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Campos de Killing

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Abstract

The purpose of this thesis is to make a rigorous and approachable introduction to Killing fields and their applications to any undergrad that is or has studied a general relativity course.

Índice

1. Motivation and introduction to symmetry in physics	1
2. Formalism of general relativity	2
2.1. Spacetimes	2
2.2. Continuity	2
2.3. Coordinates	2
2.4. Fields on the spacetime	3
Scalar fields on spacetimes	3
Parametric curves	3
Vector fields on the spacetime	3
Covectors	4
Tensors	5
2.5. Metrics	5

1

Motivation and introduction to symmetry in physics

The cornerstone of modern physics is, without a shadow of a doubt, symmetry. This is thanks to one of the most beautiful theorems of physics. **The Noether theorem.**

The Noether theorem establishes a one to one connection between symmetries and conservation laws, thus explaining the origin of conservation of energy, charge and all other conservation laws widely used in physics.

The first question that might arise is, What constitutes a symmetry? What is it? A symmetry is a transformation, such as translations, rotations or even of the internal degrees of freedom a theory might have, that maintains some aspect of the theory invariant.

In the case of classical mechanics the main object that encapsulates the behavior of the system allowing for the computation of the equations of motion. Therefore a symmetry in classical mechanics is any transformation to the lagrangian that doesn't change the equations of motion.

In our case we will find that the corresponding symmetries in general relativity are those that preserve the geometry of spacetime, meaning, the metric. The so called isometries. Killing fields are nothing more than the generators of isometries.

2

Formalism of general relativity

In order to understand symetry and motivate the definition of Killing fields first it is required to understand is, in the mathematical sense, spacetime and define flows and Lie derivatives.

To do this we will introduce little by little mathematical structure based on the cualities that a spacetime should have

2.1. Spacetimes

A spacetime in the formalism of general relativity is defined as a pseudo-Riemannian manifold. We will start by understanding this ideas.

2.2. Continuity

First of all, a spacetime has a notion that it is continuous, further than that, it is path connected, meaning one can connect any point to any other point by a continuous path¹.

The notion of continuity is defined in the mathematical field of topology A topological space is a pair of sets (M, τ) , the first of these is the set of all the points in the space, the second is called the topology of the space and represents all of the open sets. The core idea behind having a topology is introducing a notion of “closeness” without introducing a metric, in our case there will be an additional notion of closeness defined because of the metric but this idea has to be introduced later. Any topology obeys the following relations of closure

$$\begin{aligned} \emptyset, M &\in \tau \\ x_i \in \tau &\Rightarrow \bigcup_{i=0}^{\infty} x_i \in \tau \\ x_i \in \tau &\Rightarrow \bigcap_{i=0}^n x_i \in \tau \end{aligned} \tag{2.1}$$

This allows to define what a continuous function is, the idea of continuity is that any two “close” points in the input of the function will be “close” in the output. On topological spaces the definition is related to how open sets transform, here a function between topological spaces $f : (M, \tau_M) \rightarrow (N, \tau_N)$ is continous if $\forall V \in \tau_N, f^{-1}(V) \in \tau_M$ meaning all open sets in the output are open sets in the input. This definition is inspired by the $\varepsilon - \delta$ definition usually defined for metric spaces², in fact if one uses the topology defined by the open balls (sets of points closer than some distance) the definitions are equivalent.

2.3. Coordinates

Whenever one talks about any kind of state in physics it is talked about in a coordinate system. It would be expected that in spacetimes one can do the same thing and label the points in spacetime. This is covered in the mathematical field of manifolds. A manifold is a topological space that additionally can

¹This path is not required to be physical, it could be superluminic.

²Spaces with the notion of distance

be locally mapped to a cartesian coordinate system, meaning for any open set V there is a continuous bijection φ from V to \mathbb{R}^n such that φ^{-1} is continuous too.

Additionally it is required that for any two mappings $\varphi_1 : V_1 \rightarrow \mathbb{R}^n$ and $\varphi_2 : V_2 \rightarrow \mathbb{R}^n$ such that $V_1 \cap V_2 \neq \emptyset$ there has to be a function from $\psi : \varphi_1(V_1 \cap V_2) \rightarrow \varphi_2(V_1 \cap V_2)$ that is a bijection, continuous and has a continuous inverse. This means that one can “translate” one coordinate system to another if they map the same region.

In the case of physics it is additionally required that ψ is infinitely differentiable, this is the definition for smooth manifolds. This is necessary because otherwise a smooth function would be smooth on one coordinate system but it would not be smooth on a different coordinate system because of the chain rule.

The set of all coordinate systems with a smooth coordinate change is called an atlas or \mathcal{A} .

Another representation for a coordinate system is a collection of n functions $x^\mu : \mathbb{E} \rightarrow \mathbb{R}$ such that x^0 gives the 0-th component of a coordinate system φ , x^1 the first component and so on. This representation is more common in physics and will be widely used in this thesis.

