Physics 544   Spring Quarter 2011

Classical Electrodynamics
Special Relativity
Relativistic Electrodynamics
and
General Relativity

Professor: Larry Sorensen
Office: Physics-Astronomy Building B-435
e-mail: seattle@u.washington.edu
Office hours: Right after class, or by appointment

Textbooks
The Feynman Lectures on Physics Volume 2
Spacetime Physics
Exploring Black Holes
General Relativity from A to B
QED: The Strange Theory of Light and Matter

Class Website: http://faculty.washington.edu/seattle

Course grades will be based on written papers and take home exams.

Requirements

Take home exams:

(1) Electrodynamics CED and RED

(2) Special Relativity SR

(3) General Relativity GR

Primarily Qualitative Exams

Understand the Vocabulary

Short papers:

(1) QED: The Strange Theory of Light and Matter

(2) General Relativity from A to B

(3) Einstein and Minkowski SR papers

(4) Einstein $E=mc^2$ papers

	A	B	C
1			**Feynman Lectures on Physics Volume 2**
2	ED	Chapter 18	The Maxwell equations
3	ED	Chapter 20	Solutions of Maxwell's equations in free space
4	ED	Chapter 21	Solutions of Maxwell's equations with currents and charges
5			
6	RED	Chapter 25	Electrodynamics in relativistic notation
7	RED	Chapter 26	Lorentz transformations of the fields
8	RED	Chapter 27	Field energy and field momentum
9			
10			
11			**Spacetime Physics**
12	SR	Chapter 1	The Geometry of Spacetime
13	SR	Chapter 2	Momentum and Energy
14	SR	Chapter 3	The Physics of Curved Spacetime
15			
16			
17			**Exploring Black Holes**
18	GR	Chapter 1	Speeding (Review of Special Relativity).
19	GR	Chapter 2	Curving (Spacetime Near a Non-Rotating Black Hole).
20	GR	Chapter 3	Plunging (Diving Toward a Black Hole).
21	GR	Chapter 4	Orbiting (Zooming Around a Black Hole).
22	GR	Chapter 5	Seeing (Bending and Orbiting Light).
23			
24			
25			**General Relativity from A to B**
26	GR	Chapter 1	Events and Space-Time: The Basic Building Blocks
27	GR	Chapter 2	The Aristotelian View: A "Personalized" Framework
28	GR	Chapter 3	The Galilean View: A Democratic Framework
29	GR	Chapter 4	Difficulties with the Galilean View
30	GR	Chapter 5	The Interval: The Fundamental Geometrical Object
31	GR	Chapter 6	The Physics and Geometry of the Interval
32	GR	Chapter 7	Einstein's Equation: The Final Theory
33	GR	Chapter 8	An Example: Black Holes
34			
35			
36	QED		**QED: The Strange Theory of Light and Matter**
37	QED	Chapter 1	Introduction
38	QED	Chapter 2	Photons: Particles of Light
39	QED	Chapter 3	Electrons and their interactions
40	QED	Chapter 4	Loose Ends

Electrodynamics

Maxwell's Equations
are
Truly Wonderful

(1) They are Lorentz invariant
(2) They were Einstein's key to special relativity
(3) They are almost always QM correct

Feynman

From a long view of the history of mankind---seen from, say, ten thousand years from now---there can be little doubt that the most significant event of the nineteenth century will be judged as Maxwell's discovery of the laws of electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade.

We will be concerned with fields, that is, functions of space and time. It is therefore quite clear that we must first get to know the structure of spacetime. Unfortunately, because the velocity of light is so large, everyday experience leads us to acquire a certain number of misconceptions about the structure of spacetime. This set of misconceptions goes under the name of Newtonian (or Galilean) spacetime. The true structure of spacetime was discovered by Einstein in a study of electrodynamics in 1905.

With Maxwell's new term we have been able to write the full field equations in terms of A and V in a form that is simple and makes it immediately apparent that there are electromagnetic waves. For many practical purposes, it will still be useful to use the original equations in terms of E and B. But they are on the other side of the mountain we have already climbed. Now we are ready to cross over to the other side of the peak. Things will look different---we are ready for some new and beautiful views.

This becomes more and more apparent the more deeply we go into the quantum theory. In the general theory of quantum electrodynamics, one takes the vector and the scalar potentials as the fundamental set of equations to replace Maxwell's equations: E and B are slowly disappearing from the modern expression of physical theory; they are being replaced by A and V.

Purcell

If we had to analyze every system of moving charges by transforming back and forth among various coordinate systems, our task would grow both tedious and confusing. There is a better way. The overall effect of one current on another, or of a current on a moving charge, can be described completely and concisely by introducing a new field, the magnetic field.

To anyone who is motivated by anything beyond the most narrowly practical, it is worthwhile to understand Maxwell's Equations for the good of his soul.

J.R. Pierce
Maxwell's Wonderful Equations

From Maxwell’s equations to the wave equations

In Newtonian spacetime => 3-vectors and 3x3 tensors

Four Maxwell equations => One wave equation for E and one for B
E and B wave equations => 6 degrees of freedom

Four Maxwell equations => One wave equation for A and one for V
A and V wave equations => 4 degrees of freedom

We live in four-dimensional spacetime => 4-vectors and 4x4 tensors

E and B are components of a tensor => 6 degrees of freedom
A and V are components of a vector => 4 degrees of freedom

A vector is much easier to deal with than a tensor
In QM, the (V, A) 4-vector is real; E and B are not!

Maxwell's Equations in Vacuum

Two vector fields, $\mathbf{E}$ and $\mathbf{B}$

in vacuum $\epsilon = \epsilon_0$ and $\mu = \mu_0$

Two Divergence Equations

Gauss' Law for Electricity

$\nabla \cdot \mathbf{E} = \rho/\epsilon_0$

Gauss' Law for Magnetism

$\nabla \cdot \mathbf{B} = 0$

Two Curl Equations

Faraday's Law of Induction

$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$

Ampere's Law with Maxwell's Extension

$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \partial \mathbf{E}/\partial t$

$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \mathbf{J_d}$

Maxwell called $\mathbf{J_d}$ the displacement current

All of Classical Physics

Feynman summarizes as the four Maxwell Equations plus

The Conservation of Charge

$\nabla \cdot \mathbf{J} = -\partial\rho/\partial t$

The Lorentz Force Law

$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$

The Law of Motion

$d\mathbf{p}/dt = \mathbf{F}$

where $\mathbf{p} = \gamma m\mathbf{v}$

The Law of Gravitation

$\mathbf{F} = -Gm_1m_2\,\hat{\mathbf{r}}/r^2$

These Eight Equations Contain All of Classical Physics

For static fields, the four Maxwell Equations are the best formulation

$\nabla \cdot \mathbf{E} = \rho/\epsilon_0$

$\nabla \cdot \mathbf{B} = 0$

$\nabla \times \mathbf{E} = -\partial\mathbf{B}/\partial t$

$\nabla \times \mathbf{B} = \mu_0\mathbf{J} + \mu_0\epsilon_0\partial\mathbf{E}/\partial t$

Maxwell's equations are four coupled first-order differential equations

The sources are ρ, $\mathbf{J}$, and each other

For dynamic fields, the wave equations are the best formulation

Decoupling the four Maxwell Equations produces two second-order differential equations

$\nabla^2\mathbf{E} = \mu\epsilon\, \partial^2\mathbf{E}/\partial^2 t = (1/v^2)\, \partial^2\mathbf{E}/\partial^2 t$

$\nabla^2\mathbf{B} = \mu\epsilon\, \partial^2\mathbf{B}/\partial^2 t = (1/v^2)\, \partial^2\mathbf{B}/\partial^2 t$

These two wave equations have six degrees-of-freedom, three for $\mathbf{E}$ and three for $\mathbf{B}$

These wave equations apply in regions where there are no sources

In vacuum

$\mu\epsilon \rightarrow \mu_0\epsilon_0$ and $\mu_0\epsilon_0 = 1/c^2$ so the two wave equations become

$\nabla^2\mathbf{E} = \mu_0\epsilon_0\, \partial^2\mathbf{E}/\partial^2 t = (1/c^2)\, \partial^2\mathbf{E}/\partial^2 t$

$\nabla^2\mathbf{B} = \mu_0\epsilon_0\, \partial^2\mathbf{B}/\partial^2 t = (1/c^2)\, \partial^2\mathbf{B}/\partial^2 t$

In a (non-magnetic) material

$\mu\epsilon = 1/v^2$ and $v = c/n$ so $n^2 = \mu\epsilon/\mu_0\epsilon_0$

Therefore

$\epsilon = n^2$ and $n = \sqrt{\epsilon}$

The vector potential and the scalar potential also obey wave equations

$$\nabla^2 \mathbf{A} = \mu\epsilon \, \partial^2 \mathbf{A}/\partial^2 t = (1/v^2) \, \partial^2 \mathbf{A}/\partial^2 t$$

$$\nabla^2 \phi = \mu\epsilon \, \partial^2 \phi/\partial^2 t = (1/v^2) \, \partial^2 \phi/\partial^2 t$$

These two wave equations have four degrees-of-freedom, one for ϕ and three for $\mathbf{A}$

As we will see later, the vector potential and the scalar potential are the components of the four-potential A_μ.

