with there was....

... Sir William Crookes (1832 - 1919)

There it is!

HIGH VOLTAGE

He noticed a stream of rays from the cathode of a high - vacuum tube....

CATHODE RAYS

To air pump

Cathode - ve

Anode +ve

LARGE VOLTAGE

These rays cast shadows and can rotate a wheel in the middle

Could they be electromagnetic waves?

Mmm.... there's a simple way to find out

Look! they're deflected by a magnet! They must be charged particles!

Two decades later, J.J. Thompson (1856 - 1940) determined the mass of these particles

Hey! they have a mass (1/1837) of a hydrogen atom

....Opening up the subatomic world

Meanwhile, Crookes' tube was leading to new surprises

Let me wrap it in black cloth

W. K. Roentgen (1845 - 1923)

Eh? Why is that luminescent paper glowing?!

With systematic experimentation Roentgen could arrive at the correct solution

This is a new kind of radiation capable of going through most material

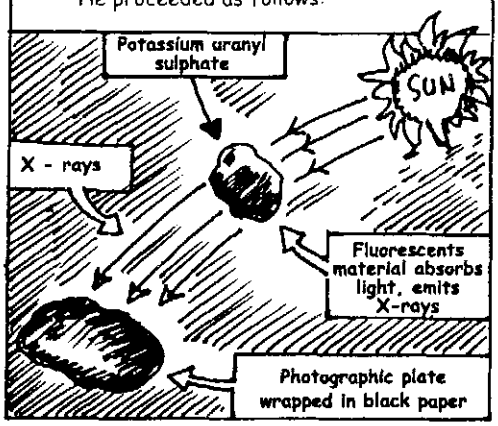
"X-RAYS"

I assure you madam, this cloth is opaque to X - rays

CLOTH

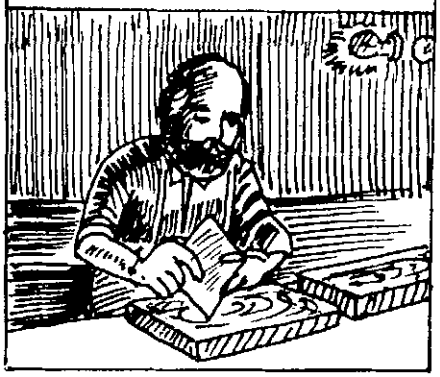
X - rays were investigated by A. H. Becquerel (1852 - 1908) the French physicist who was looking at the X - rays emitted by fluorescent material

He proceeded as follows:

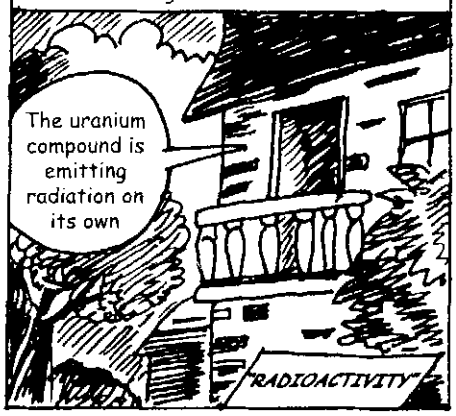


Then came a cloudy day....

Something prompted him to develop the plate even though it wasn't exposed to sunlight!



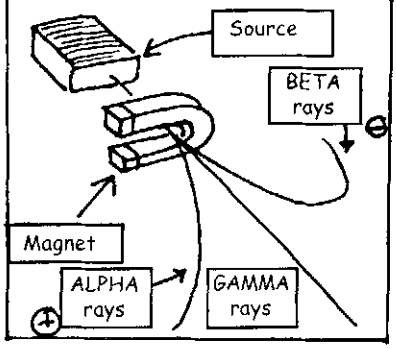
Becquerel was forced to the startling conclusion



This idea was actively pursued by the Curies

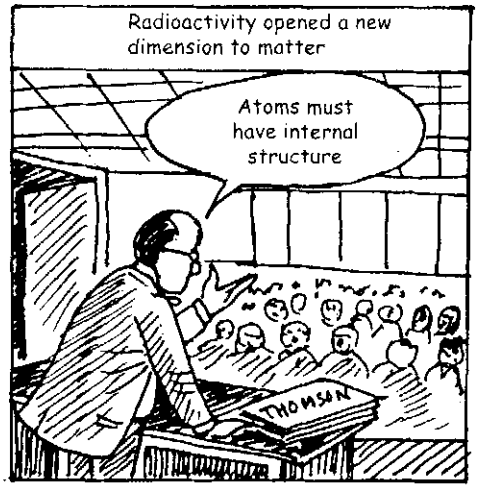
The answer was bizarre

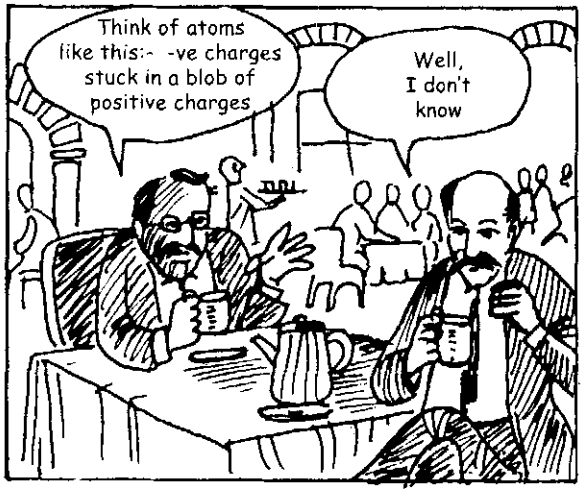
There are three kinds of radiation : alpha, beta and gamma



After years of toil they isolated of powerful radioactive source - "radium"

Radioactivity opened a new dimension to matter





Thomson's model of the atom kept both positive and negative charge together

Just like seeds in a water-melon....

J. J. THOMSON

E. RUTHERFORD

Smooth distribution of +ve charge

- ve charge stuck in it

THOMSON'S ATOM

There must be a way of testing this

If I hit the atom with an alpha particle....

.... the scattered path of the alpha particle will tell me about the atom....

POK!

Thomson's atom would hardly deflect an alpha particle

Rutherford examined the scattering of alpha particles by metal foils

THE MADDENING DETAILS

A: Source of alpha particles
B: Metal foil
S: Scintillating screen
M: Microscope
R: Rotating cavity
C: Coffee

The result was sensational

EXPECTED:

SMALL DEFLECTION

OBSERVED:

ATOMS ?

TOTAL BOUNCE

LARGE DEFLECTIONS

Question: What atomic model can produce the observed scattering? Answer:

R.C. FOWLER

I can calculate it theoretically, you know!