2.4. Fields on the spacetime

Now it is time to start talking about what can we “place” on spacetime.

Scalar fields on spacetimes

A scalar field assigns a number to each point of our spacetime \mathbb{E} . So it will be any function of the form

$$\phi : \mathbb{E} \rightarrow \mathbb{R} \quad (2.2)$$

This function can be “placed” in a coordinate system by defining $\phi_\varphi : \mathbb{R}^n \rightarrow \mathbb{R}$ by taking a coordinate system from the atlas $\varphi \in \mathcal{A}$ and applying the inverse to the input $\phi_\varphi = \phi \circ \varphi$. From now on ϕ_φ will be denoted just ϕ whenever the coordinate system is clear.

The set of all infinitely differentiable scalar fields on a manifold will be denoted $\mathcal{C}^\infty(M)$

Parametric curves

If one wishes to keep track of the path of a particle on a spacetime one would naturally use this kind of object. A parametric curve may be defined as a function

$$\gamma : \mathbb{R} \rightarrow \mathbb{E} \quad (2.3)$$

Again this path can be represented in a coordinate system by composing it with a map $\varphi \in \mathcal{A}$, $\gamma_\varphi : \mathbb{R} \rightarrow \mathbb{R}^n$, $\gamma_\varphi = \varphi \circ \gamma$.

Vector fields on the spacetime

Motivated from the “classical” version of a vector field defined as $F : \mathbb{R}^n \rightarrow \mathbb{R}^n$ it might be tempting to define $X : \mathbb{E} \rightarrow \mathbb{R}^n$ as a vector field on an n dimensional smooth manifold. This definition has one big problem, it is not coordinate independent.

Imagine one has a 3-dimensional manifold with a coordinate system $\{x^\mu\}$ and a primed coordinate system $\{x'^\mu\}$ such that $x'^0 = x^1$, $x'^1 = x^0$, $x'^2 = x^2$. Now lets define a constant vector field on the “ x ” direction $X(p) = (1, 0, 0)$. In the x^μ coordinate system this field points in the x^0 direction while on the x'^μ coordinate system points in the x'^0 direction, this would correspond to the x^0 direction by the coordinate transformations defined. Therefore this definition of a vector field is not independent of coordinate choice.

There are two equivalent definitions for vectors on a manifold at a point p that are coordinate independent.

The first of these is in terms of tangent vectors of curves, since a curve on the manifold is defined independently of the coordinate system it would be expected that the tangent vector is coordinate independent too. In this way the set of all vectors at a point $p \in \mathbb{E}$ is defined as the set of curves γ such that $\gamma(0) = p$. Here we will have to add an equivalence relation, similarly to how rational numbers are not all of the fractions but the fractions with the fact that two fractions are equal when they follow the relation $\frac{a}{b} \sim \frac{c}{d} \Leftrightarrow ad = bc$ here two of our vectors will be “equal” if for any $\varphi \in \mathcal{A}$

$$\gamma \sim \hat{\gamma} \Leftrightarrow (\varphi \circ \gamma)' = (\varphi \circ \hat{\gamma})' \quad (2.4)$$

where $'$ is the usual derivative.

The second definition is via derivations. A derivation at a point p is defined as a linear functional

$$D : \mathcal{C}^\infty(M) \longrightarrow \mathbb{R} \quad (2.5)$$

that also obeys the product rule

$$\begin{aligned} f, g &\in \mathcal{C}^\infty \\ D(f \cdot g) &= f(p)D(g) + D(f)g(p) \end{aligned} \quad (2.6)$$

Any curve can be assigned a derivation via the following definition

$$D_\gamma f = (f \circ \gamma)'(0) \quad (2.7)$$

The equivalence of definitions may be proven by first proving both spaces have the same dimension. After that Ec. (2.7) gives a one to one correspondence on both spaces. When given a coordinate system the space of derivations has a basis defined by

$$\partial_\mu(p) = \frac{\partial}{\partial x^\mu}(p) \quad (2.8)$$

Note that for these to be derivations at p evaluation at p is required by Ec. (2.6).

With any of the two definitions the vector space of all vectors at a point p of a manifold M is denoted $T_p M$.

