5.4 HW2

Question 99

Let $F : \mathbb{R}^2 \to \mathbb{R}^3$ be the map

$$F(x, y) \triangleq (x, y, xy) = (u, v, w)$$

Let $p = (x, y) \in \mathbb{R}^2$. Compute $F_*(\frac{\partial}{\partial x}|_p)$ as a linear combination of $\frac{\partial}{\partial u}, \frac{\partial}{\partial v}, \frac{\partial}{\partial w}$

Proof. For all $f \in C^\infty(\mathbb{R}^3)$, we have

$$\frac{\partial f \circ F}{\partial x}(x, y) = \frac{\partial f}{\partial u}(F(p)) + \frac{\partial f}{\partial w}(F(p))y$$

This then give us

$$F_*\left(\frac{\partial}{\partial x}\Big|_{(x,y)}\right) = \frac{\partial}{\partial u} + y\frac{\partial}{\partial w}$$

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Question 100

Let G be a lie group with multiplication map $\mu : G \times G \to G$ and identity element e. Show that differential $\mu_{*,(e,e)} : T_{(e,e)}G \times G \to T_e G$ of μ at identity is

$$\mu_{*,(e,e)}(X_e, Y_e) = X_e + Y_e$$

Note that $T_{(p,q)}M \times N$ is isomorphic to $T_p M \oplus T_q N$ via the differential of two projection $\pi_1 : M \times N \to M$ and $\pi_2 : M \times N \to N$.

Proof. We first justify the notation of writing tangent vectors in $T_{(e,e)}G \times G$ as (X_e, Y_e), and the proof will follow. Consider the projection $\pi_1 : G \times G \to G$ and $\pi_2 : G \times G \to G$

$$\pi_1(g, h) \triangleq g \text{ and } \pi_2(g, h) \triangleq h$$

Consider charts $(U, \varphi), (V, \psi)$ for G centering e. We can induce a chart $(U \times V, \Phi)$ for $G \times G$ centering e by

$$\Phi(g, h) \triangleq (\varphi(g), \psi(h))$$

In local coordinate, we have

$$\pi_1(\mathbf{x}^1, \ldots, \mathbf{x}^n, \mathbf{y}^1, \ldots, \mathbf{y}^n) = (\mathbf{x}^1, \ldots, \mathbf{x}^n) \text{ and } \pi_2(\mathbf{x}^1, \ldots, \mathbf{x}^n, \mathbf{y}^1, \ldots, \mathbf{y}^n) = (\mathbf{y}^1, \ldots, \mathbf{y}^n)$$

In abuse of notation, this give us

$$(\pi_1)_*\left(\sum_{i=1}^n v^i \frac{\partial}{\partial \mathbf{x}^i} + w^i \frac{\partial}{\partial \mathbf{y}^i}\right) = \sum_{i=1}^n v^i \frac{\partial}{\partial \mathbf{x}^i} \text{ and } (\pi_2)_*\left(\sum_{i=1}^n v^i \frac{\partial}{\partial \mathbf{x}^i} + w^i \frac{\partial}{\partial \mathbf{y}^i}\right) = \sum_{i=1}^n w^i \frac{\partial}{\partial \mathbf{y}^i}$$

This then give us a vector space isomorphism between $T_{(e,e)}G \times G$ and $T_e G \oplus T_e G$, on which our notation stand. Now, let $\gamma : (-\epsilon, \epsilon) \to G$ be a smooth curve centering e such that $\gamma'(0) = X_e$. Define another smooth curve $\alpha : (-\epsilon, \epsilon) \to G \times G$ in $G \times G$ by

$$\alpha(t) \triangleq (\gamma(t), e)$$

Because $\pi_2 \circ \alpha$ is constant and $\pi_1 \circ \alpha = \gamma$, we now see

$$(\pi_1)_{*,(e,e)}(\alpha'(0)) = (\pi_1 \circ \alpha)'(0) = \gamma'(0) \text{ and } (\pi_2)_{*,(e,e)}(\alpha'(0)) = 0$$

This implies $\alpha'(0) = (X_e, 0)$. Compute

$$\mu \circ \alpha(t) = \gamma(t) + e = \gamma(t)$$

We now can deduce

$$\mu_{*,(e,e)}(X_e, 0) = \mu_{*,(e,e)}(\alpha'(0)) = (\mu \circ \alpha)'(0) = \gamma'(0) = X_e$$

Similar procedure can be applied to show

$$\mu_{*,(e,e)}(0, Y_e) = Y_e$$

It now follows from linearity of $\mu_{*,(e,e)}$ that

$$\mu_{*,(e,e)}(X_e, Y_e) = X_e + Y_e$$

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Question 101

Let $S^2 = \{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 + z^2 = 1\}$ be the sphere in $\mathbb{R}^3$. Consider the function $h : S^2 \to \mathbb{R}$ defined by

$$h(x, y, z) \triangleq z$$

Find the critical points of h.

