

		$x_1 = \phi(x_0)$
		$x_2 = \phi(x_1)$
		\vdots
	$\forall x_0 \in X$, Define	\vdots
1		$x_j = \phi(x_{j-1})$
1		\vdots
3		\vdots
		$x_n = \phi(x_{n-1})$
5		$d(x_{n+1}, x_n) = d(\phi(x_n), \phi(x_{n-1})) \leq cd(x_n, x_{n-1}) \leq \cdots \leq c^nd(x_1, x_0)$
5		for some $0 < c < 1$.
5		$d(x_m, x_n) \leq d(x_n, x_{n-1}) + d(x_{n-1}, x_m) \leq d(x_n, x_{n-1}) + d(x_{n-1}, x_{n-2}) + \cdots + d(x_{m+1}, x_m) \leq \sum_{k=n-1}^m c^kd(x_1, x_0)$
5		
7		Thus, $\forall \epsilon > 0$, $\exists n_0 > 0$, (n_0 large enough) s.t. $\forall m, n \in \mathbb{N}$ s.t. $n_0 < n < m$,
8		$d(x_m, x_n) \leq \sum_{k=n-1}^m c^kd(x_1, x_0) < \epsilon d(x_1, x_0)$

ABSTRACT. Everything about Differential Geometry, Differential Topology

Thus, $\{x_n\}$ Cauchy sequence. Since X complete, \exists limit pt. $y \in X$ of $\{x_n\}$.

$$\phi(y) = \phi(\lim_n x_n) = \lim_n \phi(x_n) = \lim_n x_{n+1} = y$$

Part 1. Manifolds

1. INVERSE FUNCTION THEOREM

Shastri (2011) had a thorough and lucid and explicit explanation of the Inverse Function Theorem [4]. I will recap it here. The following is also a blend of Wienhard’s Handout 4 <https://web.math.princeton.edu/~wienhard/teaching/M327/handout4.pdf>

Definition 1. Let (X, a) metric space.

contraction $\phi : X \rightarrow X$ if \exists constant $0 < c < 1$ s.t. $\forall x, y \in X$

$$d(\phi(x), \phi(y)) \leq cd(x, y)$$

Theorem 1 (Contraction Mapping Principle). Let (X, d) complete metric space.

Then \forall contraction $\phi : X \rightarrow X$, $\exists !y \in X$ s.t. $\phi(y) = y$, y fixed pt.

Proof. Recall def. of complete metric space X , X metric space s.t. \forall Cauchy sequence in X is convergent in X (i.e. has limit in X).

If $\exists y_1, y_2 \in X$ s.t. $\phi(y_1) = y_1$, then

$$\phi(y_2) = y_2$$
$$d(y_1, y_2) = d(\phi(y_1), \phi(y_2)) \leq cd(y_1, y_2) \text{ with } c < 1$$

so $c = 1$ □

Theorem 2 (Inverse Function Theorem). Suppose open $U \subset \mathbb{R}^n$, let $C^1 f : U \rightarrow \mathbb{R}^n$, $x_0 \in U$ s.t. $Df(x_0)$ invertible.

Then \exists open neighborhoods $V \ni x_0$, $W \ni f(x_0)$ s.t. $V \subseteq U$ and $W \subseteq \mathbb{R}^n$, respectively, and s.t.

(i) $f : V \rightarrow W$ bijection

(ii) $g = f^{-1} : V \rightarrow U$ differentiable, i.e. $g = f^{-1} : W \rightarrow V$ is C^1

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- (iii) $D(f^{-1})$ cont. on W .
- (iv) $Dg(y) = (Df(g(y)))^{-1} \quad \forall y \in W$

Also, notice that $f(g(y)) = y \forall y \in W$.

Proof. Consider $\tilde{f}(x) = (Df(x_0))^{-1}(f(x + x_0) - f(x_0))$. Then $\tilde{f}(0) = 0$ and

$$\begin{aligned} D\tilde{f} &= (Df(x_0))^{-1}(Df(x + x_0) - 0) \\ D\tilde{f}(0) &= (Df(x_0))^{-1}Df(x_0) = 1 \end{aligned}$$

So let $\tilde{f} \rightarrow f$ (notation) and so assume, without loss of generality, that $U \ni 0$, $f(0) = 0$, $Df(0) = 1$. Choose $0 < \epsilon \leq \frac{1}{2}$. Let $0 < \delta < 1$ s.t. open ball $V = B_\delta(0) \subseteq U$, and $\|Df(x) - 1\| < \epsilon$. $\forall x \in U$, since Df cont. at 0. Let $W = f(V)$.

$\forall y \in W$, define $\phi_y : V \rightarrow \mathbb{R}^n$
 $\phi_y(x) = x + (y - f(x))$

$$\begin{aligned} D(\phi_y)(x) &= 1 + -Df(x) \quad \forall x \in V \\ \|D(\phi_y)(x)\| &= \|1 - Df(x)\| \leq \epsilon < 1 \end{aligned}$$

$\forall x_1, x_2 \in V$, by mean value Thm. (not the equality that is only valid in 1-dim., but the inequality, that's valid for \mathbb{R}^d ,

$$\|\phi_y(x_1) - \phi_y(x_2)\| \leq \|D(\phi_y)(x')\| \|x_1 - x_2\|$$

for some $x' = cx_2 + (1 - c)x_1$, $c \in [0, 1]$. V only needed to be convex set.

$$\implies \|\phi_y(x_1) - \phi_y(x_2)\| \leq \epsilon \|x_1 - x_2\|$$

Then ϕ_y contraction mapping.