The four-potential A_μ also obeys a wave equation

$$\nabla_\mu \nabla_\mu A_\mu = j_\mu/\epsilon_0$$

This wave equation for A_μ together with another equation for the four-current

$$\nabla_\mu j_\mu = 0$$

is equivalent to Maxwell's four equations. This formulation contains the sources j_μ.

Electrodynamics

http://www.its.caltech.edu/~phys1/java/phys1/MovingCharge/MovingCharge.html
http://webphysics.davidson.edu/applets/retard/Retard_FEL.html

Special Relativity

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General Relativity

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http://einstein.stanford.edu/Media/Simple_Expt_Anima-Flash.html

http://www.youtube.com/watch?v=AAqSCuHA0j8 **Gravity in terms of space-time**
http://www.youtube.com/watch?v=DbhuRcmSkMg **How gravity really works**
http://www.youtube.com/watch?v=O-p8yZYxNGc **Newton vs Einstein**

http://faraday.physics.utoronto.ca/PVB/Harrison/GenRel/Flash/Precession.html **GR vs CM Orbits**
http://www.fourmilab.ch/gravitation/orbits/ **GR Orbits**
http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/kepler6.htm **CM Orbits**
http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/morekep.html
http://astro.unl.edu/naap/pos/animations/kepler.swf
http://burtleburtle.net/bob/physics/solar.html
http://www.youtube.com/watch?v=nuX1BKLPITU **Gravity Well - Exploratorium**
http://www.youtube.com/watch?v=HrVdb9027yQ **Blue well for coins**

http://archive.ncsa.illinois.edu/Cyberia/NumRel/mathmine1.html **2D GR 3 pages**
http://test1.alan-dale.com/tapir/numrel2.html **3D GR 100 pages**
http://grtensor.phy.queensu.ca/NewDemo/index.html **416 diagonal and 519 off-diagonal terms**

Special Relativity

Special Relativity

The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.

Minkowski 1908

SPACE AND TIME

BY

H. MINKOWSKI

A Translation of an Address delivered at the 80*th Assembly of German Natural Scientists and Physicians, at Cologne,* 21 *September*, 1908.

SPACE AND TIME

By H. MINKOWSKI

THE views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.

I

First of all I should like to show how it might be possible, setting out from the accepted mechanics of the present day, along a purely mathematical line of thought, to arrive at changed ideas of space and time. The equations of Newton's mechanics exhibit a two-fold invariance. Their form remains unaltered, firstly, if we subject the underlying system of spatial co-ordinates to any arbitrary *change of position;* secondly, if we change its state of motion, namely, by imparting to it any *uniform translatory motion;* furthermore, the zero point of time is given no part to play. We are accustomed to look upon the axioms of geometry as finished with, when we feel ripe for the axioms of mechanics, and for that reason the two invariances are probably rarely mentioned in the same breath. Each of them by itself signifies, for the differential equations of mechanics, a certain group of transformations. The existence of the first group is looked upon as a fundamental characteristic of space. The second group is preferably treated with disdain, so that we with untroubled minds may overcome the difficulty of never being able to decide, from physical phenomena, whether space, which is supposed to be stationary, may not be after all in a

ON THE ELECTRODYNAMICS OF MOVING BODIES

By A. EINSTEIN

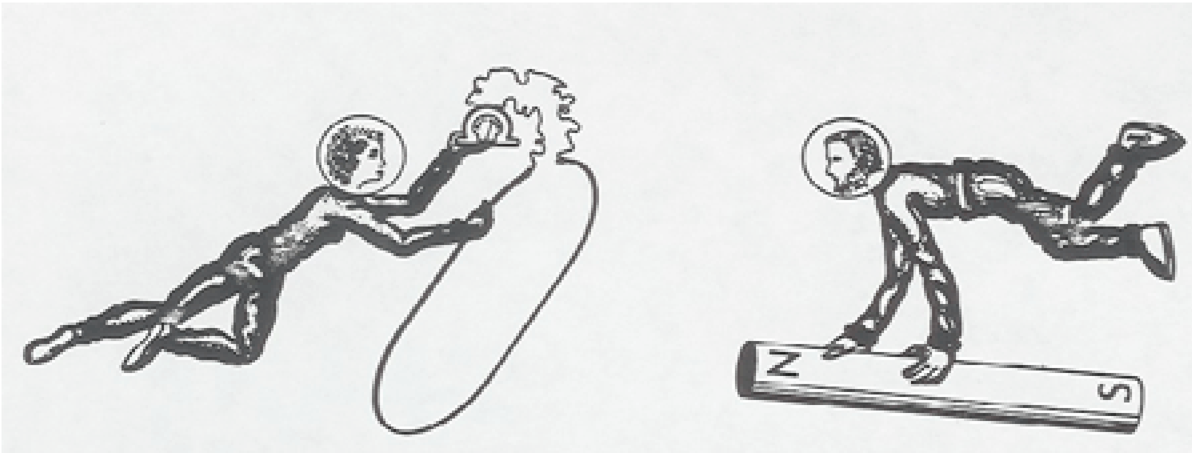
June 30, 1905

It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case.

Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good.[1] We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties, nor

[1] The preceding memoir by Lorentz was not at this time known to the author.

The relativity of Induction



We see Lucy and Ringo both moving, approaching each other.

Lucy says: The loop is stationary and the magnet is moving toward it. There is a magnetic field, but it can't produce any force on my electrons since they are stationary within the loop. Instead, the magnetic field is changing, growing stronger as the magnet gets closer, and this changing magnetic field produces an electric field which causes forces on the electrons, and drives them around the loop and produces the current in the galvanometer.

Ringo says: The magnet is stationary and the loop is moving toward it. The electrons in the loop, since they are moving with the loop, feel a magnetic force, $F = q\, v \times B$, which drives them around the loop and produces the current in the galvanometer. There is no electric field.

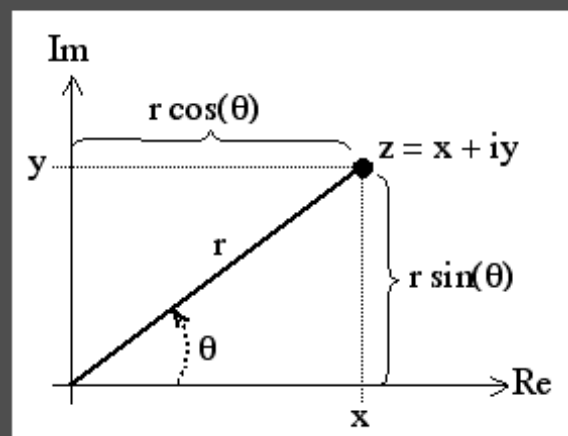
The Conclusion: Electric and magnetic fields are not invariant entities themselves, but are aspects of a single entity, the electromagnetic field, which manifests itself differently to different moving observers.

Anyone who studies relativity without understanding how to use simple spacetime diagrams is as much inhibited as a student of functions of a complex variable who does not understand the Argand diagram.

