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Theoretical Physics

On differential geometry:

manifolds and all that

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Study notes taken during the master degree

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Manifolds

Chapter 1

Manifolds and tensors

1.1 Differentiable Manifolds

A differential manifold $\mathcal{M}$ is a topological space which looks locally like $\mathbb{R}^N$.
In a topological space, the notions of contiguity and continuity are well defined. A topological space $(\mathcal{M},\ \{A_i\})$ is a set of points $\mathcal{M}$ in which is defined a family of open sets $\{A_i\}$ such that $\{\emptyset,\ \mathcal{M},\ \cup_i A_i,\ \cap_{i<\infty} A_i\} \in \{A_i\}$. In particular, an Haussdorf space has the property that $\forall P,\ Q \in \mathcal{M} \quad \exists U \in P,\ V \in Q \quad : \quad U \cap V = \emptyset$. Two points are contiguous if they belong to the same open subset, called neighbourhood.
A map is an application $\phi\colon D \subset \mathcal{M} \to \mathbb{R}^n$. In a topological space, a map is continuous if maps open sets into open sets.
A chart is a pair $A,\ \phi$, where $A \subset \mathcal{M}$ and $\phi\colon A \to \mathbb{R}^n$ invertible continuous, which associates a set of n real coordinates $x^i = \phi$ for the open set A. An atlas is a colection of charts that covers entirely the manifold $\mathcal{A} = \{\{(A_i\ \phi_i)\}\colon \cup_i A_i \supseteq \mathcal{M}\}$.
A consistency map between two charts ϕ_1 and ϕ_2, over a point $P \in A_1 \cap A_2$, is $\phi\colon \phi(A_2) \subseteq \mathbb{R}^n \to \psi(A_2) \subseteq \mathbb{R}^n$ invertible such that $\psi(\phi_1(P)) = \phi_2(P)$ or $(\phi_2^{-1} \circ \psi \circ \phi_1) = \mathbb{I}$ or, equivalently, $\psi^{-1}(\phi_2(P)) = \phi_1(P)$ or $(\phi_1^{-1} \circ \psi \circ \phi_2) = \mathbb{I}$. ψ is a change of coordinates in $\mathbb{R}^n$. It follows that the dimension n must be the same for all charts, hence it is the dimension of the manifold. If $\psi \in C^p(\mathbb{R}^n)$, the manifold is a p-differentiable manifold.
A manifold is an equivalence class of atlases, where two atlases are equivalent if there exists a bijective correspondence between them.

1.2 Curves

A curve is a continuous map $\gamma\colon I \subseteq \mathbb{R} \to \mathcal{M}$. Introducing a chart $\phi \circ \gamma\colon I \subseteq \mathbb{R} \to \mathbb{R}^n$, or $x^i = x^i(\lambda)$, where λ is a real parameter. If $x^i(\lambda) \in C^p(\mathbb{R})$, then *gamma* is p-differentiable. A reparameterization $\gamma' = \gamma'(\gamma)$ defines a different curve, although the images of the curves coincide.

1.3 Scalars

A function is a map $f\colon \mathcal{M} \to \mathbb{R}$. Introducting a chart $f \circ \phi^{-1}\colon \mathbb{R}^n \to \mathbb{R}$, or $f = f(x^i)$. If ϕ' is another chart, then $f'(x'(P)) = f(x(P))$, showing that it is indeed a scalar.

1.4 Vectors

A vector at a point $P \in \mathcal{M}$ is a map that associates to the derivative to a function defined in a neighbourhood of P $v_\gamma\colon f \to v_\gamma(f) = \frac{df}{d\lambda}\Big|_{\lambda_P} \in \mathbb{R}$, where $\gamma(\lambda_P) = P$. Introducing a chart