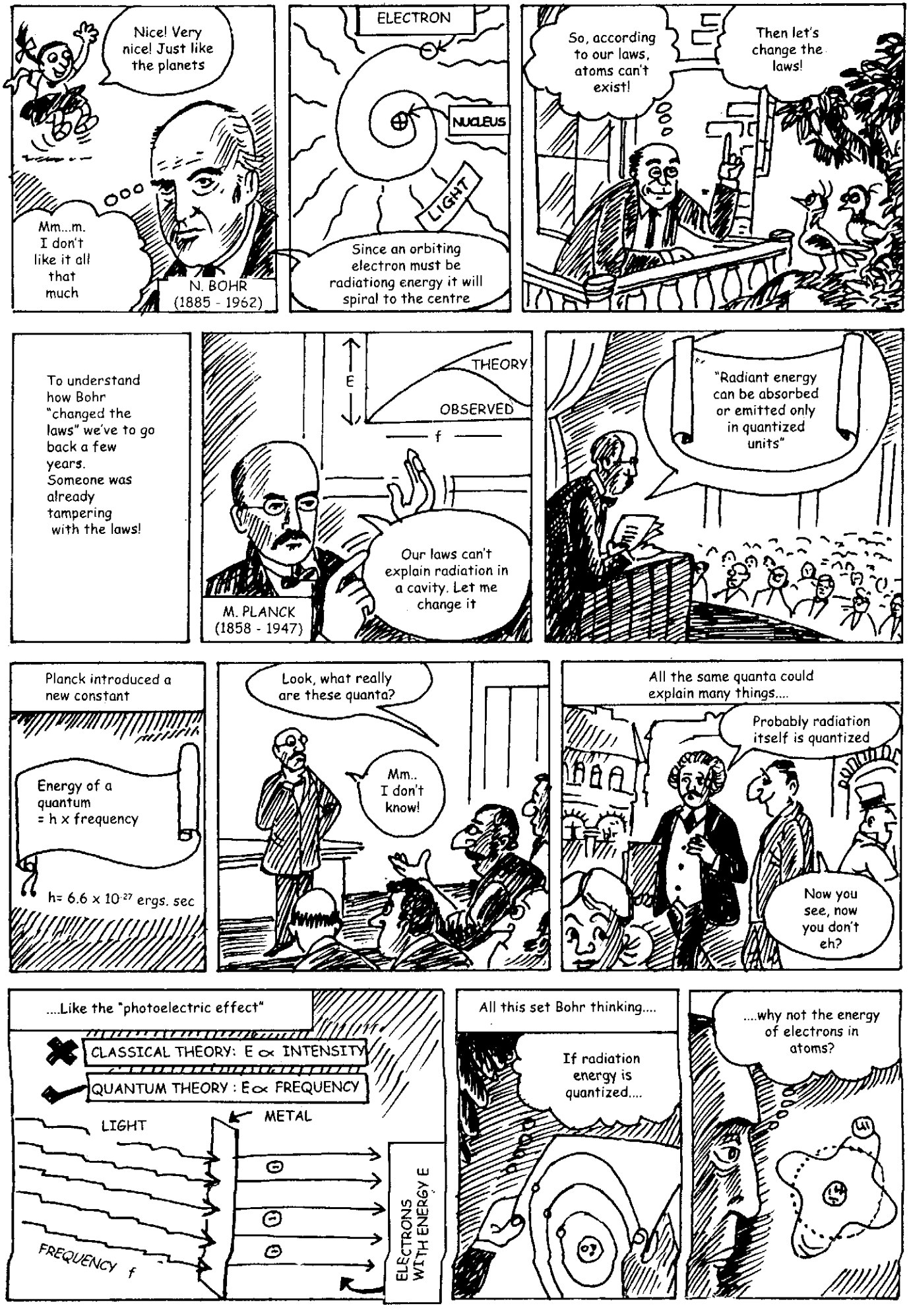
Theory? Bah!

Okay, go ahead

Good; here it is!

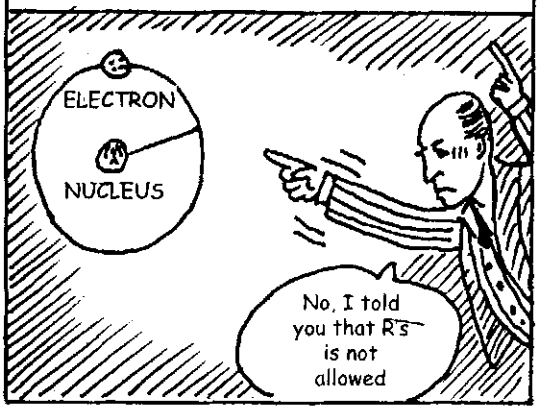
- ve charges in orbit

+ve charges at centre

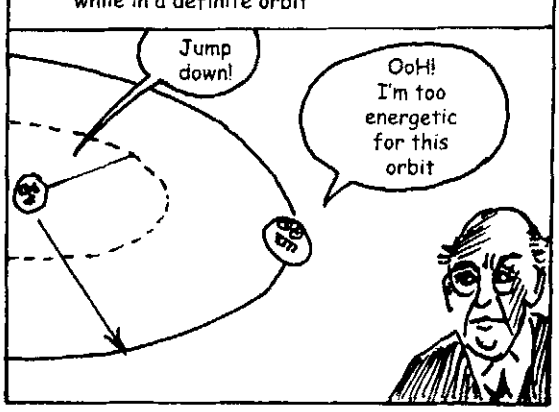

Nice! Very nice! Just like the planets
Mm...m. I don't like it all that much
N. BOHR (1885 - 1962)
ELECTRON
NUCLEUS
LIGHT
Since an orbiting electron must be radiationg energy it will spiral to the centre
So, according to our laws, atoms can't exist!
Then let's change the laws!
To understand how Bohr "changed the laws" we've to go back a few years. Someone was already tampering with the laws!
E
THEORY
OBSERVED
f
Our laws can't explain radiation in a cavity. Let me change it
M. PLANCK (1858 - 1947)
"Radiant energy can be absorbed or emitted only in quantized units"
Planck introduced a new constant
Energy of a quantum = h x frequency
h= 6.6 x 10-27 ergs. sec
Look, what really are these quanta?
Mm.. I don't know!
All the same quanta could explain many things....
Probably radiation itself is quantized
Now you see, now you don't eh?
....Like the "photoelectric effect"
CLASSICAL THEORY: E ∝ INTENSITY
QUANTUM THEORY : E ∝ FREQUENCY
LIGHT
METAL
FREQUENCY f
ELECTRONS WITH ENERGY E
All this set Bohr thinking....
If radiation energy is quantized....
....why not the energy of electrons in atoms?

Niels Bohr had to give up many cherished principles to implement his idea

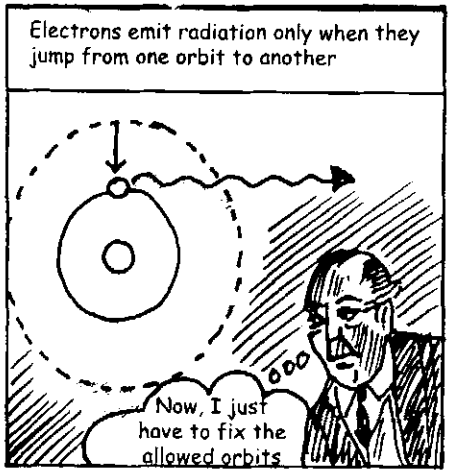
Electrons cannot orbit at all distances

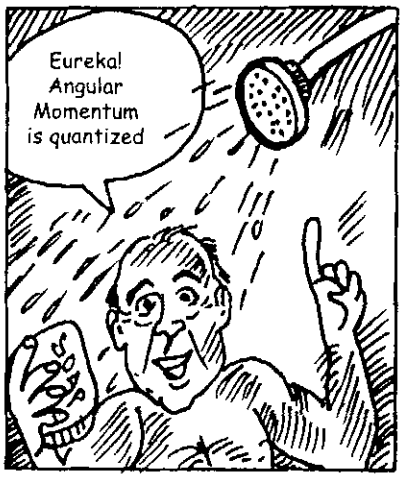


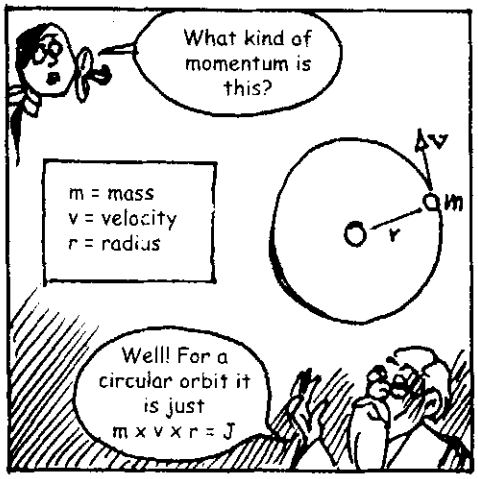
Though accelerated, they can't radiate while in a definite orbit