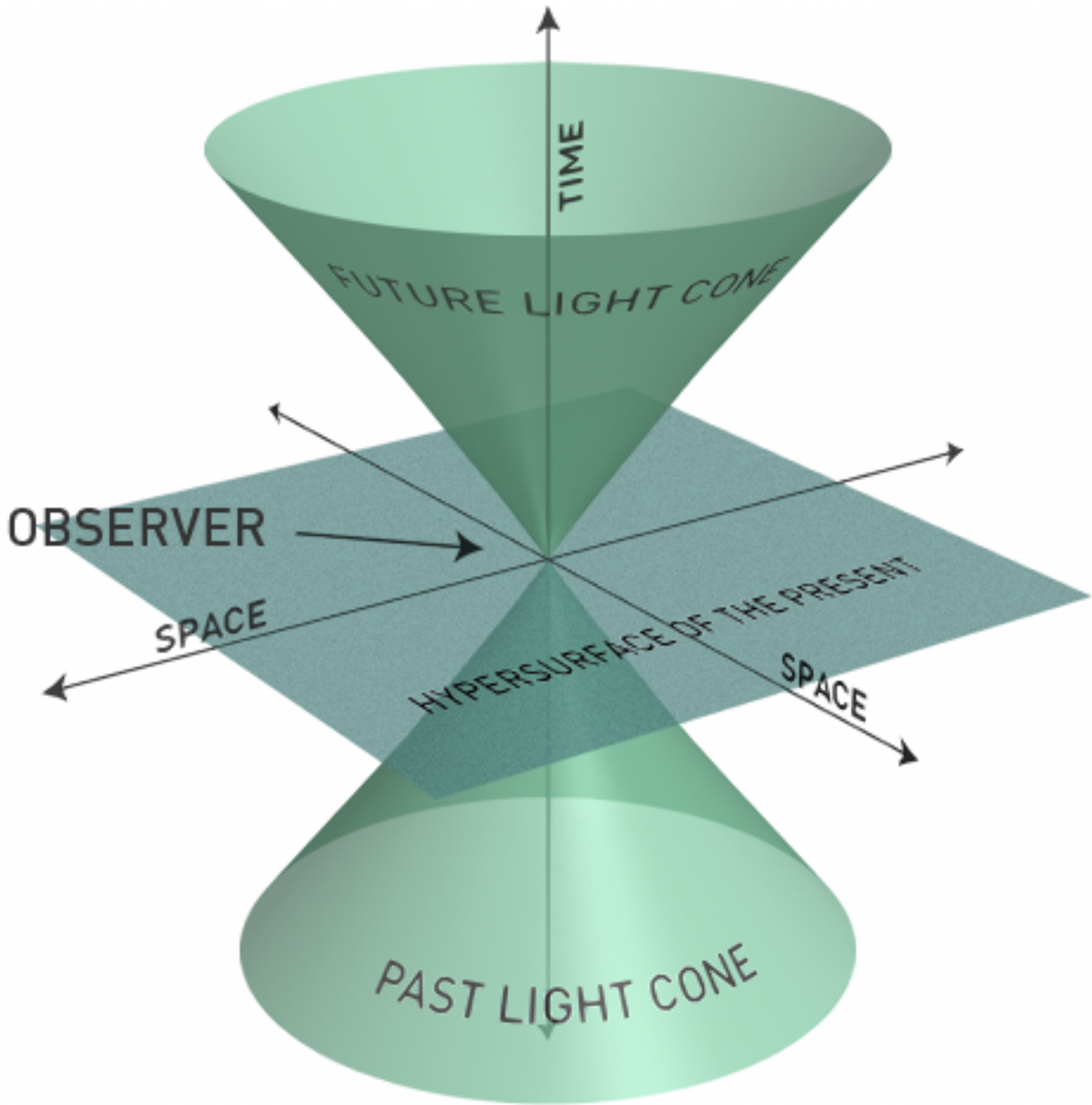
J.L. Synge

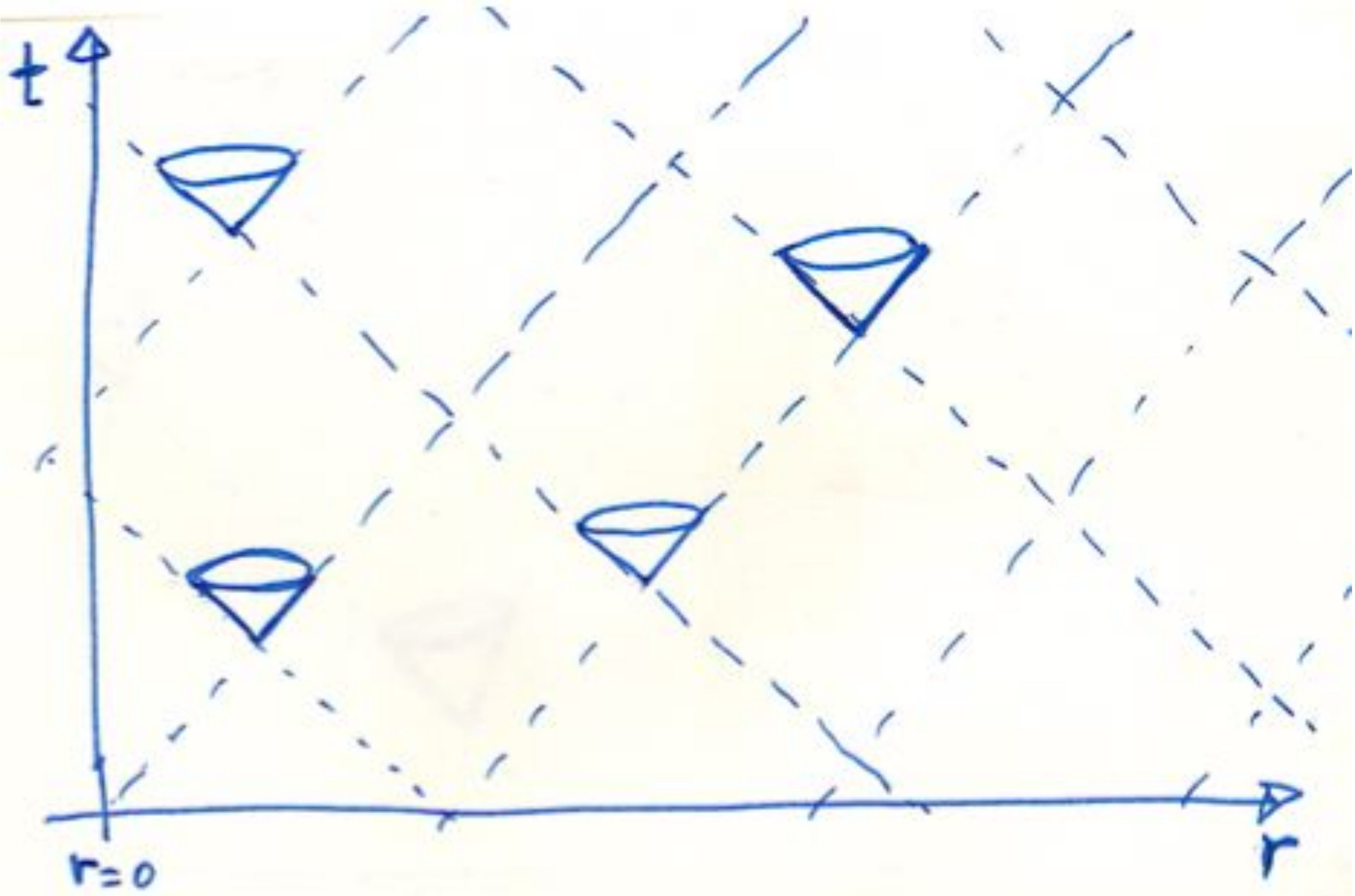
Argand diagram

A way of representing complex numbers as points on a coordinate plane, also known as the **Argand plane** or the **complex plane**, using the *x*-axis as the real axis and the *y*-axis as the imaginary axis. It is named for the French amateur mathematician Jean Robert Argand (1768–1822) who described it in a paper in 1806.[1] A similar method had been suggested 120 years earlier by John Wallis and had been developed extensively by Casper Wessel. But Wessel's paper was published in Danish and wasn't circulated in the languages more common to mathematics at that time. In fact, it wasn't until 1895 that his paper came to the attention of the mathematical community – long after the name "Argand diagram" had stuck.



In the diagram shown here, a complex number *z* is shown in terms of both Cartesian (*x*, *y*) and polar (*r*, *θ*) coordinates.