$$\begin{aligned}
v_{\gamma,\ P}(f) &= \frac{d(f\circ\gamma)}{d\lambda}\Big|_{\lambda_P}\\
&= \frac{d}{d\lambda}(f \circ \mathbb{I} \circ \gamma)\Big|_{lambda_P}\\
&= \frac{d}{d\lambda}(f \circ \phi^{-1} \circ \phi \circ \gamma)\Big|_{lambda_P}\\
&= \frac{d}{d\lambda}(f(x^i) \circ x^i(\lambda))\Big|_{\lambda_P}\\
&= \frac{d}{d\lambda}f(x^i(\lambda))\Big|_{\lambda_P} = \frac{\partial f}{\partial x^i}\frac{dx^i}{d\lambda}
\end{aligned}$$

and since it is true $\forall f$

$$v_\gamma = dv\lambda = \frac{dx^i}{d\lambda}\frac{\partial}{\partial x^i} \tag{1.1}$$

which means that a vector is the tangent to a curve γ at a point P.
By definition a vector is a linear functional

$$v_\gamma(af + bg) = \frac{d}{d\lambda}(af + bg) = a\frac{df}{d\lambda} + b\frac{dg}{d\lambda}$$

From (1.1)

$$v = \underbrace{\frac{dx^i}{d\lambda}}_{v_i}\underbrace{\frac{\partial}{\partial x^i}}_{e_i} = v^i e_i$$

where v^i are the components and e_i are the coordinate basis vectors, whose vectors tangent to the coordinate line defined by constant x^j for $i \neq j$.
Under a change of coordinates

$$y^i = y^i(x^j)$$

components transform by

$$v^i = \frac{dx^i}{d\lambda} = \frac{\partial x^i}{\partial y^{j'}}\frac{dy^{j'}}{d\lambda} = \frac{\partial x^i}{\partial y^{j'}}v^{j'}$$

and basis vectors transform by

$$e_i = \frac{\partial}{\partial x^i} = \frac{\partial y^{j'}}{\partial x^i}\frac{\partial}{\partial y^{j'}} = \frac{\partial y^{j'}}{\partial x^i} e_{j'}$$

Remember that components transform but basis change too, inversely, then the vector remains the same.
A vector field in an open set $U \subseteq \mathcal{M}$ is map from each point $P \in U$ into a vector $v(P)$. Introducing a chart, $v(x^i) = v \circ \phi^{-1}$.
The coordinate vectors $e_i = \frac{\partial}{\partial x^i}$ form a basis of a linear space composed by all the vectors tangent to a point P, called the tangent space T_P.

Proof. First, every tangent vector can be expressed as linear combination.
Consider two curves, parametrized by λ and σ, across a point P which generate two vectors $v = \frac{\partial}{\partial \lambda}$ and $w = \frac{d}{d\sigma}$. Hence, a generic linear combination of them

$$av+bw = a\frac{d}{d\lambda}+b\frac{d}{d\sigma} = a\frac{\partial x^i}{\partial \lambda}\frac{\partial}{\partial x^i}+b\frac{dx^i}{d\sigma}\frac{\partial}{\partial x^i} = \left(a\frac{\partial x^i}{\partial \lambda}+b\frac{dx^i}{d\sigma}\right)\frac{\partial}{\partial x^i} = \left(a\frac{\partial x^i}{\partial \lambda}+b\frac{dx^i}{d\sigma}\right)e_i$$

Since there are n coordinates x^i, we have n indipendent curves.
Second, the coordinate basis vectors are linearly independent.
The determinant of the jacobian matrix of $y^i = y^i(x^j)$ must not vanish

$$\det J = \det \begin{pmatrix} \frac{\partial y^1}{\partial x^1} & \dots & \frac{\partial y^1}{\partial x^n} \\ \dots & \dots & \dots \\ \frac{\partial y^n}{\partial x^1} & \dots & \frac{\partial y^n}{\partial x^n} \end{pmatrix}$$

hence, there are n columns (or rows) which are linearly independent and also n basis vector

$$e_i = \frac{\partial}{\partial x^i} = \frac{\partial y^j}{\partial x^i}\frac{\partial}{\partial y^j}$$

q.e.d.

It is important to remark that coordinate basis vectors at different points belong to different tangent space and cannot be linearly combined.