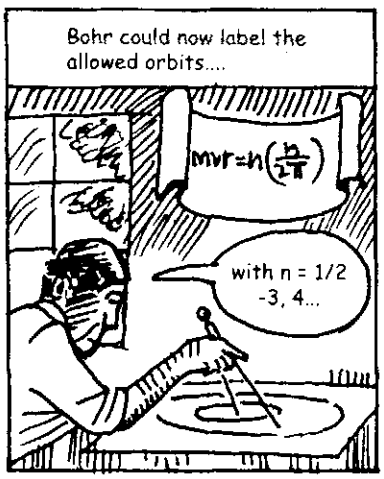
Electrons emit radiation only when they jump from one orbit to another



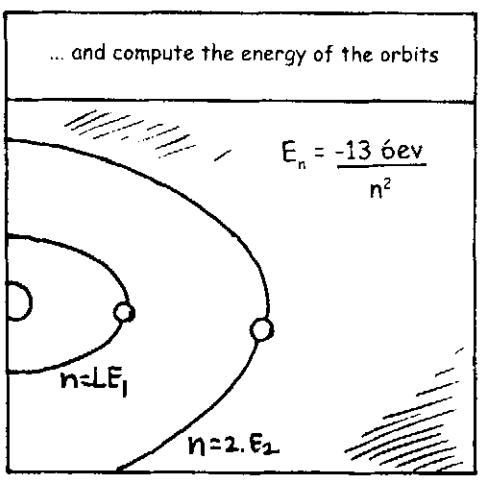


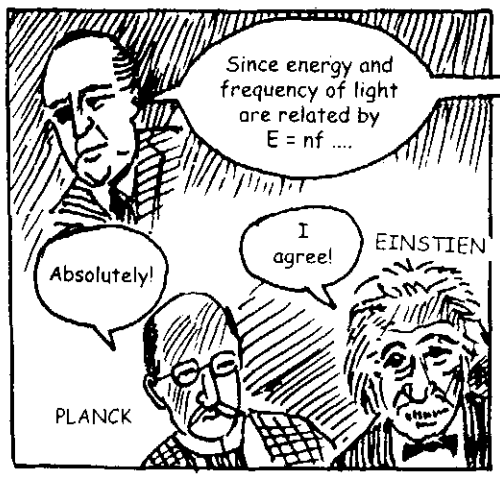


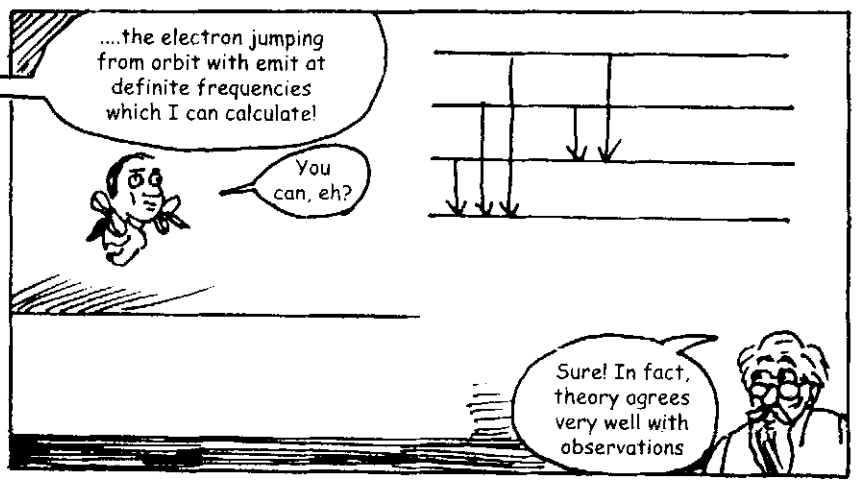
Bohr could now label the allowed orbits....



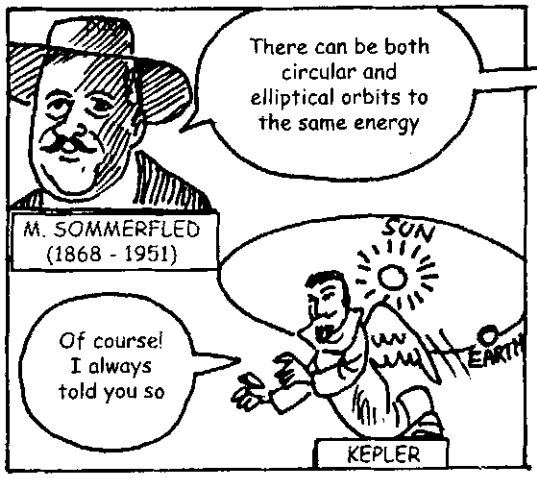
... and compute the energy of the orbits

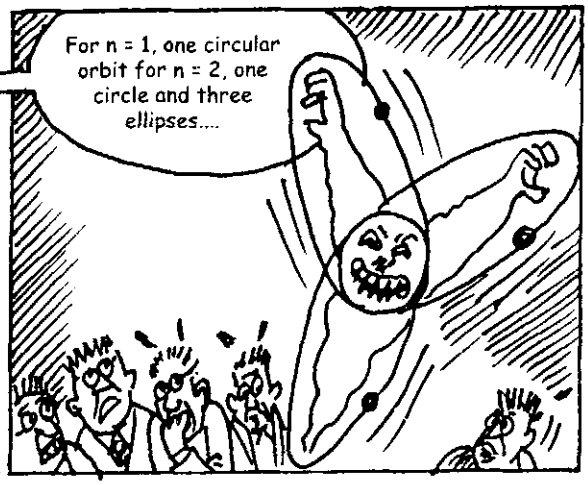




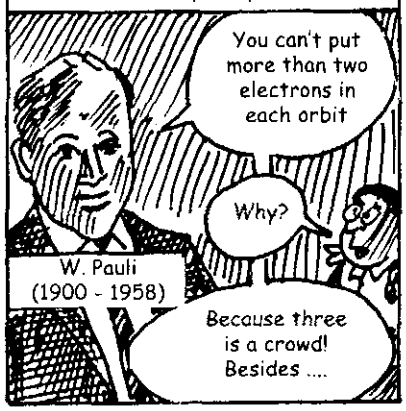


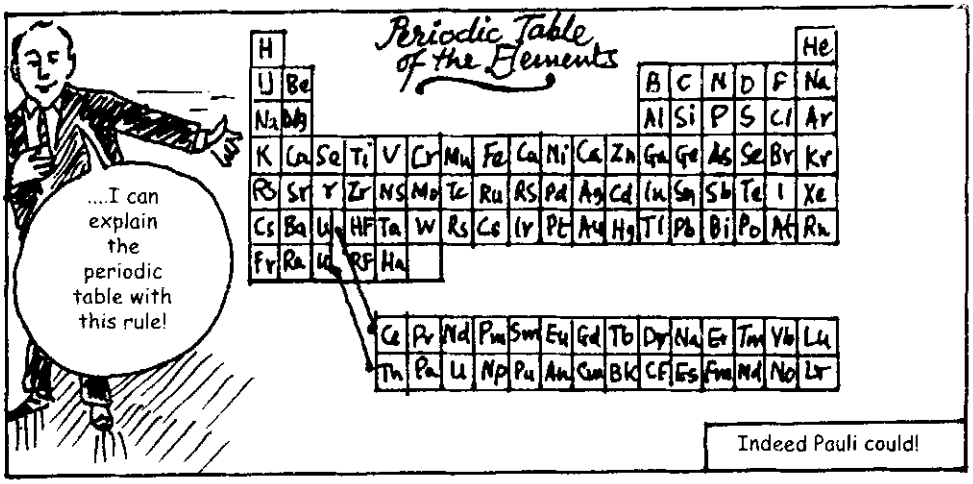
Further complications led to better understanding. First, Sommerfeld introduced elliptical orbits