TIME
FUTURE LIGHT CONE
OBSERVER
SPACE
HYPERSURFACE OF THE PRESENT
SPACE
PAST LIGHT CONE


t
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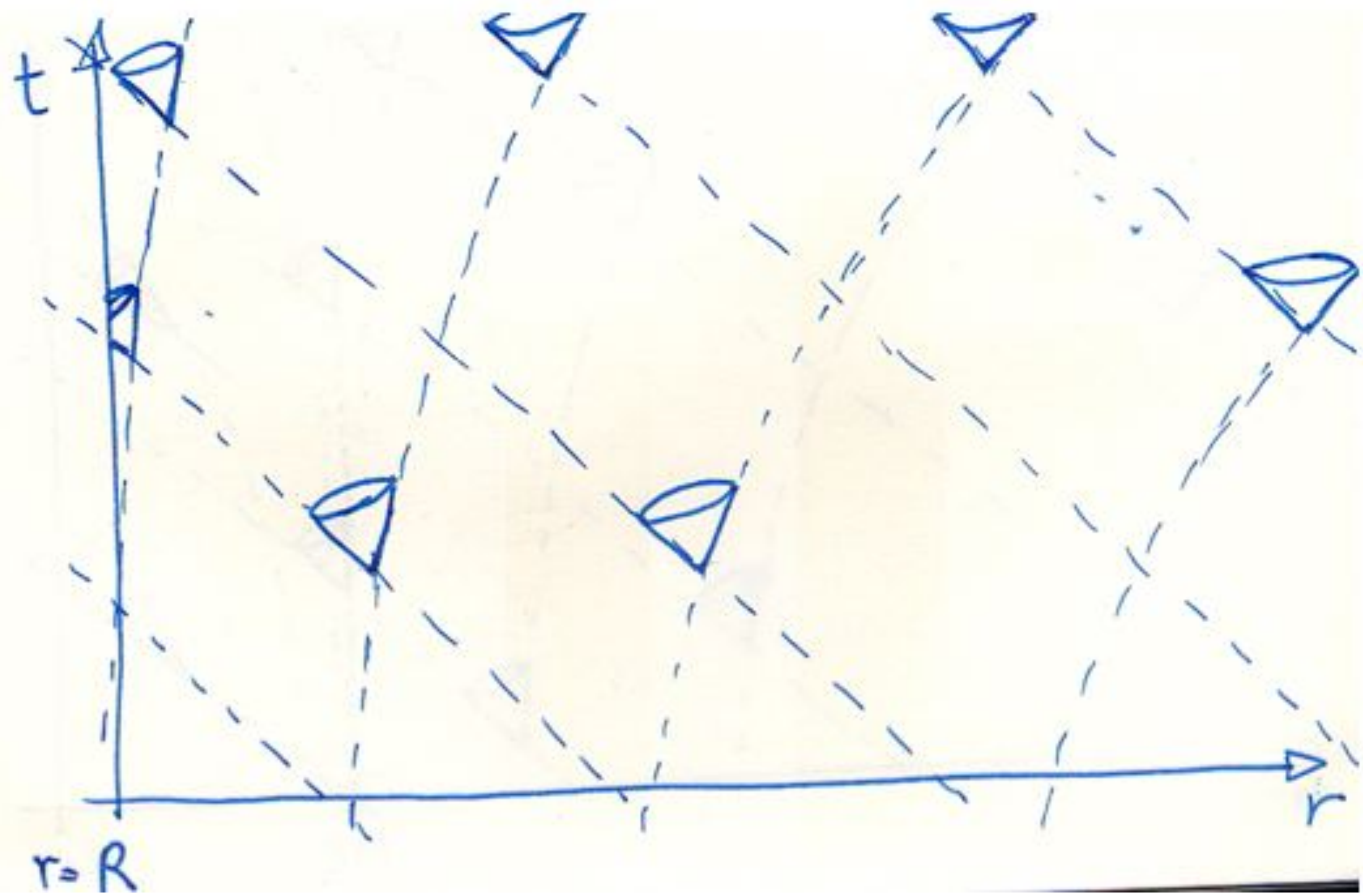
t
r
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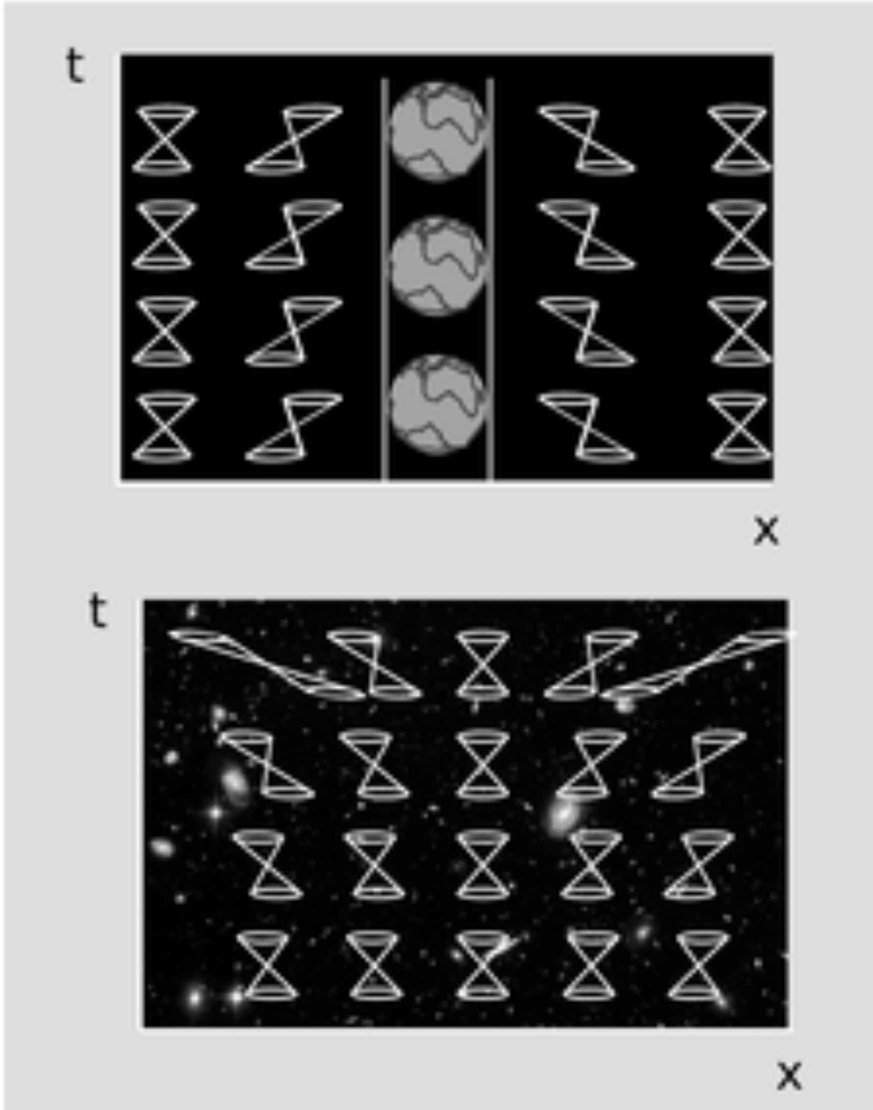

c / Light cones tip over for two reasons in general relativity: because of the presence of masses, which have gravitational fields, and because of the cosmological constant. The time and distance scales in the bottom figure are many orders of magnitude greater than those in the top.

Newtonian Spacetime is Euclidean

The three space-like components are Euclidean

The time-like component is separate

Spacetime is not Euclidean !!!

We live in a four-dimensional spacetime

The three space-like components are Euclidean

The one time-like component is Hyperbolic

For one spatial dimension

The Geometry Is hyperbolic

The Structure of Spacetime

Virtual Text 2 starts by saying

"Lorentz transformations are just hyperbolic rotations."

I am going to go one step further by asserting

Special Relativity is hyperbolic geometry.

Newtonian Spacetime

Space and time are different separate entities.

Distances are calculated using the Pythagorean Theorem

$s^2 = x^2 + y^2 + z^2$

Also called Euclidean Spacetime, Cartesian Spacetime, Galilean Spacetime

For 81 proofs of the Pythagorean Theorem see http://www.cut-the-knot.org/pythagoras/index.shtml

Relativistic Spacetime

Space and time are one entity.