Suppose $f(x_1) = f(x_2) = y$, $x_1, x_2 \in V$.

$$\begin{aligned} \phi_y(x_1) &= x_1 \\ \phi_y(x_2) &= x_2 \end{aligned}$$

$$\|\phi_y(x_1) - \phi_y(x_2)\| = \|x_1 - x_2\| \leq \epsilon \|x_1 - x_2\| \quad \forall \epsilon > 0 \implies x_1 = x_2$$

$\implies f|_U$ injective.

$W = f(V)$, so $f : V \rightarrow W$ surjective. f bijective.

Fix $y_0 \in W$, $y_0 = f(x_0)$, $x_0 \in V$.

Let $r > 0$ s.t. $B_r(x_0) \subset V$.

Consider $B_{r\epsilon}(y_0)$. If $y \in B_{r\epsilon}(y_0)$.

$$\begin{aligned} r\epsilon > \|y - y_0\| &= \|y - f(x_0)\| = \|\phi_y(x_0) - x_0\| \text{ with} \\ \phi_y(x) &= x + (y - f(x)) \end{aligned}$$

If $x \in B_r(x_0)$,

$$\|\phi_y(x) - x_0\| \leq \|\phi_y(x) - \phi_y(x_0)\| + \|\phi_y(x_0) - x_0\| \leq \epsilon \|x - x_0\| + r\epsilon < 2r\epsilon = r$$

Thus $\phi(B_r(x_0)) = B_r(x_0)$.

By contraction mapping principle, $\exists a \in B_r(x_0)$, s.t. $\phi_y(a) = a$. Then $\phi_y(a) = a + (y - f(a)) = a \implies f(a) = y$.

$y \in f(V) = W$.

So $B_{r\epsilon}(y_0) \subset W$. W open.

Let $\text{Mat}(n, n) \equiv$ space of all $n \times n$ matrices; $\text{Mat}(n, n) = \mathbb{R}^{n^2}$.

□

There is a proof of the implicit function theorem and its various forms in Shastri (2011) [4], but I found Wienhard's Handout 4 for Math 327 to be clearer.¹

¹<https://web.math.princeton.edu/~wienhard/teaching/M327/handout4.pdf>

Theorem 3 (Implicit Function Theorem). *Let open $U \subset \mathbb{R}^{m+n} \equiv \mathbb{R}^m \times \mathbb{R}^n$*

$C^1 f : U \rightarrow \mathbb{R}^n$

$(a, b) \in U$ s.t. $f(a, b) = 0$ and $D_y f|_{(a, b)}$ invertible.

Then \exists open $V \ni (a, b)$, $V \subset U$

\exists open neighborhood $W \ni a$, $W \subseteq \mathbb{R}^m$

$\exists!$ $C^1 g : W \rightarrow \mathbb{R}^n$ s.t.

$$\{(x, y) \in V | f(x, y) = 0\} = \{(x, g(x)) | x \in W\}$$

Moreover,

$$dg_x = - (d_y f)^{-1} \Big|_{(x, g(x))} d_x f|_{(x, g(x))}$$

and g smooth if f .

Proof. Define $F : U \rightarrow \mathbb{R}^{m+n}$

$$F(x, y) = (x, f(x, y))$$

Then $F(a, b) = (a, 0)$ (given), and

$$DF = \begin{bmatrix} 1 & \\ \frac{\partial f^i(x, y)}{\partial x^j} & \frac{\partial f^i(x, y)}{\partial y^j} \end{bmatrix} \equiv \begin{bmatrix} 1 & \\ D_x f & D_y f \end{bmatrix}$$

$DF(a, b)$ invertible.

By inverse function theorem, since $DF(a, b)$ invertible at pt. (a, b) ,

\exists open neighborhoods $V \ni (a, b) \subseteq \mathbb{R}^m \times \mathbb{R}^n$ s.t. F diffeomorphism with $F^{-1} : \widetilde{W} \rightarrow V$.

$$\widetilde{W} \ni (a, 0) \subseteq \mathbb{R}^m \times \mathbb{R}^n$$

Set $W = \{x \in \mathbb{R}^m | (x, 0) \in \widetilde{W}\}$. Then $\pi_1(\widetilde{W}) = W$ open in \mathbb{R}^m .

Define $g : W \rightarrow \mathbb{R}^n$,

$$g(x) = \pi_2 \circ F^{-1}(x, 0) \text{ or}$$

$$F^{-1}(x, 0) = (h(x), g(x))$$

Now $FF^{-1}(x, 0) = (x, 0) = (h(x), f(h(x), g(x)))$ so $h(x) = x \forall x \in W$, $0 = f(x, g(x))$.

Then

$$\{(x, y) \in V | f(x, y) = 0\} = \{(x, y) \in V | F(x, y) = (x, 0)\} = \{(x, g(x)) | x \in W, 0 = f(x, g(x))\}$$

Since π smooth and F^{-1} is C^1 , g is C^1 .

To reiterate, $f(x, g(x)) = 0$ on W .

Using chain rule while differentiating $f(x, g(x)) = 0$,

$$\begin{aligned} \partial_{x^j} f(x, g(x)) &= \frac{\partial f(x, g(x))}{\partial x^k} \frac{\partial x^k}{\partial x^j} + \frac{\partial f(x, g(x))}{\partial y^k} \frac{\partial g^k(x)}{\partial x^j} = D_x f|_{(x, g(x))} + (D_y f)|_{(x, g(x))} \cdot (Dg)_x = 0 \text{ or} \\ (Dg)_x &= - (D_y f)|_{x, g(x)} D_x f|_{(x, g(x))} \end{aligned}$$

□

Definition 2. *smooth $f : M \rightarrow N$, s.t. $Df(p) : T_p M \rightarrow T_{f(p)} N$ injective. Then f immersion at p .*

Shastri (2011) has this as the “Injective Form of Implicit Function Theorem”, Thm. 1.4.5, pp. 23 and Guillemin and Pollack (2010) has this as the “Local Immersion Theorem” on pp. 15, Section 3 “The Inverse Function Theorem and Immersions” [3].