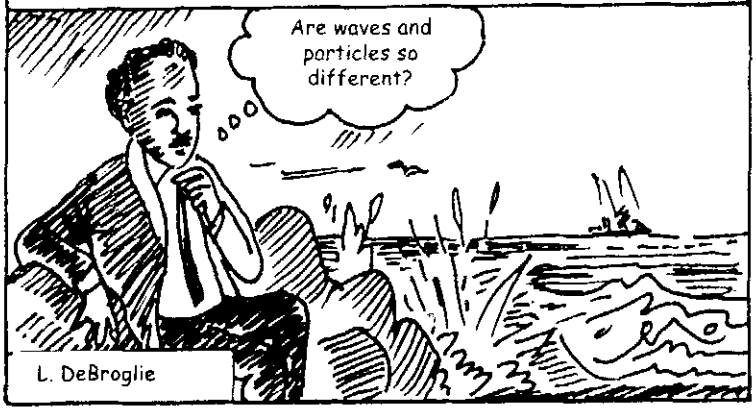


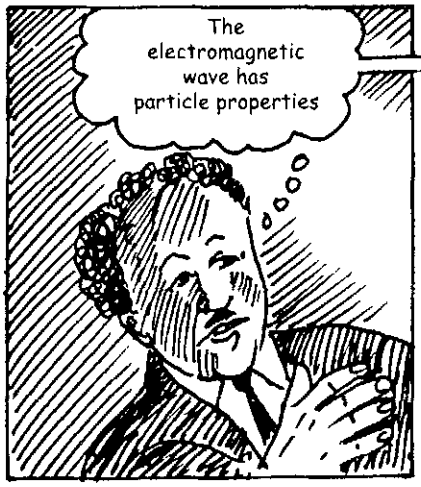
Then came "Pauli's exclusion principle"

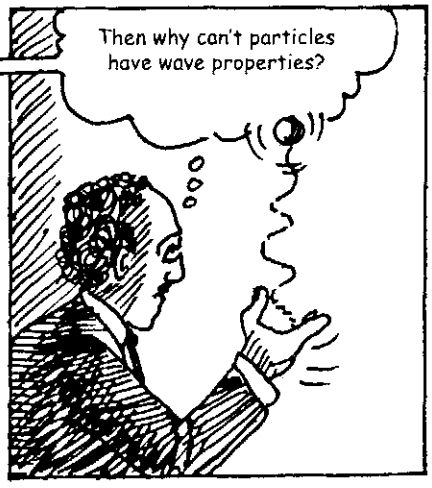




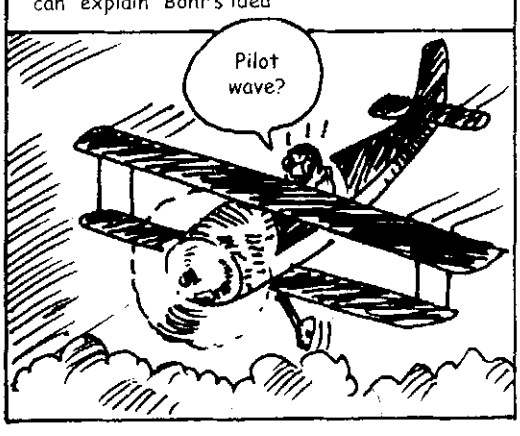
It took sometime for more definite answers to emerge



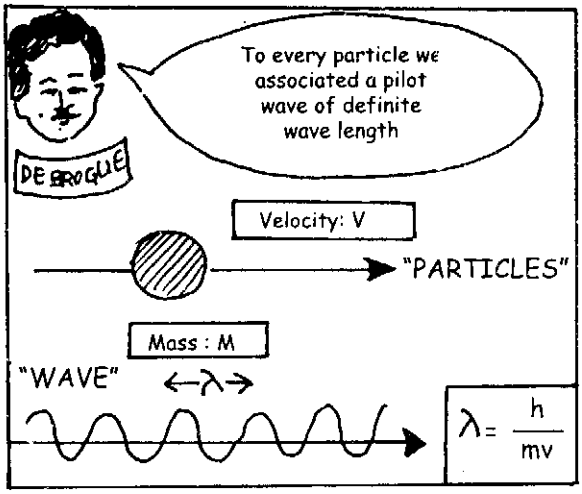


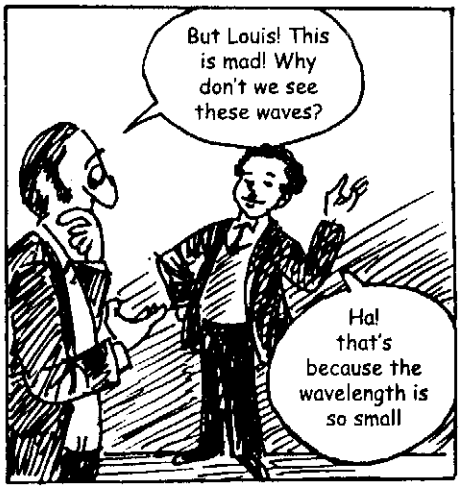


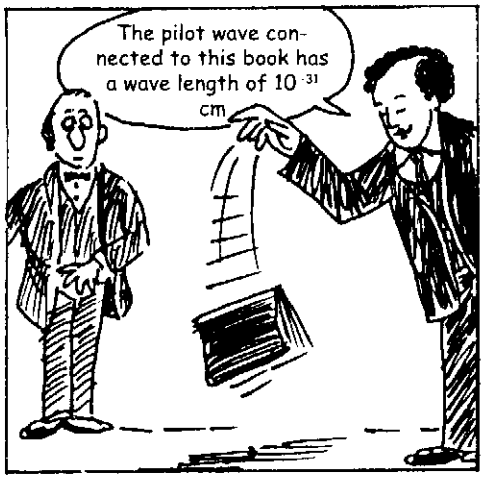
Associating a "pilot" wave with an electron can "explain" Bohr's idea

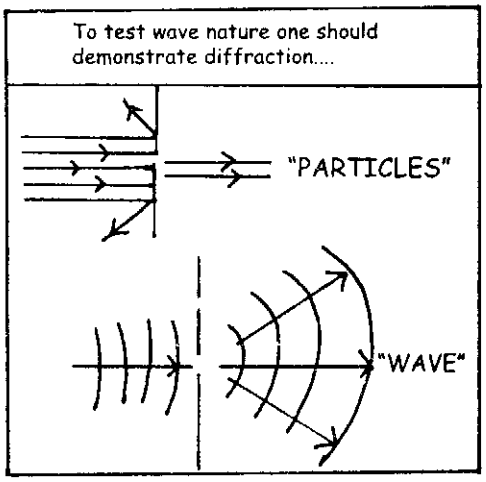


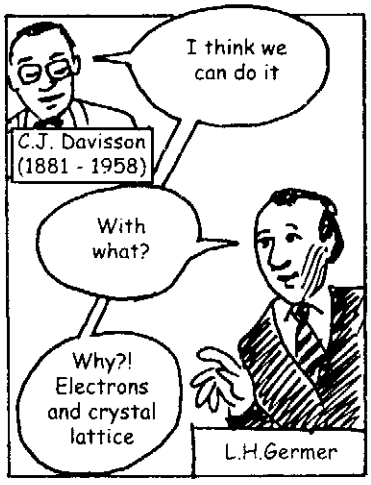
with one bold stroke DeBroglie eliminated the distance between wave and particle