1.5 Fiber bundles

A tangent bundle is the set of all tangent space at each point together with the manifold itself $\mathcal{TM} = \{\mathcal{M},\ \{T_P \colon \forall P \in \mathcal{M}\}\}$. It can be shown that $\mathcal{TM}$ is a manifold too.

1.6 Exponential map

An integral curve $\gamma = \gamma(\lambda)$ of a vector field V is the curve which as tangent vector $\frac{d}{d\lambda}$ has the element of V in $P \in \gamma$, i.e.

$$V = \frac{d}{d\lambda}$$

Introducing a point P_0 and a chart x^i

$$\begin{aligned} V^i(\lambda) &= \frac{dx^i(\lambda)}{d\lambda} \\ x^i(P_0) &= x^i(\lambda_0) \end{aligned} \tag{1.2}$$

which are a system of n Cauchy problems and the components of V at an arbitrary point $P = \phi^{-1}(x^i(\lambda))$ are $V(P) = V^i(x^j(\lambda))\frac{\partial}{\partial x^i} = V^i(\lambda)\frac{\partial}{\partial x^i}$.
Theorems of calculus in $\mathbb{R}^n$ ensure that locally tha solution of (1.2) always exists, which is indeed the integral curve $\gamma(\lambda)$.
Formally, the solution of (1.2) is the exponential map

$$x^i(\lambda) = \exp((\lambda - \lambda_0)V)x^i\Big|_{\lambda_0}$$

which describes the flow of V in a neighbourhood of P.

Proof. Let $V = \frac{d}{d\lambda}$ be a vector fields with integral curve $\gamma = \gamma(\lambda)$. Introducing a chart x^i and Taylor expanding around P_0 along γ

$$\begin{aligned} x^i(\lambda_0 + \epsilon) &= x^i(\lambda_0) + \epsilon\frac{dx^i}{d\lambda}\Big|_{\lambda_0} + \frac{\epsilon^2}{2}\frac{d^2x^i}{d\lambda^2}\Big|_{\lambda_0} + \dots \\ &= \left(1 + \epsilon\frac{d}{d\lambda}\Big|_{\lambda_0} + \frac{\epsilon^2}{2}\frac{d^2}{d\lambda^2}\Big|_{\lambda_0} + \dots\right) x^i(\lambda_0) \\ &= \exp(\epsilon\frac{d}{d\lambda})\ x^i\Big|_{\lambda_0} \\ &= \exp(\epsilon V)\ x^i\Big|_{\lambda_0} \end{aligned}$$

q.e.d.

For an arbitrary function f in a neighbourhood of P

$$f(\lambda_0 + \epsilon) = \exp\left(\epsilon\frac{d}{d\lambda}\right) f\Big|_{\lambda_0} = \exp(\epsilon V)\ f\Big|_{\lambda_0}$$

1.7 Lie brackets

Introducing a chart x^i, the Lie brackets of two vector fields $V = \frac{d}{d\lambda} = v^i \frac{\partial}{\partial x^i}$ and $W = \frac{d}{d\mu} = w^i \frac{\partial}{\partial x^i}$ are

$$\begin{aligned}
[V,\ W] &= \frac{d}{d\lambda}\frac{d}{d\mu} - \frac{d}{d\mu}\frac{d}{d\lambda} \\
&= v^i \frac{\partial}{\partial x^i}\Big(w^j \frac{\partial}{\partial x^j}\Big) - w^i \frac{\partial}{\partial x^i}\Big(v^j \frac{\partial}{\partial x^j}\Big) \\
&= \cancel{v^i w^j \frac{\partial}{\partial x^i}\frac{\partial}{\partial x^j}} + v^i \frac{\partial w^j}{\partial x^i}\frac{\partial}{\partial x^j} - \cancel{v^j w^i \frac{\partial}{\partial x^i}\frac{\partial}{\partial x^j}} - w^i \frac{\partial v^j}{\partial x^i}\frac{\partial}{\partial x^j} \\
&= \Big(v^i \frac{\partial w^j}{\partial x^i} - w^i \frac{\partial v^j}{\partial x^i}\Big)\frac{\partial}{\partial x^j}
\end{aligned}$$