Theorem 4 (Local immersion Theorem i.e. Injective Form of Implicit Function Theorem). *Suppose $f : M \rightarrow N$ immersion at p , $q = f(p)$.*

Then \exists local coordinates around p, q , x, y , respectively s.t. $f(x_1 \dots x_m) = (x_1 \dots x_m, 0 \dots 0)$.

Proof. Choose local parametrizations

$$\begin{array}{ccc} U \subseteq M & \xrightarrow{f} & N \supseteq V \\ \downarrow \phi & & \downarrow \psi \\ \phi(U) & \xrightarrow{f} & \psi(V) \end{array} \quad \begin{array}{l} \phi(p) = x \\ \psi(q) = y \end{array}$$

$D(\psi f \varphi^{-1}) \equiv Df$. $Df(p)$ injective (given f immersion). $Df(p) \in \text{Mat}(n, m)$

By change of basis in \mathbb{R}^n , assume $Df(p) = \begin{pmatrix} I_m \\ 0 \end{pmatrix}$.

Now define $G : \phi(U) \times \mathbb{R}^{n-m} \rightarrow \mathbb{R}^n$

$$G(x, z) = f(x) + (0, z)$$

Thus, $DG(x, z) = 1$ and for open $\phi(U) \times U_2$, $G(\phi(U) \times U_2)$ open.

By inverse function theorem, G local diffeomorphism of \mathbb{R}^n , at 0.

Now $f = G \circ \mathbf{i}$, where \mathbf{i} is canonical immersion.

$$\begin{aligned} G(x, 0) &= f(x) \\ \implies G^{-1}G(x, 0) &= (x, 0) = G^{-1}f(x) \end{aligned}$$

Use $\psi \circ G$ as the local parametrization of N around pt. q . Shrink U, V so that

$$\begin{array}{ccc} U \subseteq M & \xrightarrow{f} & N \supseteq V \\ \downarrow \phi & & \downarrow \psi \circ G \\ \phi(U) & \xrightarrow{\mathbf{i}} & \psi \circ G(V) \end{array}$$

Theorem 5 ((Implicit Function Thm.)). *Let open subset $U \subseteq \mathbb{R}^n \times \mathbb{R}^d$, $(x, y) = (x^1 \dots x^n, y^1 \dots y^k)$ on U . Suppose smooth $\Phi : U \rightarrow \mathbb{R}^k$, $(a, b) \in U$, $c = \Phi(a, b)$*

If $k \times k$ matrix $\frac{\partial \Phi^i}{\partial y^j}(a, b)$ nonsingular, then \exists neighborhoods $V_0 \subseteq \mathbb{R}^n$ of a and smooth $F : V_0 \rightarrow W_0$ s.t. $W_0 \subseteq \mathbb{R}^k$ of b

$\Phi^{-1}(c) \cap (V_0 \times W_0)$ is graph of F , i.e.

$\Phi(x, y) = c$ for $(x, y) \in V_0 \times W_0$ iff $y = F(x)$.

Jeffrey Lee (2009) [1]

John Lee (2012) [2]

2. TENSORS

I'll go through Ch.7 *Tensors* of Jeffrey Lee (2009) [1].

Definition 3 (7.1[1]). *Let V, W be modules over commutative ring R , with unity. Then, algebraic W -valued tensor on V is multilinear map.*

$$(1) \quad \tau : V_1 \times V_2 \times \dots \times V_m \rightarrow W$$

where $V_i = \{V, V^*\} \quad \forall i = 1, 2, \dots m$.

If for r, s s.t. $r + s = m$, there are $r \quad V_i = V^*$, $s \quad V_i = V$, tensor is r -contravariant, s -covariant; also say tensor of total type $\begin{pmatrix} r \\ s \end{pmatrix}$.

EY : 20170404 Note that

$$(\tau_\beta^{i\alpha} \frac{\partial}{\partial x^i} \text{ or } \tau_\beta^{i\alpha} e_i)(\omega_j dx^j \text{ or } \omega_j e^j \in V^*)$$

$$(\tau_{i\alpha}^\beta dx^i \text{ or } \tau_{i\alpha}^\beta e^i)(X^j \frac{\partial}{\partial x^j} \text{ or } X^j e_j \in V)$$

\exists natural map $V \rightarrow V^{**}$, $\tilde{v} : \alpha \mapsto \alpha(v)$. If this map is an isomorphism, V is **reflexive** module, and identify V with V^{**} .

Exercise 7.5. Given vector bundle $\pi : E \rightarrow M$, open $U \subset M$, consider sections of π on U , i.e. cont. $s : U \rightarrow E$, where $(\pi \circ s)(u) = u, \quad \forall u \in U$.

Consider $E^* \ni \omega = \omega_i e^i$.

$\forall s \in \Gamma(E)$, $\omega(s) = \omega_i(s(x))e^i, \quad \forall x \in U \subset M$. So define $\tilde{s} : \omega, x \mapsto \omega(s(x)), \quad \forall x \in U$.

If $\tilde{s} = 0$, $\tilde{s}(\omega, x) = \omega(s(x)) = 0 \quad \forall \omega \in E^*, \forall x \in U$, and so $s = 0$. (Let $\omega_i = \delta_{iJ}$ for some J , and so $s^J(x) = 0 \quad \forall J$).

$s = 0$. So $\ker(s \mapsto \tilde{s}) = \{0\}$ (so condition for injectivity is fulfilled).

Since $\tilde{s} : \omega, x \mapsto \omega(s(x)), \forall \omega \in E^*, \forall x \in U$, $s \mapsto \tilde{s}$ is surjective.

$s \mapsto \tilde{s}$ is an isomorphism so $\Gamma(E)$ is a *reflexive* module.