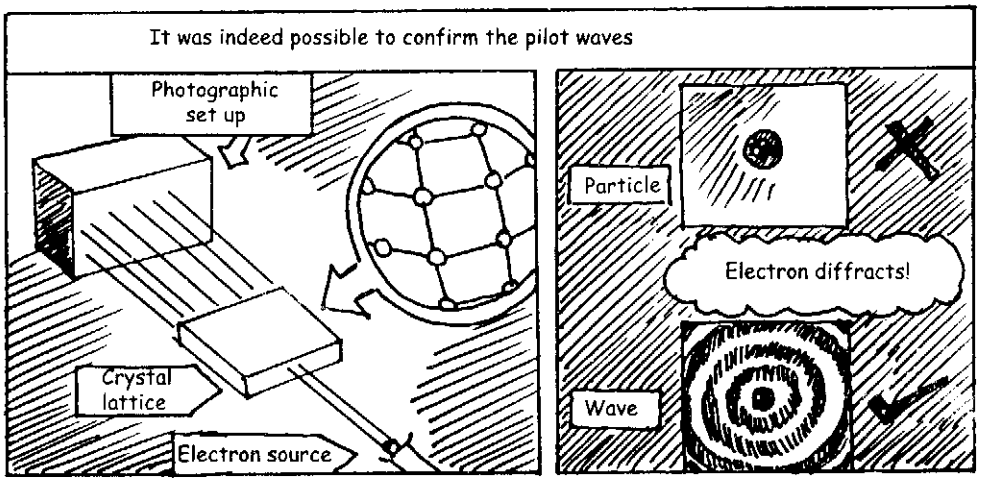




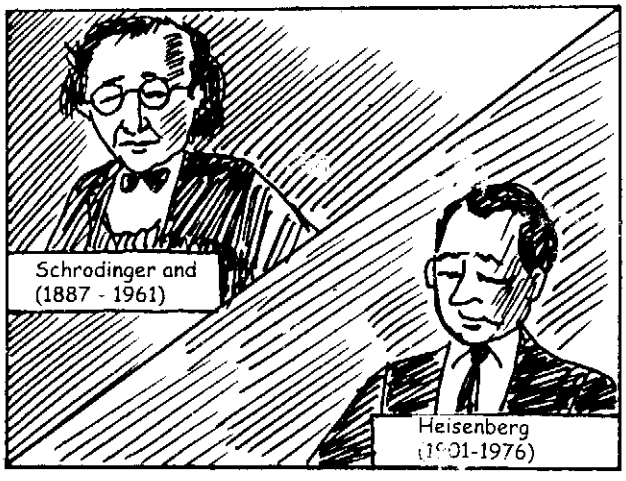


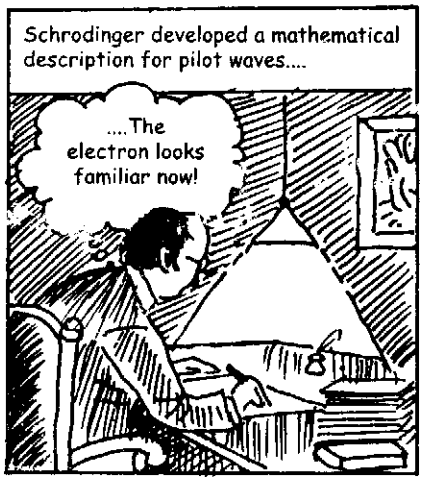






From the sketchy idea of pilot wave to a full fledged wave mechanics was a complex transition. The main contributors were





....allowing one to make detailed comparisons of atomic spectra

Third-rate chaps are doing first-rate work

But disturbing questions remained

EINSTEIN

SCHRODINGER

WHAT IS A PILOT WAVE

HEISENBERG

BOHR

Ha! It describes the density of charge

Nonsense! It gives density of probability

Density of pro.... probability!!

When you roll a die, you don't know what face will turn up

But the probability to get, say 2 is 1/6

Similarly, you don't know where an electron in the atom is. All that we can predict is the ....

Probability to catch an electron at a place

PROBABILITY

DISTANCE

Just like the dice, you see!

But Herr Bohr! God does not play dice

Come now, stop telling God what to do

The concepts of quantum theory are bizarre and slowly evolved into a working sets of rules. A central concept was the uncertainity principle

If you know where an electron is you don'tknow where it is going

BUS STOP

OH! That's like public transport

There was, however, one problem

It doesn't agree with Special relativity

It's all wrong anyway

P.A.M.Dirac changed the equations so that they did agree with relativity

They are better now except that....

P.A.M.Dirac (1902-1984)