Proof. Consider the atlas $\{(U, \varphi), (V, \psi)\}$ for S^2 where $U = S^2 \setminus \{(0, 0, 1)\}, V = S^2 \setminus \{(0, 0, -1)\}$ and

$$\varphi(x, y, z) \triangleq \left(\frac{x}{1-z}, \frac{y}{1-z}\right) \text{ and } \psi(x, y, z) = \left(\frac{x}{1+z}, \frac{y}{1+z}\right)$$

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Some algebra trick and tedious efforts shows that this indeed form a smooth atlas and gives us their inverse

$$\varphi^{-1}(u, v) = \left(\frac{2u}{u^2 + v^2 + 1}, \frac{2v}{u^2 + v^2 + 1}, \frac{u^2 + v^2 - 1}{u^2 + v^2 + 1} \right)$$

$$\psi^{-1}(u, v) = \left(\frac{2u}{u^2 + v^2 + 1}, \frac{2v}{u^2 + v^2 + 1}, \frac{1 - u^2 - v^2}{u^2 + v^2 + 1} \right)$$

Compute

$$[d(h \circ \varphi^{-1})_{(u,v)}] = \left[\frac{-4u}{(u^2+v^2+1)^2} \quad \frac{-4v}{(u^2+v^2+1)^2} \right]$$

$$[d(h \circ \psi^{-1})_{(u,v)}] = \left[\frac{4u}{(u^2+v^2+1)^2} \quad \frac{4v}{(u^2+v^2+1)^2} \right]$$

This then shows the set of critical points is exactly

$$\{\varphi^{-1}(0,0), \psi^{-1}(0,0)\} = \{(0,0,-1), (0,0,1)\}$$

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Question 102

A smooth map $f : M \to N$ is said to be **a traversal to an embedded submanifold** $S \subseteq N$ if for every point $p \in f^{-1}(S)$, we have

$$f_{*,p}(T_p M) + T_{f(p)} S = T_{f(p)} N$$

The goal of this exercise is to prove the Transversality Theorem: If a smooth map $f : M \to N$ is a traversal to an embedded submanifold S of codimension k in N, then $f^{-1}(S)$ is a regular submanifold of codimension k in M. Let $p \in f^{-1}(S)$ and $(U, \mathbf{x}^1, \ldots, \mathbf{x}^n)$ be an adapted chart for N centering $f(p)$ with respect to S. Define $g : U \to \mathbb{R}^k$ by

$$g(\mathbf{x}^1, \ldots, \mathbf{x}^n) \triangleq (\mathbf{x}^{n-k+1}, \ldots, \mathbf{x}^n)$$

(a) Show that $f^{-1}(U) \cap f^{-1}(S) = (g \circ f)^{-1}(\mathbf{0})$.

(b) Show that $f^{-1}(U) \cap f^{-1}(S)$ is a regular level set of the function $g \circ f : f^{-1}(U) \to \mathbb{R}^k$.

(c) Prove the Transversality Theorem.

Proof. At first, we shall point out that $g \circ f$ is a function defined only on $f^{-1}(U)$. (a) follows trivially from the fact that $(U, \mathbf{x}^1, \ldots \mathbf{x}^n)$ is an adapted chart. We now prove (b).

Fix arbitrary $p \in f^{-1}(U) \cap f^{-1}(S)$. Trivially, by definition of g,

$$T_{f(p)}S \subseteq \operatorname{Ker} g_{*,f(p)}$$

Explicit formula of g shows that $g_{*,f(p)}$ is a vector space epimorphism that maps $T_{f(p)}N$ into $T_{g \circ f(p)}\mathbb{R}^k$, which implies that $\operatorname{Ker} g_{*,f(p)}$ has dimension $n - k$, same as $T_{f(p)}S$ and give us

$$T_{f(p)}S = \operatorname{Ker} g_{*,f(p)}$$

It now follows from f being a traversal and $g_{*,f(p)}$ being surjective that

$$(g \circ f)_{*,p}(T_pM) = g_{*,f(p)} \circ f_{*,p}(T_pM) = \operatorname{Im} g_{*,f(p)} = T_{g \circ f(p)}\mathbb{R}^k$$

We have shown that $g \circ f$ is regular at p. (b) then follows from p is arbitrary selected from $f^{-1}(U) \cap f^{-1}(S)$.

Now, by Regular level set Theorem, we see that $f^{-1}(U) \cap f^{-1}(S)$ is an embedded submanifold of $f^{-1}(U)$ with codimension k. Because f is continuous, we know $f^{-1}(U)$ is open, thus an embedded submanifold of M with dimension m. It now follows that $f^{-1}(U) \cap f^{-1}(S)$ is an embedded submanifold of M with codimension k.

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