By defining the set of all vectors tangent to the manifold $TM = \bigcup_{p \in M} T_p M$ a vector field may be defined as

$$\begin{aligned} X : M &\longrightarrow TM \\ p &\longrightarrow X(p) \in T_p M \end{aligned} \quad (2.9)$$

When given a coordinate system a vector field may be written as

$$X(p) = X^\mu(p) \partial_\mu \quad (2.10)$$

So a **smooth vector field** is defined as a vector field whose component functions, X^μ , are smooth. The set of all smooth vector fields is denoted as $\mathfrak{X}(M)$

Covectors

It is easy now to define covectors. A covector at a point p is defined as a linear function

$$\omega : T_p M \longrightarrow \mathbb{R} \quad (2.11)$$

so the cotangent space T_p^*M is the space of all covectors at a point p and the set of all covectors $T^*M = \bigcup_{p \in M} T_p^*M$ a covector field is

$$\begin{aligned}\omega : M &\longrightarrow T^*M \\ p &\longrightarrow \omega(p) \in T_p^*M\end{aligned}\tag{2.12}$$

for any basis ∂_μ the canonical basis for the covector space can be defined as a covector collection such that $dx^\mu(\partial_\nu) = \delta_\nu^\mu$ where δ_ν^μ is the chroneker delta.

A covector will be smooth if for a coordinate system the covector has components ω_μ defined by

$$\omega = \omega_\mu dx^\mu\tag{2.13}$$

are $\mathcal{C}^\infty(M)$ functions

Tensors

A tensor represents a multilinear map, meaning that for any input slot

$$T(a, b, \dots, \alpha c + \beta d, \dots, z) = \alpha T(a, b, \dots, c, \dots, z) + \beta T(a, b, \dots, d, \dots, z)\tag{2.14}$$

The most basic definition of a tensor one can come up with is

$$T : V_1 \times V_2 \times \dots \times V_n \rightarrow \mathbb{R}\tag{2.15}$$

This is a tensor that takes n vectors as input and as output gives a number

It could be also output more vectors defining

$$\hat{T} : V_1 \times V_2 \times \dots \times V_n \longrightarrow V_{n+1}\tag{2.16}$$

however by evaluating the output of \hat{T} with a covector the result is a number representing some component. So it is common to represent this kind of tensors by

$$\hat{T} : V_1 \times V_2 \times \dots \times V_n \times V_{n+1}^* \longrightarrow \mathbb{R}\tag{2.17}$$

Therefore the definition of a tensor over a vector space V of kind (q, p) or q times contravariant, p times covariant is defined as

$$T : \underbrace{V^* \times \dots \times V^*}_{q \text{ copies}} \times \underbrace{V \times \dots \times V}_{p \text{ copies}} \longrightarrow \mathbb{R}\tag{2.18}$$

In our case the corresponding vector spaces are the $T_p M$ and a tensor field will be a map

$$T : \underbrace{T^*M \times \dots \times T^*M}_{q \text{ copies}} \times \underbrace{TM \times \dots \times TM}_{p \text{ copies}} \longrightarrow \mathbb{R}\tag{2.19}$$

The components of a tensor can be obtained by feeding it some vectors and applying Ec. (2.10) and Ec. (2.13)

$$T(\omega, \dots, X, \dots) = T(\omega_\mu dx^\mu, \dots, X^\nu \partial_\nu, \dots) = \omega_\mu X^\nu \dots T(dx^\mu, \dots, \partial_\nu, \dots) =: \omega_\mu X^\nu \dots T_{\nu, \dots}^{\mu, \dots}\tag{2.20}$$

So a tensor field is called smooth if the component functions $T_{\nu, \dots}^{\mu, \dots}$ are $\mathcal{C}^\infty(M)$

2.5. Metrics

The last piece for constructing a spacetime is adding a notion of magnitude to our vectors and distance. This is constructed by adding a tensor field to the spacetime Manifold which we will call the metic.

The metric defines a dot product between vectors

$$X \cdot Y = g(X, Y) = X^\mu Y^\nu g_{\mu\nu} \quad (2.21)$$

also allowing to lower the indices of vectors and tensors by contracting with the metric

$$X_\mu = g_{\mu\nu} X^\nu \quad (2.22)$$

since we would like to be able to invert the relation it is defined $g^{\mu\nu}$ such that

$$g^{\mu\alpha} g_{\alpha\nu} = \delta_\nu^\mu \quad (2.23)$$

so $X^\mu = g^{\mu\nu} X_\nu$

A Manifold equipped with a metric is called Riemannian if a metric can be diagonalized with all positive eigenvalues and pseudo-Riemannian if it can have both positive and negative.

In general relativity the equivalence principle can be stated in terms of the metric so that for any point there is a coordinate system such that

$$g_{\mu\nu} = \eta_{\mu\nu} + \mathcal{O}(x^2) \quad (2.24)$$

where η is the Minkowski metric.

This allows to define a distance³ function between two points of the manifold by denoting $\Gamma(p, q)$ the set of all curves starting at p and ending at q

$$d(p, q) = \min_{\gamma \in \Gamma(p, q)} \int_\gamma (g(\gamma'(\tau), \gamma'(\tau))) d\tau \quad (2.25)$$

where γ' is the tangent vector to γ

³This will only be a distance function whenever the manifold is Riemannian, for pseudo-Riemannian it is not since it can be negative, in general relativity the sign will be a way to encode when a path moves in the “time direction”, in the “space direction” or like light.