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Problem Sets
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The Free Index
Define a Space-Time Vector
Space-Time Vector
Transformation Law
Einstein Field Equations - for beginners! - Einstein Field Equations - for beginners! by DrPhysicsA 4,458,018 views 10 years ago 2 hours, 6 minutes - Einstein's Field Equations for **General Relativity**, - including the Metric Tensor, Christoffel symbols, Ricci Cuvature Tensor, ...
Principle of Equivalence
Light bends in gravitational field
Ricci Curvature Tensor
Curvature Scalar

Cosmological Constant
Christoffel Symbol
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Introduction
Newtons gravitational constant
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tidal forces
gravitational attraction
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The Basic Newtonian Equation
Newtonian Equation
Acceleration
Newton's First and Second Law
The Equivalence Principle
Equivalence Principle
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Experiments
Newton's Third Law the Forces Are Equal and Opposite
Angular Frequency
Kepler's Second Law
Electrostatic Force Laws
Tidal Forces
Uniform Acceleration
The Minus Sign There Look As Far as the Minus Sign Goes all It Means Is that every One of these Particles Is Pulling on this Particle toward It as Opposed to Pushing Away from It It's Just a Convention Which Keeps Track of Attraction Instead of Repulsion Yeah for the for the Ice Master That's My Word You Want To Make Sense but if You Can Look at It as a Kind of an in Samba Wasn't about a Linear Conic Component to It because the Ice Guy Affects the Jade Guy and Then Put You Compute the Jade Guy When You Take It Yeah Now What this What this Formula Is for Is Supposing You Know the Positions or All the Others You Know that Then What Is the Force on the One
This Extra Particle Which May Be Imaginary Is Called a Test Particle It's the Thing That You'Re Imagining Testing Out the Gravitational Field with You Take a Light Little Particle and You Put It Here and You See How It Accelerates Knowing How It Accelerates Tells You How Much Force Is on It in Fact It Just Tells You How It Accelerates and You Can Go Around and Imagine Putting It in Different Places and Mapping Out the Force Field That's on that Particle or the Acceleration
It's the Thing That You'Re Imagining Testing Out the Gravitational Field with You Take a Light Little Particle and You Put It Here and You See How It Accelerates Knowing How It Accelerates Tells You How Much Force Is on It in Fact It Just Tells You How It Accelerates and You Can Go Around and Imagine Putting It in Different Places and Mapping Out the Force Field That's on that Particle or the Acceleration Field since We Already Know that the Force Is Proportional to the Mass Then We Can Just Concentrate on the Acceleration
And You Can Go Around and Imagine Putting It in Different Places and Mapping Out the Force Field That's on that Particle or the Acceleration Field since We Already Know that the Force Is Proportional to the Mass Then We Can Just Concentrate on the Acceleration the Acceleration all Particles Will Have the Same Acceleration Independent of the Mass so We Don't Even Have To Know What the Mass of the Particle Is We Put Something over There a Little Bit of Dust and We See How It Accelerates Acceleration Is a Vector and So We Map Out in Space the Acceleration of a Particle

at every Point in Space either Imaginary or Real Particle
And We See How It Accelerates Acceleration Is a Vector and So We Map Out in Space the Acceleration of a Particle at every Point in Space either Imaginary or Real Particle and that Gives Us a Vector Field at every Point in Space every Point in Space There Is a Gravitational Field of Acceleration It Can Be Thought of as the Acceleration You Don't Have To Think of It as Force Acceleration the Acceleration of a Point Mass Located at that Position It's a Vector It Has a Direction It Has a Magnitude and It's a Function of Position so We Just Give It a Name the Acceleration due to All the Gravitating Objects
If Everything Is in Motion the Gravitational Field Will Also Depend on Time We Can Even Work Out What It Is We Know What the Force on the Earth Particle Is All Right the Force on a Particle Is the Mass Times the Acceleration So if We Want To Find the Acceleration Let's Take the Ayth Particle To Be the Test Particle Little Eye Represents the Test Particle over Here Let's Erase the Intermediate Step Over Here and Write that this Is in Ai Times Ai but Let Me Call It Now Capital a the Acceleration of a Particle at Position X