....they have a large number of negative energy states

E_1

mc^2

ZERO ENERGY

$-mc^2$

$-E_1$

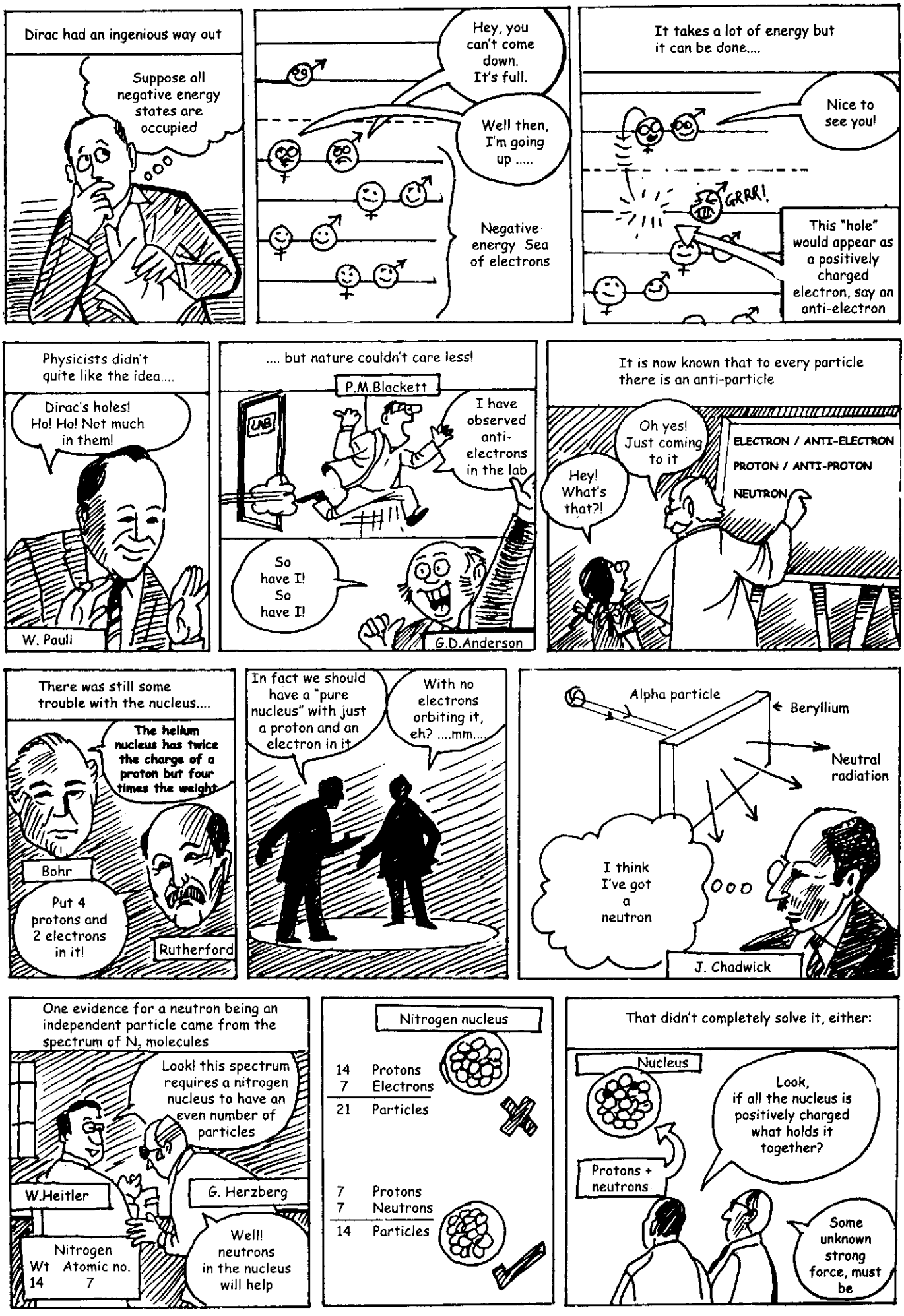
My, my this won't do

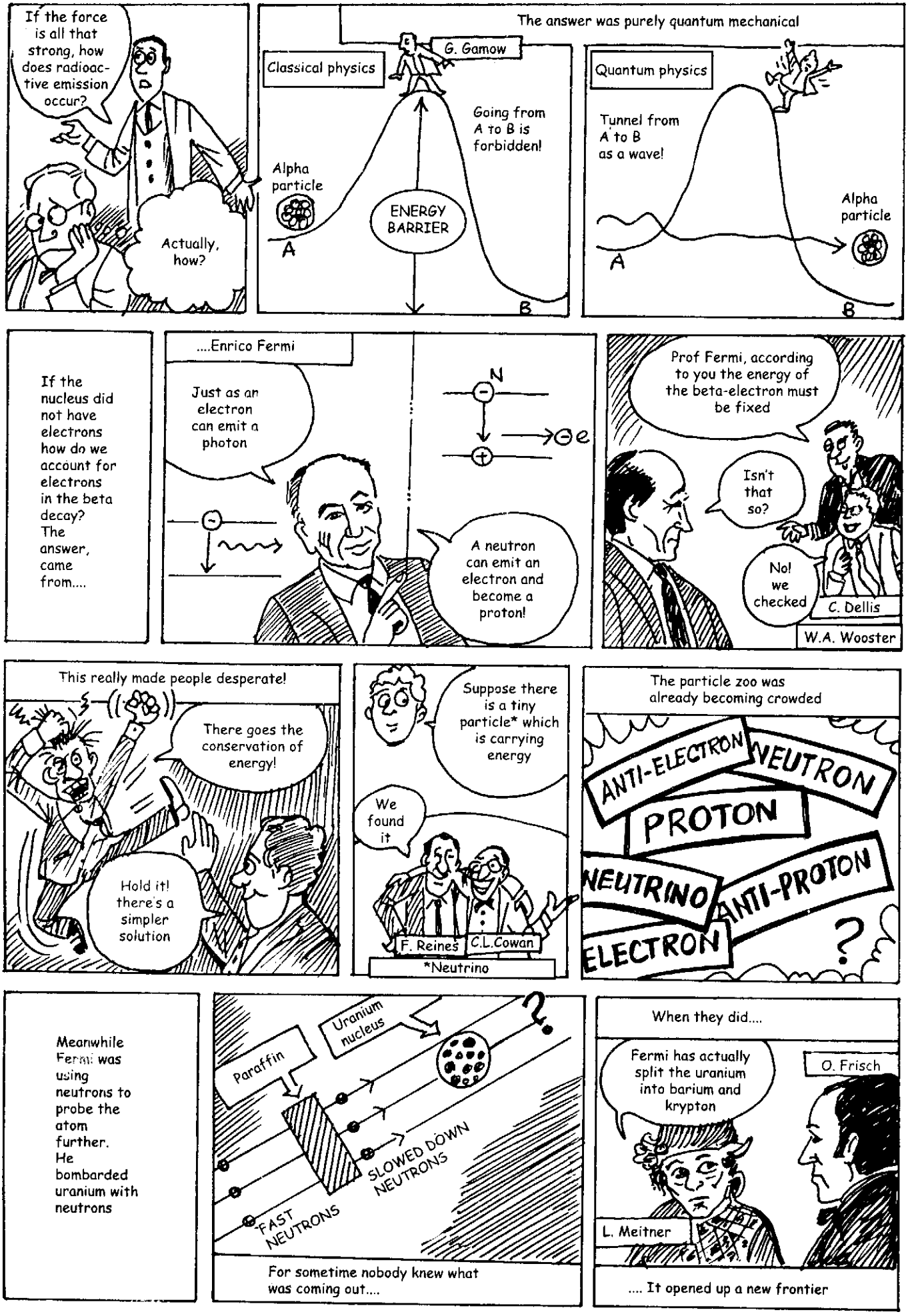
mc^2

0

mc^2

The particle will keep sinking down the negative energy sea


Dirac had an ingenious way out
Suppose all negative energy states are occupied
Hey, you can't come down. It's full.
Well then, I'm going up .....
Negative energy Sea of electrons
It takes a lot of energy but it can be done....
Nice to see you!
GRRR!
This "hole" would appear as a positively charged electron, say an anti-electron
Physicists didn't quite like the idea....
Dirac's holes! Ho! Ho! Not much in them!
W. Pauli
.... but nature couldn't care less!
P.M.Blackett
LAB
I have observed anti-electrons in the lab
So have I! So have I!
G.D.Anderson
It is now known that to every particle there is an anti-particle
Oh yes! Just coming to it
Hey! What's that?!
ELECTRON / ANTI-ELECTRON
PROTON / ANTI-PROTON
NEUTRON
There was still some trouble with the nucleus....
The helium nucleus has twice the charge of a proton but four times the weight
Bohr
Put 4 protons and 2 electrons in it!
Rutherford
In fact we should have a "pure nucleus" with just a proton and an electron in it
With no electrons orbiting it, eh? ....mm....
Alpha particle
Beryllium
Neutral radiation
I think I've got a neutron
J. Chadwick
One evidence for a neutron being an independent particle came from the spectrum of N2 molecules
Look! this spectrum requires a nitrogen nucleus to have an even number of particles
W.Heitler
G. Herzberg
Nitrogen
Wt 14
Atomic no. 7
Well! neutrons in the nucleus will help
Nitrogen nucleus
14 Protons
7 Electrons
21 Particles
7 Protons
7 Neutrons
14 Particles
That didn't completely solve it, either:
Nucleus
Protons + neutrons
Look, if all the nucleus is positively charged what holds it together?
Some unknown strong force, must be


If the force is all that strong, how does radioactive emission occur?
Actually, how?
The answer was purely quantum mechanical
G. Gamow
Classical physics
Going from A to B is forbidden!
Alpha particle
ENERGY BARRIER
A
B
Quantum physics
Tunnel from A to B as a wave!
Alpha particle
A
B
If the nucleus did not have electrons how do we account for electrons in the beta decay? The answer, came from....
....Enrico Fermi
Just as an electron can emit a photon
N
e
A neutron can emit an electron and become a proton!
Prof Fermi, according to you the energy of the beta-electron must be fixed
Isn't that so?
No! we checked
C. Dellis
W.A. Wooster
This really made people desperate!
There goes the conservation of energy!
Hold it! there's a simpler solution
Suppose there is a tiny particle* which is carrying energy
We found it
F. Reines
C.L.Cowan
*Neutrino
The particle zoo was already becoming crowded
ANTI-ELECTRON
NEUTRON
PROTON
NEUTRINO
ANTI-PROTON
ELECTRON
?
Meanwhile Fermi was using neutrons to probe the atom further. He bombarded uranium with neutrons
Paraffin
Uranium nucleus
SLOWED DOWN NEUTRONS
FAST NEUTRONS
For sometime nobody knew what was coming out....
When they did....
Fermi has actually split the uranium into barium and krypton
O. Frisch
L. Meitner
.... It opened up a new frontier

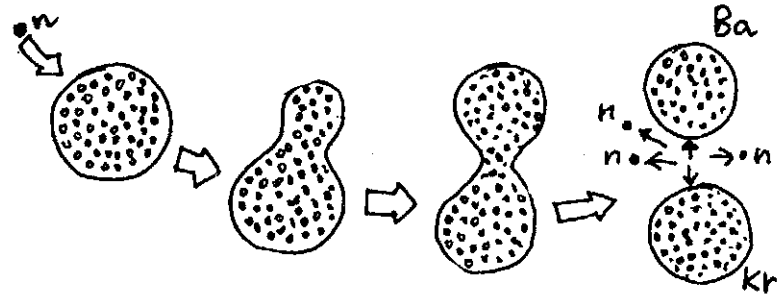
DECEMBER 1938

Fermi has actually split the atom

Frisch

Meitner

The process was something like this



If the neutrons released produce more fissions, we will have a gigantic source of energy (and explosion!)

