General Relativity

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1 Lecture: Introduction

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General Relativity is our best theory of gravitation on the largest scales. It is classical, geometrical and dynamical.

1.1 Differentiable Manifolds

The basic object of study in differential geometry is the (differentiable) manifold. This is an object which 'locally looks like $\mathbb{R}^n$', and has enough structure to let us do calculus.

Definition 1.1: A **differentiable manifold** of dimension n is a set M, together with a collection of coordinate charts (O_α, ϕ_α) where

- $O_\alpha \subset M$ are subsets of M such that $\cup_\alpha O_\alpha = M$,
- ϕ_α is a bijective map (one to one and onto) from $O_\alpha \to U_\alpha$, an open subset of $\mathbb{R}^n$,
- If $O_\alpha \cap O_\beta \neq \emptyset$, then $\phi_\beta \circ \phi_\alpha^{-1}$ is a smooth (infinitely differentiable) map from $\phi_\alpha\left(O_\alpha \cap O_\beta\right) \subset U_\alpha$ to $\phi_\beta\left(O_\alpha \cap O_\beta\right) \subset U_\beta$.

Note. We could replace smooth with finite differentiability (*e.g.* k-differentiable) but it is not particularly interesting.

Further, these charts define a topology of M, $\mathcal{R} \subset M$ is open iff $\phi_\alpha\left(\mathcal{R} \cap O_\alpha\right)$ is open in $\mathbb{R}^n$ for all α.

Every open subset of M is itself a manifold (restrict charts to $\mathcal{R}$).

Definition 1.2: The collection $\{(O_\alpha, \phi_\alpha)\}$ is called an **atlas**. Two atlases are **compatible** if their union is an atlas. An atlas A is **maximal** if there exists no atlas B with $A \subsetneq B$.

Every atlas is contained in a maximal atlas (consider the union of all compatible atlases). We can assume without loss of generality we are working with the maximal atlas.

Examples.

i) If $U \subset \mathbb{R}^n$ is open, we can take $O = U$ and

$$\phi : O \to U \tag{1}$$
$$\phi\left(x^i\right) = x^i, \tag{2}$$

and $\{(U, \phi)\}$ is an atlas.

ii) $S^1 = \{\mathbf{p} \in \mathbb{R}^2 \mid |p| = 1\}$. If $\mathbf{p} \in S^1 \setminus \{(-1,0)\} = \mathcal{O}_1$, there is a unique $\theta_1 \in (-\pi, \pi)$ such that $\mathbf{p} = (\cos\theta_1, \sin\theta_1)$.

If $\mathbf{p} \in S^1 \setminus \{(1,0)\} = \mathcal{O}_2$, then there is a unique $\theta_2 \in (0, 2\pi)$ such that $\mathbf{p} = (\cos\theta_2, \sin\theta_2)$ such that

$$\phi_1 : \mathbf{p} \to \theta_1, \text{ for } \mathbf{p} \in \mathcal{O}_1, U_1 = (-\pi, \pi), \tag{3}$$
$$\phi_2 : \mathbf{p} \to \theta_2, \text{ for } \mathbf{p} \in \mathcal{O}_2, U_2 = (0, 2\pi). \tag{4}$$

We have that $\phi_1\left(\mathcal{O} \cap \mathcal{O}_2\right) = (-\pi, 0) \cup (0, \pi)$ and

$$\phi_2 \circ \phi_1^{-1}(\theta) = \begin{cases} \theta, & \theta \in (0, \pi), \\ \theta + 2\pi, & \theta \in (-\pi, 0). \end{cases} \tag{5}$$

This is smooth where defined and similarly for $\phi_1 \circ \phi_2^{-1}$ and thus S_1 is a 1-manifold.

iii) $S^n = \left\{\mathbf{p} \in \mathbb{R}^{n+1} \middle| |\mathbf{p}| = 1\right\}$. We define charts by stereographic projection if $\{\mathbf{E}_1, \cdots, \mathbf{E}_{n+1}\}$ is a standard basis for $\mathbb{R}^{n+1}$ and $\{\mathbf{e}_1, \cdots, \mathbf{e}_n\}$ is a standard basis for $\mathbb{R}^n$, we write

$$\mathbf{p} = p^i \mathbf{e}_i. \tag{6}$$

We set $\mathcal{O}_1 = S^n \setminus \{E_{n+1}\}$ and

$$\phi_1(\mathbf{p}) = \frac{1}{1-p^{n+1}}\left(p^i \mathbf{e}_i\right), \tag{7}$$

and $\mathcal{O}_2 = S^n \setminus \{-E_{n+1}\}$ such that

$$\phi_2(\mathbf{p}) = \frac{1}{1+p^{n+1}}\left(p^i \mathbf{e}_i\right). \tag{8}$$

We have $\phi_1(\mathcal{O}_1 \cap \mathcal{O}_2) = \mathbb{R}^n \setminus \{0\}$ and $\phi_2 \circ \phi_1^{-1}(\mathbf{x}) = \frac{\mathbf{x}}{|\mathbf{x}|^2}$.

Proof. Take $\mathbf{x} \in \phi_1(\mathcal{O}_1 \cap \mathcal{O}_2) \subset \mathbb{R}^n$. We have that $\phi_1^{-1}(\mathbf{x}) = \frac{1}{1+x_j x^j}\left(2x^i, x^j x_j - 1\right)$ which satisfies $\left|\phi_1^{-1}(\mathbf{x})\right| = 1$ and is an inverse as

$$\begin{aligned}
\phi_1 \circ \phi_1^{-1}(x_i) &= \frac{1}{1-\frac{x^j x_j - 1}{1+x_j x^j}} \frac{2x^i}{1+x_j x^j} &(9)\\
&= \frac{1+x_j x^j}{1+x_j x^j - (x^j x_j - 1)} \frac{2x^i}{1+x_j x^j} &(10)\\
&= \frac{1}{2} 2x^i = x^i. &(11)
\end{aligned}$$

Similarly, we have

$$\begin{aligned}
\phi_2 \circ \phi_1^{-1}(x_i) &= \frac{1}{1+\frac{x^j x_j - 1}{1+x_j x^j}} \frac{2x^i}{1+x_j x^j} &(12)\\
&= \frac{1+x_j x^j}{1+x_j x^j + (x^j x_j - 1)} \frac{2x^i}{1+x_j x^j} &(13)\\
&= \frac{1}{2x_j x^j} 2x^i = \frac{x^i}{|x|^2}, &(14)
\end{aligned}$$

which is well defined on $\mathbb{R}^n \setminus \{0\}$ as desired. □

This is smooth on $\mathbb{R}^n \setminus \{0\}$ and similarly for $\phi_1 \circ \phi_2^{-1}$. Thus S^n is an n-manifold.

2 Lecture: Smooth Functions on Manifolds

14/10/2024

2.1 Smooth Functions

Suppose M, N are manifolds of $\dim n, n'$ respectively. Let $f : M \to N$ and $p \in M$. We pick charts $(\mathcal{O}_\alpha, \phi_\alpha)$ for M and $\left(\mathcal{O}'_\beta, \phi'_\beta\right)$ for N with $p \in \mathcal{O}_\alpha$ and $f(p) \in \mathcal{O}_\beta$.

Then $\phi'_\beta \circ f \circ \phi_\alpha^{-1}$ maps an open neighbourhood of $\phi_\alpha(p)$ in $U_\alpha \subset \mathbb{R}^n$ to $U'_\beta \subset \mathbb{R}^{n'}$.

Definition 2.1: If $\phi'_\beta \circ f \circ \phi_\alpha^{-1} : (U_\alpha \subset \mathbb{R}^n) \to \left(U'_\beta \subset \mathbb{R}^{n'}\right)$ is smooth for all possible choices of charts, we say $f : M \to N$ is **smooth**.

Note. A smooth map $\Psi : M \to N$ which has a smooth inverse Ψ^{-1} is called a **diffeomorphism** and this implies $n = n'$.

Also, if $N = \mathbb{R}$ or $\mathbb{C}$, we sometimes call f a **scalar field**. Further if M is an (open) interval such that $M = I \subset \mathbb{R}$, then $f : I \to N$ is a smooth curve in N.

Lastly, if f is smooth in one atlas, it is smooth with respect to all compatible atlases.

Examples.

1) Recall $S^1 = \{\mathbf{x} \in \mathbb{R}^2 \mid |x| = 1\}$. Let $f(x, y) = x,\ f : S^1 \to \mathbb{R}$.

   Using previous charts,

$$f \circ \phi_1^{-1} : (-\pi, \pi) \to \mathbb{R} \tag{15}$$
$$f \circ \phi_1^{-1}(\theta_1) = \cos\theta_1, \tag{16}$$

   and similarly,

$$f \circ \phi_2^{-1} : (0, 2\pi) \to \mathbb{R} \tag{17}$$
$$f \circ \phi_2^{-1}(\theta_2) = \cos\theta_2. \tag{18}$$

   In both cases, f is smooth.

2) If $(\mathcal{O}, \phi)$ is a coordinate chart on M, write for $\mathbf{p} \in \mathcal{O}$,

$$\phi(\mathbf{p}) = \left(x^1(\mathbf{p}), x^2(\mathbf{p}), \cdots, x^n(\mathbf{p})\right), \tag{19}$$

   then $x^i(\mathbf{p})$ defines a map from $\mathcal{O}$ to $\mathbb{R}$. This is a smooth map for each $i = 1, \cdots, n$. If $(\mathcal{O}', \phi')$ is another overlapping coordinate chart, then $x^i \circ \phi'^{-1}$ is the ith component of $\phi \circ \phi'^{-1}$, which is smooth.

3) We can define a smooth function chart by chart. For simplicity, we take $N = \mathbb{R}$. Let $\{(\mathcal{O}_\alpha, \phi_\alpha)\}$ be an atlas on M. Define smooth functions $F_\alpha : U_\alpha \to \mathbb{R}$, and suppose that

$$F_\alpha \circ \phi_\alpha = F_\beta \circ \phi_\beta, \tag{20}$$

   on $\mathcal{O}_\alpha \cap \mathcal{O}_\beta$ for all α, β. Then for $\mathbf{p} \in M$, we can define $f(\mathbf{p}) = F_\alpha \circ \phi_\alpha(\mathbf{p})$ where $(\mathcal{O}_\alpha, \phi_\alpha)$ is any chart with $\mathbf{p} \in \mathcal{O}_\alpha$ as this is constant by construction of F. f is smooth as

$$f \circ \phi_\beta^{-1} = F_\alpha \circ \underbrace{\phi_\alpha \circ \phi_\beta^{-1}}_{\text{always smooth}}. \tag{21}$$

   In practice, we often don't distinguish between f and its **coordinate chart representation** F_α. This coordinate chart representation F_α captures f but maps from $U_\alpha \subset \mathbb{R}^n$ rather than from subsets of M. One can think of $F_\alpha = f \circ \phi_\alpha^{-1}$ as finding the point on M that ϕ_α mapped from and evaluating f at that point.

2.2 Curves and Vectors

For a surface in $\mathbb{R}^3$, we have a notion of a tangent space at a point, consisting of all vectors tangent to the surface. Such tangent spaces are vector spaces (copies of $\mathbb{R}^2$). Different points have different tangent spaces.

In order to define the tangent space for a manifold, we first consider tangent vectors of a curve.

Recall that a smooth map from an interval $\lambda : I \subset \mathbb{R} \to M$ is a smooth curve in M.

If $\lambda(t)$ is a smooth curve in $\mathbb{R}^n$ and $f : \mathbb{R}^n \to \mathbb{R}$ is a smooth function, then for $f(\lambda(t)) : \mathbb{R} \to \mathbb{R}$, the chain rule gives

$$\frac{\mathrm{d}}{\mathrm{d}t}[f(\lambda(t))] = \mathbf{X}(t) \cdot \boldsymbol{\nabla} f(\lambda(t)), \tag{22}$$

where $\mathbf{X}(t) = \frac{\mathrm{d}\lambda(t)}{\mathrm{d}t}$ is the **tangent vector** to λ at t. The idea is that we identify the tangent vector $\mathbf{X}(t)$ with the differential operator $\mathbf{X}(t) \cdot \boldsymbol{\nabla}$.

Definition 2.2: Let $\lambda : I \to M$ be a smooth curve with $\lambda(0) = \mathbf{p}$. The **tangent vector** to λ at $\mathbf{p}$ is the linear map $X_{\mathbf{p}}$ from the space of smooth functions, $f : M \to \mathbb{R}$ given by

$$X_{\mathbf{p}}(f) = \frac{\mathrm{d}}{\mathrm{d}t} f(\lambda(t)) \bigg|_{t=0}. \tag{23}$$

We observe a few things of note.

1) $X_{\mathbf{p}}$ is linear such that $X_{\mathbf{p}}(f + ag) = X_{\mathbf{p}}(f) + aX_{\mathbf{p}}(g)$ for f, g smooth and $a \in \mathbb{R}$.
2) $X_{\mathbf{p}}$ satisfies the Leibniz rule,

$$X_{\mathbf{p}}(fg) = (X_{\mathbf{p}}(f))\, g + f X_{\mathbf{p}}(g). \tag{24}$$

3) If $(\mathcal{O}, \phi)$ is a chart with $\mathbf{p} \in \mathcal{O}$, we write

$$\phi(\mathbf{p}) = \left(x^1(\mathbf{p}), \cdots, x^n(\mathbf{p})\right). \tag{25}$$

Let $F = f \circ \phi^{-1}$, $x^i(t) = x^i(\lambda(t))$ and $\mathbf{x}(t) = \phi(\lambda(t))$. Then we have

$$f \circ \lambda(t) = f \circ \phi^{-1} \circ \phi \circ \lambda(t) = F \circ \mathbf{x}(t), \tag{26}$$

and thus the tangent vector defined in Eq. (23) can also be written as

$$X_{\mathbf{p}}(f) \equiv \frac{\mathrm{d}}{\mathrm{d}t}(f(\lambda(t))) \bigg|_{t=0} = \frac{\partial F(x)}{\partial x^\mu} \frac{\mathrm{d}x^\mu}{\mathrm{d}t} \bigg|_{t=0}, \tag{27}$$

where $\frac{\partial F}{\partial x^\mu}$ depends on f and ϕ and $\frac{\mathrm{d}x^\mu}{\mathrm{d}t}$ depends on λ and ϕ.

3 Lecture: Tangent Spaces

16/10/2024

3.1 The Tangent Space is a Vector Space

Proposition 3.1: The set of tangent vectors to curves at $\mathbf{p}$ forms a vector space, $T_{\mathbf{p}}M$ of dimension $n = \dim M$. We call $T_{\mathbf{p}}M$, the **tangent space** to M at $\mathbf{p}$.

Proof. Given $X_{\mathbf{p}}, Y_{\mathbf{p}}$ are tangent vectors, we need to show that $\alpha X_{\mathbf{p}} + \beta Y_{\mathbf{p}}$ is a tangent vector for $\alpha, \beta \in \mathbb{R}$. Let λ, κ be smooth curves with $\lambda(0) = \kappa(0) = \mathbf{p}$ and whose tangent vectors at $\mathbf{p}$ are $X_{\mathbf{p}}$ and $Y_{\mathbf{p}}$ respectively. Let $(\mathcal{O}, \phi)$ be a chart with $p \in \mathcal{O}$ such that $\phi(\mathbf{p}) = 0$. We call this a *chart centered at* $\mathbf{p}$.

Let $\nu(t) = \phi^{-1}\left[\alpha\phi(\lambda(t)) + \beta\phi(\kappa(t))\right]$ where notice $\nu(0) = \phi^{-1}(0) = \mathbf{p}$.

From Eq. (27), we have that if Z_p is the tangent to ν at $\mathbf{p}$, we have

$$\begin{aligned} Z_{\mathbf{p}}(f) &= \frac{\mathrm{d}}{\mathrm{d}t}\left(f(\nu(t))\right)\Big|_0 && (28)\\ &= \frac{\partial F}{\partial x^\mu}\Big|_0 \frac{\mathrm{d}}{\mathrm{d}t}\left[\alpha x^\mu(\lambda(t)) + \beta x^\mu(\kappa(t))\right]\Big|_{t=0} && (29)\\ &= \alpha\frac{\partial F}{\partial x^\mu}\Big|_0 \frac{\mathrm{d}}{\mathrm{d}t}x^\mu(\lambda(t))\Big|_{t=0} + \beta\frac{\partial F}{\partial x^\mu}\Big|_0 \frac{\mathrm{d}}{\mathrm{d}t}x^\mu(\kappa(t))\Big|_{t=0} && (30)\\ &= \alpha X_{\mathbf{p}}(f) + \beta X_{\mathbf{p}}(f), && (31)\end{aligned}$$

as desired. Therefore $T_{\mathbf{p}}M$ is a vector space. □

To see that $T_{\mathbf{p}}M$ is n-dimensional, consider the curves

$$\lambda_\mu(t) = \phi^{-1}\left(0, \cdots, 0, \underbrace{t}_{\mu\text{th component}}, 0, \cdots, 0\right). \tag{32}$$

We denote the tangent vector to λ_μ at $\mathbf{p}$ by $\left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}}$.

Note. This is **not** a differential operator.

However observe that by definition, we have

$$\left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}}(f) = \frac{\partial F}{\partial x^\mu}\Big|_{\phi(\mathbf{p})=0}, \tag{33}$$

and thus it acts like a differential operator in $\mathbb{R}^n$ on the coordinates of the chart.