And that's the Way I'M GonNa Use It Well for the Moment It's Just an Arbitrary Vector Field a It Depends on Position When I Say It's a Field the Implication Is that It Depends on Position Now I Probably Made It Completely Unreadable a of X Varies from Point to Point and I Want To Define a Concept Called the Divergence of the Field Now It's Called the Divergence because One Has To Do Is the Way the Field Is Spreading Out Away from a Point for Example a Characteristic Situation Where We Would Have a Strong Divergence for a Field Is if the Field Was Spreading Out from a Point like that the Field Is Diverging Away from the Point Incidentally if the Field Is Pointing Inward The Field Is the Same Everywhere as in Space What Does that Mean that Would Mean the Field That Has both Not Only the Same Magnitude but the Same Direction Everywhere Is in Space Then It Just Points in the Same Direction Everywhere Else with the Same Magnitude It Certainly Has no Tendency To Spread Out When Does a Field Have a Tendency To Spread Out When the Field Varies for Example It Could Be Small over Here Growing Bigger Growing Bigger Growing Bigger and We Might Even Go in the Opposite Direction and Discover that It's in the Opposite Direction and Getting Bigger in that Direction Then Clearly There's a Tendency for the Field To Spread Out Away from the Center Here the Same Thing Could Be True if It Were Varying in the Vertical
It Certainly Has no Tendency To Spread Out When Does a Field Have a Tendency To Spread Out When the Field Varies for Example It Could Be Small over Here Growing Bigger Growing Bigger Growing Bigger and We Might Even Go in the Opposite Direction and Discover that It's in the Opposite Direction and Getting Bigger in that Direction Then Clearly There's a Tendency for the Field To Spread Out Away from the Center Here the Same Thing Could Be True if It Were Varying in the Vertical Direction or Who Are Varying in the Other Horizontal Direction and So the Divergence Whatever It Is Has To Do with Derivatives of the Components of the Field
If You Found the Water Was Spreading Out Away from a Line this Way Here and this Way Here Then You'D Be Pretty Sure that some Water Was Being Pumped In from Underneath along this Line Here Well You Would See It another Way You Would Discover that the X Component of the Velocity Has a Derivative It's Different over Here than It Is over Here the X Component of the Velocity Varies along the X Direction so the Fact that the X Component of the Velocity Is Varying along the Direction There's an Indication that There's some Water Being Pumped in Here Likewise
You Can See the In and out the in Arrow and the Arrow of a Circle Right in between those Two and Let's Say that's the Bigger Arrow Is Created by a Steeper Slope of the Street It's Just Faster It's Going Fast It's Going Okay and because of that There's a Divergence There That's Basically It's Sort of the Difference between that's Right that's Right if We Drew a Circle around Here or We Would See that More since the Water Was Moving Faster over Here than It Is over Here More Water Is Flowing Out over Here Then It's Coming in Over Here
It's Just Faster It's Going Fast It's Going Okay and because of that There's a Divergence There That's Basically It's Sort of the Difference between that's Right that's Right if We Drew a Circle around Here or We Would See that More since the Water Was Moving Faster over Here than It Is over Here More Water Is Flowing Out over Here Then It's Coming In over Here Where Is It Coming from It Must Be Pumped in the Fact that There's More Water Flowing Out on One Side Then It's Coming In from the Other Side Must Indicate that There's a Net Inflow from Somewheres Else and the Somewheres Else Would Be from the Pump in Water from Underneath
Water Is an Incompressible Fluid It Can't Be Squeezed It Can't Be Stretched Then the Velocity Vector Would Be the Right Thing To Think about Them Yeah but You Could Have no You'Re Right You Could Have a Velocity Vector Having a Divergence because the Water Is Not because Water Is Flowing in but because It's Thinning Out Yeah that's that's Also Possible Okay but Let's Keep It Simple All Right

and You Can Have the Idea of a Divergence Makes Sense in Three Dimensions Just As Well as Two Dimensions You Simply Have To Imagine that all of Space Is Filled with Water and There Are some Hidden Pipes Coming in Depositing Water in Different Places
Having a Divergence because the Water Is Not because Water Is Flowing in but because It's Thinning Out Yeah that's that's Also Possible Okay but Let's Keep It Simple All Right and You Can Have the Idea of a Divergence Makes Sense in Three Dimensions Just As Well as Two Dimensions You Simply Have To Imagine that all of Space Is Filled with Water and There Are some Hidden Pipes Coming in Depositing Water in Different Places so that It's Spreading Out Away from Points in Three-Dimensional Space in Three-Dimensional Space this Is the Expression for the Divergence All Right and You Can Have the Idea of a Divergence Makes Sense in Three Dimensions Just As Well as Two Dimensions You Simply Have To Imagine that all of Space Is Filled with Water and There Are some Hidden Pipes Coming in Depositing Water in Different Places so that It's Spreading Out Away from Points in Three-Dimensional Space in Three-Dimensional Space this Is the Expression for the Divergence if this Were the Velocity Vector at every Point You Would Calculate this Quantity and that Would Tell You How Much New Water Is Coming In at each Point of Space so that's the Divergence Now There's a Theorem Which