BOHR
FERMI
WIGNER
SZILARD
TELLER
HEISENBERG
OTTO HAHN
KAPITZA
LANDAU
SAKHAROV

U.S.A.

GERMANY

RUSSIA

The technological consequences are too well known

There was a weird inevitibility about it all

Meanwhile, pure physics was forging ahead

Some strong force must be holding protons in the nucleus

H. Yukawa
(1907 - 1981)

Just as electromagnetic forces are due to exchange of photons....

ELEC-
TRONS

PHOTONS

ELECTRONS

A crude analogy due to Gamov!

....strong force is due to the exchange of a "meson"

MASS m

MESON

PROTON

PROTON

Predicted : m = 1/7 x proton mass

After a false start such a particle was found in 1947

NOBEL PRIZE WINNERS

1950

C. POWELL

1949

FIRST JAPANESE NOBEL PRIZE WINNER H. YUKAWA

Physicists now knew of four different forces....

Strong

keeps nucleus together

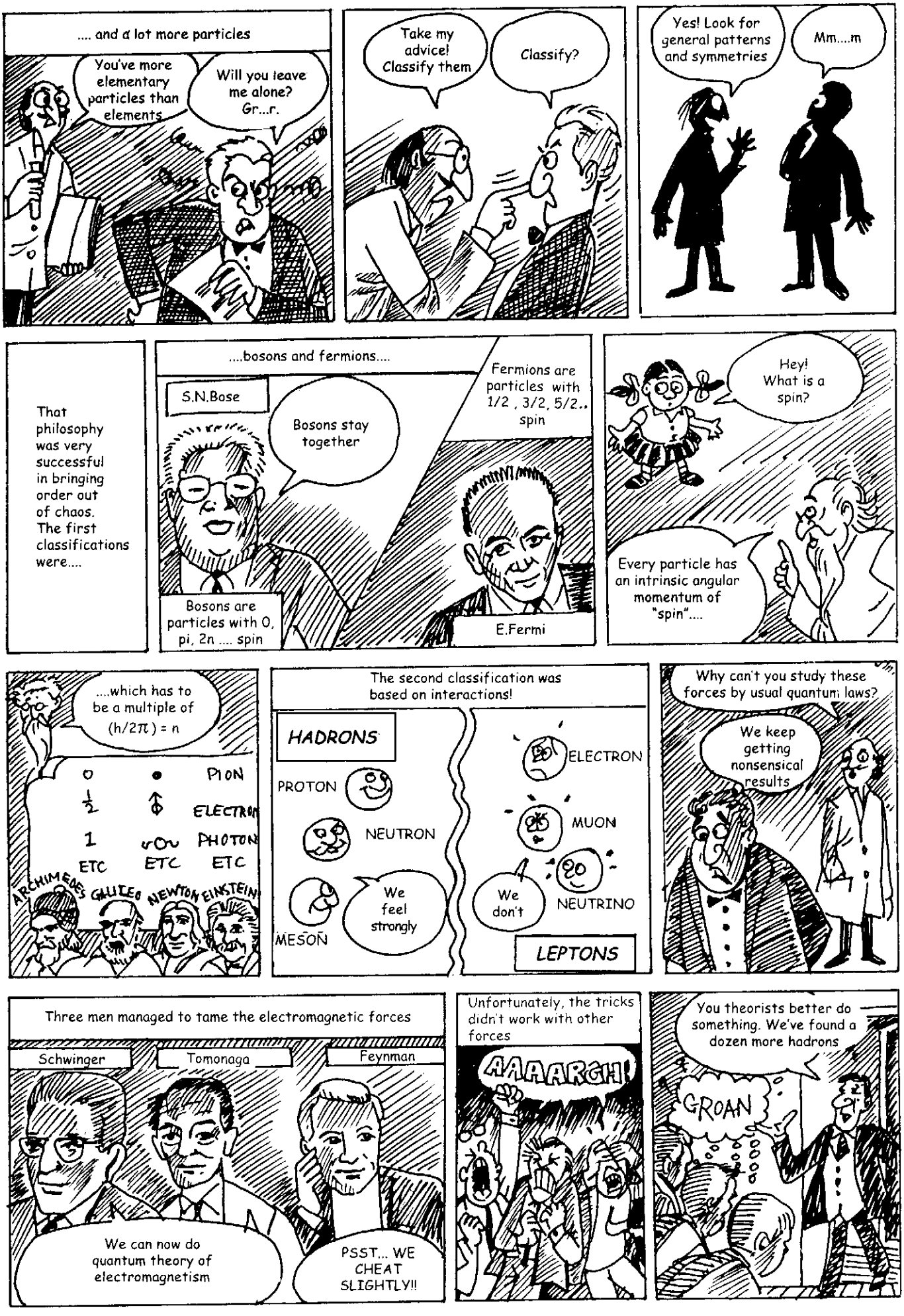
Weak

Produces beta decay

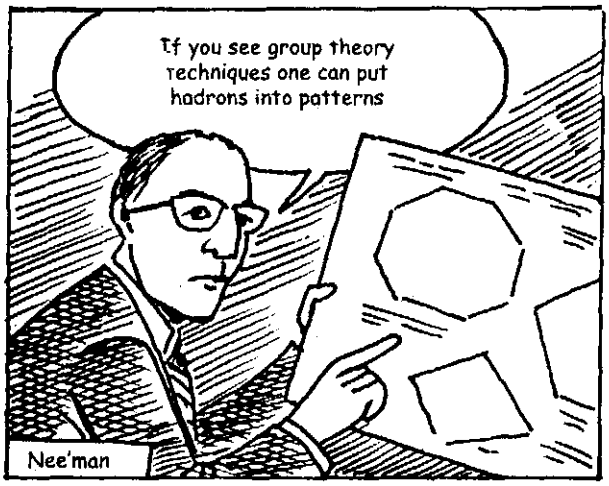
Electromagnetic keeps atoms together

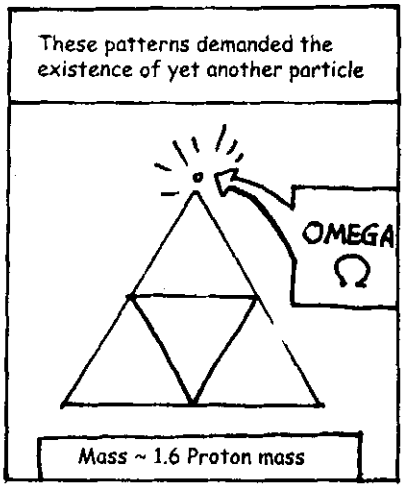
Gravity

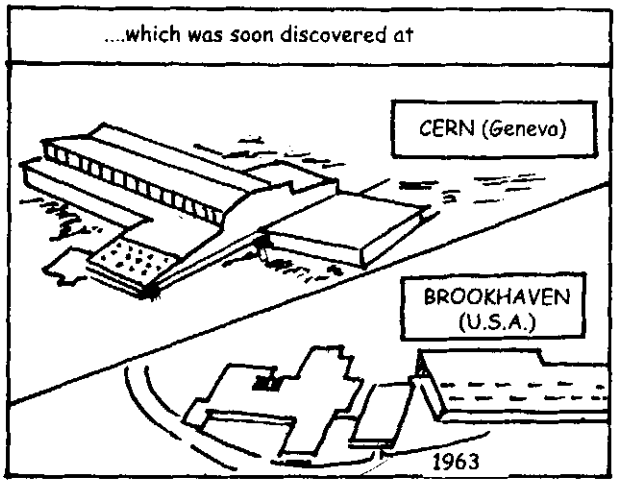
Prevents physicists from going away

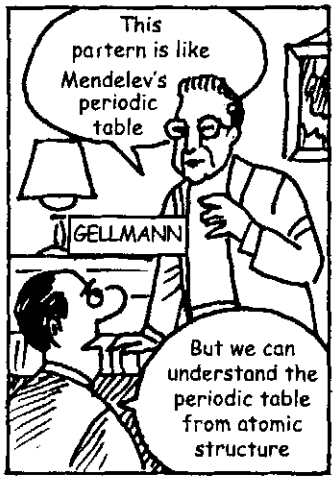

.... and a lot more particles
You've more elementary particles than elements
Will you leave me alone? Gr...r.
Take my advice! Classify them
Classify?
Yes! Look for general patterns and symmetries
Mm....m
That philosophy was very successful in bringing order out of chaos. The first classifications were....
....bosons and fermions....
S.N.Bose
Bosons stay together
Bosons are particles with 0, pi, 2n .... spin
Fermions are particles with 1/2 , 3/2, 5/2.. spin
E.Fermi
Hey! What is a spin?
Every particle has an intrinsic angular momentum of "spin"....
....which has to be a multiple of (h/2π) = n
0
PION
1/2
ELECTRON
1
PHOTON
ETC
ETC
ETC
ARCHIMEDES
GALILEO
NEWTON
EINSTEIN
The second classification was based on interactions!
HADRONS
PROTON
NEUTRON
MESON
We feel strongly
ELECTRON
MUON
We don't
NEUTRINO
LEPTONS
Why can't you study these forces by usual quantum laws?
We keep getting nonsensical results