Proposition 1. *For R a ring (special case), \exists module homomorphism:*

tensor product space \rightarrow tensor, as a multilinear map, i.e. \exists

$$(2) \quad \begin{aligned} &(\otimes_{i=1}^r V) \otimes (\otimes_{j=1}^s V^*) \rightarrow T_s^r(V; R) \\ &u_1 \otimes \dots \otimes u_r \otimes \beta^1 \otimes \dots \otimes \beta^s \in (\otimes^r V) \otimes (\otimes^s V^*) \mapsto (\alpha^1 \dots \alpha^r, v_1 \dots v_s) \mapsto \alpha^1(u_1) \dots \alpha^r(u_r) \beta^1(v_1) \dots \beta^s(v_s) \end{aligned}$$

Indeed, consider

$$(\alpha^1 \dots \alpha^r, v_1 \dots v_s) \in \underbrace{V^* \times \dots \times V^*}_r \times \underbrace{V \times \dots \times V}_s \mapsto \alpha^1(u_1) \dots \alpha^r(u_r) \beta^1(v_1) \dots \beta^s(v_s)$$

□

and so for

$$\begin{aligned} \alpha^i &= \alpha_\mu^i e^\mu, \quad i = 1, 2, \dots r, \mu = 1, 2, \dots \dim V^* & \alpha^i(u_i) &= \alpha_\mu^i u_i^\mu \\ v_i &= v_i^\mu e_\mu, \quad i = 1, 2, \dots s, \mu = 1, 2, \dots \dim V & \beta^i(v_i) &= \beta_\mu^i v_i^\mu \end{aligned}$$

So that

$$\begin{aligned} \alpha^1(u_1) \dots \alpha^r(u_r) \beta^1(v_1) \dots \beta^s(v_s) &= \alpha_{\alpha_1}^1 u_1^{\alpha_1} \dots \alpha_{\alpha_r}^r u_r^{\alpha_r} \beta_{\mu_1}^1 v_1^{\mu_1} \dots \beta_{\mu_s}^s v_s^{\mu_s} = \\ &= (u_1^{\alpha_1} \dots u_r^{\alpha_r} \beta_{\mu_1}^1 \dots \beta_{\mu_s}^s) (\alpha_{\alpha_1}^1 \dots \alpha_{\alpha_r}^r v_1^{\mu_1} \dots v_s^{\mu_s}) \end{aligned}$$

Identify $u_1 \otimes \dots \otimes u_r \otimes \beta^1 \otimes \dots \otimes \beta^s$ with this multiplinear map.

Proposition 2. *If V is finite-dim. vector space, or if $V = \Gamma(E)$, for vector bundle $E \rightarrow M$, map*

$$(3) \quad (\otimes_{i=1}^r V) \otimes (\otimes_{j=1}^s V^*) \rightarrow T_s^r(V; R)$$

is an isomorphism.

Definition 4. *tensor that can be written as*

$$(4) \quad u_1 \otimes \dots \otimes u_r \otimes \beta^1 \otimes \dots \otimes \beta^s \equiv u_1 \otimes \dots \otimes \beta^s$$

*is **simple** or **decomposable**.*

Now well that not *all* tensors are simple.

Definition 5 (7.7[1], tensor product). $\forall S \in T_{s_1}^{r_1}(V), \forall T \in T_{s_2}^{r_2}(V)$,
define tensor product

$$(5) \quad S \otimes T \in T_{s_1+s_2}^{r_1+r_2}(V) \\ S \otimes T(\theta^1 \dots \theta^{r_1+r_2}, v_1 \dots v_{s_1+s_2}) := S(\theta^1 \dots \theta^{r_1}, v_1 \dots v_{s_1})T(\theta^{r_1+1} \dots \theta^{r_1+r_2}, v_{s_1+1} \dots v_{s_1+s_2})$$

Proposition 3 (7.8[1]).

$$\tau^{i_1 \dots i_r}_{j_1 \dots j_s} e_{i_1} \otimes \dots \otimes e_{i_r} \otimes e^{j_1} \otimes \dots \otimes e^{j_s} = \tau(e^{i_1} \dots e^{i_r}, e_{j_1} \dots e_{j_s}) e_{i_1} \otimes \dots \otimes e_{i_r} \otimes e^{j_1} \otimes \dots \otimes e^{j_s} = \tau$$

So $\{e_{i_1} \otimes \dots \otimes e_{i_r} \otimes e^{j_1} \otimes \dots \otimes e^{j_s} | i_1 \dots i_r, j_1 \dots j_s \in 1 \dots n\}$ spans $T_s^r(V; R)$

Exercise 7.11. Let basis for V $e_1 \dots e_n$, corresponding dual basis for V^* $e^1 \dots e^n$

Let basis for V $\bar{e}_1 \dots \bar{e}_n$, corresponding dual basis for V^* $\bar{e}^1 \dots \bar{e}^n$

s.t.

$$\bar{e}_i = C_{i_k}^k e_k \\ \bar{e}^i = (C^{-1})^i_k e^k$$

EY:20170404, keep in mind that

$$Ax = e_i A_{i_k}^i e^k (x^j e_j) = e_i A_{j_i}^i x^j = A_{j_i}^i x^j e_i$$

$$Ae_j = e_k A_{i_k}^k e^i (e_j) = A_{j_k}^k e_k = \bar{e}_j$$

$$\bar{\tau}_{jk}^i \bar{e}_i \otimes \bar{e}^j \otimes \bar{e}^k = \bar{\tau}_{jk}^i C_{i_l}^l e_l (C^{-1})_m^j e^m (C^{-1})_n^k e^n = \bar{\tau}_{jk}^i C_{i_l}^l (C^{-1})_m^j (C^{-1})_n^k = \tau_{mn}^l$$

$$\bar{\tau}_{jk}^i = C_k^c C_j^b (C^{-1})_a^i \tau_{bc}^a$$

On Remark 7.13 of Jeffrey Lee (2009) [1]: first, egregious typo for $L(V, V)$; it shoudl be $L(V, W)$. Onward,
for $L(V, W)$,
consider $W \otimes V^* \ni w \otimes \alpha$ s.t.