The vectors $\left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}}$ are linearly independent. Otherwise $\exists\alpha^\mu \in \mathbb{R}$ not all zero such that

$$\alpha^\mu\left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}} = 0, \tag{34}$$

which implies

$$\alpha^\mu\frac{\partial F}{\partial x^\mu} = 0, \tag{35}$$

for all F. Setting $F = x^\nu$ gives $\alpha^\nu = 0$ and thus these vectors are linearly independent and spanning. They are therefore a basis for the vector space.

Further one can see that $\left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}}$ form a basis for $T_{\mathbf{p}}M$, since if λ is any curve with tangent $X_{\mathbf{p}}$ at $\mathbf{p}$, we have

$$X_{\mathbf{p}}(f) = \frac{\partial F}{\partial x^\mu}\Big|_{x=0}\frac{\mathrm{d}}{\mathrm{d}t}x^\mu(\lambda(t)) = X^\mu\left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}}(f), \tag{36}$$

where $X^\mu = \frac{\mathrm{d}}{\mathrm{d}t}x^\mu(\lambda(t))\Big|_{t=0}$ are the **components** of $X_{\mathbf{p}}$ with respect to the basis $\{\left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}}\}_{\mu=1,\cdots,n}$ for $T_{\mathbf{p}}M$.

Note. The basis $\{(\frac{\partial}{\partial x^\mu})_{\mathbf{p}}\}_{\mu=1,\cdots,n}$ depends on the coordinate chart ϕ.

Suppose we choose another chart $(\mathcal{O}', \phi')$, again centered at $\mathbf{p}$. We write $\phi' = \left(\left(x^{'}\right)^1, \cdots, (x')^n\right)$. Then if $F' = f \circ \phi'^{-1}$, we have

$$\begin{aligned} F(x) &= f \circ \phi^{-1}(x) && (37)\\ &= f \circ \phi'^{-1} \circ \phi' \circ \phi^{-1}(x) && (38)\\ &= F'(x'(x)). && (39) \end{aligned}$$

Therefore,

$$\begin{aligned} \left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}} (f) &= \left.\frac{\partial F}{\partial x^\mu}\right|_{\phi(\mathbf{p})} && (40)\\ &= \left.\left(\frac{\partial x'^\nu}{\partial x^\mu}\right)\right|_{\phi(\mathbf{p})} \left.\left(\frac{\partial F'}{\partial x'^\nu}\right)\right|_{\phi'(\mathbf{p})} && (41)\\ &= \left.\left(\frac{\partial x'^\nu}{\partial x^\mu}\right)\right|_{\phi(\mathbf{p})} \left(\frac{\partial}{\partial x'^\nu}\right)_{\mathbf{p}} (f). && (42) \end{aligned}$$

We then deduce that

$$\left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}} = \left.\left(\frac{\partial x'^\nu}{\partial x^\mu}\right)\right|_{\phi(\mathbf{p})} \left(\frac{\partial}{\partial x'^\nu}\right)_{\mathbf{p}}. \tag{43}$$

Let X^μ be components of $X_{\mathbf{p}}$ with respect to the basis $(\frac{\partial}{\partial x^\mu})_{\mathbf{p}}$, and X'^μ be components of $X_{\mathbf{p}}$ with respect to the basis $(\frac{\partial}{\partial x^\mu})_{\mathbf{p}}$ such that

$$\begin{aligned} X_{\mathbf{p}} = X^\mu \left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}} &= X'^\mu \left(\frac{\partial}{\partial x'^\mu}\right)_{\mathbf{p}} && (44)\\ &= X^\mu \left(\frac{\partial x'^\sigma}{\partial x^\mu}\right) \left(\frac{\partial}{\partial x'^\sigma}\right)_{\mathbf{p}}, && (45) \end{aligned}$$

and therefore

$$X'^\mu = \left(\frac{\partial x'^\mu}{\partial x^\nu}\right) X^\nu. \tag{46}$$

Note. We do note have to choose a coordinate basis such as $(\frac{\partial}{\partial x^\mu})_{\mathbf{p}}$. With respect to a general basis $\{e_\mu\}$, for $T_{\mathbf{p}}M$, we can write $X_{\mathbf{p}} = X^\mu e_\mu$ for $X^\mu \in \mathbb{R}$.

We always use summation convention, contracting covariant indices with contravariant indices.

3.2 Covectors

Recall that if V is a vector space over $\mathbb{R}$, the dual space V^* is the space of linear maps $\phi : V \to \mathbb{R}$. If V is n-dimensional then so is V^* (the spaces are then isomorphic). Given a basis $\{e_\mu\}$ for V, we can define the dual basis $\{f^\mu\}$ for V^* by requiring that

$$f^\mu(e_\nu) = \delta^\mu{}_\nu = \begin{cases} 1, & \text{if } \mu = \nu, \\ 0, & \text{if } \mu \neq \nu. \end{cases} \tag{47}$$

If V is finite dimensional, then $V^{**} = (V^*)^* \simeq V$. Namely, to an element $X \in V$, we assign the linear map

$$\Lambda_X : V^* \to \mathbb{R}, \tag{48}$$
$$\Lambda_X (\omega) = \omega (X), \tag{49}$$

for $\omega \in V^*$.

Definition 3.1: The dual space of $T_{\mathbf{p}}M$ is denoted $T^*_{\mathbf{p}}M$ and is called the **cotangent space** to M at $\mathbf{p}$. An element of this space is a **covector** at $\mathbf{p}$. If $\{e_\mu\}$ is a basis for $T_{\mathbf{p}}M$ and $\{f^\mu\}$ is the dual basis for $T^*_{\mathbf{p}}M$, we can expand a covector η as

$$\eta = \eta_\mu f^\mu, \tag{50}$$

for **components** $\eta_\mu \in \mathbb{R}$.

4 Lecture: Tensors

18/10/2024

4.1 Tangent bundle

Notice that

$$\eta (e_\nu) = \eta_\mu f^\mu (e_\nu) = \eta_\mu \delta^\mu{}_\nu = \eta_\nu, \tag{51}$$

and thus we can get the components of η by acting it on basis vectors in the tangent space. Further as we have $X = X^\mu e_\mu$,

$$\begin{aligned} \eta (X) &= \eta (X^\mu e_\mu) && (52)\\ &= X^\mu \eta (e_\mu) && (53)\\ &= X^\mu \eta_\mu, && (54) \end{aligned}$$

and thus the action of the covector η on the vector X is essentially a contraction between the components.

Recall that a vector X is defined by its action on a function f, $X : f \to \mathbb{R}$, eating a smooth function and returning the rate of change as one moves in the direction of X.

Analogously, given a function f, one can consider a linear operator of that function being eaten by a generic vector X.

Definition 4.1: If $f : M \to \mathbb{R}$ is a smooth function, then we can define a covector $(df)_{\mathbf{p}} \in T^*_{\mathbf{p}}M$, the **differential** of f at $\mathbf{p}$, by

$$(df)_{\mathbf{p}} (X) = X (f), \tag{55}$$

for any $X \in T_{\mathbf{p}}M$. This is also sometimes called the **gradient** of f at $\mathbf{p}$.

If f is constant, $X (f) = 0$ which implies $(df)_{\mathbf{p}} = 0$.

If $(\mathcal{O}, \phi)$ is a coordination chart with $\mathbf{p} \in \mathcal{O}$ and $\phi = (x^1, \cdots, x^n)$ then we can set $f = x^\mu$ to find $(dx^\mu)_{\mathbf{p}}$. Observe

$$(dx^\mu)_{\mathbf{p}} \left(\frac{\partial}{\partial x^\nu}\right)_{\mathbf{p}} = \left(\frac{\partial x^\mu}{\partial x^\nu}\right)_{\phi(\mathbf{p})} = \delta^\mu{}_\nu. \tag{56}$$

Therefore the coordinate differentials $\{(dx^\mu)_{\mathbf{p}}\}$ is the dual basis to $\{\left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}}\}$.

In this basis, we can compute

$$\left[(df)_{\mathbf{p}}\right]_\mu = (df)_{\mathbf{p}}\left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}} = \left(\frac{\partial}{\partial x^\mu}\right)_{\mathbf{p}} f = \left(\frac{\partial F}{\partial x^\mu}\right)_{\phi(\mathbf{p})}. \tag{57}$$

This justifies the language of *gradient*.

Exercise 1: Show that if $(\mathcal{O}', \phi')$ is another chart with $\mathbf{p} \in \mathcal{O}'$, then

$$(dx^\mu)_{\mathbf{p}} = \left(\frac{\partial x^\mu}{\partial (x')^\nu}\right)_{\phi'(\mathbf{p})} \left(d(x')^\nu\right)_{\mathbf{p}}, \tag{58}$$

where $x(x') = \phi \circ (\phi')^{-1}$, and hence if η_μ, η'_μ are components with respect to these bases,

$$\eta'_\mu = \left(\frac{\partial x^\nu}{\partial (x')^\mu}\right)_{\phi'(\mathbf{p})} \eta_\nu. \tag{59}$$

Proof.

□

Definition 4.2 (Tangent bundle): We can glue together the tangent spaces $T_{\mathbf{p}}M$ as $\mathbf{p}$ varies to get a new $2n$ dimensional manifold TM, the **tangent bundle**. We define the tangent bundle to be

$$TM := \bigcup_{\mathbf{p}\in M} \{\mathbf{p}\} \times T_{\mathbf{p}}M. \tag{60}$$

Namely, it is the set of ordered pairs $(\mathbf{p}, X)$, with $\mathbf{p} \in M$, $X \in T_{\mathbf{p}}M$.

If $\{(\mathcal{O}_\alpha, \phi_\alpha)\}$ is an atlas on M, we obtain an atlas for TM by setting

$$\mathcal{O}_\alpha = \bigcup_{\mathbf{p}\in \mathcal{O}_\alpha} \{\mathbf{p}\} \times T_{\mathbf{p}}M, \tag{61}$$

and

$$\widetilde{\phi}_\alpha((p, X)) = (\phi(\mathbf{p}), X^\mu) \in \mathcal{U}_\alpha \times \mathbb{R}^n = \widetilde{\mathcal{U}}_2, \tag{62}$$

where X^μ are the components of X with respect to the coordinate basis of ϕ_α.

Exercise 2: If $(\mathcal{O}, \phi)$ and $(\mathcal{O}', \phi')$ are two charts on M, show that on $\widetilde{U} \cap \widetilde{U}'$, if we write $\phi' \circ \phi^{-1}(x) = x'(x)$, then

$$\widetilde{\phi}' \circ \widetilde{\phi}^{-1}(x, X^\mu) = \left(x'(x), \left(\frac{\partial (x')^\mu}{\partial x^\nu}\right)_x X^\nu\right). \tag{63}$$

Deduce that TM is a (differentiable) manifold.

Proof.

□

A similar construction permits us to define the cotangent bundle $T^*M = \cup_{\mathbf{p}\in M}\{\mathbf{p}\} \times T^*_{\mathbf{p}}M$.

Exercise 3: Show that the map $\Pi : TM \to M$ which projects onto the point such that

$$(\mathbf{p}, X) \mapsto \mathbf{p}, \tag{64}$$

is smooth.

Proof.

□

4.2 Abstract Index Notation

We have used Greek letters μ, ν etc. to label components of vectors (or covectors) with respect to the basis $\{e_\mu\}$ (respectively $\{f^\mu\}$). Equations involving these quantities refer to a specific basis.

Example. Taking $X^\mu = \delta^\mu$, this says X^μ only has one non-zero component in the current basis. This won't be true in other bases as X^μ transforms.

We know some equations do hold in all bases, for example,

$$\eta\left(X\right) = X^\mu \eta_\mu. \tag{65}$$

To capture this, we use *abstract index notation*. We denote a vector with X^a, where the Latin index a does not denote a component, rather it tells us X^a is a vector. Similarly, we denote a covector η by η_a.

If an equation is true in all bases, we can replace Greek indices by Latin indices, for example

$$\eta\left(X\right) = X^a \eta_a = \eta_a X^a, \tag{66}$$

or

$$X\left(f\right) = X^a \left(df\right)_a. \tag{67}$$

Such notation tells us that the expression is **independent** of the choice of basis. One can go back to Greek letter by picking a basis and swapping $a \to \mu$.

4.3 Tensors

Definition 4.3: A **tensor** of type (r, s) at p is a multilinear map

$$T : \underbrace{T^*_{\mathbf{p}}\left(M\right) \times \cdots \times T^*_{\mathbf{p}}\left(M\right)}_{r \text{ factors}} \times \underbrace{T_{\mathbf{p}}\left(M\right) \times \cdots \times T_{\mathbf{p}}\left(M\right)}_{s \text{ factors}} \to \mathbb{R}, \tag{68}$$

where multilinear map means linear in each argument.

Examples.

- A tensor of type $(0,1)$ is a linear map $T_{\mathbf{p}}(M) \to \mathbb{R}$, i.e. it is a covector.
- A tensor of type $(1,0)$ is a linear map from $T^*_{\mathbf{p}}(M) \to \mathbb{R}$, i.e. an element of $\left(T^*_{\mathbf{p}}(M)\right)^* \simeq T_{\mathbf{p}}(M)$ thus it is a vector.
- We can define a $(1,1)$ tensor, δ by $\delta(\omega, X) = \omega(X)$ for any covector ω and vector X.

Definition 4.4: If $\{e_\mu\}$ is a basis for $T_{\mathbf{p}}M$ and $\{f^\mu\}$ is the dual basis, the components of an (r,s) tensor T are

$$T^{\mu_1 \cdots \mu_r}{}_{\nu_1 \cdots \nu_s} = T\left(f^{\mu_1}, \cdots, f^{\nu_r}, e_{\nu_1} \cdots e_{\nu_s}\right). \tag{69}$$

In abstract index notation we write T as $T^{a_1 \cdots a_r}{}_{b_1 \cdots b_s}$.

Note. Tensors of type (r,s) at p form a vector space over $\mathbb{R}$ of dimension n^{r+s}.

Examples.

1) Consider the δ tensor above. It has components

$$\delta^\mu{}_\nu := \delta(X, \omega) = f^\mu(e_\nu), \tag{70}$$

which recovers our expected Kronecker delta δ^μ_ν.

2) Consider a $(2,1)$ tensor T. If $\omega, \eta \in T^*_{\mathbf{p}}M$, $X \in T_{\mathbf{p}}M$,

$$\begin{aligned} T(\omega, \eta, X) &= T\left(\omega_\mu f^\mu, \eta_\nu f^\nu, X^\sigma e_\sigma\right) && (71)\\ &= \omega_\mu \eta_\nu X^\sigma T\left(f^\mu, f^\nu, e^\sigma\right) && (72)\\ &= \omega_\mu \eta_\nu X^\sigma T^{\mu\nu}{}_\sigma. && (73) \end{aligned}$$

which in abstract index notation is $T(\omega, \eta, X) = \omega_a \eta_b X^c T^{ab}{}_c$. This generalised to higher ranks.

5 Lecture: Tensor Fields

21/10/2024

I now drop the bold face on $\mathbf{p} \in M \to p \in M$.

5.1 Change of Bases

We've seen how components of X or η change with respect to a coordinate basis (X^μ, η_ν, respectively). Under a change of coordinates, we don't only have to consider coordinate bases.

Suppose $\{e_\mu\}$ and $\{e'_\mu\}$ are two bases for T_pM with dual bases $\{f^\mu\}$ and $\{f'^\mu\}$.

We can expand

$$f'^\mu = A^\mu{}_\nu f^\nu \text{ and } e'_\mu = B^\nu{}_\mu e_\nu, \tag{74}$$

but

$$\begin{aligned} \delta^\mu_\nu &= f'^\mu\left(e'_\nu\right) && (75)\\ &= A^\mu{}_\tau f^\tau\left(B^\sigma{}_\nu e_\sigma\right) && (76) \end{aligned}$$

$$\begin{aligned}
&= A^{\mu}{}_{\tau} B^{\sigma}{}_{\nu} f^{\tau}(e_{\sigma}) && (77)\\
&= A^{\mu}{}_{\tau} B^{\sigma}{}_{\nu} \delta^{\tau}{}_{\sigma} && (78)\\
&= A^{\mu}{}_{\sigma} B^{\sigma}{}_{\nu}, && (79)
\end{aligned}$$

Thus $B^{\mu}{}_{\nu} = \left(A^{-1}\right)^{\mu}{}_{\nu}$.

If $e_{\mu} = \left(\frac{\partial}{\partial x^{\mu}}\right)_p$ and $e'_{\mu} = \left(\frac{\partial}{\partial x^{\mu}}\right)_p$. We've already seen

$$A^{\mu}{}_{\nu} = \left(\frac{\partial x'^{\mu}}{\partial x^{\nu}}\right)_{\phi(p)} \qquad B^{\mu}{}_{\nu} = \left(\frac{\partial x^{\mu}}{\partial x'^{\nu}}\right)_{\phi(p)}. \tag{80}$$

Therefore we see that a change of bases induces a transformation of tensor components. For example, if T is a $(1,1)$-tensor,

$$\begin{aligned}
T^{\mu}{}_{\nu} &= T\left(f^{\mu}, e_{\nu}\right) && (81)\\
T'^{\mu}{}_{\nu} &= T\left(f'^{\mu}, e'_{\nu}\right) && (82)\\
&= T\left(A^{\mu}{}_{\sigma} f^{\sigma}, \left(A^{-1}\right)^{\tau}{}_{\nu} e_{\tau}\right) && (83)\\
&= A^{\mu}{}_{\sigma} \left(A^{-1}\right)^{\tau}{}_{\nu} T\left(f^{\sigma}, e_{\tau}\right) && (84)\\
&= A^{\mu}{}_{\sigma} \left(A^{-1}\right)^{\tau}{}_{\nu} T^{\sigma}{}_{\tau}. && (85)
\end{aligned}$$

5.2 Tensor operations

Definition 5.1: Given an (r,s) tensor, we can form an $(r-1,s-1)$ tensor by **contraction**.