Distances are calculated differently

$s^2 = t^2 - x^2 - y^2 - z^2$

In two dimensions

$s^2 = t^2 - x^2$

This is how distance is measured in two-dimensional hyperbolic geometry

Also called Minkowski Spacetime

Calculating Distances

In Euclidean Spacetime, distances are calculated using the inner product

$$\mathbf{r} = \begin{bmatrix} x \\ y \end{bmatrix}$$

$$\mathbf{r} \cdot \mathbf{r} = \mid \mathbf{r} \mid^2 = x^2 + y^2$$

In Minkowski Spacetime, distances are calculated using a different inner product

$$\mathbf{s} = \begin{bmatrix} t \\ x \end{bmatrix}$$

$$\mathbf{s} \cdot \mathbf{s} = \mid \mathbf{s} \mid^2 = t^2 - x^2$$

Formally, we can define the inner product using a matrix

For Euclidean Spacetime

$$\mathbf{M} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

For Minkowski Spacetime

$$\mathbf{M} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

Distance is given by the inner product $d^2 = \mathbf{v}^T\mathbf{M}\mathbf{v}$

The matrix $\mathbf{M}$ that defines distance is called the metric.

On the west coast

$$\mathbf{M} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \quad \text{and} \quad s^2 = t^2 - x^2 - y^2 - z^2$$

On the east coast

$$\mathbf{M} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad s^2 = -t^2 + x^2 + y^2 + z^2$$

The important thing about distances—also called intervals—is that they have the same value independent of the coordinate system used to measure them.

The Lorentz Transformations

Coordinate system changes in Minkowski Spacetime are given by the Lorentz transformations

The Lorentz transformations are the only linear coordinate transformations that produce invariant distances. The transformations must be linear so that the worldlines of free particles are straight lines in all coordinate systems.

$$t' = At + Bx$$

$$x' = Ct + Dx$$

The Lorentz transformations are given by

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

$$x' = \frac{x - vt}{\sqrt{1 - (v^2/c^2)}}$$

Written more compactly

$$t' = \gamma t - \beta\gamma x$$

$$x' = \gamma x - \beta\gamma t$$

Where

$$\beta = v/c$$

$$\gamma = \frac{1}{\sqrt{1 - (v^2/c^2)}}$$

As the author of Virtual Text 2 asserted, we will see later that the Lorentz transformations are hyperbolic rotations.

http://www.univie.ac.at/future.media/moe/galerie/struct/struct.html

http://webphysics.davidson.edu/applets/Minkowski/Minkowski_FEL.html

The Principle of Relativity

All laws of physics must be invariant under Lorentz transformations.

Invariant means:

(1) The law has the same mathematical form

(2) All numerical constants have the same values

A potpouri of four-vectors and four-operators

spacetime 4-vector $s = (t, x, y, z)$

energy-momentum 4-vector (E, p_x, p_y, p_z)

4-potential $A_\mu = (\phi, A_x, A_y, A_z)$

4-current $j_\mu = (\rho, j_x, j_y, j_z)$

4-dimensional $\nabla = \nabla_\mu = (\partial/\partial t, \nabla)$

D'Alembertian $= \nabla_\mu \nabla_\mu = (\partial^2/\partial t^2, -\nabla^2)$ 4-Laplacian

All 4-vectors transform in precisely the same way.

Electrodynamics

http://www.its.caltech.edu/~phys1/java/phys1/MovingCharge/MovingCharge.html
http://webphysics.davidson.edu/applets/retard/Retard_FEL.html

Special Relativity

http://www.cco.caltech.edu/~phys1/java/phys1/Einstein/Einstein.html
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General Relativity

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http://einstein.stanford.edu/Media/Einsteins_Universe_Anima-Flash.html
http://einstein.stanford.edu/Media/Simple_Expt_Anima-Flash.html

http://www.youtube.com/watch?v=AAqSCuHA0j8 Gravity in terms of space-time
http://www.youtube.com/watch?v=DbhuRcmSkMg How gravity really works
http://www.youtube.com/watch?v=O-p8yZYxNGc Newton vs Einstein

http://faraday.physics.utoronto.ca/PVB/Harrison/GenRel/Flash/Precession.html GR vs CM Orbits
http://www.fourmilab.ch/gravitation/orbits/ GR Orbits
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http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/morekep.html
http://astro.unl.edu/naap/pos/animations/kepler.swf
http://burtleburtle.net/bob/physics/solar.html
http://www.youtube.com/watch?v=nuX1BKLPITU Gravity Well - Exploratorium
http://www.youtube.com/watch?v=HrVdb9027yQ Blue well for coins

http://archive.ncsa.illinois.edu/Cyberia/NumRel/mathmine1.html 2D GR 3 pages
http://test1.alan-dale.com/tapir/numrel2.html 3D GR 100 pages
http://grtensor.phy.queensu.ca/NewDemo/index.html 416 diagonal and 519 off-diagonal terms

General Relativity

Newtonian Worldview

Space is absolute and Euclidean

Time is absolute

Special Relativity

Spacetime is Minkowskian

General Relativity

Spacetime is Riemannian

Physics is geometry!

"The magic of General Relativity is that it transforms conceptually simple ideas into concrete equations and uses them to make astonishing predictions about the nature of physical reality."

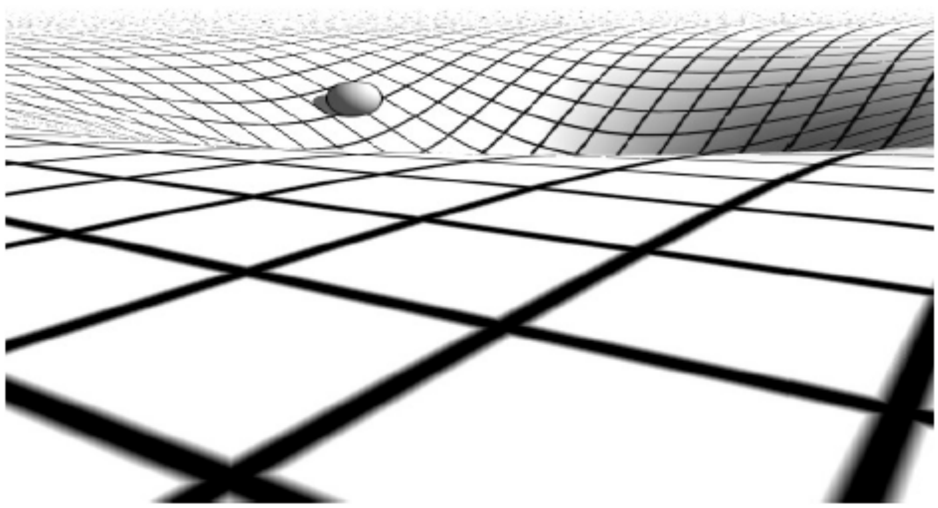


FIG. 1: An artist's depiction of planetary motion in general relativity. Heavy bodies such as our sun bend space-time. Planets go 'as straight as they can' in this curved geometry. In the flat space perspective of Newtonian physics, however, the same orbits appear to be elliptical, being eternally pulled to the sun by gravity. Thus the familiar gravitational force of Newtonian physics is just a 'poor man's way' of describing effects of space-time curvature using a flat space framework. Image: Boris Starosta, www. Starosta.com

The magic of general relativity is that, through elegant mathematics, it transforms these conceptually simple ideas into concrete equations and uses them to make astonishing predictions about the nature of physical reality. It predicts that clocks should tick faster in Kathmandu than in Bombay. Galactic nuclei should act as giant gravitational lenses and provide spectacular, multiple images of distant quasars. Two neutron stars orbiting around each other must lose energy through ripples in the curvature of space-time caused by their motion and spiral inward in an ever tightening embrace. Over the last thirty years, astute measurements have been performed to test if these and other even more exotic predictions are correct. Each time, general relativity has triumphed [2]. The accuracy of some of these observations exceeds that of the legendary tests of quantum electrodynamics. This combination of conceptual depth, mathematical elegance and observational successes is unprecedented. This is why general relativity is widely regarded as the most sublime of all scientific creations [3].

General Relativity

Matter tells space how to curve.
Space tells matter how to move.