Three men managed to tame the electromagnetic forces
Schwinger
Tomonaga
Feynman
We can now do quantum theory of electromagnetism
PSST... WE CHEAT SLIGHTLY!!
Unfortunately, the tricks didn't work with other forces
AAAARGH!
You theorists better do something. We've found a dozen more hadrons
GROAN

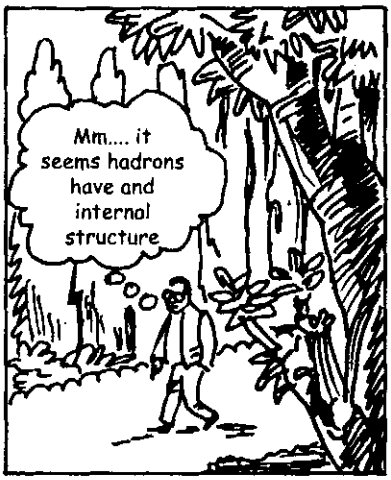
The first step in ordering hadrons were taken by M. Gellmann and Y. Nee'man

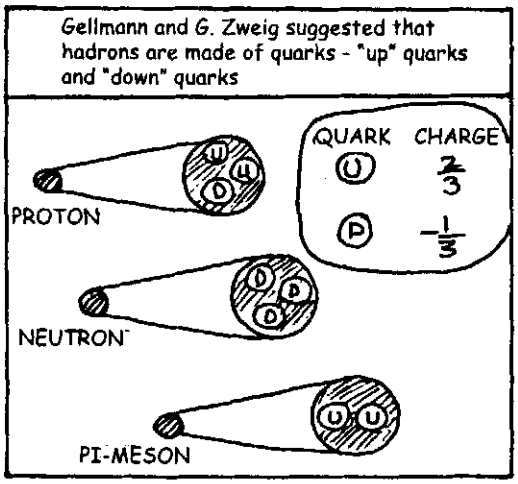


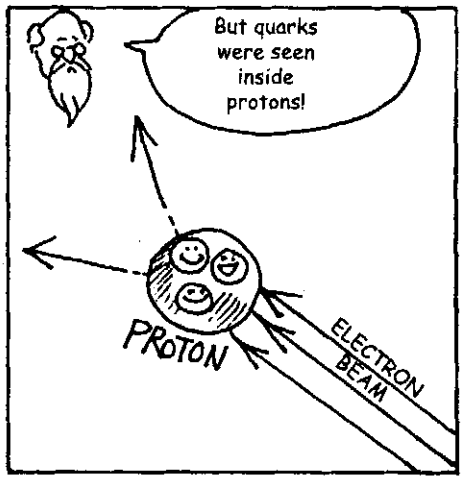




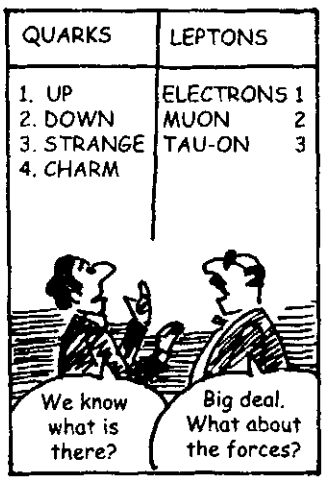


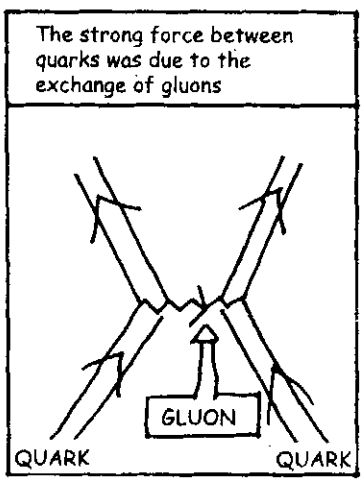


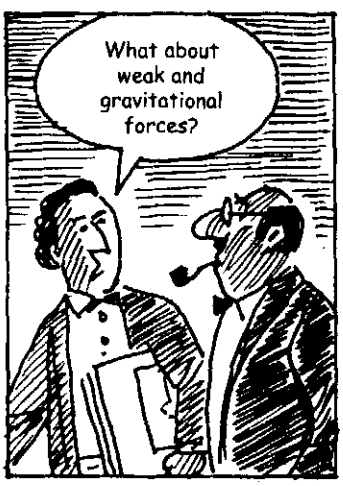




The problem was reduced to studying QUARKS and LEPTONS. It was soon discovered that there are more of them







After years of toil there was a breakthrough

A. Salam

S. Weinberg

Electric and weak forces can be unified as one electro-weak force

The electro-weak model predicted new "exchange" particles, which were soon discovered

Do you think they have struggled enough?

EARTH

Yes. Let's give them the W and Z bosons now!

That was the last definitive progress in this story of physics. Several new attempts were made to extend our understanding further

Strong forces can be tackled similarly if ....

If?

If you've got the guts

Gutsy physicists made a definite prediction

Protons are unstable

What do you mean. Dad isn't there?

Dad is made of nucleons isn't he?

COMIC TAX

Experiments all over the world are yet to confirm the prediction

KOLAR

INDIA

Yet another headache is always there

What about gravity?

I wish it wasn't there

NEWTON

The "taming of gravity" is an on-going tale of ups and downs

1980 - 83

Supersymmetry describes gravity very well

GRAVITY

The most fashionable pastime nowadays is based on a formalism called "superstrings"

Gravity is tied down by strings you see.

(!?!)

But may be only in 10 dimensions

....and so on .....

What we call the beginning is often the end. And to make an end is to make a beginning. The end is where we started from.

YOU ARE HERE !