For simplicity assume T is a $(2,2)$ tensor. Define a $(1,1)$ tensor S by

$$S(\omega, X) = T\left(\omega, f^{\mu}, X, e_{\mu}\right). \tag{86}$$

To see that this is independent of the choice of basis, observe that a different basis would give

$$\begin{aligned}
S(\omega, X) = T\left(\omega, f'^{\mu}, X, e'_{\mu}\right) &= T\left(\omega, A^{\mu}{}_{\sigma} f^{\sigma}, X, \left(A^{-1}\right)^{\tau}{}_{\mu} e_{\tau}\right) && (87)\\
&= A^{\mu}{}_{\sigma} \left(A^{-1}\right)^{\tau}{}_{\mu} T\left(\omega, f^{\sigma}, X, e_{\tau}\right) && (88)\\
&= \delta^{\tau}_{\sigma} T\left(\omega, f^{\sigma}, X, e_{\tau}\right) && (89)\\
&= T\left(\omega, f^{\sigma}, X, e_{\sigma}\right) = S(\omega, X), && (90)
\end{aligned}$$

and thus we have basis independence as desired. Thus we write the components of these tensors as

$$S^{\mu}{}_{\nu} = T^{\mu\sigma}{}_{\nu\sigma}, \tag{91}$$

which in abstract index notation, is written

$$S^{a}{}_{b} = T^{ac}{}_{bc}. \tag{92}$$

This can be generalized to contract any pair of covariant (lower) and contravariant (upper) indices on an arbitrary tensor.

Another way to form new tensors is to use a *tensor product*.

Definition 5.2: If S is a (p,q) tensor and T is an (r,s) tensor then $S \otimes T$ is a $(p+r, q+s)$ tensor given by

$$S \otimes T \left(\omega^1, \cdots, \omega^p, \eta^1, \cdots, \eta^r, X_1, \cdots, X_q, Y_1, \cdots, Y_s\right), \tag{93}$$

which in abstract index notation can be written

$$(S \otimes T)^{a_1 \cdots a_p b_1 \cdots b_r}{}_{c_1 \cdots c_q d_1 \cdots d_s} = S^{a_1 \cdots a_p}{}_{c_1 \cdots c_q} T^{b_1 \cdots b_r}{}_{d_1 \cdots d_s}. \tag{94}$$

Exercise 4: For any $(1,1)$ tensor T, in a basis we have

$$T = T^{\mu}{}_{\nu}\, e_\mu \otimes f^\nu. \tag{95}$$

Proof.

□

The final tensor operations we require are anti-symmetrization and symmetrization.

Definition 5.3: If T is a $(0,2)$ tensor, we can define two new tensors

$$S(X,Y) = \frac{1}{2}\left(T(X,Y) + T(Y,X)\right) \tag{96}$$

$$A(X,Y) = \frac{1}{2}\left(T(X,Y) - T(Y,X)\right), \tag{97}$$

which in abstract index notation become

$$S_{ab} = \frac{1}{2}\left(T_{ab} + T_{ba}\right) \tag{98}$$

$$A_{ab} = \frac{1}{2}\left(T_{ab} - T_{ba}\right), \tag{99}$$

one also writes $S_{ab} = T_{(ab)}$ and $A_{ab} = T_{[ab]}$ to denote symmetrization and antisymmetrization respectively.

These operations can be applied to any pair of matching indices. Similarly, to symmetrize over n indices we sum over all permutations and divide by $n!$, and identically to antisymmetrize, with the addition of a minus sign for odd permutations.

For example,

$$T^{(abc)} = \frac{1}{3!}\left(T^{abc} + T^{bca} + T^{cab} + T^{acb} + T^{cba} + T^{bac}\right) \tag{100}$$

$$T^{[abc]} = \frac{1}{3!}\left(T^{abc} + T^{bca} + T^{cab} - T^{acb} - T^{cba} - T^{bac}\right). \tag{101}$$

Lastly, to exclude indices from symmetrization, we use vertical lines such that

$$T^{(a|b|c)} = \frac{1}{2}\left(T^{abc} + T^{cba}\right). \tag{102}$$

5.3 Tensor Bundles

Definition 5.4: The space of (r, s) tensors at a point p is the vector space $\left(T^r{}_s\right)_p M$. These can be glued together to form the **bundle** of (r, s)-tensors, which we write

$$T^r{}_s M = \bigcup_{p \in M} \{p\} \times \left(T^r{}_s\right)_p M. \tag{103}$$

If $(\mathcal{O}, \phi)$ is a coordinate chart on M, set

$$\widetilde{\mathcal{O}} = \bigcup_{p \in \mathcal{O}} \{p\} \times \left(T^r{}_s\right)_p M \subset T^r{}_s M, \tag{104}$$

where $\widetilde{\phi}\left(p, S_p\right) = \left(\phi\left(p\right), S^{\mu_1 \cdots \mu_r}{}_{\nu_1 \cdots \nu_s}\right)$

$T^r{}_s M$ is a manifold with a natural smooth map $\Pi : T^r{}_s M \to M$ such that $\Pi\left(p, S_p\right) = p$.

Definition 5.5: An (r, s) tensor field is a smooth map $T : M \to T^r{}_s M$ such that $\Pi \circ T = \mathrm{id}$ (namely, that $T : p \mapsto (p, S_p)$). If $(\mathcal{O}, \phi)$ is a coordinate chart on M then

$$\widetilde{\phi} \circ T \circ \phi^{-1}\left(x\right) = \left(x, T^{\mu_1 \cdots \mu_r}{}_{\nu_1 \cdots \nu_s}\left(x\right)\right), \tag{105}$$

which is smooth provided the components $T^{\mu_1 \cdots \mu_r}{}_{\nu_1 \cdots \nu_s}\left(x\right)$ are smooth functions of x.

One can think of a tensor field as defining a tensor at every point with respect to the coordinate basis at that point.

If $T^r{}_s M = T^1{}_0 M \sim TM$, the tensor field is called a **vector field**. In a local coordinate patch, if X is a vector field, we can write

$$X\left(p\right) = \left(p, X_p\right), \tag{106}$$

with $X_p = X^\mu\left(x\right)\left(\frac{\partial}{\partial x^\mu}\right)_p$.

In particular, $\frac{\mathrm{d}}{\mathrm{d}x^\mu}$ are always smooth but only defined locally.

6 Lecture: The metric tensor

23/10/2024

A vector field can be thought of as we usually do, as placing a vector at every point on the manifold. A vector field can also act on a function $f : M \to \mathbb{R}$ to give a new function

$$Xf\left(p\right) = X_p\left(f\right), \tag{107}$$

which in a coordinate basis becomes

$$Xf\left(p\right) = X^\mu\left(\phi\left(p\right)\right) \left.\frac{\partial F}{\partial x^\mu}\right|_{\phi(p)}, \tag{108}$$

which we now think of as a function of p across the manifold.

6.1 Integral curves

Definition 6.1: Given a vector field X on M, we say a curve $\lambda : I \to M$, is an **integral curve** of X if its tangent vector at every point along it is X. Namely, denote the tangent vector to λ at t by $\frac{\mathrm{d}\lambda}{\mathrm{d}t}(t)$, then

$$\frac{\mathrm{d}\lambda}{\mathrm{d}t}(t) = X_{\lambda(t)}, \tag{109}$$

$\forall t \in I$.

Through each point p, an integral curve passes, and is unique up to reparametrization or curve extension.

To see that this is true, pick a chart ϕ with $\phi = \left(x^1, \cdots, x^n\right)$ and assume $\phi(p) = 0$. In this chart, Eq. (109) becomes

$$\frac{\mathrm{d}x^\mu}{\mathrm{d}t}(t) = X^\mu(x(t)), \tag{110}$$

where $x^\mu(t) = x^\mu(\lambda(t))$. Assuming without loss of generality that $\lambda(0) = p$, we get an initial condition that $x^\mu(0) = 0$.

Standard ODE theory gives us that Eq. (110) with an initial condition has a solution unique up to extension.

6.2 Commutators

Suppose X and Y are two vector fields and $f : M \to \mathbb{R}$ is smooth. Then $X(Y(f))$ is a smooth function. Is it of the form $K(f)$ for some vector field K? No, as

$$\begin{aligned} X(Y(fg)) = X(fX(g) + gY(f)) &= X(Y(fg)) && (111)\\ &= X(fX(g)) + X(gY(f)) && (112)\\ &= fX(Y(g)) + gX(Y(f)) + X(f)Y(g) + X(g)Y(f), && (113) \end{aligned}$$

and thus the Leibniz rule does not hold, implying this cannot be a vector field. However notice that the last two terms that ruin this are symmetric in f and g, and thus if we instead consider

$$[X, Y](f) = X(Y(f)) - Y(X(f)), \tag{114}$$

then the Leibniz rule will hold and (while we have not show it explicitly) this does in fact define a vector field.

To see this, use coordinate bases such that

$$\begin{aligned} [X, Y](f) &= X\left(Y^\nu \frac{\partial F}{\partial x^\nu}\right) - Y\left(X^\mu \frac{\partial F}{\partial x^\mu}\right) && (115)\\ &= X^\mu \frac{\partial}{\partial x^\mu}\left(Y^\nu \frac{\partial F}{\partial x^\nu}\right) - Y^\nu \frac{\partial}{\partial x^\nu}\left(X^\mu \frac{\partial F}{\partial x^\mu}\right) && (116)\\ &= X^\mu Y^\mu \frac{\partial^2 F}{\partial x^\mu \partial x^\nu} - Y^\nu X^\mu \frac{\partial^2 F}{\partial x^\nu \partial x^\mu} + X^\mu \frac{\partial Y^\nu}{\partial x^\mu}\frac{\partial F}{\partial x^\nu} - Y^\nu \frac{\partial X^\mu}{\partial x^\nu}\frac{\partial F}{\partial x^\mu}. && (117) \end{aligned}$$

As mixed partials on smooth functions in $\mathbb{R}^n$ commute, the first two terms cancel leaving

$$[X, Y](f) = X^\mu \frac{\partial Y^\nu}{\partial x^\mu}\frac{\partial F}{\partial x^\nu} - Y^\nu \frac{\partial X^\mu}{\partial x^\nu}\frac{\partial F}{\partial x^\mu} \tag{118}$$

$$= \left(X^\mu \frac{\partial Y^\nu}{\partial x^\nu} - Y^\mu \frac{\partial X^\nu}{\partial x^\mu} \right) \frac{\partial F}{\partial x^\nu} \tag{119}$$

$$= [X, Y]^\nu \frac{\partial F}{\partial x^\nu}, \tag{120}$$

where $[X, Y]^\nu = X^\mu \frac{\partial Y^\nu}{\partial x^\mu} - Y^\mu \frac{\partial X^\nu}{\partial x^\mu}$ are the components of the commutator.

Since f is arbitrary, the expression

$$[X, Y] = [X, Y]^\nu \frac{\partial}{\partial x^\nu}, \tag{121}$$

is valid only once one has chosen a coordinate basis.

6.3 The metric tensor

We're familiar from Euclidean geometry (and special relativity) with the fact that the fundamental object of when discussing distance and angles (time intervals/rapidity) is an inner product between vectors.

Definition 6.2: A **metric tensor** at $p \in M$ is a $(0, 2)$-tensor g, satisfying two conditions:

i) g is *symmetric* such that $g(X, Y) = g(Y, X)$, $\forall X, Y \in T_pM$, i.e. $g_{ab} = g_{ba}$,

ii) g is *non-degenerate*, $G(X, Y) = 0$, $\forall Y \in T_pM \Leftrightarrow X = 0$.

Sometimes we write $g(X, Y) = \langle X, Y \rangle = \langle X, Y \rangle_g = X \cdot Y$.

By adapting the Gram-Schmidt algorithm, we can always find a basis $\{e_\mu\}$ for the tangent space at p, T_pM, such that

$$g(e_\mu, e_\nu) = \begin{cases} 0, & \mu \neq \nu, \\ +1 \text{ or } -1, & \mu = \nu. \end{cases} \tag{122}$$

Note this basis is not unique, but the **signature** (the number of $+1$'s and -1's) does not depend on the choice of basis (Sylvestre's Law of inertia).

If g has signature $(+ + \cdots +)$ we say it is **Riemannian**.

If g has signature $(- + \cdots +)$, we say it is **Lorentzian**.

Definition 6.3: A **Riemannian manifold** (or respectively a Lorentzian manifold) is a pair (M, g) where M is a manifold and g is a Riemannian (or respectively Lorentzian) metric tensor field.

On a Riemannian manifold, the norm of a vector is

$$|X| = \sqrt{g(X, X)}, \tag{123}$$

and the angle between $X, Y \in T_pM$, is given by

$$\cos\theta = \frac{g(X, Y)}{|X|\,|Y|}. \tag{124}$$

The length ℓ of a curve $\lambda : (a,b) \to M$ is given by

$$\ell(\lambda) = \int_a^b \left| \frac{\mathrm{d}\lambda}{\mathrm{d}t}(t) \right| \mathrm{d}t\,. \tag{125}$$

Exercise 5: If $\tau : (c,d) \to (a,b)$ with $\frac{\mathrm{d}t}{\mathrm{d}\tau} > 0$ and $\tau(c) = a$, $\tau(d) = b$, then

$$\widetilde{\lambda} = \lambda \circ \tau : (c,d) \to M, \tag{126}$$

is a reparametrization of λ such that $\ell\left(\widetilde{\lambda}\right) = \ell(\lambda)$.

Proof.

□

7 Lecture: Proper time

25/10/2024

In a coordinate basis, $g = g_{\mu\nu}\,\mathrm{d}x^\mu \otimes \mathrm{d}x^\nu$. We often write

$$\mathrm{d}x^\mu\,\mathrm{d}x^\nu = \frac{1}{2}\left(\mathrm{d}x^\mu \otimes \mathrm{d}x^\nu + \mathrm{d}x^\nu \otimes \mathrm{d}x^\mu\right), \tag{127}$$

and by convention often write $g = \mathrm{d}s^2$ so that

$$g = \mathrm{d}s^2 = g_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu\,. \tag{128}$$

Examples.

i) $\mathbb{R}^n$ with $g = \mathrm{d}s^2 = \left(\mathrm{d}x^1\right)^2 + \cdots + \left(\mathrm{d}x^n\right)^2 = \delta_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu$ is called **Euclidean space**. Any chart covering $\mathbb{R}^n$ in which the metric takes this form is called **Cartesian**.

ii) $\mathbb{R}^{1+3} = \left\{\left(x^0, x^1, x^2, x^3\right)\right\}$ with

$$\begin{aligned} g = \mathrm{d}s^2 &= -\left(\mathrm{d}x^0\right)^2 + \left(\mathrm{d}x^1\right)^2 + \left(\mathrm{d}x^2\right)^2 + \left(\mathrm{d}x^3\right)^2 && (129)\\ &= \eta_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu\,, && (130)\end{aligned}$$

is **Minkowski space**. A coordinate chart covering $\mathbb{R}^{1+3}$ in which the metric takes this form is called an **inertial frame**.

iii) On $S^2 = \{\mathbf{x} \in \mathbb{R}^3 \mid |\mathbf{x}| = 1\}$. Define a chart by

$$\begin{aligned} \phi^{-1} &: (0,\pi) \times (-\pi,\pi) \to S^2 && (131)\\ (\theta,\phi) &\mapsto (\cos\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)\,, && (132)\end{aligned}$$

In this chart, the **round metric** is

$$g = \mathrm{d}s^2 = \mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\,. \tag{133}$$

This covers $S^2 \setminus \{|\mathbf{x}| = 1,\ x^2 = 0,\ x' \leq 0\}$. To cover the rest, let

$$\widetilde{\phi}^{-1} : (0,\pi) \times (-\pi,\pi) \to S^2 \tag{134}$$

$$(\theta', \phi') \mapsto (-\sin\theta' \cos\phi', \cos\theta', \sin\theta' \sin\phi') \,. \tag{135}$$

This covers $S^2 \setminus \{|\mathbf{x}| = 1,\ x^3 = 0,\ x' \geq 0\}$ and thus setting

$$g = \mathrm{d}\theta'^2 + \sin^2\theta' \,\mathrm{d}\phi'^2 \,. \tag{136}$$

Defines a metric on all of S^2.

Since g_{ab} is non-degenerate, it is invertible as a matrix in any basis. We can check that the inverse defines a symmetric $(2,0)$ tensor, g^{ab} satisfying

$$g^{ab} g_{bc} = \delta^a_c. \tag{137}$$

Example. In the ϕ coordinates of the S^2 example.

$$g^{\mu\nu} = \left(1, \frac{1}{\sin^2\theta}\right). \tag{138}$$

An important property of the metric is that it induces a canonical identification of T_pM and T_p^*M. Given $X^a \in T_pM$, we define a covector $g_{ab}X^b = X_a$ and given $\eta_a \in T_p^*M$ we define a vector $g^{ab}\eta_b = \eta^a$.