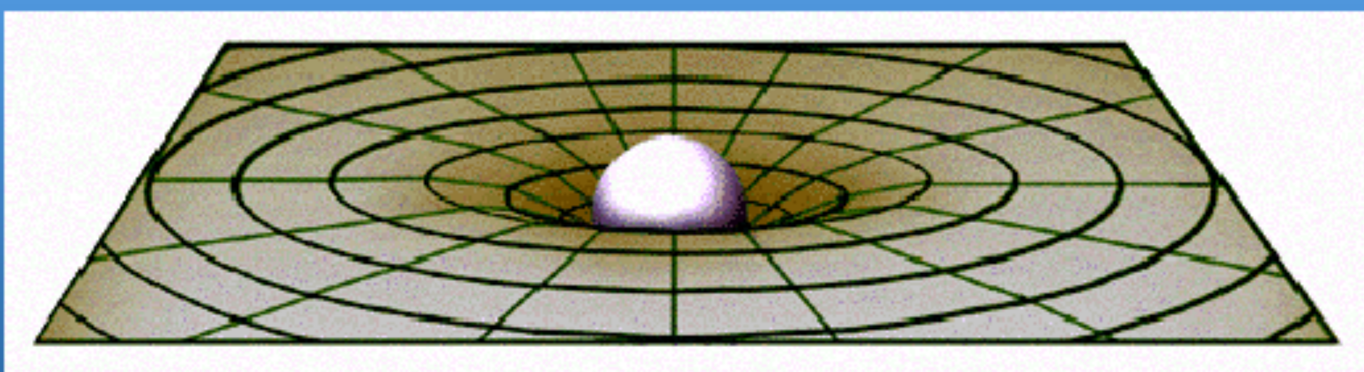
John Wheeler

Newtonian Gravity

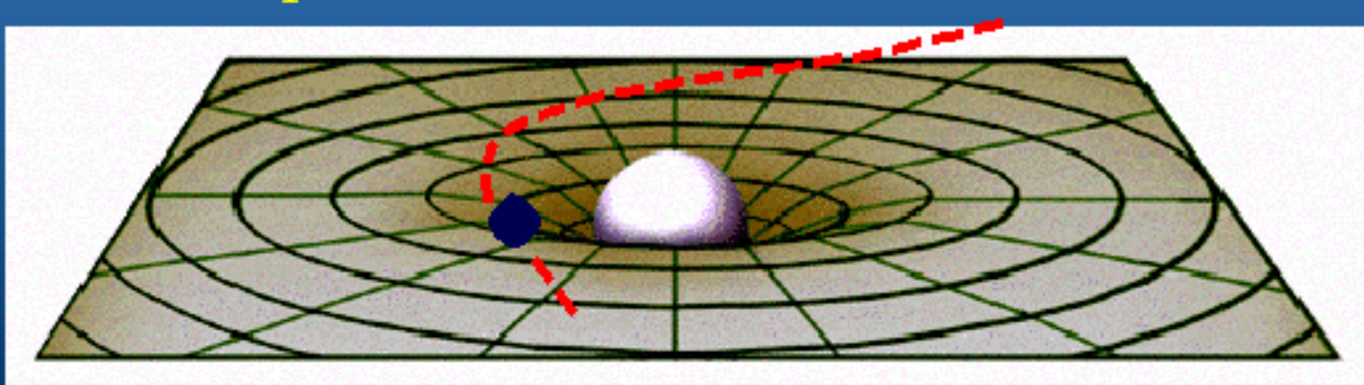
Matter tells matter how to move.