The Divergence Could Be Over Here Could Be Over Here Could Be Over Here Could Be Over Here in Fact any Ways Where There's a Divergence Will Cause an Effect in Which Water Will Flow out of this Region Yeah so There's a Connection There's a Connection between What's Going On on the Boundary of this Region How Much Water Is Flowing through the Boundary on the One Hand and What the Divergence Is in the Interior the Connection between the Two and that Connection Is Called Gauss's Theorem What It Says Is that the Integral of the Divergence in the Interior That's the Total Amount of Flow Coming In from Outside from underneath the Bottom of the Lake
The Connection between the Two and that Connection Is Called Gauss's Theorem What It Says Is that the Integral of the Divergence in the Interior That's the Total Amount of Flow Coming In from Outside from underneath the Bottom of the Lake the Total Integrated and Now by Integrated I Mean in the Sense of an Integral the Integrated Amount of Flow in that's the Integral of the Divergence the Integral over the Interior in the Three-Dimensional Case It Would Be Integral Dx Dy Dz over the Interior of this Region of the Divergence of a
The Integral over the Interior in the Three-Dimensional Case It Would Be Integral Dx Dy Dz over the Interior of this Region of the Divergence of a if You Like To Think of a Is the Velocity Field That's Fine Is Equal to the Total Amount of Flow That's Going Out through the Boundary and How Do We Write that the Total Amount of Flow That's Flowing Outward through the Boundary We Break Up Let's Take the Three-Dimensional Case We Break Up the Boundary into Little Cells each Little Cell Is a Little Area
So We Integrate the Perpendicular Component of the Flow over the Surface That's through the Sigma Here That Gives Us the Total Amount of Fluid Coming Out per Unit Time for Example and that Has To Be the Amount of Fluid That's Being Generated in the Interior by the Divergence this Is Gauss's Theorem the Relationship between the Integral of the Divergence on the Interior of some Region and the Integral over the Boundary Where Where It's Measuring the Flux the Amount of Stuff That's Coming Out through the Boundary Fundamental Theorem and Let's Let's See What It Says Now And Now Let's See Can We Figure Out What the Field Is Elsewhere outside of Here So What We Do Is We Draw a Surface Around There We Draw a Surface Around There and Now We'Re Going To Use Gauss's Theorem First of all Let's Look at the Left Side the Left Side Has the Integral of the Divergence of the Vector Field All Right the Vector Field or the Divergence Is Completely Restricted to some Finite Sphere in Here What Is Incidentally for the Flow Case for the Fluid Flow Case What Would Be the Integral of the Divergence Does Anybody Know if It Really Was a Flue or a Flow of a Fluid
So What We Do Is We Draw a Surface Around There We Draw a Surface Around There and Now We'Re Going To Use Gauss's Theorem First of all Let's Look at the Left Side the Left Side Has the Integral of the Divergence of the Vector Field All Right the Vector Field or the Divergence Is Completely Restricted to some Finite Sphere in Here What Is Incidentally for the Flow Case for the Fluid Flow Case What Would Be the Integral of the Divergence Does Anybody Know if It Really Was a Flue or a Flow of a Fluid It'Ll Be the Total Amount of Fluid That Was Flowing
Why because the Integral over that There Vergence of a Is Entirely Concentrated in this Region Here and There's Zero Divergence on the Outside So First of All the Left Hand Side Is Independent of the Radius of this Outer Sphere As Long as the Radius of the Outer Sphere Is Bigger than this Concentration of Divergence Iya so It's a Number Altogether It's a Number Let's Call that Number M I'M Not Evan Let's Just Qq That's the Left Hand Side and It Doesn't Depend on the Radius on the

Other Hand What Is the Right Hand Side Well There's a Flow Going Out and if Everything Is Nice and Spherically Symmetric Then the Flow Is Going To Go Radially Outward