In Euclidean space $\left(\mathbb{R}^3, \delta\right)$ we often do this without realising.

More generally, this allows us to raise tensor indices with g^{ab} and lower them with g_{ab}. Namely, if $T^{ab}{}_c$ is a $(2,1)$ tensor, then $T_a{}^{bc}$ is the $(2,1)$ tensor given by

$$T_a{}^{bc} = g_{ad} g^{ce} T^{db}{}_e \,. \tag{139}$$

7.1 Lorentzian signature

At any point p in a Lorentzian manifold we can find a basis $\{e_\mu\}$ such that

$$g\left(e_\mu, e_\nu\right) = \eta_{\mu\nu} = \mathrm{diag}\left(-1, 1, \cdots, 1\right). \tag{140}$$

This basis is not unique. Namely, if $e'_\mu = \left(A^{-1}\right)^\nu{}_\mu e_\nu$ is another such basis, then

$$\begin{aligned}
\eta_{\mu\nu} = g\left(e'_\mu, e'_\nu\right) &= \left(A^{-1}\right)^\sigma{}_\mu \left(A^{-1}\right)^\tau{}_\nu g\left(e_\sigma, e_\tau\right) \left(A^{-1}\right)^\sigma{}_\mu \left(A^{-1}\right)^\tau{}_\nu && (141)\\
&= \left(A^{-1}\right)^\sigma{}_\tau \left(A^{-1}\right)^\tau{}_\nu \eta_{\sigma\tau} && (142)\\
\Rightarrow A^\mu{}_\kappa A^\nu{}_\rho \eta_{\mu\nu} = \eta_{\kappa\rho}, &&& (143)
\end{aligned}$$

which is the condition that $A^\mu{}_\nu$ is a **Lorentz transformation**.

The tangent space at p has $\eta_{\mu\nu}$ as a metric tensor (in this basis) so has the structure of Minkowski space.

Definition 7.1: $X \in T_pM$ is

$$\begin{cases} \text{spacelike,} & \text{if } g\left(X, X\right) > 0, \\ \text{null-like/light-like,} & \text{if } g\left(X, X\right) = 0, \\ \text{timelike,} & \text{if } g\left(X, X\right) < 0. \end{cases} \tag{144}$$

A curve $\lambda : I \to M$ in a Lorentzian manifold is spacelike/timelike/null if the tangent vector is spacelike/timelike/null everywhere respectively.

A spacelike curve has a well-defined **length**, given by the same formula as in the Riemannian case. For a timelike curve $\lambda : (a,b) \to M$, the relevant quantity is the **proper time**

$$\tau(\lambda) = \int_a^b = \sqrt{-g_{ab}\frac{\mathrm{d}\lambda^a}{\mathrm{d}u}\frac{\mathrm{d}\lambda^b}{\mathrm{d}u}}\,\mathrm{d}u\,. \tag{145}$$

If $g_{ab}\frac{\mathrm{d}\lambda^a}{\mathrm{d}u}\frac{\mathrm{d}\lambda^b}{\mathrm{d}u} = -1$ for all u, then λ is parametrised by proper time.

In this case we call the tangent vector

$$u^a \equiv \frac{\mathrm{d}\lambda^a}{\mathrm{d}u}, \tag{146}$$

the **4-velocity** of λ.

7.2 Curves of extremal proper time

Suppose $\lambda : (0,1) \to M$ is timelike, satisfies $\lambda(0) = p$, $\lambda(1) = q$ and extremizes proper time among all such curves. This is a variational problem, associated to (in a coordinate chart),

$$\tau[\lambda] = \int_0^1 G\left(x^\mu(u), \dot{x}^\mu(u)\right)\mathrm{d}u\,, \tag{147}$$

with

$$G\left(x^\mu(u), \dot{x}^\mu(u)\right) = \sqrt{-g_{\mu\nu}\left(x(u)\right)\dot{x}^\mu(u)\,\dot{x}^\nu}, \tag{148}$$

where $\dot{x} = \frac{\mathrm{d}x}{\mathrm{d}u}$. The Euler Lagrange equation is

$$\frac{\mathrm{d}}{\mathrm{d}u}\left(\frac{\partial G}{\partial \dot{x^\mu}}\right) = \frac{\partial G}{\partial x^\mu}. \tag{149}$$

We can compute

$$\frac{\partial G}{\partial \dot{x}^\mu} = -\frac{1}{G}g_{\mu\nu}\dot{x}^\nu \tag{150}$$

$$\frac{\partial G}{\partial x^\mu} = -\frac{1}{2G}\frac{\partial}{\partial x^\mu}\left(g_{\sigma\tau}\right)\dot{x}^\sigma\dot{x}^\tau \tag{151}$$

$$= -\frac{1}{2G}g_{\sigma\tau,\mu}\dot{x}^\sigma\dot{x}^\tau. \tag{152}$$

This does not have a unique solution as one can re-parametrize the curve without changing the proper time τ.

8 Lecture: Christoffel Symbols

28/10/2024

8.1 Geodesic Equation

Therefore we fix the parameterisation such that the curve is parameterized by the proper time τ itself. Doing this, since

$$\frac{\mathrm{d}x^\mu}{\mathrm{d}\tau} = \dot{x}^\mu \frac{\mathrm{d}u}{\mathrm{d}\tau} \text{ and } -1 = g_{\mu\nu}\frac{\mathrm{d}x^\mu}{\mathrm{d}\tau}\frac{\mathrm{d}x^\nu}{\mathrm{d}\tau}, \tag{153}$$

we have that

$$-1 = g_{\mu\nu}\dot{x}^\mu\dot{x}^\nu \left(\frac{\mathrm{d}u}{\mathrm{d}\tau}\right)^2 \Rightarrow \frac{\mathrm{d}u}{\mathrm{d}\tau} = \frac{1}{\sqrt{G}}, \tag{154}$$

which then implies

$$\frac{1}{G}\frac{\mathrm{d}}{\mathrm{d}u} = \frac{\mathrm{d}}{\mathrm{d}\tau}. \tag{155}$$

Returning to the Euler Lagrange equation, we find that we can write it as

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\left(g_{\mu\nu}\frac{\mathrm{d}x^\nu}{\mathrm{d}\tau}\right) = \frac{1}{2}g_{\nu\rho,\mu}\frac{\mathrm{d}x^\nu}{\mathrm{d}\tau}\frac{\mathrm{d}x^\rho}{\mathrm{d}\tau}. \tag{156}$$

This then becomes

$$g_{\mu\nu}\frac{\mathrm{d}^2x^\nu}{\mathrm{d}\tau^2} + g_{\mu\nu,\rho}\frac{\mathrm{d}x^\nu}{\mathrm{d}\tau}\frac{\mathrm{d}x^\rho}{\mathrm{d}\tau} - \frac{1}{2}g_{\sigma\rho,\mu}\frac{\mathrm{d}x^\sigma}{\mathrm{d}\tau}\frac{\mathrm{d}x^\rho}{\mathrm{d}\tau} = 0. \tag{157}$$

Where notice that we can replace

$$g_{\mu\nu,\rho}\frac{\mathrm{d}x^\nu}{\mathrm{d}\tau}\frac{\mathrm{d}x^\rho}{\mathrm{d}\tau} = g_{\mu(\nu,\rho)}\frac{\mathrm{d}x^\nu}{\mathrm{d}\tau}\frac{\mathrm{d}x^\rho}{\mathrm{d}\tau}, \tag{158}$$

as it is symmetric in ν and ρ.

Thus, notice that we can write this as

$$\frac{\mathrm{d}^2x^\nu}{\mathrm{d}\tau^2} + \Gamma_\mu{}^\nu{}_\rho\frac{\mathrm{d}x^\mu}{\mathrm{d}\tau}\frac{\mathrm{d}x^\rho}{\mathrm{d}\tau} = 0, \tag{159}$$

where

$$\Gamma_\mu{}^\nu{}_\rho \equiv \frac{1}{2}g^{\nu\sigma}\left(g_{\mu\sigma,\rho} + g_{\sigma\rho,\mu} - g_{\nu\rho,\sigma}\right), \tag{160}$$

are the **Christoffel symbols** of g.

Notes.

- These symbols have a symmetry such that

$$\Gamma_\nu{}^\mu{}_\rho = \Gamma_\rho{}^\mu{}_\nu. \tag{161}$$

- Christoffel symbols are **not** tensor components as they do not transform desirably under coordinate transformations.
- Solutions to Eq. (159) are obtainable with standard ODE theory. Such solutions are called **geodesics**.
- The same equation governs curves of extremal length in a Riemannian manifold (or spacelike curves in a Lorentzian manifold) parameterized by arc-length.

Exercise 6: Show that Eq. (159) can be obtained as the Euler-Lagrange equation for the Lagrangian

$$L = -g_{\mu\nu}\left(x\left(\tau\right)\right)\dot{x}^{\mu}\left(\tau\right)\dot{x}^{\nu}\left(\tau\right). \tag{162}$$

Examples.

1) In Minkowski space, in an inertial frame $g_{\mu\nu} = \eta_{\mu\nu}$ so $\Gamma_{\mu\ \rho}^{\ \nu} = 0$ and the geodesic equation is

$$\frac{\mathrm{d}^2 x^{\mu}}{\mathrm{d}\tau^2} = 0, \tag{163}$$

which has geodesics (solutions) which are straight lines.

2) The Schwarzschild metric in Schwarzschild coordinates is a metric on $M = \mathbb{R}_t \times (2m, \infty)_r \times S^2_{\theta,\phi}$ given by

$$\mathrm{d}s^2 = -f\,\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{f} + r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right), \tag{164}$$

where $f = 1 - \frac{2m}{r}$.

One can then write the Lagrangian as

$$L = f\left(\frac{\mathrm{d}t}{\mathrm{d}\tau}\right)^2 - \frac{1}{f}\left(\frac{\mathrm{d}r}{\mathrm{d}\tau}\right)^2 - r^2\left(\frac{\mathrm{d}\theta}{\mathrm{d}\tau}\right)^2 - r^2\sin^2\theta\left(\frac{\partial\phi}{\partial t}\right)^2. \tag{165}$$

The Euler-Lagrange equation for $t\left(\tau\right)$ is

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\left(\frac{\partial L}{\partial t'}\right) = \frac{\partial L}{\partial t}, \tag{166}$$

where $t' = \frac{\mathrm{d}t}{\mathrm{d}\tau}$. This gives us

$$2\frac{\mathrm{d}}{\mathrm{d}\tau}\left(f\frac{\mathrm{d}t}{\mathrm{d}\tau}\right) = 0, \tag{167}$$

which implies

$$f\frac{\mathrm{d}^2 t}{\mathrm{d}\tau^2} + \frac{\mathrm{d}f}{\mathrm{d}r}\left(\frac{\mathrm{d}r}{\mathrm{d}\tau}\right)\left(\frac{\mathrm{d}t}{\mathrm{d}\tau}\right) = 0. \tag{168}$$

Comparing this to the geodesic equation Eq. (159), we see

$$\Gamma_{1\ 0}^{\ 0} = \Gamma_{0\ 1}^{\ 0} = \frac{1}{2}\frac{1}{f}\frac{\mathrm{d}f}{\mathrm{d}r}, \tag{169}$$

and $\Gamma_{\mu\ \nu}^{\ 0} = 0$ otherwise. The rest of the symbols can be found from the other Euler Lagrange equations.

8.2 Covariant Derivative

For a function $f : M \to \mathbb{R}$, we know that

$$\frac{\partial f}{\partial x^\mu} \text{ are the components of a covector } (df)_a. \tag{170}$$

For a vector field we can't just differentiate it's components as the basis vectors themselves can have spatial dependence.

Exercise 7: Show that if V is a vector field, then

$$T^\mu{}_\nu := \frac{\partial V^\mu}{\partial x^\nu}, \tag{171}$$

are not the components of a $(1,1)$ tensor.

Definition 8.1: A **covariant derivative** ∇ on a manifold M is a map sending smooth vector fields X, Y to a vector field $\nabla_X Y$ satisfying

i) linearity in the first vector such that

$$\nabla_{fX+gY} Z = f\nabla_X Z + g\nabla_Y Z, \tag{172}$$

ii) linearity in the second such that

$$\nabla_X (Y + Z) = \nabla_X Y + \nabla_X Z, \tag{173}$$

iii) and a Leibniz rule such that

$$\nabla_X (fY) = f\nabla_X Y + (\nabla_X f) Y, \tag{174}$$

where $\nabla_X f = X(f)$ and X, Y, Z are smooth vector fields and f, g are functions.

Note. This first condition implies that $\nabla Y : X \mapsto \nabla_X Y$ is a linear map of T_pM to itself and so defines a $(1,1)$ tensor, which we call the covariant derivative of Y.

In abstract index notation, one can write

$$(\nabla Y)^a{}_b = \nabla_b Y^a \text{ or } Y^a{}_{;b}\,. \tag{175}$$

Definition 8.2: In a basis $\{e_\mu\}$ the **connection components** $\Gamma_\nu{}^\mu{}_\rho$ are defined by

$$\nabla_{e_\rho} e_\nu = \Gamma_\nu{}^\mu{}_\rho e_\mu. \tag{176}$$

Once we know these connection components, they completely determine ∇. Namely, take

$$\nabla_X Y = \nabla_{X^\mu e_\mu} (Y^\nu e_\nu) \tag{177}$$

$$\overset{\text{i)}}{=} X^\mu \nabla_{e_\mu} (Y^\nu e_\nu) \tag{178}$$

$$\overset{\text{ii) \& iii)}}{=} X^\mu \left(e_\mu (Y^\nu) e_\nu + Y^\sigma \nabla_{e_\mu} e_\sigma\right) \tag{179}$$

$$= \left(X^\mu e_\mu \left(Y^\nu\right) + \Gamma_\sigma{}^\nu{}_\mu Y^\sigma X^\mu\right) e_\nu. \tag{180}$$

Hence the components of the covariant derivative can be written as

$$\left(\nabla_X Y\right)^\nu = X^\mu \left(e_\mu \left(Y^\nu\right) + \Gamma_\sigma{}^\nu{}_\mu Y^\sigma\right), \tag{181}$$

or identically, in different notation,

$$\begin{aligned} Y^\nu{}_{;\mu} &= e_\mu \left(Y^\nu\right) + \Gamma_\sigma{}^\nu{}_\mu Y^\sigma &(182)\\ &= Y^\nu{}_{,\mu} + \Gamma_\sigma{}^\nu{}_\mu Y^\sigma, &(183)\end{aligned}$$

where $Y^\nu{}_{,\mu} = \frac{\partial Y^\nu}{\partial x^\mu}$.

Note. Remember that $\Gamma_\mu{}^\nu{}_\sigma$ are not the components of a tensor, hence we call them *symbols*, like the Levi-Civita symbol $\varepsilon_{\mu\nu\rho\tau}$.

We extend ∇ to arbitrary tensor field by requiring the Leibniz property holds.