Gravity: Space as a Rubber Sheet

- Matter tells space how to curve



- Curved space tells matter how to move



Einstein Equation

$$G = T$$

curvature of spacetime

matter/energy content

Einstein tensor

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Einstein Tensor

$$G_{\mu\nu} = R_{\mu\nu} - (1/2)\, g_{\mu\nu} R$$

$R_{\mu\nu}$ **Ricci Tensor**

$g_{\mu\nu}$ **Metric Tensor**

R **scalar curvature**

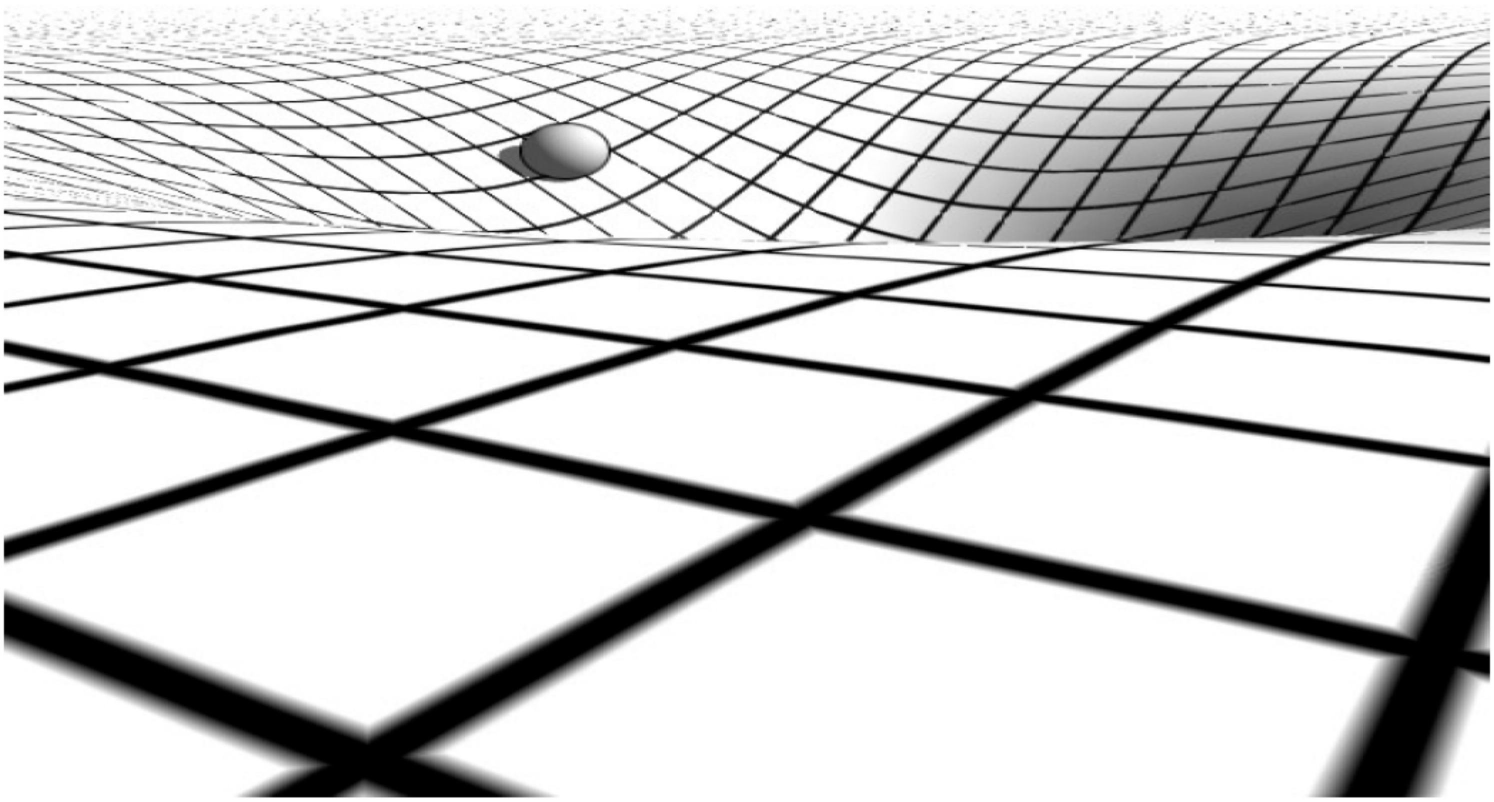
G **Universal Gravitation Constant**

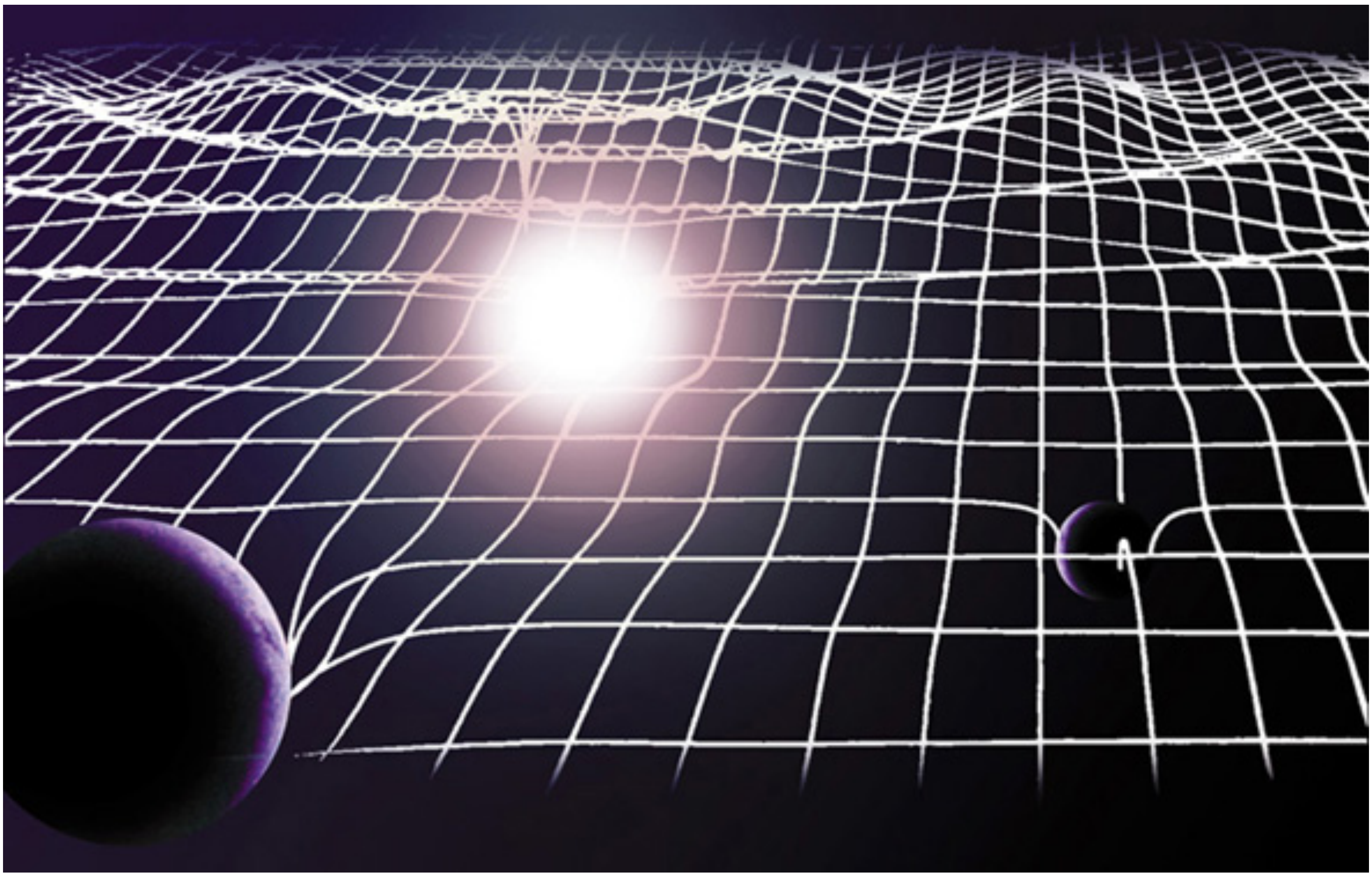
Einstein Field Equations (EFE)

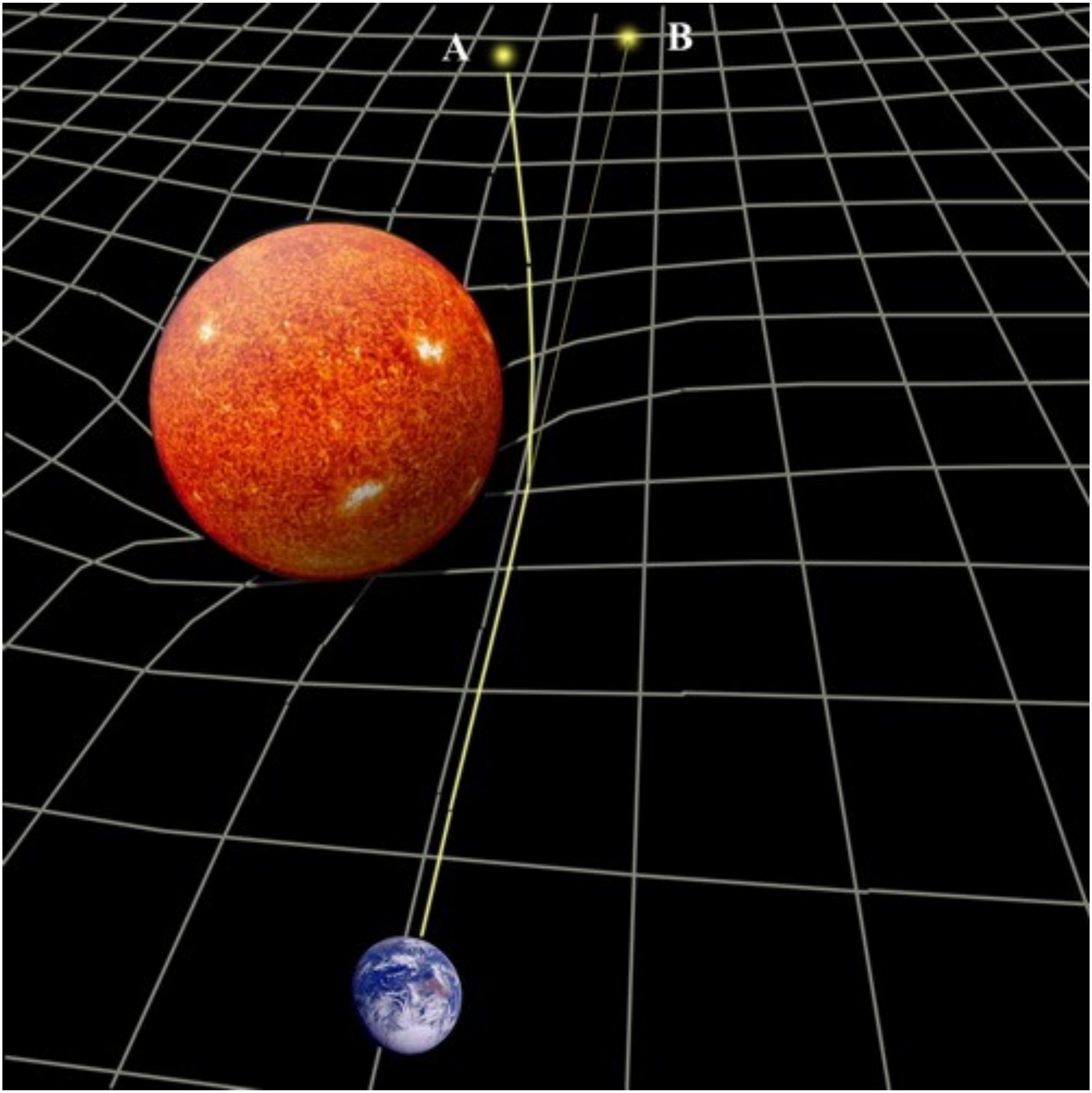
$$G_{\mu\nu} + g_{\mu\nu}\,\Lambda = (8\pi G/c^4)\; T_{\mu\nu}$$