$$(w \otimes \alpha)(v) = \alpha(v)w \in W, \forall v \in V, \text{ so } w \otimes \alpha \in L(V, W)$$

Now consider (category of) left R -module,

$$(6) \quad {}_R \mathbf{Mod} \ni {}_{\text{Mat}_{\mathbb{K}}(N, M)} \mathbb{K}^N$$

where

$$V = \mathbb{K}^N$$

$$W = \mathbb{K}^M$$

For $A \in \text{Mat}_{\mathbb{K}}(N, M)$, $x \in \mathbb{K}^N$,

$$e_i A_{i_\mu}^i e^\mu (x^\nu e_\nu) = Ax = e_i A_{i_\mu}^i x^\mu, \quad i = 1, 2, \dots M, \mu = 1, 2, \dots N$$

$$A \in \text{Mat}_{\mathbb{K}}(N, M) \cong W \otimes V^* \cong L(V, W)$$

Consider

$$\alpha \in (\mathbb{K}^N)^* = V^* \quad \alpha = \alpha_\mu e^\mu$$

$$w \in \mathbb{K}^M = W \quad w = w^i e_i$$

$$\alpha \otimes w = w \otimes \alpha = w^i \alpha_\mu e_i \otimes e^\mu$$

(remember, isomoprhism between $\text{Mat}_{\mathbb{K}}(N, M)$ and $W \otimes V^*$ guaranteed, if V, W are free R -modules, $R = \mathbb{K}$).

Let V, W be left R -modules, i.e. $V, W \in {}_R \mathbf{Mod}$.

$$V^* \in \mathbf{Mod}_R$$

For $V^* \otimes W \in \mathbf{Mod}_R \otimes {}_R \mathbf{Mod}$

$$\alpha \in V^*, w \in W$$

$$(\alpha \otimes w)(v) = \alpha(v)w, \text{ for } v \in V \in {}_R \mathbf{Mod}$$

But $(w \otimes \alpha)(v) = w\alpha(v)$.

Note $\alpha(v) \in R$.

Let V, W be right R -modules, i.e. $V, W \in \mathbf{Mod}_R$.

$$V^* \in {}_R \mathbf{Mod}$$

For $W \otimes V^* \in \mathbf{Mod}_R \otimes {}_R \mathbf{Mod}$.

$$\alpha \in V^*, w \in W$$

$$(v)(w \otimes \alpha) = w\alpha(v), \text{ with } \alpha(v) \in R, v \in V$$

So $W \otimes V^* \cong L(V, W)$, for $V, W \in \mathbf{Mod}_R$

Definition 6 (7.20[1], contraction). Let $(e_1, \dots e_n)$ basis for V , $(e^1 \dots e^n)$ dual basis.

If $\tau \in T_s^r(V)$, then for $k \leq r, l \leq s$, define

$$(7) \quad C_l^k \tau \in T_{s-1}^{r-1}(V) \\ C_l^k \tau(\theta^1 \dots \theta^{r-1}, w_1 \dots w_{s-1}) := \\ \sum_{a=1}^n \tau(\theta^1 \dots \underbrace{e^a}_{kth \text{ position}} \dots \theta^{r-1}, w_1 \dots \underbrace{e_a}_{ith \text{ position}} \dots w_{s-1})$$

C_l^k is called **contraction**, for some single $1 \leq k \leq r$, some single $1 \leq l \leq s$,

$$C_l^k : T_s^r(V) \rightarrow T_{s-1}^{r-1}(V)$$

s.t.

$$(C_l^k \tau)^{i_1 \dots \hat{i}_k \dots i_r}_{j_1 \dots \hat{j}_l \dots j_s} := \tau^{i_1 \dots a \dots i_r}_{j_1 \dots a \dots j_s}$$

Universal mapping properties can be invoked to give a basis free definition of contraction (EY : 20170405???)
IN general,

$$\forall v_1 \dots v_s \in V, \forall \alpha^1 \dots \alpha^r \in V^*$$

so that

$$v_j = v_j^\mu e_\mu \quad j = 1 \dots s, \quad \mu = 1, \dots \dim V$$

$$\alpha^i = \alpha_\mu^i e^\mu \quad i = 1 \dots r, \quad \mu = 1 \dots \dim V^*$$

then $\forall \tau \in T_s^r(V)$,

$$\tau(\alpha^1 \dots \alpha^r, v_1 \dots v_s) = \tau(\alpha_{\mu_1}^1 e^{\mu_1} \dots \alpha_{\mu_r}^r e^{\mu_r}, v_1^{\nu_1} e_{\nu_1} \dots v_s^{\nu_s} e_{\nu_s}) = \\ = \alpha_{\mu_1}^1 \dots \alpha_{\mu_r}^r v_1^{\nu_1} \dots v_s^{\nu_s} \tau(e^{\mu_1} \dots e^{\mu_r}, e_{\nu_1} \dots e_{\nu_s}) = \alpha_{\mu_1}^1 \dots \alpha_{\mu_r}^r v_1^{\nu_1} \dots v_s^{\nu_s} \tau^{\mu_1 \dots \mu_r}_{\nu_1 \dots \nu_s}$$

which is equivalent to

$$\tau \in T_s^r(V) \xrightarrow{\alpha^1 \otimes \dots \otimes \alpha^r \otimes v_1 \otimes \dots \otimes v_s \otimes} \alpha^1 \otimes \dots \otimes \alpha^r \otimes v_1 \otimes \dots \otimes v_s \otimes \tau \\ \downarrow \\ C_{s+1}^1 C_{s+2}^2 \dots C_{r+s}^r C_1^r C_2^{r+1} \dots C_s^{r+s} \\ \downarrow \\ \tau(\alpha^1 \dots \alpha^r, v_1 \dots v_s) \in R$$

where I've tried to express the right- R -module, "right action" on $\alpha^1 \otimes \dots \otimes \alpha^r \otimes v_1 \otimes \dots \otimes v_s \in V^* \otimes \dots \otimes V$.