Example. For a tensor field η, we define

$$\left(\nabla_X \eta\right)(Y) := \nabla_X \left(\eta\left(Y\right)\right) - \eta\left(\nabla_X Y\right). \tag{184}$$

In component form, we can write this as

$$\begin{aligned} \left(\nabla_X \eta\right) Y &= X^\mu e_\mu \left(\eta_\sigma Y^\sigma\right) - \eta_\sigma \left(\nabla_X Y\right)^\sigma &(185)\\ &= X^\mu e_\mu \left(\eta_\sigma\right) Y^\sigma + X^\mu \eta_\sigma e_\mu \left(Y^\sigma\right) - \eta_\sigma \left(X^\nu e_\nu \left(Y^\sigma\right) + X^\nu \Gamma_\tau{}^\sigma{}_\nu Y^\tau\right) &(186)\\ &= \left(e_\mu \left(\eta_\sigma\right) - \Gamma_\sigma{}^\nu{}_\mu \eta_\nu\right) X^\mu Y^\sigma, &(187)\end{aligned}$$

and thus as $\boldsymbol{\nabla}\eta$ is linear in both X and Y, it is a (0,2) tensor (it also transforms appropriately). Therefore, with respect to our basis, we have

$$\begin{aligned} \nabla_\mu \eta_\sigma &= e_\mu \left(\eta_\sigma\right) - \Gamma_\sigma{}^\nu{}_\mu \eta_\nu =: \eta_{\sigma;\mu} &(188)\\ &\Rightarrow \eta_{\sigma;\mu} = \eta_{\sigma,\mu} - \Gamma_\sigma{}^\nu{}_\mu \eta_\nu. &(189)\end{aligned}$$

9 Lecture: Connection Components

30/10/2024

Exercise 8: In a coordinate basis

$$\begin{aligned} T^{\mu_1\cdots\mu_r}{}_{\nu_1\cdots\nu_s;\rho} &= T^{\mu_1\cdots\mu_r}{}_{\nu_1\cdots\nu_s,\rho} + \Gamma^{\mu_1}{}_{\rho\sigma} T^{\sigma\mu_2\cdots\mu_r}{}_{\nu_1\cdots\nu_s} + \cdots + \Gamma^{\mu_r}{}_{\rho\sigma} T^{\mu_1\cdots\mu_{r-1}\sigma}{}_{\nu_1\cdots\nu_s} &(190)\\ &- \Gamma_{\nu_1}{}^\sigma{}_\rho T^{\mu_1\cdots\mu_r}{}_{\sigma\nu_2\cdots\nu_s} - \cdots - \Gamma_{\nu_s}{}^\sigma{}_\rho T^{\mu_1\cdots\mu_r}{}_{\nu_1\cdots\nu_{s-1}\sigma}. &(191)\end{aligned}$$

Remark. If $T^a{}_b$ is a $(1,1)$ tensor, then $T^a{}_{b;c}$ is a $(1,2)$ tensor and we can take further covariant derivatives,

$$\left(T^a{}_{b;c}\right)_{;d} = T^a{}_{b;cd} = \nabla_d \nabla_c T^a{}_b, \tag{192}$$

In general $T^a{}_{b;cd} \neq T^a{}_{b;dc}$. If f is a function $f_{;a} = (df)_a$ is a covector. In a coordinate basis $f_{;\mu} = f_{,\mu}$ which implies

$$\begin{aligned} f_{;\mu\nu} &= f_{,\mu\nu} - \Gamma_\mu{}^\sigma{}_\nu f_{,\sigma} &(193)\\ &\Rightarrow f_{;[\mu\nu]} = -\Gamma_{[\mu}{}^\sigma{}_{\nu]} f_{,\sigma}. &(194)\end{aligned}$$

Definition 9.1: A connection (eq. covariant derivative) is **torsion free** or symmetric if

$$\nabla_a \nabla_b f - \nabla_b \nabla_a f = 0. \tag{195}$$

For any f, in a coordinate basis, this is equivalent to

$$\Gamma_{[\mu}{}^{\rho}{}_{\nu]} = 0 \Leftrightarrow \Gamma_{\mu}{}^{\rho}{}_{\nu} = \Gamma_{\nu}{}^{\rho}{}_{\mu}. \tag{196}$$

Lemma 9.1: If ∇ is torsion free, then for X, Y vector fields

$$\nabla_X Y - \nabla_Y X = [X, Y]. \tag{197}$$

Proof. In a coordinate basis,

$$\begin{aligned}
(\nabla_X Y - \nabla_Y X)^\mu &= X^\sigma Y^\mu{}_{;\sigma} - Y^\sigma X^\mu{}_{;\sigma} && (198)\\
&= X^\sigma \left(Y^\mu{}_{,\sigma} + \Gamma_\rho{}^\mu{}_\sigma Y^\rho\right) - Y^\sigma \left(X^\mu{}_{,\sigma} + \Gamma_\rho{}^\mu{}_\sigma X^\rho\right) && (199)\\
&= [X, Y]^\mu + 2X^\sigma Y^\rho \Gamma_{[\rho}{}^\mu{}_{\sigma]}. && (200)
\end{aligned}$$

This is a tensor equation so if it is true in one basis, it is true in all. □

Note. Even if ∇ is torsion free, $\nabla_a \nabla_b X^c \neq \nabla_b \nabla_a X^c$ in general.

9.1 The Levi-Civita Connection

For a manifold with metric, there is a preferred connection.

Theorem 9.1 (Fundamental Theorem of Riemannian geometry): If (M, g) is a manifold with a metric, there is a unique torsion free connection ∇ satisfying $\nabla g = 0$. This is called the **Levi-Civita connection**.

Proof. Suppose such a connection exists. By the Leibniz rule, if X, Y, Z are smooth vector fields, then

$$\begin{aligned}
X(g(Y, Z)) &= \nabla_X (g(Y, Z)) && (201)\\
&= (\nabla_X g)(Y, Z) + g(\nabla_X Y, Z) + g(Y, \nabla_X Z) && (202)\\
X(g(Y, Z)) &= g(\nabla_X Y, Z) + g(Y, \nabla_X Z) && (203)\\
\Rightarrow Y(g(Z, X)) &= g(\nabla_Y Z, X) + g(Z, \nabla_Y X) && (204)\\
\Rightarrow Z(g(X, Y)) &= g(\nabla_Z X, Y) + g(X, \nabla_Z Y). && (205)
\end{aligned}$$

Taking Eq. (203) + Eq. (204) - Eq. (205),

$$X(g(Y, Z)) + Y(g(Z, X)) - Z(g(X, Y)) = g(\nabla_X Y + \nabla_Y X, Z) + g(\nabla_X Z - \nabla_Z X, Y) \tag{206}$$

$$+ g\left(\nabla_X Z - \nabla_Z X, Y\right) + g\left(\nabla_Y Z - \nabla_Z Y, X\right). \tag{207}$$

As $\nabla_X Y - \nabla_Y X = [X, Y]$, this becomes

$$X\left(g\left(Y,Z\right)\right) + Y\left(g\left(Z,X\right) - Z\left(g\left(X,Y\right)\right)\right) = 2g\left(\nabla_X Y, Z\right) - g\left(\left[X,Y\right],Z\right) \tag{208}$$

$$- g\left(\left[Z,X\right],Y\right) + g\left(\left[Y,Z\right],X\right). \tag{209}$$

Therefore

$$g\left(\nabla_X Y, Z\right) = \frac{1}{2}\Bigg(X\left(g\left(y,Z\right)\right) + Y\left(g\left(Z,X\right)\right) - Z\left(g\left(X,Y\right)\right) \tag{210}$$

$$+ g\left(\left[X,Y\right],Z\right) + g\left(\left[Z,X\right]Y\right) - g\left(\left[Y,Z\right],X\right)\Bigg), \tag{211}$$

and therefore $\nabla_X Y$ is uniquely determined since g is non-degenerate and X, Y and Z are general. □

Conversely, we can use this expression to define $\nabla_X Y$. We then need to check the properties of a symmetric connection hold.

Example. Observe that

$$g\left(\nabla_{fX} Y, Z\right) = \frac{1}{2}\Bigg(fX\left(g\left(y,Z\right)\right) + Y\left(fg\left(Z,X\right)\right) - Z\left(fg\left(X,Y\right)\right)$$

$$+ g\left(\left[fX,Y\right],Z\right) + g\left(\left[Z,fX\right]Y\right) - g\left(\left[Y,Z\right],fX\right)\Bigg) \tag{212}$$

$$= \frac{1}{2}\Bigg(fXg\left(Y,Z\right) + fY\left(g\left(Z,X\right) - fZ\left(g\left(X,Y\right)\right)\right) + \left(Y\left(f\right)g\left(Z,X\right) - Z\left(f\right)g\left(X,Y\right)\right)$$

$$+ g\left(f\left[X,Y\right] - Y\left(f\right)X, Z\right) + g\left(f\left[Z,X\right] + Z\left(f\right)X, Y\right) - fg\left(\left[Y,Z\right],X\right)\Bigg) \tag{213}$$

$$= g\left(f\nabla_X Y, Z\right), \tag{214}$$

which implies

$$g\left(\nabla_{fX} Y - f\nabla_X Y\right) = 0, \tag{215}$$

$\forall Z$. Therefore $\nabla_{fX} Y = f\nabla_X Y$ as g is non-degenerate.

Exercise 9: Check the other properties.

In a coordinate basis, we can compute

$$g\left(\nabla_{e_\mu} e_\nu, e_\sigma\right) = \frac{1}{2}\Bigg(e_\mu\left(g\left(e_\nu, e_\sigma\right)\right) + e_\nu\left(g\left(e_\sigma, e_\mu\right) - e_\sigma\left(g\left(e_\mu, e_\nu\right)\right)\right)\Bigg) \tag{216}$$

$$g\left(\Gamma_\nu{}^\tau{}_\mu e_\tau, e_\sigma\right) = \Gamma_\nu{}^\tau{}_\mu g_{\tau\sigma} = \frac{1}{2}\left(g_{\sigma\nu,\mu} + g_{\sigma\mu,\nu} - g_{\mu\nu,\sigma}\right). \tag{217}$$

This provides

$$\Gamma_\nu{}^\tau{}_\mu = \frac{1}{2} g^{\sigma\tau}\left(g_{\sigma\nu,\mu} + g_{\mu\sigma,\nu} - g_{\mu\nu,\sigma}\right), \tag{218}$$

which is exactly the form of the Christoffel symbols.

Thus if ∇ is a Levi-Civita connection, we can raise/lower indices and it commutes with covariant differentiation.

9.2 Geodesics

We found that a curve extremizing proper time τ satisfies

$$\frac{\mathrm{d}^2 x^\mu}{\mathrm{d}\tau^2} + \Gamma_\nu{}^\mu{}_\rho \left(x\left(\tau\right)\right) \frac{\mathrm{d}x^\nu}{\mathrm{d}\tau} \frac{\mathrm{d}x^\rho}{\mathrm{d}\tau} = 0. \tag{219}$$

The tangent vector X^a to the curve has components $X^\mu = \frac{\mathrm{d}x^\mu}{\mathrm{d}\tau}$, we get a vector field of which the geodesic is an integral curve. We note that

$$\frac{\mathrm{d}^2 x^\mu}{\mathrm{d}\tau^2} = \frac{\mathrm{d}}{\mathrm{d}\tau}\left(\frac{\mathrm{d}x^\mu}{\mathrm{d}\tau}\right) \tag{220}$$

$$= \frac{\mathrm{d}X^\mu}{\mathrm{d}x^\nu}\frac{\mathrm{d}x^\nu}{\mathrm{d}\tau} \tag{221}$$

$$= X^\mu{}_{,\nu} X^\nu. \tag{222}$$

Using the geodesic equation, Eq. (219) we have

$$X^\mu{}_{,\nu} X^\nu + \Gamma_\nu{}^\mu{}_\rho X^\nu X^\rho = 0 \Leftrightarrow X^\nu X^\mu{}_{;\nu} = 0 \Leftrightarrow \nabla_X X = 0. \tag{223}$$

We can extend this to any connection.

Definition 9.2: Let M be a manifold with connection ∇. An **affinely parameterized geodesic** satisfies

$$\nabla_X X = 0, \tag{224}$$

where X is the tangent vector to the curve.

10 Lecture: Parallel Transport

01/11/2024

Note. If we reparameterize $t \to t\left(u\right)$ then

$$\underbrace{\frac{\mathrm{d}x^\mu}{\mathrm{d}u}}_{Y} = \underbrace{\frac{\mathrm{d}x^\mu}{\mathrm{d}t}}_{X}\frac{\mathrm{d}t}{\mathrm{d}u}, \tag{225}$$

so $X \to Y = hX$ with $h > 0$. Notice

$$\boldsymbol{\nabla}_Y Y = \boldsymbol{\nabla}_{hX}\left(hX\right) = h\left(\boldsymbol{\nabla}_X\left(hX\right)\right) = h^2 \boldsymbol{\nabla}_X X + hX \cdot X\left(h\right) = fY, \tag{226}$$

with $f = X\left(h\right) = \frac{\mathrm{d}(h)}{\mathrm{d}t} = \frac{1}{h}\frac{\mathrm{d}h}{\mathrm{d}u} = \frac{1}{h}\frac{\mathrm{d}^2 t}{\mathrm{d}u^2}$. Therefore

$$\boldsymbol{\nabla}_Y Y = 0 \Leftrightarrow t = \alpha u + \beta, \tag{227}$$

for $\alpha, \beta \in \mathbb{R}$ and $\alpha > 0$.

Theorem 10.1: Given $p \in M$, $X_p \in T_P M$, there exists a unique **affinely parameterized geodesic** $\lambda : I \to M$ satisfying

$$\lambda(0) = p, \qquad \dot{\lambda}(0) = X_p. \tag{228}$$

Proof. Choose coordinate with $\phi(p) = 0$, $x^\mu(t) = \phi(\lambda(t))$ satisfies $\boldsymbol{\nabla}_X X = 0$ with $X = X^\mu \frac{\partial}{\partial x^\mu}$, $X^\mu = \frac{\mathrm{d}x^\mu}{\mathrm{d}t}$. This becomes

$$\frac{\mathrm{d}^2 x^\mu}{\mathrm{d}t^2} + \Gamma_\nu{}^\mu{}_\sigma \frac{\mathrm{d}x^\nu}{\mathrm{d}t}\frac{\mathrm{d}x^\sigma}{\mathrm{d}t} = 0, \tag{229}$$

with $x^\mu(0) = 0$ and $\frac{\mathrm{d}x^\mu}{\mathrm{d}t}(0) = X_p^\mu$. □

This has a unique solution $x^\mu : (-\varepsilon, \varepsilon) \to \mathbb{R}^n$ for ε sufficiently small by standard ODE theory.

Postulate 10.1: In general relativity, free particles move along geodesics of the Levi-Civita connection. These are **timelike** for **massive** particles and **null** for **massless** particles.

10.1 Normal Coordinates

If we fix $p \in M$, we can map $T_p M$ into M by setting $\psi(X_p) = \lambda_{X_p}(1)$ where λ_{X_p} is the unique affinely parameterized geodesic with $\lambda_{X_p}(0) = 0$ and $\dot{\lambda}_{X_p}(0) = X_p$. Notice that $\lambda_{\alpha X_p}(t) = \lambda_{X_p}(\alpha t)$ for $\alpha \in \mathbb{R}$, since if $\widetilde{\lambda}(t) = \lambda_{X_p}(\alpha t)$, this is an affine reparametrization so is still a geodesic and $\widetilde{\lambda}(0) = p$, where also $\dot{\widetilde{\lambda}}(0) = \alpha \dot{\lambda}_{X_p}(0) = \alpha X_p$. Moreover $\alpha \mapsto \psi(\alpha X_p) = \lambda_{X_p}(\alpha)$ is an affinely parameterized geodesic.

Claim. If $U \subset T_P M$ is a sufficiently small neighbourhood of the origin, then $\psi : T_P M \to M$ is one to one and onto.

Definition 10.1: Suppose $\{e_\mu\}$ is a basis for $T_p M$. We construct normal coordinates at p as follows. For $q \in \psi(U) \subset M$. We define

$$\phi(q) = \left(X^1, \cdots, X^n\right), \tag{230}$$

where X^μ are components of the unique $X_p \in U$ with $\psi(X_p) = q$ with respect to the basis $\{e_\mu\}$.

By our previous observation, the curve given in normal coordinates by $X^\mu(t) = tY^\mu$ for Y^μ constant is an affinely parameterized geodesic. Thus from the geodesic equation Eq. (229),

$$\Gamma_\nu{}^\mu{}_\sigma(Y) Y^\nu Y^\sigma = 0. \tag{231}$$

Setting $t = 0$, we deduce (as such Y are arbitrary) that $\Gamma_{(\nu}{}^\mu{}_{\sigma)}\Big|_p = 0$. So if ∇ is torsion free, $\Gamma_\nu{}^\mu{}_\sigma\Big|_p = 0$ in *normal coordinates*. Note that as Γ is not a tensor, this does not hold in other coordinate systems.

Claim. If ∇ is the Levi Civita connection of a metric, then

$$g_{\mu\nu,\rho}\Big|_p = 0. \tag{232}$$

Proof.

$$\begin{aligned} g_{\mu\nu,\rho} &= \frac{1}{2}\left(g_{\mu\nu,\rho} + g_{\rho\nu,\mu} - g_{\mu\rho,\nu}\right) + \frac{1}{2}\left(g_{\mu\nu,\rho} + g_{\mu\rho,\nu} - g_{\rho\nu,\mu}\right) && (233)\\ &= \Gamma_{\mu\ \rho}^{\ \sigma} g_{\sigma\nu} + \Gamma_{\rho\ \nu}^{\ \sigma} g_{\sigma\mu}, && (234) \end{aligned}$$

which vanishes at p. □

We can always choose the basis $\{e_\mu\}$ for T_pM on which we base the normal coordinates to be orthonormal.

Lemma 10.1: On a Riemannian (or Lorentzian) manifold, we can choose normal coordinates at p such that $g_{\mu\nu,\rho}\mid_p = 0$, and

$$g_{\mu\nu}\Big|_p = \begin{cases} \delta_{\mu\nu}, & \text{Riemannian,} \\ \eta_{\mu\nu}, & \text{Lorentzian.} \end{cases} \tag{235}$$

Proof. The curve given in normal coordinates by $t \mapsto (t, 0, \cdots, 0)$ is the affinely parameterized geodesic with $\lambda(0) = p$ and $\dot{\lambda}(0) = e_1$ by the previous argument. But by the definition of a coordinate basis, this vector is $\left(\frac{\partial}{\partial x_1}\right)_p$, so if $\{e_\mu\}$ is orthonormal, at p the set $\{\left(\frac{\partial}{\partial x^\mu}\right)_p\}$ form an orthonormal basis. □

10.2 Curvature: Parallel Transport

Suppose $\lambda : I \to M$ is a curve with tangent vector $\dot{\lambda}(t)$. We say a tensor field T is **parallel transported** along λ if

$$\boldsymbol{\nabla}_{\dot{\lambda}} T = 0, \tag{236}$$

on λ.

If λ is an affinely parameterized geodesic, then $\dot{\lambda}$ is parallel transported along λ. A parallel transported tensor is determined everywhere on λ by its value at one point.