where it is used the facf that the partial derivatives commute. Hence the commutator of two vectors is still a vector.
The geometrical meaning of the commutator is the following: consider two vector fields $V = \frac{d}{d\lambda}$ and $W = \frac{d}{d\mu}$. Using the exponential map, the coordinates of A, moving before along V and then along W, are

$$x^i(A) = \exp\Big(\epsilon_2 \frac{d}{d\mu}\Big) \exp\Big(\epsilon_1 \frac{d}{d\lambda}\Big)\ x^i\Big|_P$$

whereas the coordinates of B, moving before along W and then along Y, are

$$x^i(B) = \exp\Big(\epsilon_1 \frac{d}{d\lambda}\Big) \exp\Big(\epsilon_2 \frac{d}{d\mu}\Big)\ x^i\Big|_P$$

Computing the difference

$$x^i(B) - x^i(A) = \epsilon_1 \epsilon_2 \Big[\frac{d}{d\lambda},\ \frac{d}{d\mu}\Big]\ x^i\Big|_P + O(\epsilon^3)$$

Hence, if the commutator does not vanish, the final points are different $A \neq B$ and the path $PA \cup PB$ does not close.
A sufficient and necessary condition for a set of fields to be coordinate vectors is that their commutator vanishes.

Proof. First, the sufficient condition. Consider two coordinate vector fields $V = \frac{\partial}{\partial x^1}$ and $W = \frac{\partial}{\partial x^2}$. Then $v^i = \delta^i{}_1$, $w^j = \delta^j{}_2$ and the commutator vanishes, since the derivative of a constant is so.
Second, the necessary condition. Consider two commuting vector fields $V = \frac{\partial}{\partial x^1}$ and $W = \frac{\partial}{\partial x^2}$. Suppose also that they are linearly independent

$$aV(P) + bW(P) = 0 \quad \Longleftrightarrow \quad a = b = 0. \tag{1.3}$$

Introducing a chart x^i, moving from P along V by $\Delta\lambda = \alpha$ to a point R

$$x^(R) = \exp\left(\alpha \frac{d}{d\lambda}\right) x^i\Big|_P$$

and then along W by $\Delta\mu = \beta$ to a point Q

$$x^(Q) = \exp\left(\beta \frac{d}{d\mu}\right) \exp\left(\alpha \frac{d}{d\lambda}\right) x^i\Big|_P \tag{1.4}$$

If α and β are coordinates, the corresponding basis vectors are $\frac{\partial}{\partial\alpha} = \frac{\partial x^i}{\partial\alpha}$ and $\frac{\partial}{\partial\beta} = \frac{\partial x^i}{\partial\beta}$. Hence, using (1.4)

$$\begin{aligned}
\frac{\partial x^i}{\partial\alpha} &= \frac{\partial}{\partial\alpha}\left(\exp\left(\beta \frac{d}{d\mu}\right) \exp\left(\alpha \frac{d}{d\lambda}\right) x^i\Big|_P\right) \\
&= \exp\left(\beta \frac{d}{d\mu}\right) \frac{\partial}{\partial\alpha}\left(\exp\left(\alpha \frac{d}{d\lambda}\right) x^i\Big|_P\right) \\
&= \exp\left(\beta \frac{d}{d\mu}\right) \exp\left(\alpha \frac{d}{d\lambda}\right) \frac{dx^i}{d\lambda}\Big|_P
\end{aligned}$$

and, similarly,

$$\frac{\partial x^i}{\partial\beta} = \exp\left(\beta \frac{d}{d\mu}\right) \exp\left(\alpha \frac{d}{d\lambda}\right) \frac{dx^i}{d\mu}\Big|_P$$