Conlon (2008) [10]

Part 2. Prástaro

Prástaro (1996) [6]

2.0.1. *Affine Spaces.* cf. Sec. 1.2 - *Affine Spaces* of Prástaro (1996) [6]

Definition 7 (affine space).

$$(8) \qquad \begin{aligned} & \text{affine space} \qquad (M, \mathbf{M}, \alpha) \\ & \qquad \qquad \qquad \text{with} \\ & M \equiv \text{ set (set of pts.)} \\ & \mathbf{M} \equiv \text{ vector space (space of free vectors)} \\ & \alpha \equiv \mathbf{M} \times M \rightarrow M \equiv \text{ translation operator} \\ & \alpha : (v, p) \mapsto p' \equiv p + v \end{aligned}$$

*Note: α is a **transitive** action and without fixed pts. (free).
i.e. $\forall p \in M$,*

$$\begin{aligned} & \forall \text{ pt. } O \in M, \alpha : (v, O) \mapsto O' \equiv O + v, \alpha(\cdot, O) \equiv \alpha_O \equiv \alpha(O). \quad \alpha_O(v) = O' = O + \mathbf{v} \qquad \forall O' \in M, \exists \mathbf{v} \in \mathbf{M} \text{ s.t. } O' = O + \mathbf{v} \\ & \implies M \equiv \mathbf{M}. \end{aligned}$$

$$\forall (O, \{e_i\})_{1 \leq i \leq n}, \text{ where } \{e_i\} \text{ basis of } \mathbf{M}, M \equiv \mathbf{M} = \mathbb{R}^n \text{ so isomorphism } M \simeq \mathbb{R}^n$$

Definition 8. $(O, \{e_i\}) \equiv$ affine frame.
 \forall affine frame $(O, \{e_i\})$, \exists coordinate system $x^\alpha : M \rightarrow \mathbb{R}$,
where $x^\alpha(p)$ is α th component, in basis $\{e_i\}$, of vector $p - O$

Theorem 6 (1.4 Prástaro (1996) [6]). *Let $(x^\alpha), (\bar{a}^\alpha)$ 2 coordinate systems correspond to affine frames $(O, \{e_i\})$, $(\bar{O}, \{\bar{e}_i\})$, respectively.*

$$(9) \qquad \bar{x}^\alpha = A^\alpha_\beta x^\beta + y^\alpha$$

where

$$y^\alpha \in \mathbb{R}^n, \qquad A^\alpha_\beta \in GL(n; \mathbb{R})$$

Definition 9 (1.10 Prástaro (1996) [6]).

$$(10) \qquad A(n) \equiv Gl(n, \mathbb{R}) \times \mathbb{R}^n$$

affine group of dim. n

Theorem 7 (1.5). *symmetry group of n -dim. affine space, called affine group $A(M)$ of M . \exists isomoprhism,*

$$(11) \qquad A(M) \simeq A(n), \qquad f \mapsto (f^\alpha_\beta, y^\alpha); \qquad f^\alpha \equiv x^\alpha \circ f = f^\alpha_\beta x^\beta + y^\alpha$$

cf. Eq. 1.4 Prástaro (1996) [6]

Part 3. Complex Manifolds

EY : 20170123 I don’t see many good books on Complex Manifolds for physicists other than Nakahara’s. I will supplement this section on Complex Manifolds with external links to the notes of other courses that I found useful to myself.

[Complex Manifolds - Lecture Notes](#) Koppensteiner (2010) [7]
[Lectures on Riemannian Geometry, Part II: Complex Manifolds by Stefan Vandoren](#)
Vandoren (2008) [8]

Part 4. Morse Theory

3. MORSE THEORY INTRODUCTION FROM A PHYSICIST

I needed some physical motivation to understand Morse theory, and so I looked at Hori, et. al. [9].
cf. pp. 43, Sec. 3.4 Morse Theory, from Ch. 3. Differential and Algebraic Topology of Hori, et. al. [9].
Consider smooth $f : M \rightarrow \mathbb{R}$, with non-degenerate critical points.
If no critical values of f between a and b ($a < b$), then subspace on which f takes values less than a is deformation retract of subspace where f less than b , i.e.

$$\{x \in M | f(x) < b\} \times [0, 1] \xrightarrow{F} \{x \in M | f(x) < b\}$$

$$\forall x \in M \text{ s.t. } f(x) < b,$$

$$\begin{aligned} F(x, 0) &= x \\ F(x, 1) &\in \{x \in M | f(x) < a\} \end{aligned} \qquad \text{and } F(a', 1) = a' \qquad \forall a' \in M \text{ s.t. } f(a') < a$$

To show this, consider $-\nabla f / |\nabla f|^2$
Morse lemma: \forall critical pt. p s.t. \exists choice of coordinates s.t.

$$f = -(x_1^2 + x_2^2 + \cdots + x_\mu^2) + x_{\mu+1}^2 + \cdots + x_n^2$$

where $f(p) = 0$ and p is at origin of these coordinates.