Example. If T is a $(1,1)$ tensor, then in coordinates its parallel transport can be written as

$$\begin{aligned} 0 &= \frac{\mathrm{d}x^\mu}{\mathrm{d}t} T^\nu{}_{\sigma;\mu} && (237)\\ &= \frac{\mathrm{d}x^\mu}{\mathrm{d}t}\left(T^\nu{}_{\sigma,\mu} + \Gamma_{\rho\ \mu}^{\ \nu} T^\rho{}_\sigma - \Gamma_{\sigma\ \mu}^{\ \rho} T^\nu{}_\rho\right). && (238) \end{aligned}$$

However, $T^{\nu}{}_{\sigma,\mu}\frac{\mathrm{d}x^{\mu}}{\mathrm{d}t}=\frac{\mathrm{d}}{\mathrm{d}t}\left(T^{\nu}{}_{\sigma}\right)$, so

$$0=\frac{\mathrm{d}}{\mathrm{d}t}T^{\nu}{}_{\sigma}+\left(\Gamma_{\rho}{}^{\nu}{}_{\mu}T^{\rho}{}_{\sigma}-\Gamma_{\sigma}{}^{\rho}{}_{\mu}T^{\nu}{}_{\rho}\right)\frac{\mathrm{d}x^{\mu}}{\mathrm{d}t}. \tag{239}$$

This is a linear ODE for $T^{\nu}{}_{\sigma}\left(x\left(t\right)\right)$ so ODE theory gives us a unique solution once $T^{\mu}{}_{\sigma}\left(x\left(0\right)\right)$ specified.

Parallel transport along a curve from p to q gives an isomorphism between tensors at p and q. This isomorphism critically depends on the choice of curve in general.

11 Lecture: The Riemann Tensor

04/11/2024

11.1 The Riemann Tensor

The Riemann tensor captures the extent to which parallel transport depends on the curve we take.

Definition 11.1: Given X,Y,Z are smooth vector fields, and ∇ is a connection, we define

$$R\left(X,Y\right)Z=\nabla_{X}\nabla_{Y}Z-\nabla_{Y}\nabla_{X}Z-\nabla_{[X,Y]}Z. \tag{240}$$

Then

$$\left(R\left(X,Y\right)Z\right)^{a}=R^{a}{}_{bcd}X^{c}Y^{d}Z^{b}, \tag{241}$$

for a $(1,3)$ tensor $R^{a}{}_{bcd}$, called the **Riemann curvature tensor**.

Note. This tensor does not depend on any derivatives of X, Y or Z.

Proof. Suppose f is a smooth function. Then

$$\begin{aligned}
R\left(fX,Y\right)Z&=\nabla_{fX}\nabla_{Y}Z-\nabla_{Y}\nabla_{fX}Z-\nabla_{[fX,Y]}Z && (242)\\
&=f\nabla_{X}\nabla_{Y}Z-\nabla_{Y}\left(f\nabla_{X}Z\right)-\nabla_{f[X,Y]-Y(f)X}Z && (243)\\
&=f\nabla_{X}\nabla_{Y}Z-f\nabla_{Y}\nabla_{X}Z-Y\left(f\right)\nabla_{X}Z-f\nabla_{[X,Y]}Z+Y\left(f\right)\nabla_{X}Z && (244)\\
&=f\nabla_{X}\nabla_{Y}Z-f\nabla_{Y}\nabla_{X}Z-f\nabla_{[X,Y]}Z && (245)\\
&=fR\left(X,Y\right)Z. && (246)
\end{aligned}$$

Since $R\left(X,Y\right)Z=-R\left(Y,X\right)$, we have $R\left(X,fY\right)=fR\left(X,Y\right)Z$.

Exercise 10: $R\left(X,Y\right)\left(fZ\right)=fR\left(X,Y\right)Z$

Proof.

□

Now suppose we pick a basis $\{e_{\mu}\}$ with dual basis $\{f^{\mu}\}$, then

$$\begin{aligned}
R\left(X,Y\right)Z&=R\left(X^{\rho}e_{\rho},Y^{\sigma}e_{\sigma}\right)\left(Z^{\nu}e_{\nu}\right)=X^{\rho}Y^{\sigma}Z^{\nu}R\left(e_{\rho},e_{\sigma}\right)e_{\nu} && (247)\\
&=\left(R^{\mu}{}_{\nu\rho\sigma}X^{\rho}Y^{\sigma}Z^{\nu}\right)e_{\mu}, && (248)
\end{aligned}$$

where $R^\mu{}_{\nu\rho\sigma} = f^\mu\left(R\left(e_\rho, e_\sigma\right)e_\nu\right)$ are components of $R^a{}_{bcd}$ in this basis. Since this result holds in one basis, it holds in all as we showed the linearity properties in a coordinate independent fashion. $\square$

In a coordinate basis, $e_\mu = \frac{\partial}{\partial x^\mu}$ and $[e_\mu, e_\nu] = 0$ so

$$R\left(e_\mu, e_\sigma\right)e_\nu = \nabla_{e_\rho}\left(\nabla_{e_\sigma}e_\nu\right) - \nabla_{e_\sigma}\left(\nabla_{e_\rho}e_\nu\right) - \nabla_{e_\rho}\left(\Gamma_\nu{}^\tau{}_\sigma e_\tau\right) - \nabla_{e_\sigma}\left(\Gamma_\nu{}^\tau{}_\rho e_\tau\right) \tag{249}$$

$$= \partial_\rho\left(\Gamma^\tau{}_{\nu\sigma}\right)e_\tau + \Gamma_\nu{}^\tau{}_\sigma\Gamma_\tau{}^\mu{}_\rho e_\mu - \partial_\sigma\left(\Gamma_\nu{}^\tau{}_\rho\right)e_\tau - \Gamma_\nu{}^\tau{}_\rho\Gamma_\tau{}^\mu{}_\sigma e_\mu. \tag{250}$$

Therefore,

$$R^\mu{}_{\nu\rho\sigma} = \partial_\rho\left(\Gamma_\nu{}^\mu{}_\sigma\right) - \partial_\sigma\left(\Gamma_\nu{}^\mu{}_\rho\right) + \Gamma_\nu{}^\tau{}_\sigma\Gamma_\tau{}^\mu{}_\rho - \Gamma_\nu{}^\tau{}_\rho\Gamma_\tau{}^\mu{}_\sigma, \tag{251}$$

where in normal coordinates one can drop the last two terms.

Example. Take the Levi-Civita connection ∇ of Minkowski space in an inertial frame, $\Gamma_\mu{}^\nu{}_\sigma = 0$ so $R^\mu{}_{\nu\sigma\tau} = 0$ hence $R^a{}_{bcd} = 0$. Such a connection is called **flat**.

Conversely, for a Lorentzian spacetime, with flat Levi-Civita connection, we can locally find coordinates such that $g_{\mu\nu} = \operatorname{diag}\left(-1, 1, \cdots, 1\right)$.

Note. One must be cautious as

$$\left(\nabla_X\nabla_Y Z\right)^c = X^a\nabla_a\left(Y^b\nabla_b Z^c\right) \neq X^aY^b\nabla_a\nabla_b Z^c. \tag{252}$$

Hence

$$\left(R\left(X,Y\right)Z\right)^c = X^a\nabla_a\left(Y^b\nabla_b Z^c\right) - Y^a\nabla_a\left(X^b\nabla_b Z^c\right) - [X,Y]^b\,\nabla_b Z^c \tag{253}$$

$$= X^aY^b\nabla_a\nabla_b Z^c - Y^aX^b\nabla_a\nabla_b Z^c + \left(\nabla_X Y - \nabla_Y X - [X,Y]\right)^b\nabla_b Z^c \tag{254}$$

$$= X^aY^bR^c{}_{dab}Z^d. \tag{255}$$

So if ∇ is torsion free

$$\nabla_a\nabla_b Z^c - \nabla_b\nabla_a Z^c = R^c{}_{dab}Z^d, \tag{256}$$

which is called the **Ricci identity**. See Exercise Sheet 2.

We can construct a new tensor from $R^a{}_{bcd}$ by contraction.

Definition 11.2: The **Ricci tensor** is the $(0,2)$ tensor

$$R_{ab} = R^c{}_{acd}. \tag{257}$$

Suppose X, Y are vector fields satisfying $[X,Y] = 0$.

We construct a rectangle with points A, B, C and D and define it by flowing from A to B a distance ε along an integral curve of X, We then flow from B to C a distance ε along an integral curve of Y. Then we return flowing in the opposite direction along both curves in sequence. Since $[X,Y]$, we indeed return to the start.

Claim. If Z is parallel transported around $ABCD$ to a vector Z', then

$$\left(Z - Z'\right)^\mu = \varepsilon^2R^\mu{}_{\nu\rho\sigma}Z^\nu X^\rho Y^\sigma + \mathcal{O}\left(\varepsilon^3\right). \tag{258}$$

11.2 Geodesic Deviation

Let ∇ be a symmetric connection. Suppose $\lambda : I \to M$ is an affinely parameterized geodesic through p. We can pick normal coordinate centered at p such that λ is given by $t \mapsto (t, 0, \cdots, 0)$.

Suppose we start a geodesic with $|s| \ll 1$ and

$$x_s^\mu(0) = s x_0^\mu \qquad \dot{x}_s^\mu(0) = s x_1^\mu + (1, 0, \cdots, 0). \tag{259}$$

Then we find

$$x_s^\mu(t) = x^\mu(s,t) = (t, 0, \cdots, 0) + sY^\mu(t) + \mathcal{O}(s^2), \tag{260}$$

where

$$Y^\mu(t) = \left.\frac{\partial x^\mu}{\partial s}\right|_{s=0}, \tag{261}$$

are components of a vector field along λ measuring the infinitesimal deviation of the geodesics. We have

$$\frac{\partial^2 x^\mu}{\partial t^2} + \Gamma_\nu{}^\mu{}_\sigma(x^\mu(s,t))\frac{\partial x^\nu}{\partial t}\frac{\partial x^\sigma}{\partial t} = 0. \tag{262}$$

We take the partial derivative of this with respect to s at $s = 0$ and see that, with $T^\mu \equiv \left.\frac{\partial x^\mu}{\partial t}\right|_{s=0}$,

$$\frac{\partial^2 Y^\mu}{\partial t^2} + \partial_\rho(\Gamma_\nu{}^\mu{}_\sigma)\Big|_{s=0} T^\nu T^\sigma Y^\rho + 2\Gamma_\rho{}^\mu{}_\sigma \frac{\partial Y^\rho}{\partial t} T^\sigma = 0 \tag{263}$$

$$\Rightarrow T^\nu\left(T^\sigma Y^\mu{}_{,\sigma}\right)_{,\nu} + \partial_\rho(\Gamma_\nu{}^\mu{}_\sigma)\Big|_{s=0} T^\nu T^\sigma Y^\rho + 2\Gamma_\rho{}^\mu{}_\sigma \frac{\partial Y^\rho}{\partial t} T^\sigma = 0. \tag{264}$$

At $p = 0$, $\Gamma = 0$ so

$$T^\nu\left(T^\sigma Y^\mu_{;\sigma} - \Gamma_\rho{}^\mu{}_\sigma T^\sigma Y^\rho\right)_{;\nu} + \left(\partial_\rho \Gamma_\nu{}^\mu{}_\sigma\right)_\rho T^\nu T^\sigma Y^\rho = 0. \tag{265}$$

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Notice that we can write this expression (as the terms quadratic in Γ are zero here) equivalently as

$$(\nabla_T \nabla_T Y)^\mu + R^\mu{}_{\sigma\rho\nu} T^\nu T^\sigma Y^\rho = 0. \tag{266}$$

Therefore,

$$\nabla_T \nabla_T Y + R(Y,T)T = 0. \tag{267}$$

This is the **geodesic deviation** or **Jacobi equation**.

12.1 Symmetries of the Riemann tensor

From the definition, it is clear that

$$R^a{}_{bcd} = -R^a{}_{bdc} \Leftrightarrow R^a{}_{b(cd)} = 0. \tag{268}$$

Proposition 12.1: If ∇ is torsion free, then

$$R^a{}_{[bcd]} = 0. \tag{269}$$

Proof. Fix $p \in M$, and choose normal coordinates at p. Work in a coordinate basis. Then $\Gamma_\mu{}^\sigma{}_\nu \Big|_p = 0$ and $\Gamma_\mu{}^\sigma{}_\nu = \Gamma_\nu{}^\sigma{}_\mu$ everywhere.

Then

$$R^\mu{}_{\nu\rho\sigma} = \partial_\rho \left(\Gamma_\nu{}^\mu{}_\sigma\right)\Big|_p = \partial_\sigma \left(\Gamma_\nu{}^\mu{}_\rho\right)\Big|_p, \tag{270}$$

implies that

$$R^\mu{}_{[\nu\rho\sigma]}\Big|_p = 0. \tag{271}$$

As p is arbitrary, $R^\mu{}_{[\nu\rho\sigma]} = 0$ everywhere. □

Proposition 12.2: If ∇ is torsion free, then the (differential) Bianchi identity holds such that

$$R^a{}_{b[cd;e]} = 0. \tag{272}$$

Proof. Choose coordinates as above. Then $R^\mu{}_{\nu\rho\sigma;\tau}\Big|_p = R^\mu{}_{\nu\rho\sigma,\tau}\Big|_p$.

Schematically, we have $R \sim \partial\Gamma + \Gamma\Gamma$ and thus $\partial R \sim \partial\partial\Gamma + \partial\Gamma \cdot \Gamma$, where as $\Gamma\Big|_p = 0$, we deduce

$$R^\mu{}_{\nu\rho\sigma,\tau}\Big|_p = \partial_\tau\partial_\rho\Gamma_\nu{}^\mu{}_\sigma\Big|_p - \partial_\tau\partial_\sigma\left(\Gamma_\nu{}^\mu{}_\rho\right)\Big|_p. \tag{273}$$

By the symmetry of the mixed partial derivatives, we see that $R^\mu{}_{\nu[\rho\sigma,\tau]}\Big|_p = 0$. Since p is arbitrary, the result follows. □

Suppose ∇ is the Levi-Civita connection of a manifold with metric g. We can lower an index with g_{ab} and consider R_{abcd}.

Proposition 12.3: R_{abcd} satisfies

$$R_{abcd} = R_{cdab}. \tag{274}$$

This also implies that $R_{(ab)cd} = 0$.

Proof. Pick normal coordinates at some point p so that $\partial_\mu g_{\nu\rho} = 0$. We notice that

$$0 = \partial_\mu \delta^\nu_\sigma \bigg|_p = \partial_\mu \left(g^{\nu\tau} g_{\tau\sigma}\right) \bigg|_p = \left(\partial_\mu g^{\nu\tau}\right) g_{\tau\sigma} \bigg|_p . \tag{275}$$

Thus $\partial_\mu g^{\nu\tau} \bigg|_p = 0$ and hence

$$\partial_\rho \Gamma_\nu{}^\sigma{}_\mu \bigg|_p = \partial_\rho \left(\frac{1}{2} g^{\mu\tau} \left(g_{\tau\sigma,\nu} + g_{\nu\tau,\sigma} - g_{\nu\sigma,tau}\right)\right) \bigg|_p \tag{276}$$

$$= \frac{1}{2} g^{\mu\tau} \left(g_{\tau\sigma,\nu\rho} + g_{\nu\tau,\sigma\rho} - g_{\nu\sigma,\tau\rho}\right) \bigg|_p . \tag{277}$$

We then have that

$$R_{\mu\nu\rho\sigma} \bigg|_p = g_{\mu\kappa \left(\partial_\rho \Gamma_\nu{}^\kappa{}_\sigma - \partial_\sigma \Gamma_\nu{}^\kappa{}_\rho\right)} \bigg|_p \tag{278}$$

$$= \frac{1}{2} \left(g_{\mu\sigma,\nu\rho} + g_{|nu\rho,\mu\sigma} - g_{\nu\sigma,\mu\rho - g_{|mu\rho,\nu\sigma}}\right) \bigg|_p . \tag{279}$$

This satisfies that $R_{\mu\nu\rho\sigma} \bigg|_p = R_{\rho\sigma\mu\nu} \bigg|_p$ and thus is true everywhere.

□

Corollary 12.1: The Ricci tensor is symmetric such that

$$R_{ab} = R_{ba} . \tag{280}$$

Proof.

$$R_{ab} = R^c{}_{acb} = g^{cd} R_{cadb} = g^{cd} R_{dbca} = R_{ba} . \tag{281}$$

□

Definition 12.1: The **Ricci scalar (scalar curvature)** is

$$R = R_a{}^a = g^{ab} R_{ab} . \tag{282}$$

The **Einstein tensor** is

$$G_{ab} = R_{ab} - \frac{1}{2} g_{ab} R . \tag{283}$$

Exercise 11: The (contracted) Bianchi identity implies $\nabla_a G^a{}_b = 0$

12.2 Diffeomorphisms and the Lie Derivative

Suppose $\phi : M \to N$ is a smooth map, then ϕ induces maps between corresponding vector bundles.

Definition 12.2: Given $f : N \to \mathbb{R}$, the **pull back** of f by ϕ is the map $\phi^* f : M \to \mathbb{R}$ given by $\phi^* f(p) = f(\phi(p))$.

Definition 12.3: Given $X \in T_P M$, we define the **push forward** of X by ϕ, $\phi_* X \in T_{\phi(p)} N$ as follows.

Let $\lambda : I \to M$ be a curve with $\lambda(0) = p$. $\dot{\lambda}(0) = X$. Then $\widetilde{\lambda} = \phi \circ \lambda$ where $\widetilde{\lambda} : I \to N$ gives a curve in N with $\widetilde{\lambda}(0) = \phi(p)$. We set $\phi_* X = \dot{\widetilde{\lambda}}(0)$.