So a Point Mass Can Be Thought of as a Concentrated Divergence of the Gravitational Field Right at the Center Point Mass the Literal Point Mass Can Be Thought of as a Concentrated Concentrated Divergence of the Gravitational Field Concentrated in some Very Very Small Little Volume Think of It if You like You Can Think of the Gravitational Field as the Flow Field or the Velocity Field of a Fluid That's Spreading Out Oh Incidentally of Course I'Ve Got the Sign Wrong Here the Real Gravitational Acceleration Points Inward Which Is an Indication that this Divergence Is Negative the Divergence Is More like a Convergence Sucking Fluid in So the Newtonian Gravitational
Or There It's a Spread Out Mass this Big As Long as You'Re outside the Object and As Long as the Object Is Spherically Symmetric in Other Words As Long as the Object Is Shaped like a Sphere and You'Re outside of It on the Outside of It outside of Where the Mass Distribution Is Then the Gravitational Field of It Doesn't Depend on whether It's a Point It's a Spread Out Object whether It's Denser at the Center and Less Dense at the Outside Less Dense in the Inside More Dense on the Outside all It Depends on Is the Total Amount of Mass the Total Amount of Mass Is like the Total Amount of Flow
Whether It's Denser at the Center and Less Dense at the Outside Less Dense in the Inside More Dense on the Outside all It Depends on Is the Total Amount of Mass the Total Amount of Mass Is like the Total Amount of Flow through Coming into the that Theorem Is Very Fundamental and Important to Thinking about Gravity for Example Supposing We Are Interested in the Motion of an Object near the Surface of the Earth but Not So near that We Can Make the Flat Space Approximation Let's Say at a Distance Two or Three or One and a Half Times the Radius of the Earth
It's Close to this Point that's Far from this Point That Sounds like a Hellish Problem To Figure Out What the Gravitational Effect on this Point Is but Know this Tells You the Gravitational Field Is Exactly the Same as if the Same Total Mass Was Concentrated Right at the Center Okay That's Newton's Theorem Then It's Marvelous Theorem It's a Great Piece of Luck for Him because without It He Couldn't Have Couldn't Have Solved His Equations He Knew He Meant but It May Have Been Essentially this Argument I'M Not Sure Exactly What Argument He Made but He Knew that with the 1 over R Squared Force Law and Only the One over R Squared Force Law Wouldn't Have Been Truth Was One of Our Cubes 1 over R to the Fourth 1 over R to the 7th
But He Knew that with the 1 over R Squared Force Law and Only the One over R Squared Force Law Wouldn't Have Been Truth Was One of Our Cubes 1 over R to the Fourth 1 over R to the 7th with the 1 over R Squared Force Law a Spherical Distribution of Mass Behaves Exactly as if All the Mass Was Concentrated Right at the Center As Long as You'Re outside the Mass so that's What Made It Possible for Newton To To Easily Solve His Own Equations That every Object As Long as It's Spherical Shape Behaves as if It Were Appoint Appointments
But Yes We Can Work Out What Would Happen in the Mine Shaft but that's Right It Doesn't Hold It a Mine Shaft for Example Supposing You Dig a Mine Shaft Right Down through the Center of the Earth Okay and Now You Get Very Close to the Center of the Earth How Much Force Do You Expect that We Have Pulling You toward the Center Not Much Certainly Much Less than if You Were than if All the Mass Will Concentrate a Right at the Center You Got the It's Not Even Obvious Which Way the Force Is but It Is toward the Center
So the Consequence Is that if You Made a Spherical Shell of Material like that the Interior Would Be Absolutely Identical to What It What It Would Be if There Was no Gravitating Material There At All on the Other Hand on the Outside You Would Have a Field Which Would Be Absolutely Identical to What Happens at the Center Now There Is an Analogue of this in the General Theory of Relativity We'Ll Get to It Basically What It Says Is the Field of Anything As Long as It's Fairly Symmetric on the Outside Looks Identical to the Field of a Black Hole I Think We'Re Finished for Tonight Go over Divergence and All those Gauss's Theorem Gauss's Theorem Is Central
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Complex numbers examples

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Spacetime Diagrams vs. Spacetime
Testing for Curvature
A Hidden Coordinate Transformation
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Linear algebra (Best book to study, why you should study)
Calculus and vectors (Why you should study, best book)
Vectors (Best book to study)
Special theory of relativity (Best book to study)
Tensors and differential geometry (Best book to study)
Topology (Best book to study)
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General Relativity Lecture 3 - General Relativity Lecture 3 by Stanford 371,527 views 11 years ago 1 hour, 52 minutes - (October 8, 2012) Leonard Susskind continues his discussion of Riemannian **geometry**, and uses it as a foundation for **general**, ...