This shows that $\frac{\partial}{\partial\alpha}$ and $\frac{\partial}{\partial\beta}$ are respectively the vector fields $\frac{d}{d\lambda}$ and $\frac{\partial}{\partial\mu}$ evaluated in Q, using the fact that the commutator is vanishing. Then the determinant of the Jacobians is not zero

$$\det J = \det \begin{bmatrix} \frac{\partial x^1}{\partial\alpha} & \frac{\partial x^2}{\partial\alpha} \\ \frac{\partial x^1}{\partial\beta} & \frac{\partial x^2}{\partial\beta} \end{bmatrix} \neq 0$$

since we assumed the linearly independence of $\frac{d}{d\lambda}$ and $\frac{d}{d\mu}$. q.e.d.

1.8 1-forms

A 1-form is a linear functional w acting on a vector $w\colon T_P \to \mathbb{R}$ such that $w(\alpha v + \beta u) = \alpha w(v) + \beta w(u)$ and $(\alpha w + \alpha z)(v) = \alpha w(v) + \beta z(v)$. Linearity implies that the action of a 1-form is completely determined by the action on a basis of T_P. 1-forms acting on the same T_P form a linear space T_P^*, called the cotangent space. A cotangent bundle is the set of all cotangent space at each point together with the manifold itself $\mathcal{T}^*\mathcal{M} = \{\mathcal{M},\ \{T_P^*\colon \forall P \in \mathcal{M}\}\}$. A 1-form field is a map associates a 1-form of T^*P to each point $P \in \mathcal{M}$.
One way of thinking 1-forms is in the following way: given an arbitrary function, a vector field is defined by $V(f) = \frac{df}{d\lambda}$ whereas given an arbitrary vector field, a 1-form

is defined by $V(f) = \frac{df}{d\lambda} = df(\frac{d}{d\lambda})$. The difference is the in the former V is fixed and f is arbitrary, whereas in the latter f is fixed and V is arbitrary. Introducing a chart x^i

$$\frac{df}{d\lambda} = \frac{\partial f}{\partial x^i}\frac{dx^i}{d\lambda} = \nabla_i f \frac{dx^i}{d\lambda} = df_i \frac{dx^i}{d\lambda}$$

where df_i are the components of the 1-form df, called the gradient of f.
Geometrically, the gradient of a function can be seen as the number of contour lines that a vector V crosses in a neighbourhood of P. Generalizing for 1-forms, they can be seen as a set of level surfaces whose action on a vector is the number of surface the vector crosses.
Let $\{e_i\}$ be a basis of T_P. A basis of T_P^* is not related to it, however it is convenient to choose the dual basis, which completely defined a basis of T^*P by a basis in T_P in the following way

$$e^i(e_j) = \delta^i{}_j$$

or, equivalently, applying it to a vector v

$$e^i(v) = e^i(v^j e_j) = v^j e^i(e_j) = v^j \delta^i{}_j = v^i$$

Consequently, $\mathcal{M}$, T_P and T_P^* have the same dimension n. $\{e^i\}$ are actually a basis of T_P^*, since given an arbitrary 1-form q

$$q(v) = q(v^i e_i) = v^i q(e_i) = v^i q_i$$

and

$$v^i q_i = q_i e^i(v)$$

Remember that under a change of coordinates, vectors or 1-forms do not change, only their components and basis change, the latter inversely.
Differentials are the basis 1-form dual to the coordinate basis vectors

$$\frac{df}{d\lambda} = \frac{\partial f}{\partial x^i}\frac{dx^i}{d\lambda} = \frac{\partial f}{\partial x^i} dx^i \Big(\frac{dx^j}{d\lambda}\frac{\partial}{\partial x^j}\Big) = \frac{\partial f}{\partial x^i}\frac{dx^j}{d\lambda} dx^i \Big(\frac{\partial}{\partial x^j}\Big) = \frac{\partial f}{\partial x^i}\frac{\partial x^j}{\partial \lambda}\delta^i{}_j = \frac{\partial f}{\partial x^i}\frac{\partial x^i}{\partial \lambda}$$

1.9 Tensors

List of Theorems