- difference between

$$f^{-1}(\{x \leq -\epsilon\}), f^{-1}(\{x \leq +\epsilon\})$$

can be determined by local analysis and only depends on μ , $\mu \equiv$ “Morse index” = number of negative eigenvalues of Hessian of f at critical pt.
Answer:

$$f^{-1}(\{x \leq +\epsilon\}) \text{ can be obtained from } f^{-1}(\{x \leq -\epsilon\}) \text{ by “attaching } \mu\text{-cell” along boundary } f^{-1}(0)$$

- “attaching μ -cell to X mean, take μ -ball $B_\mu = \{|x| \leq 1\}$ in μ -dim. space, identity pts. on boundary $S^{\mu-1}$ with pts. in the space X , through cont. $f : S^{\mu-1} \rightarrow X$, i.e. take

$$X \coprod B_\mu$$

- with $x \sim f(x) \quad \forall x \in \partial B_\mu = S^{\mu-1}$.
- find homology of M ,
 f defines chain complex C_f^* , k th graded piece C^{α_k} , α_k is number of critical pts. with index k .

$$\begin{aligned} \partial : C_p^k &\rightarrow C_p^{k-1} \\ \partial x_a &= \sum_b \Delta_{a,b} x_b \end{aligned}$$

where $\Delta_{a,b} :=$ signed number of lines of gradient flow from x_a to x_b , b labels pts. of index $k - 1$.

- Gradient flow line is path $x(t)$ s.t. $\dot{x} = \nabla(f)$, with $x(-\infty) = x_a$
 $x(+\infty) = x_b$
- To define this number ($\Delta_{a,b}$?), construct moduli space of such lines of flow (???)
by intersecting outward and inward flowing path spaces from each critical point, and then show this moduli space is oriented, 0-dim. manifold (pts. with signs)

- $\partial^2 = 0$ proof

∂ , boundary of space of paths connecting critical points, whose index differs by 2 = union over compositions of paths between critical pts. whose index differs by 1.

\implies coefficients of ∂^2 are sums of signs of pts. in 0-dim. space, which is boundary of 1-dim. space.

These signs must therefore add to 0, so $\partial^2 = 0$.

Hori, et. al. [9] is good for physics, but there isn't much thorough, step-by-step explanations of the math. I will look at Hirsch (1997) [5] and Shastri (2011) [4] at the same time.

3.1. Introduction, definitions of Morse Functions, for Morse Theory. cf. Ch. 6, Morse Theory of Hirsch (1997) [5], Section 1. Morse Functions, pp. 143-

Recall for TM , $T_x M \xrightarrow{\varphi} \mathbb{R}^n$.

Cotangent bundle T^*M defined likewise:

$$T_x^* M \xrightarrow{\varphi} \text{dual vector space } (\mathbb{R}^n)^* = L(\mathbb{R}^n, \mathbb{R})$$

i.e.

$$T^*M = \bigcup_{x \in M} (M_x^*) \quad M_x^* = L(M_x, \mathbb{R})$$

If chart (φ, U) on M , natural chart on T^*M is

$$\begin{aligned} T^*U &\rightarrow \varphi(U) \times (\mathbb{R}^n)^* \\ \lambda &\in M_x^* \mapsto (\varphi(x), \lambda\varphi_x^{-1}) \end{aligned}$$

Projection map

$$\begin{aligned} p : T^* &\rightarrow M \\ M_x^* &\mapsto x \end{aligned}$$

Let C^{r+1} map, $1 \leq r \leq \omega$, $f : M \rightarrow \mathbb{R}$, $\forall x \in M$, linear map $T_x f : M_x \rightarrow \mathbb{R}$ belongs to M_x^*

$$T_x f = Df_x \in M_x^*$$

Then

$$\begin{aligned} Df : M &\rightarrow T^*M \\ x &\mapsto Df_x = Df(x) \end{aligned}$$

is C^r section of T^*M .

Definition 10. critical point x of f is zero of Df , i.e.

$$(14) \quad Df(x) = 0$$

of vector space M_x^* .

Thus, set of critical pts. of f is counter-image of submanifold $Z^* \subset T^*M$ of zeros.

Note $Z^* \approx M$, codim. of Z^* is $n = \dim M$.

Definition 11. Morse function f if \forall critical pts. of f are nondegenerate.

Note set of critical pts. closed discrete subset of M .

Let open $U \subset \mathbb{R}^n$, let C^2 map $g : U \rightarrow \mathbb{R}$,

critical pt. $p \in U$ nondegenerate iff

- linear $D(Dg)(p) : \mathbb{R}^n \rightarrow (\mathbb{R}^n)^*$ bijective
- identify $L(\mathbb{R}^n, (\mathbb{R}^n)^*)$ with space of bilinear maps $\mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}$, \implies equivalent to condition that symmetric bilinear $D^2g(p) : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}$ non-degenerate
- $n \times n$ Hessian matrix

$$\left[\frac{\partial^2 g}{\partial x^i \partial x^j}(p) \right]$$

has rank n

Hessian of g at critical pt. p is quadratic form $H_p f$ associated to bilinear form $D^2g(p)$

$$\implies H_p f(y) = D^2g(p)(y, y) = \sum_{i,j} \frac{\partial^2 g}{\partial x^i \partial x^j}(p) y^i y^j$$

Let open $V \subset \mathbb{R}^n$, suppose C^2 diffeomorphism $h : V \rightarrow U$.

Let $q = h^{-1}(p)$, so q is critical pt. of $gh : V \rightarrow \mathbb{R}$.

$$\begin{array}{ccc} \mathbb{R}^n & \xrightarrow{H_q(gh)} & \mathbb{R} \\ \downarrow Dh(q) & \nearrow H_p g & \\ \mathbb{R}^n & & \end{array}$$

(quadratic) form $(H_p f)$ invariant under diffeomorphisms.

Let C^2 $f : M \rightarrow \mathbb{R}$.

\forall critical pt. x of f , define

Hessian quadratic form

$$H_x f : M_x \rightarrow \mathbb{R}$$

$$H_x f : M_x \xrightarrow{D\varphi_x} \mathbb{R}^n \xrightarrow{H_{\varphi(x)}(f\varphi^{-1})} \mathbb{R}$$

where φ is any chart at x .