12. Introduction to Relativity - 12. Introduction to Relativity by YaleCourses 433,400 views 15 years ago 1 hour, 11 minutes - Fundamentals of **Physics**, (PHYS 200) This is the first of a series of **lectures**, on **relativity**,. The **lecture**, begins with a historical ...
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Chapter 5. Length Contraction and Time Dilation
Chapter 6. Deriving the Lorentz Transformation
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The Mathematics of Slow Time
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The Reality of Past, Present, and Future
Time Dilation: Intuitive Explanation
Motion's Effect On Space
Motion's Effect On Space: Mathematical Form
Length Contraction: Travel of Proxima Centauri
Length Contraction: Disintegrating Muons
Length Contraction: Distant Spaceflight
Length Contraction: Horizontal Light Clock In Motion
Coordinates For Space
Coordinates For Space: Rotation of Coordinate Frames
Coordinates For Space: Translation of Coordinate Frames
Coordinates for Time
Coordinates in Motion
Clocks in Motion: Examples
Clocks in Motion: Length Expansion From Asynchronous Clocks
Clocks in Motion: Bicycle Wheels
Clocks in Motion: Temporal Order
Clocks in Motion: How Observers Say the Other's Clock Runs Slow?
The Lorentz Transformation
The Lorentz Transformation: Relating Time Coordinates
The Lorentz Transformation: Generalizations

The Lorentz Transformation: The Big Picture Summary
Lorentz Transformation: Moving Light Clock
Lorentz Transformation: Future Baseball
Lorentz Transformation: Speed of Light in a Moving Frame
Lorentz Transformation: Sprinter
Combining Velocities
Combining Velocities: 3-Dimensions
Combining Velocities: Example in 1D
Combining Velocities: Example in 3D
Spacetime Diagrams
Spacetime Diagrams: Two Observers in Relative Motion
Spacetime Diagrams: Essential Features
Spacetime Diagrams: Demonstrations
Lorentz Transformation: As An Exotic Rotation
Reality of Past, Present, and Future: Mathematical Details
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Invariants: Spacetime Distance
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Cause and Effect: A Spacetime Invariant
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The Twin Paradox: Spacetime Diagrams
Twin Paradox: The Twins Communicate
The Relativistic Doppler Effect
Twin Paradox: The Twins Communicate Quantitative
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Einstein's General Theory of Relativity | Lecture 3 - Einstein's General Theory of Relativity | Lecture 3 by Stanford 624,784 views 15 years ago 1 hour, 50 minutes - In this **lecture**,, Leonard Susskind continues his discussion of Einstein's theory of **general relativity**,. He also gives a broad **overview-**, ...
starting with the elevator at rest
remove the effects of gravity
removing the curvature of a curved space
introduce some notation
get its components by dropping perpendicular to the axes
drop perpendiculars from the tip of the vector
relating the coordinates of a vector in one frame of reference
connecting components of a vector in the y frame
transforming tensors
spend a few more minutes with the idea of a covariant vector
write the corresponding thing for the covariant vector
come to the idea of a metric tensor
the simplest set of coordinates cartesian coordinates

invent a new symbol
start with a general expression among the x components
drop a perpendicular
rewrite the metric in terms of r
write down the components of the metric
work out the metric in terms of x and y
look at the lines of constant r
locate it by a polar angle
write down the distance from one point to another using pythagoras
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Gauss's Theorem
Gauss's Theorem
Gauss's Law
The Gravitational Field
Newton's Law
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The Bending of Light by the Sun
Acceleration due to Gravity
Tidal Forces
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