Note. If $f : N \to \mathbb{R}$, then

$$\phi_* X(f) = \frac{\mathrm{d}}{\mathrm{d}t}\left(f \circ \widetilde{\lambda}(t)\right)\Big|_{t=0} \tag{284}$$

$$= \frac{\mathrm{d}}{\mathrm{d}t}\left(f \circ \phi \circ \lambda(t)\right)\Big|_{t=0} \tag{285}$$

$$= \frac{\mathrm{d}}{\mathrm{d}t}\left(\phi^* f \circ \lambda(t)\right)\Big|_{t=0} \tag{286}$$

$$= X(\phi^* f). \tag{287}$$

Exercise 12: If x^μ are coordinate on M near p, and y^α are coordinates on N near $\phi(p)$. Then ϕ gives a map $y^\alpha(x^\mu)$. Show that in a coordinate basis

$$(\phi_* X)^\alpha = \left(\frac{\partial y^\alpha}{\partial x^\mu}\right)_p x^\mu, \tag{288}$$

or

$$\phi_*\left(\frac{\partial}{\partial x^\mu}\right)_p = \left(\frac{\partial y^\alpha}{\partial x^\mu}\right)_p \left(\frac{\partial}{\partial y^\alpha}\right)_{\phi(p)}. \tag{289}$$

Proof.

□

On the cotangent bundle, we go backwards.

Definition 12.4: If $\eta \in T^*_{\phi(p)} N$, then the pullback of η, $\phi^*\eta \in T^*_p M$ is defined by

$$\phi^*\eta(X) = \eta(\phi_* X), \tag{290}$$

$\forall X \in T_p M$.

Note. If $f : N \to \mathbb{R}$, then $\phi^* (df) [X] = df [\phi_* X] = \phi_* X (f) = X (\phi^* f) = d (\phi^* f) [X]$.

As X is arbitrary, we have

$$\phi^* df = d (\phi^* f) , \tag{291}$$

namely pullbacks commute with differentials.

Exercise 13: With notation as before,

$$(\phi^* \eta)_\mu = \left(\frac{\partial y d\alpha}{\partial x^\mu} \right) \eta_\alpha \qquad \phi^* (dy^\alpha)_p = \left(\frac{\partial y^\alpha}{\partial x^\mu} \right)_p (dx^\mu)_p . \tag{292}$$

Proof.

□

We can extend the pull-back to map a $(0, s)$ tensor T at $\phi (p) \in N$ to a $(0, s)$ tensor $\phi^* T$ at $p \in M$ by requiring that

$$\phi^* T (X_1, \cdots , X_s) = T (\phi_* X_1, \cdots , \phi_* X_s) , \tag{293}$$

$\forall X_i \in T_p M$. Similarly, we can push forward a $(s, 0)$ tensor S at $p \in M$ to a $(s, 0)$ tensor ϕ_* at $\phi (p) \in N$ by

$$\phi * S (\eta_1, \cdots , \eta_s) = S (\phi^* \eta_1, \cdots \phi^* \eta_s) , \tag{294}$$

$\forall \eta_1, \cdots , \eta_s \in T^*_{\phi(p)} N$.

If $\phi : M \to N$ has the property that $\phi_* : T_p M \to T_{\phi(p)} N$ is injective (one-to-one), we say ϕ is an immersion (this requires $\dim N \geq \dim M$).

If N is a manifold with metric g, and $\phi : M \to N$ is an immersion, we can consider $\phi^* g$. If g is Riemannian, then $\phi^* g$ is non-degenerate and positive definite so defines a metric on M, the **induced metric**.

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Exercise 14: Let $(N, g) = \left(\mathbb{R}^3, \delta\right)$, $M = S^2$. Let ϕ be the map taking a point on S^2 with spherical coordinates (θ, ϕ) to

$$\left(x^1, x^2, x^3\right) = (\cos\theta \cos\phi, \sin\theta \sin\phi, \cos\theta) , \tag{295}$$

where

$$\phi^* \left(\left(\mathrm{d}x^1\right)^2 + \left(\mathrm{d}x^2\right)^2 + \left(\mathrm{d}x^3\right)^2 \right) = \mathrm{d}\theta^2 + \sin^2\theta \, \mathrm{d}\phi^2 . \tag{296}$$

Proof.

□

If ϕ is an immersion and (N, g) is *Lorentzian*, then $\phi^* g$ is *not* in general a metric on M. There are 3 important cases

- If $\phi^* g$ is a Riemannian metric, we say $\phi(M)$ is *spacelike*.
- If $\phi^* g$ is a Lorentzian metric, we say $\phi(M)$ is *timelike*.
- If $\phi^* g$ is everywhere degenerate, we say $\phi(M)$ is *null*.

Recall that $\phi : M \to N$ is a diffeomorphism if it is bijective with a smooth inverse. If we have a diffeomorphism, we can push forward a general (r, s) tensor at p to an (r, s) tensor at $\phi(p)$ by

$$\phi_* T\left(\eta^1, \cdots, \eta^r, X_1 \cdots, X_s\right) = T\left(\phi^* \eta^1, \cdots, \phi^* \eta^r, \phi_*^{-1} X_1, \cdots, \phi_*^{-1} X_s\right), \tag{297}$$

$\forall \eta_i \in T^*_{\phi(p)} N$ and $X_i \in T_{|phi(p)} N$. Namely, we define a pullback by $\phi_*^{-1} = \phi^*$.

If M, N are diffeomorphic, we often don't distinguish between them. We can think of $\phi : M \to M$ as a symmetry of T if $\phi_* T = T$. If T is the metric, we say ϕ is an **isometry**.

Example. In Minkowski space, with an inertial frame,

$$\phi\left(x^0, x^1, \cdots, x^n\right) = \left(x^0 + 1, x^1, \cdots, x^n\right), \tag{298}$$

is a symmetry of g.

An important class of diffeomorphisms are those generated by a vector field. If X is a smooth vector field, we associate to each point $p \in M$ the point $\phi_t^X(p) \in M$ given by flowing a parameter distance t along the integral curve of X starting at p.

Suppose $\phi_t^X(p)$ is well defined for all $t \in I \subset \mathbb{R}$ for each $p \in M$. Then $\phi_t^X : M \to M$ is a diffeomorphism for all $t \in I$.

Further, we have some nice properties.

- If $t, s, t + s \in I$, Then $\phi_t^X \circ \phi_s^X = \phi_{t+s}^X$ and $\phi_0^X = \mathrm{id}$. If $I = \mathbb{R}$, this gives $\{\phi_t^X\}_{t \in \mathbb{R}}$ the structure of a one parameter abelian group.
- If ϕ_t is any smooth family of diffeomorphisms satisfying these group conditions, we can define a vector field by $X_p = \frac{\mathrm{d}}{\mathrm{d}t}\left(\phi_t(p)\right)\Big|_{t=0}$. Then $\phi_t = \phi_t^X$.

13.1 The Lie Derivative

We can use ϕ_t^X to compare tensors at different points. As $t \to 0$, this gives a new notion of a derivative, the **Lie derivative**.

Suppose $\phi_t^X : M \to M$ is the smooth one parameter family of diffeomorphisms generated by the vector field X.

Definition 13.1: For a tensor field T, the **Lie derivative** of T with respect to X is

$$\left(\mathcal{L}_X T\right)_p = \lim_{t \to 0} \frac{\left(\left(\phi_t^X\right)^* T\right)_p - T_p}{t}. \tag{299}$$

By construction, one can see that for constants α, β and (r,s) tensors S, T,

$$\mathcal{L}_X(\alpha S + \beta T) = \alpha \mathcal{L}_X S + \beta \mathcal{L}_X T. \tag{300}$$

To see how $\mathcal{L}_X$ acts in components, it is helpful to construct coordinates adapted to X. Near p we can construct an $(n-1)$-surface Σ which is transverse to X, i.e. nowhere tangent. Pick coordinates x^i on Σ and assign the coordinate $\left(t, x^i\right)$ to the point a parameter distance t along the integral curve of X starting at x^i on Σ.

In these coordinates. We can check that $X = \frac{\partial}{\partial t}$ and $\phi_t^X\left(\tau, x^i\right) = \left(\tau + t, x^i\right)$. So if $y^\mu = \left(\phi_t^X\right)^*(x^\mu)$, then

$$\frac{\partial y^\mu}{\partial x^\nu} = \delta^\mu_\nu. \tag{301}$$

Likewise,

$$\left[\left(\phi_t^X\right)^* T\right]^{\mu_1 \cdots \mu_r}{}_{\nu_1 \cdots \nu_s}\Bigg|_{(t,x^i)} = T^{\mu_1 \cdots \mu_r}{}_{\nu_1 \cdots \nu_s}\Bigg|_{(\tau+t,x^i)}. \tag{302}$$

Thus, in this system of coordinates, the Lie derivative has components

$$\left(\mathcal{L}_X\right)^{\mu_1 \cdots \mu_r}{}_{\nu_1 \cdots \nu_s}\Bigg|_p = \frac{\partial T^{\mu_1 \cdots \mu_r}{}_{\nu_1 \cdots \nu_s}}{\partial t}\Bigg|_p. \tag{303}$$

So in these coordinates, $\mathcal{L}_X$ acts on components by $\frac{\partial}{\partial t}$. In particular, we immediately see

$$\mathcal{L}_X(S \otimes T) = (\mathcal{L}_X S) \otimes T + S \otimes \mathcal{L}_X T. \tag{304}$$

Observe that $\mathcal{L}_X$ also commutes with contraction.

To write $\mathcal{L}_X$ in a coordinate free fashion, we can simply seek a basis independent expression that agrees with $\mathcal{L}_X$ in these coordinates.

Example. For a function, $\mathcal{L}_X f = \frac{\partial f}{\partial t} = X(f)$ in these coordinates.

For a vector field Y we observe that as in these coordinates $X^\sigma = (1, 0, \cdots, 0)$,

$$\frac{\mathrm{d}Y^\mu}{\mathrm{d}t} = X^\sigma \frac{\mathrm{d}}{\mathrm{d}x^\sigma}(Y^\mu) \tag{305}$$

$$\frac{\mathrm{d}Y^\mu}{\mathrm{d}t} = X^\sigma \frac{\mathrm{d}}{\mathrm{d}x^\sigma}(Y^\mu) - \underbrace{Y^\sigma \frac{\partial}{\partial x^\sigma} X^\mu}_{0} \tag{306}$$

$$\mathcal{L}_X Y = [X, Y]^\mu. \tag{307}$$

Exercise 15: In any coordinate basis, show that if ω_a is a covector field,

$$\left(\mathcal{L}_X \omega\right)_\mu = X^\sigma \partial_\sigma \omega_\mu + \omega_\sigma \partial_\mu X^\sigma. \tag{308}$$

If ∇ is torsion free,

$$\left(\mathcal{L}_X \omega\right)_a = X^b \nabla_b \omega_a + \omega_b \nabla_a X^b. \tag{309}$$

If g_{ab} is a metric tensor and ∇ the Levi Civita connection, then,

$$\left(\mathcal{L}_X g\right)_{ab} = \nabla_a X_b + \nabla_b X_a. \tag{310}$$

See example sheet 2.9.

If ϕ_t is a one-parameter family of isometries for a manifold with metric g. Then $\mathcal{L}_X g = 0$.

Conversely, if $\mathcal{L}_X g = 0$, then X generates a one parameter family of isometries.

Definition 13.2: A vector field K satisfying $\mathcal{L}_K g = 0$ is called a **Killing vector field**. It satisfies *Killing's equation*,

$$\nabla_a K_b + \nabla_b K_a = 0, \tag{311}$$

where ∇ is the Levi-Civita connection.

Lemma 13.1: Suppose that K is Killing and $\lambda : I \to M$ is a geodesic of the Levi Civita connection. Then $g_{ab}\dot{\lambda}^a K^b$ constant along λ.

Proof. With

$$\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}\left(K_b \dot{\lambda}^b\right) &= \dot{\lambda}^a \nabla_a \left(K_b \dot{\lambda}^b\right) && (312)\\
&= \left(\nabla_a K_b\right) \dot{\lambda}^a \dot{\lambda}^b + K_b \dot{\lambda}^a \nabla_a \dot{\lambda}^b && (313)\\
&= \left(\nabla_{(a} K_{b)}\right) \dot{\lambda}^a \dot{\lambda}^b + K_b \left(\nabla_{X_\lambda} X_\lambda\right)^b && (314)\\
&= 0 + 0, && (315)
\end{aligned}$$

as K is Killing and λ is a geodesic respectively. □

Enumerating all possible solutions to Killing's equations, in $3+1$ Minkowski space we find 4 translations, 3 boosts and 3 rotations.

14 Lecture: Physics in Curved Spacetime

11/11/2024

Part I

Physics in Curved Spacetime

We review physical theories in Minkowski space, $\mathbb{R}^{1+3}$, equipped with $\eta = \operatorname{diag}(-1, 1, 1, 1)$. We set $c = 1$ as before.

We begin with the Klein-Gordon equation, written

$$\partial_\mu \partial^\mu \Phi - m^2 \Phi = 0. \tag{316}$$

Note that in inertial coordinates, we could replace $\partial_\mu \to \nabla_\mu$. As we are in an inertial frame, we do not have any Christoffel symbols. The Klein-Gordon equation can then be phrased in a covariant manner with

$$\nabla_a \nabla^a \Phi - m^2 \Phi = 0. \tag{317}$$

Associated to the non-covariant Klein Gordon equation is the energy momentum tensor,

$$T_{\mu\nu} = \partial_\mu \Phi \partial_\nu \Phi - \frac{1}{2} \eta_{\mu\nu} \left(\partial_\sigma\right) \partial^\sigma \Phi + m^2 \Phi^2, \tag{318}$$

or covariantly,

$$T_{ab} = \nabla_a \Phi \nabla_b \Phi - \frac{1}{2} \eta_{ab} \left(\nabla_c \Phi \nabla^c \Phi + m^2 \Phi^2\right). \tag{319}$$

This is a symmetric tensor such that $T_{ab} = T_{ba}$. It also is conserved such that $\nabla_a T^a{}_b = 0$.

The Maxwell field is an antisymmetric $(0, 2)$ tensor $F_{\mu\nu} = -F_{\nu\mu}$, where $F_{0i} = E_i$ and $F_{ij} = \varepsilon_{ijk} B_k$.

If j_μ is the charge current density, then Maxwell's equations can be written

$$\partial_\mu F^\mu{}_\nu = 4\pi j_\nu \qquad \partial_{[\mu} F_{\nu\delta]} = 0, \tag{320}$$

or covariantly,

$$\nabla_a F^a{}_c = 4\pi j_c \qquad \nabla_{[a} F_{bc]} = 0. \tag{321}$$

Associated to these equations, we identically have an energy momentum tensor,

$$T_{\mu\nu} = F_\mu{}^\delta F_{\nu\delta} - \frac{1}{4} \eta_{\mu\nu} F_{\delta\tau} F^{\delta\tau}. \tag{322}$$

Promoting this to a coordinate free expression we have

$$T_{ab} = F_a{}^c F_{bc} - \frac{1}{4} \eta_{ab} F_{cd} F^{cd}. \tag{323}$$

One can check $T_{ab} = T_{ba}$ and $\nabla_a T^a{}_b = 0$.

The last matter model we will consider is that of a perfect fluid. A perfect fluid is described by a local velocity field U^μ satisfying $U^\mu U_\mu = -1$ (as it has mass, it needs to travel along a timelike trajectory). It also has a pressure P and a density ρ. These variables satisfy the first law of thermodynamics,

$$U^\mu \partial_\mu \rho + (\rho + P) \partial_\mu U^\mu = 0, \tag{324}$$

a relativistic analogue of the continuity equation. This becomes the covariant equation,

$$U^a \nabla_a \rho + (\rho + P) \nabla_a U^a = 0. \tag{325}$$

We also have Euler's equations in a relativistic setting which are

$$(\rho + P)\, U^\nu \partial_\nu U^\mu + \partial^\mu P + U^\mu U^\nu \partial_\nu P = 0, \tag{326}$$

which becomes

$$(P + \rho)\, U^b \nabla_b U^a + \nabla^a P + U^a U^b \nabla_b P = 0. \tag{327}$$

Associated to this theory is the energy momentum tensor

$$T_{\mu\nu} = (\rho + P)\, U_\mu U_\nu + P\eta_{\mu\nu} \qquad\qquad T_{ab} = (\rho + P)\, U_a U_b + P\eta_{ab}. \tag{328}$$

We still have $T_{ab} = T_{ba}$ and if the equations of motion hold (i.e. on shell), $\nabla_a T^a{}_b = 0$.

Notice that in all cases, we can promote the Minkowski η to a general Lorentzian metric g and take ∇ to be the Levi-Civita connection for that metric. Consider normal coordinates near any point $q \in M$, such that the physics described is approximately Minkowski, with corrections of the order of curvature (second order).

14.1 General Relativity

In Einstein's theory of general relativity, we postulate that spacetime is a 4-dimensional Lorentzian manifold (M, g). We also require any matter model to consist of some matter fields Φ^A with equations of motion which can be expressed geometrically. Namely, in terms of g and its derivatives (i.e. ∇, R, etc.).

We also want an energy momentum tensor T_{ab} which depends on Φ^A and is symmetric and conserved. The matter should reduce to a non-gravitational theory when (M, g) is fixed to be Minkowski space.

Naturally, the metric g should satisfy the Einstein equations,

$$\boxed{R_{ab} - \frac{1}{2} R g_{ab} + \Lambda g_{ab} = 8\pi G T_{ab}.} \tag{329}$$

Λ is the cosmological constant. Observations suggest $\Lambda > 0$ but small. G is Newton's constant.