Thus, critical pt. of a C^2 real-valued function nondegenerate iff associated Hessian quadratic form is nondegenerate.

Let Q nondegenerate quadratic form on vector space E .

Q negative definite on subspace $F \subset E$ if $Q(x) < 0$ whenever $x \in F$ nonzero.

Index of $Q \equiv \text{Ind} Q$, is largest possible dim. of subspace on which Q is negative definite.

cf. 1.1. Morse's Lemma of Ch. 6, pp. 145, Morse Theory of Hirsch (1997) [5]

Lemma 1 (Morse's Lemma). *Let $p \in M$ be nondegenerate critical pt. of index k of C^{r+2} map $f : M \rightarrow \mathbb{R}$, $1 \leq r \leq \omega$.*

Then $\exists C^r$ chart (φ, U) at p s.t.

$$(15) \quad f\varphi^{-1}(u_1 \dots u_n) = f(p) - \sum_{i=1}^k u_i^2 + \sum_{i=k+1}^n u_i^2$$

Let ${}^T Q \equiv Q^T$ denote tranpose of matrix Q .

Lemma 2. *Let $A = \text{diag}\{a_1, \dots, a_n\}$ diagonal $n \times n$ matrix, with diagonal entries ± 1 .*

Then \exists neighborhood N of A in vector space of symmetric $n \times n$ matrices, C^∞ map

$$(16) \quad P : N \rightarrow GL(n, \mathbb{R})$$

s.t. $P(A) = I$, and if $P(B) = Q$, then $Q^T B Q = A$

Proof. Let $B = [b_{ij}]$ be symmetri matrix near A s.t. $b_{11} \neq 0$ and b_{11} has same sign as a_1 .

Consider $x = Ty$ where

$$\begin{aligned} x_1 &= \left[y_1 - \frac{b_{12}}{b_{11}} y_2 - \dots - \frac{b_{1n}}{b_{11}} y_n \right] / \sqrt{|b_n|} \\ x_k &= y_k \text{ for } k = 2, \dots, n \end{aligned}$$

□

4. LAGRANGE MULTIPLIERS

From *wikipedia:Lagrange multiplier*, https://en.wikipedia.org/wiki/Lagrange_multiplier, find local minima (maxima),
pt. $a \in N$, s.t. \exists neighborhood U s.t. $f(x) \geq f(a)$ ($f(x) \leq f(a)$) $\forall x \in U$.
For $f : U \rightarrow \mathbb{R}$, open $U \subset \mathbb{R}^n$, find $x \in U$ s.t. $D_x f \equiv Df(x) = 0$, check if Hessian $H_x f < 0$.
Maxima may not exit since U open.

References:

[Relative Extrema and Lagrange Multipliers](#)

Other interesting links:

[The Lagrange Multiplier Rule on Manifolds and Optimal Control of nonlinear systems](#)

REFERENCES

[1] Jeffrey M. Lee. **Manifolds and Differential Geometry**, *Graduate Studies in Mathematics* Volume: 107, American Mathematical Society, 2009. ISBN-13: 978-0-8218-4815-9

[2] John Lee, **Introduction to Smooth Manifolds** (Graduate Texts in Mathematics, Vol. 218), 2nd edition, Springer, 2012, ISBN-13: 978-1441999818

[3] Victor Guillemin, Alan Pollack. **Differential Topology**. American Mathematical Society. 2010. ISBN-13: 978-0821851937 https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=0ahUKEwjG96q9z63JAhWMLYgKHempDoMQFggmMAE&url=http%3A%2F%2Fwww.mat.unimi.it%2Fusers%2Fdedo%2Ftop%2520diff%2FGuillemin-Pollack_Differential%2520topology.pdf&usg=AFQjCNF5imOH5xeXRSK60qzM7zT97sdIsW

[4] Anant R. Shastri. **Elements of Differential Topology**. CRC Press. 2011. ISBN-13: 978-0415339209

[5] Morris W. Hirsch, **Differential Topology** (Graduate Texts in Mathematics), Graduate Texts in Mathematics (Book 33), Springer (September 16, 1997). ISBN-13: 978-0387901480

[6] Agostino Prástaro. **Geometry of PDEs and Mechanics**. World Scientific Publishing Co. 1996. QC125.2.P73 1996 530.1'55353–dc20.
Agostino Prástaro. *Dipartimento di Metodi e Modelli Matematici per le Scienze Applicate, Università degli Studi di Roma “La Sapienza”*.

[7] Clemens Koppensteiner. *Complex Manifolds: Lecture Notes*. <http://www.caramdir.at/uploads/math/piii-cm/complex-manifolds.pdf>

[8] Stefan Vandoren. **Lectures on Riemannian Geometry, Part II: Complex Manifolds**. <http://www.staff.science.uu.nl/~vando101/MRILectures.pdf>

[9] Kentaro Hori (Author, Editor), Sheldon Katz (Editor), Albrecht Klemm (Editor), Rahul Pandharipande (Editor), Richard Thomas (Editor), Cumrun Vafa (Editor), Ravi Vakil (Editor), Eric Zaslow (Editor). **Mirror Symmetry** (Clay Mathematics Monographs, V. 1). Clay Mathematics Monographs (Book 1). American Mathematical Society (August 19, 2003). ISBN-10: 0821829556 ISBN-13: 978-0821829554 <https://web.archive.org/web/20060919020706/http://math.stanford.edu/~vakil/files/mirrorfinal.pdf>

[10] Lawrence Conlon. **Differentiable Manifolds** (Modern Birkhäuser Classics). 2nd Edition. Birkhäuser; 2nd edition (October 10, 2008). ISBN-13: 978-0817647667