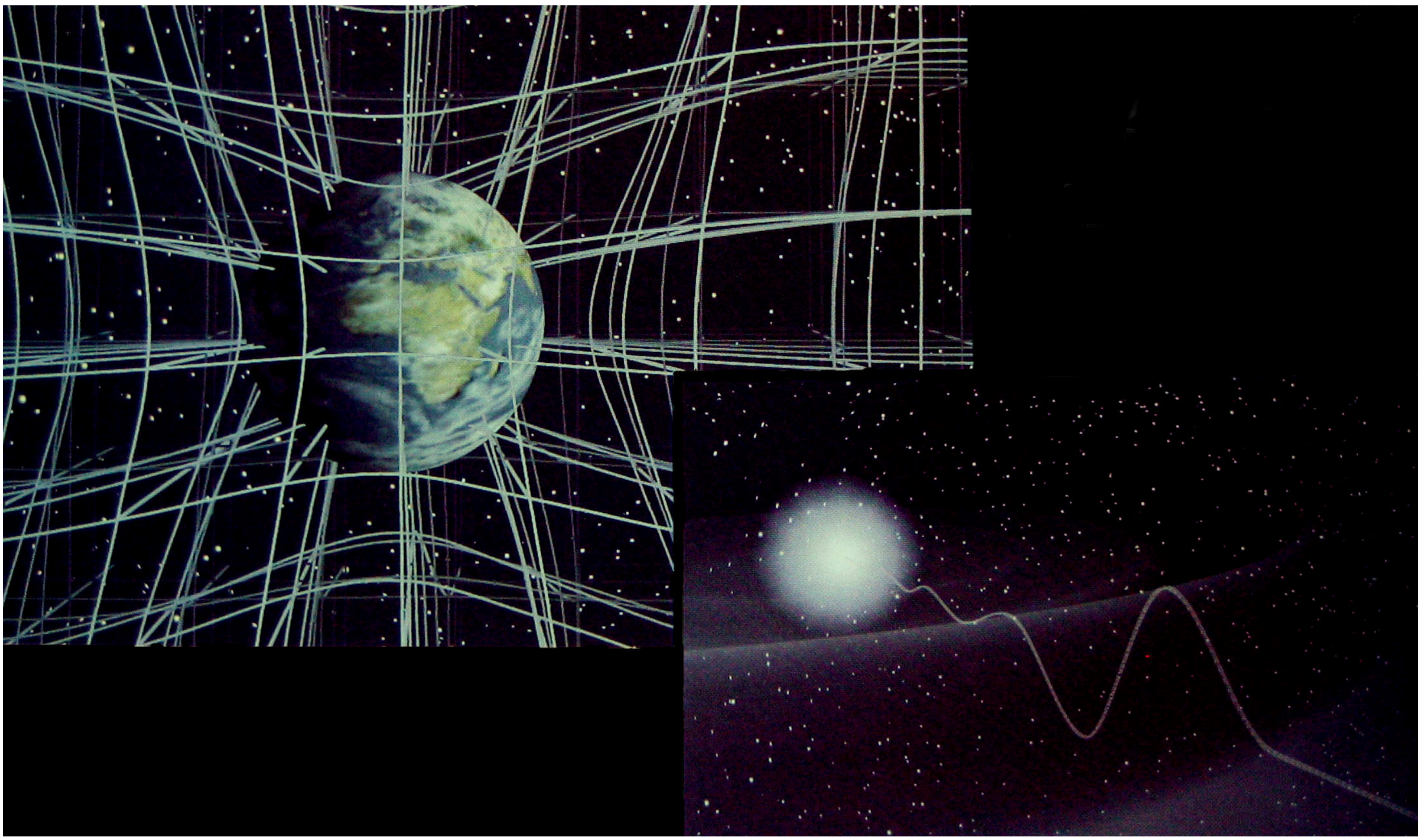
$$R_{\mu\nu} - (1/2)g_{\mu\nu}R + g_{\mu\nu}\,\Lambda = (8\pi G/c^4)\; T_{\mu\nu}$$

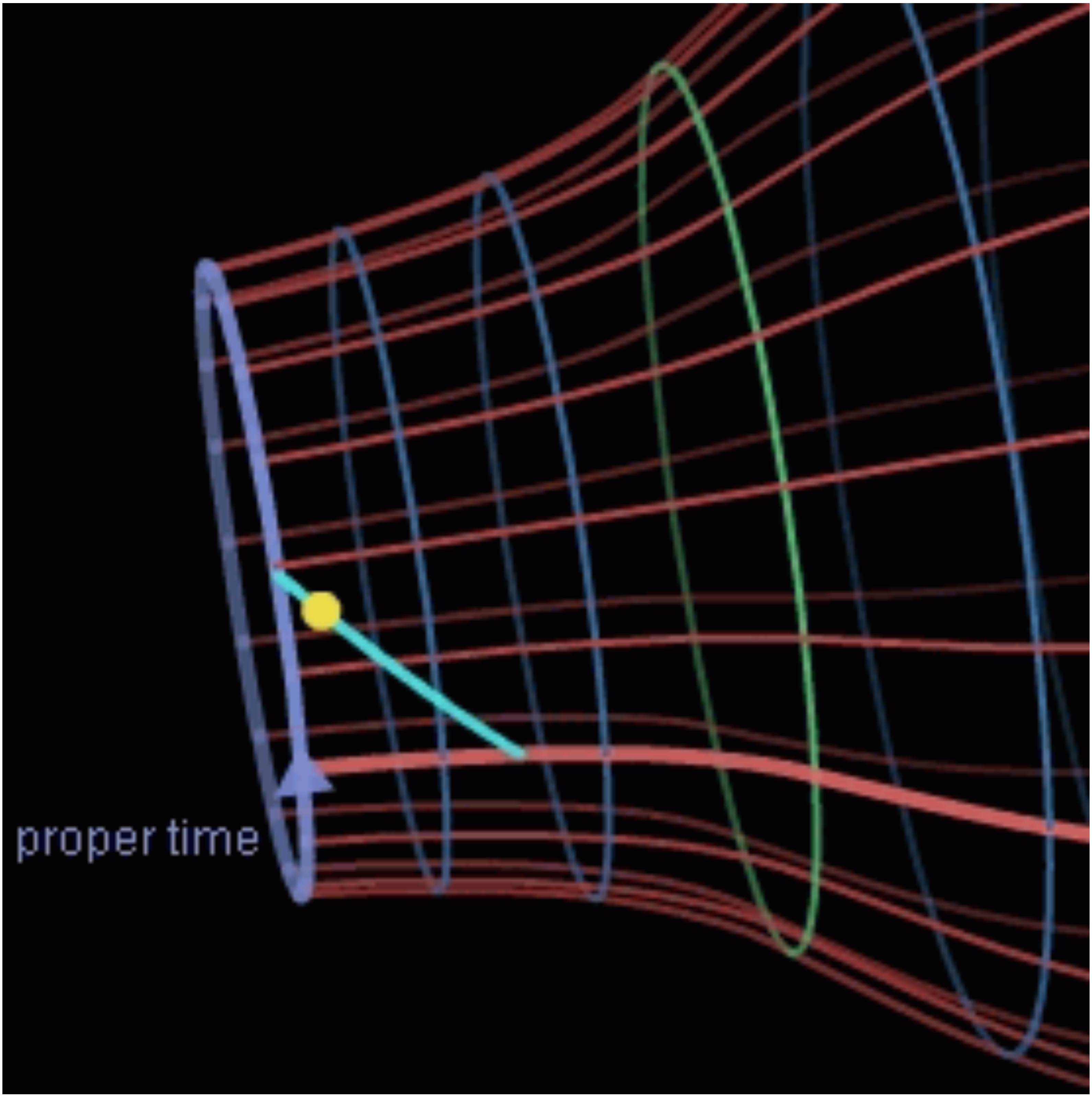
Λ cosmological constant






A
B




proper time

Electrodynamics

http://www.its.caltech.edu/~phys1/java/phys1/MovingCharge/MovingCharge.html
http://webphysics.davidson.edu/applets/retard/Retard_FEL.html

Special Relativity

http://www.cco.caltech.edu/~phys1/java/phys1/Einstein/Einstein.html
http://www.univie.ac.at/future.media/moe/galerie/struct/struct.html
http://webphysics.davidson.edu/applets/Minkowski/Minkowski_FEL.html

General Relativity

http://einstein.stanford.edu/Media/Newtons_Universe_Anima-Flash.html
http://einstein.stanford.edu/Media/Einsteins_Universe_Anima-Flash.html
http://einstein.stanford.edu/Media/Simple_Expt_Anima-Flash.html

http://www.youtube.com/watch?v=AAqSCuHA0j8 **Gravity in terms of space-time**
http://www.youtube.com/watch?v=DbhuRcmSkMg **How gravity really works**
http://www.youtube.com/watch?v=O-p8yZYxNGc **Newton vs Einstein**

http://faraday.physics.utoronto.ca/PVB/Harrison/GenRel/Flash/Precession.html **GR vs CM Orbits**
http://www.fourmilab.ch/gravitation/orbits/ **GR Orbits**
http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/kepler6.htm **CM Orbits**
http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/morekep.html
http://astro.unl.edu/naap/pos/animations/kepler.swf
http://burtleburtle.net/bob/physics/solar.html
http://www.youtube.com/watch?v=nuX1BKLPITU **Gravity Well - Exploratorium**
http://www.youtube.com/watch?v=HrVdb9027yQ **Blue well for coins**

http://archive.ncsa.illinois.edu/Cyberia/NumRel/mathmine1.html **2D GR 3 pages**
http://test1.alan-dale.com/tapir/numrel2.html **3D GR 100 pages**
http://grtensor.phy.queensu.ca/NewDemo/index.html **416 diagonal and 519 off-diagonal terms**