The Einstein equations, together with the equations of motion for Φ^A constitute a coupled system of equations which must be solved simultaneously.

Postulate 14.1 (Geodesic Postulate): Free test particles move along timelike/null geodesics if they have nonzero/zero mass.

14.2 Gauge Freedom

Consider Maxwell's theory with no sources,

$$\partial_\mu F^\mu{}_\nu = 0 \qquad\qquad \partial_{[\mu} F_{\nu\delta]} = 0. \tag{330}$$

A standard approach to solve these is to introduce a gauge potential A_μ such that

$$F_{\mu\nu} = 2\partial_{[\mu} A_{\nu]}. \tag{331}$$

Then Maxwell's equations become

$$\partial_\mu \partial^\mu A_\nu - \partial_\mu \partial_\nu A^\mu = 0. \tag{332}$$

Observe that $A_\nu = \partial_\nu \alpha$ solves this equation for any function α, and thus there is an infinite dimensional redundancy here.

We'd like to solve this equation given data at $t = 0$. However this equation does not give us a good evolution problem to solve because of this redundancy/gauge freedom.

If $\chi \in C^\infty\left(\mathbb{R}^{1+3}\right)$ which vanishes near $t = 0$, then $\widetilde{A}_\mu = A_\mu + \partial_\mu \chi$ then this identically solves the above equation and produces the same curvature as $\partial_{[\mu} A_{\nu]} = \partial_{[\mu} \widetilde{A}_{\nu]}$.

To resolve this, we fix a gauge. There are a number of ways to do this. We proceed in Lorentz gauge by imposing

$$\partial_\mu A^\mu = 0. \tag{333}$$

Then the above equation becomes

$$\partial_\mu \partial^\mu A_\nu = 0, \tag{334}$$

which is a wave equation for each component of A_ν.

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There are no nontrivial χ such that $\widetilde{A}_\nu$ also satisfies $\partial_\mu \widetilde{A} = 0$ and satisfies the same initial conditions.

If we solve the wave equation, we see that it is sufficient to set

$$\partial_\mu A^\mu \Big|_{t=0} = 0 \qquad \qquad \partial_0 \left(\partial_\mu A^\mu\right)\Big|_{t=0} = 0. \tag{335}$$

Then we find that $\partial_\mu A^\mu = 0$ and thus our solution solves the wave and hence Maxwell's equation.

15.1 Gauge Freedom in General Relativity

If (M, g) solves Einstein's equation with energy momentum tensor T and $\phi : M \to M$ a diffeomorphism, then $\phi^* g$ also solves the Einstein equations with energy momentum tensor $\phi^* T$. At a local level, this is the coordinate independence that we have built into general relativity.

This gives us an infinite dimensional set of solutions identical to the gauge freedom we saw for Maxwell. There are several approaches to fixing the coordinates.

We consider the harmonic gauge.

Lemma 15.1: In any local coordinate system

$$R_{\rho\delta\mu\nu} = \frac{1}{2}\left(g_{\rho\nu,\mu\delta} + g_{\delta\mu,\nu\rho} - g_{\rho\mu,\nu\delta} - g_{\delta\nu,\mu\rho}\right) - \Gamma_{\mu\lambda\rho}\Gamma_{\nu}{}^{\lambda}{}_{\delta} + \Gamma_{\nu\lambda\rho}\Gamma_{\mu}{}^{\lambda}{}_{\delta}, \tag{336}$$

and

$$\begin{aligned} R_{\delta\nu} = &-\frac{1}{2}\overbrace{g^{\mu\rho}g_{\delta\nu,\mu\rho}}^{g^{\mu\rho}\partial_\mu\partial_\rho g_{\delta\nu}} + \overbrace{\frac{1}{2}\partial_\delta\Gamma_{\mu\nu}{}^{\mu} + \frac{1}{2}\partial_\nu\Gamma_{\mu\sigma}{}^{\mu} - \Gamma_{\mu\lambda}{}^{\mu}\Gamma_{\nu}{}^{\lambda}{}_{\delta}}^{0} \\ &+ \Gamma_{\lambda\tau\nu}\Gamma^{\lambda\tau}{}_{\delta} + \Gamma_{\lambda\tau\nu}\Gamma^{\tau}{}_{\sigma}{}^{\lambda} + \Gamma_{\lambda\tau\sigma}\Gamma^{\tau}{}_{\nu}{}^{\lambda}. \end{aligned} \tag{337}$$

Proof.

□

Where notice that if $g = \eta$, then $g^{\mu\rho}\partial_\mu\partial_\rho g_{\delta\nu}$ is the wave operator. As we are now in a globally hyperbolic setting (i.e. Lorentzian), this is a curved wave operator. This is a quasi-linear second order ODE.

This form of Ricci is well-adapted to wave/harmonic coordinates. Suppose we choose a system of coordinates $\{x^\nu\}$ which satisfy the wave equation, $\nabla_\mu\nabla^\mu x^\nu = 0$ where ν here is a label not a vector component. We then see that

$$0 = \nabla^\mu\partial_\mu x^\nu \tag{338}$$

$$= \partial^\mu\partial_\mu x^\nu + \Gamma^{\mu\delta}{}_{\mu}\partial_\delta x^\nu \tag{339}$$

$$0 = \Gamma^{\mu\nu}{}_{\mu}. \tag{340}$$

Writing the Christoffel symbol in terms of the metric, we see this implies

$$\frac{1}{2}g^{\mu\delta}\left(g_{\mu\kappa,\sigma} - \frac{1}{2}g_{\mu\sigma,\kappa}\right) = 0. \tag{341}$$

For such coordinates, $R_{\delta\nu} =$

$$R_{\delta\nu} = -\frac{1}{2}g^{\mu\rho}g_{\delta\nu,\mu\rho} + \Gamma_{\lambda\tau\nu}\Gamma^{\lambda\tau}{}_{\delta} + \Gamma_{\lambda\tau\nu}\Gamma^{\tau}{}_{\sigma}{}^{\lambda} + \Gamma_{\lambda\tau\sigma}\Gamma^{\tau}{}_{\nu}{}^{\lambda}. \tag{342}$$

These Christoffel symbol terms are quadratic in the metric g and its derivative ∂g. Therefore $R_{\sigma\nu} = 0$ reduces to a system of nonlinear wave equations in this gauge. We *can* solve this (locally in time) given initial data.

Further, we can show that if the gauge condition is initially satisfied, it will remain true for all (t, x) where the solution is defined. This was proved by Choquet-Bruhart in 1954.

15.2 Linearised theory

Suppose we are in a situation where the gravitational field is weak. We expect to be able to describe the metric as a perturbation of Minkowski such that

$$g_{\mu\nu} = \eta_{\mu\nu} + \varepsilon h_{\mu\nu}, \tag{343}$$

where $\eta_{\mu\nu} = \operatorname{diag}(-1,1,1,1)$ and $\varepsilon \ll 1$ is a small parameter such that we neglect terms of $\mathcal{O}\left(\varepsilon^2\right)$.

If the metric has this form we say we're in "almost inertial" coordinates. One can check $g^{\mu\nu} = \eta^{\mu\nu} - \varepsilon h^{\mu\nu}$ where $h^{\mu\nu} = \eta^{\mu\delta} h_{\delta\tau}\eta^{\tau\nu}$. Namely, for $\mathcal{O}(\varepsilon)$, quantities, one can raise/lower with η.

Suppose that our metric is also in wave gauge, we then have Eq. (341) and then

$$0 = g^{\mu\delta}\left(g_{\mu\kappa,\delta} - \frac{1}{2}g_{\mu\delta,\kappa}\right) = \varepsilon\partial^{\mu}\left(h_{\mu\kappa} - \frac{1}{2}\eta_{\mu\kappa}h\right), \tag{344}$$

where $h = \eta^{\mu\nu}h_{\mu\nu}$. Then using our expression for the Ricci tensor,

$$R_{\mu\nu} = -\frac{\varepsilon}{2}\eta^{\delta\tau}\partial_\delta\partial_\tau h_{\mu\nu}. \tag{345}$$

In order for the Einstein equation to hold, we must have the stress energy tensor $\mathbb{T}_{\mu\nu} = \varepsilon T_{\mu\nu}$.

Then to order ε in the Einstein equation, we have

$$-\frac{1}{2}\Box h_{\mu\nu} + \frac{1}{4}\eta_{\mu\nu}\eta^{\delta\tau}\partial_\delta\partial_\tau h = 8\pi G T_{\mu\nu} \tag{346}$$

$$\boxed{\Box\overline{h}_{\mu\nu} = -16\pi G T_{\mu\nu},} \qquad \boxed{\partial_\mu \overline{h}^{\mu}{}_{\nu} = 0,} \tag{347}$$

where $\overline{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}h\eta_{\mu\nu}$ is the *trace reversed metric perturbation.*

These are the linearised Einstein equation in wave (also harmonic, Lorentz, de Donder) gauge. We can solve these given initial data at $t = 0$.

If the data satisfies the gauge condition, $\left.\partial_\mu \overline{h}^{\mu}{}_{\nu}\right|_{t=0} = \left.\partial_0\left(\partial_\mu \overline{h}^{\mu}{}_{\nu}\right)\right|_{t=0} = 0$, then we can check that this gauge condition is propagated.

Since $\partial_\mu T^{\mu}{}_{\nu} = 0$, we have $\Box\left(\partial_\mu \overline{h}^{\mu}{}_{\nu}\right) = 0$, so the gauge condition holds for all times.

15.3 Linearised gauges

Suppose we have a physically equivalent solution that is not necessarily in wave gauge. We've seen that 2 such equivalent solutions are related by a diffeomorphism. In order that the diffeomorphism reduces smoothly to the identity as $\varepsilon \to 0$, it should take the form ϕ^{ξ}_{ε} for some vector field ξ. If S is any tensor field, then from the definition of the Lie derivative,

$$\left(\Phi^{\xi}_{\varepsilon}\right) S = S + \varepsilon\mathcal{L}_\xi S + \mathcal{O}\left(\varepsilon^2\right). \tag{348}$$

In particular,

$$\left(\left(\Phi^{\xi}_{\varepsilon}\right)^{*}\eta\right)_{\mu\nu} = \eta_{\mu\nu} + \varepsilon\underbrace{\left(\partial_\mu\xi_\nu + \partial_\nu\xi_\mu\right)}_{h_{\mu\nu}} + \mathcal{O}\left(\varepsilon^2\right). \tag{349}$$

Solutions that take this form are called a *linear gauge transformation.*

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Notice that if $S = \mathcal{O}(\varepsilon)$, it will be invariant under gauge transformations to order ε. Tensors which vanish on Minkowski (i.e. are order ε) are gauge invariant in linear perturbation theory.

In particular $T_{\mu\nu}$ is gauge invariant and $g_{\mu\nu}$ is not.

However,

$$\left[\left(\phi^{\xi}_{\varepsilon}\right)^{*}\eta\right]_{\mu\nu} = \eta_{\mu\nu} + \varepsilon\left(\partial_{|}mu\xi_{\nu} + \partial_{\nu}\xi_{\mu}\right) + \mathcal{O}\left(\varepsilon^{2}\right). \tag{350}$$

Thus, $h_{\mu\nu} \to h_{\mu\nu} + \partial_{\mu}\xi_{\nu} + \partial_{\nu}\xi_{\mu}$ represents a linear gauge transformation (analogously to $A_{\mu} \to A_{\mu} + \partial_{\mu}\xi$).

From the formulae in the last lecture, if we linearize $R_{\mu\nu}$ without fixing a gauge, we find

$$R_{\mu\nu} = \varepsilon\left(\partial^{\rho}\partial_{(\mu}h_{\nu)\rho}\right) - \frac{1}{2}\partial^{\rho}\partial_{\rho}h_{\mu\nu} - \frac{1}{2}\partial_{|}mu\partial_{\nu}h. \tag{351}$$

Substituting in $h_{\mu\nu} = \partial_{\mu}\xi_{\nu} + \partial_{\nu}\xi_{\mu}$, we can check that $R_{\mu\nu}$ vanishes, and so $h_{\mu\nu}$ solves the vacuum Einstein equations. We call such a solution a pure gauge solution.

Exercise 16: Show that if $h'_{\mu\nu} = h_{\mu\nu} + \partial_{\mu}\xi_{\nu} + \partial_{\nu}\xi_{\mu}$ then

$$\partial_{\mu}\overline{h}'^{\mu}{}_{\nu} = \partial_{\mu}\overline{h}^{\mu}{}_{\nu} + \partial_{\mu}\partial^{\mu}\xi_{\nu}. \tag{352}$$

Deduce that

a) any linearised perturbation can be put into wave gauge by gauge transformation,

b) any pure gauge solution of the wave gauge fixed equations, which vanishes $\xi_{\mu}\Big|_{t=0} = 0$ and $\partial_{0}\xi_{\mu}\Big|_{t=0} = 0$, vanishes everywhere.

Proof.

□

16.1 The Newtonian Limit

We'd expect if GR is a good theory of gravity, we should be able to receiver Newton's theory of gravitation in the limits where the fields are weak and matter is slowly moving in comparison with the speed of light, $c = 1$.

Let us suppose that matter is modelled as a perfect fluid with velocity field U^{a}, density ρ and pressure P.

In all but the most extreme situations, $\rho \gg P$, namely such that $\frac{P}{\rho} \approx v_{\text{sound}}^{2} \ll c^{2}$. We choose coordinates such that $U^{a} = \frac{\partial}{\partial t}$. This is Lagrangian coordinates for the fluid (See Mach's principle).

Note. This does not imply that the fluid is at rest. The distances are measured with the metric, and while the coordinates are not moving, the distance between coordinates can change as the metric moves.

The condition that the fluid moves non-relativistically becomes the assumption that we are in the weak field limit such that

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \tag{353}$$

where $h_{\mu\nu} \sim \mathcal{O}(\varepsilon)$ and the ε is now implicit in $h_{\mu\nu}$.

We also want the motion of particles to be slow, which is equivalent to $\partial_0 h_{\mu\nu}\varepsilon^{\frac{1}{2}} h_{\mu\nu}$ and $\partial_0\partial_0 h_{\mu\nu} \sim \varepsilon h_{\mu\nu}$.

For consistency, we require that $\rho = \mathcal{O}(\varepsilon)$ and $p = \mathcal{O}(\varepsilon^2)$. The linearised Einstein equations then become

$$\partial^\mu \partial_\mu \overline{h}_{\sigma\tau} = -16\pi T_{\sigma\tau}, \tag{354}$$

and $T_{00} = \rho$, $T_{0i} = T_{ij} = 0$ to order ε^2. We can deduce that

$$\partial^\mu \partial_\mu \overline{h}_{00} = -16\pi\rho. \tag{355}$$

Since $h_{\mu\nu} = \overline{h}_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} hbar$, and $\overline{h} = -\overline{h}_{00}$, we have

$$h_{00} = \frac{1}{2}\overline{h}_{00}. \tag{356}$$

Therefore

$$\partial_\mu \partial^\mu \left(-\frac{1}{2}h_{00}\right) - 4\pi\rho. \tag{357}$$

Recall that in Newton's gravity, one has $\partial_\mu \partial^\mu \phi = 4\pi G\rho$. This suggests we identify $-\frac{1}{2}h_{00}$ with the Newtonian potential ϕ.

By the geodesic postulate, its motion is determined by the Lagrangian

$$\begin{aligned} \mathcal{L} &= g_{\mu\nu}\dot{x}^\mu \dot{x}^\nu && (358)\\ &= \eta_{\mu\nu}\dot{x}^\mu \dot{x}^\nu + h_{\mu\nu}\dot{x}^\mu \dot{x}^\nu && (359)\\ &= -\dot{t}^2 + |\dot{x}|^2 + h_{00}\dot{t}^2 + \mathcal{O}(\varepsilon^2). && (360) \end{aligned}$$

Suppose motion is non-relativistic, so $|\dot{x}|^2 = \mathcal{O}(\varepsilon)$. Conservation of $\mathcal{L}$ gives

$$-\dot{t}^2 = -1 + \mathcal{O}(\varepsilon) \Rightarrow \dot{t} = 1 + \mathcal{O}(\varepsilon). \tag{361}$$

Then the Euler Lagrange equation for x is given by

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\left(\frac{\partial \mathcal{L}}{\partial \dot{x}^i}\right) = \frac{\partial \mathcal{L}}{\partial x^i} \tag{362}$$

$$2\frac{\mathrm{d}}{\mathrm{d}\tau}(\dot{x}_i) = 2\ddot{x}_i = h_{00,i}\dot{t}^2. \tag{363}$$

Since $\dot{t} = 1 + \mathcal{O}(\varepsilon)$, $\frac{\mathrm{d}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}\tau} + \mathcal{O}(\varepsilon)$, we have

$$\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} = \frac{1}{2} h_{00,i} + \mathcal{O}\left(\varepsilon^2\right) \tag{364}$$

$$= -\partial_i \phi + \mathcal{O}\left(\varepsilon^2\right). \tag{365}$$

Thus, we have recovered Newton's laws of gravitation.

16.2 Gravitational waves

One of the most spectacular recent results in gravitational physics was the measurement in 2015 of gravitational waves sourced by two colliding black holes. Near the source the field is not weak, but by the time we detect the waves, the weak field approximation is relevant.